DEVELOPING MAINTAINABILITY FOR TOKAMAK FUSION POWER SYSTEMS

Phase II Report Volume II — Study Results

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PREFACE

VOLUME II

This report presents the results of the second phase of a 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.A001. The reporting period covers 1 November 1977 through 31 October 1978.

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. In the first phase emphasis was placed on scheduled maintenance using remotely controlled operations and primarily determined by the limited life of the first wall/blanket. Five demonstration or commercial reactor concepts representing large, intermediate and small first wall/blanket modules were selected. The relative maintainability of the conceptual designs is evaluated by the relative availability and cost of electricity of each design.

In this second phase the impact of unscheduled maintenance, several vacuum wall arrangements, and maintenance of other reactor interfacing subsystems and maintenance equipment are added to the evaluation of the maintainability of the reactor concepts. Four concepts are normalized to common performance parameters and evaluated for their capability to achieve availability and cost of electricity goals considering both scheduled and unscheduled maintenance. The results of this evaluation are used to generate a series of maintainability design guidelines and to select the more desirable features and design options which are used to configure a preliminary reactor concept having improved maintainability.

This report contains three volumes. Volume I is an executive summary. Volume II is the discussion of the study results. Volume III includes appendixes which present more detailed data on the reactor maintenance time estimates, on maintenance equipment failure recovery time estimates, and on maintenance equipment conceptual designs and performance.

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1.0 INTRODUCTION

This report describes the results of a maintainability analysis of four reference tokamak fusion reactor concepts. The four selected reference reactor design concepts are Culham Mk-II representative of large first wall/blanket modules, UWMAK-III representative of intermediate size first wall/blanket modules, and ORNL Cassette and the General Atomic Doublet both representative of small first wall/blanket modules. The objectives in the analysis were to (1) assess the impact of reactor design approach on maintenance downtime; (2) to identify desirable maintenance design features; and (3) to formulate total maintenance system concepts.

This particular study is an extension of maintainability analyses initiated in 1977. These earlier studies emphasized scheduled first wall/blanket replacement for a series of five 5000 MW_{th} tokamak fusion power systems. In the 1978 studies we normalized the reference reactor concepts (four in number) to a 3000 MW_{th} size and standardized certain subsystems. The emphasis was on the establishment of unscheduled downtime requirements for making comparisons among the concepts. In addition we configured an improved maintenance system which incorporated many of the results of the comparative analyses.

The availability of a fusion power system for the production of electrical energy is a function of the frequency of shutdowns and the duration of the shutdowns. For scheduled shutdowns, the frequency is related to the life of critical components for which redundancy is either technically infeasible or economically undesirable. For unscheduled shutdowns, the frequency is a function of the reliability of the various subsystems. The duration of either scheduled or unscheduled shutdowns is, of course, a direct result of the maintainability of the system.

In selecting design approaches for new system concepts, it is helpful to establish goals which, if achieved, offer a measure of confidence that the new system will be economically competitive. Such a goal for a new power system would be the cost of producing electrical energy. Since this cost is inversely proportional to the plant availability we are immediately confronted with a dilemma in that the reliability history of new and advanced technologies are not readily at hand. Hence, we cannot accurately predict the total downtime required for a given concept. However, if we set a goal for the cost of electricity and estimate the annual cost, the requirements for plant availability may be established. Furthermore, if we can identify the driver for scheduled shutdowns we can then

establish unscheduled downtime budgets which can then be translated into reliability goals.

The design characteristics most directly influencing the scheduled maintenance time required have been assumed in this study to be those of the first wall and blanket. This subsystem has a limited life resulting from high temperatures, cyclic operation and radiation damage. It therefore requires periodic replacement throughout the life of the reactor. The radiation emitted by the irradiated wall and blanket and the degree of difficulty in accessing this subsystem also strongly influence the reactor maintainability. Considering the need for periodic replacement and the potentially adverse environment, the characteristics affecting the maintainability of the first wall and blanket become critically important and must be closely analyzed.

The characteristics which affect maintainability include the first wall module size; reactor size; the location, number and type of construction of vacuum walls; ease of access; the arrangement of critical subsystems such as cryogenic vacuum pumps and neutral beam injectors or R.F. heaters; divertor design features; the geometric proportions of the reactor; and, the location of poloidal field coils.

The report is organized according to the 1978 study tasks which are:

<u>Task</u>	<u>Section</u>
6 Selecting and Defining the Candidate Reference Systems	3.0
7 Developing the Maintenance Plans	4.0
8 Conducting the Trade-Offs	} 5.0
9 Evaluating the Maintenance Features	
10 Defining a Maintenance System	6.0

In addition to this general organization there are several specific topics which may be useful for reference purposes but are difficult to identify. Table 1.0-1 is provided to aid the reader in locating several of these topics.

TABLE 1.0-1
SPECIFIC TOPIC LOCATION

TOPIC	LOCATION	
	SECTION	PAGE
REFERENCE REACTOR NORMALIZATION PARAMETERS	3.1	3-2
SCHEDULED DOWNTIME COMPARISONS	5.1	5-4
ALLOWABLE UNSCHEDULED DOWNTIMES	5.6	5-20
EFFECT OF VACUUM WALL ARRANGEMENTS	4.2	4-17
IMPACT OF CONTACT OPERATIONS	5.1	5-6, 5-10
IMPROVED MAINTENANCE SYSTEM LAYOUTS	6.1	6-3
EQUIPMENT LISTS	4.3	4-35, 4-87
SKETCHES OF MAINTENANCE EQUIPMENT	APPENDIX B	B-3, B-41
PERSONNEL REQUIREMENTS	5.1	5-4

2.0 SUMMARY OF BASIC DATA

The study required the generation of the basic data needed as inputs to the trade studies and evaluation analyses. These analyses, in turn, are used to identify the relative maintainability of the reactor concepts. The basic data generated is of two types. One is the reactor design data and the other is the time, equipment and personnel data. Design data identifies the hardware on which the maintenance functional flow sequences and scenarios are based. This data is detailed in Section 3.0. The maintenance plan data identifies the characteristics of each scenario in terms of maintenance scheduled and unscheduled downtimes, the equipment required and the maintenance personnel used to conduct the operations. The generation of this data is detailed in Section 4.0.

2.1 REFERENCE REACTOR DESIGN DATA - Four of the tokamak demonstration or commercial size reactor concepts examined in the initial phase of the study (Reference 2-1) are resized to common performance characteristics, insofar as feasible. These four reactor concepts are the UWMAK-III, General Atomic-DPR (Doublet), Culham Mark II and ORNL Cassette. Major subsystems of these four concepts were normalized. The use of these normalized subsystems permits the definition of maintainability and cost impacts that are based solely on the unique characteristics of each reactor concept and not on unrelated subsystem variations. The subsystems addressed were the first wall/blanket, vacuum pumping, primary cooling, supplemental plasma heating and magnets.

The normalized characteristics for the four reactor concepts are summarized in Table 2.1-1. Wherever possible the same value is selected for each pertinent parameter that defines the concept design. However, primarily because of the core dimensional constraints and the use of minimum cost of electricity as a criterion for selection, the major radii selected range from 6.5 to 7.5 meters. Plasma chamber wall areas and wall power loadings vary because of the differences in wall design, plasma elongation ratios and the major radius variations. All plasma characteristics are examined over a range of major radii and the particular values then are chosen at the point of the constant power curve that results in minimum cost of electricity.

The four reactor concepts are shown in cross section to the same scale in Figure 2.1-1. These sections show the divertor and cryovacuum pump arrangement selected for each concept. The UWMAK-III cryovacuum pump arrangement is selected for all concepts except the GA-Doublet because, aside from the fact that its performance is defined, it provides an arrangement with maximum conductance and a

TABLE 2.1-1
REFERENCE REACTOR CHARACTERISTIC SUMMARY

REACTOR TYPE	UWMAK-III	GA-DOUBLET	CULHAM	ORNL CASSETTE
PEAK THERMAL POWER, MW_{th}	3000	3000	3000	3000
MAJOR RADIUS, m	6.5	6.5	7.5	7.5
ASPECT RATIO	3.7	4.6	3.9	3.9
PLASMA ELONGATION RATIO	2	3	2	2
NEUTRON WALL LOADING, MW/m^2	2.74	2.36	2.12	2.02
WALL AREA, m^2	781	888	991	1037
NUMBER OF TOROIDAL FIELD MAGNETS	16	16	16	16
NUMBER OF NEUTRAL BEAM INJECTORS	12	12	12	12
WALL/BLANKET COOLANT	LITHIUM (OUTER) HELIUM (INNER)	HELIUM	HELIUM	HELIUM

SELECTED REFERENCE DESIGNS:

13-1956

FIGURE 2.1-1

pumping area that is readily adaptable to meet the requirements of single or double divertors. The flowing plasma boundary impurity control concept of the GA-Doublet differs from the divertors used for the other concepts and cylindrical pumps are selected. The vacuum pump characteristics are summarized in Table 2.1-2.

The toroidal field magnet sizes are determined by the required envelope for each concept. All coils approach the constant tension design shape but are designed to fit the plasma chamber as closely as possible and still retain the maintenance

TABLE 2.1-2
VACUUM PUMPING SYSTEM SUMMARY

REACTOR CONCEPT	UWMAK-III	GA-DOUBLET	ORNL CULHAM CASSETTE	
<u>PLASMA CHAMBER SYSTEM</u>				
PUMP TYPE	←←	CRYOSORPTION	→→	
PUMP TEMPERATURE, °K	←←	4.2	→→	
NUMBER OF CHAMBERS	2	1	2	2
NUMBER OF PUMPS	*32	32 UPPER, 16 LOWER	*16	*16
TOTAL ACTIVE AREA PER PUMP, m ²	26.5	32.2 UPPER, 64.5 LOWER	52.4	52.4
<u>NEUTRAL BEAM SYSTEM</u>				
PUMP TYPE	←←	CRYOSORPTION	→→	
PUMP TEMPERATURE, °K	←←	4.2	→→	
NUMBER OF PUMPS	←←	*12	→→	
TOTAL ACTIVE AREA PER PUMP, m ²	←←	66	→→	
<u>REGENERATION PUMPING</u>				
NUMBER OF PUMP SETS	←	4	→	
PUMP/SET				
ROOTS BLOWERS	1	2	1	1
ROTARY PISTON PUMPS	3	4	3	3
PUMP DRIVE POWER/SET, HP	90	140	90	90
REGENERATION PUMPING TIME, Hrs.	5.3	5.7	5.3	5.3
<u>SECONDARY CHAMBER PUMPING</u>				
NUMBER OF PUMP SETS	2	--	9	9
PUMPS/SET				
ROOTS BLOWERS	1	--	2	2
ROTARY PISTON PUMPS	3	--	-	-
ESH PUMPS, SINGLE STAGE	-	--	4	4
PUMP DRIVE POWER/SET, HP	90	--	1500	1500
PUMPDOWN TIME, HRS.	12.2	--	32	32

* DUAL PUMPS - ONLY ONE SIDE OPERATING AT A TIME

features of the original concept. Poloidal field magnets are arranged as closely as possible to the arrangement of the concept except that the ORNL Cassette concept utilizes a combined arrangement to accommodate the divertor that is not included in the original ORNL Demonstration Power Study. All coils are superconducting with NbTi conductors and of unitary design, i.e., not segmented. Scaling of the magnet locations is based on a relationship incorporated in the TOCOMO code for all reactors. A summary of the magnet characteristics for each concept is included in Table 2.1-3.

Neutral beam injectors (NBI's) of the type designed for the Tokamak Fusion Test Reactor (TFTR) being built at Princeton are selected for all concepts. Hence, for UWMak-III, the RF heater system is replaced by NBI's. The maintenance characteristics of a reactor will be affected by the selection of RF heaters or NBI's and the latter is selected because of their relative feasibility at this time. The characteristics of these NBI's are summarized in Table 2.1-4.

The primary cooling system for each concept influences the cross sections shown in Figure 2.1-1 to the extent that all primary coolant lines are passed through the floor of the reactor room to the pumps, heat exchangers and the secondary coolant loops. Two cooling systems are defined. Both use the thermal energy distribution

TABLE 2.1-3
MAGNET SYSTEM SUMMARY

REACTOR CONCEPT	UWMak-III	GA-DOUBLET	CULHAM	ORNL CASSETTE
<u>TOROIDAL FIELD MAGNETS</u>				
NUMBER OF MAGNETS	16	16	16	16
HEIGHT OVERALL, m	20.4	15.1	22.3	19.3
OUTER RADIUS FROM REACTOR G , m	14.4	13.8	15.6	14.0
MAXIMUM FIELD, T	8.66	8.66	8.66	8.66
ON AXIS FIELD, T	4.11	4.62	3.87	3.88
STORED ENERGY, GJ	57.0	44.9	64.0	52.0
<u>POLOIDAL FIELD MAGNETS</u>				
NUMBER OF VERTICAL FIELD MAGNETS	40	32	15	15
LOCATION (RELATIVE TO TF COILS)	INSIDE	INSIDE	8 INSIDE 6 OUTSIDE	INSIDE
NUMBER MOVABLE FOR MAINTENANCE	10	NONE	3	NONE
STORED ENERGY, GJ	3.4	3.1	11.3	5.7
NUMBER OF TRANSFORMER MAGNETS	26	32	14	15

TABLE 2.1-4
NEUTRAL BEAM INJECTOR CHARACTERISTIC SUMMARY

REACTOR CONCEPTS	ALL
NUMBER OF NBI UNITS	12
NUMBER OF ION SOURCES/UNIT	3
INJECTED POWER/SOURCE, MW	1.67
BEAM ENERGY, keV	120
CHAMBER SIZE, m X m X m	5.7L X 3.0W x 5.0H
CHAMBER WEIGHT, TONS	~60

between the divertor and first wall/blanket employed for the UWMAK-II. One system uses lithium and the other uses helium in the first wall/blanket cooling loop. Sodium is used as the coolant by both of the divertor primary loops and by all of the secondary cooling loops. The primary loops service 2 reactor sectors per loop and include 2 loops for each primary system, thus requiring 4 systems for each reactor. The characteristics of these systems are summarized in Table 2.1-5.

The first wall/blanket design for each reference reactor differs significantly as indicated by the module summary shown in Figure 2.1-2. The UWMAK-III first wall/blanket module uses a "U" bend section with a uniform cross section around the torus except for the graphite panels used on the plasma chamber inner wall. The heat cells for the GA-Douplet and the cells lining the Culham concept sectors are similar in that both are domed cylinders. However, the Culham design includes the inner shield and all cells in one sector are mounted in a single removable sector module (not including the cells at the divertor). The ORNL Cassette concept uses a tubular, helium cooled first wall configured in flat cassettes and requires 3 cassette layers to make up the total blanket thickness. These configurations results in 5 first wall/blanket modules and 3 graphite panels for each UWMAK-III sector, in a 2 large modules with a total of 175 heat cells for each Culham sector, in 36 cassettes and one divertor module for each ORNL Cassette reactor sector and in 113 modules in each GA-Douplet sector. Each reference reactor configuration contains a total of 16 sectors. These four widely different blanket designs and modularization techniques are retained as closely as possible from the original concepts, but are changed in size or number as required to satisfy the revised reactor sizes.

The designs presented in this report are normalized to the point where comparative maintenance plans (for example, for first wall/blanket replacement) will

TABLE 2.1-5
COOLING SYSTEM CHARACTERISTIC SUMMARY

REACTOR CONCEPT	UWMAK-III	GA-DOUBLET	CULHAM	ORNL CASSETTE
<u>PRIMARY COOLANT LOOP</u>				
BLANKET COOLANT				
OUTER WALL	LITHIUM	HELIUM	HELIUM	HELIUM
INNER WALL	HELIUM	HELIUM	HELIUM	HELIUM
COOLANT TEMP, MAX, °C	540	540	540	540
NUMBER OF LOOPS PER REACTOR	8	8	8	8
NUMBER OF COOLANT SYSTEMS/REACTOR	4 ⁽¹⁾	4 ⁽²⁾	4 ⁽²⁾	4 ⁽²⁾
TOTAL THERMAL POWER PER LOOP, MW	317.5	317.5	317.5	317.5
<u>SECONDARY COOLANT LOOP</u>				
COOLANT	SODIUM	SODIUM	SODIUM	SODIUM
COOLANT TEMP, MAX. °C	510	510	510	510
<u>DIVERTOR PRIMARY COOLANT LOOP</u>				
COOLANT	LITHIUM	---	LITHIUM	LITHIUM
COOLANT TEMP, MAX, °C	600		600	600
NUMBER OF LOOPS PER REACTOR	1		1	1
TOTAL THERMAL POWER, MW	429		429	429

- NOTES: ○ DIVERTOR SECONDARY LOOP USES SODIUM COOLANT.
 ○ SECONDARY LOOPS INCLUDE THERMAL STORAGE SYSTEMS.

(1) SYSTEM SHARES ONE INTERMEDIATE HEAT EXCHANGER AND ONE STEAM GENERATOR FOR TWO LOOPS

(2) SYSTEM SHARES ONLY STEAM GENERATOR FOR TWO LOOPS

be based upon reactors that are similar enough in size and performance to show the significant advantages and disadvantages of the design concepts without the influence of extraneous factors. These maintenance plans are summarized in quantitative terms of downtime, manpower and the capital cost of maintenance equipment and facilities in the next section.

2.2 MAINTENANCE PLAN INPUT DATA - Maintenance plan scenarios have been developed for all four reference reactors but to varying degrees of complexity for different analyses. All scenarios are first developed for maintenance of a single sector in either a scheduled or unscheduled, fully remote or contact

REFERENCE REACTOR FIRST WALL/BLANKET MODULES

FIGURE 2.1-2

assisted operation and with up to three different vacuum wall arrangements. However, it was necessary to develop scenarios for only a limited number of these potential combinations in order to provide the data base for the desired analyses. Figure 2.2-1 indicates all of the conditions for which scenarios have been developed, including the scenarios for selected subsystem components other than first wall/blanket and the scenarios for maintenance equipment failures. In identifying equipment failure scenarios, the figure indicates an "X" for each different failure mode examined.

Figure 2.2-2 illustrates the location of the outer, or primary, vacuum wall location for the three vacuum wall location arrangements cited in Figure 2.2-1. Arrangement 1 usually has only one vacuum zone, except for the Culham concept which has two. Arrangements 2 and 3 each have two vacuum zones, except 3 are used for Culham. The time requirements differ among the vacuum wall arrangements for each reactor concept because of different pump down times and different sequences in the

SCOPE OF MAINTENANCE SCENARIO DEFINITIONS

MAINTENANCE TYPE	CULHAM				UWMK-III				ORNL CASSETTE				GA-DOUBLET			
	SCHEDULED		UNSCHEDULED		SCHEDULED		UNSCHEDULED		SCHEDULED		UNSCHEDULED		SCHEDULED		UNSCHEDULED	
	CONTACT	REMOTE	CONTACT	REMOTE	CONTACT	REMOTE	CONTACT	REMOTE	CONTACT	REMOTE	CONTACT	REMOTE	CONTACT	REMOTE	CONTACT	REMOTE
MAINTENANCE SCENARIO																
o FIRST WALL/BLANKET EXCHANGE																
- VACUUM WALL LOCATION NO. 1	-	-	X	-	X	X	X	X	-	-	X	-	X	X	X	X
- VACUUM WALL LOCATION NO. 2	-	-	X	-	X	X	X	X	-	-	X	-	-	-	-	-
- VACUUM WALL LOCATION NO. 3	X	X	X	X	X	X	X	X	X	X	X	X	-	-	-	-
o CRYOVACUUM PUMP VALVE EXCHANGE																
- VACUUM WALL LOCATION NO. 1	-	-	-	-	-	-	X	X	-	-	-	-	-	-	X	X
- VACUUM WALL LOCATION NO. 2	-	-	-	-	-	-	X	X	-	-	-	-	-	-	-	-
- VACUUM WALL LOCATION NO. 3	-	-	-	-	-	-	X	X	-	-	-	-	-	-	-	-
o CRYOVACUUM PUMP EXCHANGE																
- VACUUM WALL LOCATION NO. 1	-	-	-	-	-	-	X	X	-	-	-	-	-	-	X	X
- VACUUM WALL LOCATION NO. 2	-	-	-	-	-	-	X	X	-	-	-	-	-	-	-	-
- VACUUM WALL LOCATION NO. 3	-	-	-	-	-	-	X	X	-	-	-	-	-	-	-	-
o NBI ION SOURCE EXCHANGE																
- VACUUM WALL LOCATION NO. 1	← VALID FOR ALL REFERENCE REACTORS →															
- VACUUM WALL LOCATION NO. 2	← VALID FOR ALL REFERENCE REACTORS →															
- VACUUM WALL LOCATION NO. 3	← VALID FOR ALL REFERENCE REACTORS →															
o MAINTENANCE EQUIPMENT FAILURE (SELECTED SCENARIOS)																
- REMOTE REPAIR	N/A	N/A	-	XX	N/A	N/A	-	XX	N/A	N/A	-	XXX	N/A	N/A	-	XXX
- CONTACT REPAIR	N/A	N/A	-	-	N/A	N/A	X	-	N/A	N/A	-	-	N/A	N/A	-	-

VACUUM WALL LOCATION DEFINITIONS

LOCATION NUMBER	PRIMARY VACUUM WALL LOCATION
1	FIRST WALL OR BLANKET
2	OUTER SHIELD OR LSAP
3	REACTOR ROOM WALL

LEGEND: X; SCENARIO DEFINED
 -; NO SCENARIO DEFINED
 N/A; NOT APPLICABLE

FIGURE 2.2-1

NOTE: CULHAM PRIMARY VACUUM WALL AT OUTER SHIELD FOR ARRANGEMENT #1. GA-DOUBLET DEFINED FOR ONLY ARRANGEMENT #1.

FIGURE 2.2-2

maintenance operations. Trends found in the UWMAK-III scenarios are estimated to hold for the other concepts, except for the GA-Doubllet where no measureable time difference is expected. Therefore, estimates were made for only the scenarios indicated. This data and the detailed supporting estimates serve as the basis for the optimization scenarios defined for first wall/blanket exchange and for the first wall/blanket failure mode scenarios.

The elapsed time required to conduct the maintenance actions for each first wall/blanket scenario is tabulated in Table 2.2-1. These times assume three shift operation with a productivity factor of .75 which results in an effective working period per man per shift of 6 hours.

The translation of the down time estimates in Table 2.2-1 into maintenance plans necessitates the definition of the maintenance equipment required to conduct each scenario. Individual equipment items are combined into a basic equipment set, including spares, for conducting operations on one sector. The weight of all equipment items are combined into a set weight. For the variations in operations required by alternative scenarios, additional individual equipment items are added as required and an equivalent number of sets is calculated based on total weights. Table 2.2-2 indicates the weight of each set of equipment and the multiple sets required when conducting scheduled operations on the first wall/blanket.

TABLE 2.2-1
SUMMARY OF FIRST WALL/BLANKET REPLACEMENT DOWNTIMES AT
VARIOUS VACUUM WALL LOCATIONS

PRIMARY VACUUM WALL LOCATION ⁽²⁾	REPLACEMENT TIME (WORKING DAYS) ⁽¹⁾		
	#1 (AT BLANKET)	#2 (AT SHIELD/LSAP)	#3 (AT REACTOR ROOM WALL)
REFERENCE REACTOR CONCEPT (INCLUDING MAINTENANCE SCENARIO)			
CULHAM			
UNSCHEDULED MAINTENANCE ⁽³⁾			
CONTACT OPERATIONS	19.4	19.7	17.5
REMOTE OPERATIONS	--	--	24.7
SCHEDULED MAINTENANCE			
CONTACT OPERATIONS	--	--	20.2
REMOTE OPERATIONS	--	--	27.4
UWMAK-III			
UNSCHEDULED MAINTENANCE ⁽³⁾			
CONTACT OPERATIONS	47.7	43.6	41.3
REMOTE OPERATIONS	67.1	64.2	59.7
SCHEDULED MAINTENANCE			
CONTACT OPERATIONS	41.9	37.7	35.5
REMOTE OPERATIONS	61.3	58.4	53.9
ORNL			
UNSCHEDULED MAINTENANCE ⁽³⁾			
CONTACT OPERATIONS	33.2	30.9	31.04
REMOTE OPERATIONS	--	--	35.7
SCHEDULED MAINTENANCE			
CONTACT OPERATIONS	--	--	45.0
REMOTE OPERATIONS	--	--	55.2
GA-DOUBLET			
UNSCHEDULED MAINTENANCE ⁽³⁾			
CONTACT OPERATIONS	7.1	--	--
REMOTE OPERATIONS	7.1	--	--
SCHEDULED MAINTENANCE			
CONTACT OPERATIONS	15.2	--	--
REMOTE OPERATIONS	15.2	--	--

- (1) TIME IS DILUTED, i.e., PRODUCTIVITY FACTOR OF .75 IS INCLUDED, ASSUMES 3 SHIFT OPERATION
- (2) REFERENCE FIGURE 2.2-2 FOR LOCATION DEFINITIONS.
- (3) UNSCHEDULED MAINTENANCE FOR ONE MODULE ONLY, SCHEDULED MAINTENANCE FOR ONE SECTOR.

These operations are conducted on 8 sectors at one time out of the total of 16 sectors in the UWMAK-III, Culham and ORNL Cassette reactors, or on 456 modules out of the total of 1808 in the GA-Douplet. The scheduled maintenance scenario to which this equipment applies results in the minimum COE for each reference reactor. Several similar scenarios were compared to select this minimum COE scenario. Additional equipment details are found in Sections 4.3 and 4.4 and in Appendix B, Volume III.

TABLE 2.2-2
MAINTENANCE EQUIPMENT REQUIREMENTS FOR
FIRST WALL/BLANKET SCENARIOS

	CULHAM	UWMAK-III	ORNL CASSETTE	GA-DOUBLET
BASIC SET WEIGHT (TONNES) ⁽¹⁾				
CONTACT OPERATIONS	3310.8	2528.8	1407.8	9826.9 ^{(2) (3)}
REMOTE OPERATIONS	3310.8	2528.8	1407.8	2623.2
EQUIVALENT SETS REQUIRED				
UNSCHEDULED				
CONTACT	1.01	1.0	1.0	.88
REMOTE	1.01	.99	.99	.86
SCHEDULED				
CONTACT	2.62	4.43	4.22	1.07
REMOTE	2.62	4.41	4.48	1.16
SECTORS WORKED SIMULTANEOUSLY ⁽⁴⁾	8.0	8.0	8.0	16.0 ⁽⁵⁾
TOTAL SECTORS (MODULES) WORKED	8.0	8.0	8.0	(456) ⁽⁶⁾

(1) DOES NOT INCLUDE OVERHEAD CRANE

(2) INCLUDES EQUIPMENT SHIELDING

(3) INCLUDES OVERHEAD REMOTE MANIPULATOR AND 8 BASIC MAINTENANCE MACHINES

(4) SCENARIO FOR MINIMUM COST OF ELECTRICITY SELECTED AS EXAMPLE

(5) USING A COMPLETE SET OF 8 IN-PLACE UNITS.

(6) 25% OF MODULES ARE REPLACED IN EACH OF OF THE 16 SECTORS.

The number of direct operating personnel required to operate the maintenance equipment and to conduct the contact maintenance operations were also estimated for each first wall/blanket scenario and are summarized in Table 2.2-3. This table shows the maximum number of operators and floor crew (used for contact operations) required during the maintenance operation for each scenario. The mix of operators and floor crew varies during a maintenance operation but skill interchangeability is assumed. Also, the COE values defined for the first wall/blanket maintenance analyses considered that these personnel are required only during the downtime

period and that a nominal maintenance force is sufficient for all other plant maintenance and repair operations. Since the time required to conduct all maintenance operations except shutdown and startup is directly a function of the effectiveness of the maintenance personnel, a productivity factor of 75% is applied to this time rather than increasing the number of personnel to overcome this deficiency. This factor accounts for such lost time as training, shift change, lunch, and personal needs. While this factor appears high, compensating conditions can possibly attract the type of individual that will achieve such a level of proficiency.

TABLE 2.2-3
MAXIMUM DIRECT OPERATING PERSONNEL PER SHIFT FOR
FIRST WALL/BLANKET SCENARIOS

	CULHAM	UWMAK-III	ORNL CASSETTE	GA-DOUBLET
UNSCHEDULED MAINTENANCE				
CONTACT	12	20	12	7
REMOTE	8	8	11	4
SCHEDULED MAINTENANCE				
CONTACT ⁽¹⁾	82	146	76	24
REMOTE ⁽¹⁾	50	50	74	14
SECTORS WORKED SIMULTANEOUSLY	8	8	8	16
TOTAL SECTORS (MODULES) WORKED	8	8	8	(456) ⁽²⁾

(1) THE FLOOR CREWS REQUIRED FOR CONTACT MAINTENANCE EXCEED THE DIFFERENCE IN DIRECT OPERATING PERSONNEL BETWEEN CONTACT AND REMOTE MAINTENANCE FOR SOME MAINTENANCE FUNCTIONS.

(2) 25% OF THE MODULES ARE REPLACED IN EACH OF THE 16 SECTORS.

Maintenance plans for unscheduled first wall/blanket maintenance utilize the unscheduled operations time specified in Table 2.2-1. For each plan the scenario assumes that the failure mode is a leak in the least accessible module for the specific reference reactor. Thus, for Culham the leak is in the divertor module, for UWMAK-III the divertor module is also chosen, for the ORNL Cassette concept the leak is in the third blanket zone module in the upper outboard blanket, and for the GA-Doublet an average module location is selected because access time differs very little for any single module. Additional detail is found in Section 4.3 and Appendix A, Volume III.

Maintenance plans for scheduled first wall/blanket replacement require consideration of the number of sectors worked simultaneously and the fraction of the first wall blanket replaced during any one outage. The downtime per outage is

defined for each plan by establishing a functional sequence which includes multiple parallel operations and traffic requirements and which utilizes the detailed single sector functional sequences on which the elapsed times listed in Table 2.2-1 are based. Table 2.2-4 gives the total elapsed time required for the minimum COE maintenance plans. Other maintenance plans for scheduled first wall/blanket replacement have been developed using different numbers of sectors worked at one time and different wall fractions replaced during an outage. The comparison of the COE resulting from these plans was used to determine the minimum COE plan. Table 2.2-5 defines the selected sector combinations for which plans have been developed for each reactor. The details of the data developed for each of these plans are found in Section 4.4.

TABLE 2.2-4
TOTAL OUTAGE TIME REQUIRED FOR SCHEDULED
FIRST WALL/BLANKET REPLACEMENT

	CULHAM	UWMAK-III	ORNL CASSETTE	GA-DOUBLET
SCHEDULED DOWNTIME, DAYS ⁽¹⁾				
CONTACT OPERATIONS	30.4	56.9	54.9	43.4
REMOTE OPERATIONS	37.7	78.3	64.1	45.0
SECTORS WORKED SIMULTANEOUSLY	8	8	8	16
TOTAL SECTORS (MODULES) REPLACED	8	8	8	(456) ⁽²⁾

(1) ALL TIME ESTIMATES ARE DILUTED BY A PRODUCTIVITY FACTOR OF .75 AND ASSUME A 3 SHIFT OPERATION.

(2) 25% OF MODULES ARE REPLACED IN EACH SECTOR.

For the failure analysis of subsystem components other than the first wall/blanket, only the outage times were developed and evaluated. The additional equipment and personnel required appear to be insignificant when compared with the first wall/blanket requirements. Table 2.2-6 delineates the total time required to replace the other subsystem components examined in this study. These times assume that the replacement is required as the result of an unscheduled component failure. The major variation in downtime among the different vacuum wall arrangements is caused by the increase in pump down time during reactor startup operations. Additional detail is found in Section 4.5.

The maintenance requirements for selected failure modes of the maintenance equipment were also developed and are summarized in Table 2.2-7. Each of these failure modes is assumed to occur during either a scheduled or an unscheduled maintenance operation. All failure modes except those listed as "General" can occur

TABLE 2.2-5
FIRST WALL/BLANKET SECTOR COMBINATIONS
SELECTED FOR MAINTENANCE PLANS

	CULHAM		UWMAK-III		ORNL CASSETTE		GA-DOUBLET	
	TOTAL SECTORS WORKED	SECTORS WORKED SIMULTANEOUSLY	TOTAL SECTORS WORKED	SECTORS WORKED SIMULTANEOUSLY	TOTAL SECTORS WORKED	SECTORS WORKED SIMULTANEOUSLY	TOTAL MODULES WORKED ⁽¹⁾	SECTORS WORKED SIMULTANEOUSLY
CONTACT OPERATIONS	16	8	8	8	16	8	456	16
	16	4	8	4	16	4	360	16
	8	8	8	2	8	8	304	16
	8	4	4	4	8	4		
	4	4	4	2	4	4		
	4	2	4	1	4	2		
REMOTE OPERATIONS	16	8	16	8	16	8	456	16
	16	4	16	4	16	4	360	16
	8	8	8	8	8	8	304	16
	8	4	8	4	8	4		
	4	4	4	4	4	4		
	4	2	4	2	4	2		
MODULES REPLACED/SECTORS	2		3		16		VARIES WITH REPLACEMENT FRACTION	

(1) A TOTAL OF 1808 MODULES ARE IN THE GA-DOUBLET REACTOR. REPLACED MODULE QUANTITIES ARE DIVIDED UNIFORMLY AMONG THE 16 SECTORS.

TABLE 2.2-6
TOTAL OUTAGE TIME REQUIRED BY SELECTED
SUBSYSTEM FAILURE

MAINTENANCE MODE		ESTIMATED DOWNTIME DAYS/FAILURE ⁽¹⁾					
		CONTACT OPERATIONS			REMOTE OPERATIONS		
VACUUM WALL ARRANGEMENT		1	2	3	1	2	3
REACTOR	FAILED COMPONENT						
ALL	NEUTRAL BEAM ION SOURCE	3.1	3.3	3.8	3.8	4.0	4.5
GA-DOUBLET	CRYOVACUUM PUMP VALVE	4.2	-	-	4.4	-	-
GA-DOUBLET	CRYOVACUUM PUMP	4.8	-	-	5.6	-	-
UWMAK-III	CRYOVACUUM PANEL	5.0	5.3	5.7	6.1	6.4	6.8

(1) ALL TIME ESTIMATES DILUTED BY .75 PRODUCTIVITY FACTOR

during scheduled first wall/blanket operations and can be added to scheduled downtime in the maintenance analysis. The failure recovery times shown in Table 2.2-7 are the net increases in the scheduled downtime for each maintenance action during which the maintenance equipment failure occurs. This net increase is the additional downtime required to return to the same point in the scheduled outage at which the equipment failure occurred. On the other hand, the failure reaction time is the elapsed time required for all additional maintenance operations required by the failure. This is the time during which additional equipment and personnel are required and, therefore, this failure reaction time determines when such equipment and personnel are unavailable for other maintenance operations. Since failed equipment maintenance operations can overlap continuing scheduled operations, the reaction time is frequently larger than the recovery time. Reaction times can also be shorter than recovery times when scheduled operations must be repeated as a result of the failure. The failure frequencies shown in Table 2.2-7 are assumed values based on the maintenance equipment complexity, technology required, and maintainability. Most of the recovery times are relatively short except where internal access to the plasma chamber must be reworked such as for the UWMAK-III and the GA-Doublet. Additional detail is defined in Section 4.6 and Appendix B.

TABLE 2.2-7
MAINTENANCE EQUIPMENT FAILURE MODE
RECOVERY TIME SUMMARY

FAILURE MODE			FAILURE RECOVERY TIME DAYS ⁽¹⁾	FAILURE REACTION TIME DAYS ⁽¹⁾	ASSUMED UNIT FAILURE FREQUENCY, CALENDAR YRS
REACTOR	EQUIPMENT	FUNCTION			
CULHAM	MODULE TRANSPORTER	MODULE WITHDRAWAL	5.4	5.9	20
	COOLANT DUCT WORKHEAD	WELDING DUCT FLANGE	1.0	1.0	10
UWMAK-III	"B" MODULE WORKHEAD	LOWERING "B" MODULE	20.2	59.7	10
	"A" MODULE WORKHEAD	"A" MODULE WITHDRAWAL	2.4	3.3	10
	MAGNET RETRACTION ACTUATOR	PF MAGNET RETRACTION	4.1	7.8	3
ORNL	"A" CASSETTE EXTRACTOR	"A" CASSETTE EXTRACTION	2.2	2.2	10
	DIVERTOR MODULE WORKHEAD	DIVERTOR MODULE EMPLACEMENT	2.8	2.8	10
	CAB ENVIRONMENTAL CONTROL	CREW ATMOSPHERE CONTROL	1.9	1.9	2
GA-DOUBLET	REMOTE MAINTENANCE MACHINE	REMOVING MODULE	8.0	8.0	10 ⁽²⁾
	RMM ISOLATION VALVE	SEAL	9.5	9.1	10 ⁽²⁾
GENERAL	GENERAL PURPOSE MAINT. MACH. OPERATIONAL MAINT. UNIT	REPLACE VACUUM PUMP VALVE	.6	.6	5
		REPLACE ION SOURCE	.3	.3	8

(1) ALL TIME ESTIMATES DILUTED BY .75 PRODUCTIVITY FACTOR.
THESE ARE THE TOTAL DAYS REQUIRED/FAILURE.

(2) ASSUMES REGULAR PREVENTATIVE MAINTENANCE.

2.3 MAINTENANCE PLAN OUTPUT DATA - The maintenance plan data derived for each combination of first wall/blanket sector replacement identified in Table 2.2-5 was used to compute the availability and cost of electricity for each plan. The TOCOMO code used to compute those values also selected the plant for each reactor which produced electricity at the lowest unit cost. Table 2.3-1 summarizes the outputs for each maintenance plan. The plans included in this table are all for scheduled replacement of the first wall/blanket. Data defined for failure outages is summarized in Section 2.2 since working on multiple sectors with integrated procedures is not required for that type of maintenance action.

The total downtime per outage given in Table 2.3-1 was derived from the data for the selected vacuum wall arrangement and the single sector scenarios identified in Table 2.2-1. Nominal traffic delays and movement time for equipment and reactor components is included. The availability is the ratio of the reactor operating time between scheduled outages to the total time between scheduled outages. The total time includes the reactor operating time, the downtime during the scheduled outage with concurrent balance of plant maintenance outages, and allowances for forced outages. The cost of electricity is the total annual operating cost per unit of electricity produced during the year and includes the effects of reduced production caused by all outages during the year.

The basic data from each of the maintenance plans summarized in Table 2.3-1 was used to conduct many of the trade studies presented in Section 5.0.

2.4 REFERENCES

- 2-1. "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 Department of Energy, Report No. C00-4184-4, October 1977.

TABLE 2.3-1
DATA OUTPUT FROM FIRST WALL/BLANKET SCHEDULED MAINTENANCE PLANS

	WALL FRACTION REPLACED	WALL FRACTION WORKED AT ONE TIME (1)	TOTAL DOWNTIME PER OUTAGE, DAYS (2)				AVAILABILITY				COST OF ELECTRICITY MILLS/kWh			
			CULHAM	UWMAK-III	ORNL CASSETTE	GA- DOUBLET (1)	CULHAM	UWMAK-III	ORNL CASSETTE	GA- DOUBLET (1)	CULHAM	UWMAK-III	ORNL CASSETTE	GA- DOUBLET (1)
CONTACT OPERATIONS	1	1/2	47	-	99	-	.78	-	.75	-	52.2	-	53.0	-
	1	1/4	69	-	176	-	.77	-	.70	-	52.6	-	55.7	-
	1/2	1/2	30*	57*	55*	-	.79*	.74*	.76*	-	50.3*	51.4*	51.0*	-
	1/2	1/4	50	85	100	-	.77	.70	.71	-	51.6	53.1	54.1	-
	1/2	1/8	-	161	-	-	-	.60	-	-	-	60.7	-	-
	1/4	1/2	-	-	-	43	-	-	-	.71	-	-	-	53.3
	1/4	1/4	26	48	51	-	.77	.68	.71	-	50.8	53.5	52.9	-
	1/4	1/8	45	79	93	-	.72	.60	.63	-	53.5	59.4	59.2	-
	1/4	1/16	-	149	-	-	-	.48	-	-	-	73.7	-	-
	1/5	1/2	-	-	-	35	-	-	-	-	-	-	-	53.4
	1/6	1/2	-	-	-	31	-	-	-	-	-	-	-	53.8
	1/8	1/8	-	43	-	-	-	.59	-	.71	-	60.5	-	-
	1/8	1/16	-	74	-	-	-	.48	-	.70	-	72.9	-	-
REMOTE OPERATIONS	1	1/2	63	131	113	-	.77	.71	.74	-	52.8	53.8	53.9	-
	1	1/4	103	226	205	-	.75	.64	.69	-	54.2	59.5	57.0	-
	1/2	1/2	38	78	64	-	.78	.71	.75	-	50.9	53.1	51.9	-
	1/2	1/4	65	126	115	-	.75	.64	.69	-	52.8	57.2	55.3	-
	1/4	1/2	-	-	-	45*	-	-	-	.71*	-	-	-	50.9*
	1/4	1/4	34	68	60	-	.75	.63	.69	-	51.9	57.5	54.4	-
	1/4	1/8	59	120	112	-	.69	.54	.60	-	55.9	67.7	62.5	-
	1/5	1/2	-	-	-	37	-	-	-	.70	-	-	-	51.2
	1/6	1/2	-	-	-	32	-	-	-	.70	-	-	-	51.3

(1) FOR THE GA-DOUBLET 8 MODULES ARE WORKED AT ONE TIME IN 8 SECTORS UNTIL THE SAME NUMBER OF MODULES IS REPLACED IN EACH OF THE 16 SECTORS.

(2) TIME IS ADJUSTED FOR A PRODUCTIVITY FACTOR OF .75.

(3) ASTERISKS IDENTIFY OPTIMUM MAINTENANCE PLAN DATA FOR EACH REFERENCE REACTOR.

3.0 CANDIDATE REFERENCE SYSTEMS - TASK 6

Four tokamak fusion power system concepts have been selected for use as candidate reference systems in this study. These systems represent a wide range of variation in design features for commercial or demonstration power reactors. The four conceptual designs are the UWMAK-III, the Culham Mk-II, the GA-DPR and the ORNL Cassette concept.

This section defines the system selection and normalization of the designs to common performance parameters, insofar as possible. Five critical subsystems that interface with the reactor are defined and normalized designs are selected that are compatible with the basic reactor concept. These subsystems are the first wall/blanket, the toroidal field and poloidal field magnets, the supplementary plasma heating system, the vacuum system and the coolant loops. These subsystems are integrated with the candidate systems to form reference reactor concepts which serve as a base for the definition of maintenance plans and trade studies.

3.1 SYSTEM SELECTION - In the first phase of the study five design concepts were evaluated for scheduled maintenance impacts of the first wall/blanket on the cost of electricity. These included two concepts employing first wall/blanket modules consisting of the largest possible portion of a reactor sector (the UWMAK-I and the Culham Mk-II), one concept with first wall/blanket sector using intermediate sized segments (the UWMAK-III) and two concepts with many smaller sized modules of the first wall/blanket in a reactor sector (the ORNL Cassette concept and the General Atomic Demonstration Power Reactor). In this study phase the selection of only four concepts allows increased emphasis on the definition of the unscheduled maintenance effects. The selected concepts required the lower percentage increases in cost of electricity because of first wall/blanket scheduled maintenance. These concepts also represent the range of reactor module sizes previously examined. Two small module concepts have been retained since they include significantly different approaches to accessing the modules.

System Normalization Studies - A relatively extensive examination of the selected design concepts has been conducted for the purpose of bringing them to a consistent size and performance regime before conducting further maintenance analyses. The procedure employed to normalize the design concepts requires the selection of parametric values that are unique to each concept and the selection of those parametric values required to size the reactor. Table 3.1-1 lists the selected parameters, i.e., those marked with an asterisk, and the resultant characteristics for each of the reference reactors.

TABLE 3.1-1

REFERENCE REACTOR CONCEPT CHARACTERISTICS

	UWMAK-III	GA-DOUBLET	CULHAM	ORNL
* POWER, MW _{th}	3000	3000	3000	3000
* NET ELECTRICAL POWER, MW _e	992	902	962	962
* FIRST WALL/BLANKET CONFIGURATION	UWMAK-III	CANISTER	CANISTER	CASSETTE
* FIRST WALL COOLANT	LITHIUM (OUTER WALL) HELIUM (INNER WALL)	HELIUM	HELIUM	HELIUM
* DIVERTER COOLANT	LITHIUM	-	LITHIUM	LITHIUM
* AUXILIARY HEATING	NBI	NBI	NBI	NBI
* VACUUM SYSTEM	UWMAK-III	GA-DPR	UWMAK-III TYPE	UWMAK-III TYPE
* DIVERTER	UWMAK-III (DOUBLE NULL)	FLOWING PLASMA BOUNDARY	SINGLE NULL	UWMAK-III TYPE (SINGLE NULL)
* T. F. MAGNETS, NUMBER	16	16	16	16
* MAX. TOROIDAL FIELD STRENGTH (B _{max}), TESLA	8.66	8.66	8.66	8.66
FIELD STRENGTH ON-AXIS (B ₀) TESLA	4.109	4.616	3.871	3.882
* PLASMA STABILITY FACTOR	2.5	2.5	2.5	2.5
* PLASMA BURN TIME, SEC	3600	3600	3600	3600
* PLASMA REJUVENATION TIME, SEC	100	100	100	100
* PLASMA ECCENTRICITY	2	3 (DOUBLET)	2	2
* PLASMA MAJOR RADIUS, m	6.5	6.5	7.5	7.5
PLASMA MINOR RADIUS, m	1.75	1.405	1.924	1.924
PLASMA VOLUME, m ³	785.87	796.98	1096.0	1096.0
WALL AREA, m ²	781.02	888.04	990.8	1037.3
POLOIDAL BETA	3.714(A)	2.315(A/2)	3.906(A)	3.906(A)
NEUTRON WALL LOADING, MW/m ²	2.74	2.364	2.121	2.026
ION TEMPERATURE, T _i , KeV	12.8	15.8	12.9	13.0
ELECTRON TEMPERATURE, T _e , KeV	13.8	15.8	13.8	13.9
DENSITY, n _i PARTICLES/m ³	1.57 x 10 ²⁰	1.22 x 10 ²⁰	1.31 x 10 ²⁰	1.31 x 10 ²⁰
CONFINEMENT TIME τ _p , SEC	2.32	2.90	2.72	2.70
n _i τ _p PARTICLE-SEC/m ³	3.64 x 10 ²⁰	3.54 x 10 ²⁰	3.57 x 10 ²⁰	3.57 x 10 ²⁰
FUSION REACTION RATE, <σv> m ³ /SEC	2.0 x 10 ⁻²²	3.11 x 10 ⁻²²	2.05 x 10 ⁻²²	2.05 x 10 ⁻²²
THRUPUT, TORR-L/SEC	2127	5143	2116	2128
CRYO PANEL AREA, m ² (OPERATING FACE AREA)	425	1027	423	426
WALL LIFE, YRS.	1.8	2.1	2.4	2.5

* INDEPENDENT SELECTED PARAMETERS

A = ASPECT RATIO

A short study was made to define the variation in minor radius and wall loading over a range of major radii for each concept. The inner wall thickness is

defined for each concept based on blanket design data. These data, together with the other selected parameters, are used to define the plasma characteristics, critical magnet dimensions, and vacuum system requirements by employing the system analysis portion of the TOCOMO code. These data then serve as the basic parameters for defining each reactor general arrangement. The principle criteria used in this normalization process are to bring all concepts to a common size and arrangement, insofar as possible, while attaining the common performance parameters of 3000 MW_{th} maximum output and minimum cost of electricity. Table 3.1-1 lists the parameters that have been fixed for these concepts. Normalizing to a common thermal power is selected rather than normalizing to a common electrical power since it is desired to make the physical size of the reactors as close as possible to each other and to make this size independent of the power conversion system and recirculated power. Thus the maintenance features of each concept should have the correct impact on maintenance and these features can be evaluated rather than evaluating the complete reactor concept. The net electrical power output of the four concepts ranges only from 902 MW_e for the GA-Doublet to 992 MW_e for the UWMAK-III. Normalizing the concepts to an average of 955 MW_e would have no measurable impact on maintenance downtimes and a relatively small impact on total cost of electricity.

The selected power level, 3000 MW_{th}, results in a reactor which is approximately comparable in electrical power output to the fission power reactors being installed at the present time. Figure 3.1-1 compares reactors at this power level with those at the 5000 MW_{th} level used in the first phase of this study. The increase in minimum cost of electricity (COE) is only about 11%. Figure 3.1-1 is based upon UWMAK-I blanket geometry and cost relationships and was developed in a parallel systems study (Reference 3-1). The COE used for the study for which this figure is derived is based on a different maintenance plan than defined in the first phase of this study for the maintainability of tokamak reactors. Therefore, the absolute values of cost shown in this figure are different than indicated by the results of the current study.

The first wall/blanket configurations selected are those defined for each principal design concept. These configurations are more completely defined in References 3-2 through 3-8 and in Section 3.2.1 which follows. The coolants are generally those selected in the original design of the concepts.

The auxiliary heating system has been standardized to use neutral beam injectors (NBI's) for all concepts. NBI's are selected instead of RF heaters since these are being developed for use in near term experimental machines and better

COST OF ELECTRICITY IMPACT OF REACTOR AND POWER SCALING (TRAPPED ION CONFINEMENT)

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FIGURE 3.1-1

definitions exist than for the RF heaters. The original UWMAK-III selected RF heating which requires about the same time for disconnecting from the plasma chamber as a neutral beam injector (NBI). However, it is found necessary to remove as many as three NBI's for one sector when they are installed with the beams tangential to the plasma centerline. More recent information indicates that the NBI's will probably have to be installed normal to the high density plasmas required by commercial concepts to achieve the required penetration. Therefore, the NBI's for all concepts are installed in this manner. Since the definition of the auxiliary heating system for the Culham Mark II and the ORNL Cassette concepts are only sketchily defined, the same system as selected for the UWMAK-III and the GA-Doublet is used for these concepts.

The vacuum systems are also standardized to the point that the same type of roughing pumps and cryovacuum pumps are selected for all four reactor concepts. The arrangement and size differs with the divertor arrangement used with each

reactor. Since the GA-Doublet employs a flowing plasma boundary and limiter instead of a poloidal divertor system, such as that defined for the UWMAK-III, the cryo-vacuum pump configurations defined for the GA-Doublet are used but are sized in accordance with the throughput required by the GA-Doublet and with the performance defined for the UWMAK-III pumps. UWMAK-III performance estimates are used for all cryovacuum pump configurations. Vacuum systems and divertors for the Culham Mark II and the ORNL Cassette concepts also are standardized to use the same general cryovacuum pump unit configuration and performance base as the UWMAK-III except that single null poloidal divertors, such as that specified for the Culham concept, are used for both concepts.

While poloidal divertors are used with the UWMAK-III and Culham concepts as originally specified, the use of the poloidal divertor with the ORNL Cassette concept deviates from the recommended use of several bundle divertors implied by the original concept description (Reference 3-4). Specific performance and configuration information for the bundle divertors is lacking and it is deemed best to assume the use of the poloidal divertor and vacuum system similar to the UWMAK-III design in the ORNL Cassette configuration.

The remaining parameters are selected to normalize the plasma parameters for all concepts. Sixteen toroidal field magnets are selected. Sixteen magnets provide sufficient space between magnets to allow ease of access to the first wall/blanket sectors or withdrawal of a complete sector while keeping the outboard magnet legs reasonably close to the plasma chamber. Also, the sixteen magnets permit attaining significantly less than the limiting value of 2% for the ripple factor with the magnet legs still close to the plasma chamber. This balance of the access and ripple requirements matches that for the GA-DPR (16 magnets) and deviates only slightly from the UWMAK-III (18 magnets) or the Culham Mark II (20 magnets) or the ORNL Cassette concept (18 magnets). Thus, 16 magnets achieves approximately the smallest size and cost for the toroidal field magnet system while remaining within the range of the number of magnets used by the original concepts.

One of the basic parameters selected is the maximum toroidal field strength ($B_{\max}$). While a toroidal field strength study for the specific concepts being considered may have improved the rigor of the analysis for selecting the $B_{\max}$ value, the results of parallel system studies provided a base for estimating a reasonable value for $B_{\max}$. The maximum toroidal field strength selected is based on the COE variation with field strength as indicated in Figure 3.1-2 (from Reference 3-9). While this data is based on UWMAK-I blanket configurations and a shape factor of

2.0 the relative COE variations with maximum field strength appear typical. It is desired to select field strengths that can be attained with NbTi alloys since these are expected to be less costly than magnets made with NbSn alloys. Also, even without a cost variation in materials and fabrication, which is not considered in the plots shown in Figure 3.1-2, the minimum COE is relatively insensitive to the maximum field strength at values less than 9 Tesla. Since this appears to be the case independent of the value used for poloidal beta, a nominal maximum field strength of 8.66 Tesla is selected as the normalized value for all concepts.

The individual central core dimension is defined for each reactor concept by using the specific requirements of each blanket neutronics design in order to derive the required plasma dimensions. The minimum dimensions to the inner separatrix from the reactor centerline are varied for each reactor depending upon the toroidal field strength and the blanket design. The blanket designs used for

COST INFLUENCE OF WALL LOADING

FIGURE 3.1-2

the UWMAK-III and the GA-Douplet are as specified in References 3-2 and 3-3, respectively. Figure 3.1-3, 3.1-4 and 3.1-5 define the blanket, inner shield and supporting structure dimensions of the Culham Mark II concept and Figures 3.1-6 and 3.1-7 define the ORNL Cassette design and dimensions. While the cassette concept is maintained, the blanket thickness dimensions are selected as the best compromise to approximate the breeding requirements of Reference 3-10, the cassette designs of Reference 3-5, and the requirement for structural support of each cassette. The structural support of the cassettes in the reactor has not been defined in the ORNL study so it is necessary to devise a plausible concept for

CULHAM MK II BLANKET SECTOR MODULE SUPPORT STRUCTURE AND MANIFOLDING

FIGURE 3.1-3

CULHAM MK II BLANKET MODULE WITH COOLANT FLOW ARRANGEMENT

FROM REFERENCE 3-8

FIGURE 3.1-4

INNER BLANKET TYPICAL DIMENSIONS USED FOR CULHAM

ZONE	MATERIAL	DENSITY FACTOR	THICKNESS (m)	
				0
			PLASMA	1.924
				1.924
			SCRAPE OFF	.20
				2.124
			LINER (SS)	.02
				2.144
3	STAINLESS	.5		
	Li ₇ Pb ₂	.10		
4	GRAPHITE	.228		
	Li ₄ SiO ₄	.306		
	STAINLESS	.025		
			BLANKET	.35
				2.494
5	STAINLESS		STRUCTURE & MANIFOLDS	.75
				222 cm
				3.244
6	B ₄ C	.508		
	SS	.10	INNER SHIELD	.35
				3.594
7	Pb	.51		
	B ₄ C	.34		
	AL	.10	OUTER SHIELD	.40
				3.994
	VACUUM			
			MAGNET DEWAR	.15
				4.144

FIGURE 3.1-5

ORNL CASSETTE DESIGN CONCEPT

ORNL-DWG 77-4984

FIGURE 3.1-6

supporting these cassettes during the reactor operation that will also permit rapid replacement. The approach of supporting each cassette by the integral structure of the cassette in the next blanket zone away from the plasma has been assumed.

A series of zero dimensional plasma code runs have been conducted using various major radii with plasma eccentricities of two for all concepts (except the GA-Doublet which employs an eccentricity of 3); using a plasma MHD stability factor of 2.5 for all plasmas; and using poloidal betas equal to the aspect ratio (except for the GA-Doublet where the poloidal beta is one half of the aspect ratio). Figure 3.1-8 shows the variation in the resultant minor radii and neutron wall loading when maintaining a power level of $3000 \text{ MW}_{\text{th}}$ for each of the reactor concepts. Since the ORNL and the Culham inner wall blanket thicknesses differ by only 4 cm, the data for the Culham concept can also be used for the ORNL with some

INNER BLANKET TYPICAL CASSETTE BLANKET DIMENSIONS

FIGURE 3.1-7

RANGE OF PLASMA GEOMETRY FOR MAINTENANCE STUDY

variations that will be defined. Based on this data a major radius of 6.5 meters is selected for the UWMK-III and the GA-Douplet configurations and 7.5 meters for the Culham and the ORNL Cassette configurations. These selections are at the region of the major radius vs minor radius (R-a) curve where other general system studies indicate the minimum cost of electricity will occur. The specific point for minimum cost for each concept was determined only after the concepts were more completely defined. However, since the sensitivity of the COE to the variation in the major radius is slight over the region near the minimum COE, the potential error in selecting a common major radius for several concepts is small. As shown by Figure 3.1-8, the reactor core radius limits for the Culham and the ORNL concepts require that the major radius be increased for these two designs over the 6.5 meters feasible with the UWMK-III and the GA-DPR designs.

The selected major radii results in neutron wall loadings varying from approximately 2.1 to 2.7 MW/m² as shown in Figure 3.1-8. The neutron wall loading value of 2.02 MW/m² shown in Table 3.1-1 for the ORNL Cassette concept is less than that derived for the Culham concept since the first wall of the cassettes is

formed from straight line wall elements which only approximate the outer plasma boundary and, therefore, is larger in area than the calculated, elliptically shaped, minimum area wall. The first wall area and plasma volumes are calculated directly from wall loading, plasma size, and the design shape factors.

An eccentricity (height to width ratio) of 2.0 is selected for all concepts except the GA-Douplet which employs the doublet plasma configuration with a height to width ratio of 3. The lower ratio of 2.0 is selected as a nominal value since this approximates the values selected for the majority of concepts in the reference design documents (1.75 for the Culham Mark II, 1.6 for the ORNL Demonstration Study and 2.0 for the UWMAK-III). While this value may slightly exceed that obtainable with poloidal field magnets outside of the toroidal field magnets, as for the Culham Mark II concept, it will provide a relatively low cost of electricity compared with lower eccentricity values and is a suitable maximum for general normalization in other than doublet configurations.

With the eccentricity of 2.0 the maximum poloidal beta generally believed achievable is equal to the aspect ratio (A). The assumption of this maximum poloidal beta produces a design with lower cost of electricity than with lower values of poloidal beta. The maximum poloidal beta defined by General Atomic for the doublet concept, however, is only one half of the aspect ratio. This still yields a neutron wall loading of 2.36 MW/m^2 , which is in the same regime as the wall loading for all other concepts. A larger poloidal beta for the doublet would increase wall loading. Normalization of all concepts to approximately the same wall loading defines reactors of approximately the same size and, consequently, the maintenance times, size of the maintenance equipment and size of components to be replaced are comparable.

The plasma eccentricity also affects other plasma parameters. The GA-Douplet configuration with its eccentricity of 3.0 demonstrates that the higher on-axis field strength (B_0) attained with the same maximum field strength (B_{max}) results in higher ion and electron temperatures and higher reaction rates. Since the eccentricity of 3.0 is an important characteristic of the doublet concept and deviates significantly from the 2.0 used for the other three concepts, it is impossible to maintain complete uniformity of plasma characteristics among the four reference reactors in the normalization process.

In addition to the foregoing considerations, the vacuum pumping requirements shown in Table 3.1-1 for the GA-Douplet concept are more than double those of the other concepts. This requirement is imposed by the employment of the flowing

plasma boundary (FPB) technique of impurity control, which is unique to this concept, instead of the divertor techniques employed by all other concepts. The FPB technique employs a cold gas boundary layer introduced into the plasma chamber which significantly increases the gas throughput of the chamber and, consequently, increases the pumping requirements.

The foregoing procedure produces sufficient similarity in all four concepts to allow comparison of maintenance plans developed for each concept and the subsequent isolation of the more beneficial design features by analysis of cost trends for power generation. Some variation in the initial assumptions has been required as a result of the variation in each concept in order to achieve similarity of the critical parameters affecting the study of maintainability. The rationale for these variations has been described in the preceding paragraphs. More detailed definition of each design concept is included in the following sections.

3.2 SUBSYSTEM DEFINITION - The documentation in References 3-2 through 3-8 and References 3-11 through 3-18 has defined conceptual designs for fusion power systems. This documentation incorporates subsystem descriptions that vary extensively in principle among the conceptual designs for the same supporting functions. These descriptions also vary widely in the degree of detail given, depending on the emphasis of the conceptual study. To evaluate the maintainability impacts of these subsystems on the overall reactor concept, normalization of the subsystem approaches is established to the extent that the common functions performed by a fusion power system will employ similar subsystem designs. At the same time the essential reactor conceptual design characteristics are retained. To accomplish this objective, the subsystems that are being studied have been defined to a uniform level of detail for each of the four candidate reactor reference systems and similar principles of design are employed. Size variations are based upon the performance required by each reactor concept for these "standardized" subsystems.

The subsystem definitions employed are based on the breakdown of a reactor plant as found in the "Standard Accounts for Cost Estimates" (Reference 3-19) which has been coordinated through the Department of Energy. A listing of the top level titles and cost accounts is given in Table 3.2-1. Table 3.2-1 includes only those second and third level breakouts of cost accounts which identify the subsystems of interest to this study. These accounts are presently used or will be used in the TOCOMO costing code employed for this study.

The subsystems which are evaluated for maintainability impacts are those with direct interface with the plasma chamber and with the first wall/blanket. These

TABLE 3.2-1
SUBSYSTEM BREAKDOWN

SYSTEM TITLE ⁽¹⁾	COST ACCOUNT
STRUCTURES AND SITE FACILITIES	21
REACTOR PLANT EQUIPMENT	22
REACTOR EQUIPMENT	22.01
BLANKET AND FIRST WALL (2)	22.01.01
SHIELD	22.01.02
MAGNETS (2)	22.01.03
SUPPLEMENTAL HEATING (2)	22.01.04
PRIMARY STRUCTURE AND SUPPORT	22.01.05
REACTOR VACUUM SYSTEMS (2)	22.01.06
POWER SUPPLY SWITCHING AND ENERGY STORAGE	22.01.07
IMPURITY CONTROL	22.01.08
DIRECT ENERGY CONVERTOR (3)	22.01.09
MAIN HEAT TRANSFER AND TRANSPORT SYSTEMS	22.02
PRIMARY COOLANT SYSTEM (2)	22.02.01
INTERMEDIATE COOLANT SYSTEM	22.02.02
AUXILIARY COOLING SYSTEM	22.03
RADIOACTIVE WASTE TREATMENT AND DISPOSAL	22.04
FUEL HANDLING AND STORAGE SYSTEMS	22.05
OTHER REACTOR PLANT EQUIPMENT	22.06
MAINTENANCE EQUIPMENT	22.06.01
(OTHER SYSTEMS UNDER 22.06 NOT LISTED HERE)	
INSTRUMENTATION AND CONTROL	22.07
TURBINE PLANT EQUIPMENT	23
ELECTRIC PLANT EQUIPMENT	24
MISCELLANEOUS PLANT EQUIPMENT	25

- (1) BREAKDOWN IS DETAILED ONLY TO LEVEL OF INTEREST TO THIS STUDY.
- (2) SUBSYSTEMS DEFINED, AT LEAST IN PART, FOR THIS STUDY PHASE.
- (3) DIRECT CONVERTORS ARE NOT CONSIDERED IN THE CONCEPTS INCLUDED IN THIS STUDY. THIS COST ACCOUNT INCLUDED FOR COMPLETENESS OF BREAKDOWN AT THIS LEVEL.

include the Magnets, Supplemental Heating (particularly the Neutral Beam Injectors), Reactor Vacuum Systems (particularly Plasma Chamber, Supplemental Heating and Reactor Enclosure vacuum) and the Primary Cooling System. Failure modes and the required maintenance actions are selected for these four interfacing subsystems for definition of their impact on the maintenance plans. For each subsystem, alternate designs and arrangements are defined to provide a "standardized" nominal design and arrangement for each reactor concept.

The subsystem characteristics and alternatives that are defined include:

- o Magnet systems which use superconducting magnets in the configuration defined by each reactor concept. An alternative system considers segmented demountable magnets such as the DEALS magnet concept defined in References 3-20 and 3-21.
- o A supplemental heating system which uses neutral beam injectors is selected. These injectors will incorporate three neutral beams in each assembly and employ the design being developed for the tokamak fusion test reactor (TFTR) as defined in Reference 3-17. All injectors are installed with the beams normal to the plasma toroidal axis and a total of 12 - 5.0 MW units are used for each reactor.
- o The reactor vacuum system cryovacuum pumps and roughing pumps have been sized for all concepts. The principal variation among the reactor concepts is the sizing and the arrangement of the cryovacuum pump panels. For the UWMAK-III, Culham and ORNL Cassette concepts the UWMAK-III general arrangement is used except that the size is varied when the single null poloidal divertor is used. The cryovacuum pump area required for the GA-Douplet is sized for the flowing plasma boundary requirements and apportioned between the auxiliary and the main vacuum ports in accordance with the requirements of References 3-3 and 3-12. The UWMAK-III arrangement is used as a "standard" since it is reasonably well defined in Reference 3-2 and the conductance from the bombardment plates to the cryosorption panels appears to be as close to a maximum as practical. The roughing pump arrangements are common for all reactors and are sized to accommodate both the neutral beam injectors and the primary vacuum chamber. A separate roughing pump system is defined for the secondary vacuum chamber when one is used, and this system is varied in size with the size of the secondary chamber.
- o For the primary cooling system two designs have been defined, one for lithium and one for helium coolant. The lithium system will be used with

the UWMAK-III concept and the helium system for the other three concepts. Since the divertor and shield cooling systems require different thermal cycles, these are defined as separate cooling loops. All divertor systems use lithium as the coolant and the shield systems use helium. The primary cooling and divertor systems both use a sodium secondary system to generate steam and store energy during the reactor 100 second downtime between burns. The tritium and fuel extraction systems have not been considered except that, in all cases except the ORNL Cassette concept, the tritium from the blanket is primarily carried from the reactor room with the primary coolant.

The design parameters and system definitions used for each of these subsystems and for the first wall/blanket subsystem for each concept are discussed in the following sections.

3.2.1 First Wall/Blanket Subsystems - Conceptual designs of the First Wall/Blanket subsystem are unique to each tokamak design concept and are defined in detail in References 3-2 through 3-8 and Reference 3-22. A summary of each concept is presented in the following subsections.

3.2.1.1 UWMAK-III First Wall/Blanket - The blanket design incorporated in the UWMAK-III employs two concepts, one for the inner plasma chamber wall and one for the outer wall. The inner wall is a 25 cm layer of graphite which "acts to soften, reflect and attenuate the neutrons incident to the plasma" (Reference 3-2). This ISSEC (Internal Spectral Shifter and Energy Converter) is not actively cooled but radiates heat to the structural wall behind it and to the first wall on the outer portion of the plasma chamber. The blanket on the outer wall of the plasma chamber and the blanket on the divertor islands is illustrated in Figure 3.2-1. This blanket consists of a liquid lithium cooled convoluted stainless steel surface backed by a complex coolant flow structure with 60 cm of lithium coolant channels, 30 cm of graphite cooled by the lithium and 10 cm of lithium cooled stainless steel header structure. Tritium formed in these blanket zones is removed with the lithium. Figure 3.2-2 shows the arrangement of the blanket modules around a poloidal section of the torus. Each module in the breeder blanket is the full width of one sector of the sixteen sectors that make up the torus. The five modules that make up the breeding portion of the blanket include the upper and lower central wall (divertor) modules, the upper and lower "B" modules and the "A" module. Table 3.2-2 summarizes the design assumptions for the UWMAK-III blanket concept.

The detailed design of the "A" module is also illustrated in Figure 3.2-1. The reduction in reactor size from the original design concept to the normalized design

**TYPICAL UWMK-III OUTER WALL MODULE (REGION "A")
(3000 MW_{th} UWMK-III)**

FIGURE 3.2-1

UWMAK-III FIRST WALL BLANKET (MODULAR ARRANGEMENT IN POLOIDAL PLANE)

FIGURE 3.2-2

requires reduction in the number of coolant cells per section to 4 but 8 sections are used in the module as in the basic concept. The "B" modules and central wall modules also are made up of 4 cells because of their smaller size. The weight of each module is then approximately 32.4 tonnes, 6.1 tonnes and 7.0 tonnes for the "A", "B" and central wall modules, respectively.

The module attachment methods vary, depending on the vacuum wall arrangement being investigated. Figure 3.2-3 illustrates the method of attaching the frames of adjacent "A" modules to each other along the sides and to the "B" modules at the

TABLE 3.2-2
DESIGN ASSUMPTIONS AND DEFINITIONS
(UWMAK-III FIRST WALL/BLANKET)

- LITHIUM BLANKET CELLS ARE REDUCED FROM 6 PER SECTION TO 4 FOR 3000 MW_{th} REACTOR. 12 SECTIONS IN 5 MODULES PER REACTOR SECTOR.
- MODULE WEIGHTS REDUCED TO 32.4, 6.1 AND 7.0 TONNES FOR "A", "B", AND CENTRAL WALL MODULES, RESPECTIVELY.
- ADJACENT "A" MODULES ARE ATTACHED STRUCTURALLY TO EACH OTHER BY BOLTS AND THE VACUUM SEAL IS FORMED BY A WELDED CAP OVER THE BOLTED FLANGE.
- "B" MODULES ARE BOLTED TO THE SHIELD STRUCTURE WITH A WELDED VACUUM SEAL BETWEEN MODULES.
- GRAPHITE BLOCKS PROTECT THE STRUCTURAL ATTACHMENTS IN THE SPACE BETWEEN ADJACENT "B" MODULES.
- THE CARBON CURTAIN IS ATTACHED TO THE OUTER WALL AND IS REMOVED WITH THE WALL MODULE.
- THE ISSEC IS DIVIDED INTO 3 SEGMENTS PER REACTOR SECTOR.
- THE ARRANGEMENT OF COOLANT MANIFOLDS IS DEFINED ONLY TO THE DEGREE REQUIRED TO ESTABLISH THE MAINTENANCE ACTIVITY FUNCTIONS AND TIME ESTIMATES.
- THE LITHIUM COOLANT MANIFOLD LINE JOINTS ARE MECHANICALLY DIS-CONNECTED (NOT WELDED).

upper and lower joints. For this design, the "A" module is assumed to be structurally supported by the "B" modules and the frame to which they are attached. The "A" module attachments are made with the welded vacuum cap when the pressure outside of the blanket is designed for greater than 10^{-4} torr. This vacuum cap is omitted when a secondary vacuum zone of approximately 10^{-4} torr is included in the design. The "B" module attachment is shown in Figure 3.2-3. This figure depicts a portion of a toroidal section showing the method of attachment to the structural frame. Access is provided from within the plasma chamber by removal of the graphite insert. The attachment design is similar to the "A" module wherein the welded vacuum seal inserts can be omitted when a secondary vacuum zone at approximately

UWMAK-III BLANKET MODULE ATTACHMENTS "A" MODULE JOINT ATTACHMENT

FIGURE 3.2-3

10^{-4} torr is provided external to the blanket.

The central wall module attachment in the toroidal direction is similar to that used for the "B" module with the joint between modules protected by graphite blocks and sealed when necessary. Figure 3.2-4 illustrates a method of connecting the coolant manifold to the central wall module. The vacuum seals at the plasma chamber are never penetrated since the coolant feed and return lines pass outside of the divertor slots where they are narrowed to pass between the TF magnets. The welded vacuum seals between central wall modules are omitted when the secondary vacuum zone shown in the figure is maintained at approximately 10^{-4} torr.

As indicated in Figures 3.2-4 and 3.2-5, the lithium manifold disconnects for all modules are equipped with LN₂ freeze units for forming freeze plugs in the lithium lines prior to disconnecting these manifolds. The size of the freeze units and the diameter of the manifolds is typical for location only. Figure 3.2-5 pictures one of four manifolds required by the "A" and "B" module for one reactor sector (i.e., two supply, upper and lower, and two return, upper and lower, are required). The shield plugs are removed and provide clearance around the stub lines for the shield door to swing clear of the "A" module or to allow the removal of the "B" module to the interior of the plasma chamber. The alternative of draining the lithium from the modules and manifolds prior to disconnecting them is accompanied by uncertainties of design and operation and is deemed to require potentially more total time, including reassembly, than the selected method.

CENTRAL WALL MODULE AND MANIFOLD INSTALLATION

The general arrangement of the three ISSEC inner wall panels is indicated in Figure 3.2-6. These panels are arranged to overlap the bolted connections and require removal of the upper panel to access the panel beneath it. The upper bolt row is protected by a graphite block, held in place by bolts in a manner similar to the attachment of interstitial graphite blocks required by the General Atomic concept (Section 3.2.1.2).

3.2.1.2 General Atomic DPR First Wall/Blanket - The blanket design for the General Atomic Demonstration Power Reactor (GA-DPR) employs multiple cylindrical modules with ellipsoidal outer domes which are attached to the permanent shield and vacuum wall of the plasma chamber from inside the chamber. The blanket modules are helium cooled. All modules are identical throughout the plasma chamber.

**OUTER WALL COOLANT MANIFOLD ARRANGEMENT
(LOWER MANIFOLD, TYPICAL)**

FIGURE 3.2-5

13-719

FIGURE 3.2-6

Tritium breeding occurs in a blanket made up of solid lithium alloy rods contained within the module. The module structure is Inconel 718. The general arrangement of these modules on the plasma chamber wall is shown in Figure 3.2-7. This figure depicts the arrangement used for the GA-DPR study (Reference 3-3) and may be revised slightly for the reactor size used as a candidate reference system. Modules must be omitted for the vacuum ports and neutral beam injector penetrations.

Table 3.2-3 summarizes the characteristics of this first wall/blanket design. These characteristics reflect the module design defined in Reference 3-13 as applicable to the GA-Douplet reference system.

The first wall and blanket module has been modified from that used in the first phase of the study to that defined in Reference 3-13. A cross section of the revised design is shown in Figure 3.2-8. The first wall is the domed Inconel 718 pressure vessel. This wall is separate from the breeder section and is "bolted

BLANKET ASSEMBLY GENERAL ARRANGEMENT (TYPICAL)

FROM REFERENCE 3-3

FIGURE 3.2-7

to the structure through a hexagonal flange at the module base by 12 bolts. The flange is thick and narrow to provide the rigidity necessary to seal a double seal. The bolts are 2.5 cm in diameter and "are cooled by conduction through the structure to the helium" (Reference 3-13).

The breeder section is installed by threading it into the shield structure and locking it in position. The pressure vessel is installed after the breeder section is secured. The breeder section uses lithium lead and lithium orthosilicate as breeding materials in the two breeding zones. Only the pressure vessel and the breeder section are replaced during normal maintenance operations. The inner shield is made up of stainless steel/boron carbide and is attached to the support structure for the blanket module. Interstitial blocks of silicon carbide or graphite are installed between the modules to protect the module flanges and inner shield in these areas. It is assumed that three refractory studs are used to attach each block in a manner similar to that shown in Figure 3.2-9 (Reference 3-12). A removable graphite ring covers the module attachment bolt heads as indicated in Figure 3.2-10. This ring is removed prior to removing the pressure

TABLE 3.2-3

DESIGN ASSUMPTIONS AND DEFINITIONS
(GA-DOUBLET FIRST WALL/BLANKET)

- APPROXIMATELY 1800 MODULES REQUIRED FOR 3000 MW_{th} REACTOR.
- MODULES ARE ATTACHED DIRECTLY TO THE SHIELD STRUCTURE IN 2 SEGMENTS. THE BREEDER SEGMENT IS THREADED AND THE PRESSURE DOME IS BOLTED.
- ALL MODULES ARE IDENTICAL IN SIZE AND WEIGHT (i.e., .7m DIAMETER AND APPROXIMATELY 500 kg).
- GRAPHITE OR SILICON CARBIDE BLOCKS PROTECT THE STRUCTURAL ATTACHMENTS BETWEEN BLANKET MODULES. BLOCKS ARE BOLTED IN PLACE WITH REFRACTORY STUDS.
- ALL FIRST WALL SURFACES ARE COATED WITH A THIN CARBON LAYER IN SITU.
- A METHOD OF SHUTTING OFF HELIUM FLOW TO APPROPRIATE GROUPS OF MODULES IS POSSIBLE.
- THE NEUTRAL BEAM INJECTOR SYSTEM INSTALLATION WILL NOT INTERFERE WITH ACCESS TO THE FIRST WALL/BLANKET MODULES FOR MAINTENANCE.

vessel dome. Cooling of the graphite block and ring is by radiation to the surrounding structure or to the plasma chamber wall.

Blanket modules are cooled by gaseous helium at 50 atmospheres ($\approx$ 5 MPa). The flow path shown in Figure 3.2-8 is toward the plasma along the module outer wall in the inner shield and through ports in the shield structure to the space between the first wall pressure vessel and the breeder section. Return flow of the heated gases is through the breeder material to a small plenum between the breeder section and the inner shield and then through the inner shield to the outlet manifold. The small plenum eliminates the requirement for accurate rotational alignment of the breeder section with the inner wall coolant ports.

DEMONSTRATION POWER REACTOR BLANKET MODULE

FIGURE 3.2-8

GRAPHITE BLOCK INSTALLATION BETWEEN BLANKET MODULES

FIGURE 3.2-9

GRAPHITE BLOCK AND RING ARRANGEMENT

FIGURE 3.2-10

The two pressure vessel seals provide a small chamber (Figure 3.2-8 inset) from which leakage of the 50 atmosphere helium from the pressure vessel through the first seal can be exhausted before passing through the second seal into the plasma chamber. This secondary chamber also provides a means of testing both seals after exchanging modules.

3.2.1.3 Culham Mark II First Wall/Blanket - The blanket design of the Culham Mark II reactor concept employs multiple blanket and inner shield modules attached to a common structural frame for each of the reactor sectors. Each module consists of a cylindrical blanket heat cell mounted on a rectangular shield block as shown in Figure 3.1-4. The shield and blanket are cooled with high pressure helium at approximately 60 atmospheres. Approximately 175 modules are required per sector module when using 16 sectors to make up the reactor for a total of 2800 modules in the reactor. A lithium moderator is assumed for the blanket with the tritium permeating a network of niobium alloy tubing and being carried off with the helium coolant. The blanket and inner shield modules are arranged to be removed to the side of each sector module and, therefore, cannot be removed individually until a complete sector module is removed from the reactor and access is available from the side.

The general arrangement of the small modules on the plasma chamber walls is illustrated in Figures 3.2-11 and 3.2-12. The model of the Mark-II reactor concept depicted in these photographs utilizes a 20 sector plasma chamber. The different size modules are evident in these general arrangement views. The opening in the outer wall is designed to accommodate a neutral beam injector. This conceptual design is considered in the large module class for maintenance purposes since a complete sector is replaced in any maintenance action and the small modules are subsequently replaced in a repair cell outside of the immediate vicinity of the reactor.

Table 3.2-4 summarizes the design assumptions for the Culham reference reactor blanket concept. The characteristics identified in this table reflect the design discussed in References 3-7, 3-8 and 3-23 and extensions of this design assumed for the purpose of this study.

The structure to which the blanket and inner shield modules are attached for each sector is illustrated in Figure 3.2-13. This structure also supports the coolant manifolds for each sector as shown in Figure 3.1-3. The structure shown is for a 20 sector reactor and is only typical of the approach to be taken for a 16 sector reactor. The serrated inner shield blocks are designed to minimize neutron streaming but they must be assembled to the sector structure by moving laterally with respect to the module axis to mesh the serrations. Then the bolts are tightened

CULHAM LABORATORY MODEL OF MARK IIB TOKAMAK REACTOR

USED BY PERMISSION

Figure 3.2-11

CULHAM MODEL OF MARK IIB REMOVABLE FIRST WALL/BLANKET SECTOR

USED BY PERMISSION

Figure 3.2-12

TABLE 3.2-4
DESIGN ASSUMPTIONS AND DEFINITIONS
(CULHAM FIRST WALL/BLANKET)

- EACH BLANKET SECTOR IS MADE UP OF APPROXIMATELY 175 BLANKET AND INNER SHIELD MODULES IN 4 DIFFERENT DIAMETERS. ASSUME THAT THE NUMBER OF MODULES REMAINS CONSTANT WITH ANY VARIATION IN REACTOR SIZE.
- BLANKET AND INNER SHIELD MODULE WEIGHT, INCLUDING INNER SHIELD BLOCKS, ARE ASSUMED TO VARY FROM 250 kg TO 700 kg, VARYING WITH THE MODULE DIAMETER.
- SIXTEEN BLANKET SECTORS MAKE UP THE REACTOR BLANKET AND INNER SHIELD. EACH SECTOR IS REMOVED AND INSTALLED AS A UNIT (A SECTOR MODULE).
- BLANKET AND INNER SHIELD MODULES ARE BOLTED TO THE INSIDE OF THE SECTOR STRUCTURAL FRAME.
- ADJACENT SECTORS ARE SEPARATED FROM EACH OTHER BY APPROXIMATELY A 1 cm GAP WHEN AT OPERATING TEMPERATURES.
- HELIUM COOLANT MANIFOLDS LEAVE THE SECTOR IN ONE CONCENTRIC CONNECTION FOR BOTH SUPPLY AND RETURN LINES.
- THE PRINCIPAL HELIUM COOLANT LINE JOINT IS MECHANICALLY CONNECTED.

and the seals seated in the base provided in the structural base plate. Thermal expansion during operation will tend to close any small gaps in the serrated edges.

It is to be noted that, in this concept, interstitial graphite blocks and/or rings are not specified for protection of the inner shield and attachment bolts. The height of the breeder zone and pressure vessel above the shield is expected to afford sufficient protection from neutrons other than those moving approximately normal to the chamber wall.

Figure 3.2-13 does not show the manifolds but, considering the manifold shown in Figure 3.1-3, the concentric manifold connection with the supply and return main is located at the bridge shown in Figure 3.2-13. The bridge is emplaced after the coolant manifold is disconnected and the stub is retracted below floor level.

TYPICAL CULHAM REACTOR SECTOR STRUCTURE

FIGURE 3.2-13

The concentric manifold design shown in Figure 3.1-3 is retained for the purposes of this study. Only one main joint must be disconnected at the base of each sector. This joint is clamped or welded but only the outer duct is secured with a leak tight connection. The inner line is held in position with spacers and the butt joint is sealed by longitudinal pressure from the other pipe connection. A small amount of bypass leakage from the outer to the inner line may be tolerated. A study of remote operations on these types of lines is found in Reference 3-23.

The retraction of the lower stub of the main coolant line connection requires additional consideration but, for the purposes of this study, a long bellows or dual bellows is assumed to provide for the required retraction and differential thermal expansion of the concentric lines.

The complete sector is installed either by rolling it into place on wheeled trucks moving on permanent tracks embedded in the reactor room floor or by floating the entire sector into position on air bearings arranged on either side of the V groove shown in Figure 3.2-13. The V groove provides directional guidance and small air bearings in the groove guide can provide lateral clearance. To use such flotation techniques, the bridge must be rigidly secured and sealed at the joints and guidance of the top of the module during initial withdrawal movement is required to prevent binding. A small, vertical air bearing may be built into the upper structure for this purpose. The structure shown in Figure 3.2-13 is assumed to contain all air bearing devices but the air supply will be provided by or through the fixture used for removal of the module. If a wheeled system is used the wheels are retracted or removed after emplacing the module. Locating lugs or pins may be required both below and above the module to accurately locate it and hold it in position during operation. However, it has been assumed that these devices would be self-centering, such as the V groove, or would be operated remotely. In either mode of operation, the impact of this portion of the operation on downtime for replacement of the first wall/blanket sector is not a significant factor in this analysis.

For the purpose of this study, the sector structure, manifolds, the blanket and shield structure and the first wall are all assumed to be made of stainless steel. The module breeding zone lattice for tritium diffusion and the breeding materials will be similar to those used in the GA-DPR module (Nb alloy, Li_7Pb_2 and Li_4SiO_4 , respectively). Shielding materials similar to the GA-DPR inner shield will also be used (SS/ B_4C). The structure shown in Figure 3.2-13 requires approximately 2.05 meters from the toroidal magnet to the first wall at the inner blanket. This exceeds the allowance for the inner blanket dimensions given in Figure 3.1-5 by 18 cm but will not significantly affect the normalization parameters defined in Table 3.1-1.

3.2.1.4 Oak Ridge National Laboratory Cassette Blanket Concept - The cassette blanket concept employs first wall blanket modules shaped as flat panels that are emplaced in the blanket through slots in the plasma chamber shield. A shield block is mounted at the end of each panel to block the slot in the shield. Figure 3.2-14 illustrates the general arrangement of these cassettes in one sector of a tokamak reactor without a divertor. Since a divertor is used in the reference reactor a somewhat varied arrangement is used.

At every point around the periphery of the blanket chamber the cassettes are

ORNL CASSETTE BLANKET CONCEPT

FIGURE 3.2-14

arranged three deep. This arrangement, i.e., the first blanket zone approach, allows only those zones that require replacement to be replaced at the desired time. Thus, since the life of the first blanket zone (nearest the plasma) is shorter than that of the second or third zone, the panels in this zone may be replaced several times (approximately 5) for every required replacement of a second or third zone panel.

For each reactor sector, nine panels are used to cover a toroidal section of the plasma chamber. A total of 45 panels is then required for the typical sector shown in Figure 3.2-14.

Table 3.2-5 summarizes the design assumptions and definitions for the ORNL Cassette first wall/blanket. These assumptions are based on the module design given in References 3-4 and 3-5.

TABLE 3.2-5
DESIGN ASSUMPTIONS AND DEFINITIONS
(ORNL CASSETTE FIRST WALL/BLANKET)

- CASSETTE SIZE VARIES WITH REACTOR SIZE TO PROVIDE A TOTAL OF 37 CASSETTES FOR EACH REACTOR SECTOR WHEN A SINGLE NULL POLOIDAL DIVERTOR IS USED FOR A TOTAL OF 592 IN A 16 SECTOR REACTOR. ONLY ONE MODULE (CASSETTE) IS USED AT THE DIVERTOR.
- MODULE WEIGHTS VARY WITH LOCATION IN THE POLOIDAL SECTION UP TO APPROXIMATELY 5 TONNES MAXIMUM.
- CASSETTES ARE ASSUMED TO BE SUPPORTED IN PLACE BY STRUCTURE ATTACHED TO THE CASSETTE IN THE NEXT ZONE AWAY FROM THE PLASMA. THIS STRUCTURE GUIDES THE CASSETTE IN AND OUT OF POSITION DURING REPLACEMENT.
- CASSETTES ARE ATTACHED TO EACH OTHER AND TO THE OUTER SURFACE OF THE SHIELD AT THE OUTSIDE OF THE SHIELD BY BOLTS ONLY. A SEAL IS USED WHEN THE VACUUM WALL ARRANGEMENT REQUIRES IT.
- EACH CASSETTE REQUIRES COOLANT AND TRITIUM RECLAMATION DISCONNECTS WHENEVER IT IS REPLACED. ALL LINE JOINTS USE QUICK DISCONNECT FITTINGS.
- FIRST BLANKET ZONE CASSETTE SIZES, INCLUDING SHIELD BLOCKS, VARY AS FOLLOWS:
 - 12.8 m LONG X .69 m WIDE (MAX) X .25 m THICK;
INNER WALL CASSETTE
 - 5.2 m LONG X 1.37 m WIDE (MAX) X .25 m THICK;
BOTTOM CASSETTE
 - 7.1 m LONG X 1.55 m WIDE (MAX) X .25 m THICK;
BOTTOM/OUTER WALL CASSETTE
 - 4.8 m LONG X 1.49 m WIDE (MAX) X .25 m THICK;
TOP/OUTER WALL CASSETTE
 - 2.7 m LONG X 3.50 m WIDE (MAX) X .95 m THICK;
DIVERTOR
- SECOND AND THIRD ZONE CASSETTES ARE .35 m THICK TO INCLUDE THE SUPPORT STRUCTURE.

Two cassette module designs are defined in Reference 3-5. One incorporates a single layer of lithium and coolant and the other utilizes a double layer of lithium and coolant. The selected option is the double cassette module shown in Figure 3.1-6 since this is expected to provide sufficient lithium for attaining a tritium breeding ratio of at least 1.2. Reference 3-10 indicates that more than 25 cm of lithium is required. When a tube diameter of 4 cm is selected in order to keep pumping power below 1%, in accordance with the tables in Reference 3-5, the lithium depth per breeding layer will then be only an average of 6 cm. This depth requires a minimum of 4 single or 2 double cassette modules to make up the 25 cm. Since the arrangement in Figure 3.1-7 differs from that given in Reference 3-10 and structure between the blanket zones has been added, three double modules, each 25 cm thick, have been selected for the blanket. A detailed neutronics and structural analysis has not been conducted since the maintenance requirements are relatively insensitive to the detailed design of the module at the level of maintenance analysis employed in this study.

The method of attaching the cassettes to the external face of the shield or the shield support structure that is assumed for the cassette concept is illustrated in Figure 3.2-15. Seals may or may not be used depending on the vacuum wall requirements. Figure 3.2-15 also indicates the sequence of installation and removal. Cassette 9 is the first removed and last emplaced. Sectors 1, 4 and 7 or 2, 5 and 8 must be installed in sequence but the two sets may be reversed in order. The flat plate ends are assumed to have the seals installed before the modules are put in place. Figure 3.2-16 indicates an approach to the seal installation at a typical corner joint. In all ORNL Cassette vacuum configurations at least a double vacuum wall is used and the seals are required only to increase the impedance in the molecular flow regime. Therefore, a perfect vacuum seal is not attempted at this point. Additional consideration must be given to the juncture with modules in adjacent sectors. The structural support of the shield is assumed to provide the attachment point shown in Figure 3.2-16 since the right and left modules are moved to the center before removal, leaving space for supporting structure.

The gaseous He coolant and tritium manifold connections are disconnected at each module. The line connections required at the center row of modules (modules 3, 6 and 9) to allow removal of these modules are typically illustrated in Figure 3.2-17. The connections at all other modules can be of the same arrangement but need only allow initial lateral movement of the module. Valving in these lines is sufficient to pressurize one bank of modules at a time with coolant gas for leak detection. With this arrangement, 3 piping connections are required for each module.

TYPICAL CASSETTE ATTACHMENT ARRANGEMENT

- MODULES NUMBERED IN SEQUENCE OF INSERTION
- CONNECTING He AND T LINES NOT SHOWN
- ATTACHMENT TO ADJACENT SECTOR NOT DETAILED

FIGURE 3.2-15

3.2.2 Reactor Magnet Systems - The magnet system designs are unique to each reactor concept, particularly in the number and arrangement of the poloidal field coils. The significant physical characteristics affecting maintenance of the magnet systems for each of the four candidate reference systems are listed in Table 3.2-6.

In general, the magnet systems include the same number and type of coils as defined for the original design concept. That is, all magnets are of unitary (one piece) design and all employ NbTi superconductors. The original selection for the GA-DPR concept vertical field (F) coils employed normal Cu conductors and segmented all of these coils into six 60° sections with bolted joints. However, the alternate design of nonsegmented superconducting coils was chosen for this study to establish uniform costing and services. A brief analysis of segmented superconducting magnets is conducted as a part of this study.

TYPICAL CASSETTE ATTACHMENT SEAL ARRANGEMENT

FIGURE 3.2-16

TYPICAL ARRANGEMENT OF FLUID LINE CONNECTIONS AT ONE BANK OF CASSETTES

NOTE: CONNECTIONS AND BELLOWS ILLUSTRATE ARRANGEMENT
AND NOT A SPECIFIC DESIGN.
REFER TO FIGURE 3.2-15 FOR INSERTION SEQUENCE

FIGURE 3.2-17

TABLE 3.2-6
MAGNET SYSTEM CHARACTERISTICS FOR REFERENCE SYSTEMS

	UWMAK-III	GA-DPR	CULHAM MARK II	ORNL CASSETTE
TOROIDAL FIELD COILS				
TOROIDAL FIELD COILS, NUMBER	16	16	16	16
TYPE OF CONDUCTOR FOR TF COILS	NbTi	NbTi	NbTi	NbTi
ON AXIS FIELD, B_0	4.11	4.62	3.87	3.87
MAXIMUM FIELD AT CONDUCTOR, B_m , TESLA	8.66	8.66	8.66	8.66
CONSTRUCTION	UNITARY	UNITARY	UNITARY	UNITARY
POLOIDAL FIELD COILS				
VERTICAL FIELD COILS, NUMBER	40	32	10	10
LOCATION	INSIDE TF COILS	INSIDE TF COILS	4 INSIDE TF COILS 6 OUTSIDE TF COILS	9 INSIDE TF COILS 1 OUTSIDE TF COILS
MOVEABLE FOR MAINTENANCE	10	NONE	3	NONE
CONDUCTOR	NbTi	NbTi	NbTi	NbTi
CONSTRUCTION	UNITARY	UNITARY	UNITARY	UNITARY
OHMIC HEATING COILS, NUMBER	26	32	14	15
LOCATION	16 INSIDE CORE 10 OUTSIDE CORE	18 INSIDE CORE 14 OUTSIDE TF COIL	10 INSIDE CORE 4 OUTSIDE CORE	13 INSIDE CORE 2 OUTSIDE CORE
MOVEABLE FOR MAINTENANCE	2	NONE	NONE	2
CONDUCTOR	NbTi	NbTi	NbTi	NbTi
CONSTRUCTION	UNITARY	UNITARY	UNITARY	UNITARY
EQUILIBRIUM (STABILIZATION) COILS	0	0	5	5
LOCATION	-	-	INSIDE TF COILS	INSIDE TF COILS
CONDUCTOR	-	-	NbTi	NbTi
CONSTRUCTION	-	-	UNITARY	UNITARY

To provide normalization of the designs for maintenance insofar as feasible, some deviation from the published concepts is accepted. Major factors affecting maintenance of other subsystems include the coil locations and the dewar arrangements. When normalizing the reactor conceptual designs to the 3000 MW_{th} level, the same number of magnets as specified for the baseline concept is retained but they are repositioned to approximate the desired magnetic flux surfaces. The energy in the coils is recomputed and the coil size is varied. These computations are conducted as part of the systems code of the TOCOMO program used to define reactor costs. However, the variation in the size of each coil has little influence on the maintenance plans for other subsystems.

Additional design assumptions and coil characteristics are summarized in Table 3.2-7. In particular, this table indicates the type of support and attachment joints that are defined for the coils used in each reactor concept. For consistency of design comparison in some cases these coil support and attachment concepts are defined differently than those indicated in the reports that define the basic design concepts (References 3-2 through 3-8).

UWMAK-III - The TF and PF coil arrangement for the UWMAK-III configuration is illustrated in Figure 3.2-18. All coils are superconducting and use pool boiling of liquid helium as coolant. The ohmic heating coils (denoted by the solid sections)

TABLE 3.2-7

REFERENCE SYSTEM MAGNETIC FIELD COIL DEFINITIONS

	UMMAK-III	GA-DOUBLET	CULHAM	ORNL CASSETTE (LIKE UMMAK-III)
TOROIDAL FIELD COILS COIL SUPPORT COIL INTERCONNECTION TYPE OF DEWAR	SHEAR BOLTS IN CORE CONTINUOUS SHEAR PANELS BOLTED TO COIL CASE COMMON AT CORE, LHe COOLED AND COMMON VACUUM	FLOOR COLUMNS, BALL JOINTS COLD INTERCOSTALS (2/COIL) BOLTED TO COIL CASE COMMON AT CORE AND INTERCOSTALS, LHe COOLED AND COMMON VACUUM	FLOOR COLUMNS CONTINUOUS SHEAR PANELS BOLTED TO COIL CASE COMMON AT CORE, LHe COOLED AND COMMON VACUUM	SHEAR BOLTS IN CORE CONTINUOUS SHEAR PANELS BOLTED TO COIL CASE COMMON AT CORE, LHe COOLED AND COMMON VACUUM
POLYIDAL FIELD COILS VERTICAL FIELD COILS COIL SUPPORT FIXED COILS RETRACTABLE COILS ACTUATION TYPE OF DEWAR COILS IN CORE (OR SHIELD) COILS OUTSIDE CORE OHMIC HEATING COILS COIL SUPPORT COILS IN CORE COILS OUTSIDE CORE TYPE OF DEWAR COILS IN CORE COILS OUTSIDE CORE	BOLTED TO EXTERNAL STRUCTURE COLLAPSIBLE STRUCTURE AUTOMATIC INDIVIDUAL COIL, LHe COOLED, SHARED VACUUM INDIVIDUAL COIL, LHe COOLED AND INDIVIDUAL VACUUM BY CORE STRUCTURE BY EXTERNAL STRUCTURE, BOLTED INDIVIDUAL COIL, LHe COOLED, SHARED VACUUM INDIVIDUAL COIL, LHe COOLED, AND INDIVIDUAL VACUUM	BOLTED TO EXTERNAL STRUCTURE AND SHIELD NONE COMMON JACKET, LHe COOLED INDIVIDUAL JACKET, LHe COOLED BY CORE STRUCTURE BY EXTERNAL STRUCTURE, BOLTED COMMON FOR ALL COILS, LHe COOLED, VACUUM SHARED WITH CORE INDIVIDUAL COIL, LHe COOLED AND INDIVIDUAL VACUUM	BOLTED TO EXTERNAL STRUCTURE RETRACTABLE STRUCTURE AUTOMATIC (INTEGRAL IN SHIELD, LHe COOLED) INDIVIDUAL COIL, LHe COOLED AND INDIVIDUAL VACUUM BY CORE STRUCTURE BY EXTERNAL STRUCTURE INDIVIDUAL COIL, LHe COOLED, SHARED VACUUM INDIVIDUAL COIL, LHe COOLED AND INDIVIDUAL VACUUM	BOLTED TO EXTERNAL STRUCTURE RETRACTABLE STRUCTURE AUTOMATIC (ON COILS) INDIVIDUAL COIL, LHe COOLED SHARED VACUUM INDIVIDUAL COIL, LHe COOLED AND INDIVIDUAL VACUUM BY CORE STRUCTURE BY EXTERNAL STRUCTURE, BOLTED INDIVIDUAL COIL, LHe COOLED, SHARED VACUUM INDIVIDUAL COIL, LHe COOLED AND INDIVIDUAL VACUUM

are located primarily in the reactor core but with eight coils outside of the core region as shown. The sixteen in the core structure are extended by four coils above and two coils below the core mounted on external structure. The forty vertical field coils (denoted by the open sections) are installed inside of the TF coils (except for one above and one below) as indicated. Ten of these coils (and two of the ohmic heating coils) must be retracted to allow the shield doors to be opened.

The TF coils are the modified constant tension configuration and are attached to the reactor core by shear beams inserted into slots near the top and bottom of the straight leg of the coil. These shear beams are held in place by shear bolts running vertically through the core and the upper shear beam in each coil.

Figure 3.2-19 is a diagrammatic sketch of a cross section of the TF coil showing the thermal isolation system and dewar arrangement. The dewars for each TF coil are welded into a common dewar at the reactor core. The continuous shear panels are attached to the coil outer wall and react loads through the epoxy struts. Since pool boiling of LHe is used to cool the coils, the He vapor cooled leads are installed at the top of the coils.

The dewars are all assumed to include a superinsulation blanket. A number of the concepts include another insulated LN₂ jacket. Since the maintenance actions considered are only concerned with removal of the complete coil, the detailed design characteristics of the coils and dewars are defined only insofar as the replacement operations are affected. The LN₂ jacket increases the number of connections that

UWMAK III MAGNET ARRANGEMENT

FIGURE 3.2-18

are broken and remade during the removal operations and these replacement operations would be simplified if it could be omitted.

Many of the poloidal field coils shown in Figure 3.2-18 are installed in the core. The ohmic heating (OH) coils in the core structure are assumed to be buried in this structure and must be wound in place (in addition to all poloidal field coils inside of the TF coils) before installation of the TF coils. The vertical field coils installed between the vertical inner leg of the TF coils and the shield are inside of the common dewar but have individual LHe cooling. Electrical leads are assumed to be extended through the dewar to the top of the TF coil where they exit in He vapor cooled connections.

Reference 3-2

FIGURE 3.2-19

The remaining ohmic heating coils above and below the core structure are assumed to be bolted to external structure with individual coil LHe cooling systems and dewar vacuum connections. Two additional ohmic heating coils are inside the TF coil and have a similar support and dewar design to the vertical field coils in the same region. The remaining two OH coils are located outside of the outer leg of the TF coil and must be retractable to allow for egress to the lateral support access panels between the TF coils.

All of the poloidal field coils inside of the TF coils are assumed to be wound in place and attached to structure which supports the coils, manifolds and plasma chamber. This basic structure is assumed to be permanent so that coil winding apparatus will fit within the space available, or within the space that can be made available through disassembly of the plasma chamber.

The retractable coils are supported by a collapsible truss structure that will react the toroidal loads. A split "X" structure between retraction actuators that will be hinged to collapse within the space available inside of the TF coil appears feasible. A latching system is assumed for this structure to lock it in place and allow automatic retraction and extension. Without such a system all lateral support access panels must be removed to retract any one coil.

Retraction actuators may be pneumatically or hydraulically operated. Electrical operation is questionable because of the potential magnetic field effects on such equipment. However, the mechanism selected has little effect on maintenance operations at the level of detail being considered. To avoid disconnecting the services required by the retractable PF coils these lines are assumed to be routed along a helical path and the coil rotates slightly when retracting to minimize flexing these service lines.

GA-DPR - The TF and PF coil arrangement for the GA-DPR concept is illustrated in Figure 3.2-20. The TF coils and the ohmic heating coils are all superconducting and each is a continuous coil (unitary) design. The ohmic heating coils consist of 150 turns with approximately 126 turns inside of the core and 24 external. The vertical field coils are also superconducting and of unitary design for consistency with the other reference designs. All 32 vertical field coils are installed within the bore of the TF coils.

FIGURE 3.2-20

Normal coils with copper conductors that are segmented into six 60° segments were originally selected for the GA-DPR in a comparative study with superconducting coils. This type of coil produces a more maintainable concept. However, the costing will differ so superconducting coils are selected for the GA-Doublet configuration defined in this study.

The TF coils are supported by floor mounted columns located outboard of the coil center of gravity. The coil then rests on the reactor center core. A ball joint and thermal insulator is provided in the mounting column to provide for radial movement. Radial loads and the resultant motion are minimized by the use of a constant tension design for these coils. The lateral loads are reacted by coil keys in the core and by circular intercostal tie rods between coils. Only two intercostal supports are shown but more may be required to reduce deflection. The UWMAK-I concept (Reference 3-16) requires one intercostal support every 2 or 3 meters around the periphery of the coil but coil loading studies (Reference 3-24) indicate that the spacing and number required may vary considerably around the coil periphery. The intercostals are enclosed in a vacuum dewar that is common with the dewar of the TF coils to reduce heat leaks. It is assumed that the intercostal is bolted to special connectors attached to the case of the magnet within the dewar. The magnet vacuum dewars are common with each other and the ohmic heating coil dewar at the reactor core. The coils are cooled by pool boiling of LHe and lead connections similar to those used for the UWMAK-III are assumed.

The superconducting ohmic heating coils in the core are enclosed by a vacuum dewar that is common with the TF coil dewar but a separate pressurized flow LHe cooling system is assumed. Electrical leads and helium connections are similar to those used for the UWMAK-III and located at the top of the ohmic heating coil stack. It is assumed that coils in the central core ohmic heating coil stack may be wound off-site and installed by slipping them over the top of the core structure before emplacing the crown structure. The ohmic heating coil case must be capable of transferring the TF coil centering loads to the reactor core structure. The crown structure and its coils are also assumed to be assembled as a single unit but the coils below the reactor are individually installed. Each of the ohmic heating coils mounted to external structure is bolted in place and is equipped with vacuum dewars. Each dewar has its individual LHe cooling system.

The vertical field coils are built up inside of the TF coil. The coils at the core (between the inner and outer shields) are installed prior to installing the plasma chamber. Other coils are assembled as the installation of the plasma

chamber and shields progress. For the GA-Doublet concept, none of the vertical field coils need be retractable for first wall/blanket maintenance. Therefore, all coils are attached to fixed structure.

Culham - The TF and PF coil arrangements for the Culham Mark II are not available in as much detail as are the magnet systems for the UWMAK-III and the GA-DPR reactor concepts. The arrangement shown in Figure 3.2-21 requires poloidal field coils consisting of only 10 vertical field coils, 14 ohmic heating coils and 5 equilibrium coils. All of these coils are superconducting with individual coil vacuum dewars except for the ohmic heating coils in the reactor core which are included in the common core dewar. The TF coils have individual dewars which become

CULHAM CONCEPT MAGNET ARRANGEMENT

FIGURE 3.2-21

common at the reactor core. The TF coils are cooled by pool boiling LHe and the PF coils employ pressurized flow of LHe. The coil arrangement is simplified in that only a single null divertor is used but this requires that four vertical field coils are embedded in the shielding around the divertor region and inside of the TF coil bore. The equilibrium coils are also within the TF coil bore. All other vertical field coils and the ohmic heating coils are outside of the TF coils.

For the Culham reference reactor, the modified constant tension TF coil configuration selected for the UWMAK-III is employed and made large enough to include the divertor and particle trapping surfaces. These coils are supported in a manner similar to that used for the GA-DPR with floor mounted columns outboard of the coil center of gravity and with the inside vertical leg keyed to the reactor core. The centering loads are transmitted through the supports between the ohmic heating coils to the bucking cylinder structure.

The TF coil lateral support structure is made up of continuous shear panel supports bolted to the coil case attachments. For the comparison of vacuum wall locations, one wall location is at the TF coils and, in this case, a lateral support access panel is used that is similar to that defined for the UWMAK-III. In all vacuum wall cases the lateral support panels are assumed to be at ambient temperature instead of the insulated cooled structure used in the Culham concept. The TF coil cross section is assumed to be similar to that shown in Figure 3.2-19 for the UWMAK-III. These modifications of the Culham concept are available in the TOCOMO code.

The four retractable superconducting poloidal field coils are all located outside of the TF coil bore. The feasibility of design of the collapsible structure that reacts the toroidal loads is more credible in this location than for the structure inside of the TF coils as required by the UWMAK-III. Retraction mechanisms similar to those indicated for the UWMAK-III are assumed. In the Culham concept these are the only coils that require flexible connections for LHe, vacuum and power to allow retraction. However, connections are more accessible than in the UWMAK-III concept and, if required, rigid connections provide a reasonable alternative.

The coils in the divertor are assumed to require removable shield blocks to permit winding in place during assembly. The area above the coils has been increased to provide access and space for winding the coils. The divertor island, and, consequently, divertor coil support is from structure that shields the TF coils and is located inside the TF coils.

The ohmic heating coils are supported by structure which can be inserted in place after the coils are wound into it. This structure is assumed to be in several sections to simplify this assembly. The lower section may be used to provide additional support for the TF coils, if required, and is assumed to be moved downward for access to the coil(s) supported by it. The inner sleeve is moved vertically along the central column. This access is similar to that provided for the ohmic heating coils in the GA-Doublet concept.

ORNL Cassette - The TF and PF coil arrangement for the reactor employing the ORNL Cassette first wall/blanket as defined in the demonstration study (Reference 3-4) is illustrated in Figure 3.2-22. Since the cassettes are applied to a reference reactor design with a plasma height to width ratio of 2:1 and with a poloidal

ORNL CASSETTE TYPE REACTOR MAGNET ARRANGEMENT

FIGURE 3.2-22

divertor to normalize its performance with the other reference concepts, the TF and PF coils must of necessity vary from those indicated for the coil geometry and construction described in Reference 3-5. To define a complete reactor concept employing the ORNL first blanket zone (FBZ) cassette concept, the UWMAK-III reactor definition is integrated with the ORNL Cassette blanket design concept. However, the poloidal field magnet system must vary, of necessity, from that used for the UWMAK-III since only a single null divertor is considered. Therefore, the PF coils have been assumed similar in arrangement to a mixture of the Culham concept - to account for the single null divertor - but mounted inside the TF coils as for the UWMAK-III. Also, the UWMAK-III concept for the ohmic heating coils is employed. Only two ohmic heating coils outside of the TF coils are required to be retractable for this concept.

Toroidal field coils are supported by floor supports mounted outboard of the coil center of gravity and use a ball joint or similar device to allow for radial motion as for the GA-Douplet. In this configuration the bucking cylinder and adjacent TF coils provide support at the core of the reactor when the reactor is not in operation. The toroidal field coils are cooled by pool boiling LHe and have individual dewars which become common at the core. This common vacuum encloses both the TF coil and the ohmic heating coils in the same manner as the UWMAK-III dewar. Continuous shear panels at ambient temperatures are used between the TF coils. These are either totally closed to form a vacuum wall or are designed with openings to allow access to the cassettes for those cases in which the vacuum walls are located elsewhere.

The ohmic heating coils are assumed to be reduced in number from 26 for the UWMAK-III to 15 for ORNL because of the use of a single null divertor. The two coils outside of the TF coil legs are retractable to permit movement of maintenance equipment and lateral support access panels (when used). The coils in the core region are mounted in structure which can be sectionalized and lowered into the core region around the central core after the coils are in place in the same manner as the Culham and the GA-Douplet concepts.

The vertical field coils are assumed to be reduced in number from the 40 required for the UWMAK-III to approximately 15 for ORNL. This reduction is assumed since the Culham concept utilizes only 15 coils and the reduced interference to maintenance access with fewer coils is desired. However, more coils are assumed to be required when located inside the TF coil bores as shown in Figure 3.2-22. This location is chosen rather than outside of the TF coils since the assurance is higher that a plasma height to width ratio of 2:1 can be attained. The coil locations

shown in Figure 3.2-22 are for illustration only. It is assumed further that these coils can be located so that none are moved to gain access to the blanket modules. The access and shielding provisions provided for the Culham coils in the divertor region apply here also. Furthermore, the individual vertical field coil design defined for UWMAK-III is assumed for use in this configuration. As indicated in Table 3.2-7, these coils are bolted to structure within the TF coil bore and cooled by pressurized LHe with individual cooling and vacuum dewars.

3.2.3 Supplemental Plasma Heating System - The major part of the plasma heating for ignition is provided by the Ohmic Heating system. However, to attain ignition conditions supplemental heating is accomplished by injecting energetic particles into the plasma. This supplemental plasma heating system has a significant impact on the maintenance plans for the reference reactors.

3.2.3.1 Neutral Beam Injector System Selection - Two approaches have been used in the reference tokamak systems for supplementary heating: neutral beam and radio frequency (RF). Of the reference reactors selected for this study, the original concepts for the General Atomic-DPR, the Culham Mk II and the ORNL Demonstration Study use the neutral beam injectors and the UWMAK-III uses the RF heaters.

The supplemental heating system significantly influences both the maintenance time and techniques required. To reduce the design and cost variables to those parameters influenced primarily by the reactor concept it is desirable to use a common heater concept. The first phase of the study (Reference 3-25) has shown that the RF heater approach requires less downtime to obtain access to the plasma chamber and allows maintenance of the RF source during operation. These and other maintainability advantages of this technique are of value but the more advanced developmental status of the neutral beam approach and its selection by three of the conceptual designs led to its selection for all designs evaluated in this study.

The neutral beam injector operating characteristics are listed in Table 3.2-8. These characteristics are taken from requirements defined for the Neutral Beam Injector System specified by the Argonne National Laboratory, Experimental Power Reactor Study (ANL-EPR), Reference 3-14, and for the Oak Ridge National Laboratory Experimental Power Reactor (ORNL-EPR), Reference 3-15. The neutral beam injector unit defined for the ANL-EPR is illustrated in Figure 3.2-23 with two beam lines per unit arranged above each other. The characteristics of this design are similar to those specified for the neutral beam injectors to be used by the Tokamak Fusion Test Reactor (TFTR) being built for the Princeton Plasma Physics Laboratory

TABLE 3.2-8
NEUTRAL BEAM INJECTOR SYSTEM OPERATIONAL REQUIREMENTS

	ANL-EPR		ONRL-EPR	GA-EPR
	PER SYSTEM	PER NBI (12 REQ'D)	PER SYSTEM	PER SYSTEM
ATOMIC ION TYPE	D ⁺	D ⁺	D ⁻	D ⁺
INJECTED BEAM POWER, P _B	60 MW	5 MW	50 MW	60 MW
INJECTED BEAM ENERGY, W _B	180 keV	180 keV	200 keV	125 keV
NO. OF INJECTORS, NBI'S	12	1	6	16
NO. OF BEAM LINES	24	2	12	2
BEAM ANGLE FROM HORIZONTAL	-	10°	0°	0°
INJECTOR SIZE (METERS)	-	9Lx7Wx4H	-	-
INJECTOR WEIGHT (TONNES)	-	150-200	-	-
ION BEAM VOLTAGE, V (MV)	.180	.180	.200	-
ION BEAM CURRENT, A (AMPS)	333	333	250	80
DC/AC CONVERTER				
SOURCE POWER, P _A (MW)	207 MW	-	100 MW	400 MW
SOURCE CURRENT, I _A (AMPS)	500	-	500	2000
SOURCE VOLTAGE, V _A (MV)	.243	-	-	.138
DC POWER SUPPLY				
NO. REQ'D	12	1	6	32
OUTPUT POWER, P _S (MW)	-	10	-	-
OUTPUT CURRENT, I _S (AMPS)	-	41.66	-	-
OUTPUT VOLTAGE, V _S (MV)	-	.24	-	-
PULSE LENGTH, t _p (SEC)	-	5	5	2-3
VACUUM PARAMETERS				
VACUUM CHAMBER NO. 1 PRESS. (TORR)	-	10 ⁻⁴	} 10 ⁻⁵	} 10 ⁻⁵
VACUUM CHAMBER NO. 2 PRESS. (TORR)	-	10 ⁻⁵		
CRYOSORPTION PUMP				
COOLANT MEDIA	-	LHe	LHe	LHe
PANEL TEMP, T _p (°K)	-	10-20	10-20	-
PANEL AREA, A _{PT} (m ²) (TOTAL)	-	250	-	-
PANEL AREA, A _{PL} (m ²) (ON-LINE)	-	125	120	260
COOL-DOWN TIME (HR)	-	4	4	-
GASES PUMPED	-	H ISOTOPES	H ISOTOPES	H ISOTOPES
PUMPING SPEED, S _p (L/SEC)	-	6x10 ⁶	6x10 ⁶	-
REGENERATION PERIOD, T _{OP} (HRS)	-	24	24	-
REGENERATION PUMPING SYSTEM				
GASES PUMPED	H ISOTOPES			
VOLUME, V _R (m ³ /HR)	259		-	-
IONIZATION CHAMBER COOLING SYSTEM				
HEAT REJECTION RATE (MW)	3.40	.284	-	-
LN ₂ REFRIGERATION SYSTEM				
CHEVRON SHIELD TEMP., T _S (°K)		~ 77	~ 77	~ 77
D ₂ GAS SUPPLY SYSTEM				
TO NEUTRALIZER, S _M (TORR-L/SEC)	-	41.4	-	-
TO IONIZATION CHAMBER, S _I (TORR-L/SEC)	-	15.4	-	-
TOTAL (12 NBI'S), (TORR-L/SEC)	681	-	-	2080

ANL EPR NEUTRAL BEAM INJECTOR

FIGURE 3.2-23

(References 11 and 17). The size, weight, power and number of beam drives per unit are compared in Table 3.2-9. A side elevation of the concept being developed for the TFTR is shown in Figure 3.2-24. This is the configuration proposed by LBL/LLL. It is noted that the three beam lines in this configuration are arranged in the same horizontal plane.

Of the two configurations, the LBL/LLL was selected as the baseline for use in the maintainability study for the following reasons. First, the principal maintenance action is expected to be the scheduled exchange of the ion sources because of the relatively short life expected from current and extrapolated state-of-the-art. Also, sufficient data is available to define the performance of this ion source configuration and the access at the rear of the neutral beam injector unit is good for the configuration shown. In addition, because the injected power specified varies for the different reference reactor concepts from approximately 60 Mw of 125 keV

TABLE 3.2-9
NEUTRAL BEAM INJECTOR UNIT SIZES

	ANL/EPR	TFTR LBL/LLL
DIMENSIONS:		
LENGTH (VACUUM CHAMBER), m	9	5.7
(TO FIRST WALL), m	12.75	8.9
WIDTH, m	4	3
HEIGHT (VACUUM CHAMBER), m	7	5
WEIGHT, TONS	150-200	70
NUMBER OF ION SOURCES	2	3
INJECTED POWER/SOURCE, MW	2.5	1.67-2

TFTR NEUTRAL BEAM SIDE ELEVATION

REFERENCE 3-11

FIGURE 3.2-24

neutral atoms (Reference 3-12) to possibly as much as 100 Mw of 550 keV neutral atoms (Reference 3-3), the use of three, instead of two, beam lines in one unit may give room for growth in injected power, if needed. This appears to require increases in size and weight of the unit for the commercial reactor so that the estimated weight of the ANL concept at 150 tons (136 tonnes) may be more realistic than the 70 ton weight allotted for the TFTR injector. The larger weight will be used for maintenance estimates.

3.2.3.2 Neutral Beam Injector Unit Services - The principal maintenance functions to be studied are (1) the removal and replacement of the neutral beam injector units in their entirety for the purpose of gaining access to other subsystems and (2) the exchange of the ion sources for each beam line. Therefore, the detailed design of each unit is necessary only to the extent required to indicate the internal interfaces, the interface with plant services, and the environments in which the maintenance is conducted. The principle of operation of the units required for the TFTR is shown in Figure 3.2-25 (from Reference 3-17). This is typical of the design used for this study. Since the operation of the neutral beam injector system occurs only during ignition of each burn cycle in tokamak reactors, the fast valve is used to isolate the unit from radiation dosages during burning and thus prolong the life of the ion source. Since the high energy neutron dosage is larger for a

REFERENCE 3-11

FIGURE 3.2-25

commercial reactor, this valve will require significantly greater radiation shielding than the TFTR design and also active cooling. The isolation valve is used to seal the plasma chamber and permit a vacuum to be maintained in it if the neutral beam enclosure is brought to atmospheric pressure. The functions of both valves and the calorimeter may be combined when used in a demonstration or commercial reactor. The unit required for the commercial reactor is also expected to require shielding around the attachment duct and, possibly, shielding enclosing the ion sources. The latter requirement depends upon the radiation dosage experienced by the ion source, the life of the source between scheduled replacements, and the degree of contact maintenance utilized. The Neutral Beam Power Supply system is assumed to be remotely located and need only be disconnected and reconnected to exchange a replacement neutral beam injector unit.

The plant or system services required for a neutral beam injector are illustrated in Figure 3.2-26. While this illustration is for a unit with only two beam lines and is based on the ANL-EPR concept, it is typical of the requirements for the selected unit using the three beam lines. The following service connections to the neutral beam injector unit are required.

- o DC power for ion sources, neutralizer and magnets,
- o DC power from direct convertor,
- o Coolant (water) for ion sources, calorimeter and/or valves, feed and return lines,
- o Deuterium supply to neutral beam lines,
- o Deuterium and H isotope return from cryosorption pumps (Vacuum return lines),
- o LHe coolant for cryosorption pumps, feed and return lines,
- o LN₂ coolant for cryosorption pumps, feed and return lines,
- o GHe coolant for neutral beam duct shielding,
- o SF₆ pressurization and purge lines for ion sources, feed and return,
- o Central instrumentation, control and data acquisition system (CICADA) connections.

These service lines are expected to be small in comparison with the reactor coolant and vacuum lines. Therefore, quick disconnects or mechanical joints are considered feasible and are assumed for use in this study.

3.2.3.3 Ion Sources - With current technology the ion sources required for the neutral beam injectors appear to have a very short life and, for the purpose of this study, replacement of these sources is considered the most frequent scheduled maintenance requirement. A current design for a source of D⁺ ions is exemplified

TYPICAL NEUTRAL BEAM INJECTOR SYSTEM SCHEMATIC (BASED ON ANL-EPR)

FIGURE 3.2-26

by the LBL 120 keV source shown in Figure 3.2-27. This design requires many power input, deuterium gas and cooling water connections for each source. It is enclosed in a high dielectric gas (SF_6) which must be contained or removed for maintenance. Disassembly can be conducted in place to remove the filament (source) section or combined filament and accelerator (extractor) sections. It is contemplated that the services required will be contained in a cover or hat section, not shown in Figure 3.2-27, which can be withdrawn a short distance and which disconnects the power and coolant lines. However, numerous interconnections between sections must be disconnected. Therefore, a somewhat simplified arrangement has been defined for the purpose of this study.

The study considers the ion source connections to be as indicated in Figure 3.2-28. Each ion source, three for each neutral beam injector unit, will be removed as a complete unit with only five service connections and the structural attachments to be disconnected. The structural attachment is a bolted flange located at the mating line with the neutral beam injector vacuum chamber. A double vacuum seal at this flange is feasible with relatively simple access for replacement. This installation arrangement permits removal of the entire ion source without disrupting

FIGURE 3.2-27

the integrity of the SF_6 pressurized compartment. It is believed feasible to develop a suitable alignment system within the ion source enclosure. Also, extended development for commercial use should permit ganging the service connections for removal as a unit. However, the impact of unsatisfactory reseating of some of these connections during reassembly makes the use of several separate connectors desirable and, therefore, several connectors are assumed in this study.

3.2.4 Reactor Vacuum Systems - Vacuum requirements in tokamak fusion reactors exist for the following regions:

- o the plasma chamber,
- o the divertor regions,
- o the neutral beam injector chambers, and
- o the secondary vacuum regions (if used).

NEUTRAL BEAM ION SOURCE ASSEMBLY

FIGURE 3.2-28

These vacuum requirements vary with the configuration of the reference reactors but the requirements for the UWMAK-III, Culham and the ORNL Cassette concepts are similar. The vacuum pumping systems for these three concepts employ a common system for the plasma chamber, divertor, and neutral beam injectors. Another system is employed for a secondary vacuum chamber when one is used with the basic reactor concept. Since the vacuum requirements for the GA-Douplet concept differ significantly from the other reference systems, its vacuum pumping system will also differ. The system for the GA-Douplet is only outlined in this discussion.

3.2.4.1 Primary Vacuum System - The pumping requirements for the plasma chamber and the neutral beam injectors of the four reference concepts are defined in Table 3.2-10. The nominal plasma chamber cryovacuum pump system designs discussed

TABLE 3.2-10
PRIMARY VACUUM SYSTEM PUMPING REQUIREMENTS

	CULHAM, ORNL	UWMAK-III	GA
PLASMA CHAMBER REQUIREMENTS			
THRUPUT @ 300°K, TORR-L/SEC	2103	2126	5175
PUMPING SPEED, L/SEC	2.103×10^7	2.126×10^7	5.175×10^7
CRYOPANEL AREA, m ²			
ACTIVE	420	424	1031
TOTAL	840	848	2062
TOTAL (INCL. STRUCTURE)	1292	1304	3172
CHAMBER OPERATING PRESSURE, TORR	1×10^{-5}	1×10^{-5}	1×10^{-5}
CHAMBER BASE PRESSURE, TORR	1×10^{-8}	1×10^{-8}	1×10^{-8}
REJUVENATION PERIOD, HRS.	6	6	6
GAS VOLUME/6 HRS (STP), LITERS	59760	60414	147056
NEUTRAL BEAM INJECTOR REQUIREMENTS			
	(ALL CONFIGURATIONS)		
NUMBER OF NBI UNITS (3 ION SOURCES/ UNIT)		12	
THRUPUT (12 UNITS), TORR-L/SEC		1980	
NBI FINAL PRESSURE (15 SEC PULSE), TORR		1×10^{-5}	
NBI BASE PRESSURE, TORR		1×10^{-8}	
PUMPING SPEED, L/SEC		1.65×10^6	
CRYOPANEL AREA, m ²			
ACTIVE		396	
NUMBER OF BURN CYCLES BETWEEN REGENERATION		6	
ABSORPTION CAPACITY OF PUMPS (STP), LITERS		247	
GAS ACCUMULATED IN 6 CYCLES (STP), LITERS		234	
REGENERATION PUMPING			
TOTAL GAS VOLUME (STP), LITERS	59994	60661	147303
ALLOWABLE PUMPING TIME, HRS	6	6	6
PUMPING TEMPERATURE, °K	300	300	300
PLENUM PRESSURE, TORR	100	100	100
FINAL PRESSURE, TORR	1×10^{-1}	1×10^{-1}	1×10^{-1}
PUMP DOWN VOLUME, TOTAL, m ³	9432	9059	14132
PER REGENERATION*, m ³	8112	8112	13172

* DOES NOT INCLUDE PLASMA CHAMBER

in this section are based on the requirements for the Culham and ORNL reactor concepts. Since the requirements for the UWMAK-III are very close to the nominal design values the nominal design is used for this concept also. The requirements for the General Atomic-Doublet configuration are significantly greater than for the other configurations because of the use of the flowing plasma boundary instead of the divertors. This increases the required gas throughput from 2103 to 5175 torr-liters/sec. The cycle time and rejuvenation period are held constant for all reactors and the pump sizes revised to satisfy the throughput requirements.

The throughput requirements for the Culham, ORNL and UWMAK-III concepts are computed by the TOCOMO system analysis code based on the estimated requirements for UWMAK-III given in Reference 3-2. The throughput requirements of the GA-Doublet concept also computed by TOCOMO but are based on the estimates provided by General Atomic in References 3-3 and 3-12.

The requirements for the neutral beam injectors are based on the data given for the Argonne National Laboratory Experimental Power Reactor in Reference 14 and revised for the three ion source NBI's defined in Section 3.2.3. These NBI requirements represent only a small part of the total cryosorption pumping requirements. Therefore, they are combined with the plasma chamber requirements when defining the regeneration system and both systems are regenerated at the same time.

The primary vacuum system consists of the cryosorption vacuum pumps for the plasma chamber and the neutral beam injectors, and the roughing pumps for both systems. The diagram shown in Figure 3.2-29 defines the arrangement of these pumps and the minimum valving required. Each set of cryosorption pumps consists of two pumps and isolation valving to allow recycling of one pump while the other pump is operating. This arrangement is required for the neutral beam injector pumps as well as for the plasma chamber pumps because the pump regeneration time is greater than the plasma chamber burn time and would require either shutdown of the reactor or the use of redundant neutral beam injectors. In Figure 3.2-29 a cross manifold is provided to permit the use of one set of regeneration or roughing pumps to service any one of several sets of plasma chamber and NBI cryosorption pumps and also to allow the use of redundant sets of roughing pumps, if desirable.

The performance capabilities of the pumps required by the primary system are listed in Table 3.2-11. The cryosorption pumps differ for the three basic vacuum pumping requirements. The Culham and ORNL Cassette concepts employ 16 pumps mounted between the TF coils and above the single null poloidal divertor in a similar arrangement to that used by the UWMAK-III concept. The principal difference is that

PRIMARY VACUUM SYSTEM SCHEMATIC

FIGURE 3.2-29

each pump for the Culham and ORNL Cassette concepts will have a total active area of 26.25 m² instead of the 13.25 m² used by the UWMAK-III arrangement because the UWMAK-III requires two single null poloidal divertors with vacuum pumps at each divertor. The increased flow required by the GA-Douplet concept necessitates the use of cryosorption pumps at both the auxiliary vacuum ports above the plasma chamber and the main ports near the bottom of the plasma chamber. Thirty two pumps are used above the chamber (16 operating at one time) and 16 below the chamber (8 operating at one time). In this arrangement the pumps below the chamber have about 26 times the area per pump as the smaller pumps above the chamber as indicated by their relative pumping speed requirements in Reference 3-12. The pumps used for the GA-Douplet concept are assumed to be cylindrical as shown in Reference 3-12 and for the other reference concepts the design will be flat panels as indicated in the UWMAK-III design shown in Reference 3-2. The flat panels each contain two sets of pumps which are used alternately by operating valves at the inlet and outlet of each pump section. For this study these are assumed to be sliding valves incorporated into each cryopanel. On the other hand, the pumps used by the GA-Douplet concept are isolated when it is desired to regenerate these pumps by an arrangement of gate valves in the vacuum lines, as indicated in Figure 3.2-29.

TABLE 3.2-11

PRIMARY VACUUM SYSTEM PUMPING PERFORMANCE

	CULHAM, ORNL	UWMAK-III	GA-DOUBLET
<u>PLASMA CHAMBER CRYOSORPTION PUMPS</u>			
NUMBER OF PUMPS (TOTAL/ACTIVE)	32/16	64/32	48/24
CRYOPANEL AREA, ACTIVE, m ²	420	424	1031
TOTAL, m ²	840	848	2062
OUTER CHEVRON TEMP, °K	80	80	80
INNER CHEVRON TEMP, °K	20	20	20
MOLECULAR SIEVE TEMP, °K	4.2	4.2	4.2
TOTAL MOLECULAR SIEVE MTL, Kg.	2100	2120	5155
ABSORPTION CAPACITY, 5°K (STP), L/SEC	3.15 x 10 ⁵	3.18 x 10 ⁵	7.75 x 10 ⁵
NUMBER OF BURN CYCLES TO SATURATE PUMPS	31	31	31
<u>NEUTRAL BEAM INJECTOR CRYOSORPTION PUMPS</u> (ALL CONFIGURATIONS)			
NUMBER OF PUMPS (TOTAL/ACTIVE)	24/12		
ACTIVE CRYOPANEL AREA (12 NBI's), m ²	396		
TEMPERATURES	SAME AS PLASMA CHAMBER PUMPS		
TOTAL MOLECULAR SIEVE MTL, Kg	990		
ABSORPTION CAPACITY, (STP), L/SEC	297		
NUMBER OF BURN CYCLES TO SATURATE PUMPS	7.61		
<u>REGENERATION PUMPING</u>			
NUMBER OF PUMP SETS	4	4	4
PUMPS/SET,			
L-H RA 9001 ROOTS BLOWER	1	1	2
L-H. TR 630 ROTARY PISTON PUMPS	3	3	4
TOTAL EFFECTIVE PUMPING SPEED, CFM	6000	6000	12000
PUMP DOWN TIME (REGENERATION)			
CRYOSORPTION PUMP, GAS @ 100 TORR, MINUTES	2.7	2.7	5.0
PUMP DOWN 100 TORR TO 1 x 10 ⁻¹ TORR, MINUTES	196.3	196.3	214.9
WARMUP AND COOL CRYOPANELS, MIN.	120.0	120.0	120.0
TOTAL:	319.0	319.0	339.9
PUMP DRIVE POWER/SET, HP	90	90	140

The neutral beam injectors all use the same size cryovacuum pump with an active area for each operating pump of 33 m², or a total pumping area of 66 m² for each NBI. Regeneration of the NBI pumps during reactor operation requires two sets of pumps for this purpose. These pumps are used in the same manner as are the pumps provided for the plasma chamber vacuum system.

The total pump area for both the plasma chamber and the NBI pumps is determined by doubling the active area to meet regeneration requirements. The design area required is assumed to provide only 65% net open area when making the pump layouts.

The regeneration pump systems defined in Table 3.2-10 are arranged as shown in Figure 3.2-30 with the three Leybold Heraeus TR 630 pumps in parallel with each other and in series with the Roots blower. Each set of pumps has sufficient capacity to service four sets of plasma chamber cryosorption pumps and three NBI pumps (i.e., one quarter of the reactor cryosorption pump regeneration requirements). Therefore, only four sets of regeneration pumps are required for the reactor. The arrangement shown in Figure 3.2-30 differs for the GA-Doublet system in that a second Roots blower and a fourth TR 630 pump are deemed necessary to keep the regeneration time within the six hour requirement. In these arrangements, the TR 630 pumps are assumed to pump down to about 10 torr and the Roots blowers then operate to approximately 10^{-1} torr before cooling the cryosorption pumps to the operating conditions. The addition of more pumps to reduce the time further appears of limited value since the time for regeneration falls within the 6 hour period selected and a significant part of the regeneration time (35-38%) is the fixed period to heat and cool the cryosorption pumps.

FIGURE 3.2-30

The use of four systems for each reactor is arranged in the reactor building in the manner shown in Figure 3.2-31. This arrangement is compatible with the primary coolant loop arrangements discussed in Section 3.2.5.

3.2.4.2 Secondary Vacuum System - The requirements and system specification for the secondary vacuum chamber system are listed in Table 3.2-12. The secondary vacuum chamber system is completely independent of the plasma system and differs significantly for two of the three classes of secondary chamber vacuum wall locations studied. It is assumed that the secondary vacuum chambers for each class will be the same size for all four reactor concepts. While some differences exist, the impact of these differences among the reactor concepts on the pump system selected is expected to be insignificant. The principal differences among the reactor concepts in the secondary vacuum chamber selected vacuum system performance is in the time and power required to pump down the secondary chambers to operating levels.

REGENERATION/VACUUM PUMPING SYSTEM PLAN VIEW

FIGURE 3.2-31

TABLE 3.2-12
SECONDARY VACUUM CHAMBER PUMPING SYSTEM

REQUIREMENTS:

CASE 1 - SECONDARY CHAMBER BETWEEN PLASMA CHAMBER AND TF COILS

CHAMBER VOLUME, m³ 9341

CASE 2 - SECONDARY CHAMBER IS ENTIRE REACTOR ROOM

ROOM DIAMETER, m 100
ROOM VOLUME, m³ 544000

SYSTEM PERFORMANCE:

CASE 1 -

NUMBER OF PUMP SYSTEMS/REACTOR 2
TOTAL PUMPING TIME 760 TO 10⁻⁴ TORR, HRS. 12.2
PUMPS/SYSTEM
L-H RA 9001 ROOTS BLOWERS 1
L-H TR 630 ROTARY PISTON PUMPS 3
PUMP DRIVES, TOTAL HP/SYSTEM 90

CASE 2 -

NUMBER OF PUMP SYSTEMS/REACTOR 9
PUMPING TIME, 760 TO 10 TORR, HRS. 16
PUMPING SPEED, L/SEC 4.54 X 10⁴
PUMPS/SYSTEM 4
PUMP SPECIFICATION ESH 31 X 11 SINGLE STAGE
PUMP RATING, L/SEC @ 634 TORR 1285
PUMP DRIVE, HP 125

PUMPING TIME, 10 TO 10⁻⁴ TORR, HRS. 16
PUMPING SPEED, L/SEC 1.29 X 10⁵
PUMPS/SYSTEM 2
PUMP TYPE ROOTS BLOWERS
PUMP RATING, L/SEC 7160
PUMP DRIVE, HP 500

TOTAL PUMPING TIME, HRS. 32

TOTAL PUMP DRIVE, HP/SYSTEM 1500

The three vacuum wall arrangements for the four candidate reference systems are defined in Figure 3.2-32. These arrangements are defined by the location and type of vacuum seal used for each vacuum wall in a given reactor arrangement. In general, vacuum wall arrangement number 1 uses only a single vacuum wall with a

VACUUM WALL LOCATION ARRANGEMENTS

FIGURE 3.2-32

welded seal. This vacuum wall is located either at the back of the blanket away from the plasma chamber as for the UWMAK-III and the GA-Doublet, at the outer shield as for the Culham concept, or at the lateral support access panel (LSAP) as for the ORNL Cassette concept. Vacuum wall configuration number 2 generally employs a double wall with both walls bolted and the inner wall located as in arrangement number 1 but providing a high impedance or sealed joint which can leak without imposing too great a load on the vacuum system. The outer wall serves as the

primary seal, and, because the secondary vacuum chamber is provided with its own vacuum pumping system, this chamber is maintained at a low enough pressure to allow only molecular flow to the plasma chamber. The vacuum systems required by these configurations are represented by Case 1 in Table 3.2-12. A different configuration is employed for the GA-Doublet in which the secondary chamber is a small void between seals at the plasma chamber wall. Only one vacuum wall arrangement is studied for the GA-Doublet since no advantages appear to exist for this concept when other arrangements are used. The third vacuum wall configuration maintains the inner wall at the plasma chamber but the secondary wall is at the wall of the reactor room. The third vacuum wall configuration indicated here is represented by Case 2 in Table 3.2-12.

The secondary vacuum system performance is given in Table 3.2-12. Case 1 requires the smaller pumps. Two sets of pumps are used for pump down to provide redundancy although no allowance is made for leakage which, if it occurs, will require the additional capacity. The pump down to 10^{-4} torr is selected to provide for molecular flow between the secondary and primary vacuum chamber and to be below the level at which electrical discharge is a problem. This also establishes a maximum pump down time although the use of Roots blowers to achieve this pressure level may be optimistic. A total of 180 horsepower (134.3 kW) is required for the pump drives for the two pump sets. Similar conditions are assumed for Case 2 and nine pump sets are used. The total drive power required for the nine pump sets of the Case 2 secondary pumping system is 13500 horsepower (10071 kW). The diagram shown in Figure 3.2-33 indicates a possible arrangement for the pumps specified for Case 2 in Table 3.2-12 in which the secondary vacuum system is required to maintain a vacuum in the entire reactor room.

3.2.5 Main Heat Transfer and Transport Systems - The main heat transfer and transport system (primary coolant system) includes the primary cooling loop for the plasma chamber first wall/blanket, the intermediate cooling loop and the divertor cooling loop. This study defines a common system for each of these functional loops with alternatives using either helium or lithium for the primary loop coolant. The secondary loop coolant selected is sodium and the divertor loop is defined for the alternatives of lithium and sodium. Helium was also investigated as a coolant for the divertor loop but discarded because of the low heat transfer rate at the divertor bombardment plates.

The system using lithium coolant in the primary cooling loop is applied to the UWMAK-III concept. The Culham and ORNL Cassette concepts use the system with helium

TYPICAL SECONDARY VACUUM PUMPING SYSTEM FOR REACTOR ROOM

THIS SYSTEM REPEATED 9 TIMES FOR PUMPDOWN OF REFERENCE
DESIGN CONFINEMENT BUILDING

FIGURE 3.2-33

as the primary loop coolant. The GA-Doublet configuration would require a similar system but different size equipment is necessary because the distribution of heat transfer between the blanket cooling and particle collector cooling systems may differ from the other concepts. Since this distribution is unknown, maintenance is based on the systems described in this section without resizing for the GA-Doublet configuration.

3.2.5.1 Primary Cooling System - Lithium Media - The energy balance for a 3000 MW_{th} tokamak reactor employing a poloidal divertor and lithium coolant for the primary cooling loop is illustrated in the schematic diagram of Figure 3.2-34. Since the pumping power for the coolant is a function of MHD effects and is difficult to define, it is omitted from this approximate analysis. The system uses a thermal

PRIMARY COOLING SYSTEM WITH LITHIUM BLANKET COOLANT (ENERGY BALANCE SCHEMATIC)

FIGURE 3.2-34

storage loop in the secondary loop of both the blanket and the divertor cooling systems to maintain heat flow to the steam generator during the regeneration part of the reactor cycle. The shield cooling system is included in Figure 3.2-34 to complete the heat balance but this is low quality heat and is released to the atmosphere through the cooling tower. The allocation of energy to the divertor and shield are based on data from the UWMAK-II analysis in Reference 3-18.

The primary power conversion system flow is illustrated in Figure 3.2-35 when using lithium for the primary loop coolant. A maximum coolant temperature of 540°C is assumed for use with stainless steel and is common for both types of coolant considered. This flow diagram is based on the system defined for UWMAK-I (Reference 3-16). A precipitator is provided for lithium cleanup. It is assumed that up to 10% of the flow will pass through this by-pass system with only a small quantity being removed as waste. Since tritium is reclaimed from the lithium, the tritium reclamation system connections are indicated but the system is not shown. Cross mains are

LITHIUM PRIMARY LOOP POWER CONVERSION SYSTEM DIAGRAM

FIGURE 3.2-35

provided to allow the use of a system for more than one set of modules in the event of failure of another system. Such an arrangement allows the inclusion of a redundant heat transfer capability should this prove to be economically desirable. The storage tank shown is for use during shutdown periods. Lithium makeup will be on the cold side of the intermediate heat exchanger.

The secondary, or intermediate, loop of the primary power conversion system uses sodium as the coolant. During the reactor burning period about 2.8 percent of the sodium passing through the Intermediate Heat Exchanger (IHX) is stored until the time between burns when it will be used as the heat source for uniform heat and electrical generation. The intermediate loop is installed in the secondary confinement area of the reactor building. The heat conversion (steam) loop is considered balance of plant equipment for this analysis.

Table 3.2-13 indicates the sizes of the major equipment items required for the

TABLE 3.2-13
LITHIUM COOLING SYSTEM MAJOR COMPONENT SIZES

NUMBER OF PRIMARY COOLING LOOPS - 8
NUMBER OF REACTOR SECTORS PER LOOP - 2

COMPONENT	SIZE	NUMBER/PRIMARY LOOP
Li-Na INTERMEDIATE HEAT EXCHANGER (IHX)	10.0 m LONG X 2.1 m DIA.	1/2
Li STORAGE (DUMP) TANK	5.6 m LONG X 4.0 m DIA.	1
Li PUMP	7.5 m LONG X 3.3 m DIA.	1
Li/IHX FEEDER LINE	.4 m DIA.	1
Li/SECTOR FEEDER LINE	.3 m DIA.	2
Na/IHX FEEDER LINE	.5 m DIA.	1
Na THERMAL STORAGE TANK (HOT)	4.5 m DIA. SPHERE	1
Na THERMAL STORAGE (COLD) AND SYSTEM RESIDUAL	6.3 m LONG X 4.5 m DIA.	1
Na PUMP	14 m LONG X 2.4 m DIA.	1

primary and intermediate loops of the primary power conversion system. The number of primary loops required is 8 with two reactor sectors cooled by each loop. This number is selected because the pump size required is believed within the state of art for liquid metal pumps at a flow rate of approximately 10,000 gpm. Though lithium pumps for this capacity have not been found, liquid sodium pumps for FFTF that are rated at 14,500 gpm and a head of 500 ft of sodium are being developed (Reference 3-26). The intermediate heat exchanger is sized to accommodate two primary cooling loops. However, eight intermediate cooling loops are still used with a common IHX and steam generator for each two loops. These steam generators are manifolded to a single steam turbine system. The performance requirements and capabilities of the intermediate heat exchangers used to define the dimensions in Table 3.2-13 are listed in Table 3.2-14. This data is based on heat exchanger designs from several sources, including the UWMAK-III, Reference 3-2. The size of the equipment is illustrated in the general arrangement sketches showing the plan view and elevation of two primary and two intermediate loops in Figures 3.2-36 and 3.2-37, respectively. Four of these systems are required for a complete reactor system. The overall radius of the reactor building is 90 meters. This provides space for an annular secondary confinement area for installation of the primary and intermediate cooling loops as well as for entry and egress airlocks to the reactor room. Space is provided for access around the large equipment items and catch tanks are shown for the major equipment items. All major equipment is accessible from the overhead crane and all piping runs have sufficient bends to allow for expansion and space for support systems. The catch tanks for the lowest level equipment items are the lined concrete wells in which they are installed. The primary cooling loop supply and return line installation is below the reactor floor level to allow almost complete system drainage without requiring power if the need arises.

3.2.5.2 Primary Cooling System-Helium Media - The energy balance for the primary power conversion system that employs helium coolant for the primary cooling loop is illustrated in the schematic diagram of Figure 3.2-38. This system utilizes the gaseous helium at 50 atmospheres from the primary loop to provide power for pumping the fluid through the primary loop. Therefore, this pumping power is included in the energy balance. The use of gaseous helium for pumping requires a helium turbine instead of the electrically driven pumps employed by the lithium system. The allocation of energy to the divertor and the shield cooling systems is based on the same thermal distribution as the lithium cooled system discussed in the previous section. A thermal storage system is used in the sodium cooled intermediate loop and the

TABLE 3.2-14
 DIMENSIONS AND PERFORMANCE OF PRIMARY COOLING LOOP
 INTERMEDIATE HEAT EXCHANGER, Li-Na MEDIA
 3000 MW_{th} REFERENCE DESIGN

MEDIAS	Li-Na
SHELL SIDE-MEDIA	Na
SHELL SIDE MEDIA TEMP. IN	260°C
SHELL SIDE MEDIA TEMP. OUT	510°C
SHELL SIDE MEDIA FLOW RATE	3.62 X 10 ⁶ Kg/Hr
SHELL SIDE MEDIA TRANSFER COEF, h _o	3.42 W/cm ² -°K
TUBE SIDE-MEDIA	Li
TUBE SIDE MEDIA TEMP. IN	540°C
TUBE SIDE MEDIA TEMP. OUT	288°C
TUBE SIDE MEDIA FLOW RATE	1.10 X 10 ⁶ Kg/Hr
TUBE SIDE MEDIA TRANSFER COEF., h _o	2.35 W/cm ² -°K
THERMAL LOAD, MW _{th} PER LOOP	317.5 MW _{th}
OVERALL COFF. OF HEAT TRANSFER, U _o	1.31 W/cm ² -°K
MEAN TEMP. DROP	27.42°C
HEAT TRANSFER AREA, A _{PER LOOP}	882 m ²
TUBE MATERIAL	316 S.S.
TUBE O.D.	2.06 cm
TUBE WALL THICKNESS	0.087 cm
TUBE PERIPHERY	6.47 cm
TUBE LENGTH	8.0 m
TUBE DENSITY RATIO	3.05
NO. OF TUBES/EXCHANGER	3407
SHELL I.D.	2.10 m
SHELL AREA	3.46 m ²
SHELL LENGTH	10.0 m
SHELL MATERIAL	316 S.S.
NO. OF EXCHANGERS REQ'D. (TOTAL)	4 (ONE/2 LOOPS)
NO. OF HEAT TRANSPORT LOOPS (TOTAL)	8
NO. OF LITHIUM STORAGE TANKS (TOTAL)	8
STORAGE TANK DIA. (SPHERE)	4.68 m
STORAGE PRESSURE	1 ATM
TANK VOLUME/TANK	53.61 m ³

NOTE: ALL DATA GIVEN ON A PER-LOOP BASIS UNLESS OTHERWISE NOTED.

POWER CONVERSION SYSTEM ARRANGEMENT – LITHIUM COOLANT

FIGURE 3.2-36

POWER CONVERSION SYSTEM ARRANGEMENT – LITHIUM COOLANT

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FIGURE 3.2-37

PRIMARY COOLING SYSTEM WITH HELIUM BLANKET COOLANT (ENERGY BALANCE SCHEMATIC)

FIGURE 3.2-38

reactor duty cycle times (i.e., burn and rejuvenation times) are the same as for the lithium cooled system.

The primary power conversion system flow and performance is shown in Figure 3.2-39. The effects of the helium turbine on the system schematic are indicated. Both the turbine exhaust and the recirculated helium are compressed to 50 atmospheres. The turbine exhaust is cooled by a heat exchanger before recompression. The mixed gases enter the blanket at 300°C and approximately 50 atmospheres. On reactor startup, compressed helium is bled into the system from the helium high pressure storage tank through a small turbine to initiate the flow through the blanket. The gaseous helium is stored in this tank whenever the primary cooling loop is opened for maintenance. This tank may be a series of tanks if further analysis shows that varying amounts of high pressure helium are required for startup and maintenance.

Temperatures throughout the system are kept the same as for the lithium cooled primary loop system and the maximum of 540°C at the blanket outlet is maintained.

HELIUM PRIMARY LOOP POWER CONVERSION SYSTEM DIAGRAM

FIGURE 3.2-39

Cross mains are provided as for the lithium cooled primary loop system and the same subdivision of reactor sectors (2 per loop) and number of primary loops (a total of 8) is used. However, because of the larger equipment size required for the intermediate heat exchangers (IHX's), an intermediate sodium cooled loop is provided for each primary loop. These feed a single steam generator for each two intermediate loops. Thus, a total of only four steam generators is used for the single turbine generator.

Table 3.2-15 indicates the sizes of the major equipment items required for the primary and intermediate loops of the power conversion system. While the sizes differ from those required for the lithium system, the line size increase is probably the most significant. The helium storage tank size is based on a storage pressure of 5000 psi (340 atmospheres). The number of equipment items per loop are the same as for the lithium cooled primary system as shown in Table 3.2-13, except for the IHX's as mentioned above. Helium storage, however, is unlikely in a single tank for safety

TABLE 3.2-15
HELIUM COOLING SYSTEM MAJOR COMPONENT SIZES

NUMBER OF PRIMARY COOLING LOOPS 8
NUMBER OF REACTOR SECTORS/LOOP 2
NUMBER OF INTERMEDIATE COOLING LOOPS 8

COMPONENT	SIZE	NUMBER/PRIMARY LOOP
He-Na INTERMEDIATE HEAT EXCHANGER (IHX)	12.0 m LONG X 3.68 m DIA.	1
He STORAGE TANK	6.4 m DIA. SPHERE (OR EQUIVALENT)	1
He TURBINE	7.3 m LONG X 2.4 m DIA.	1
He/IHX FEEDER LINE	1.73 m DIA.	1
He/SECTOR FEEDER LINE	1.22 m DIA.	2
Na/IHX FEEDER LINE	.5 m DIA.	1
Na THERMAL STORAGE TANK (HOT)	8.0 m LONG X 3.0 m DIA.	1
Na THERMAL STORAGE (COLD) AND SYSTEM RESIDUAL	6.3 m LONG X 4.5 m DIA.	1
Na PUMP	14 m LONG X 2.4 m DIA.	1

reasons so, while a single tank is specified, a high pressure cylinder bank is more likely to be used. The intermediate heat exchanger design parameters are also radically affected. Table 3.2-16 lists the parameters for the primary cooling loop heat exchanger design when using helium.

The equipment sizes are the basis for the general arrangement sketches of the plan view and elevation of the two primary cooling loops and the associated intermediate loops shown in Figures 3.2-40 and 3.2-41, respectively. Four of these systems are required for the complete reactor. This arrangement differs from that used when lithium is the primary loop coolant in that an IHX is used for each primary loop. Also, since helium gas is used in the primary cooling loop, the helium equipment can be placed at the level of the reactor room floor. Catch tanks are only required for the equipment of the intermediate sodium cooling loop. The same criteria for access are used as were previously defined for the lithium cooled system and the same reactor building diameter (90 meters) is used although the space for maintenance equipment is more restricted.

3.2.5.3 Divertor Cooling System - The cooling system for removal of energy from the divertor system is separated from the blanket cooling system in accordance with the arrangement used for UWMAK-III. The divertor uses TZM in the cooling loop at the particle bombardment plates which permits the use of higher coolant temperatures than the blanket system.

The temperatures and flows of the divertor system are shown in Figure 3.2-42. This system includes primary, intermediate and steam generation loops with a turbine generator separate from the turbine generator for the first wall/blanket primary cooling system. A thermal storage system arrangement is assumed for the intermediate loop of the divertor system which operates in the same manner as in the primary cooling system for the first wall/blanket. The divertor bombardment plate coolant outlet temperature is selected at 600°C to keep the maximum structural temperature below 880°C. This is the temperature defined for the UWMAK-III system which also uses TZM plates. A coolant temperature rise of 200°C is allowed from the coolant inlet to the outlet from these plates.

Three potential coolant media for the divertor primary coolant loop are compared in Table 3.2-17. This table includes the data from the UWMAK-III study as a reference. All heat loads and temperatures are held constant. Case 1 in Table 3.2-17 defines the UWMAK-III particle plate operating conditions. Case 2 is similar in that it uses sodium as a coolant and retains the same heat flux (5.87 MW/m^2) but the particle plates are resized for the lower thermal load of $429 \text{ MW}_{\text{th}}$. The particle

TABLE 3.2-16

DIMENSIONS AND PERFORMANCE OF PRIMARY COOLING LOOP
INTERMEDIATE HEAT EXCHANGER, He-Na MEDIA
3000 MW_{th} REFERENCE DESIGN

MEDIAS	He-Na
SHELL SIDE -MEDIA	Na
SHELL SIDE MEDIA TEMP. IN	260°C
SHELL SIDE MEDIA TEMP. OUT	510°C
SHELL SIDE MEDIA FLOW RATE	3.32 X 10 ⁶ Kg/Hr
SHELL SIDE MEDIA TRANSFER COEF., h _o	3.42 W/cm ² -°C
TUBE SIDE -MEDIA	He
TUBE SIDE MEDIA TEMP. IN	540°C
TUBE SIDE MEDIA TEMP. OUT	288°C
TUBE SIDE MEDIA FLOW RATE	6.160 X 10 ⁶ Kg/Hr
TUBE SIDE MEDIA TRANSFER COEF., h _o	0.20 W/cm ² -°C
THERMAL LOAD, MW _{th} PER LOOP	291.13
OVERALL COFF. OF HEAT TRANSFER, U _o	0.1748 W/cm ² -°C
MEAN TEMP. DROP	27.42°C
HEAT TRANSFER AREA, A _{PER LOOP}	607½ m ²
TUBE MATERIAL	316 S.S.
TUBE O.D.	4.0 cm
TUBE WALL THICKNESS	0.87 cm
TUBE PERIPHERY	12.5 cm
TUBE LENGTH	10.0 m
TUBE DENSITY RATIO	1.75
NO. OF TUBES/EXCHANGER	4859
SHELL I.D.	3.68 m
SHELL AREA	10.62 m ²
SHELL LENGTH	12.0 m
SHELL MATERIAL	316 S.S.
NO. OF EXCHANGERS REQ'D. (TOTAL)	8
NO. OF HEAT TRANSPORT LOOPS (TOTAL)	8
NO. OF HELIUM STORAGE TANKS (TOTAL)	8
STORAGE TANK DIA. (SPHERE)	6.38 m
STORAGE PRESSURE	340 Atm
TANK VOLUME/TANK	136 m ³

NOTE: ALL DATA GIVEN ON A PER-LOOP BASIS UNLESS OTHERWISE NOTED.

POWER CONVERSION SYSTEM ARRANGEMENT – HELIUM COOLANT

FIGURE 3.2-40

POWER CONVERSION SYSTEM ARRANGEMENT — HELIUM COOLANT

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FIGURE 3.2-41

FIGURE 3.2-42

TABLE 3.2-17

COMPARISON OF PARTICLE BOMBARDMENT PLATE PERFORMANCE WITH DIFFERENT COOLING MEDIA

	REFERENCE DESIGNS			
	CASE 1: UWMAK-III	CASE 2	CASE 3	CASE 4
THERMAL POWER LEVEL	5000 MW _{th}	3000 MW _{th}	3000 MW _{th}	3000 MW _{th}
THERMAL LOAD	725 MW _{th}	429 MW _{th}	429 MW _{th}	429 MW _{th}
TOTAL AREA	123 m ²	7306 m ²	12767 m ²	1276 m ²
SACRIFICIAL WALL THICKNESS	.1 mm	.1 mm	.1 mm	.1 mm
SACRIFICIAL WALL REPLACEMENT RATE	ONCE EVERY 17 HRS.	EVERY 17 HRS.	EVERY 29.7 HRS.	EVERY 296 HRS.
STRUCTURE MATERIAL	TZM	TZM	TZM	TZM
STRUCTURE TEMPERATURE	680 TO 880°C	680-880°C	680-880°C	680 - 880°C
COOLANT	Na	Na	Li	He
COOLANT TEMPERATURE	400 to 600°C	400 TO 600°C	400 TO 600°C	400 TO 600°C
COOLANT FLOW RATE	1.04X10 ⁷ Kg/HR	6.177X10 ⁶ Kg/HR	1.86X10 ⁶ Kg/HR	1.48X10 ⁶ Kg/HR
COOLANT VELOCITY	1.48 m/SEC	1.31 m/SEC	.78 m/SEC	.192 m/SEC
MAXIMUM MAGNETIC FIELD	0.4 TESLA	0.4 TESLA	0.4 TESLA	0.4 TESLA
PRESSURE DROP	100 PSI	88.5 PSI	104.5 PSI	1 ATM (14.7 PSI)
PUMPING POWER	1 MW	.525 MW	1.86 MW	--
HEAT FLUX TO BOMBARDMENT PLATES	5.87 MW/m ²	5.87 MW/m ²	3.36 MW/m ²	.336 MW/m ²
SINGLE PLATE SIZE	1 m X 3 m	1 m X 2.28 m	2 m X 2 m	4 m X 10 m

NOTE: ALL REFERENCE DESIGNS BASED UPON 32 PLATES

plate width of 1 meter is retained and the plates shortened to 2.28 m. The coolant flow rate required is reduced to attain the required temperatures. Case 3 uses lithium as the coolant and requires a reduced flow rate because of the larger specific heat for lithium (4.142 joules/gm-°K) instead of sodium. The heat transfer area requires an increase in size to 4 m² per plate because of the lower heat transfer coefficient for lithium. This increased area reduces the allowable heat flux and increases the plate life to 29.7 hours. In addition, the pumping power is significantly increased over that required by Case 1. Case 4 uses helium as the coolant and results in a requirement for approximately 40 m² per plate because of the low heat transfer coefficients of this coolant. While this decreases the allowable heat flux to .336 MW/m², thereby increasing the plate life to approximately 296 hours, the capability to uniformly spread the magnetic flux surfaces in the divertor region over this area is questionable.

Further comparison of the lithium and sodium coolant performance in the divertor primary loop is shown for the divertor cooling system intermediate heat exchanger (IHX) requirements in Table 3.2-18. The IHX requirements indicate that the lithium IHX is slightly larger. Both IHX requirements appear to be small enough to fit in the additional area allowed at one of the primary cooling system assemblies. Such an arrangement whereby the coolant from all plates is manifolded to one IHX requires flow control valves at each divertor particle bombardment plate assembly and the manifolding of all coolant supply and return lines to a common line beneath the reactor room floor.

All plate sizes shown in Table 3.2-17 are based on the use of 32 divertor plate assemblies similar to the arrangement defined for the UWMak-III. When only a single divertor is used in the reactor configuration the area of each plate must be doubled, since only 16 plate assemblies can be installed, and the magnetic flux redistributed to accommodate this increased area.

Since the GA-Douplet concept uses a flowing plasma boundary (FPB) configuration with limiters instead of the divertor the distribution of energy between the blanket and limiters will probably differ. However, the essential cooling system elements required when using the helium coolant are assumed to be similar and the maintenance characteristics applicable to the other candidate configurations will be appropriate.

3.3 REFERENCE SYSTEM DEFINITIONS - The performance characteristics of the four normalized reference systems selected for study are summarized in Section 3.1, Table 3.1-1 and the critical dimensions of each configuration are summarized in

TABLE 3.2-18
DIMENSIONS AND PERFORMANCE OF
THE DIVERTOR SYSTEM
INTERMEDIATE HEAT EXCHANGERS
(3000 MW_{th} REACTORS)

	CASE 2*	CASE 3*
MEDIAS	Na-Na	Li-Na
SHELL SIDE - MEDIA	Na	Na
SHELL SIDE MEDIA TEMP. IN	360°C	360°C
SHELL SIDE MEDIA TEMP. OUT	560°C	560°C
SHELL SIDE MEDIA FLOW RATE	6.17 X 10 ⁶ Kg/HR	5.86 X 10 ⁶ Kg/HR
SHELL SIDE MEDIA TRANSFER COEF., h _o	3.42 W/cm ² -°C	3.42 W/cm ² -°C
TUBE SIDE - MEDIA	Na	Li
TUBE SIDE MEDIA TEMP. IN	600°C	600°C
TUBE SIDE MEDIA TEMP. OUT	400°C	400°C
TUBE SIDE MEDIA FLOW RATE	6.17 X 10 ⁶ Kg/HR	1.86 X 10 ⁶ Kg/HR
TUBE SIDE MEDIA TRANSFER COEF., h _o	3.42 W/cm ² -°C	2.35 W/cm ² -°C
THERMAL LOAD, MW _{th}	429 MW _{th}	429 MW _{th}
OVERALL COFF. OF HEAT TRANSFER, U _o	10200 W/m ² -°C	8600 W/m ² -°C
MEAN TEMP. DROP	200°C	200°C
HEAT TRANSFER AREA, A _(TOTAL)	1051 m ²	1247 m ²
TUBE MATERIAL	316 S.S.	316 S.S.
TUBE O.D.	2.06 cm	2.06 cm
TUBE WALL THICKNESS	.087 cm	.087 cm
TUBE PERIPHERY	6.47 cm	6.47 cm
TUBE LENGTH	8.0 m	8.0 m
TUBE DENSITY RATIO	3.05	3.05
NO. OF TUBES	2031	2409
SHELL I.D.	1.62 m	1.76 m
SHELL AREA	2.06 m ²	2.44 m ²
SHELL LENGTH	10.0 m	10.0 m
SHELL MATERIAL	316 S.S.	316 S.S.

*See Table 3.2-17 for Case definitions.

Table 3.3-1. For comparison, the relative size of the four reference systems is shown in Figure 3.3-1. The configuration of these design concepts are discussed in the following sections.

The characteristic features of the original concepts have been retained insofar as possible. However, deviations in subsystem characteristics have been allowed for the purpose of utilizing common subsystems among as many of the reference designs as possible where this approach does not significantly affect the essential features of the concepts.

3.3.1 Culham Concept - The resized Culham Mk-IIB conceptual design is designated as the Culham reference reactor design in this phase of the study. A cross section of the design concept as modified for this study is shown in Figure 3.3-2 with a plan view in Figure 3.3-3.

TABLE 3.3-1
SIGNIFICANT DIMENSIONS OF REFERENCE REACTOR CONCEPTUAL DESIGNS

	CULHAM	UWMAK-III	ORNL CASSETTE	GA DOUBLET
MAJOR RADIUS, m	7.5	6.5	7.5	6.5
MINOR RADIUS, m	1.92	1.75	1.92	1.4
PLASMA HEIGHT/WIDTH	2.0	2.0	2.0	3.0
TF MAGNETS				
- OVERALL HEIGHT, m	22.3	20.4	19.3	15.1
- OUTER RADIUS, m	15.6	14.4	14.0	13.8
- WIDTH W/DEWAR, m	1.19	1.07	1.19	1.23
- DEPTH W/DEWAR, m	.89	.92	.89	.88
- RADIUS TO B_{max} , m	3.4	3.1	3.4	3.5
CENTER CORE RADIUS, m	2.6	2.3	2.6	2.7
REACTOR ROOM				
- DIAMETER, m	100	100	100	100
- HEIGHT, m	50	50	50	50
TRANSFORMER				
- EFFECTIVE LENGTH, m	20.5	34.3	17.0	17.2
- EFFECTIVE RADIUS, m	2.6	2.3	2.1	2.4

SELECTED REFERENCE DESIGNS

FIGURE 3.3-1

3.3.1.1 Culham Reference System - The general characteristics of the Culham reference reactor design are compared with the Culham Mk-IIB characteristics in Table 3.3-2. The Culham concept is characterized by the following maintenance design features in this study. The concept requires the use of a large module which includes the entire first wall/blanket for each reactor sector (excluding the divertor plug module), and it also includes the inner shield, supporting structure and coolant manifolding. A single supply and a single coolant return line are the lines that must be disconnected to free the module for replacement. The sector module is removed from the reactor through an opening in the outer shield provided by a removable shield door. The divertor module is lowered from above and removed through the same opening. A single null poloidal divertor is used with the particle bombardment plates inside of the toroidal field coil bore. The number of poloidal field coils inside of the toroidal field coil bore is minimized. A double vacuum chamber is used to permit installation of the sector first wall/blanket modules without making structural connections or without requiring seals between the modules at the inner chamber vacuum wall. All other characteristics of the reference system design can be varied without altering the unique nature of the Culham Mk-II concept.

CULHAM TYPE TOKAMAK REFERENCE REACTOR (SECTION THROUGH TORUS)

FIGURE 3.3-2

Table 3.3-3 lists the characteristics of the first wall/blanket module employed in the Culham reference system used in this study. The small domed cylindrical modules which make up the first wall/blanket of the large sector module are illustrated in Figure 3.1-4 (Section 3.1).

3.3.1.2 Design Assumptions - The design assumptions on which this modified configuration of the Culham concept is based are summarized in Table 3.3-4.

3.3.1.3 Culham Reference Reactor Design and Arrangement - The small first wall/blanket module proposed by Culham Laboratories and described in Sections 3.1 and 3.2.1.3 is retained. The major radius of the reference reactor is larger than

CULHAM TOKAMAK REFERENCE REACTOR — TOP VIEW

FIGURE 3.3-3

the radius of the UWMAK-III and the GA-Douplet concepts because the individual blanket cell coolant manifolding is behind the inner blanket wall for each reactor sector and the outer shield is required to protect the toroidal field magnet at the inner wall. These considerations and the required toroidal field (TF) coil cross section increase the minimum dimension of the reactor major radius to approximately 7.1 meters. However, 7.5 meters is selected as the major radius since this is at the minimum cost configuration region on the curve shown in Figure 3.1-8 (Section 3.1).

TABLE 3.3-2
CULHAM REFERENCE REACTOR CHARACTERISTICS

	CULHAM MK-11B (REFERENCE 3-8)	CULHAM REFERENCE REACTOR
NET ELECTRICAL POWER, MW_e	1200	962
GROSS THERMAL POWER, MW_{th}	3820	3000
MAJOR RADIUS, m	6.7	7.5
MINOR RADIUS (MID PLANE), m	1.95	1.92
ASPECT RATIO	3.5	3.9
PLASMA ELONGATION	1.75	2.0
FIRST WALL POWER LOADING		
TOTAL, MW/m^2	4.7	---
NEUTRONS, MW/m^2	---	2.12
MAGNETIC FIELD		
ON AXIS, MA/m	3.12	3.08 (3.87T) } $\mu = 1$
PEAK, MA/m	6.09	6.89 (8.66T) }
PLASMA CURRENT, MA	10.3	9.09
MHD SAFETY FACTOR (AT WALL), q	2.6	2.5
PLASMA PRESSURE RATIO, β_p	1.86	3.898
PLASMA PRESSURE RATIO, β_t	.093	.103
PLASMA DENSITY $\times 10^{-20}$, ions/ m^3	3.2	1.315
ENERGY CONFINEMENT TIME REQUIRED, s	1.7	2.715

TABLE 3.3-3
FIRST WALL/BLANKET MODULE PHYSICAL PARAMETERS
(CULHAM REFERENCE REACTOR)

o MODULE WEIGHTS	- SECTOR MODULE	225 TONNES
	- DIVERTOR MODULE	3 TONNES
o FIRST WALL/BLANKET COOLANT		HELIUM
o SHIELD COOLANT		HELIUM
o FIRST WALL MATERIAL		STAINLESS STEEL
o FIRST WALL CONFIGURATION		DOMED CYLINDERS
o VACUUM JOINTS	- BLANKET	NON STRUCTURAL
	- OUTER SHIELD	MECHANICAL SEAL, BOLTED STRUCTURE
o MAJOR COMPONENTS IN MODULE		FIRST WALL BREEDING BLANKET INNER SHIELD SUPPORT STRUCTURE COOLANT MANIFOLDS
o MODULE SIZES	- SECTOR MODULE	11.5m X 8.0m X 4.0m MAX
	- DIVERTOR MODULE	1.0m X 1.8m X 3.0m MAX

TABLE 3.3-4

CULHAM REFERENCE REACTOR DESIGN ASSUMPTIONS

- USE 12 NEUTRAL BEAM INJECTORS OF THE TYPE DEVELOPED FOR TFTR.
- REACTOR ROOM DIAMETER OF 100 METERS IS PROVIDED TO ACCOMMODATE MAINTENANCE EQUIPMENT WITH 2 LARGE DOORS FOR EQUIPMENT AND MATERIAL TRANSFER.
- AN OVERHEAD CRANE IS AVAILABLE IN THE REACTOR ROOM SUPPORTED FROM THE WALL AND CENTRAL STRUCTURAL CORE, WITH NO OVERHEAD LINES IMPAIRING FREE MOVEMENT OF A SUSPENDED OBJECT AROUND THE REACTOR ROOM.
- A MECHANICAL HELIUM COOLANT LINE JOINT IS FEASIBLE WITH CONCENTRIC SUPPLY AND RETURN LINES.
- THE VACUUM AND FIRST WALL/BLANKET/SHIELD COOLANT REQUIREMENTS ARE COMPATIBLE WITH THE NORMALIZED SUBSYSTEM DESIGNS.
- THE MAGNET ARRAYS ARE CAPABLE OF SUPPORTING A PLASMA h/w OF 2.0.
- THE JOINTS BETWEEN FIRST WALL/BLANKET SECTORS WILL PROVIDE HIGH IMPEDANCE BETWEEN VACUUM CHAMBERS WITHOUT PHYSICAL ATTACHMENT TO EACH OTHER.
- THE REACTOR IS DIVIDED INTO 16 SECTORS WITH 16 TF COILS.
- POLOIDAL FIELD MAGNETS CAN BE AUTOMATICALLY RAISED OR LOWERED.
- THE NEUTRAL BEAM INJECTOR PORT INSIDE OF THE OUTER SHIELD VACUUM WALL NEED NOT BE PHYSICALLY ATTACHED TO THE BLANKET PORT BUT A HIGH IMPEDANCE JOINT IS USED.
- AN OVERHEAD MANIPULATOR IS MOUNTED ON THE OVERHEAD CRANE BRIDGE OR A SEPARATE BRIDGE BELOW IT FOR DISCONNECTING SUBSYSTEMS ABOVE THE REACTOR.
- THE OHMIC HEATING COIL ARRAY PROVIDES A BASIS FOR COST ESTIMATES FOR AN AIR CORE TRANSFORMER USED IN LIEU OF AN IRON CORE TRANSFORMER.
- FIRST WALL MATERIAL IS STAINLESS STEEL WITH BLANKET BREEDERS USING Li_7Pb_2 , Li_4SiO_4 , GRAPHITE REFLECTOR, AND STAINLESS STEEL STRUCTURE WITH A NIOBIUM ALLOY FOR THE BLANKET CELLULAR STRUCTURE.
- BLANKET TRITIUM IS REMOVED WITH THE HELIUM COOLANT FOR PROCESSING.
- GRAPHITE BLOCKS ARE USED BETWEEN THE SMALL CYLINDRICAL FIRST WALL/BLANKET MODULES TO REDUCE INCIDENT RADIATION ON THE RECTANGULAR INTERLOCKING SHIELD BLOCKS OF THE SMALL MODULES.

The manifolding used for each first wall/blanket sector module leaves the module through the floor of the outer shield. This manifold consists of concentric supply and return lines, as shown in Figure 3.1-3, with a mechanical joint, located at the floor, similar to that defined in Reference 3-23. The large sector module is

removed for the first wall/blanket maintenance, either scheduled or unscheduled, and the small modules which line the wall of this sector module are replaced off-stream in a hot cell workroom. Figure 3.2-11 (Section 3.2.1) shows clearly how the small first wall/blanket modules are arranged in the sector module. Four different module diameters are used to provide maximum coverage of the wall area. The model shown in this figure also illustrates the general arrangement of the Mark II-B reactor. Figure 3.2-12 illustrates the composition of the reactor sector and the arrangement of the first wall/blanket modules along the inner wall. A total of 175 modules are required for one sector in the reference design. The rectangular opening provides for the neutral beam injector insertion.

The concentric helium supply and return manifold for each small module is welded to the main manifold as indicated in Figure 3.3-3 and Figure 3.1-3 (Section 3.1). The combined manifold for each sector is disconnected at the floor joint when removing the sector module. The stub end of this joint is retracted when the sector module is removed through the shield door opening. This arrangement reduces the number of first wall/blanket coolant connections that must be broken to the absolute minimum when removing one reactor sector.

The inner shield and outer shield form a double walled vacuum chamber for the plasma. The joints between inner shield wall sectors present high impedance to molecular flow while the outer wall forms a sealed chamber. The joints in the outer wall occur at the removable shield doors and at the small doors in the divertor (not shown in the figure). These small doors are used for removal of the particle bombardment plates from each sector.

For the vacuum wall location study the lateral support access panels (LSAP's) between the TF coils are used as the primary vacuum wall instead of the shield door in the second vacuum wall arrangement shown in Figure 3.2-32 (Section 3.2.4). In this case, as well as in the other two vacuum wall arrangements, the vacuum wall at the inner shield presents a high impedance to molecular flow even though the sector modules are not physically attached to each other. This joint design requires more study to confirm the feasibility of this assumption. In the first vacuum wall arrangement shown in Figure 3.2-32 the outer shield door is assumed to require a welded seal with the LSAP bolted in place but open to allow atmospheric flow to the outer shield door. The third arrangement shown in Figure 3.2-32 assumes that the outer shield door is bolted in place and that the primary vacuum barrier is the reactor room wall. In all cases the region between the inner shield and the primary vacuum wall is evacuated to a pressure of 1×10^{-4} torr by a pump system that is

independent of the plasma chamber system. The pumping system for the reactor room evacuation (the third arrangement) is described in Section 3.2.4.

The toroidal forces between the TF coils are reacted by the use of the LSAP's in the same manner as proposed for the UWMAK-III (Reference 3-2). These panels are maintained at room temperature instead of being cooled as are the intercostal support members of the Culham Mk-II concept shown in the Culham Laboratory model (Figure 3.2-11). This selection assumes that warm intercostals are feasible and will allow a reduction in the preparation time for removal of the shield door in each sector.

The TF coil is a modified constant tension configuration similar to that used for the UWMAK-III but elongated vertically to provide space for the divertor and particle bombardment plates inside of the TF coil bore above the plasma and for the module support platform (outer shield) and equilibrium coils inside the TF coil bore below the plasma. The outer leg of the TF coil is as close as possible to the plasma but far enough removed to allow passage of the sector modules between adjacent coils. This approach permits the poloidal field (PF) coils to be located outside of the TF coils yet to be moved as close as possible to the plasma. It is assumed that the height/width ratio of 1.75 proposed by Culham can be increased to 2.0 without requiring additional PF coils inside the TF coil bore.

In Figure 3.3-2 the TF coils are shown attached to the core by lugs and shear pins in the same manner as UWMAK-III. An alternative is to support these coils by mounts from the floor of the reactor well.

The support for the reactor vacuum chamber is from the floor of the reactor well through the floor of the outer shield structure. The removable sector modules are supported by this floor. Wheels are indicated as the support for these modules during withdrawal from the reactor although these must be retracted and the modules rested on, or attached to, the support platform during operation. Culham Laboratory has proposed the use of air or gas bearings with an axial "V" groove to center and guide the module out of the reactor. This is an alternative to the use of a wheeled mechanism. A removable bridge must be emplaced between the reactor room floor and the outer shield floor for removal of the first wall/blanket sector module between the TF coils. Figure 3.3-4 illustrates the removable shield door and the partial extraction of the sector module between the TF coils as seen in the Culham Laboratory model of the Mark IIB. The structural web to which the door is attached is shown to remain in place and the two intercostals between the TF coils have been removed.

The outboard poloidal field coils are retracted automatically to allow space

CULHAM LABORATORY MODEL SHOWING EXTRACTION OF FIRST WALL/BLANKET SECTOR

USED BY PERMISSION

FIGURE 3.3-4

for removal of the outer shield doors. The PF coils in the divertor region and below the outer shield floor are embedded in shielding and structure. All PF coils are superconducting. It is assumed that the PF coils in the TF magnet bore will be segmented since this characteristic or some similar technique is required to provide for the replacement of these PF coils or any of the TF coils.

The ohmic heating coils are shown embedded in the core structure. This structure may also be segmented to provide for removing most of the coils vertically with the core structure, assuming that the TF coil mounting is supported by the reactor well floor instead of by using the shear pin arrangement shown. The ohmic heating coils shown in Figure 3.3-2 employ the same configuration defined for the Culham Mk-II defined in Reference 3-6. Figure 3.3-2 indicates, however, that an air core transformer is used for the reference design concept employed in this study instead of the iron core transformer shown for the Culham Mk-II. This modification of the transformer may require additional coils above and below the reactor in an array similar in arrangement to those employed for the UWMAK-III or the UWMAK-I. Both of these concepts employ air core transformers. The requirements have not been defined in this study but a space envelope is retained to allow for the addition of such coils.

The first wall/blanket at the annular divertor plug is removed in segments, each of which spans one reactor sector. The helium coolant supply and return lines run vertically behind the particle bombardment plates and alongside of the cryo-vacuum pump plenum chamber. These lines are disconnected above the TF coils and then the first wall/blanket sector is lowered into the void which occurs when the large sector module is removed as shown in Figure 3.3-5. The annular divertor region plug is structurally mounted to the reactor through the outer shield and the structure that protects the upper part of the TF coils and bridges the gap between them.

The cryovacuum pump design proposed for UWMAK-III is adapted to the single null poloidal divertor configuration by approximately doubling the area of the panels since only 16 instead of 32 pumps are used, and by mounting the plenum directly above the space between the TF coils. This arrangement provides the maximum conductance between the divertor chamber and the cryovacuum pumps for the particles leaving the bombardment plates.

Neutral beam injectors are installed with the beam axis along a horizontal reactor radius at the selected sector centerline. The beam ports are located in the outer shield doors (Figure 3.3-2) and in the blanket as shown in Figure 3.1-3. The beam duct passes through the lateral support access panel between the TF coils

CULHAM LABORATORY MODEL WITH DIVERTOR MODULE LOWERED
PRIOR TO REMOVAL FROM REACTOR

USED BY PERMISSION

but is not attached to it except when this panel is also used as a vacuum wall in the study of alternative vacuum wall locations. Twelve NBI units at 5kW each are installed. Figure 3.3-3 shows the installation of three of the units. The design of each unit is based on the ion sources developed for the TFTR (Reference 3-17).

3.3.2 UWMAK-III Concept - The characteristics of the resized UWMAK-III conceptual design which is used as the UWMAK-III reference reactor design for this phase of the study are outlined in Section 3.1, Table 3.1-1. A cross section of the design is shown in Figure 3.3-6 with a plan view in Figure 3.3-7. In general,

FIGURE 3.3-6

all systems are the same as the 5000 MW_{th} version defined in the original concept except that neutral beam injectors replace the RF heaters.

3.3.2.1 UWMAK-III Reference Design General Characteristics - The general characteristics of the UWMAK-III as defined in Reference 3-2 are compared with those of the smaller reference system used in this study in Table 3.3-5.

The UWMAK-III is characterized in this study by the following design features that are critical to maintenance. These features include the access to the first wall/blanket through the outer wall shield with removal of the first wall/blanket

FIGURE 3.3-7

TABLE 3.3-5
UWMAK-III REFERENCE REACTOR CHARACTERISTICS

		UWMAK-III (REFERENCE 3-2)	UWMAK-III REFERENCE REACTOR
NET ELECTRICAL POWER,	MW _e	1899	992
GROSS THERMAL POWER,	MW _{th}	5000	3000
MAJOR RADIUS,	m	8.1	6.5
MINOR RADIUS,	m	2.7	1.75
ASPECT RATIO		3.0	3.7
PLASMA ELONGATION		2.0	2.0
FIRST WALL POWER LOADING			
NEUTRON, AVG.,	MW/m ²	1.91	2.744
MAGNETIC FIELD			
ON AXIS, B _o ,	TESLA	4.051	4.109
PEAK, B _{MAX} ,	TESLA	8.750	8.660
PLASMA CURRENT,	MA	15.7	9.178
MHD STABILITY FACTOR,	q	2.69	2.5
PLASMA PRESSURE RATIO,	β _p	2.3	3.716
PLASMA PRESSURE RATIO,	β _t	.083	.108
PLASMA DENSITY × 10 ⁻²⁰ ,	IONS/m ³	.646	1.572
ENERGY CONFINEMENT	SEC	1.66	2.316
TIME,			

from the reactor by first removing the largest possible module in the outer wall from outside of the plasma chamber and between the TF coils. The remaining first wall/blanket modules are removed and replaced through the opening provided by the large outer wall module. Unlike the Culham concept, the plasma chamber is sealed at the outside of the blanket. The initial UWMAK-III concept utilized RF heaters which need only be disconnected and not moved to aid access to the first wall/blanket. These are replaced by NBI's in the reference reactor design in order to normalize the concepts even though the access capability is hindered. The use of a double null poloidal divertor is unique for maintenance of this reactor. No constraint is placed on the number and location of poloidal field coils within the TF coil bore. All other characteristics of the reference system design can be varied without nullifying the unique nature of the UWMAK-III maintainability concept.

Table 3.3-6 summarizes the characteristics of the first wall blanket modules employed in the UWMAK-III reference system used in this study. These modules are illustrated in Figure 3.3-8 which also shows their relative location in the plasma chamber wall. The Internal Spectral Shifter and Energy Converter (ISSEC) region is assumed to be made up of three graphite panels as indicated in Figure 3.3-8. The wall life varies in the poloidal plane to such an extent that replacement of the "B" modules, central wall modules and ISSEC panels is conducted at only one

TABLE 3.3-6
FIRST WALL/BLANKET MODULE PHYSICAL PARAMETERS
(UWMAK-III REFERENCE REACTOR)

○ MODULE WEIGHTS	- "A" MODULE	≈ 32.4 TONNES
	- "B" MODULE	≈ 6.1 TONNES
	- DIVERTOR MODULE	≈ 7.0 TONNES
	- ISSEC PLATES	≈ 2.6 TONNES
○ FIRST WALL/BLANKET COOLANT	- "A" AND "B" MODULES	LITHIUM
	- DIVERTOR MODULE	LITHIUM
	- ISSEC	RADIATION COOLED
○ SHIELD COOLANT		GASEOUS HELIUM
○ FIRST WALL MATERIAL		STAINLESS STEEL
○ FIRST WALL CONFIGURATION		U BEND
○ VACUUM JOINTS	- BLANKET	BOLTED STRUCTURE, WELDED SEAL
	- ACCESS PANELS	BOLTED STRUCTURE, NO SEAL
○ MAJOR COMPONENTS IN MODULE		FIRST WALL BREEDING BLANKET STRUCTURAL FRAME COOLANT MANIFOLDS
○ MODULE SIZES	- "A" MODULE	≈ 7.0m X 3.1m X 1m
	- "B" MODULE	≈ 1.9m X 2.8m X 1m
	- DIVERTOR MODULE	≈ 2.2m X 2.2m X 1m
	- ISSEC PLATES	≈ 3.0m X 1.8m X .25m

UWMAK-III REFERENCE SYSTEM FIRST WALL/BLANKET MODULES

FIGURE 3.3-8

half the frequency of the replacement of the "A" modules in the outer wall. Therefore, at every maintenance period the "A" module and only one of each type of the remaining modules are replaced. Wall loading values given in TOCOMO code data used to generate Table 3.1-1 are average values with the approximate assumption that this produces the maximum life for "A" modules and one half the life of the other modules.

The analysis of the larger UWMAK-III in the previous phase of the study (Reference 3-25) employed six plates in the ISSEC region of each reactor sector. These have been reduced to three plates because of the smaller size reactor being studied.

3.3.2.2 Design Assumptions - The design assumptions used as the basis for the modified UWMAK-III configuration are summarized in Table 3.3-7. These assumptions are necessary to define the design characteristics of the reactor in sufficient detail for the estimation of maintenance functions and to assure comparable reference systems for the concepts being examined.

3.3.2.3 UWMAK-III Reference Reactor Design and Arrangement - The overall configuration of the UWMAK-III design concept developed by the University of Wisconsin

TABLE 3.3-7

UWMAK-III REFERENCE REACTOR DESIGN ASSUMPTIONS

- USE 12 NEUTRAL BEAM INJECTORS OF THE TYPE DEVELOPED FOR TFTR WITH 3 INJECTORS EACH AND A TOTAL OUTPUT OF 5.0 MW.
- REACTOR ROOM DIAMETER OF 100 METERS IS PROVIDED TO ACCOMMODATE MAINTENANCE EQUIPMENT WITH 2 LARGE DOORS FOR EQUIPMENT AND MATERIAL TRANSFER.
- AN OVERHEAD CRANE IS AVAILABLE IN THE REACTOR ROOM SUPPORTED FROM THE WALL AND CENTRAL STRUCTURAL CORE WITH NO POWER OR FLUID LINES IMPAIRING MOVEMENT OF A SUSPENDED OBJECT AROUND THE REACTOR ROOM.
- ADJACENT "A" MODULES ARE ATTACHED TO EACH OTHER BY BOLTS AND THE VACUUM SEAL EMPLOYS A WELDED FLANGE AS DESCRIBED IN REFERENCE 3-25.
- "B" MODULES ARE BOLTED TO THE SHIELD STRUCTURE WITH A WELDED VACUUM SEAL BETWEEN MODULES. THIS SEAL NEED NOT BE BROKEN WHEN THE MODULES ARE REMOVED TO THE INSIDE OF THE PLASMA CHAMBER.
- GRAPHITE BLOCKS PROTECT THE BOLTS BETWEEN THE "B" MODULES.
- A CARBON CURTAIN IS ATTACHED TO THE OUTER FIRST WALL IN REMOVABLE SECTIONS.
- MECHANICAL JOINTS ARE FEASIBLE FOR ALL LITHIUM COOLANT MANIFOLD DISCONNECTS REQUIRED FOR MAINTENANCE.
- ALL COOLANT MANIFOLDS ARE ARRANGED TO PERMIT MAINTENANCE ACTIVITIES TO PROCEED AS DEFINED. SEE REFERENCE 3-25 FOR DETAILS.
- THE VACUUM AND FIRST WALL/BLANKET/SHIELD COOLANT REQUIREMENTS ARE COMPATIBLE WITH THE NORMALIZED SUBSYSTEM DESIGNS.
- THE REACTOR IS DIVIDED INTO 16 SECTORS WITH 16 TF COILS.
- POLOIDAL FIELD MAGNETS CAN BE AUTOMATICALLY RAISED OR LOWERED WITHIN THE BORE OF THE TF MAGNETS TO CLEAR THE OUTER WALL SHIELD DOORS WHEN OPEN.
- AN OVERHEAD MANIPULATOR IS MOUNTED ON THE OVERHEAD CRANE BRIDGE OR A SEPARATE BRIDGE BELOW IT FOR DISCONNECTING SUBSYSTEMS ABOVE THE REACTOR.
- THE FIRST WALL MATERIAL IS STAINLESS STEEL.
- COOLANT TEMPERATURES ARE REDUCED FOR COMPATIBILITY WITH STAINLESS STEEL INSTEAD OF TZM AS SPECIFIED IN REFERENCE 3-2.

and reported in Reference 3-2 is retained with the principal modification being a reduction in size to accommodate the 3000 MW_{th} capacity. The configuration shown in Figures 3.3-6 and 3.3-7 reflects this approach.

A major radius of 6.5 meters is selected to place the design near the minimum cost of electricity point on the major radius vs minor radius (R-a) curve shown in

Figure 3.1-8 (Section 3.1) and to be compatible with the other reference designs insofar as possible. This value for the major radius results in an increase in the aspect ratio to 3.7 instead of 3.0 as attained in the 5000 MW_{th} reactor. The value of 3.7 is approximately the same as that used for the Culham reference system of 3.9. In the UWMAK-III design, however, the use of the ISSEC permits reduction of the major radius to 6.5 meters because of the reduced thickness of the inner wall configuration instead of requiring the 7.5 meters selected for the Culham reference design.

The supply and return lithium coolant manifolds behind the outer wall shield are removable to provide access to the shield and blanket. Drainage and total refill of these manifolds without resulting in vapor locks appears to be a very difficult design requirement in the constrained space available. Therefore, permanently installed freeze units are used to generate frozen lithium plugs similar to the concept used for the UWMAK-III discussed in Section 3.2.1 and in Reference 3-25. The manifold configuration is also the same as defined in that reference. The joints at the point of disconnect for manifold removal all employ mechanical connections of the same type as the larger reactor previously examined.

The design of the first wall/blanket/shield for the reactor shown in Figure 3.3-5 is the same as that used in the original UWMAK-III concept except that stainless steel is used as the first wall material instead of the TZM. This change in material is used to bring the costs of the reference reactors to a more common base for the materials employed. The thickness of the first wall/blanket/shield is essentially the same as the 5000 MW_{th} reactor but all other components are scaled approximately to the 3000 MW_{th} requirements.

The number of TF magnets has been reduced to 16 for consistency with the other reference configurations. However, the number of PF coils is assumed to be the same and their position has been revised in accordance with the change in scale of the reactor. It is assumed that sufficient space exists between the PF coils and the TF coil to permit automatic retraction of the PF coils that interfere with opening the outer wall shield doors. The radius to the outer leg of the TF coil is determined by the requirement to open the shield doors and remove the "A" module between the TF coil outer legs. No consideration is made for the removal of a TF coil or PF coil in this design. Some of these problems are discussed in Section 3.3.1 for the Culham reference system.

The ohmic heating coils, the divertor (central wall) first wall/blanket module and the cryovacuum pumps with particle bombardment plate installations all use

the same conceptual design as the 5000 MW_{th} reactor described in the Phase I report (Reference 3-25). No consideration has been given to the removal of the ohmic heating coils. The cryovacuum pump design concept used for UWMAK-III is also used as the basis for the pumps installed on the Culham concept and the ORNL concept.

Three vacuum wall arrangements are postulated for the vacuum wall study. These are discussed generally in Section 3.2.4. The vacuum wall configuration outlined earlier in this section is similar to the original design except that the pressure of 75 torr absolute used in the original design concept between the LSAP and the blanket is changed to atmospheric pressure. This is the first vacuum wall arrangement shown in Figure 3.2-32 and provides only the vacuum zone in the plasma chamber. The second arrangement shown in the figure requires only bolting the joints at the back of the blanket modules without a welded seal and designing the joint for high impedance to molecular flow. In this case the LSAP is then bolted in place with a mechanical seal to define a primary pressure barrier. The pressure in the zone between the blanket and the LSAP is maintained at 1×10^{-4} torr to allow only molecular flow through the blanket joint. The pumping system for this region is independent of the plasma chamber pump system but would probably not require cryopumps. For the third arrangement, the primary vacuum wall is at the reactor room wall and the pressure in the vacuum room is maintained at 1×10^{-4} torr. The LSAP is bolted in place with no seal. The pumps required for this outer region are defined in Section 3.2.4.

The neutral beam injector installation is with the beam axis along a horizontal poloidal and toroidal radius as shown in Figure 3.3-7. Twelve NBI's are used, as for Culham, to produce 60 MW of total injected beam power. The beam ducts for this installation penetrate both the lateral support access panel (LSAP) between the TF coils and the "A" module. Provisions for this installation with the first vacuum wall arrangement described above must include a sealed penetration at the blanket, since a vacuum region is not maintained outside of the blanket. A bolted joint in the beam duct is provided at the LSAP. The joint at the LSAP is broken when the NBI is removed. The LSAP is free from the beam duct so that it can be removed and installed independent of the duct. The beam duct between the blanket and the LSAP is removed as a separate unit. Both joints in the beam duct are mechanical (i.e., not welded) and of the same type considered for the 5000 MW_{th} NBI installations on such reactors as the UWMAK-I in the previous study phase (Reference 3-25).

3.3.3 Oak Ridge National Laboratory Cassette Concept - Since the reactor conceptual design defined in Reference 3-4 requires extensive additional elaboration

tion for a study of the maintainability of the cassette concept, the concept is applied to conceptual design features defined in other reference concepts. The plasma characteristics of the ORNL Cassette reference reactor are defined in Section 3.1, Table. 3.1-1, and the cross section arrangement of this reactor is shown in Figure 3.3-9. The overall arrangement employs a single null poloidal divertor with the particle bombardment plates above the TF coils as in the UWMAK-III design. The arrangement also uses TF coils and ohmic heating coils with an air core transformer as in the UWMAK-III, and PF coils within the TF coil bore similar to the UWMAK-III, except that the PF coils associated with the second divertor are omitted.

3.3.3.1 ORNL Reference Design General Characteristics - The general characteristics selected for the reference system are compared with those defined in the ORNL Fusion Power Demonstration Study in Table 3.3-8. The data from Reference 3-4 is for a reactor with a thermal power output of $1700 \text{ MW}_{\text{th}}$. For the purposes of this study the power output is boosted to $3000 \text{ MW}_{\text{th}}$ with corresponding changes in plasma performance.

The ORNL Cassette concept is characterized in this study by the following features critical to maintenance. These features include the use of the multiple zone first wall/blanket concept, described in Section 3.2.1, which requires replacement of only the first zone (i.e., the zone closest to the plasma) at the minimum replacement interval. Also unique to this concept is the removal of segmented first wall/blanket cassettes, including shield plugs, from a position outside of the shield and between the TF coils. The cassettes are self-supporting and made in straight slabs. All cassettes are accessible without removing magnets, even though some poloidal magnets may be raised or lowered. All fluid disconnects are made or broken outside of the shield. The vacuum wall is at the outside of the shield. Other features of the reactor may be varied as desired without nullifying the maintainability characteristics of this concept.

Table 3.3-9 summarizes the characteristics of the first wall/blanket modules employed in the ORNL Cassette reference system used in this study. The location of these modules is indicated in Figure 3.3-9. The arrangement differs from that disclosed by ORNL in Reference 3-5 in that the shield block is removed from the center of the outer wall and the bent modules are dropped downward from the upper outer wall instead of being on the bottom of the chamber. This arrangement allows all modules except those at the inner wall to be removed from the side of the reactor where the distance between TF coils is the largest. This arrangement

ORNL CASSETTE TOKAMAK REFERENCE REACTOR – SIDE VIEW

FIGURE 3.3-9

also requires the minimum distance below the floor level for module removal. A single zone divertor module is used to replace one bank of cassettes since the fluid connections for this module must be disconnected above the blanket at the shield and the module then moved laterally as a single entity in order to remove it. Detailed definitions of these modules are given in Section 3.2.1.

The basic concept discussed in Reference 3-5 indicates that two different module thicknesses are considered. The 25 cm double module is chosen for all three blanket zones since this provides sufficient thickness of breeder material to give an estimated breeding ratio greater than 1.2. The support structure for

TABLE 3.3-8

ORNL CASSETTE REFERENCE REACTOR CHARACTERISTICS

		ORNL CASSETTE (REFERENCE 3-4)	ORNL CASSETTE REFERENCE REACTOR
GROSS ELECTRICAL POWER,	MW _e	600	1141
NET ELECTRICAL POWER,	MW _e	---	962
GROSS THERMAL POWER,	MW _{th}	1700	3000
MAJOR RADIUS, (R),	m	6.0	7.5
MINOR RADIUS, (a),	m	1.5	1.924
ASPECT RATIO		4.0	3.9
PLASMA ELONGATION		1.6	2.0
FIRST WALL POWER LOADING			
NEUTRON, AVG.,	MW/m ²	3.0	2.026
MAGNETIC FIELD			
ON AXIS, B ₀ ,	TESLA	3.6	3.882
PEAK, B _{max} ,	TESLA	7.1	8.660
PLASMA CURRENT,	MA	4.0	9.108
MHD STABILITY FACTOR,	q	3.0	2.5
PLASMA PRESSURE RATIO,	β _p	---	3.898
PLASMA PRESSURE RATIO,	β _t	.15	.103
PLASMA DENSITY X 10 ⁻²⁰ ,	IONS/m ³	---	1.316
	ELECTRON/m ³	1.7	---
ENERGY CONFINEMENT TIME,	SEC	1.5	2.703

each module zone is assumed to be provided on the module behind it, except for the third zone where the structure is a part of the shield. An additional thickness of 10 cm is allowed for this supporting structure at each blanket zone.

3.3.3.2 Design Assumptions - The design assumptions used as the basis for modification of the UWMAK-III configuration to contain the ORNL Cassette concept are summarized in Table 3.3-10. These assumptions are necessary to define the design characteristics of the reactor in sufficient detail for the estimation of maintenance functions and to assure comparable reference systems for the concepts being examined.

The arrangement of the poloidal field coils is an assumption of particular importance since this arrangement allows the toroidal field coils to be brought

TABLE 3.3-9

FIRST WALL/BLANKET MODULE PHYSICAL PARAMETERS
(ORNL CASSETTE REFERENCE REACTOR)

MODULE WEIGHTS	- SECTION A (LOWER OUTER WALL)	3.189 TONNES AVG.
	- SECTION B (UPPER OUTER WALL)	2.830 TONNES AVG.
	- SECTION C (BOTTOM WALL)	1.809 TONNES AVG.
	- SECTION D (INNER WALL)	2.960 TONNES AVG.
	- DIVERTOR	8.544 TONNES
MODULE SIZES	- SECTION A	7.1 m X 1.55 m MAX X .25 m
	- SECTION B	4.8 m X 1.49 m MAX X .25 m
	- SECTION C	5.2 m X 1.37 m MAX X .25 m
	- SECTION D	12.8 m X .69 m MAX X .25 m
	- DIVERTOR	2.7 m X 3.50 m MAX X .95 m
NUMBER OF CASSETTES/SECTOR	- SECTION A	9
	- SECTION B	9
	- SECTION C	9
	- SECTION D	9
	- DIVERTOR	1
FIRST WALL/BLANKET COOLANT		GASEOUS HELIUM
FIRST WALL MATERIAL		STAINLESS STEEL
FIRST WALL CONFIGURATION		4 cm TUBING
VACUUM JOINTS	- BLANKET	BOLTED STRUCTURE
	- REACTOR ROOM	HIGH IMPEDANCE
		PRESSURE SEALED DOORS
MAJOR COMPONENTS IN MODULES		FIRST WALL COOLANT TUBING BREEDING BLANKET TRITIUM TUBING STRUCTURAL SUPPORT SHIELD BLOCK

as close as possible to the shield and thus reduce TF coil required energy and cost. If the PF coil arrangement requires movement of these coils to clear the cassettes during replacement, more space in the TF coil bore is necessary. A magnetic field analysis of the required positions of these coils for the plasma postulated has not been conducted. For cost purposes, the energy requirements of each coil is estimated based upon other similar configurations.

3.3.3.3 ORNL Cassette Reference Reactor Design and Arrangement - The overall configuration of the ORNL Cassette reference system is assembled from features of several conceptual design studies in addition to that developed by ORNL in Reference 3-4. The configuration shown in Figure 3.3-9 reflects this approach.

The major radius for this reference system is selected at 7.5 meters to place

TABLE 3.3-10

ORNL CASSETTE REFERENCE REACTOR DESIGN ASSUMPTION

- o THE ENTIRE REACTOR BUILDING IS EVACUATED AS DISCUSSED IN REFERENCE 4. THE CASSETTE JOINTS AT THE OUTSIDE OF THE REACTOR STRUCTURE, AS SHOWN IN SECTION 3.2.1.4, ARE DESIGNED TO BE A SECOND VACUUM WALL WITH ONLY HIGH IMPEDANCE TO MOLECULAR FLOW.
- o A SINGLE NULL DIVERTOR SIMILAR TO THAT SPECIFIED FOR THE CULHAM MK-II IS INCORPORATED INTO THE DESIGN OF THE CASSETTE ARRANGEMENT DEFINED IN REFERENCE 3-5.
- o CRYOSORPTION VACUUM PUMPS LIKE THOSE USED IN UWMAK-III AND OF THE SAME CAPACITY EMPLOYED FOR THE CULHAM REFERENCE SYSTEM ARE INCORPORATED IN THE DESIGN.
- o LATERAL SUPPORT ACCESS PANELS BETWEEN THE TF COILS SIMILAR TO THOSE USED FOR THE UWMAK-III ARE USED FOR STRUCTURAL SUPPORT BUT NOT AS A VACUUM CLOSURE (EXCEPT IN THE VACUUM WALL TRADE STUDY). THESE PANELS ARE OPEN WHERE PENETRATIONS ARE REQUIRED FOR NEUTRAL BEAM INJECTORS.
- o EACH BLANKET ZONE USES A THICKNESS OF ONE DOUBLE CASSETTE AS DEFINED IN REFERENCE 3-5. THE DOUBLE THICKNESS, INSTEAD OF SINGLE THICKNESS, CASSETTE IS ASSUMED NECESSARY TO ATTAIN THE REQUIRED BREEDING MATERIAL FOR A COMMERCIAL REACTOR.
- o TWELVE NEUTRAL BEAM INJECTORS OF THE TYPE DEVELOPED FOR TFTR ARE USED. EACH HAS 3 ION SOURCES FOR A TOTAL OUTPUT OF 5 MW FROM THE THREE ION SOURCES.
- o EACH CASSETTE HAS THREE CONNECTIONS. THESE ARE THE COOLANT (HELIUM) SUPPLY AND RETURN, AND THE TRITIUM RECOVERY RETURN.
- o THE POLOIDAL COIL ARRAY EMPLOYS THE CHARACTERISTICS OF THE UWMAK-III, BEING WITHIN THE TF COIL BORE, BUT USES THE CULHAM ARRANGEMENT AT THE BOTTOM WHERE NO DIVERTOR IS USED. AN ARRANGEMENT IS ASSUMED WHICH DOES NOT OBSTRUCT THE REMOVAL AND REPLACEMENT OF CASSETTES. PF COILS NEED NOT BE DISPLACED FOR FIRST WALL/BLANKET MAINTENANCE.
- o A REACTOR ROOM DIAMETER OF 100 METERS AND A HEIGHT OF 50 METERS IS PROVIDED TO ACCOMMODATE MAINTENANCE EQUIPMENT WITH 2 LARGE DOORS FOR EQUIPMENT AND MATERIAL TRANSFER.
- o AN OVERHEAD CRANE IS AVAILABLE IN THE REACTOR ROOM SUPPORTED FROM THE WALL AND THE CENTRAL STRUCTURAL CORE WITH NO POWER OR FLUID LINES IMPAIRING MOVEMENT OF A SUSPENDED OBJECT AROUND THE REACTOR ROOM.
- o THE LATERAL JOINTS BETWEEN CASSETTES AROUND THE TORUS ARE DESIGNED TO PREVENT NEUTRON STREAMING WITHOUT THE USE OF GRAPHITE BLOCKS OR STRUCTURAL ATTACHMENTS.
- o THE VACUUM AND FIRST WALL/BLANKET/SHIELD COOLANT REQUIREMENTS ARE COMPATIBLE WITH THE NORMALIZED SUBSYSTEM DESIGNS.
- o THE REACTOR IS DIVIDED INTO 16 SECTORS WITH 16 TF COILS.
- o AN OVERHEAD MANIPULATOR IS MOUNTED ON THE OVERHEAD CRANE BRIDGE OR A SEPARATE BRIDGE BELOW IT FOR DISCONNECTING SUBSYSTEMS ABOVE THE REACTOR.
- o REACTOR SUPPORT STRUCTURE DOES NOT INTERFERE WITH MAINTENANCE EXCEPT AS INDICATED FOR LATERAL SUPPORT ACCESS PANELS AND OHMIC HEATING COILS ABOVE THE REACTOR.

the design near the minimum cost of electricity position on the major radius vs minor radius (R-a) curve shown in Figure 3.1-8 (Section 3.1). Since the entire first wall/blanket/shield thickness is between the TF coil and the plasma chamber at the inner wall and since this thickness is increased over the basic cassette dimensions by additional structure required to support the cassettes, the inner wall radius is approximately the same as for the Culham reference system. This results in a R-a curve identical to the Culham reference system and the choice of the same major radius (i.e., 7.5 meters).

A horizontal section through one reactor sector at the plasma centerline is illustrated in Figure 3.3-10. Three inner wall blanket modules must be used to make their width narrow enough to fit within the space between the TF coils. The outer wall modules shown in the figure, as well as the bottom modules, can readily pass the center row of the three rows of modules that make up one sector between the TF coils. The divertor module can be a single cassette and still be narrow enough to move between the TF coils. However, since the coolant and tritium connections are at the back of this module, only one zone is used. It is assumed that the blanket zone of the divertor module can be redesigned for coolant supply and return, as well as for other connections at the back of the module. The connections for all other cassettes are made at the back of the shield block which is a part of each cassette. This requires 3 connections at each cassette, a total of 42 connections, to remove the first blanket zone cassettes from one sector, exclusive of the divertor modules.

The vacuum wall arrangement for this configuration requires a double vacuum chamber since the plasma chamber seals at the outside of the shield area are bolted in place and, at best, use a mechanical seal. This seal arrangement is complex, as shown in Figure 3.2-15 of Section 3.2.1.4, and is impractical for holding pressures of 1×10^{-8} torr. Therefore, the primary vacuum wall arrangements used for the vacuum wall location study have included a primary vacuum wall at the lateral support access panel (LSAP) between the TF coils, and at the reactor room wall. In Section 3.2.4, Figure 3.2-32, the first vacuum wall arrangement requires only high impedance joints at the outside of the shield without using a seal but uses a welded seal at the LSAP. The space between the shield and the LSAP uses a separate pumping system to maintain 1×10^{-4} torr in this region. The second vacuum wall arrangement shown in Figure 3.2-32 uses a sealed and bolted joint for each cassette at the outside of the shield and a bolted LSAP joint with a mechanical seal. The pumping systems are independent as in the first arrangement. The third arrangement uses the reactor

FIGURE 3.3-10

room wall as the primary vacuum wall with the LSAP bolted in place to satisfy structural requirements but open to pressure flow. The pressure of 1×10^{-4} torr is maintained in the reactor room with the independent pumping system described in Section 3.2.4.

The neutral beam injector installation mounts the beam duct to a cooled shield plug between the upper and lower outer wall at the center bank of cassettes in each sector. A cross section of this arrangement is illustrated in Figure 3.3-11. The center bank of cassettes in the lower outer wall is bent over in the same manner as the upper outer wall cassettes to make room for the beam duct and the

ORNL CASSETTE REFERENCE SYSTEM (NEUTRAL BEAM INJECTOR DUCT PENETRATION)

FIGURE 3.3-11

shield plug. If the entire reactor room is a vacuum chamber, the joint between the shield plug and the NBI beam duct need only be a high impedance attachment. The beam duct is not attached to the lateral support access panel. For removal of the NBI, however, a joint in the beam duct outside of the access panel is first disconnected and the NBI is removed to gain access to the lateral support access panel. All joints in the beam duct are mechanically connected (i.e., not welded). After the LSAP is removed, the beam duct and shield plug are accessed for removal. Twelve NBI's are used, as for the other reference reactors, to produce 60 MW input to the plasma.

All fluid lines to the cassettes are assumed to run from manifolds below the toroidal field coils to the cassette shield blocks and the shield segments. The areas that must be clear of fluid lines which have been disconnected from the cassettes are at the center cassettes in each sector, the removable shield plugs and the access doors. Some cassette removal equipment designs also require the connecting fluid lines for the cassettes to the right and left of the center bank to be moved clear of the cassette shield blocks after disconnecting them. These lines are all contained between the LSAP and the shield and are assumed to pass between the TF coils above or below the LSAP after combining into common manifolds.

The space allocated for these lines between the LSAP and the shield may be insufficient and require increasing the radius to the outer legs of the TF coils to provide additional space. A typical arrangement at the face of the cassette shield blocks for clearing this area of fluid lines is indicated in Figure 3.2-17 (Section 3.2.1.4).

Helium is assumed as the first wall/blanket/shield coolant based on the selection defined in the more recent cassette study reported in Reference 3-5.

The cryosorption vacuum pump installation is the same design as that used for the Culham reference system. The arrangement of the particle bombardment plates which places them above the TF coils assumes that the poloidal field coil configuration is capable of achieving this magnetic field shaping with the coils shown. For the purpose of costing it is assumed that all poloidal field coils are superconducting.

A space for ohmic heating coils is available in Figure 3.3-9 in the region above the TF coils in the same array as used for the UWMAK-III air core transformer. The envelope allowed for these coils is that potentially required by the use of an air core transformer instead of the iron core used with the Culham configuration from which the remainder of the ohmic heating coil array is derived. Such an array may interfere with the removal of the inner wall cassettes and require vertical displacement before cassette removal is feasible. However, for this study the coils are assumed to be arranged to provide the capability to clear them when removing the inner wall cassettes.

3.3.4 General Atomic - Demonstration Power Reactor Concept - The General Atomic Demonstration Power Reactor (GA-DPR) is modified for this study phase as described in Section 3.1 with the characteristics shown in Table 3.1-1. The revised arrangement is referred to as the GA-Doublet reference reactor and is shown in Figure 3.3-12. This cross section is primarily extracted from Reference 3-3 but includes the revised access and NBI installation.

3.3.4.1 GA-Doublet Reference Design General Characteristics - The general characteristics selected for the reference system are compared with those defined in the GA-DPR study in Table 3.3-11. The data from Reference 3-3 indicates that the GA-DPR design will produce $1764 \text{ MW}_{\text{th}}$ gross instantaneous power. However, when using the same confinement law and maximum magnetic field (B_m) as the other reference systems, the power output is increased to $3414 \text{ MW}_{\text{th}}$. Since the desired output is $3000 \text{ MW}_{\text{th}}$ the size of the reference system will differ only slightly from that of the GA-DPR. This result is indicated in the Table 3.3-11. The higher power density is primarily responsible for the increase in neutron wall

GA DOUBLET REFERENCE REACTOR – SIDE VIEW

FIGURE 3.3-12

loading indicated in the table.

The characteristics of the GA-Doublet concept that are critical to maintenance include the replacement of small modules of the first wall/blanket by operations within the plasma chamber and then removing these modules through auxiliary penetrations of the chamber. The use of the flowing plasma boundary impurity control concept also influences maintenance because of the elimination of the divertor requirement and the accompanying complexity of divertor coils, divertor first wall/blanket modules, and particle bombardment or collector plates. Limiters are used with the flowing plasma boundary concept to define the plasma separatrix.

TABLE 3.3- 11

GA-DOUBLET REFERENCE REACTOR CHARACTERISTICS

		GA-DPR (REFERENCE 3-3)	GA-DOUBLET REFERENCE REACTOR
NET ELECTRICAL POWER,	MW _e	611	902
GROSS THERMAL POWER,	MW _{th}	1764	3000
MAJOR RADIUS, (R),	m	7.0	6.5
MINOR RADIUS, (a),	m	1.8	1.4
ASPECT RATIO		3.89	4.6
PLASMA ELONGATION		3.0	3.0
DOUBLET CONSTRICTION RATIO		.5	.5
FIRST WALL POWER LOADING			
NEUTRON, AVG.,	MW/m ²	.97	2.365
MAGNETIC FIELD			
ON AXIS, B _o ,	TESLA	3.86	4.616
PEAK, B _{max} ,	TESLA	7.5	8.660
PLASMA CURRENT,	MA	18.6	14.62
MHD STABILITY FACTOR,	q	2.5	2.5
PLASMA PRESSURE RATIO,	β_p	1.94	2.315
PLASMA PRESSURE RATIO,	β_t	.10	.091
PLASMA DENSITY X 10 ⁻²⁰ ,	IONS/m ³	1.1	1.221
ENERGY CONFINEMENT TIME,	SEC	1.4	2.9

The flowing plasma boundary increases the vacuum pumping requirements so that two sets of cryovacuum pumps, one above and one below the plasma chamber, are required in each sector instead of the single set used with a single divertor system. Also unique to this concept is the attachment of the modules to permanent structure and the requirement to provide a module seal which separates the plasma chamber from the high pressure coolant. The permanent structure becomes the vacuum wall and this need not be broached at the module location to replace the first wall/blanket modules. The doublet configuration also requires the use of dual NBI's, i.e. for the upper and lower plasma region. While the doublet shape is peculiar to the reactor concept, by itself the shape has little influence on the maintainability except that it requires such close proximity of the field shaping coils to the inner shield of the reactor. Other characteristics of the reactor concept may be varied as desired without negating the maintainability features of this concept.

Table 3.3-12 summarizes the characteristics of the first wall/blanket modules employed in this concept. These modules are described in detail in Section 3.2.1.2 and in Reference 3-13. This module design differs from that used in the earlier part of this study (Reference 3-25) by using a completely mechanical attachment and seal concept (i.e. without a welded seal). The module diameter is retained even though the reactor size is less and fewer modules are required.

3.3.4.2 Design Assumptions - The design assumptions used as the basis for the modified GA-DPR configuration are summarized in Table 3.3-13. While these assumptions attempt to assure comparable reference systems, the variations in the impurity control system causes changes in coolant flow and vacuum flow distribution and in mass flow rates. Therefore, the subsystems must be resized and slightly rearranged to accommodate these variations in the concept. This work is reported in Section 3.2 where variations have been defined.

TABLE 3.3-12
FIRST WALL/BLANKET MODULE PHYSICAL PARAMETERS
(GA-DOUBLET REFERENCE REACTOR)

MODULE WEIGHT		
PRESSURE VESSEL (FIRST WALL)	kg	100
BREEDER SECTION	kg	500
TOTAL	kg	600
MODULE SIZE		
	m	.69 DEEP x .7 DIAMETER
NUMBER OF MODULES		
TOTAL		1808
SECTOR		113
FIRST WALL/BLANKET COOLANT		HELIUM
FIRST WALL MATERIAL		INCONEL 718
FIRST WALL CONFIGURATION		DOMED CYLINDERS WITH INTERSTITIAL GRAPHITE BLOCKS
VACUUM JOINTS		
BREEDER SECTION		THREADED TO SHIELD
FIRST WALL		BOLTED, DOUBLE SEAL WITH VACUUM PORTS BETWEEN SEALS
MAJOR COMPONENTS IN MODULE		FIRST WALL DOMES BREEDING BLANKET COOLANT TUBING STRUCTURAL SUPPORT

TABLE 3.3-13
GA-DOUBLET REFERENCE REACTOR DESIGN ASSUMPTIONS

- THE AUXILIARY VACUUM PORTS AT THE TOP OF THE REACTOR ARE LARGE ENOUGH TO PASS A MODULE THROUGH THE PORT.
- THE AUXILIARY VACUUM PORTS MAY BE RELOCATED TO THE VERTICAL AXIS OF THE CHAMBER TO MOUNT THE MAINTENANCE EQUIPMENT IF REQUIRED.
- THE CRYOSORPTION VACUUM PUMPS ARE DESIGNED AS IN THE GA-DPR BUT RESIZED FOR THE DIFFERENT FLOW REQUIREMENTS.
- ALL REACTOR MODULES ARE IDENTICAL IN SIZE.
- TWELVE NEUTRAL BEAM INJECTORS ARE REQUIRED WITH 6 INSTALLED AT THE UPPER PLASMA ZONE AND 6 AT THE LOWER ZONE. EACH NBI USES 3 ION SOURCES FOR A TOTAL OUTPUT OF 5 MW FROM THE THREE ION SOURCES.
- A REACTOR ROOM DIAMETER OF 100 METERS AND A HEIGHT OF 50 METERS IS PROVIDED TO ACCOMMODATE MAINTENANCE EQUIPMENT. TWO LARGE DOORS ARE PROVIDED IN THE REACTOR ROOM WALL FOR EQUIPMENT AND MATERIAL TRANSFER.
- TWO OVERHEAD CRANES ARE AVAILABLE IN THE REACTOR ROOM SUPPORTED FROM THE OUTER WALL AND THE CENTRAL CORE COLUMN OF THE REACTOR. POWER OR FLUID LINES DO NOT IMPAIR MOVEMENT OF A SUSPENDED OBJECT AROUND THE REACTOR ROOM.
- TWO OVERHEAD MANIPULATORS ARE MOUNTED ON SEPARATE BRIDGES BELOW THE OVERHEAD CRANES FOR USE IN DISCONNECTING SUBSYSTEMS AND MAINTENANCE EQUIPMENT ABOVE THE REACTOR.
- THE REACTOR IS DIVIDED INTO 16 SECTORS WITH 16 TF COILS.
- THE FIRST WALL/BLANKET/SHIELD COOLANT REQUIREMENTS AND THE VACUUM PUMPING REQUIREMENTS MUST BE REDISTRIBUTED AND RESIZED FROM THOSE USED FOR THE NORMALIZED SUBSYSTEM DESIGNS USED IN OTHER REFERENCE SYSTEM CONCEPTUAL DESIGNS.
- REACTOR SUPPORT STRUCTURE DOES NOT INTERFERE WITH MAINTENANCE.
- A METHOD OF SHUTTING OFF HELIUM COOLANT FLOW TO GROUPS OF MODULES IS POSSIBLE.
- THE NEUTRAL BEAM INJECTION SYSTEM WILL NOT INTERFERE WITH FIRST WALL/BLANKET MAINTENANCE.
- THE REMOVAL OF VACUUM PUMPS IS NOT REQUIRED FOR FIRST WALL/BLANKET MAINTENANCE.
- THE REACTOR SUPPORT STRUCTURE WILL CARRY MAINTENANCE EQUIPMENT LOADS.

The principal difference between the reference system and the GA-DPR concept that are assumed to be feasible, aside from the resizing of the reactor, are the moving of the auxiliary vacuum port to the vertical axis of the plasma chamber with an access port installed in the duct, and the use of 12 NBI's for 60 MW of 120 keV beam power instead of 100 MW of 250 to 550 keV power indicated in Reference

3-3. This latter choice is made for normalization purposes and because the design details of the higher energy beam units are uncertain at this time.

3.3.4.3 GA-Doublet Reference Reactor Design and Arrangement - The overall configuration of the GA-DPR design concept developed by General Atomic and reported in Reference 3-3 is retained with only slight revisions in size to conform to the normalized 3000 MW_{th} requirements defined for this study.

The selection of the major radius of 6.5 meters instead of the 7.0 meters used in Reference 3-3 is still larger than the core constraint shown in Figure 3.1-8 of Section 3.1 and is selected to produce near minimum cost of electricity as indicated on the same figure. This revision in major radius increases the aspect ratio to 4.6 instead of the GA-DPR value of 3.89 reported in Reference 3-3. The reduction in major radius is achieved by reshaping the TF coil section to provide for movement of these coils closer to the reactor center before they interfere with each other. This results in a slightly smaller radius for the ohmic heating transformer core. Also, the plasma height to width ratio of 3.0 with the attendant poloidal field coil configuration provides for a smaller TF coil than the other reference designs and this, together with the relatively low thickness of the first wall/blanket/shield design permits a smaller major radius than the ORNL and Culham reference systems.

The first wall/blanket module arrangement is similar to that used in the GA-DPR but replacement requires only the removal of the graphite ring and blocks, the first wall pressure vessel, and the breeding section of the module. The liner plate has been omitted in this design. The pressure dome is removed by unfastening 12 bolts and the breeder section is unlocked and then unscrewed. More detail is shown in Section 3.2.1.2 and Reference 3-13.

The auxiliary vacuum ducts in each section are modified to include a port in the duct which can be opened to pass maintenance equipment and modules through to and from the interior of the plasma chamber. The cover over this opening is assumed to be an automatically operated isolation valve which must provide a vacuum seal. Since it is also subject to direct neutron bombardment the valve cover must be cooled, replaceable and backed with shielding.

The helium coolant lines penetrate the inner shield and vacuum wall to each module and are manifolded together in small groups as an aid to isolating leaking modules. The manifolding along the inner wall is undefined and may require more space than presently provided. However, for the first wall blanket replacement maintenance this has no impact. Inspection and leak detection methods for this

inner wall piping have not been examined. All coolant manifolds are assumed to be joined together at or beneath the reactor room floor to connect with the main primary coolant loop discussed in Section 3.2.5.

The cryosorption vacuum pumps use the same number of pumps as in the GA-DPR design concept, i.e., 32 pumps at the 16 auxiliary vacuum ports and 16 pumps at the lower vacuum slot in the plasma chamber. Only half of these pumps operate at one time and the other half are regenerated. The regeneration vacuum lines are manifolded together beneath the reactor room floor and pass outside of the reactor room to the regeneration vacuum pumps defined in Section 3.2.4.

Limiters are installed in the lower vacuum slot in the plasma chamber. In the absence of detailed definition of these limiters it is assumed that they do not interfere with the first wall/blanket maintenance. It is also assumed that they will be cooled and will require periodic maintenance. Their design should be such that removal from the inside of the plasma chamber through the same auxiliary vacuum ports that are used for the first wall/blanket modules is feasible. A potential alternative is the replacement of these limiters through the lower cryovacuum pump ducts but additional maintenance equipment would be required.

The TF coil support arrangement and the PF coil arrangement are assumed to be the same as that defined for the GA-DPR. The structural support for the TF coils uses a floor mounted pier for each coil but the support for the PF coils is not defined in detail. The maintenance functions studied assumed no interference from these structural support members. Since the TF coils and PF coils are both superconducting and assumed to be unitary in design, any maintenance of these coils becomes extremely difficult and time consuming. Brief studies of alternate design approaches are being made and will be discussed in Sections 4.0 and 5.0.

The neutral beam injector installation assumes that the beam duct will be detached at the NBI before it passes through the outer shield. This penetration of the outer shield as well as the beam duct itself must be shielded and the disconnect is assumed to be a mechanically sealed vacuum tight joint. The penetration of the inner shield is welded in place since this is the vacuum wall of the plasma chamber.

For the vacuum wall location analysis, alternate locations of the vacuum wall for this GA-Douplet reference reactor appear of little, if any, value. The alternates considered are the use of the outer shield or the reactor room wall as primary vacuum walls, thus reducing the stringent requirements for the vacuum seals at the back of the inner shield. These alternatives may be of value to

reduce the impact of leaks in the vacuum wall since the leaks could be better tolerated and the field shaping coils would not have to be removed as often for repair access. However, for the first wall/blanket analysis, all operations are accomplished without working on the vacuum wall except at the vacuum ports so the condition of the wall is not a factor to be considered. This situation arises because the seals that are broken and remade when replacing each first wall/blanket module are between the plasma chamber and the helium coolant at 50 atmospheres and not between the plasma chamber and the reactor room at a pressure of 1 atmosphere. Therefore, only the vacuum wall arrangement used in the GA-DPR conceptual design is considered since the addition of other vacuum walls to form a secondary vacuum chamber can only increase the access time and capital cost of this configuration.

3.3.5 Reactor Related Facilities - The facilities influenced by the maintenance of the reactor include seven major areas. These are:

- o Reactor Room
- o Hot Material Transfer
- o Hot Material Storage Room
- o Hot Material Workroom and Holding Room
- o Maintenance Equipment Transfer
- o Maintenance Equipment Decontamination Room
- o Maintenance Equipment Servicing Room
- o Spares Storage

Figure 3.3-13 is a typical arrangement of the reactor room and the secondary confinement building with some of the auxiliary facilities located but not sized for any particular reactor. This figure also illustrates the arrangement of the coolant loops.

The two types of coolant loops discussed in Section 3.2.5 are shown in typical installations in the secondary confinement areas in Figure 3.3-13. Two systems using the lithium coolant in the primary loop occupy bays on the left of the figure and two systems using helium coolant occupy bays on the right of the figure. The lithium equipment occupies less space in this plan. For any one reference reactor all four systems use the same coolant and the steam lines are assumed to be manifolded to a single turbine. Space for vacuum roughing and regeneration pumps and for reactor room pumps is also available in the secondary confinement areas. This arrangement is used to provide the shortest piping run between the reactor and the heat exchangers. The space in the four bays not occupied by the

REACTOR BUILDING TYPICAL ARRANGEMENT

FIGURE 3.3-13

pumping systems is available for installation of other auxiliary equipment and provides access to the reactor room through the two entry doors with their auxiliary decontamination room and hot cell facilities.

The reactor room must provide sufficient area to move equipment around its periphery. While the reference reactors vary slightly in their maximum diameter, it can be seen from Figure 3.3-1 that this variation would change the reactor room diameter only slightly. Therefore, the reactor room diameter is maintained at 100 meters for all four reference reactors. The outer wall must be of sufficient thickness to provide radiation shielding during maintenance of the first wall/blanket and to withstand vacuum loads when the reactor room is used as the secondary vacuum zone, which is the selected arrangement for the ORNL and the Culham concept reference reactors. It is believed that the vacuum wall requirement can be omitted for the UWMAK-III and the GA-Doublet reference systems and that the GA-Doublet system may further reduce the radiation requirement for the reactor room wall if all first wall/blanket modules are continuously encapsulated in shielded casks. The reactor room height of 50 meters is assumed to be required to allow clearance for the overhead cranes and lifting clearances for equipment at the top of the reactor. A more detailed study of this height is necessary to minimize it.

The flow of the reactor components through these facilities is shown diagrammatically in Figure 3.3-14. The irradiated material removed from the reactor is transferred to the combined hot material workroom and holding-room through the transfer lock. This lock is required to isolate the hot cell, storage room and reactor room environments. The reactor modules are processed in the workroom and made ready to install in the reactor. The hot material storage room is used to store all waste material removed from the reactor until it can be shipped for further disposition. This room also contains irradiated spare modules which are not immediately required for replacement in the reactor.

The nonirradiated material is removed through the maintenance equipment airlock. This material is decontaminated in a separate room to allow replacement spares and maintenance equipment to be moved through the airlock from the servicing room without undue delay. This equipment and spare parts are checked and prepared for use in the maintenance equipment servicing room.

Helium gas is assumed for use as an inert atmosphere in all hot material areas and in the reactor room when pressurized and remote maintenance is the selected mode for maintenance operations. The other areas use an air atmosphere

FIGURE 3.3-14

to allow contact maintenance on decontaminated equipment and spares. In those cases where contact maintenance is conducted in the reactor room on nonirradiated equipment, an air atmosphere may be used even though breathing apparatus are assumed to be required for personnel under these conditions.

The sizes of all facilities outside of the reactor room are based on the size of the modules from the first wall/blanket, the number of modules processed during a scheduled maintenance shutdown, and on the time period for which the material is stored or held in the area. Clearance factors are applied to all module sizes to allow for working room. The storage period sizes only the hot material storage room since a storage period of three years is assumed for this room based on the University of Wisconsin studies. The time required for all operations conducted in the other rooms is assumed to be less than one operating period until further analyses of repair times are conducted. These facility sizes are all determined as a part of the TOCOMO code operation.

3.4 References

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4.0 MAINTENANCE PLANS - TASK 7

Maintenance plans are developed for all four reference reactor systems defined in Task 6. These plans include the necessary downtime estimates, maintenance equipment definition and personnel requirements to serve as the basis for the trade studies and evaluation of reactor and maintenance system design features conducted in Tasks 8 and 9. The evaluation of the design features is discussed in Section 5.0.

The maintenance plans developed include plans for unscheduled and scheduled replacement of the first wall/blanket of the reference reactors and the unscheduled replacement of some components of other critical subsystems that are a part of each reactor or interface with it. Unscheduled maintenance of maintenance equipment is the basis for additional maintenance plans. In addition, maintenance plans are developed for contact (hands on) operations wherever possible and for totally remote maintenance of the same subsystem. The variations in maintenance plans with different vacuum wall locations are also defined for the purpose of supporting the analysis of these alternatives.

The types of maintenance requirements and the approach used to develop them through the use of maintenance plans are discussed in the following section.

4.1 DEVELOPMENT OF MAINTENANCE REQUIREMENTS - Maintenance requirements for each reference reactor system are defined from maintenance plans which are developed for selected maintenance operations required by each system. The maintenance operations selected are those which result in the most significant impacts on the cost of electricity produced by the reference reactor systems. The requirements to be defined include downtime, maintenance equipment and the personnel needed.

This section discusses the scope of the maintenance actions for which maintenance plans are developed and the approach to maintenance plan development used in this study.

4.1.1 Maintenance Requirement Development Scope - Maintenance plans are developed for each of the following reactor concepts:

- o CULHAM
- o UWMK-III
- o ORNL CASSETTE
- o GA-DOUBLET

Prior studies have shown that the physical location of the primary vacuum wall at the first wall/blanket area presents difficult maintenance problems and tends to increase maintenance downtimes. In this study, three different vacuum wall locations are evaluated from a maintenance standpoint for each reactor concept except the GA-Doublet. The three vacuum wall locations considered are (1) at the first wall/blanket area, (2) at the toroidal field magnet lateral support panel area (or alternatively, in the case of the Culham reactor, at the outer shield), and (3) at the reactor room wall. A complete discussion of these vacuum wall alternatives is presented in Section 4.2. The location of the vacuum wall at the first wall proves to require substantially longer maintenance outage times in most cases.

Figure 4.1-1 presents an overview of the maintenance plan scenarios developed during the course of this study. The type of maintenance specified in the figure indicates whether the scenario was concerned with scheduled or unscheduled maintenance. The headings under "maintenance scenario" show the reactor subsystem or element that is evaluated and whether partial contact or fully remote maintenance is employed and which vacuum wall alternative location is considered. The cross marks in the vertical columns show each case for which a maintenance scenario has been prepared.

The unscheduled maintenance scenarios in either the partial contact or fully remote maintenance modes are primarily based upon the exchange of one first wall/blanket module sector. Scheduled maintenance scenario evaluations had to consider various combinations of sector exchanges with different numbers of equipment sets, for both the contact and remote maintenance situations. These scenario combinations are defined in Section 4.4. The maintenance equipment and facility concepts are tailored to replace a first wall section in the shortest possible time, and later expanded to encompass scheduled replacement activities.

Other failure modes selected for evaluation involve the unscheduled replacement of a cryosorption pump valve and a Neutral Beam Injector (NBI) ion source. The maintenance plan scenarios for responding to these subsystem failures are defined in Section 4.5.

The impact and effects of failures occurring in the maintenance equipment proper during a selected maintenance activity are presented in Section 4.6. The attempt is made to select for evaluation those types of failures which have the greatest time impact on scheduled activities. Generally, given adequate spares and with proper machine design, the maintenance system can back out of most situations without incurring too great a time impact.

SCOPE OF MAINTENANCE SCENARIO DEFINITIONS

MAINTENANCE TYPE	CULHAM				UWMK-III				ORNL CASSETTE				GA-DOUBLET			
	SCHEDULED		UNSCHEDULED		SCHEDULED		UNSCHEDULED		SCHEDULED		UNSCHEDULED		SCHEDULED		UNSCHEDULED	
	CONTACT	REMOTE	CONTACT	REMOTE	CONTACT	REMOTE	CONTACT	REMOTE	CONTACT	REMOTE	CONTACT	REMOTE	CONTACT	REMOTE	CONTACT	REMOTE
<u>MAINTENANCE SCENARIO</u>																
o FIRST WALL/BLANKET EXCHANGE																
- VACUUM WALL LOCATION NO. 1	-	-	X	-	X	X	X	X	-	-	X	-	X	X	X	X
- VACUUM WALL LOCATION NO. 2	-	-	X	-	X	X	X	X	-	-	X	-	-	-	-	-
- VACUUM WALL LOCATION NO. 3	X	X	X	X	X	X	X	X	X	X	X	X	-	-	-	-
o CRYOVACUUM PUMP VALVE EXCHANGE																
- VACUUM WALL LOCATION NO. 1	-	-	-	-	-	-	X	X	-	-	-	-	-	-	X	X
- VACUUM WALL LOCATION NO. 2	-	-	-	-	-	-	X	X	-	-	-	-	-	-	-	-
- VACUUM WALL LOCATION NO. 3	-	-	-	-	-	-	X	X	-	-	-	-	-	-	-	-
o CRYOVACUUM PUMP EXCHANGE																
- VACUUM WALL LOCATION NO. 1	-	-	-	-	-	-	X	X	-	-	-	-	-	-	X	X
- VACUUM WALL LOCATION NO. 2	-	-	-	-	-	-	X	X	-	-	-	-	-	-	-	-
- VACUUM WALL LOCATION NO. 3	-	-	-	-	-	-	X	X	-	-	-	-	-	-	-	-
o NBI ION SOURCE EXCHANGE																
- VACUUM WALL LOCATION NO. 1	VALID FOR ALL REFERENCE REACTORS															
- VACUUM WALL LOCATION NO. 2	VALID FOR ALL REFERENCE REACTORS															
- VACUUM WALL LOCATION NO. 3	VALID FOR ALL REFERENCE REACTORS															
o MAINTENANCE EQUIPMENT FAILURE (SELECTED SCENARIOS)																
- REMOTE REPAIR	N/A	N/A	-	XX	N/A	N/A	-	XX	N/A	N/A	-	XXX	N/A	N/A	-	XXX
- CONTACT REPAIR	N/A	N/A	-	-	N/A	N/A	X	-	N/A	N/A	-	-	N/A	N/A	-	-

LEGEND: X; SCENARIO DEFINED
 -; NO SCENARIO DEFINED
 N/A; NOT APPLICABLE

VACUUM WALL LOCATION DEFINITIONS

LOCATION NUMBER	PRIMARY VACUUM WALL LOCATION
1	FIRST WALL OR BLANKET
2	OUTER SHIELD OR LSAP
3	REACTOR ROOM WALL

FIGURE 4.1-1

The time saving impacts of contact versus fully remote maintenance are considered in all maintenance plan scenarios. In all cases, contact maintenance results in lower maintenance outage times. Also, a lower Cost of Electricity (COE) is exhibited in all reactor concepts except the GA-Douplet, where the cost of extra shielding around the in-place maintenance machines increases the COE value slightly over the completely remote maintenance situation.

4.1.2 Maintenance Requirement Development Approach - The approach used to develop basic maintenance plans for each of the reactor concepts is illustrated in Figure 4.1-2. Each concept for a commercial power producing reactor must satisfy certain operational requirements in order to be economically viable for use by a utility. Examples of typical Tokamak top level operational requirements are shown in Table 4.1-1. These operational requirements in turn impose constraints on the reactor design which affect and limit the maintenance system parameters. A list of common Tokamak operational and design constraints is presented in Tables 4.1-2 and 4.1-3. Of particular importance is the constraint of the radiation environment on the use of contact maintenance which limits the use of contact maintenance for all first wall/blanket maintenance scenarios.

DEVELOPMENT OF MAINTENANCE REQUIREMENTS

FIGURE 4.1-2

TABLE 4.1-1
COMMON OPERATIONAL REQUIREMENTS

- 3000 MW_t POWER OUTPUT (~1000 MW_e)
- 30 YEAR LIFE
- 72% AVAILABILITY OR GREATER
- COE OF 40-60 MILLS/KW-HR

TABLE 4.1-2
COMMON OPERATIONAL CONSTRAINTS AFFECTING MAINTENANCE

- 28 DAYS DOWNTIME FOR ANNUAL SCHEDULED BOP MAINTENANCE.
- 65 DAYS DOWNTIME PER OPERATING YEAR FOR UNSCHEDULED MAINTENANCE ON REACTOR AND BOP.
- FIRST WALL LIFE FLUENCE LIMIT (SET AT 5MW - YEAR/M² IN THIS STUDY).
- WALL LOADING LIMITS FIRST WALL LIFE (1.8 - 2.5 YEARS IN THIS STUDY).
- LATENT RADIOACTIVITY AFTER SHUTDOWN RESTRICTS MAINTENANCE PERSONNEL FROM REACTOR ROOM WHEN PLASMA CHAMBER SHIELDING IS OPEN.
- HIGH MAGNETIC FIELDS REQUIRED FOR OPERATION ARE REDUCED TO NEAR ZERO FOR MAINTENANCE.

TABLE 4.1-3
COMMON DESIGN CONSTRAINTS IMPOSED ON THE MAINTENANCE SYSTEM

- EXTENSIVE SUPPORT STRUCTURE BETWEEN TOROIDAL FIELD (TF) COILS
- POLOIDAL FIELD (PF) COILS INTERTWINED INSIDE TF COILS.
- EXTENSIVE, HEAVY SHIELDING AROUND PLASMA CHAMBER
- VACUUM ENCLOSURE AROUND THE PLASMA CHAMBER
- LARGE CRYOSORPTION PUMPS AND LINES ON TOP OF THE REACTOR WHICH OBSCURES ACCESS TO MOST LARGE REACTOR COMPONENTS BY AN OVERHEAD CRANE.
- REACTOR COMPONENT SUPPORT STRUCTURES ARE NOT DEFINED AND MAY INTERFERE WITH MAINTENANCE OPERATIONS.

Figure 4.1-2 shows how the operational requirements of the reactor drive the maintenance systems and impact available options and alternatives. The maintenance system can take many forms, as exemplified by plans 1 thru X, and each plan imposes unique requirements on the maintenance equipment complement, personnel, and facility support requirements. Evaluation and iterations eventually determine which plan is optimum.

The ability of the maintenance system to keep total outage downtimes at an absolute minimum is partially dependent upon the extent to which the maintenance system can constrain or otherwise impact the reactor design. This interchange is part of the evaluation of a finalized reactor design but the iteration process is far from complete at this time.

The final outputs of a developed maintenance plan, considering all the variations and alternatives within the scope of the evaluation conducted in this study, are shown in Figure 4.1-3. These outputs include the definition of requirements and significant design characteristics for maintenance equipment, facilities, and personnel.

4.1.3 Sample Maintenance Plan Development - The assessment and development of an overall maintenance plan, for either scheduled or unscheduled events involves execution of the following tasks:

- o Define the maintenance activities, sequences, and phasing required to accomplish a stated objective.
- o Evaluate each activity to define the performance requirements imposed upon the maintenance system, which consists of equipment items, facility support services, and personnel.

FIGURE 4.1-3

- o Define maintenance ground rules and assumptions concerning the design configuration of each reactor concept.
- o Conceptually define the various maintenance machine types and configurations and selection of the most suitable for the application.
- o Integrate the maintenance machines into a self-consistent set of equipment items which complement each other.
- o Estimate the time required to perform maintenance activities considering the reactor concept, the assumptions made, and the maintenance equipment postulated for the task.
- o Define the overall facility configuration to complement and support the maintenance equipment.
- o Estimate maintenance personnel requirements for machine crews and floor crews to define a base complement of direct support personnel.

An example of the plan developed for each maintenance scenario discussed in later sections is illustrated by the following figures and tables.

The example scenario selected is for the Culham reference reactor concept wherein eight reactor sectors are replaced simultaneously on a scheduled basis using contact maintenance operations where possible and eight sets of maintenance equipment, assisted by a floor crew consisting of eight teams. This scenario also uses a primary vacuum wall located at the reactor room wall. The principal assumptions upon which this scenario is based are:

- o There is no time sharing of maintenance equipment between reactor sections for the same maintenance activity.
- o No contingencies or unplanned events occur during the scheduled maintenance activity.
- o The serial time necessary to account for utilization congestion of the poloidal crane, overhead remote manipulator, and traffic congestion within the reactor room is included in the time estimates.

Figure 4.1-4 shows the overall timeline for exchanging the eight reactor sectors. The reactor shutdown and startup functions are assumed to be automated functions. The access, exchange, and reassembly times are developed from second level expansions as illustrated by Figures 4.1-5, 4.1-6 and 4.1-7, respectively, wherein each maintenance activity is identified and organized in relation to other serial and parallel activities. These more detailed timelines are based upon the use of the maintenance equipment items shown in Figure 4.1-8. The times defined for each task are based on the performance capabilities of each item of maintenance equipment required for that task.

CULHAM REFERENCE REACTOR CONTACT MAINTENANCE SCENARIO

FIGURE 4.1-4

CULHAM - REPLACE 8 SECTORS SIMULTANEOUSLY USING CONTACT MAINTENANCE - GAIN ACCESS

FIGURE 4.1-5

CULHAM – REPLACE 8 SECTORS SIMULTANEOUSLY USING CONTACT MAINTENANCE – EXCHANGE MODULES

FIGURE 4.1-6

CULHAM – REPLACE 8 SECTORS SIMULTANEOUSLY USING CONTACT MAINTENANCE – REASSEMBLE REACTOR

FIGURE 4.1-7

SUMMARY OF CULHAM MAINTENANCE EQUIPMENT ITEMS

ITEM NO.	MAINTENANCE EQUIPMENT ITEMS	ITEM WEIGHT (MT)
1	POLOIDAL CRANE	* 4980.00
2	TUG VEHICLE	80.00
3	OVERHEAD REMOTE MANIPULATOR	1660.00
4	OPERATIONAL MAINT. UNIT (OMU)	77.50
5	NBI PORT PLUG	1.25
6	NBI PORT PLUG DOLLY	.50
7	NBI INJECTOR DUCT SLING	1.00
8	NBI INJ. DUCT T&S DOLLY	2.00
9	LINE CONNECTOR INS/REM TOOL	.30
10	IMPACT WRENCH	.40
11	MOBILE MANLIFT UNIT	.30
12	PRIMARY MAINTENANCE MACHINE (PMM)	250.00
13	LSAP WORKHEAD	70.00
14	LSAP & LSAP W/H T&S DOLLY	50.00
15	SHIELD DOOR WORKHEAD	75.00
16	SHIELD DOOR & W/H T&S DOLLY	60.00
17	AUXILIARY SERVICES WORKHEAD	13.00
18	AUX SERVICES W/H DOLLY	4.00
19	HELIUM COOLANT MANIFOLD COVER	3.50
20	HELIUM MANIFOLD COVER DOLLY	1.00
21	REACTOR MODULE TRANSPORTER	20.00
22	DIVERTER MODULE WORKHEAD	9.00
23	DIVERTER MODULE W/H DOLLY	3.00
24	DIVERTER MODULE T&S DOLLY	3.00
25	INSPECTION WORKHEAD	60.00
26	INSPECTION WORKHEAD DOLLY	20.00
27	LEAK TEST WORKHEAD	.30
TOTAL SET WT =		2465.05

* WEIGHT OF THIS ITEM NOT INCLUDED IN TOTAL

FIGURE 4.1-8

The time estimates for the exchange of multiple first wall/blanket modules and any other subsystem components are developed from initial estimates for the exchange of one module or component. A summary of this estimate at the second level of detail is illustrated in Table 4.1-4 for the Culham candidate reference reactor concept. The estimates are made at the next greater level of detail and summarized for this table. These detailed 3rd level estimates are necessary to define the break points at which additional time is required when conducting operations on several sectors at one time. The integration of these estimates into the complete maintenance plan is conducted as illustrated in Figure 4.1-5, 4.1-6, and 4.1-7.

TABLE 4.1-4

CULHAM REFERENCE REACTOR
FIRST WALL/BLANKET REPLACEMENT

(SCHEDULED CONTACT OPERATIONS - VACUUM WALL ARRANGEMENT NO. 3)

LEVEL 1 TASK	LEVEL 2 TASK	DURATION (HRS:MIN)
SHUTDOWN	REACTOR SHUTDOWN	17:00
ACCESS	MOVE NBI	19:10
	POLOIDAL MAGNET RETRACTION	31:00*
	LATERAL SUPPORT PANEL REMOVAL	12:30
	REMOVE SHIELD DOOR	18:55
	DISCONNECT MODULE COOLANT MANIFOLD	7:00
REMOVAL	REMOVE REACTOR MODULE	17:00
	DISCONNECT DIVERTOR MODULE MANIFOLD	9:50*
	REMOVE DIVERTOR MODULE	22:00
INSPECTION	INSPECTION OF REMAINING MODULE	76:35
REPLACEMENT	REPLACE DIVERTOR MODULE	29:00
	REPLACE REACTOR MODULE	16:15
REASSEMBLY	CONNECT DIVERTOR MODULE MANIFOLD	11:10*
	CONNECT MODULE COOLANT MANIFOLD	7:50
	PRESSURIZE COOLANT MANIFOLD AND TEST	15:30
	REPLACE SHIELD DOOR	21:20
	LATERAL SUPPORT PANEL REPLACEMENT	17:30
	REPOSITION POLOIDAL MAGNETS	42:45*
	REINSTALL NBI	29:55
STARTUP	VALIDATION AND STARTUP	36:00
TOTAL:		363:30

*PARALLEL EFFORT. NOT INCLUDED IN TOTAL TIME

The number of sets of maintenance equipment employed in each scenario are computed for this example as shown in Figures 4.1-9 and 4.1-10. In Figure 4.1-9 the spare equipment items required for the base set of equipment are defined and their weights summarized. The spare components required for equipment items that are repaired in place are not included and critical multiple usage items, such as the reactor module transporters, are provided with several spares. This set of spares is added to the base set of equipment and also the equipment items required for the scenario being developed. For any scenario the quantity of each item of

CULHAM MAINTENANCE EQUIPMENT SET WEIGHTS

CASE NO. SC-CUL-BSA SCENERIO 7				CASE NO. SC-CUL-SPA SCENERIO 7		
WEIGHT SUMMARY FOR CULHAM MAINTENANCE EQUIPMENT BASE				MAINTENANCE EQUIPMENT SPARES		
ITEM	QTY	ITEM WT (MT)	SET WEIGHT (MT)	QTY	ITEM WT (MT)	SET WEIGHT (MT)
1	0	4980.00	4980.00	0	4980.00	0.00
2	1	80.00	80.00	1	80.00	80.00
3	1	1660.00	1660.00	0	1660.00	0.00
4	1	77.50	77.50	1	77.50	77.50
5	1	1.25	1.25	1	1.25	1.25
6	1	.50	.50	1	.50	.50
7	1	1.00	1.00	1	1.00	1.00
8	1	2.00	2.00	1	2.00	2.00
9	1	.30	.30	2	.30	.60
10	1	.40	.40	2	.40	.80
11	1	.30	.30	1	.30	.30
12	1	250.00	250.00	1	250.00	250.00
13	1	70.00	70.00	1	70.00	70.00
14	1	50.00	50.00	1	50.00	50.00
15	1	75.00	75.00	1	75.00	75.00
16	1	60.00	60.00	1	60.00	60.00
17	1	13.00	13.00	1	13.00	13.00
18	1	4.00	4.00	1	4.00	4.00
19	1	3.50	3.50	1	3.50	3.50
20	1	1.00	1.00	1	1.00	1.00
21	1	20.00	20.00	3	20.00	60.00
22	1	9.00	9.00	1	9.00	9.00
23	1	3.00	3.00	1	3.00	3.00
24	1	3.00	3.00	1	3.00	3.00
25	1	60.00	60.00	1	60.00	60.00
26	1	20.00	20.00	1	20.00	20.00
27	1	.30	.30	1	.30	.30
TOTAL SET WT = 2465.05				TOTAL SET WT = 845.75		

EQUIVALENT EQUIPMENT SET DERIVATION

FIGURE 4.1-9

CASE NO. SC-CUL-3	
SCENARIO NO. 7	
A. BASE EQUIPMENT SET WEIGHT (EQUIPMENT REQUIRED TO REPLACE 1 SECTOR)	= 2465.05 TONNES
B. SPARES EQUIPMENT SET WEIGHT (QUANTITY VARIES, BUT USUALLY 1 OF EACH ITEM)	= 845.75 TONNES
C. REFERENCE SET WEIGHT = A + B	3310.80 TONNES
D. SCENARIO BASE SET WEIGHT (X NO. OF EACH ITEM)	= 7829.80 TONNES
E. SPARES EQUIPMENT SET WEIGHT (SAME AS "B" ABOVE)	= 845.75 TONNES
F. SCENARIO SET WEIGHT = D + E =	= 8675.55 TONNES
G. EQUIVALENT NO. OF SETS = $\frac{F}{C}$	= $\frac{8675.55}{3310.80} = 2.620$

FIGURE 4.1-10

equipment is determined individually, as indicated in the "number required" column of Figure 4.1-11, and the gross weight is computed. The total number of equivalent sets of equipment is then computed as illustrated in the example of Figure 4.1-10.

Personnel requirements are estimated for the floor crew size using the breakdown shown in Figure 4.1-11. For each reference concept the number of operating crew members required for each item of equipment is estimated. The total number of operators for this equipment is determined as the product of the number of items of equipment used at one time and the number of personnel required for each item. The functions for which each item of equipment is required is indicated by the marks in each functional column of the figure. The floor crew size is estimated separately by defining the number of personnel required to support each function and multiplying by the number of simultaneous operations. The maximum number of direct personnel required is then the maximum sum of personnel required for any one function. These personnel are assumed to be available for all maintenance functions as required. Where operators must be exchanged for floor crew or visa versa, the personnel are assumed to be drawn from a skilled pool and only charged against the maintenance functions as they are used.

The foregoing information defines the maintenance plan to the extent required to perform the trade studies and evaluation of each maintenance action. This data is summarized in later sections and used to compute the cost of electricity and critical cost parameters through use of the TOCOMO code defined for each specific reference reactor concept.

4.2 VACUUM WALL ALTERNATIVES - One of the more significant reactor concept alternatives evaluated in this study is the location of the vacuum wall(s) and the resultant vacuum chamber arrangements. These are evaluated to determine the impact of the alternative locations on the maintainability of the reference reactor concepts. The vacuum wall arrangements influence primarily the downtime required to exchange the first wall/blanket of each of the reference reactors. Maintenance equipment requirements are influenced only slightly and the relative impact on remote or contact maintenance downtimes is minor.

The vacuum wall locations are also investigated to select those arrangements which are used for further maintenance plan development. Therefore, the downtime estimates made for first wall/blanket replacement for the modules in one reactor sector have been investigated first to allow selection of a preferred vacuum wall location for each reference reactor and thereby to reduce the number of maintenance plans that must be more fully developed in the sections which follow.

MAINTENANCE PERSONNEL REQUIREMENTS

CASE NO. SC-CUL-3

NO. SECTORS REPLACED – 8 PER OUTAGE WITH 8 EQUIPMENT SETS

13-1641A

VACUUM WALL LOCATION NO. 3
MAX NO. OF DIRECT PERSONNEL: 82

VACUUM WALL LOCATION NO. 3 MAX NO. OF DIRECT PERSONNEL: 82				MAINTENANCE ACTIVITY ITEM														
I T E M NO.	MAINTENANCE EQUIPMENT ITEMS	CREW SIZE	NO. REQ'D	SHUTDOWN REACT	R/I NBI's	R/L POL. MAGNETS	R/I LSAP	R/I SHIELD DOOR	D/R COOLANT MAN	R/I REACTOR MOD.	D/R DIV. MAN.	R/I DIV. MOD	LEAK TEST MAN.	VAL. & STARTUP	INS. MODULES			
1	POLOIDAL CRANE	2	1				X	X				X						
2	TUG VEHICLE	2	8		X		X	X		X		X						
3	OVERHEAD REMOTE MANIPULATOR	1	1								X		X					
4	OPERATIONAL MAINT. UNIT (OMU)	3	6		X													
5	NBI PORT PLUG	1	16		X													
6	NBI PORT PLUG DOLLY	1	8		X													
7	NBI INJECTOR DUCT SLING	1	8				X											
8	NBI INJ. DUCT. T & S DOLLY	1	8				X											
9	LINE CONNECTOR INS/REM TOOL	1	16		X			X			X							
10	IMPACT WRENCH	1	16		X		X	X	X		X							
11	MOBILE MANLIFT. UNIT	1	16		X		X	X										
12	PRIMARY MAINTENANCE MACHINE	4	8				X	X	X									
13	LSAP WORKHEAD	1	8				X	X										
14	LSAP & LSAP W/H T & S DOLLY	1	8				X											
15	SHIELD DOOR WORKHEAD	1	8					X										
16	SHIELD DOOR & W/H T & S DOLLY	1	8					X										
17	AUXILIARY SERVICES WORKHEAD	1	8					X	X									
18	AUX. SERVICES W/H DOLLY	1	8					X	X									
19	He COOLANT MANIFOLD COVER	1	8					X	X									
20	He MANIFOLD COVER DOLLY	1	8						X									
21	REACTOR MODULE TRANSPORTER	1	16							X								
22	DIVERTOR MODULE WORKHEAD	1	8									X						
23	DIV. MOD. W/H DOLLY	1	8									X						
24	DIV. MOD. T & S DOLLY	1	16									X						
25	INSPECTION WORKHEAD	2	4										X			X		
26	INSPECTION WORKHEAD DOLLY	1	4													X		
27	LEAK TEST WORKHEAD	1	16										X					
28																		
29																		
30																		
FLOOR CREW SIZE				0	48	0	32	32	0	0	0	0	0	0	0			
TOTAL DIRECT PERSONNEL				0	82	0	82	50	32	16	1	18	1	0	8			

LEGEND:

R/I = REMOVE/INSTALL
R/L = RAISE/LOWER
D/R = DISCONNECT/RECONNECT
MAN. = MANIFOLD
VAL. = VALIDATE
INS. = INSTALL
DIV. = DIVERTOR
POL. = POLOIDAL

FIGURE 4.1-11

The vacuum wall locations are briefly defined in Table 4.2-1 and further described in Figure 3.2-32, Section 3.2.4. The selection of these locations is discussed in this section along with their impact on the single sector replacement downtimes.

4.2.1 First Wall/Blanket Downtime Summary - The vacuum wall location analysis is conducted through use of the first wall/blanket replacement time estimates. The downtime variation for each vacuum wall arrangement is determined using scheduled and unscheduled maintenance operations and remote and contact maintenance operations.

The first wall/blanket replacement maintenance action is selected for this investigation since it is the most significant scheduled or unscheduled downtime examined thus far in the maintainability studies. That is, it has the largest impact on reactor availability and, consequently, on the cost of electricity. Also,

TABLE 4.2-1
VACUUM WALL LOCATION SCENARIOS

VACUUM WALL ARRANGEMENT NUMBER	REFERENCE REACTOR*	CONFIGURATION
1	UWMAK-III	PRIMARY VACUUM WALL LOCATED AT THE FIRST WALL BLANKET AS DEFINED IN SECTION 3.2.4 AND REFERENCES 4-1 AND 4-2. UNLIKE THE UNIVERSITY OF WISCONSIN DESIGN, NO SECONDARY VACUUM WALL EXISTS AT THE LSAP.
2	UWMAK-III	PRIMARY VACUUM WALL LOCATED AT THE TF MAGNETS AND LSAP WITH A HIGH IMPEDANCE JOINT AT THE FIRST WALL BLANKET.
3	UWMAK-III	PRIMARY VACUUM WALL LOCATED AT THE REACTOR ROOM WALLS WITH A HIGH IMPEDANCE JOINT AT THE FIRST WALL BLANKET. NO VACUUM WALL OF ANY TYPE AT THE TF MAGNETS.
1	GA-DOUBLET	PRIMARY VACUUM WALL LOCATED AT THE FIRST WALL BLANKET AS DEFINED BY THE GENERAL ATOMIC DESIGN IN SECTION 3.2.4, REFERENCES 4-3 AND 4-4.
1	CULHAM	PRIMARY VACUUM WALL LOCATED AT THE OUTER SHIELD DOOR (WELDED), WITH A HIGH IMPEDANCE JOINT AT THE INNER SHIELD.
2	CULHAM	PRIMARY VACUUM WALL LOCATED AT THE LSAP WITH THE OUTER SHIELD DOOR (BOLTED) AND A HIGH IMPEDANCE JOINT AT THE INNER SHIELD AS DEFINED FOR THE CULHAM DESIGN IN SECTION 3.2.4 AND REFERENCE 4-5.
3	CULHAM	PRIMARY VACUUM WALL LOCATED AT THE REACTOR ROOM WALLS WITH A HIGH IMPEDANCE JOINT BOTH AT THE OUTER SHIELD DOOR AND AT THE INNER SHIELD. NO VACUUM WALL OF ANY TYPE AT THE TF MAGNETS. THREE VACUUM ZONES ARE PROVIDED BY THIS ARRANGEMENT.
1	ORNL CASSETTE	THE VACUUM WALL IS LOCATED AT THE TF MAGNETS/LSAP AND EMPLOYS A WELDED SEAL. A HIGH IMPEDANCE JOINT IS LOCATED AT THE CASSETTE/SHIELD ATTACHMENT POINTS.
2	ORNL CASSETTE	THE PRIMARY VACUUM WALL IS LOCATED AT THE TF MAGNETS/LSAP USING A BOLTED JOINT WITH A HIGH IMPEDANCE JOINT AT THE CASSETTE/SHIELD ATTACHMENT POINTS.
3	ORNL CASSETTE	THE PRIMARY VACUUM WALL IS LOCATED AT THE REACTOR ROOM WALLS WITH A HIGH IMPEDANCE JOINT AT THE CASSETTE/SHIELD ATTACHMENT POINTS AS DEFINED IN SECTION 3.2.4 AND REFERENCE 4-6. NO VACUUM WALL OF ANY TYPE IS USED AT THE TF MAGNETS.

*THE REFERENCE REACTOR REFERS TO THE NORMALIZED REACTOR CONCEPT BASED ON THE CONCEPTUAL DESIGN FROM WHENCE THE GENERIC NAME IS DERIVED.

this maintenance action generally determines the concept for maintenance equipment requirements and it is expected that the same basic equipment will, with minor additions and/or modifications, satisfy the other maintainability requirements in the reactor room. The equipment contained in this room is the primary area of interest in any evaluation of vacuum wall location concepts.

Table 4.2-2 is a summary of the total continuous downtime required to replace modules of the first wall/blanket for each of the four reference reactors. This table shows the trends in downtime for the different vacuum wall arrangements with either the maintenance action being unscheduled and involving only a minimum number of modules or with the maintenance action being scheduled and requiring replacement of the modules in a complete reactor sector. The trends for remote and contact maintenance operations can also be compared. The time estimates are based on the assumptions that all services and equipment required are available in any quantity needed, that as many personnel as required are available, that operations are continuous without interruption for breaks, shift change, etc., and no allowances are made for traffic congestion.

The UWMAK-III reference reactor is selected as the baseline and downtime estimates have been made for all options. The UWMAK-III is chosen because this design has been more thoroughly investigated during the earlier study phase and the impact on the time estimates is believed to be more sensitive to design variations, in this case specifically to changes in the vacuum wall location.

From the estimates made for the UWMAK-III reference reactor it is evident that the vacuum wall location resulting in the minimum downtime for all four types of maintenance actions is arrangement number 3 with the primary wall at the reactor room wall. With this as a base, the downtimes have been estimated for the Culham and ORNL Cassette reference reactors primarily for the arrangement with the reactor room wall as the primary vacuum barrier. Since the contact operations indicate the lower downtime requirement compared with fully remote operations, the impact of the various vacuum wall arrangements is also defined for the Culham and ORNL Cassette reactors when conducting this type of maintenance. The other types of operations are believed to indicate no additional trends and are, therefore, omitted from the analysis.

The time estimates for the GA-Doublet configuration are also shown in Table 4.2-2. These are defined only for the vacuum wall arrangement used in the basic GA-DPR conceptual design. This arrangement is the only one considered because

TABLE 4.2-2
FIRST WALL/BLANKET REPLACEMENT TIME SUMMARY FOR VARIOUS VACUUM WALL ARRANGEMENTS

REFERENCE REACTOR CONCEPT (INCLUDING MAINTENANCE SCENARIO)	REPLACEMENT TIME (HOURS: MINUTES) (1) (PRIMARY VACUUM WALL LOCATION) (2)		
	#1 (AT BLANKET)	#2 (AT SHIELD/LSAP)	#3 (AT REACTOR ROOM WALL)
CULHAM			
UNSCHEDULED MAINTENANCE (3)			
CONTACT OPERATIONS	346:00	354:45	314:55
REMOTE OPERATIONS	--	--	444:30
SCHEDULED MAINTENANCE			
CONTACT OPERATIONS	--	--	363:30
REMOTE OPERATIONS	--	--	493:00
UWMAK-111			
UNSCHEDULED MAINTENANCE (3)			
CONTACT OPERATIONS	858:30	783:55	743:25
REMOTE OPERATIONS	1208:40	1155:15	1075:20
SCHEDULED MAINTENANCE			
CONTACT OPERATIONS	753:50	679:25	638:55
REMOTE OPERATIONS	1104:10	1050:45	970:50
ORNL			
UNSCHEDULED MAINTENANCE (3)			
CONTACT OPERATIONS	597:45	555:25	558:45
REMOTE OPERATIONS	--	--	643:05
SCHEDULED MAINTENANCE			
CONTACT OPERATIONS	--	--	810:00
REMOTE OPERATIONS	--	--	994:00
GA-DOUBLET			
UNSCHEDULED MAINTENANCE (3)			
CONTACT OPERATIONS	127:35	--	--
REMOTE OPERATIONS	127:35	--	--
SCHEDULED MAINTENANCE			
CONTACT OPERATIONS	273:40	--	--
REMOTE OPERATIONS	273:40	--	--

(1) TIME IS UNDILUTED, i.e., PRODUCTIVITY FACTOR FOR PERSONNEL IS OMITTED

(2) REFERENCE FIGURE 4.2-1 FOR LOCATION DEFINITIONS.

(3) UNSCHEDULED MAINTENANCE FOR ONE MODULE ONLY, SCHEDULED MAINTENANCE FOR ONE SECTOR.

additional vacuum walls only reduce the requirements imposed on the isolation valves installed at the auxiliary vacuum ports and are assumed to have little effect on the total downtime.

A comparison of these results reveals that the shortest time for the Culham and the UWMAK-III reference reactors occurs when using the reactor room wall as the primary vacuum barrier. For the ORNL Cassette concept the shortest time occurs when using the Lateral Support Access Panel (LSAP) between the TF coils as the primary vacuum wall, although, this time differs little from that required when the primary vacuum barrier is at the reactor room wall.

While this analysis is based on time estimates only, further design study of the impacts of the vacuum wall requirements on the reactor room wall construction and entry doors is necessary to define the total cost impact of using the reactor room as the secondary vacuum chamber. Similarly, other design alternatives, such as the use of state of the art seals or welded joints to install the isolation valve in the GA-Douplet auxiliary vacuum line will impact the cost as well as the times estimated and should be given further consideration before selecting a vacuum wall configuration.

In general, if the use of double vacuum chambers, or even triple vacuum chambers as found in the Culham reference reactor arrangements, allows the use of seals closer to the state of art and mechanical instead of welded assembly methods then these techniques result in significantly decreased downtime and may warrant the additional capital cost of the reactor. The maintenance operations and design variations for each reference reactor are described briefly in the following paragraphs.

4.2.2 UWMAK-III Vacuum Wall Location Impacts - The vacuum wall arrangement number 1 most closely approaches the original design concept insofar as maintenance operations are concerned since the principle vacuum wall is at the back of the first wall/blanket and the connecting joints are bolted with a welded seal. Also, the Lateral Support Access Panels (LSAP's) are bolted in place. While no seal is required at the LSAP and no secondary vacuum chamber is used as required by the original UWMAK-III concept, the access operations are virtually unchanged.

The second level functional sequences for the maintenance operations required by this vacuum wall arrangement are included in Tables A-1 through A-4, Appendix A. The principal variation in the maintenance operations from those used in the earlier study phase is the removal and installation of the neutral beam injectors

(NBI's) instead of the RF heaters. The removal of the NBI's, however, is similar to their removal for the UWMAK-I reactor (Reference 4-1) and the time estimates made for the UWMAK-I are used as a base.

The times estimated for the removal of the LSAP and the "A" module in the outside reactor wall are 13.5 and 65.5 hours, respectively, when using contact maintenance operations and 34.3 and 65.5 hours, respectively, when using remote maintenance operations. The location of the welded seal requires remote maintenance in both scenarios to avoid radiation exposure when removing the "A" module.

When the vacuum wall arrangement number 2 is used (see Table A-5 through A-8, Appendix A), the welded seal cap around the "A" module no longer is present and only the bolts are removed. This reduces the "A" module removal time to 32.5 hours for either contact or remote operations. Similarly, replacement of the "A" module is reduced from 106.0 to 75.25 hours. The requirement for a sealed joint in the LSAP, on the other hand, increases the LSAP removal time from 13.5 to 16.5 hours and the replacement time from 18.75 to 21.75 hours for contact maintenance operations. For remote maintenance operations the removal time increases from 34.3 to 43.5 hours and the replacement time from 63.9 to 82.5 hours. The replacement times for the "B" modules and divertor modules are affected in the same manner. In addition to these time changes a slight penalty exists, which is estimated at four hours, when starting the reactor in order to test, prepare and pump down the secondary vacuum chamber associated with this vacuum wall arrangement.

The use of the vacuum wall arrangement number 3, which requires seals for neither the first wall/blanket modules nor the LSAP's but has the primary seal at the reactor room wall, reduces the operating times even further. Tables A-9 through A-12, Appendix A, show that the LSAP removal and replacement times are the same as for arrangement number 1 but the time reduction in module removal and replacement achieved by arrangement number 2 is still valid. Additional time savings are realized by combining the neutral beam duct removal and replacement with the LSAP operations since a sealed connection to neither the LSAP nor the "A" module is required. The time is increased for startup from 24 to 36 hours in order to more effectively seal the reactor room and pump it down to operating pressures. The equipment and time requirements for accomplishing this pump down are defined in Section 3.2.4. While the additional pump power required is approximately 13,500 HP this total power is not continuously required after arriving at operating pressures. The increase in recirculated power is considered relatively insignificant.

The functional sequence variations required for these three vacuum wall arrangements are relatively minor except for the variation in the pumpdown and validation of the vacuum chambers. A preliminary vacuum check is considered essential when a welded seal is required because of the time required for setup and reaccessing the joint. This procedure requires that a plug be installed in the NBI port and then the vacuum check is made. Since the primary vacuum barrier is at the LSAP in arrangement number 2 the difference is small between preparation for this test by inserting the plug or installing the NBI, which is the next step, so the test is delayed until reactor verification and startup with a net reduction in time. For arrangement number 3, the test cannot be conducted until the reactor room is sealed and, therefore, the preliminary test is omitted in this sequence also.

4.2.3 Culham Vacuum Wall Location Impacts - The vacuum wall locations used for the Culham reference reactor have been examined only for the unscheduled contact maintenance scenario but the time relationships between unscheduled and scheduled maintenance, and between contact and remote maintenance are expected to be similar to those that exist for the UWMAK-III configuration.

The vacuum wall arrangement number 2 used for the Culham analysis approaches that defined for the original concept. Table A-14, Appendix A, defines the functional sequence for maintenance operations with this wall arrangement. In this arrangement both the outer shield doors and the LSAP's are bolted in place with the seal at the LSAP's. The original concept employs a seal at the shield door and uses cooled intercostal members, which must be removed, instead of the LSAP's. This current arrangement is used in order to be similar to the other reference reactors for comparison purposes. The LSAP concept is selected because, if feasible, it is relatively simple to remove and install and serves the dual purpose of a vacuum barrier as well as reacting the magnet lateral loads. This concept effectively defines three vacuum chambers, namely, the plasma chamber, the space between the inner shield and the outer shield and the space between the outer shield and the TF coils. Two of the vacuum walls, i.e., the inner shield and the outer shield, are provided with only high impedance joints with only the outer shield being structurally connected to the reactor frame.

In this reactor concept, the significant maintenance operations influenced by the vacuum wall arrangement are the removal and installation of the shield doors, the LSAP's and the NBI beam ducts. These require 15.25, 15.6 and 18.9 hours,

respectively, for removal and 21.3, 26.9 and 20.1 hours, respectively, for replacement of each door, LSAP and NBI beam duct. These times change significantly for the other vacuum wall arrangements.

For the vacuum wall arrangement number 1, the shield door is assumed to require a welded seal in addition to the bolts in order to achieve the vacuum chamber integrity. The LSAP is only required to take structural loads. The NBI beam duct is sealed at the entry to the outer shield door and not attached to the LSAP. Thus, only one disconnect need be made to remove the NBI and then the LSAP at any sector. This arrangement results in only two vacuum chambers, namely, the plasma chamber and the space between the inner and outer shields.

The time estimates and functional sequence for this arrangement are defined in Table A-13, Appendix A. The time required for removal and installation of the NBI beam duct is eliminated and the times for removal and installation of the LSAP without a seal are reduced from those required for arrangement number 2 to 12.5 and 17.5 hours respectively. The installation of the welded seal at the outer shield door increases the removal and installation times to 22.3 and 37.0 hours, respectively. The startup time is assumed to decrease from 28.0 to 24.0 hours because of the smaller secondary vacuum chamber. The net result of these time variations is a decrease in time for the use of the vacuum wall arrangement number 1.

The vacuum wall arrangement number 3 uses the reactor room wall as the primary vacuum barrier with high impedance joints both at the inner shield and at the outer shield in each sector. The LSAP is only used to react lateral loads from the TF coils. Thus, three vacuum chambers are formed as for arrangement number 2 with the outer chamber extending to the reactor room wall. The functional sequence and time estimates for this arrangement are shown in Figure A-15, Appendix A. This arrangement allows the time for the LSAP and NBI beam duct replacement to be reduced to that required by arrangement number 1 and the outer shield door replacement times for arrangement number 2 to be used. The only time increase is the validation and startup time which requires 36.0 hours for the same reasons as the UWMAK-III arrangement number 3.

Also, as for the UWMAK-III, arrangements number 2 and 3 do not provide potential time savings (arrangement number 2) or the opportunity for the preliminary vacuum chamber test (arrangement number 3). Therefore, for these arrangements this test is delayed until the verification operation with slightly increased risk for a rework. However, this risk may be negated because the vacuum seal requirements are not quite so stringent with these arrangements. On the other hand, the potential

benefit of this test when using two chambers in arrangement number 1 is deemed significant enough to include the preliminary vacuum test for this arrangement.

4.2.4 ORNL Cassette Concept Vacuum Wall Location Impacts - Vacuum wall locations for the ORNL Cassette reference reactor have been examined only for the unscheduled contact maintenance scenario. This limitation is the same used for analysis of the impacts on the Culham reference reactor and, here too, the time variations between scheduled and unscheduled and between contact and remote are believed to illustrate similar impacts from varying the vacuum wall location to those evidenced by the examination of the unscheduled contact maintenance. Unscheduled contact maintenance scenarios are chosen because Table 4.2-1 indicates the contact maintenance times are less than those achieved with remote maintenance operations and the unscheduled maintenance impacts require the evaluation of only one reactor sector.

Vacuum wall arrangement number 3 is that defined for the ORNL Cassette concept in the original study, Reference 4-6. Table A-21, Appendix A, defines the functional sequence for maintenance operations with this wall arrangement. When the primary vacuum barrier is at the reactor room wall, the LSAP's are not sealed. This arrangement results in two vacuum chambers in the reactor room, namely, the reactor room and the plasma chamber. Also, this arrangement requires that the plasma chamber vacuum verification test is incorporated in the verification and startup procedure with the relative risk considerations the same as those discussed for the UWMAK-III analysis. The time required for these variable operations are 9.1 hours for LSAP removal and 14.25 hours for installation. Verification and startup requires 36.0 hours primarily because of the increased time to pump down the reactor room.

The endeavor to reduce the maintenance time for first wall/blanket replacement by moving the primary vacuum barrier closer to the plasma chamber led to sealing the LSAP's mechanically in wall arrangement number 2. This is similar to arrangement number 2 for the UWMAK-III and the Culham reference reactors since multiple vacuum chambers are employed and the inner chamber requires only high impedance joints for the cassettes. When this arrangement is employed, the level 2 functional sequence is as shown in Table A-20, Appendix A. The time for removal of the LSAP is increased to 11.8 hours and for installation to 16.4 hours. These times, coupled with the reduction of the time to verify and startup to 28.0 hour, result in a net total time of 3.3 hours less than the time required for arrangement number 3.

The vacuum wall arrangement number 1 also uses the LSAP as the primary vacuum barrier but assumes that either the mechanical LSAP seals in arrangement number 2 or the sealing of the joints at the cassette shield blocks is impractical and, therefore, a welded seal is used at the LSAP. In this reactor concept a primary barrier inside of the LSAP does not appear practical since sealing of the cassettes is quite complex, as discussed in Section 3.2.1, and since the shielding is not divided to allow a secondary barrier zone. The functional sequence for this arrangement is shown in Table A-19, Appendix A.

In arrangement number 1 the time required for removal of the LSAP's is increased to 15.1 hours and for installation to 31.25 hours. The verification and startup estimate is the same as for arrangement number 2 because the secondary vacuum chamber is the same size. In addition, the preliminary vacuum test is conducted before completion of the assembly. These factors all result in a relatively large increase in downtime (7 percent or 39.0 hours) over arrangement number 3.

4.2.5 Maintenance Equipment Requirements - The variations employed for the vacuum wall arrangements of all reference reactor concepts utilize only the structure or barriers already included in each reactor concept. For this reason, additional movement of large components is unnecessary for any of the concepts. Therefore, the major equipment concepts which dominate the maintenance procedures and equipment costs are unchanged with the various vacuum wall locations considered in this study.

Minor equipment variations are required for installation of seals, welding joints, testing and other small tool or workhead variations. These equipment requirements all appear feasible even though the items have yet to be defined. Cost changes have not been included to incorporate the effects of such minor changes.

4.3 UNSCHEDULED MAINTENANCE PLANS - The effects of unscheduled maintenance on the selection of desirable maintainability features are to be defined. To provide the necessary basis for this definition, maintenance plans are developed for unscheduled maintenance actions for each reference reactor concept. The principal subsystem that varies in its maintenance requirements among the reference reactor concepts and for which unscheduled maintenance can be a significant factor is the first wall/blanket. While the unscheduled maintenance of other subsystems also is discussed later in Section 4.6, this has a relatively common impact on all reactor concepts. Therefore, the consideration of first wall/blanket impacts

is used to compare the relative impact of unscheduled maintenance on the reference reactors.

The occurrence of a small leak in a first wall module is considered representative of a typical failure mode resulting in a forced outage situation. This type of failure is also one of the more difficult and time consuming situations to correct on an unscheduled basis.

The failure mode involving a small leak in a first wall module is employed as the basis for an unscheduled outage for each of the four reactor concepts evaluated in this study. In all cases, the assumption is made that the leak is detectable and capable of being isolated at least to one reactor sector by diagnostic instrumentation built into the reactor in the vacuum pumping and heat transport systems. Another implied assumption is that the frequency of failure is the same for all reactor concepts and is independent of vacuum wall location.

A plan has been developed for each reference reactor concept to conduct the exchange of the failed first wall module as quickly as possible. The maintenance equipment concepts developed to implement planned activities for an unscheduled reactor module replacement have also been developed. It is desired that the equipment defined for these concepts are also useful for scheduled first wall/blanket module exchanges. Also for each reference reactor, a maintenance plan and associated timelines have been developed for each concept variation where the location of the primary vacuum wall can have an impact on unscheduled outage times.

The following paragraphs define the essential characteristics of the plans developed for determining the first wall/blanket unscheduled maintenance requirements of each reference reactor.

4.3.1 Culham Concept Unscheduled Maintenance Plans - The Culham unscheduled maintenance plan is based on the activity sequence presented in Table 4.3-1. The activities must be performed in the sequence indicated to exchange a failed divertor module in one sector of the reactor in either the partial contact or fully remote maintenance scenarios.

The general assumptions made concerning the Culham reactor and the unscheduled maintenance events are as follows:

- o Reactor sector modules and divertor modules are exchanged as a unit and removed to hot cells. No attempt is made to repair individual modules or wall sections in-place.
- o Spare reactor components are available on demand.

TABLE 4.3-1
CULHAM UNSCHEDULED MAINTENANCE
ACTIVITY SEQUENCE

LEVEL 1 ACTIVITY	LEVEL 2 MAINTENANCE ACTIVITY
SHUTDOWN	SHUTDOWN REACTOR ISOLATE LEAKING MODULE
GAIN ACCESS	REMOVE NBI RETRACT POLOIDAL MAGNET REMOVE LATERAL SUPPORT ACCESS PANEL REMOVE SHIELD DOOR DISCONNECT MODULE COOLANT MANIFOLD
REMOVE	REMOVE REACTOR MODULE DISCONNECT DIVERTOR MODULE MANIFOLD REMOVE DIVERTOR MODULE
REPLACE	REPLACE DIVERTOR MODULE REPLACE REACTOR MODULE
REASSEMBLE	CONNECT DIVERTOR MODULE MANIFOLD CONNECT REACTOR MODULE COOLANT MAINFOLD PRESSURIZE COOLANT MANIFOLDS & LEAK TEST REPLACE SHIELD DOOR REPLACE LATERAL SUPPORT ACCESS PANEL REPOSITION POLOIDAL MAGNET REINSTALL NBI
STARTUP	VALIDATE REACTOR SYSTEMS VACUUM CHECK PLASMA CHAMBER & RR STARTUP REACTOR

- o Access to reactor components is from the side of the reactor using maintenance machines that operate on radial tracks at each reactor sector.
- o The Neutral Beam Injectors are normally positioned on these radial tracks and can be disconnected and removed as a unit. The NBI's are shielded in the case of contact maintenance.
- o Contact maintenance is permissible for activities through the removal of the lateral support access panel and up to the point where the outer shield door movement is initiated. After completion of this activity, all exchange operations must be performed remotely until the shield door is in place again.

- o The shield panel immediately behind the LSAP is of sufficient thickness to protect the personnel who are in contact with the reactor exterior.
- o The large helium supply duct to the reactor module sector has a mechanical joint. The lower half of the duct retracts automatically into the reactor support structure to clear an egress path for the reactor module.
- o The reactor module rests on wheels or slides which enable the module to be extracted radially onto a transporter device. The force required to translate the reactor module laterally is provided by a mechanism on the transporter.
- o The divertor module inlet and outlet manifolds are disconnected at the top of the reactor. The divertor module is secured and lowered by maintenance equipment.
- o All PF coils which interfere with the reactor module egress route can be raised or lowered automatically from the reactor control room. All power leads and coolant lines, remain connected during the operation.
- o All reactor components, such as modules, shield doors, LSAP's, NBI's, etc. are assumed to be interchangeable.
- o For an unscheduled outage caused by a failure in a first wall module, the certain reactor subsystems, such as the helium coolant supply to the divertor modules and vacuum pumping system, must remain operational on a sector basis to isolate a leaking module.
- o Maintenance floor crews are available on an as required basis for contact maintenance activities.
- o No other contingencies or unplanned events occur during the unscheduled maintenance activity.
- o All maintenance activity times presented in this section are given without including time dilution factors. Dilution factors are applied and used in later sections to calculate availabilities and evaluate maintenance scenarios.

4.3.1.1 Summary of Alternative Plans for the Culham Reference Reactor - Four alternate maintenance timelines have been developed for the Culham reactor, involving three different vacuum wall arrangements for contact maintenance and one vacuum wall arrangement for remote maintenance. These results are presented in Table 4.3-2.

The lowest total outage time estimate for contact maintenance is the case where the primary vacuum wall is located at the reactor room wall. (Arrangement

TABLE 4.3-2
UNSCHEDULED CULHAM MAINTENANCE PLAN SUMMARY

MAINTENANCE TYPE		VACUUM WALL ARRANGEMENT	NUMBER OF SECTORS WORKED	NUMBER MODULES REPLACED/ OUTAGE	NUMBER OF MAINTENANCE EQUIPMENT SETS	NUMBER OF DIRECT PERSONNEL	TOTAL OUTAGE TIME (HRS)	LOST REVENUE COST (MILLIONS OF \$)
CONTACT	REMOTE							
✓		1	1	1	1.005	12	346.00	16.7
✓		2	1	1	1.005	12	354.75	17.2
✓		3	1	1	1.005	12	314.90	15.2
	✓	3	1	1	1.005	8	444.50	21.5

NOTE: 1) ONE MAINTENANCE EQUIPMENT SET WEIGHT = 3310.80 TONNES
2) OUTAGE TIME SHOWS UNDILUTED HOURS.

No. 3.) Time reductions result from the situation where both the shield door and the LSAP are mechanically attached to support structure. There are no welds or seal joints which require validation upon reassembly. Note, however, that the time difference for scenarios with different vacuum wall arrangements is not great. The cost of the reactor room is kept constant in this analysis since many other considerations, such as the need for tritium confinement, will influence the cost in addition to the vacuum requirements.

Similarly, the lowest total outage time for remote maintenance is assumed to be the case where the primary vacuum wall is located at the reactor room wall. Remote maintenance downtimes are longer than downtimes when using contact maintenance because of the requirements for removing and reinstalling the NBI's and LSAP's in a completely remote mode. Since these activities are essentially independent of vacuum wall location, the remote maintenance timelines for vacuum wall arrangements 1 and 2 have been omitted.

Table 4.3-2 also shows, for comparison purposes only, the cost of the postulated unscheduled outage in terms of lost revenue calculated on the basis of 48,393 \$/hr for the Culham reactor. This cost is calculated from the simplified equation:

$$\text{Cost/hr} = \frac{\text{Total Annual Cost}}{\text{Hours/Year} \times \text{Availability}}$$

The total annual cost is defined by the TOCOMO code for the optimum scheduled maintenance plan as defined in Section 4.4 and the availability for this plan is used also.

The functional sequence listed in Table 4.3-1 is used for the unscheduled maintenance plans depicted in the following sections. A brief description of each level 2 function is given only for this scenario to provide a better understanding of the operations conducted during each function. This type of detail also applies generally to the other reference reactor scenarios with variations as required by design differences. The major items of maintenance equipment referenced in these descriptions are described in more detail in appendix B.

o Shutdown

- o Shutdown Reactor - This activity initiates the unscheduled outage. The shutdown is completely controlled from the reactor control room and utilizes only built in reactor control systems. Shutdown includes time to remove heat from the first wall, bleed energy from the magnet systems, process tritium out of the reactor vacuum pumping and heat transport systems, and otherwise prepare the reactor and facility for maintenance.
- o Isolate Leaking Module - This activity is also assumed to be an automatic function using diagnostic instrumentation built into the reactor vacuum pumping subsystems. The capability to shut off helium coolant to each reactor sector is assumed. It is also assumed that, by sequentially pressurizing each reactor sector coolant system, the leak detectors in the plasma chamber vacuum ducts will isolate a leak to a specific sector.

o Gain Access

- o Remove NBI - Each NBI is assumed to be a modular unit mounted on radial tracks emplaced in the reactor room floor. The NBI regeneration duct, and beam duct, both of which are assumed to be contaminated with radioactive debris, are remotely disengaged and reconnected. Other service lines and power leads to the NBI are disconnected manually in the case of contact maintenance but the NBI's must be shielded extensively. For completely remote maintenance all NBI service disconnects and reconnections are made by remote maintenance equipment. The NBI is moved to storage in a hot cell area by a tug vehicle. In those scenarios where the LSAP is assumed to form the primary vacuum barrier, the NBI beam duct is disconnected at an isolation valve in front of the LSAP. Where the reactor room acts as a large vacuum chamber, the LSAP is assumed to be open structure and the beam duct is disconnected at a joint on the shield door.

- o Retract Poloidal Field Magnets - This activity is assumed to be a completely automatic function which is initiated from the reactor control room, and utilizes a retraction system built into the reactor. The magnets are raised or lowered in parallel with other maintenance events in order to clear an egress path for the reactor module. It is also assumed that disconnection of the poloidal field magnet power and coolant leads is not required in order to retract the magnets, that the retraction mechanism is self-locking, and that the retraction mechanism provides adequate structural support for the magnets in the operational position.
- o Remove Lateral Support Access Panel (LSAP) - The LSAP is a structural element with an estimated weight of 90 tonnes which is positioned between the TF coils. The LSAP's are handled by a workhead attached to a radial translation carriage. The radial translation carriage moves radially in and out from the reactor center on the reactor room floor and is moved circumferentially around the reactor room on a circumferential translation carriage. The workhead provides the remotely operated tools necessary to remove or install attachment fasteners. The workhead and LSAP may be picked up as a unit by the overhead crane and moved to a transfer dolly to expedite reactor disassembly.
- o Remove Shield Door - The shield door is a nonload bearing component with an estimated weight of 105 tonnes which, like the LSAP, is also positioned between the TF coils.

All shield doors are assumed to have a common interface with a workhead, and all doors are assumed to be attached to supporting structure with mechanical fasteners in this scenario. The shield door workhead, although dedicated to handling, removing and installing the door, functions in the same manner as the LSAP workhead.

The shield doors are assumed to be cooled by gaseous helium. Remotely controlled manipulator arms, are used to disconnect and reconnect the GHe coolant lines to the shield for the remote maintenance case. This activity is accomplished manually in the contact maintenance scenarios.

- o Disconnect Reactor Module Coolant Manifold - The large helium coolant supply/return manifold immediately in front of the reactor module is assumed to have a mechanical disconnect joint which is installed or removed remotely. The lower half of the manifold is assumed to automatically

retract into the reactor support structure to clear an egress path for the reactor module. A cover plate is remotely installed over the opening created by the retracted manifold. This cover may also have to incorporate a segment of track for reactor module egress.

o Removal

- o Remove Reactor Module - The reactor module slides or rolls into its nested operational position on ways or wheels. The module is assumed to be supported on mechanical jacks during operation to relieve loads on the track structure to prevent permanent deformation.

The reactor module is removed from its nested position and rolled onto a transfer device. This transporter operates on the same tracks as used by the radial translation carriage which transports the LSAP and shield door. The transporter interfaces with the circumferential translation carriage in the same manner as the radial transporter. The transporter concept incorporates a module retraction mechanism, which attaches to the reactor module and provides the mechanical force necessary to insert or withdraw the module from its operational position.

In all scenarios, the reactor module exchange operation is performed remotely. The transporter may have built-in motive capability or can be moved along the radial tracks by a tug vehicle.

- o Disconnect Divertor Module Manifolds - The divertor module helium coolant manifolds exit at the top of the reactor between cryovacuum pumping units. The top of the reactor is inaccessible to maintenance personnel, and an overhead remotely controlled manipulator is used to disconnect and reconnect these manifolds in parallel with other maintenance units.
- o Remove Divertor Module - The divertor module is highly irradiated and must be handled remotely in all cases. A divertor module workhead, is extended into the cavity created by the removal of the reactor module, and expands upward to the vicinity of the divertor module. The workhead then releases mechanical fasteners, and lowers the module for retraction. Once retracted, the overhead crane is used to off-load the expended module and place a new module on the workhead.

- o Replace, Reassemble, and Startup - The maintenance tasks and techniques used to reassemble the reactor sector utilize the same equipment and

similar procedures to those described for disassembly. Several additional activities are required to verify the integrity of the reactor.

- o Pressurize Coolant Manifolds and Leak Test - This activity is required to validate the integrity of the reactor module and divertor module helium coolant systems. This is accomplished by pressurizing the reactor sector to proof pressure after reassembly and checking for leaks around joints remotely using probes positioned by the maintenance equipment. This check must be performed before the shield door is reinstalled.
- o Vacuum Check Plasma Chamber and Reactor Room - A seal check is essential for all scenarios. The assumed procedure is to reinstall the shield door, LSAP or reactor room door, whichever forms the primary vacuum wall, and then pump the plasma chamber and secondary chamber down using the operational evacuation and cryovacuum pumping system. Built-in pressure monitors should enable control room personnel to verify the chamber integrity. It is assumed that bakeout of the chamber is not required in conjunction with this check.

In those scenarios where the primary vacuum wall is located at the reactor room wall, a vacuum check of the reactor room is performed during reactor room pump down. Since the reactor room seals broken during maintenance are presumably limited to access door penetrations, it is assumed that the potential leak paths are accessible and repairable from outside the room by contact maintenance.

4.3.1.2 Minimum Cost Maintenance Plan using Contact Maintenance - The minimum cost maintenance plan for unscheduled maintenance using contact maintenance operations where feasible occurs when the primary vacuum wall is at the reactor room wall. An abbreviated level 2 timeline for this case is shown in Figure 4.3-1. The times shown summarize the level 2 estimates presented in Appendix A, Figure A-15. Where possible, time estimates were extrapolated from work done in Phase I of this study, with appropriate reductions to account for the change in reactor size.

The Culham minimum cost maintenance plan follows the generalized functional sequence outlined in Table 4.3-1 with the following specific selections of scenario assumptions.

- o The outer shield door provides only a high impedance joint between the inner plasma chamber and the reactor room.

CULHAM REFERENCE REACTOR MAINTENANCE SCENARIO — UNSCHEDULED CONTACT MAINTENANCE

FIGURE 4.3-1

- o The primary vacuum wall is at the reactor room wall. The pressure in the reactor room is maintained at 10^{-4} torr during reactor operation.
- o The lateral support access panel between the TF coils is an open structure.
- o The LSAP has an opening large enough to accept the NBI beam duct, such that the beam duct can be disconnected at the shield door and removed with the NBI.
- o There is no validation and leak check of seals conducted on the shielded door until after reassembly is completed and the reactor room is sealed.
- o The vacuum integrity of the reactor room is validated as a parallel function during the 36:00 hour reactor startup period.
- o Contact assistance is used to disconnect/reconnect the NBI coolant and power leads, and the shield door and LSAP fasteners. All other maintenance operations are performed remotely. NBI regeneration ducts and deuterium supply lines are disconnected remotely. NBI's reside in shielded enclosures to protect floor crews during contact maintenance activities.

The unscheduled operations require a total of 12 men directly engaged in the replacement of the divertor module (Table 4.3-2). These men are supported by the permanent plant maintenance and operating crew. The twelve men include 8 machine operators for the major maintenance equipment, the tug and the overhead crane and a floor crew of 4 to conduct the manual operations that assist the maintenance equipment.

Table 4.3-2 also indicates that 1.005 sets of equipment are required to conduct this unscheduled maintenance action. This reflects the requirement for two units of several equipment items and the addition of mobile manlift units for movement of the floor crew around the reactor. The divertor module transport dolly is not required since the module is removed while still attached to the workhead to reduce the time requirements.

4.3.1.3 Minimum Cost Maintenance Plan Using Remote Maintenance - The minimum cost maintenance plan for the unscheduled exchange of a leaking divertor module when using only remote maintenance operations has also been defined. The abbreviated level 2 timeline for this case is shown in Figure 4.3-2. As in the case of partial contact maintenance, the scenario where the vacuum wall is at the reactor room wall is believed to produce the lowest total outage time.

**CULHAM REFERENCE REACTOR MAINTENANCE SCENARIO
- UNSCHEDULED REMOTE MAINTENANCE**

FIGURE 4.3-2

For remote maintenance operations the only additional direct maintenance personnel required are the 8 maintenance equipment operators (Table 4.3-2). No additional support floor crew is required other than those available from the regular plant maintenance and control room personnel.

The number of maintenance equipment sets required as indicated in Table 4.3-2 is 1.005 which is the same as indicated for the contact maintenance scenario. Actually the mobile manlift units are omitted but the effect is negligible.

The remote maintenance plan follows the contact assisted maintenance plan exactly, except that longer downtimes are required to accomplish the following functions remotely.

- o Disconnect and reconnect the NBI services.
- o Remove and reinstall the shield door fasteners.
- o Remove and reinstall the lateral support access panel fasteners.

In the totally remote case, the Neutral Beam Injector units do not require additional shielding for personnel protection.

4.3.1.4 Culham Maintenance Equipment Concept - The maintenance equipment required to exchange the first wall/blanket of the Culham reference reactor in the manner defined by the functional sequences discussed in the previous sections is summarized in Table 4.3-3. One item of each piece of equipment in this table represents one set of equipment for the Culham reference reactor. This maintenance equipment summary lists all equipment that has been identified as being required to perform either unscheduled or scheduled maintenance on the first wall/blanket of the Culham reactor. It gives a brief description of the function of each item and defines certain characteristics of the equipment, such as lifting capability, operating location, size, and weight.

A more detailed functional description and a list of performance requirements for selected equipment items is provided in Appendix B. Other items of equipment not included in Appendix B are similar to equipment listed in the report of the previous study phase (Reference 4-1).

The maintenance equipment concept represented by the list of equipment in Table 4.3-3 is designed to the following ground rules.

- o The Primary Maintenance Machine (PMM) shown in Figure 4.3-3 is the key maintenance item and is typical of the equipment design approach used for the Culham reference reactor. Most of the other machines which handle reactor components work in conjunction or interface with the PMM. The PMM consists of two essential mechanisms. A radial carriage moves workheads and components to or away from the reactor. A circumferential translation carriage moves the radial carriage plus workheads and reactor component around the reactor room to exit doors.
- o The overhead crane augments the PMM capability and speeds up module exchange activity by exchanging workheads on the PMM, removing used components from workheads, emplacing new components, and otherwise easing traffic-congestion in the reactor room during multiple module exchange.

TABLE 4.3-3
CULHAM MAINTENANCE EQUIPMENT SUMMARY

ITEM DESIGNATION	MAJOR FUNCTION	OPERATING LOCATION	LIFTING CAPABILITY	SIZE (L X W X H)	WEIGHT (KG)
POLOIDAL CRANE	REMOVE/INSTALL CRYOPUMPS AND OTHER REACTOR COMPONENTS DURING INITIAL ASSEMBLY & MAINT.	REACTOR ROOM OVER REACTOR	170 TONNES	100m X 6.0m X 12.0m	4980 TONNES
TUG VEHICLE	PROVIDES MOTIVE POWER TO MOVE NBI'S, REACTOR MODULE TRANSPORTER & VARIOUS DOLLIES	REACTOR ROOM, HOT CELL, & STORAGE AREAS	N/A	9.45m X 6.0m X 4.0m	80 TONNES
OVERHEAD REMOTE MANIPULATOR	REPLACE PARTICLE COLLECTOR PLATES AND DISCONNECT DIV. MODULE COOLANT MANIFOLDS	REACTOR ROOM OVER REACTOR	4 TONNES	100m X 4.0m X 8.0m	1660 TONNES
OPERATIONAL MAINTENANCE UNIT (OMU)	DISCONNECTS NBI REGEN- ERATION DUCTS, INJECTOR DUCT, & SERVICE FITTINGS. INSTALLS NBI BEAM LINE PORT PLUGS	REACTOR ROOM	1300 kg	14.0m X 6.5m X 4.5m	77.5 TONNES
NBI PORT PLUG	SEAL THE END OF THE NBI BEAM LINE DUCT AFTER DISCONNECT	REACTOR ROOM	N/A	1.0m DIA X 50cm THICK	1.25 TONNES
NBI PORT PLUG DOLLY	TRANSLATES NBI PORT PLUGS BETWEEN THE MAINT. EQUIP. STAGING AREA & THE REACTOR ROOM	REACTOR ROOM, MAINT. EQUIP. STAGING AREA	SUPPORTS 7.5 TONNES (6 NBI PORT PLUGS)	6.0m X 1.0m X 1.0m	.5 TONNES (EMPTY) 8.0 TONNES (LOADED)
NBI INJECTOR DUCT SLING	SUPPORTS & HOLDS THE NBI INJECTOR DUCT DURING INSTALLATION & REMOVAL. INTERFACES WITH BOOM ARM ON ASW	REACTOR ROOM, HOT CELL	10 TONNES	4.0m LONG X .5m WIDE	1 TONNE (EMPTY) 11 TONNES (LOADED)
NBI INJECTOR DUCT TRANSPORT & STORAGE DOLLY	TRANSPORTS INJECTOR DUCT BETWEEN REACTOR ROOM & HOT CELL. HOLDS DUCT DURING STORAGE.	REACTOR ROOM, HOT CELL, & STAGING AREA	10 TONNES	4.5m LONG X 1.5m WIDE X .5m HIGH	2 TONNES (EMPTY) 12 TONNES (LOADED)
LINE CONNECTOR INSTALLATION/ REMOVAL TOOL	OPERATES QUICK-DISCONNECT FITTINGS ON NBI'S. INTERFACES WITH OMU.	REACTOR ROOM	N/A	40cm X 10cm X 35cm	200 kg
IMPACT WRENCH	AUTOMATED DEVICE WHICH REMOVES/INSTALLS LARGE FASTENERS. USED IN CONJUNCTION WITH OMU & PPM WORKHEADS	REACTOR ROOM BETWEEN T.F. COILS	N/A	70cm X 25cm X 33cm	400 kg
*MOBILE MANLIFT UNIT	PROVIDES MANNED ACCESS TO TOP OF NBI'S, FASTENERS ON LSAP, He MANIFOLDS, ETC.	REACTOR ROOM	SUPPORTS 1.0 TONNE	6.58m X 4.25m X 3.0m (COLLAPSED)	6.12 TONNES
PRIMARY MAINTENANCE MACHINE (PPM)	SUPPORTS VARIOUS WORK- HEADS FOR THE REMOVAL/ INSTALLATION OF THE LSAP, SHIELD DOOR, He DUCT COVER, ETC.	ANNULAR REGION AROUND REACTOR ROOM & BETWEEN T.F. COILS	SUPPORTS UP TO 150 TONNES	11.0m X 4.3m X 14.0m	250 TONNES (EMPTY) 430 TONNES (LOADED)
LATERAL SUPPORT ACCESS PANEL (LSAP) WORKHEAD	REMOVES & INSTALLS THE LSAP. REMAINS ATTACHED TO THE LSAP DURING TRANSIT & STORAGE. INTERFACES WITH PPM.	REACTOR ROOM, STAGING, & STORAGE AREA	SUPPORTS LSAP @ 100 TONNES	3.0m X 4.3m X 16.5m	70 TONNES (EMPTY) 170 TONNES (LOADED)
LSAP & LSAP WORKHEAD TRANSPORT AND STORAGE DOLLY	TRANSLATES THE LSAP & LSAP WORKHEAD BETWEEN THE REACTOR ROOM & STORAGE/STAGING AREA	REACTOR ROOM, STORAGE & STAGING AREAS	SUPPORTS 170 TONNES	13.5m X 5.0m X 2.0m	50 TONNES (EMPTY) 230 TONNES (LOADED)
SHIELD DOOR WORKHEAD	REMOVES & INSTALLS THE SHIELD DOOR. REMAINS ATTACHED TO THE SHIELD DOOR DURING TRANSIT & STORAGE. INTERFACES WITH PPM.	REACTOR ROOM & HOT CELL	SUPPORTS SHIELD DOOR @ 220 TONNES	3.0m X 4.3m X 15.0m	75 TONNES (EMPTY) 295 TONNES (LOADED)

**TABLE 4.3-3
CULHAM MAINTENANCE EQUIPMENT SUMMARY (CONTINUED)**

ITEM DESIGNATION	MAJOR FUNCTION	OPERATING LOCATION	LIFTING CAPABILITY	SIZE (L X W X H)	WEIGHT (kg)
SHIELD DOOR & SHIELD DOOR WORKHEAD TRANSPORT & STORAGE DOLLY	TRANSLATES THE SHIELD DOOR & SHIELD DOOR WORKHEAD BETWEEN THE REACTOR ROOM & HOT CELL	REACTOR ROOM, HOT CELL, AND STORAGE AREA	SUPPORTS SHIELD DOOR AND SHIELD DOOR WORK- HEAD @ 295 TONNES	11.0m X 5.0m X 2.0m	70 TONNES (EMPTY) 365 TONNES (LOADED)
AUXILIARY SERVICES WORKHEAD (ASW)	INSTALLS/REMOVES NBI DUCT SECTION BETWEEN LSAP & SHIELD DOOR, He MANIFOLD SECTION, & He MANIFOLD DUCT COVER	REACTOR ROOM BETWEEN T.F. COILS	10 TONNES	4.0m X 3.7m X 5.0m	13 TONNES
AUXILIARY SERVICES WORKHEAD DOLLY	TRANSLATES THE AUX. SERVICES WORKHEAD BETWEEN THE STAGING AREA & THE REACTOR ROOM	REACTOR ROOM, MAINT. EQUIP. STAGING AREA	SUPPORTS 13 TONNES	5.0m X 4.3m X 2.0m	4 TONNES (EMPTY) 17 TONNES (LOADED)
HELIUM COOLANT MANIFOLD COVER	COVERS & SEALS THE LARGE DIA. He COOLANT DUCT WHICH MUST BE DISCONNECTED TO REMOVE THE REACTOR MODULE SECTOR	REACTOR ROOM, BETWEEN T.F. COILS	N/A	1.5m DIA X .25m THICK	3.5 TONNES
He MANIFOLD COVER DOLLY	TRANSLATES THE He MAINFOLD COVER BETWEEN THE STAGING AREA AND THE REACTOR ROOM	REACTOR ROOM, MAINT. EQUIP. STAGING AREA	SUPPORTS 7.0 TONNES	1.7m X 2.0m X .50m	1.0 TONNE (EMPTY) 8.0 TONNES (LOADED)
REACTOR MODULE TRANSPORTER	RECEIVES THE REACTOR MODULE AFTER WITHDRAWAL FROM IT'S NESTED POSITION & TRANSLATES MODULE TO HOT CELL.	REACTOR ROOM, HOT CELL, & STAGING AREA	SUPPORTS 75 TONNE REACTOR MODULE	15.0m X 6.0m X 12.0m	60 TONNES (EMPTY) 155 TONNES (LOADED)
DIVERTOR MODULE WORKHEAD	REMOVES/INSTALLS THE DIVERTOR MODULES. INTERFACES WITH PMM & WORKS IN SPACE VACATED BY REACTOR MODULE	REACTOR ROOM, INSIDE PLASMA CHAMBER AREA	SUPPORTS 3 TONNES (DIVERTOR MODULE WEIGHT)	14.0m X 3.5m X 12.0m	9 TONNES (EMPTY) 12 TONNES (LOADED)
DIVERTOR MODULE TRANSPORTATION & STORAGE DOLLY	TRANSFERS NEW DIVERTOR MODULES INTO REACTOR ROOM & USED DIV. MODULES INTO HOT CELL. HOLDS UP TO 4 MODULES	REACTOR ROOM, HOT CELL, STAGING AREA	SUPPORTS 12 TONNES (4 DIVERTOR MODULES)	8.0m X 4.0m X 3.0m	3 TONNES (EMPTY) 15 TONNES (LOADED)
INSPECTION WORKHEAD	USED TO INSPECT REACTOR MODULES ADJACENT TO REMOVED MODULE. UNIT INTERFACES WITH PMM & HAS SHIELDED CAB TO PROTECT CREW	REACTOR ROOM, IN PLASMA CHAMBER AREA	N/A	8.0m X 2.5m X 6.0m	60 TONNES
INSPECTION WORKHEAD DOLLY	TRANSLATES INSPECTION WORKHEAD BETWEEN STAGING AREA & REACTOR ROOM	REACTOR ROOM, MAINT. EQUIP. STAGING AREA	SUPPORTS 60 TONNES (INS. W/H)	9.0m X 3.0m X 1.0m	10 TONNES (EMPTY) 70 TONNES (LOADED)
LEAK TEST WORKHEAD	USED TO CHECK FOR LEAKS AROUND THE He COOLANT MANIFOLD & DIVERTOR MODULE DIS- CONNECT JOINTS. INTERFACES WITH OMU, OVERHEAD REMOTE MANIPULATOR ARMS, AND AUXILIARY SERVICES WORKHEAD	REACTOR ROOM BETWEEN T.F. COILS	N/A	.50m X .30m X .30m	300 kg

* ONLY REQUIRED FOR CONTACT MAINTENANCE

CULHAM CONCEPT PRIMARY MAINTENANCE MACHINE (PMM)

FIGURE 4.3-3

- o Several maintenance machines are assumed to require crews. These are the PMM, Operational Maintenance Unit (OMU), Tug Vehicle, Inspection Workhead, Poloidal Crane and Overhead Remote Manipulator. These crews are counted as direct support personnel and are required for either fully remote or partial contact maintenance scenarios. The crews are housed in completely shielded enclosures with self-contained life support systems.
- o Most reactor components are too large to be handled manually. Even fasteners for shield doors, etc. are expected to be too large to be man-handled. Therefore, all maintenance machines are conceptually configured to perform all assigned functions remotely, even if contact maintenance is postulated.

The maintenance equipment listed in Table 4.3-3 includes both that required for unscheduled as well as scheduled maintenance and also that required for remote maintenance. Those items added for contact maintenance operations are indicated by an asterisk. While all of the items are not required for the particular unscheduled maintenance scenarios discussed in this section, other scenarios will require them. In all cases, the scheduled maintenance equipment is used for unscheduled maintenance also.

4.3.2 UWMAK-III Unscheduled Maintenance Plans - The UWMAK-III unscheduled maintenance plans are based on the activity sequence presented in Table 4.3-4. These activities are performed in the indicated sequence to exchange a failed central wall (divertor) module in one sector of the reactor when using either contact maintenance operations to assist as much as possible or fully remote operations to conduct the maintenance action.

TABLE 4.3-4
UWMAK-III UNSCHEDULED
MAINTENANCE ACTIVITY SEQUENCE

LEVEL 1 ACTIVITY	LEVEL 2 MAINTENANCE ACTIVITY
SHUTDOWN	REACTOR SHUTDOWN
GAIN ACCESS	MOVE NBI LATERAL SUPPORT ACCESS PANEL REMOVAL POLOIDAL MAGNET RETRACTION LITHIUM MANIFOLD REMOVAL RAISE/LOWER SHIELD SEGMENTS
REMOVE	"A" MODULE REMOVAL LEAK MODULE ISOLATION GRAPHITE ISSEC REMOVAL CENTRAL WALL MODULE MANIFOLD DISCONNECT "B" MODULE AND CENTRAL WALL MODULE REMOVAL
REPLACE	CENTRAL WALL MODULE AND "B" MODULE REPLACEMENT GRAPHITE ISSEC REPLACEMENT "A" MODULE REPLACEMENT
REASSEMBLE	SHIELD SEGMENT REPLACEMENT CENTRAL WALL MODULE MANIFOLD RECONNECT LITHIUM MANIFOLD RECONNECT LEAK TEST LITHIUM MANIFOLD CONNECTIONS REPOSITION POLOIDAL MAGNETS LATERAL SUPPORT ACCESS PANEL REPLACEMENT REINSTALL NBI
START-UP	VALIDATION AND START-UP

The major assumptions governing these maintenance activities for the unscheduled first wall/blanket scenario are:

- o All modules are replaced as a unit with module repair operations conducted in hot cells.
- o Modules are filled with lithium coolant when removed and replaced.
- o Spare reactor components are available on demand.
- o Access to modules is through shield doors in the side of the reactor.
- o Neutral Beam Injectors can be disconnected and removed as a unit. Shielding is provided around the NBI's for contact operations during maintenance.
- o Contact maintenance operations are feasible until the initiation of movement of the reactor shield doors and after the doors are closed.
- o Permanently installed LN₂ freeze units are used to produce freeze plugs at manifold disconnects.
- o Attachment points are built into the outside face of "A" modules and at the internally shielded sides of "B" and divertor modules.
- o Moveable PF coils are automatically retracted by actuators built into the reactor without disconnecting service lines required by these coils. Control of this operation is from the reactor control room.
- o All reactor components are interchangeable with replacement units.
- o The lithium coolant flow system must remain operational during the module exchange.
- o The failed module can be isolated to one sector by use of installed instrumentation without internal access to the reactor.
- o Isolation of the leaking module in the sector is delayed until after the plasma chamber is opened by removal of the "A" module. Positive isolation techniques for accomplishing this function earlier in the procedure are unidentified at this time.
- o Personnel are available as required for all maintenance activities including floor crews for contact operations.
- o Time dilution factors for productivity are omitted in the computation of time estimates in this section.
- o During the unscheduled outage no other contingencies occur nor is other maintenance conducted which interferes with the procedure.

4.3.2.1 Summary of Alternate Plans for the UWMAK-III Reference Reactor - Six maintenance plans have been developed for the alternate vacuum wall arrangements of the UWMAK-III reference reactor concept. These include plans for the contact

maintenance concept as well as for fully remote maintenance operations. The key characteristics of these six plans are given in Table 4.3-5.

TABLE 4.3-5
UNSCHEDULED UWMAK-III MAINTENANCE PLAN SUMMARY

TYPE OF MAINTENANCE		VACUUM WALL ARRANGEMENT	NUMBER OF SECTORS WORKED	NUMBER OF MODULES REPLACED/ OUTAGE	NUMBER OF MAINTENANCE EQUIPMENT SETS	NUMBER OF DIRECT PERSONNEL	TOTAL OUTAGE TIME (HOURS)	LOST REVENUE COST (M\$)
CONTACT ASSISTED	REMOTE							
✓		1	1-1	1	1.00	20	858.5	43.7
✓		2	1-1	1	1.00	20	783.9	39.9
✓		3	1-1	1	1.00	20	743.5	37.9
	✓	1	1-1	1	.9985	8	1208.7	61.6
	✓	2	1-1	1	.9985	8	1155.3	58.9
	✓	3	1-1	1	.9985	8	1075.3	54.8

NOTES: 1) DUE MAINTENANCE EQUIPMENT SET WEIGHT = 2528.8 TONNES
2) OUTAGE TIME SHOWS UNDILUTED HOURS

The lowest total outage time estimate occurs when using the partial contact maintenance plan with the primary vacuum barrier at the reactor room wall (arrangement number 3). Since all maintenance cost factors other than the effect of downtime are unchanged, this is also the lowest cost maintenance plan. The downtime is minimum for this maintenance plan because the time requirements for detaching and installing the modules and the NBI are kept to a minimum with the elimination of welds and sealed joints and because the preliminary vacuum verification test must necessarily be omitted. The reactor room cost is kept constant as for the Culham reference reactor case described in Section 4.3.1. The time saving of vacuum wall arrangement number 3 compared with arrangement number 1 in this reactor concept is approximately 13.3 percent, which is considered significant.

For the fully remote maintenance scenarios the lowest outage time also occurs for the vacuum wall location arrangement with the primary vacuum barrier at the reactor room wall. The remote maintenance times are longer than those when using contact maintenance because of the additional time to gain access and reassemble the reactor by fully remote means.

The maintenance plans for all three vacuum wall arrangements and for both contact and remote maintenance concepts have been investigated to establish that significant trend differences do not occur between the contact and remote maintenance scenarios.

The cost per outage in lost production shown in Table 4.3-5 is based on a cost of 50,946 \$/hour for the UWMAK-III based on the optimum scheduled maintenance plan annual cost defined by the TOCOMO code as discussed in Section 4.4. The equation for this calculation is found in Section 4.3.1.

4.3.2.2 Minimum Cost Maintenance Plan With Contact Maintenance - The minimum cost maintenance plan for unscheduled maintenance using contact operations where possible occurs when the primary vacuum wall is at the reactor room wall. The level 2 sequence of operations and estimated undiluted downtime required for each activity is shown in Table 4.3-6. This table defines an approximate timeline for the outage since most of the functions are performed in series. Those functions conducted in parallel with others are limited to the retraction and extension of the poloidal field coils that must be cleared by the "A" module and shield doors, and also the disconnecting and reconnecting of the central wall (divertor) module coolant manifolds. The poloidal field coil retraction is initiated as soon as the energy from the TF coils is dumped and continues during the NBI removal and Lateral Support Access Panel removal. The coil retraction is conducted from the reactor control room. Repositioning the PF coils is conducted in the same manner but is delayed until after the lithium coolant manifold leak checks are completed to avoid additional delay if a leak is detected. Time exists during the LSAP and NBI installation to conduct this operation. All PF coil repositioning checks are automatically read out in the reactor control room.

The central wall module coolant manifold connections are broken above the reactor and are disconnected remotely by a manipulator system installed on the central column above the reactor. If the module to be removed is below the reactor, a special machine is used to conduct this operation in parallel with the ISSEC removal and the initial stages of the divertor module removal. Similarly, the divertor module manifold connection is made during the reconnection of the lithium manifolds for the "A" and "B" modules using contact operations where possible. Contact maintenance operations cannot be used to disconnect the manifold since the leak source is not defined until after the plasma chamber is opened and the radiation level is too great.

Table 4.3-6 also indicates the functions where the time differs from that required when the vacuum wall arrangement number 2 is used. It can be seen that relatively few functions are affected. The estimates for the other maintenance plans indicated in table 4.3-5 are presented in Appendix A.

TABLE 4.3-6
UWMAK-III REFERENCE REACTOR
FIRST WALL/BLANKET REPLACEMENT
(UNSCHEDULED CONTACT OPERATIONS - VACUUM WALL ARRANGEMENT NO. 3)

LEVEL 1 TASK	LEVEL 2 TASK	DURATION (HRS:MIN)
SHUTDOWN	REACTOR SHUTDOWN	29:00
ACCESS	MOVE NBI	17:10
	LATERAL SUPPORT ACCESS PANEL REMOVAL	✓13:30
	POLOIDAL MAGNET RETRACTION	31:00*
	NBI BEAM DUCT REMOVAL	✓—
	LITHIUM MANIFOLD REMOVAL	50:45
	RAISE/LOWER SHIELD SEGMENTS	33:15
REMOVAL	"A" MODULE REMOVAL	53:30
	LEAKING MODULE ISOLATION	155:00
	GRAPHITE ISSEC REMOVAL	13:00
	CENTRAL WALL MODULE MANIFOLD DISCONNECT	31:00*
	"B" MODULE & CENTRAL WALL MODULE REMOVAL	31:20
REPLACEMENT	CENTRAL WALL MODULE & "B" MODULE REPLACEMENT	46:10
	GRAPHITE ISSEC REPLACEMENT	14:10
	"A" MODULE REPLACEMENT	75:15
REASSEMBLY	SHIELD SEGMENT REPLACEMENT	36:15
	CENTRAL WALL MODULE MANIFOLD RECONNECT	10:20*
	LITHIUM MANIFOLD RECONNECT	56:25
	LEAK TEST LITHIUM MANIFOLD CONNECTIONS	34:00
	NBI BEAM DUCT REPLACEMENT	✓—
	REPOSITION POLOIDAL MAGNETS	42:45*
	LATERAL SUPPORT ACCESS PANEL REPLACEMENT	✓18:45
	REINSTALL NBI	29:55
STARTUP	VALIDATION AND STARTUP	✓36:00
TOTAL:		743:25

*PARALLEL EFFORT. NOT INCLUDED IN TOTAL TIME

✓TASKS WHICH DIFFER FROM THE MAINTENANCE PLAN USING VACUUM WALL ARRANGEMENT NUMBER 2.

Some of the specific design assumptions that influence this maintenance plan are listed below.

- o The LSAP is mechanically connected to the TF coils and is uncooled structure. This structure is open to permit pressure equalization across it.
- o The NBI beam duct is disconnected only at one point and most of it is removed with the NBI unit. This duct is not attached to the LSAP.
- o Pressure in the reactor room is maintained at 10^{-4} torr during operation.
- o The "A" module attachment is not sealed and provides only a high impedance joint with the other modules.
- o The validation and leak check of the plasma chamber occurs only during validation and startup. It is assumed that all operations are conducted under clean room conditions and that all replacement spares and components are baked out prior to installation to reduce the outgassing and, consequently, the pump down time as much as possible.
- o Shield plugs and other devices are used as necessary prior to opening the main shield doors to provide protection from unnecessary radiation exposure during contact assisted maintenance operations.

Table 4.3-5 indicates that twenty personnel are required to conduct these operations. This includes 8 machine operators and a maximum floor crew size of 12 to conduct the manual operations that assist the maintenance machines.

The number of maintenance equipment sets required by this maintenance outage is exactly one basic equipment set required for scheduled maintenance. All items of equipment are required because the divertor module replacement necessitates removal of each of the other modules to gain access to it.

4.3.2.3 Minimum Cost Maintenance Plan With Remote Maintenance - The minimum cost maintenance plan for the unscheduled exchange of a divertor module when maintaining the UWMAK-III reference reactor by use of fully remote maintenance operations has also been defined. For minimum cost the primary vacuum wall location at the reactor room wall is selected based on the data from Table 4.3-5. Table 4.3-7 lists the level 2 maintenance functions and the undiluted required downtime estimate for each function.

As in the maintenance plans for the Culham reference reactor, the level 2 remote maintenance sequence for the UWMAK-III when using fully remote operations is the same as that used for the maintenance plan when employing contact maintenance. The difference is in the use of fully remote operations for gaining access and reassembly. Some slight time savings are attained to offset the longer

TABLE 4.3-7
UWMAK-III REFERENCE REACTOR
FIRST WALL/BLANKET REPLACEMENT
(UNSCHEDULED REMOTE OPERATIONS - VACUUM WALL ARRANGEMENT NO. 3)

LEVEL 1 TASK	LEVEL 2 TASK	DURATION (HRS:MIN)
SHUTDOWN	REACTOR SHUTDOWN	29:00
ACCESS	MOVE NBI	26:40
	LATERAL SUPPORT ACCESS PANEL REMOVAL	✓34:20
	POLOIDAL MAGNET RETRACTION	31:00*
	NBI BEAM DUCT REMOVAL	✓ —
	LITHIUM MANIFOLD REMOVAL	154:50
	RAISE/LOWER SHIELD SEGMENTS	43:55
REMOVAL	"A" MODULE REMOVAL	53:30
	LEAKING MODULE ISOLATION	155:00
	GRAPHITE ISSEC REMOVAL	13:00
	CENTRAL WALL MODULE MANIFOLD DISCONNECT	31:00*
	"B" MODULE & CENTRAL WALL MODULE REMOVAL	31:20
REPLACEMENT	CENTRAL WALL MODULE & "B" MODULE REPLACEMENT	46:10
	GRAPHITE ISSEC REPLACEMENT	14:10
	"A" MODULE REPLACEMENT	75:15
REASSEMBLY	SHIELD SEGMENT REPLACEMENT	38:45
	CENTRAL WALL MODULE MANIFOLD RECONNECT	44:20*
	LITHIUM MANIFOLD RECONNECT	172:15
	LEAK TEST LITHIUM MANIFOLD CONNECTIONS	34:00
	NBI BEAM DUCT REPLACEMENT	✓ —
	REPOSITION POLOIDAL MAGNETS	42:45*
	LATERAL SUPPORT ACCESS PANEL REPLACEMENT	✓63:55
	REINSTALL NBI	53:15
STARTUP	VALIDATION AND STARTUP	✓36:00
TOTAL:		1075:20

*PARALLEL EFFORT. NOT INCLUDED IN TOTAL TIME

✓TASKS WHICH DIFFER FROM THE MAINTENANCE PLAN USING VACUUM WALL ARRANGEMENT NUMBER 2.

time required for remote operations since the NBI's require less shielding but the result of remote maintenance operations is an increase in the total outage time by approximately 332 hours. This is partly because of the slower functioning of the remote equipment and partly because the smaller, repetitive operations are more difficult to conduct in parallel with large machinery operating on one sector. When using remote maintenance, the paralleling of the poloidal magnet retraction and repositioning operations is not as extreme as for contact maintenance since the other operations conducted in series with this retraction require longer times. The central wall (divertor) module manifold disconnect and reconnect operations are identical with the contact maintenance scenario since these are conducted remotely even in the contact assisted maintenance plan.

The specific design assumptions that influence the maintenance plan are the same as those used for the contact maintenance operations with very minor exceptions. Some of these exceptions include the reduction of shielding on the NBI's and the elimination of shield plugs, etc., that are used prior to opening the shield doors for reducing personnel radiation exposure.

Direct personnel requirements imposed by the outage are reduced to the 8 machine operators as shown in Table 4.3-5. Normal operating and plant personnel support these operators during the outage. This is the same number of operators as required for the contact maintenance operations. Only the floor crew is no longer required.

The number of maintenance equipment sets is reduced slightly to .9985 (see Table 4.3-5) since several items of equipment required for the standard scheduled maintenance equipment set are not required for this unscheduled outage when using remote maintenance.

4.3.2.4 UWMAK-III Maintenance Equipment Concept - The maintenance equipment required to exchange the first wall/blanket of the UWMAK-III reference reactor for the unscheduled maintenance scenarios described in the foregoing sections is summarized in Table 4.3-8. The equipment in this table is all included in one set of maintenance equipment for the UWMAK-III reference reactor with only one item of each piece of equipment required except for the four screw jacks, two screw jack dollies, 8 line freeze units, 2 NBI port plugs, and 4 mobile manlift units.

The equipment summary given in Table 4.3-8 lists the major characteristics and physical parameters of each item of equipment. Additional detailed functional descriptions and performance requirements for the major equipment items are provided

**TABLE 4.3-8
UWMAK-III MAINTENANCE EQUIPMENT SUMMARY**

ITEM DESIGNATION	MAJOR FUNCTIONS	OPERATING LOCATION	LIFTING CAPABILITY	SIZE (L X W X H) WEIGHT: kg
OVERHEAD CRANE	LIFT AND MOVE LARGE COMPONENTS	OVERHEAD OF REACTOR - CIRCULAR MOTION	170 TONNES	100m X 6.0m X 12.0m WT = 4,980 TONNES
PRIMARY MAINTENANCE MACHINE (PMM)	GAIN ACCESS TO FIRST WALL - REMOVE LATERAL SUPPORT ACCESS PANEL. NBI INJECTOR DUCT, SUPPORTS ETC.	ANNULAR REGION AROUND REACTOR AND BETWEEN T.F. COILS	170 TONNES	11.0m X 4.3m X 14.0m WT (EMPTY) = 250,000 kg WT (LOADED) = 420,000 kg
LATERAL SUPPORT ACCESS PANEL WORKHEAD	REMOVE/INSTALL, SUPPORT, AND STORE THE LATERAL SUPPORT ACCESS PANEL	REACTOR ROOM, HOT CELL & STORAGE AREA	100 TONNES	3.0m X 4.3m X 17.5m WT = 70,000 kg
LATERAL SUPPORT PANEL AND WORKHEAD DOLLY	MOVE LATERAL SUPPORT PANEL AND WORKHEAD FROM REACTOR ROOM TO HOT CELL OR FROM STORAGE TO REACTOR ROOM	REACTOR ROOM, HOT CELL, & STORAGE AREA	170 TONNES	13.5m X 5.0m WT (EMPTY) = 50,000 kg WT (LOADED) = 230,000 kg
AUXILIARY SERVICES WORKHEAD	REMOVE/INSTALL NBI DUCTS COOLANT MANIFOLDS, AND SHIELD SCREW JACKS	REACTOR ROOM	40 TONNES	5.0m X 4.3m X 9.0m WT (EMPTY) = 40,000 kg
LITHIUM MANIFOLD DOLLY	TRANSPORT LITHIUM MANIFOLD FROM REACTOR ROOM TO HOT CELL	REACTOR ROOM AND HOT CELL	10 TONNES	6.0m X 3.0m X 1.0m WT = 7,000 kg
SCREW JACKS (SHIELD)	OPEN SWING-OUT SHIELD SEGMENTS	REACTOR ROOM DURING MAINTENANCE	50 TONNES	11.5m X 0.75m DIA (UPPER) 6.0m X 0.75m DIA (LOWER) WT (EA) = 40,000 kg (UPPER) WT (EA) = 20,000 kg (LOWER)
SCREW JACK AND SHIELD PLUG TRANSPORT DOLLY	TRANSPORT SCREW JACKS FROM STORAGE AREA TO REACTOR SHIELD	REACTOR ROOM AND STORAGE AREA	120 TONNES	13.0m X 3.0m X 1.5m WT (EMPTY) = 70,000 kg WT (LOADED) = 190,000 kg
MODULE HANDLING MACHINE (MHH)	PROVIDES COMMON MOUNTING BASE FOR MODULE & ISSEC WORKHEADS	BETWEEN T.F. COILS AND FIRST WALL	85 TONNES	17.5m X 4.3m X 12.5m WT (EMPTY) = 174,000 kg WT (LOADED) = 260,000 kg
"A" MODULE WORKHEAD AND STORAGE FIXTURE	REMOVE/INSTALL, SUPPORT AND STORE FIRST WALL "A" MODULES	REACTOR ROOM, HOT CELL, AND STORAGE AREA	50 TONNES	3.0m X 4.3m X 10.0m WT (EMPTY) = 35,000 kg WT (LOADED) = 85,000 kg
"A" MODULE AND WORKHEAD DOLLY	MOVE "A" MODULE AND WORKHEAD FROM REACTOR ROOM TO HOT CELL	REACTOR ROOM, HOT CELL AND STORAGE AREA	85 TONNES	11.0m X 5.0m X 2.0m WT (EMPTY) = 40,000 kg WT (LOADED) = 125,000 kg
"B" MODULE AND CENTRAL WALL MODULE WORKHEAD	REMOVE/INSTALL "B" MODULES & CENTRAL WALL MODULES	REACTOR ROOM	8 TONNES	5.0m X 4.3m X 11.0m WT (EMPTY) = 14,000 kg WT (LOADED) = 22,000 kg
"B" MODULE WORKHEAD TRANSPORT & STORAGE DOLLY	TRANSPORT "B" MODULE WORKHEAD BETWEEN STAGING AREA AND REACTOR ROOM	REACTOR ROOM AND STORAGE AREA	14 TONNES	6.0m X 4.3m X 2.0m WT (EMPTY) = 5,000 kg WT (LOADED) = 19,000 kg

**TABLE 4.3-8
UWMAK-111 MAINTENANCE EQUIPMENT SUMMARY (CONTINUED)**

ITEM DESIGNATION	MAJOR FUNCTIONS	OPERATING LOCATION	LIFTING CAPABILITY	SIZE (L X W X H) WEIGHT: kg
"B" AND CENTRAL WALL TRANSPORT AND STORAGE DOLLY	TRANSPORT "B" AND CENTRAL WALL MODULES FROM REACTOR ROOM TO HOT CELL	REACTOR ROOM AND HOT CELL	21 TONNES	3.5m X 3.5m X 1.0m WT (EMPTY) = 10,000 kg WT (LOADED) = 31,000 kg
ISSEC PANEL(S) WORKHEAD	REMOVE/INSTALL ISSEC PANELS	REACTOR ROOM	3 TONNES	6.0m X 2.3m X 9.0m WT (EMPTY) = 9,000 kg WT (LOADED) = 12,000 kg
ISSEC PANEL WORK-HEAD TRANSPORT & STORAGE DOLLY	TRANSPORT ISSEC PANEL WORKHEAD BETWEEN STAGING AREA AND REACTOR ROOM	REACTOR ROOM AND STORAGE AREA	9 TONNES	10.0m X 4.3m X 2.0m WT (EMPTY) = 2,500 kg WT (LOADED) = 11,500 kg
ISSEC PANELS TRANSPORT AND STORAGE DOLLY	TRANSPORT ISSEC SEGMENTS FROM REACTOR ROOM TO HOT CELL	REACTOR ROOM AND HOT CELL	6 TONNES	5.0m X 4.5m X 1.0m WT (EMPTY) = 3,000 kg WT (LOADED) = 9,000 kg
INSPECTION WORKHEAD	INSPECT AND LEAK CHECK MODULES	INSIDE PLASMA CHAMBER	<2 TONNES	10.0m X 3.0m X 10.0m WT = 120,000 kg
INSPECTION WORKHEAD DOLLY	TRANSPORT AUXILIARY SERVICES WORKHEAD BETWEEN STAGING AREA AND REACTOR ROOM	REACTOR ROOM	120 TONNES	10.0m X 4.0m X 2.0m WT (EMPTY) = 40,000 kg WT (LOADED) = 160,000 kg
CENTRAL CORE MAINTENANCE DEVICE (UPPER)	DISCONNECT UPPER CENTRAL WALL MODULE LITHIUM MANIFOLDS	ON CENTRAL CORE ABOVE VACUUM PUMPS	10 TONNES	15.0m X 2.0m X 16.0m WT = 18,000 kg
AUXILIARY SERVICES WORKHEAD DOLLY	TRANSPORT AUXILIARY SERVICES WORKHEAD BETWEEN STAGING AREA	REACTOR ROOM	40 TONNES	6.0m X 4.3m X 2.0m WT (EMPTY) = 15,000 kg WT (LOADED) = 65,000 kg
LITHIUM LINE FREEZE UNITS	FREEZE LITHIUM IN LINE AT DISCONNECT JOINTS	PERMANENTLY INSTALLED ON LITHIUM LINES	N/A	0.45m DIA X 0.65m WT = 100 kg
TUG	PROVIDE MOTIVE POWER FOR VARIOUS DOLLIES	REACTOR ROOM, HOT CELL, AND STORAGE AREA	N/A	9.45m X 6.0m X 4.0m WT = 80,000 kg
NBI PORT PLUG	SEAL THE END OF THE NBI INJECTOR TUBE AFTER DISCONNECT	REACTOR ROOM	N/A	1.0m DIA X 50cm THICK WT = 1.25 TONNES
OPERATIONAL MAINTENANCE UNIT (OMU)	PERFORMS ASSEMBLY/DISASSEMBLY TASKS ON LINES, DUCTS, ETC. REQUIRING A HIGH DEGREE OF MANIPULATOR ARTICULATION, INTERFACES WITH LINE CONNECTOR TOOL AND IMPACT WRENCH, NBI INJECTOR DUCT	REACTOR ROOM	1.3 TONNES	14.0m X 6.5m X 4.5m WT = 155,000 kg
NBI INJECTOR DUCT TRANSPORT & STORAGE DOLLY	TRANSPORT INJECTOR DUCT BETWEEN REACTOR ROOM & HOT CELL, HOLDS DUCT DURING STORAGE	REACTOR ROOM, HOT CELL, & STAGING AREA	10 TONNES	4.5m X 1.5m WT (EMPTY) = 2 TONNES WT (LOADED) = 12 TONNES

TABLE 4.3-8
UWMAK-III MAINTENANCE EQUIPMENT SUMMARY (CONTINUED)

ITEM DESIGNATION	MAJOR FUNCTIONS	OPERATING LOCATION	LIFTING CAPABILITY	SIZE (L X W X H) WEIGHT: kg
NBI INJECTOR DUCT SLING	SUPPORT AND HOLD THE INJECTOR DUCT DURING INSTALLATION/REMOVAL. INTERFACES WITH BOOM ARM ON THE AUXILIARY SERVICES WORKHEAD	REACTOR ROOM, HOT CELL	10 TONNES	4.m X .5m X 1.0m WT (EMPTY) = 1 TONNE WT (LOADED) = 11 TONNES
NBI PORT PLUG DOLLY	TRANSLATES THE NBI PORT PLUG BETWEEN THE MAINT. EQUIP. STAGING AREA & THE REACTOR ROOM	REACTOR ROOM, MAINT. EQUIP. STAGING AREA	SUPPORT 7.5 TONNES (6 PLUGS)	6.0m X 1.0m X 1.0m WT (EMPTY) = .5 TONNES WT (LOADED) = 8.0 TONNES
IMPACT WRENCH	AUTOMATED DEVICE WHICH REMOVES/INSTALLS LARGE FASTENERS. USED IN CONJUNCTION WITH OMU & VARIOUS WORKHEADS	REACTOR ROOM BETWEEN T.F. COILS	N/A	70cm X 25cm X 33cm WT = 400 kg
MOBILE MANLIFT	PROVIDES MANNED ACCESS TO TOP OF NBI's, FASTENERS ON LSAP, LITHIUM MANIFOLDS, ETC.	REACTOR ROOM BETWEEN T.F. COILS	SUPPORTS 4-6 PERSONNEL (OR 1 TONNE)	6.5m X 4.25m X 3.0m (COLLAPSED) WT = 6.12 TONNES
LINE CONNECTOR INSTALLATION/REMOVAL TOOL	OPERATES QUICK-DISCONNECT LINE FITTINGS ON NBI's. INTERFACES WITH OMU	REACTOR ROOM	N/A	30cm X 50cm X 40cm WT = 300 kg

*REQUIRED ONLY FOR CONTACT MAINTENANCE OPERATIONS.

in Appendix B. Sketches of the conceptual configurations are also provided in Appendix B. Since many equipment items are similar to those defined in the appendix of the earlier study phase report (Reference 4-1) these are not repeated here.

The maintenance equipment concept covered in Table 4.3-8 is designed to the following ground rules.

- o The Primary Maintenance Machine (PMM) is shown in Figure 4.3-3 as the principal machine used for the Culham reference reactor concept. This same concept is appropriate for the UWMAK-III reference reactor but the workhead configuration will differ to provide for attachment to the UWMAK-III LSAP. A radial track and circumferential translation carriage are used for the UWMAK-III in the same manner as for the Culham concept.
- o A similar large machine, the Module Handling Machine (MHM), is also required for the UWMAK-III to provide entry to the gap in the reactor created by the PPM and to detach and remove the first wall/blanket modules from the reactor. This equipment illustrates the design approach for maintenance equipment applied to the UWMAK-III reference reactor. Figure 4.3-4 illustrates this machine with an "A" module attached. Additional sequences of module removal are depicted in Appendix B.

- o The overhead crane is used to augment the PMM and MHM by aiding in module exchange and the exchanging of workheads on these machines. It also aids in limiting traffic congestion on the peripheral track in the reactor room.
- o An Operational Maintenance Unit (OMU) is provided to conduct operations above the reactor and in other relatively inaccessible places. It is floor mounted on wheels but removed from the track system to allow access from the side in any sector being worked by other machinery. This unit is described in more detail in Appendix B. A similar unit is described under this name for the UWMAK-I concept in Reference 4-1.
- o The maintenance machines which require crews are the PMM, MHM, Inspection Workhead, OMU, Tug and Overhead Crane. These crews are direct support personnel and are required only during an outage for either fully remote or partial contact maintenance scenarios. Shielded enclosures and life support equipment are provided for them.
- o Heavy equipment is required even for partial contact maintenance since almost all components are too heavy for manual handling.

FIGURE 4.3-4

4.3.3 ORNL Cassette Concept Unscheduled Maintenance Plans - The ORNL Cassette reference reactor unscheduled maintenance plans are based on the functional sequence presented in Table 4.3-9. These activities are required to exchange a third blanket zone cassette (next to the shielding and farthest from the plasma) in the upper outer wall (B) region at the side of a sector. It is assumed that a leak has occurred in this cassette. The activities shown are for contact assisted maintenance operations. A slightly different sequence is possible with fully remote maintenance activities in that the NBI beam duct removal and installation can be conducted by handling this duct and the LSAP as a single unit when the primary vacuum barrier is at the reactor room wall.

TABLE 4.3-9
ORNL CASSETTE CONCEPT UNSCHEDULED
MAINTENANCE ACTIVITY SEQUENCE

LEVEL 1 ACTIVITY	LEVEL 2 MAINTENANCE ACTIVITY
SHUTDOWN	REACTOR SHUTDOWN
GAIN ACCESS	MOVE NBI POLOIDAL MAGNET RETRACTION LATERAL SUPPORT PANEL REMOVAL
REMOVE	LEAKING MODULE ISOLATION DISCONNECT CASSETTE MANIFOLDS NBI BEAM DUCT REMOVAL SHIELD BLOCK REMOVAL "A" REGION CASSETTE REMOVAL (3 CASSETTES) "B" REGION CASSETTE REMOVAL (6 CASSETTES)
REPLACE	"B" REGION CASSETTE REPLACEMENT (6 CASSETTES) "A" REGION CASSETTE REPLACEMENT (3 CASSETTES) SHIELD BLOCK REPLACEMENT NBI BEAM DUCT REPLACEMENT CONNECT CASSETTE MANIFOLDS LEAK TEST MANIFOLD CONNECTIONS
REASSEMBLE	LATERAL SUPPORT PANEL REPLACEMENT REPOSITION POLOIDAL MAGNETS REINSTALL NBI
STARTUP	VALIDATION AND STARTUP

The major assumptions used to define these activities for the unscheduled first wall/blanket scenario are as follows:

- o It is necessary to remove all first and second zone cassettes in a bank of cassettes before the third zone cassettes can be removed.
- o The cassette being replaced is either No. 2 or No. 1 in Figure 3.2-15 and, for Cassette No. 2, the removal sequence is Nos. 9, 8, 6, 5, 3, and then 2. However to remove No. 9 in the B region it is first necessary to remove the central bank of cassettes (Nos. 9, 6 and 3) in the lower outer wall (A) region because these cassettes obstruct the free passage of the same set of cassettes in the B region above (See Figure 3.3-9). Therefore, to remove cassette No. 2B, it is necessary to remove 8 other cassettes.
- o All coolant connections are capable of quick disconnect operations.
- o Spare reactor components are available on demand.
- o Removal of the cassettes requires removal of the Lateral Support Access Panel, even though this is of open design, because the LSAP, or any alternate open structural design is assumed to obstruct free passage of some of the cassettes and shield blocks.
- o Neutral Beam Injectors can be disconnected and removed as a unit. Shielding is provided around the NBI's for contact operations during maintenance.
- o Contact assisted maintenance operations are feasible until the removal of the NBI beam duct after disconnecting the cassette coolant and tritium lines and after reinstallation of this duct.
- o All cassettes are individually detachable so that only one at a time is free to move.
- o All reactor components are interchangeable with replacement units.
- o The first wall/blanket failure can be isolated to one sector by use of permanently installed diagnostic instrumentation. Isolation to a single cassette requires removal of the NBI, the use of a helium detector through the NBI duct and pressurization of groups of cassettes within a sector.
- o Personnel are available as required for all maintenance activities.
- o Time dilution factors for productivity are not included in the time estimates in this section.
- o Other maintenance does not interface with the maintenance activities defined in this section.

4.3.3.1 Summary of Alternate Maintenance Plans for the ORNL Cassette Reference Reactor - Four maintenance plans have been developed for the alternate

vacuum wall arrangements of the ORNL Cassette reference reactor concept and for both partial contact and fully remote maintenance operations. The key characteristics of these four plans are given in Table 4.3-10.

TABLE 4.3-10
UNSCHEDULED ORNL CASSETTE CONCEPT MAINTENANCE PLAN SUMMARY

TYPE OF MAINTENANCE		VACUUM WALL ARRANGEMENT	NUMBER OF SECTORS WORKED	NUMBER OF CASSETTES REPLACED/ OUTAGE	NUMBER OF MAINTENANCE EQUIPMENT SETS	NUMBER OF DIRECT PERSONNEL	TOTAL OUTAGE TIME (HRS)	LOST REVENUE COST (M\$)
CONTACT ASSISTED	REMOTE							
✓		1	1	1	1.00	12	597.75	29.3
✓		2	1	1	1.00	12	555.50	27.3
✓		3	1	1	1.00	12	558.75	27.4
	✓	1	1	1	.998	11	643.0	31.6

NOTES: 1) ONE MAINTENANCE EQUIPMENT SET WEIGHT = 703.8 TONNES..

2) OUTAGE TIME SHOWS UNDILUTED HOURS.

3) 8 CASSETTES ARE REPLACED TO ACCESS THE 9TH CASSETTE WHICH FAILED.

The lowest total outage time estimated is for contact assisted maintenance when using the LSAP as the primary vacuum barrier (arrangement number 2). The maintenance plan employing this vacuum wall arrangement and type of maintenance operation is also the lowest cost maintenance plan for an unscheduled outage. The reactor room cost is a constant for all four plans based on the same rationale as that discussed for the Culham reference reactor plans in Section 4.3.1. The time difference between vacuum wall arrangement number 2 and arrangement number 3 is insignificant. However, the potential exists with the primary vacuum wall located at the reactor room wall to reduce the time further if the cassettes can be removed without removing the LSAP or its equivalent. Therefore, since the remote maintenance plan is conducted only for vacuum wall arrangement 3 this is selected for further analysis.

The cost per outage in lost production is given in Table 4.3-10 based on a cost of 49,078 \$/hour for the ORNL Cassette reference reactor. This is derived from the lowest cost scheduled maintenance plan annual cost defined by the TOCOMO code for the ORNL Cassette reference reactor as discussed in Section 4.4. The equation for this calculation is found in Section 4.3.1.

4.3.3.2 Minimum Cost Maintenance Plan with Contact Maintenance - The maintenance plan chosen for comparison of contact and remote operations utilizes the primary vacuum wall at the reactor room wall (arrangement number 3) as originally

conceived since the time and cost savings using the closer vacuum wall at the LSAP is insignificant. The level 2 sequence of operations and estimated undiluted time for each activity is shown in Table 4.3-11. This table defines an approximate timeline for the outage since almost all of the operations are conducted in series. Those functions performed in parallel with others are limited to the retraction and extension of those poloidal field (PF) coils outside of the TF coils that interfere with the removal of the LSAP and with the access of maintenance equipment to the cassettes in the outer and bottom walls and in the divertor region. The movement of these PF coils is assumed to be automatically controlled from the reactor control room. The allotted time for these parallel operations is made as long as that required for the UWMak-III PF coil configuration since the PF coil configuration for the ORNL Cassette reference reactor may differ significantly from that postulated. It is assumed that this retraction and repositioning function may be conducted at the same time as the last part of reactor shutdown, the movement of the NBI, and the initial part of the verification and startup operations. All operations are conducted from the side of the reactor since no divertor or inner wall cassettes are removed. Therefore, no other operations can be conducted in parallel.

Table 4.3-11 also indicates where the downtime differs from that required when the primary vacuum wall is at the LSAP (arrangement number 2). These differences occur in the time required for LSAP removal and installation and in the time required for vacuum chamber pump down during startup. The time estimates for the contact maintenance plans with other vacuum wall arrangements are presented in Appendix A.

Some of the specific design assumptions that influence this maintenance plan are summarized below.

- o The LSAP is an uncooled open structure. The room pressure is equalized across this structure.
- o The NBI beam duct is disconnected at the NBI and is not attached to the LSAP. This is done to permit the removal of the LSAP and the use of contact assisted maintenance through the disconnect of the cassette fluid lines before opening the reactor by removing this duct.
- o Pressure in the reactor room is maintained at 10^{-4} torr during operation.
- o Joints between cassettes and between cassettes and shielding provide only high impedance to gas flow. Gastight seals are not required.
- o The validation and leak check of the plasma chamber occurs only during startup.

TABLE 4.3-11
ORNL CASSETTE CONCEPT UNSCHEDULED CONTACT MAINTENANCE PLAN
FOR FIRST WALL/BLANKET FAILURE
(VACUUM WALL AT REACTOR ROOM WALL)

LEVEL 1 TASK	LEVEL 2 TASK	DURATION (HRS)
SHUTDOWN	REACTOR SHUTDOWN	29:00
ACCESS	MOVE NBI	17:10
	POLOIDAL MAGNET RETRACTION	31:00*
	LATERAL SUPPORT PANEL REMOVAL	✓ 9:10
REMOVAL	LEAKING MODULE ISOLATION	26:15
	DISCONNECT CASSETTE MANIFOLDS	32:15
	NBI BEAM DUCT REMOVAL	14:50
	SHIELD BLOCK REMOVAL	9:00
	"A" REGION CASSETTE REMOVAL (3 CASSETTES)	45:30
	"B" REGION CASSETTE REMOVAL (6 CASSETTES)	67:00
REPLACEMENT	"B" REGION CASSETTE REPLACEMENT (6 CASSETTES)	81:00
	"A" REGION CASSETTE REPLACEMENT (3 CASSETTES)	52:30
	SHIELD BLOCK REPLACEMENT	14:00
	NBI BEAM DUCT REPLACEMENT	23:55
	CONNECT CASSETTE MANIFOLDS	49:45
	LEAK TEST MANIFOLD CONNECTIONS	7:15
REASSEMBLY	LATERAL SUPPORT PANEL REPLACEMENT	✓ 14:15
	REPOSITION POLOIDAL MAGNETS	42:45*
	REINSTALL NBI	29:55
STARTUP	VALIDATION AND STARTUP	✓ 36:00
TOTAL		558:45

*PARALLEL EFFORT

✓ TASKS WHICH DIFFER FROM THE PLAN USING VACUUM WALL ARRANGEMENT NO. 2.

- o All maintenance operations are conducted under clean room conditions with replacement components baked out prior to installation to reduce outgassing and pump down time as much as possible.
- o Shield plugs and shielded valves are used to reduce radiation exposure during the outage until the NBI shield block is removed.

Table 4.3-10 indicates that a maximum of 12 direct maintenance personnel are required for this outage in addition to the nominal plant maintenance and operating personnel complement. These include 8 equipment operators and a floor crew of four to conduct the manual operations.

The contact operations require only one item of equipment of each type provided for first wall/blanket maintenance but all items are required for the maintenance scenario postulated. While some items are not used they must be available for this type of unscheduled operation because the failed cassette location is unknown until well into the outage procedure.

4.3.3.3 Minimum Cost Maintenance Plan with Remote Maintenance - The maintenance plan for unscheduled replacement of a third blanket zone cassette in the upper outer wall of the reactor has also been defined when using fully remote maintenance operations. The cassette failure is assumed to be in the same location as that used for the analysis of the same maintenance action when using contact assisted operations (Section 4.3.3.2). Table 4.3-12 lists the level 2 maintenance functions and the undiluted estimated downtime required for the fully remote maintenance scenario.

The sequence defined in Table 4.3-12 differs slightly from that used for contact maintenance. Since the delay of opening the reactor is unnecessary in this scenario, the neutral beam injector duct is removed and installed with the LSAP and a separate operation is not required. The LSAP is an open structure and access through this structure is available to disconnect the beam duct joint near the shield plug. The increase in time required by the use of fully remote operations is approximately 85 hours. This is much less than for the UWMAC-III and reflects the reduced preparation time necessary to gain access to the interior of the plasma chamber.

The maximum number of direct personnel required for fully remote operations is eleven machine operators. No floor crew can be used and the operators, together with plan operators in the reactor control room, conduct all functions for this scenario.

The maintenance equipment requirements for remote maintenance are almost identical with those for contact maintenance. The mobile manlift devices are not required and, therefore, the number of sets of equipment is slightly less than for the contact maintenance scenario as indicated in Table 4.3-10.

4.3.3.4 ORNL Cassette Reference Reactor Maintenance Equipment Concept - The maintenance equipment required to exchange the first wall/blanket of the ORNL Cassette reference reactor for the unscheduled maintenance scenarios described in the foregoing sections is summarized in Table 4.3-13. One set of equipment for this concept includes one of each item of equipment in the table. Table 4.3-13 lists the major functions and physical parameters of each item of equipment. Additional func-

TABLE 4.3-12
ORNL CASSETTE CONCEPT UNSCHEDULED REMOTE MAINTENANCE PLAN
FOR FIRST WALL/BLANKET FAILURE
(VACUUM WALL AT REACTOR ROOM)

LEVEL 1 TASK	LEVEL 2 TASK	DURATION (HRS)
SHUTDOWN	REACTOR SHUTDOWN	29:00
ACCESS	MOVE NBI	✓26:40
	POLOIDAL MAGNET RETRACTION	31:00*
	LATERAL SUPPORT PANEL REMOVAL	✓30:10
REMOVAL	LEAKING MODULE ISOLATION	26:15
	DISCONNECT CASSETTE MANIFOLDS	✓43:00
	SHIELD BLOCK REMOVAL	9:00
	"A" REGION CASSETTE REMOVAL (3 CASSETTES)	45:30
	"B" REGION CASSETTE REMOVAL (6 CASSETTES)	67:00
REPLACEMENT	"B" REGION CASSETTE REPLACEMENT (6 CASSETTES)	81:00
	"A" REGION CASSETTE REPLACEMENT (3 CASSETTES)	52:30
	SHIELD BLOCK REPLACEMENT	14:00
	CONNECT CASSETTE MANIFOLDS	✓66:25
	LEAK TEST MANIFOLD CONNECTIONS	7:15
REASSEMBLY	LATERAL SUPPORT PANEL REPLACEMENT	✓56:05
	REPOSITION POLOIDAL MAGNETS	42:45*
	REINSTALL NBI	✓53:15
STARTUP	VALIDATION AND STARTUP	36:00
TOTAL		643:05

*PARALLEL EFFORT

✓TASKS WHICH DIFFER FROM THE UNSCHEDULED CONTACT SCENARIO USING
VACUUM WALL LOCATION NO. 2

tional descriptions and performance requirements, together with conceptual design sketches, of some of the major new equipment items are provided in Appendix B.

Much of the equipment in this concept is similar to that defined in the earlier study phase, Reference 4-1, and to that defined for the UWMAK-III and Culham reference reactors because the access to the first wall/blanket cassettes is principally from the side of the reactor. The maintenance equipment concept is defined to the following ground rules.

TABLE 4.3-13
ORNL CASSETTE MAINTENANCE EQUIPMENT SUMMARY

ITEM DESIGNATION	MAJOR FUNCTION	OPERATING LOCATION	LIFTING CAPABILITY	SIZE (L X W X H)	WEIGHT (KG)
POLOIDAL CRANE	INSTALL & REMOVE "D" REGION CASSETTES, CRYO-SORPTION PANELS, AND OTHER LARGE REACTOR COMPONENTS	REACTOR ROOM OVERHEAD OF THE REACTOR	155 TONNES	10.0m X 6.0m X 12.0m	4980 TONNES (EMPTY) 5135 TONNES (LOADED)
PRIMARY MAINTENANCE MACHINE (PMM)	SUPPORTS VARIOUS WORKHEADS USED TO GAIN ACCESS TO AND REMOVE "A," "B," & "C" CASSETTES	ANNULAR REGION AROUND REACTOR & BETWEEN T.F. COILS	SUPPORTS 160 TONNES	11.0m X 4.3m X 14.0m	250 TONNES (EMPTY) 410 TONNES (LOADED)
OPERATIONAL MAINTENANCE UNIT (OMU)	PERFORMS ASSEMBLY/DISASSEMBLY TASKS ON LINES, DUCTS, ETC. REQUIRING A HIGH DEGREE OF MANIPULATOR ARTICULATION. INTERFACES WITH LINE CONNECTOR TOOL AND IMPACT WRENCH, NBI'S, INJECTOR DUCT PLUG, ETC.	REACTOR ROOM	1300 kg	14.0m X 6.5m X 4.5m	77.5 TONNES
TUG VEHICLE	A MANNED VEHICLE WHICH PROVIDES MOTIVE POWER FOR THE PMM, NBI'S & VARIOUS DOLLIES	REACTOR ROOM, HOT CELLS, STORAGE AREA	N/A	9.45m X 6.0m X 4.0m	30 TONNES
LINE CONNECTOR INSTALLATION/REMOVAL TOOL	OPERATE QUICK-DISCONNECT FITTINGS ON CASSETTE & SHIELD BLOCK MODULES. INTERFACES WITH OMU	REACTOR ROOM BETWEEN T.F. COILS ON OMU	N/A	40m X 10m X 35m	200 kg
IMPACT WRENCH	AUTOMATED DEVICE WHICH REMOVES/INSTALLS LARGE FASTENERS. USED IN CONJUNCTION WITH PMM & OMU	REACTOR ROOM BETWEEN T.F. COILS ON OMU & PMM	N/A	70cm X 25cm X 33cm	400 kg
NBI PORT PLUG	SEAL THE END OF THE NBI INJECTOR TUBE AFTER DISCONNECT	REACTOR ROOM	N/A	1m DIA X 50cm THICK	1.25 TONNES
NBI PORT PLUG DOLLY	TRANSLATES THE NBI PORT PLUGS BETWEEN THE MAINTENANCE EQUIPMENT STAGING AREA AND THE REACTOR ROOM	REACTOR ROOM, MAINTENANCE EQUIPMENT STAGING AREA	SUPPORTS 2.5 TONNES	6.0m X 1.0m X 1.0m	.75 TONNES (EMPTY) 3.25 TONNES (LOADED)
LATERAL SUPPORT ACCESS PANEL WORKHEAD	REMOVES/INSTALLS THE BOLTED LATERAL SUPPORT ACCESS PANEL. INTERFACES WITH PMM.	REACTOR ROOM, BETWEEN T.F. COILS	90 TONNES	3.0m X 4.3m X 16.5m	70 TONNES (EMPTY) 160 TONNES (LOADED)
LATERAL SUPPORT ACCESS PANEL AND WORKHEAD TRANSPORT & STORAGE DOLLY	TRANSLATES LATERAL SUPPORT PANEL ON WORKHEAD FROM REACTOR ROOM TO HOT CELL OR STORAGE AREA. STORES PANEL DURING REACTOR MAINTENANCE. DOLLY IS MOVED BY TUG.	ANNULAR REGION AROUND REACTOR, HOT CELLS, STORAGE & STAGING AREAS	SUPPORTS 160 TONNES	13.5m X 5.m X 2.0	50 TONNES (EMPTY) 108 TONNES (LOADED)
INJECTOR DUCT & SHIELD BLOCK WORKHEAD	REMOVES/INSTALLS THE NBI INJECTOR PORT DUCT AND REMOVABLE SHIELD BLOCK SEGMENTS. INTERFACES WITH THE PMM.	REACTOR ROOM BETWEEN T.F. COILS	49 TONNES	5.0m X 5.0m X 7.0m	18 TONNES (EMPTY) 67 TONNES (LOADED)
INJECTOR DUCT & SHIELD BLOCK WORKHEAD DOLLY	TRANSLATES INJECTOR DUCT & SHIELD BLOCK WORKHEAD BETWEEN THE PRIMARY MAINTENANCE MACHINE (PMM) AND THE MAINTENANCE EQUIPMENT STAGING AREA. DOLLY IS MOVED BY TUG.	REACTOR ROOM, MAINTENANCE EQUIPMENT STORAGE/STAGING AREA	SUPPORTS 18 TONNES	7.0m X 6.0m X 1.0m	3 TONNES (EMPTY) 21 TONNES (LOADED)

**TABLE 4.3-13
ORNL CASSETTE MAINTENANCE EQUIPMENT SUMMARY (CONTINUED)**

ITEM DESIGNATION	MAJOR FUNCTION	OPERATING LOCATION	LIFTING CAPABILITY	SIZE (L X W X H)	WEIGHT (KG)
NBI INJECTOR DUCT TRANSPORT & STORAGE DOLLY	TRANSPORTS INJECTOR DUCT BETWEEN REACTOR ROOM, HOT CELL & STORAGE AREA	REACTOR ROOM, HOT CELL, & STORAGE AREA	SUPPORTS 162 TONNES	4.5m X 1.5m X .5m	15 TONNES (EMPTY) 162 TONNES (LOADED)
INSPECTION AND LEAK CHECK WORKHEAD	A DEVICE WHICH PENETRATES INTO THE PLASMA CHAMBER THRU THE NBI INJECTOR DUCT AREA TO INSPECT CASSETTES AND LOCATE LEAKS. INTERFACES WITH EITHER OMU OR PMM	PLASMA CHAMBER & AREA BETWEEN SHIELD & LATERAL SUPPORT ACCESS PANEL	N/A	6.0m (RETRACTED) 14.0m (EXTENDED) BY .75m DIA	1700 kg
INSPECTION & LEAK CHECK WORKHEAD DOLLY	TRANSLATES THE INSPECTION & LEAK CHECK WORKHEAD BETWEEN THE MAINTENANCE EQUIPMENT STAGING AREA AND THE REACTOR ROOM	REACTOR ROOM, MAINTENANCE EQUIPMENT STAGING AREA	SUPPORTS 3.5 TONNES (TWO WORKHEADS)	2.0m X 2.0m X 1.0m	.5 TONNES (EMPTY) 4.0 TONNES (LOADED)
"A," "B," & "C" CASSETTE MODULE WORKHEAD	REMOVES/INSTALLS THE "A," "B," & "C" CASSETTE MODULES. INTERFACES WITH PMM	REACTOR ROOM BETWEEN T.F. COILS	4 TONNES	5.0m X 4.0m X 14.0m	90 TONNES (EMPTY) 103 TONNES (LOADED)
"A," "B," & "C" CASSETTE MODULE WORKHEAD DOLLY	TRANSLATES "A," "B," & "C" MODULE WORKHEAD BETWEEN THE PRIMARY MAINTENANCE MACHINE AND THE MAINTENANCE EQUIPMENT STAGING AREA DOLLY IS MOVED BY TUG	REACTOR ROOM, MAINTENANCE EQUIPMENT STORAGE/STAGING	SUPPORTS 9 TONNES	6.0m X 6.0m X 1.0m	2 TONNES (EMPTY) 11 TONNES (LOADED)
"A" CASSETTE MODULE TRANSPORT & STORAGE DOLLY	TRANSPORT "A" CASSETTE MODULES BETWEEN REACTOR ROOM & HOT CELL/STORAGE AREA	REACTOR ROOM, HOT CELL STORAGE AREA	SUPPORTS 10.5 TONNES (6 MODULES)	6.0m X 2.0m X 3.0m	3 TONNES (EMPTY) 13.5 TONNES (LOADED)
"B" CASSETTE MODULE TRANSPORT & STORAGE DOLLY	TRANSPORTS "B" CASSETTE MODULES BETWEEN REACTOR ROOM & HOT CELL/STORAGE AREA	REACTOR ROOM, HOT CELL, STORAGE AREA	SUPPORTS 10.5 TONNES (6 MODULES)	6.0m X 2.0m X 3.0m	3 TONNES (EMPTY) 13.5 TONNES (LOADED)
"C" CASSETTE MODULE TRANSPORT & STORAGE DOLLY	TRANSPORTS "C" CASSETTE MODULES BETWEEN REACTOR ROOM & HOT CELL/STORAGE AREA	REACTOR ROOM, HOT CELL, STORAGE AREA	SUPPORTS 8.2 TONNES (6 MODULES)	6.0m X 2.0m X	3 TONNES (EMPTY) 11.2 TONNES (LOADED)
"D" CASSETTE MODULE TRANSPORT & STORAGE DOLLY	TRANSPORTS "D" CASSETTE MODULES BETWEEN REACTOR ROOM & HOT CELL/STORAGE AREA	REACTOR ROOM, HOT CELL STORAGE AREA	SUPPORTS 19.7 TONNES (12 MODULES)	6.0m X 3.0m X 14.0m	5 TONNES (EMPTY) 24.7 TONNES (LOADED)
"D" CASSETTE MODULE WORKHEAD SET	A SET OF TOOLS WHICH REMOVES & INSTALLS THE "D" CASSETTE MODULES. INTERFACES WITH THE OVERHEAD POLOIDAL CRANE.	REACTOR ROOM ABOVE REACTOR	8 TONNES (SHIELD BLOCK D)	3.0m X 1.5m X 3.3m	2.0 TONNES (EMPTY) 10 TONNES (LOADED)
DIVERTOR MODULE WORKHEAD	REMOVES/INSTALLS THE DIVERTOR MODULE AND SHIELD BLOCK IN FRONT OF THE MODULE. INTERFACES WITH THE PMM.	REACTOR ROOM NEAR TOP OF REACTOR BETWEEN T.F. COILS	71 TONNES	14.0m X 5.0m X 7.0m	14 TONNES (EMPTY) 85 TONNES (LOADED)
DIVERTOR MODULE WORKHEAD DOLLY	TRANSPORTS DIVERTOR MODULE WORKHEAD BETWEEN MAINT. EQUIP. STAGING AREA & REACTOR ROOM	REACTOR ROOM, MAINT. EQUIP. STAGING AREA	SUPPORTS 14 TONNES	14.0m X 5.0m X 1.0m	3 TONNES (EMPTY) 17 TONNES (LOADED)
DIVERTOR MODULE TRANSPORT & STORAGE DOLLY	TRANSPORTS DIVERTOR MODULE BETWEEN REACTOR ROOM & HOT CELL/STORAGE AREA	REACTOR ROOM HOT CELL STORAGE AREA	SUPPORTS 9 TONNES (1 MODULE)	8.0m X 3.0m X 1.0m	3 TONNES (EMPTY) 15 TONNES (LOADED)
MOBILE MANLIFT UNIT *	PROVIDES MANNED ACCESS TO TOP OF NBI'S, FASTENERS ON LSAP, HE MANIFOLDS, ETC.	REACTOR ROOM	SUPPORTS 1.0 TONNE	6.58m X 4.25m X 3.0m (COLLAPSED)	6.12 TONNES

*REQUIRED ONLY FOR CONTACT MAINTENANCE OPERATIONS.

- o A Primary Maintenance Machine (PMM) similar to that provided for the UWMAK-III is employed in this concept as the principal machine on which special function workheads are installed. This machine operates on radial tracks and is transported around the periphery on a carriage which also operates on sunken circumferential tracks.
- o The major item of equipment unique to this concept is the A, B and C cassette module workhead as illustrated in Figure 4.3-5. This workhead is installed on the PMM. It employs a turret arrangement to allow each arm to be used as required for withdrawing cassettes from the specific region for which the arm is designed.

A, B AND C CASSETTE MODULE WORKHEAD

FIGURE 4.3-5

- o The Operational Maintenance Unit defined for the UWMAK-III is also used to gain access for functions conducted above the reactor.
- o To overhead poloidal crane augments the PMM by aiding in the exchanging of workheads and cassette modules on the PMM and moving them to and from the transport dollys. It also is used to help limit traffic congestion

on the circumferential track as necessary.

- o The maintenance machines that require operating crews are the PMM, OMU, overhead poloidal crane and tug. Shielded enclosures and life support systems are provided since these machines operate during the period when the reactor shield is open and radiation levels require such protection. The operators are direct support personnel and are added to the normal plant complement for maintenance outage operations.
- o Heavy equipment is required for both contact assisted and remote maintenance since almost all components are too heavy for manual handling. Components are generally lighter for the ORNL Cassette reference reactor than for other concepts but still are believed heavy enough to preclude manual handling.

4.3.4 GA-Doublet Unscheduled Maintenance Plans - The GA-Doublet unscheduled maintenance plan is based on the level 2 sequence of activities listed in Table 4.3-14. The basic sequence is used to exchange one or more of the 1808 modules by use of maintenance equipment mounted at ports in the auxiliary vacuum ducts above the reactor. This equipment remains in place except when being maintained and is available for exchange of first wall/blanket modules without requiring the installation of additional equipment. The replacement procedure is the same for any module at this level of detail. Since all operations which govern the time required to accomplish this exchange operation are inside of the plasma chamber or are automated,

TABLE 4.3-14

GA-DOUBLET UNSCHEDULED MAINTENANCE ACTIVITY SEQUENCE

LEVEL 1 ACTIVITY	LEVEL 2 MAINTENANCE ACTIVITY
SHUTDOWN	REACTOR SHUTDOWN
ACCESS	OPEN VACUUM PORT HATCHES EXTEND MACHINES INTO CHAMBER ISOLATE LEAKING MODULE PREPARE FOR MODULE REMOVE
REMOVAL	REMOVE MODULE
REPLACEMENT	REPLACE MODULE
REASSEMBLY	PREPARE CHAMBER FOR STARTUP
STARTUP	VALIDATION AND STARTUP

the procedure shown is identical for either the partial contact or fully remote maintenance scenarios.

Other major assumptions which affect these maintenance activities for unscheduled first wall/blanket replacement are:

- o The failed module is assumed to be located in any sector at a position which requires the average time to replace a module.
- o Spare modules are available on demand.
- o Operations in the reactor room but external to the plasma chamber can be conducted within the time required for internal operations.
- o External equipment, such as NBI's, PF coils and structure, do require removal or relocation to gain access to the plasma chamber.
- o Shielding is provided around the maintenance equipment and all activated or contaminated components are kept in shielded casks when outside of the reactor and being moved to the hot cells.
- o All reactor components are interchangeable without adjustment in the reactor.
- o The failed module can be isolated to one sector by use of installed instrumentation without internal access to the reactor.
- o Personnel are available for all maintenance activities as required.
- o Time dilution factors for productivity are omitted in the computation of time estimates in this section.
- o During this unscheduled outage no other contingencies occur nor is other maintenance conducted which will interfere with the maintenance procedure.

4.3.4.1 Summary of Alternative Plans for the GA-Doublet Reference Reactor -

Maintenance plans have been developed for both partial contact and fully remote unscheduled maintenance scenarios applicable to the GA-Doublet reference reactor. The key characteristics of these plans are given in Table 4.3-15. This summary indicates that the time required for either contact or remote maintenance scenarios is the same and that the principal variations occur in the support equipment requirements and the number of personnel used for these operations.

For contact assisted operations a floor crew of three is used to support the machine operators conducting the maintenance operations on the sector where the failure occurred. This crew assists in the handling of casks and equipment moved in and out of the plasma chamber to speed the flow of traffic and prevent congestion on the floor. The maintenance operation requires four machine operators for the overhead remote manipulator, and the tugs. The operation of the equipment in the

TABLE 4.3-15
UNSCHEDULED GA-DOUBLET MAINTENANCE PLAN SUMMARY

TYPE OF MAINTENANCE		VACUUM WALL ARRANGEMENT	NUMBER OF SECTORS WORKED	NUMBER OF MODULES REPLACED/ OUTAGE	NUMBER OF EQUIPMENT SETS	NUMBER OF PERSONNEL REQUIRED	TOTAL OUTAGE TIME (HOURS)	LOST REVENUE COST (M\$)
CONTACT	REMOTE							
✓		1	1	1	.876	7	127.5	6.1
	✓	1	1	1	.855	4	127.5	6.1

NOTES: 1) ONE CONTACT MAINTENANCE EQUIPMENT SET WEIGHT = 9826.7 TONNES
2) ONE UNSCHEDULED MAINTENANCE EQUIPMENT SET WEIGHT = 2623.2 TONNES

plasma chamber is assumed to be controlled by the normal plant personnel from within the reactor control room.

The maintenance equipment required for replacement of one module is reduced from a complete set since the complete basic set is defined to handle eight units of remote maintenance equipment operating simultaneously in the plasma chamber.

The cost per outage in lost production shown in Table 4.3-15 is based on a cost of 48,206 \$/hour for the GA-Douplet as derived from the annual cost of operation when using the optimum scheduled maintenance plan discussed in the Section 4.4. The equation for this calculation is found in Section 4.3.1.

Table 4.3-16 defines the time required to conduct the level 2 sequence of operations for either contact assisted or remote unscheduled maintenance operations. When described at this level of detail these functions are all conducted in series when replacing only one module. Some of specific design assumptions that influence this maintenance plan are listed below.

- o The hatches in the auxiliary vacuum lines are closed by a shielded isolation valve which is operated automatically. This valve separates the maintenance equipment from the vacuum line when the reactor is operating. The valve closure plate is not replaced during this operation.
- o All maintenance machines are in place above the ports in the vacuum lines and are operative.
- o The modules are manifolded together to permit pressurization of groups of modules. Fault isolation is conducted by sensing helium in the plasma chamber. Three sectors are searched for the leaking module by inspecting two modules at a time.

4.3.4.2 GA-Douplet Maintenance Equipment Concept - The maintenance equipment required to exchange the first wall/blanket modules of the GA-Douplet reference reactor for the unscheduled maintenance scenarios is summarized in Table 4.3-17.

TABLE 4.3-16
GA-DOUBLET UNSCHEDULED MAINTENANCE PLAN FOR
FIRST WALL/BLANKET FAILURE
(VACUUM WALL AT NORMAL GA-DPR LOCATION)

LEVEL 1 TASK	LEVEL 2 TASK	DURATION (HRS)
SHUTDOWN	REACTOR SHUTDOWN	29:00
GAIN ACCESS	OPEN VACUUM PORT HATCHES	1:30
	EXTEND MACHINES INTO CHAMBER	10:00
	ISOLATE LEAKING MODULE	28:00
	PREPARE FOR MODULE REMOVAL	6:40
REMOVE	REMOVE MODULE	6:10
REPLACE	REPLACE MODULE	14:15
REASSEMBLE	PREPARE CHAMBER FOR STARTUP	8:00
STARTUP	VALIDATION AND STARTUP	24:00
TOTAL		127:35

The equipment in this table is constitutes one set of equipment when expanded to include the multiple units required for operating 8 Remote Maintenance Machines (RMM's) at one time and to handle the modules, workheads, racks and containers required for this operation.

The equipment summary in Table 4.3-17 lists the major functions performed and the physical parameters of each equipment item. Additional detailed functional descriptions and performance requirements of the more important equipment items are provided in Appendix B. Most of the equipment items are similar to those defined in the earlier study phase (Reference 4-1).

The maintenance equipment concept for the GA-Douplet reference reactor is designed to the following ground rules.

- o The Remote Maintenance Machine (RMM) is the key item of equipment and is shown in Figure 4.3-6. This machine is typical of the maintenance equipment design approach used for this reactor concept. Eight of these machines are mounted in place at alternate ports in the auxiliary vacuum line and remove and install first wall/blanket modules. A set of multiple workheads are installed on this machine outside of the reactor in a turret mechanism and are available for automatic replacement for the module replacement operation.

TABLE 4.3-17
GENERAL ATOMIC MAINTENANCE EQUIPMENT SUMMARY

ITEM DESIGNATION	MAJOR FUNCTIONS	OPERATING LOCATION	OTHER EQUIPMENT INTERFACED	LIFTING CAPABILITY	SIZE (L X W X H) WEIGHT: kg
OVERHEAD POLAR CRANES	<ul style="list-style-type: none"> o INSTALL REACTOR COMP o TRANSFER LOADER RACKS FROM FLOOR TO RLM 	TOP OF REACTOR ROOM	OVERHEAD REMOTE MANIPULATION & RLM LOADER RACKS	400 TONNES (MAIN) 2-25 TONNES (AUX)	100m X 6.0m X 12.0m WT = 4980 TONNES*
OVERHEAD REMOTE MANIPULATOR	SERVICE MAINTENANCE EQUIPMENT	TOP OF REACTOR ROOM	ALL MAINTENANCE EQUIPMENT, OVERHEAD CRANE	2 TONNES	100m X 40m X 8.0m WT = 1660 TONNES*
REMOTE MAINTENANCE MACHINE (RMM)	REMOVE & REPLACE BREEDING MODULES & MODULE PRESSURE VESSELS	MOUNTED ON TOP OF REACTOR, EXTENDS INTO PLASMA CHAMBER	RLM, WORKHEADS	281 kg	10.77m X 1.5m DIA 383 TONNES*
REMOTE LOADER MACHINE (RLM)	STAGE BREEDING MODULES AND MODULE COMPONENTS IN PLASMA CHAMBER DURING EXCHANGE OPERATIONS	MOUNTED ON TOP OF REACTOR, EXTENDS INTO PLASMA CHAMBER	RMM, LOADER RACKS	7.5 TONNES	11.84m X 1.5m DIA 176 TONNES*
LOADER RACK	HOLD BREEDING MODULES & COMPONENTS DURING REMOVAL & INSTALLATION	IN RLM	RLM, OVERHEAD CRANE	3810 kg	5.7m X 0.80m DIA 3400 kg (EMPTY)
REMOTE VIEWING MACHINE (RVM)	<ul style="list-style-type: none"> o MONITORS ACTIVITIES INSIDE PLASMA CHAMBER VIA TV CAMERAS & LIGHTS 	MOUNTED ON TOP OF REACTOR, EXTENDS INTO PLASMA CHAMBER		N/A	13.0m X 2.0m DIA 168 TONNES*
RMM WORKHEADS FOR: A) MOD. PRESS. VES. B) INTERMODULE GRAPHITE BLOCK C) GRAPHITE RING D) BREEDING MODULE E) INS & LEAK CHECK	INTERCHANGEABLE WORKHEADS WHICH: <ul style="list-style-type: none"> o GRASPS MODULES, PRESS. VESSELS, RINGS o EXCHANGES BREEDING MODULES o TORQUES MODULES & FASTENERS o LOCATES & INSTALLS COMPONENTS o CLEANS AND INSPECTS SEAL SURFACES o LEAK CHECKS MODULES 	PLASMA CHAMBER	RMM	381 kg	45 cm X 70 cm DIA 90-270 kg 200 kg (AVG)
LOADER RACK DOLLY(S)	HOLDS LOADER RACKS CONTAINING MODULES RINGS, ETC. DURING STAGING & TRANSIT	FLOOR OF REACTOR ROOM	OVERHEAD CRANE, TOW UNIT	25 TONNES	6.0m X 3.0m X 0.5m 13.4 TONNES*
SHIELDED TOW UNIT	MOVE EQUIPMENT DOLLIES FROM REACTOR ROOM TO HOT CELLS AND STAGING AREAS	FLOOR OF REACTOR ROOM	EQUIPMENT DOLLIES	N/A	5.0m X 2.0m X 3.5m 50,000 kg*
REMOTE EQUIPMENT DOLLIES	HOLDS RMM, RLM, OR RVM WHEN REMOVED FROM REACTOR	FLOOR OF REACTOR ROOM	RMM, RLM, RVM, TOW UNIT	383 TONNES	10m X 6m X 10m 40 TONNES*
WORKHEAD DOLLIES	HOLDS AN ARRAY OF VARIOUS WORKHEADS IN STAGING LOCATION DURING MAINTENANCE	FLOOR OF REACTOR ROOM	WORKHEADS, TOW UNIT	270 kg	3.0m X 2.5m X 0.5m 3,000 kg*
BREEDER MODULE CONTAINER	HOLDS BREEDER MODULES IN STAGING LOCATION DURING MAINTENANCE	STAGING AREA	BREEDER MODULES ARMS, MISC COMPONENTS, TOW UNIT	381 kg	70 cm DIA X 40 cm 600 kg
SHIELDED CONTAINERS	FITS OVER RLM. TO SHIELD LOADER RACK FROM MAINT. PERSONNEL	REACTOR ROOM	RLM, LOADER RACK DOLLY	N/A	5.0m X 1.80m OD WT = 95 TONNES*

*NOTE: ITEM WEIGHTS INCLUDE SHIELDING FOR CONTACT MAINTENANCE OPERATIONS

REMOTE MAINTENANCE MACHINE (RMM)

- RMM CONFIGURATION FOR EXCHANGING BREEDER MODULES – SIDE VIEW

FIGURE 4.3-6

- o The Remote Loader Machine (RLM) is installed at ports in the auxiliary vacuum lines of four evenly spaced sectors around the reactor. Each of the four machines services two RMM's. All module components are fed in and out of the plasma chamber through these machines.
- o The Remote Viewing Machine is also installed at ports in the auxiliary vacuum lines of four evenly spaced sectors. These machines provide illumination for the plasma chamber operations.
- o The remote overhead manipulator is used to support all loading and unloading operations external to the reactor within the capacity of this manipulator.
- o The overhead crane is used to remove and install the maintenance equipment when it requires servicing. This should not be required during a first wall/blanket replacement outage except for unscheduled failures. The light hook on this crane handles the movement of containers and auxiliary equipment between dollies on the floor and the top of the reactor.
- o The maintenance machines which require operating crews are the overhead cranes, overhead manipulators and the tugs used to move dollies about on the reactor room floor.
- o Handling equipment is required for all types of maintenance, including contact, because all reactor components and maintenance equipment are too heavy for manual handling.

A complete set of equipment contains the number of units of a particle equipment item that is required to handle replacement and storage of eight modules at a time. However, the unscheduled maintenance operations require only limited quantities of support equipment. The equipment items affected and the number that are required unscheduled contact operations are:

- o loader racks, 2 required.
- o loader rack dollies, 2 required,
- o tow unit (tug), 1 required
- o shield container, 1 required,
- o module container, 1 required,
- o remote equipment dollies, none required,
- o workhead dollies, none required,
- o spares dollies, none required.

For unscheduled remote maintenance operations the shielded container is also omitted and no shielding is provided for the remote maintenance machines and associated equipment.

4.4 SCHEDULED MAINTENANCE PLANS - Maintenance plans for scheduled maintenance of the first wall/blanket in the four reference reactor concepts utilize procedures and maintenance equipment almost identical in concept to those used for unscheduled maintenance. The principal exceptions are the elimination of all fault isolation procedures and the increase in the number of items of selected maintenance equipment to allow replacement of the first wall/blanket in several reactor sectors at one time. Coincidentally, the number of direct maintenance personnel is also increased.

For each reference concept, several maintenance plans have been developed for contact assisted and several for fully remote maintenance operations. Each plan in the set defined for each type of maintenance and reference reactor replaces a different fraction of the first wall/blanket. Except for the GA-Douplet, the wall fraction replaced in each maintenance plan always represents the first wall/blanket modules from an integer number of reactor sectors. The characteristics of different sets of these plans are used as input to the TOCOMO code and the plan with the lowest cost of electricity (COE) for a given maintenance mode, i.e., contact or remote, is selected as optimum for that mode. The results of these analyses are presented in Section 5.0 but, for illustrative purposes in this section, the timeline associated with each optimum (lowest COE) maintenance plan is presented. The timelines have been developed to include the necessary time for staggering operations and handling the multiple equipment sets required by parallel operations on several sectors. Since a detailed traffic analysis has not been conducted, such additional time requirements are conservatively estimated as serial operations instead of partially parallel.

In all cases, the reactor design concept assumptions affecting maintenance and maintenance equipment concept ground rules are the same as for unscheduled maintenance and will be found in the appropriate subsection of Section 4.3. The maintenance procedure assumptions are also quite similar to those used for unscheduled maintenance. Therefore, only significant variations will be listed in this section.

4.4.1 Culham Reference Reactor Scheduled Maintenance Plans - The basic functional sequence used when conducting all scheduled maintenance plans applicable to the Culham reference reactor is listed in Table 4.4-1. While this sequence is defined for only one sector of the reactor, it is conducted either simultaneously or sequentially among the sectors being worked and will not vary for any given sector. When multiple sectors are worked some additional time is required to stagger the use of items of equipment used in common, such as the poloidal overhead

TABLE 4.4-1
CULHAM REFERENCE REACTOR SCHEDULED MAINTENANCE ACTIVITY SEQUENCE

LEVEL 1 ACTIVITY	LEVEL 2 MAINTENANCE ACTIVITY
SHUTDOWN	REACTOR SHUTDOWN
GAIN ACCESS	MOVE NBI POLOIDAL MAGNET RETRACTION LATERAL SUPPORT PANEL REMOVAL REMOVE SHIELD DOOR DISCONNECT MODULE COOLANT MANIFOLD
REMOVE	REMOVE REACTOR MODULE DISCONNECT DIVERTOR MODULE MANIFOLD REMOVE DIVERTOR MODULE
INSPECTION	INSPECTION OF REMAINING MODULE
REPLACE	REPLACE DIVERTOR MODULE REPLACE REACTOR MODULE
REASSEMBLE	CONNECT DIVERTOR MODULE MANIFOLD CONNECT MODULE COOLANT MANIFOLD PRESSURIZE COOLANT MANIFOLD AND TEST REPLACE SHIELD DOOR LATERAL SUPPORT PANEL REPLACEMENT REPOSITION POLOIDAL MAGNETS REINSTALL NBI
STARTUP	VALIDATION AND STARTUP

crane or the reactor room peripheral transport carriages. This additional time is included in the maintenance plans.

4.4.1.1 Culham Maintenance Plan Summary - Maintenance plans have been developed for six different scenarios for contact maintenance and six scenarios for remote maintenance modes of operation. Each scenario constitutes a different combination of first wall/blanket fraction replaced and number of sectors being worked at one time. The significant characteristics of these 12 plans are summarized in Table 4.4-2. This table indicates the data derived for use in the TOCOMO analysis discussed in Section 5.0. A more detailed description of the procedure used to derive the scheduled maintenance plan data for the Culham reference reactor is found in the example used in Section 4.1.

TABLE 4.4-2

CULHAM MAINTENANCE PLAN SUMMARY

MAINTENANCE TYPE		VACUUM WALL ARRANGEMENT	NUMBER OF SECTORS REWORKED/ IN WORK	NUMBER OF MODULES REPLACED/ OUTAGE	NUMBER OF MAINTENANCE EQUIPMENT SETS	NUMBER OF DIRECT PERSONNEL	TOTAL OUTAGE TIME (HRS)
CONTACT	REMOTE						
✓		3 ↓	16	8	3.27	116	850.6
✓			16	4	2.78	44	1245.3
✓			8	8	2.62	82	546.4
✓			8	4	2.13	44	891.9
✓			4	4	1.76	44	462.3
✓			4	2	1.44	22	802.5
	✓	3 ↓	16	8	3.26	50	1137.2
	✓		16	4	2.78	26	1858.9
	✓		8	8	2.62	50	679.4
	✓		8	4	2.13	26	1168.3
	✓		4	4	1.76	26	608.1
	✓		4	2	1.44	14	1060.5

NOTE: 1) ONE MAINTENANCE EQUIPMENT SET INCLUDING SPARES WEIGHS 3310.80 TONNES.

2) OUTAGE TIME SHOWS UNDILUTED HOURS.

The vacuum wall arrangement with the primary vacuum barrier at the reactor room wall is selected for both the partial contact and fully remote maintenance scenarios based on the fact that this arrangement produced the minimum outage time. Wall fractions of 100, 50 and 25 percent are selected with all sectors being worked at one time or only half being worked at one time, with one exception. When 16 sectors are to be reworked the traffic congestion for working on 16 sectors at one time appears unreasonable so only one half and one quarter of the sectors are worked at one time.

The number of maintenance sets is defined in the manner illustrated in Section 4.1 with individual items of equipment added as required to handle the number of sectors being worked at one time. The total number of sectors being worked also influences the amount of equipment required. The multiple units required increased the equivalent sets from 1.44 to 3.27 for either contact or remote maintenance modes of operation. The minor differences discussed for unscheduled maintenance in Section 4.3.1 still apply for scheduled maintenance.

The number of direct personnel required increased in accordance with both the number of maintenance units requiring operators and with the floor crew size required to support these units when using contact assisted maintenance operations. Floor crews of 12, 24, and 48 are required when processing 2, 4 and 8 sectors at one time, respectively. When using the remote maintenance mode, the maximum number of personnel are required at a different point in the procedure than for

contact maintenance and, therefore, the personnel required for the fully remote maintenance scenario is greater than simply deleting the floor crews from the contact maintenance scenarios. It is assumed that a reserve of operators and floor crew are available since some functions require more operators and fewer floor crew and visa-versa. The maximum total used for cost computations is given in Table 4.4-2.

The maintenance scenario that attains the maximum availability and minimum COE when using contact assisted maintenance occurs when replacing the first wall/blanket in 8 sectors and when working on all 8 sectors at one time. The timeline for this scenario is illustrated in Figure 4.4-1. The total undiluted time for this scenario is estimated to be approximately 546 hours. This time is extended from the approximately 315 hours required when conducting unscheduled maintenance (297 hours without fault isolation) by the time required to emplace equipment, exchange workheads and move equipment and components in succession through the reactor room. The handling of 8 sectors does not assume time sharing of maintenance equipment except the circumferential transporter carriages and the overhead poloidal crane. Contact assisted maintenance is utilized up to the point where the shield door is moved and after the shield door is returned to its position on the reactor.

For fully remote maintenance the scenario that attained maximum availability and minimum COE uses the same wall fraction and replacement rate as the partial contact maintenance optimum scenario, that is, exchange 8 sectors all at the same time. When using fully remote maintenance, the total undiluted time for this

**CULHAM REFERENCE REACTOR MAINTENANCE SCENARIO
— SCHEDULED CONTACT MAINTENANCE**

FIGURE 4.4-1

exchange is approximately 680 hours. This time is based on the unscheduled maintenance time of 444 hours for one sector (426 hours without fault isolation). Figure 4.4-2 illustrates the level 1 flow of the maintenance operations for this scenario.

**CULHAM REFERENCE REACTOR MAINTENANCE SCENARIO
- SCHEDULED REMOTE MAINTENANCE**

FIGURE 4.4-2

4.4.1.2 Culham Maintenance Equipment Concept - The maintenance equipment concept for the Culham reference reactor scheduled maintenance operations is almost identical whether using contact or remote maintenance. The only difference is the deletion of a mobile manlift device when using remote operations. Also, the concept does not vary from that used for unscheduled maintenance when applied to scheduled maintenance. The more detailed listing of equipment and performance is presented in Section 4.3.1 and Appendix B.

Table 4.4-3 contains the number of units of each equipment item used for the Culham base set, spares set and for the set required to replace 8 sectors at one time during a scheduled outage. Some equipment items such as shield plugs and small tools are provided at the rate of two to one sector but most of the items are only provided at the rate of one per sector. Only six OMU's are used since only six NBI's are removed for the scenarios which replace the first wall/blanket of 8 sectors during one outage. Also, only four inspection workheads are used since each of these workheads is capable of inspecting the full sector on either side of the sector through which access is provided.

In all cases the overhead crane is excluded from the equipment set because the set weight is used by TOCOMO to calculate the equipment costs presented in Section

TABLE 4.4-3
CULHAM MAINTENANCE EQUIPMENT SET COMPOSITION

ITEM NO.	MAINTENANCE EQUIPMENT ITEMS	ITEM WT (MT)	BASE EQUIPMENT SET		SPARES SET		8 EQUIPMENT SETS	
			QUANTITY	SET WEIGHT	QUANTITY	SET WEIGHT	QUANTITY	SET WEIGHT
1	POLOIDAL CRANE	4980.00*	1	4980.00	0	0.00	1	4980.00
2	TUG VEHICLE	80.00	1	80.00	1	80.00	8	640.00
3	OVERHEAD REMOTE MANIPULATOR	1660.00	1	1660.00	0	0.00	1	1660.00
4	OPERATIONAL MAINTENANCE UNIT (OMU)	77.50	1	77.50	1	77.50	6	465.00
5	NBI PORT PLUG	1.25	1	1.25	1	1.25	16	20.00
6	NBI PORT PLUG DOLLY	.50	1	.50	1	.50	8	4.00
7	NBI INJECTOR DUCT SLING	1.00	1	1.00	1	1.00	8	8.00
8	NBI INJECTOR DUCT T&S DOLLY	2.00	1	2.00	1	2.00	8	16.00
9	LINE CONNECTOR INSTALL/REMOVE TOOL	.30	1	.30	2	.60	16	4.80
10	IMPACT WRENCH	.40	1	.40	2	.80	16	6.40
11	MOBILE MANLIFT UNIT	.30	1	.30	1	.30	16 (0)**	4.80
12	PRIMARY MAINTENANCE MACHINE	250.00	1	250.00	1	250.00	8	2000.00
13	LSAP WORKHEAD	70.00	1	70.00	1	70.00	8	560.00
14	LSAP & LSAP WORKHEAD T&S DOLLY	50.00	1	50.00	1	50.00	8	400.00
15	SHIELD DOOR WORKHEAD	75.00	1	75.00	1	75.00	8	600.00
16	SHIELD DOOR & WORKHEAD T&S DOLLY	60.00	1	60.00	1	60.00	8	480.00
17	AUXILIARY SERVICES WORKHEAD	13.00	1	13.00	1	13.00	8	104.00
18	AUXILIARY SERVICES WORKHEAD DOLLY	4.00	1	4.00	1	4.00	8	32.00
19	HELIUM COOLANT MANIFOLD COVER	3.50	1	3.50	1	3.50	8	28.00
20	HELIUM MANIFOLD COVER DOLLY	1.00	1	1.00	1	1.00	8	8.00
21	REACTOR MODULE TRANSPORTER	20.00	1	20.00	3	60.00	16	320.00
22	DIVERTOR MODULE WORKHEAD	9.00	1	9.00	1	9.00	8	72.00
23	DIVERTOR MODULE WORKHEAD DOLLY	3.00	1	3.00	1	3.00	8	24.00
24	DIVERTOR MODULE T&S DOLLY	3.00	1	3.00	1	3.00	16	48.00
25	INSPECTION WORKHEAD	60.00	1	60.00	1	60.00	4	240.00
26	INSPECTION WORKHEAD DOLLY	20.00	1	20.00	1	20.00	4	80.00
27	LEAK TEST WORKHEAD	.30	1	.30	1	.30	16	4.80
			TOTAL SET WT. = 7445.05		TOTAL SET WT. = 845.75		TOTAL SET WT. = 12809.80	
			-4980.00				-4980.00	
			NET SET WT. = 2465.05				NET SET WT. = 7829.80	

* OVERHEAD CRANE NOT INCLUDED IN SET WEIGHT

** QUANTITY REVISED TO PARENTHICAL AMOUNT WHEN CONDUCTING REMOTE MAINTENANCE.

5.0 separately from the crane cost. Crane costs are included in plant facility costs.

4.4.2 UWMAK-III Reference Reactor Scheduled Maintenance Plans - The level 2 functional sequence used when conducting scheduled maintenance on the first wall/blanket of the UWMAK-III reference reactor is the same for either contact assisted or fully remote operations. This sequence is shown at the second level of detail in Table 4.4-4. The sequence in Table 4.4-4 is listed for only one sector but it is applicable to maintenance plans involving any number of sectors, whether the maintenance is conducted simultaneously on all sectors or sequentially on the sectors being reworked. When multiple sectors are reworked additional time is required to stagger the use of equipment items that are applied to more than one sector, e.g., the poloidal overhead crane. This additional time is included in the maintenance plans.

The sequence shown in Table 4.4-4 differs from that used for the unscheduled maintenance primarily by the omission of the fault isolation sequences and by use

TABLE 4.4-4

UWMAK-III REFERENCE REACTOR SCHEDULED MAINTENANCE ACTIVITY SEQUENCE

LEVEL 1 ACTIVITY	LEVEL 2 MAINTENANCE ACTIVITIES
SHUTDOWN	REACTOR SHUTDOWN
GAIN ACCESS	MOVE NBI LATERAL SUPPORT ACCESS PANEL REMOVAL POLOIDAL MAGNET RETRACTION NBI BEAM DUCT REMOVAL LITHIUM MANIFOLD REMOVAL CENTRAL WALL MODULE MANIFOLD DISCONNECT RAISE/LOWER SHIELD SEGMENTS
REMOVE	"A" MODULE REMOVAL GRAPHITE ISSEC REMOVAL "B" MODULE & CENTRAL WALL MODULE REMOVAL
INSPECT	INSPECTION OF REMAINING MODULES
REPLACE	CENTRAL WALL MODULE & "B" MODULE REPLACEMENT GRAPHITE ISSEC REPLACEMENT "A" MODULE REPLACEMENT
REASSEMBLE	SHIELD SEGMENT REPLACEMENT CENTRAL WALL MODULE MANIFOLD RECONNECT LITHIUM MANIFOLD RECONNECT LEAK TEST LITHIUM MANIFOLD CONNECTIONS NBI BEAM DUCT REPLACEMENT REPOSITION POLOIDAL MAGNETS LATERAL SUPPORT ACCESS PANEL REPLACEMENT REINSTALL NBI
STARTUP	VALIDATION AND STARTUP

of a prescheduled shutdown procedure. For scheduled maintenance operations the vacuum wall arrangement number 2 is selected to utilize a variation in the wall arrangement and determine whether the wall fraction for optimum maintenance is affected by the vacuum wall arrangement. Therefore, the sequence differs from that described for unscheduled maintenance by requiring a different NBI beam duct disconnect arrangement and a separate beam duct removal and installation.

4.4.2.1 UWMAK-III Maintenance Plan Summary - The alternate maintenance plans are defined for wall fractions as low as 1/8 for the UWMAK-III. The eight plans defined for partial contact maintenance and the six defined for fully remote maintenance modes of operation are summarized in Table 4.4-5. In each of these

plans the "A" module, one of the two "B" modules, one of the two divertor modules and one-half of the ISSEC panels are replaced in each sector that is reworked. For the contact assisted maintenance mode plans are developed to rework a maximum of 8 sectors (wall fraction of 1/2). When reworking 8 sectors either 8 or 4 sectors are reworked at one time. The maximum wall fraction is increased to 1 when developing the plans which use fully remote operations.

TABLE 4.4-5
UWMAK-III MAINTENANCE PLAN SUMMARY

MAINTENANCE TYPE		VACUUM WALL ARRANGEMENT	NUMBER OF SECTORS REWORKED/ IN WORK	NUMBER OF MODULES REPLACED/ OUTAGE	NUMBER OF MAINTENANCE EQUIPMENT SETS	NUMBER OF DIRECT PERSONNEL	TOTAL OUTAGE TIME (HOURS)
CONTACT	REMOTE						
✓		2	8-8	1A, 1B, ISSEC & DIVERTOR ↓	4.427	146	1023.41
✓		2	8-4		3.044	74	1527.83
✓		2	8-2		2.416	42	2900.66
✓		2	4-4		2.325	70	857.41
✓		2	4-2		1.795	38	1421.83
✓		2	4-1		1.458	20	2685.66
✓		2	2-2		1.469	38	769.41
✓		2	2-1		1.133	20	1337.83
	✓	2	16-8		5.100	50	2351.00
	✓	2	16-4		3.789	26	4073.91
	✓	2	8-8	↓	4.412	50	1408.66
	✓	2	8-4		3.098	26	2270.50
	✓	2	4-4		2.443	26	1228.75
	✓	2	4-2	↓	1.787	14	2164.50

NOTES: 1) ONE MAINTENANCE EQUIPMENT SET WEIGHT (INCLUDING SPARES) = 2527.75 TONNES
2) OUTAGE TIME SHOWS UNDILUTED HOURS

For the UWMAK-III the number of equipment equivalent sets increases with the total number of sectors being reworked and the number reworked at one time. For this concept, the number of equivalent sets varies slightly between contact and remote maintenance when working on equivalent wall fractions. These variations are discussed later in this section.

The maximum number of direct personnel required for contact maintenance include floor crews of 12, 24, 48 or 96 men when working on 1, 2, 4 or 8 sectors at one time. The maximum number of personnel are required for the removal and installation of the lithium manifolds. Fewer personnel are required for the other tasks where contact maintenance operations are used. For remote maintenance operations, the personnel required are only equipment operators with the maximum number required during the raising and lowering of the shield doors. These estimates do not consider sequencing operations to spread the number of maintenance personnel more uniformly over the outage period.

The maintenance plans for either the contact assisted maintenance mode or the fully remote mode result in the minimum COE and maximum availability when reworking a total of 8 sectors and 8 sectors at one time. Figure 4.4-3 depicts the task flow for a level 1 functional task timeline. This flow indicates that the tasks on all sectors are conducted in parallel but the total time for each task allows for staggered utilization of common maintenance equipment or other time allowances for traffic and multiple operations.

For the partial contact maintenance plan the increase in time required brings the total time to approximately 1024 hours for 8 sectors from approximately 784 hours for a single sector of unscheduled maintenance or 680 hours for maintenance without fault isolation. Contact assisted maintenance is utilized up to the opening of the shield doors and all sectors must be delayed until all are ready to open the doors. Contact maintenance is resumed after the shield doors are closed and the reactor room is checked for contamination.

Figure 4.4-4 illustrates the functional task flow for fully remote operations similar to that shown for contact assisted operations. The time required for the module replacement is approximately the same as shown for the contact assisted maintenance mode since fully remote operations are required for this task in both maintenance plans.

The remote maintenance plan for 8 sectors conducted 8 at one time requires approximately 1409 hours. This is an extension of the time for a single sector from approximately 1156 hours for unscheduled maintenance or from 1051 hours for maintenance without the fault isolation tasks.

UWMAK—III REFERENCE REACTOR MAINTENANCE SCENARIO — SCHEDULED CONTACT MAINTENANCE

FIGURE 4.4-3

UWMAK-III REFERENCE REACTOR MAINTENANCE SCENARIO - SCHEDULED REMOTE MAINTENANCE

FIGURE 4.4-4

4.4.2.2 UWMAK-III Maintenance Equipment Concept - The maintenance equipment concept for scheduled maintenance operations on multiple sectors at one time is the same as that used for unscheduled operations except that multiple units of equipment are required for selected items. The description of the individual equipment items and their performance is given in Section 4.3.2 and in Appendix B.

Table 4.4-6 defines the number of units of each item of equipment in the basic equipment set, those required for spares and the quantity required to work on 8 sectors at one time. The equipment list for the eight sectors is defined for contact operations with the changes required for remote operations indicated in parentheses. Remote operations do not require NBI port plugs or dollies for their movement, nor do they require mobile manlife devices. The only addition is a remotely operated tool for disconnecting and reconnecting fluid or power lines.

In all cases the overhead crane is not included in the equipment set since this is costed as a facility in the TOCOMO code. The crane costs for all reactor concepts are a constant because the hoist performance is estimated to be a constant and the reactor room diameter is also kept constant.

Some equipment items require multiples of eight when working on eight sectors at one time. These include the shield screw jacks which use a set of four for each set of shield doors, lithium line freeze plugs, NBI port plugs and mobile manlift units. Two of the manlift units are required for each sector to remove the bolts from both sides of the LSAP at the same time. For those maintenance plans which conduct operations on only one-half of the reworked sectors at one time some equipment items must still be supplied at the rate of one per reworked sector. These

TABLE 4.4-6
UWMAK-III MAINTENANCE EQUIPMENT SET COMPOSITION

ITEM NO.	MAINTENANCE EQUIPMENT ITEMS	ITEM WT (MT)	BASE EQUIPMENT SET		SPARES SET		8 EQUIPMENT SETS	
			QUANTITY	SET WEIGHT	QUANTITY	SET WEIGHT	QUANTITY	SET WEIGHT
1	OVERHEAD CRANE	4980.00*	1	4980.00	0	0.00	1	4980.00
2	PRIMARY MAINTENANCE MACHINE	250.00	1	250.00	1	250.00	8	2000.00
3	LSAP WORKHEAD	70.00	1	70.00	1	70.00	8	560.00
4	LSAP WORKHEAD DOLLY	50.00	1	50.00	1	50.00	8	400.00
5	AUXILIARY SERVICES DOLLY	40.00	1	40.00	1	40.00	8	320.00
6	LITHIUM MANIFOLD DOLLY	7.00	1	7.00	1	7.00	8	56.00
7	SCREW JACKS (SHIELD)	30.00	4	30.00	2	60.00	32	960.00
8	SCREW JACKS & SHIELD PLUG DOLLY	70.00	2	70.00	1	70.00	8	560.00
9	MODULE HANDLING MACHINE (MHM)	174.00	1	174.00	1	174.00	8	1392.00
10	"A" MODULE WORKHEAD	35.00	1	35.00	1	35.00	8	280.00
11	"A" MODULE & WORKHEAD DOLLY	40.00	1	40.00	1	40.00	8	320.00
12	"B" MODULE WORKHEAD	14.00	1	14.00	1	14.00	8	112.00
13	"B" MODULE WORKHEAD DOLLY	5.00	1	5.00	1	5.00	8	40.00
14	"B" MODULE T&S DOLLY	10.00	1	10.00	1	10.00	8	80.00
15	ISSEC PANELS WORKHEAD	9.00	1	9.00	1	9.00	8	72.00
16	ISSEC PANELS WORKHEAD DOLLY	2.50	1	2.50	1	2.50	8	20.00
17	ISSEC PANELS T&S DOLLY	3.00	1	3.00	1	3.00	8	24.00
18	INSPECTION WORKHEAD	120.00	1	120.00	1	120.00	8	960.00
19	INSPECTION WORKHEAD DOLLY	40.00	1	40.00	1	40.00	8	320.00
20	CENTRAL CORE MAINTENANCE DEVICE	18.00	1	18.00	1	18.00	4	72.00
21	AUXILIARY SERVICES WORKHEAD DOLLY	15.00	1	15.00	1	15.00	8	120.00
22	LITHIUM LINE FREEZE UNITS	.10	8	.10	4	.40	32	3.20
23	TUG VEHICLE	80.00	1	80.00	1	80.00	8	640.00
24	OPERATIONAL MAINTENANCE UNIT	77.50	1	77.50	1	77.50	8	620.00
25	NBI PORT PLUG	1.25	2	1.25	1	1.25	16 (0**)	20.00
26	NBI PORT PLUG DOLLY	.50	1	.50	1	.50	8 (0**)	4.00
27	NBI INJECTOR DUCT T&S DOLLY	2.00	1	2.00	1	2.00	8	16.00
28	NBI INJECTOR DUCT SLING	1.00	1	1.00	1	1.00	8	8.00
29	MOBILE MANLIFT UNIT	1.00	4	1.00	1	1.00	16 (0**)	16.00
30	IMPACT WRENCH	.40	1	.40	2	.80	8	3.20
31	LINE CONNECTOR INSTALL/REMOVE TOOL	.30	0	.30	2	.60	0 (+8)**	0.00
			TOTAL SET WT. = 6311.20		TOTAL SET WT. = 1197.55		TOTAL SET WT. = 14978.40	
			-4980.00				-4980.00	
			NET SET WT. = 1331.20				NET SET WT. = 9998.40	

* OVERHEAD CRANE NOT INCLUDED IN SET WEIGHT

** QUANTITY REVISED AS IN PARENTHESES FOR REMOTE MAINTENANCE SCENARIO

include a workhead and/or dolly for each LSAP, lithium manifold, "A" module, "B" module, divertor module and NBI beam duct. These units generally require this support equipment during storage while awaiting installation.

4.4.3 ORNL Cassette Reference Reactor Scheduled Maintenance Plans - The level 2 functional sequence employed when conducting scheduled maintenance on the first wall/blanket of the ORNL Cassette reference reactor is given in Table 4.4-7. The sequence listed is for maintenance which employs contact maintenance assistance whenever possible. The sequence will differ when the fully remote maintenance mode is employed because the NBI beam duct is removed with the shield block. This sequence applies when the vacuum wall arrangement using the reactor room wall as the primary vacuum barrier is employed. Under these conditions only one connection is required in the NBI beam duct and shielding to protect personnel is not required.

TABLE 4.4-7

ORNL CASSETTE REFERENCE REACTOR SCHEDULED MAINTENANCE ACTIVITY SEQUENCE

LEVEL 1 ACTIVITY	LEVEL 2 MAINTENANCE ACTIVITIES
SHUTDOWN	REACTOR SHUTDOWN
GAIN ACCESS	MOVE NBI POLOIDAL MAGNET RETRACTION LATERAL SUPPORT PANEL REMOVAL
REMOVE	DISCONNECT CASSETTE MANIFOLDS NBI BEAM DUCT REMOVAL** SHIELD BLOCK REMOVAL 'A' REGION CASSETTE REMOVAL (5 CASSETTES) 'B,' 'C,' & 'D' REGION FBZ CASSETTE REMOVAL 'C' REGION 2ND BZ CASSETTE REMOVAL (3) DIVERTOR MODULE REMOVAL
INSPECT	INSPECTION OF 2ND BZ AND ADJACENT SECTOR
REPLACE	DIVERTOR MODULE REPLACEMENT 'C' REGION 2ND BZ CASSETTE REPLACEMENT (3) 'B,' 'C,' & 'D' REGION FBZ CASSETTE REPLACEMENT 'A' REGION CASSETTE REPLACEMENT (5 CASSETTES) SHIELD BLOCK REPLACEMENT NBI BEAM DUCT REPLACEMENT** CONNECT CASSETTE MANIFOLDS
REASSEMBLE	LEAK TEST MANIFOLD CONNECTIONS LATERAL SUPPORT PANEL REPLACEMENT REPOSITION POLOIDAL MAGNETS REINSTALL NBI
STARTUP	VALIDATION AND STARTUP

**NOT INCLUDED IN REMOTE MAINTENANCE SCENARIOS.

The sequence listed in Table 4.4-7 shows the functions required when reworking only one sector during the scheduled outage. However, it is applicable also for the rework of several sectors whether all at one time or in series. As in the case of the UWMAK-III and Culham reference reactors, when multiple sectors are worked at one time additional time must be allowed for delays arising from traffic in the reactor room and multiple usage of common equipment. This additional time is included in the maintenance plans presented in this section.

The scheduled maintenance sequence differs from the unscheduled sequence only by the use of a preplanned scheduled shutdown sequence and the omission of the fault isolation function.

4.4.3.1 ORNL Cassette Maintenance Plan Summary - Six alternate maintenance plans have been defined for partial contact assistance during replacement of the first wall/blanket first blanket zone and six plans have been defined for fully remote replacement operations. The characteristics of these twelve plans are listed in Table 4.4-8. For both types of maintenance the rework of 16 sectors at one time is deemed to be impractical because of traffic requirements and, therefore, a maximum of 8 sectors being reworked at one time is used. For each reactor sector a total of 18 cassettes are replaced to replace the First Blanket Zone (FBZ) and a proportionate amount of the second blanket zone. The example used in the maintenance plans replaced 5 cassettes in the lower outer wall (two of these are required to provide clearance for upper outer wall cassettes) and six cassettes in the upper outer wall (the B region). The six cassettes replaced in the upper outer wall included three in the second blanket zone to replace 1/4 of the second zone cassettes for a sector. The three cassettes in the bottom wall (the C region), and the three in the inner wall (the D region) are all FBZ cassettes. The divertor cassette is a single module for each sector for all three zones because of the divertor geometry. Other outages will replace the second blanket zone cassettes in the A, C and D regions.

The number of equipment sets required for the ORNL Cassette concept increases slightly when using fully remote maintenance operations instead of contact. This fluctuation is discussed later in this section.

The direct personnel required to conduct the contact assisted maintenance operations includes maximum floor crews of 12, 24 or 48 personnel when reworking

TABLE 4.4-8
ORNL CASSETTE MAINTENANCE PLAN SUMMARY

MAINTENANCE TYPE		VACUUM WALL ARRANGEMENT	NUMBER OF SECTORS REWORKED/ IN WORK	NUMBER OF MODULES REPLACED/ OUTAGE	NUMBER OF MAINTENANCE EQUIPMENT SETS	NUMBER OF DIRECT PERSONNEL	TOTAL OUTAGE TIME (HOURS)
CONTACT	REMOTE						
✓		3	16-8	5A's, 6B's, 3C's, 3D's, +DIVERTOR ↓	4.376	68	1789.66
✓		3	16-4		3.033	44	3172.08
✓		3	8-8		4.220	76	988.58
✓		3	8-4		2.721	44	1795.00
✓		3	4-4		2.502	44	911.00
✓		3	4-2		1.617	22	1669.00
	✓	3	16-8		4.716	74	2042.50
	✓	3	16-4	↓	3.026	38	3687.42
	✓	3	8-8		4.478	74	1154.00
	✓	3	8-4		2.714	38	2071.00
	✓	3	4-4		2.495	38	1080.00
	✓	3	4-2		1.613	26	2014.97

NOTES: 1) ONE MAINTENANCE EQUIPMENT SET WEIGHT (INCLUDING SPARES) = 1407.84 TONNES
2) OUTAGE TIME IS IN UNDILUTED HOURS

2, 4 or 8 sectors at one time. The remaining personnel listed in Table 4.4-8 are equipment operators. The number of personnel required, however, is made up of a slightly smaller floor crew and more machine operators when removing or installing the LSAP. The assumption is made that the required skills are available when needed during an outage. For contact maintenance, some saving in down time is realized with the addition of four tugs and the required operators when replacing a total of 8 sectors and working 8 at a time in contrast with replacing 16 sectors and working 8 at a time. Therefore, this maintenance scenario requires 8 additional personnel. The number of personnel required for remote operations are all machine operators and are required during the removal and installation of the NBI beam duct, the shield blocks and the A, B and C region cassettes.

The maintenance plans for either the contact assisted maintenance mode or the fully remote mode result in the minimum COE and maximum availability when replacing the cassettes in a total of 8 sectors and working on 8 sectors at one time. Figure 4.4-5 shows the down time estimated for the partial contact maintenance plan and Figure 4.4-6 defines the downtime for the fully remote maintenance plan. Both figures uses a level 1 breakdown of the maintenance functions. In these plans the exchange of cassettes involves contact operations until the removal of the shield blocks and also after their replacement. Therefore, the time required for these functions is less when employing contact operations even though a downtime penalty exists because the contact operations on all sectors must be completed before the plasma chamber can be opened. A similar condition exists during reassembly of the reactor when contact operations are started again.

**ORNL REFERENCE REACTOR MAINTENANCE SCENARIO
- SCHEDULED CONTACT MAINTENANCE**

FIGURE 4.4-5

ORNL REFERENCE REACTOR MAINTENANCE SCENARIO - SCHEDULED REMOTE MAINTENANCE

FIGURE 4.4-6

The increase in downtime required when replacing 8 sectors as shown in Figure 4.4-5 brings the total downtime for the partial contact maintenance plan to approximately 989 hours. This time is based on the unscheduled replacement time for a single leaking cassette of approximately 559 hours (521 hours without fault isolation and preplanned shutdown) which is discussed in Section 4.3.3. The causes for the extended downtime are similar to those experienced for the UWMAK-III and the Culham reference reactors.

The total downtime required for the outage when employing fully remote operations is shown by Figure 4.4-6 to be approximately 1154 hours. This is an extension of the unscheduled downtime for one sector from approximately 643 hours (605 hours without fault isolation and preplanned shutdown). In comparing this downtime with that for contact assisted maintenance the time for gaining access using fully remote operations is shorter than for contact maintenance. This arises from the necessity to install NBI port plugs to permit contact operations to continue. These plugs are also needed during reassembly. However, during reassembly the total benefit from contact operations overrides this downtime increment and the net result is that contact reassembly operations require less downtime than remote reassembly operations.

4.4.3.2 ORNL Cassette Reference Reactor Maintenance Equipment Concept - The maintenance equipment concept for scheduled maintenance operations on multiple sectors of the ORNL Cassette reference reactor is the same as that used for unscheduled operations except that some items require multiple units of equipment.

The individual equipment item descriptions and their performance is given in Section 4.3.3 and in Appendix B.

Table 4.4-9 lists the quantity required for each equipment item used in this concept for the basic equipment set, the set of equipment spares and for the 8 sets of equipment required to rework 8 sectors. The UWMAK-III and the Culham concepts treat the overhead crane as a facility and this crane remains a constant. The equipment list for 8 sets is defined for contact assisted maintenance with the quantity changes required for remote operations noted in parentheses. For remote operations, four additional OMU's are required to assist in the removal of LSAP bolts instead of using men as in contact maintenance operations.

4.4.4 GA-Doublet Scheduled Maintenance Plans - The level 2 functional sequence used when conducting scheduled maintenance on the first wall/blanket of the GA-Doublet reference reactor is the same for either contact or remote maintenance operations. This sequence of maintenance activities is listed in Table 4.4-10. Since the com-

TABLE 4.4-9
ORNL CASSETTE CONCEPT MAINTENANCE EQUIPMENT SET COMPOSITION

ITEM NO.	MAINTENANCE EQUIPMENT ITEMS	ITEM WT (MT)	BASE EQUIPMENT SET		SPARES EQUIPMENT SET		8 EQUIPMENT SETS	
			QUANTITY	SET WEIGHT	QUANTITY	SET WEIGHT	QUANTITY	SET WEIGHT
1	POLOIDAL CRANE	4980.00*	1	4980.00	0	0.00	1	4980.00
2	PRIMARY MAINTENANCE MACHINE	250.00	1	250.00	1	250.00	8	2000.00
3	OPERATIONAL MAINTENANCE UNIT	77.50	1	77.50	1	77.50	4(+4)**	310.00
4	TUG VEHICLE	80.00	1	80.00	1	80.00	8	640.00
5	LINE CONNECTOR INSTALL/REMOVE TOOL	.20	1	.20	2	.40	8	1.60
6	IMPACT WRENCH	.40	1	.40	2	.80	8	3.20
7	NBI PORT PLUG	1.25	1	1.25	2	2.50	16	20.00
8	NBI PORT PLUG DOLLY	.75	1	.75	1	.75	8	6.00
9	LSAP WORKHEAD	70.00	1	70.00	1	70.00	8	560.00
10	LSAP & WORKHEAD DOLLY	50.00	1	50.00	1	50.00	0	0.00
11	INJECTOR DUCT & SHIELD BLOCK WORKHEAD	18.00	1	18.00	1	18.00	8	144.00
12	INJECTOR DUCT & SHIELD BLOCK WORKHEAD DOLLY	3.00	1	3.00	1	3.00	8	24.00
13	NBI INJECTOR DUCT T&S DOLLY	15.00	1	15.00	1	15.00	8	120.00
14	INSPECTION & LEAK CHECK WORKHEAD	1.70	1	1.70	1	1.70	8	13.60
15	INSPECTION & LEAK CHECK WORKHEAD DOLLY	.50	1	.50	1	.50	8	4.00
16	A, B & C CASSETTE WORKHEAD	90.00	1	90.00	1	90.00	8	720.00
17	A, B & C CASSETTE WORKHEAD DOLLY	2.00	1	2.00	1	2.00	8	16.00
18	"A" CASSETTE T&S DOLLY	3.00	1	3.00	1	3.00	8	24.00
19	"B" CASSETTE T&S DOLLY	3.00	1	3.00	1	3.00	8	24.00
20	"C" CASSETTE T&S DOLLY	3.00	1	3.00	1	3.00	8	24.00
21	"D" CASSETTE T&S DOLLY	5.00	1	5.00	1	5.00	8	40.00
22	"D" CASSETTE WORKHEAD SET	3.40	1	3.40	1	3.40	8	27.20
23	DIVERTOR MODULE WORKHEAD	14.00	1	14.00	1	14.00	8	112.00
24	DIVERTOR MODULE WORKHEAD DOLLY	3.00	1	3.00	1	3.00	8	24.00
25	DIVERTOR MODULE T&S DOLLY	3.00	1	3.00	1	3.00	8	24.00
26	MOBILE MANLIFT UNIT	6.12	1	6.12	1	6.12	16(-16)**	97.92
			TOTAL SET WT. = 5683.82		TOTAL SET WT. = 704.02		TOTAL SET WT. = 9959.52	
			-4980.00				-4980.00	
			NET SET WT. 703.82				NET SET WT. 4979.52	

*OVERHEAD CRANE NOT INCLUDED IN SET WEIGHTS

**QUANTITY REVISED TO PARENTHETICAL AMOUNT FOR REMOTE MAINTENANCE

plete set of equipment required to remove all of the modules is installed on the reactor during its operation this sequence of activities does not vary with the quantity of modules replaced except to repeat the removal and replacement activities the requisite number of times to replace the desired total number of modules. There are eight active machine sets so the number of activity repetitions in one eighth of the modules replaced.

The sequence shown in Table 4.4-10 differs from that used for unscheduled maintenance in that the fault isolation task is omitted and a prescheduled reactor shutdown is used.

TABLE 4.4-10
GA-DOUBLET SCHEDULED MAINTENANCE ACTIVITY SEQUENCE

LEVEL 1 ACTIVITY	LEVEL 2 MAINTENANCE ACTIVITIES
SHUTDOWN	REACTOR SHUTDOWN
GAIN ACCESS	OPEN VACUUM PORT HATCHES EXTEND MACHINES INTO CHAMBER PREPARE FOR MODULE REMOVAL
REMOVE	REMOVE MODULE
INSPECT	INSPECTION OF REMAINING MODULES
REPLACE	REPLACE MODULE
REASSEMBLE	PREPARE CHAMBER FOR STARTUP
STARTUP	VALIDATION AND STARTUP

NOTE: THESE ACTIVITIES APPLY TO REPLACEMENT OF A SET OF 8 MODULES UNIFORMLY DISTRIBUTED AROUND THE PLASMA CHAMBER.

4.4.4.1 GA-Douplet Maintenance Plan Summary - Six maintenance plans have been defined for the GA-Douplet reference reactor. Three are for contact assisted maintenance operations and three for fully remote operations. The principal characteristics of these plans are summarized in Table 4.4-11. Maintenance plans for the GA-Douplet configuration differ from the other reference reactors because it is assumed that the modules to be replaced are evenly distributed in all sixteen sectors. Therefore, wall fractions of 1/6, 1/5 and 1/4 are used as the basis for

the maintenance plans. The nearest multiple of 8 to these fractions of the total of 1808 modules is 304, 360 and 456 modules, respectively. These quantities are exchanged in the maintenance plans derived for the GA-Douplet.

TABLE 4.4-11
GA-DOUBLET MAINTENANCE PLAN SUMMARY

MAINTENANCE TYPE		VACUUM WALL ARRANGEMENT	NUMBER OF SECTORS REWORKED/ IN WORK	NUMBER OF MODULES REPLACED/ OUTAGE	NUMBER OF MAINTENANCE EQUIPMENT SETS	NUMBER OF DIRECT PERSONNEL	TOTAL OUTAGE TIME (HOURS)
CONTACT	REMOTE						
✓		1	16	456	1.068	24	781.25
✓		1	16	360	1.045	24	638.33
✓		1	16	304	1.033	24	553.66
	✓	1	16	456	1.158	14	810.75
	✓	1	16	360	1.100	12	660.83
	✓	1	16	304	1.076	12	575.00

NOTES: 1) ONE CONTACT MAINTENANCE EQUIPMENT SET WEIGHT (INCLUDING SPARES) = 9826.90 TONNES
2) ONE REMOTE MAINTENANCE EQUIPMENT SET WEIGHT (INCLUDING SPARES) = 2623.20 TONNES
3) OUTAGE TIME IS IN UNDILUTED HOURS.

The number of equivalent equipment sets required is seen to vary only slightly with the different wall fractions replaced and it increases to only slightly greater than the basic set of equipment and equipment spares. This effect is a result of the need for additional loader racks, dollies and containers and of having the full complement of equipment for replacing modules mounted in place on the reactor.

The maximum number of direct personnel required for contact assisted maintenance operations includes the floor crew of 12 personnel used during module exchange operations. The floor crew is primarily available to assist with the traffic. A total of 12 machine operators is also required. For fully remote operations, twelve operators are still required, except for the addition of another tow unit (tug) when a wall fraction of 1/4 is used. Since the replacement operations within the plasma chamber and the loading and unloading operations through the vacuum ports are assumed to be the limiting time requirements, only a slight difference is experienced between the contact and remote maintenance modes.

Figure 4.4-7 illustrates the level 1 functional timeline for the contact assisted mode of maintenance operations when replacing a wall fraction of 1/4 (456 modules). The time for replacement of only the first wall/blanket modules is approximately 701 hours. Additional downtime over that required for the replacement of the modules is necessary to reposition the overhead crane and place floor equipment after each replacement cycle. Thus, the total time required to replace 1/4 of the modules is approximately 782 hours.

GA-DOUBLET REFERENCE REACTOR MAINTENANCE SCENARIO

FIGURE 4.4-7

Figure 4.4-8 is the level 1 functional timeline for the fully remote mode of maintenance operations. The total time for replacement of only the 456 modules is approximately 730 hours. The additional time over contact operations is necessary because the crane and equipment repositioning is assumed to require additional time. For both the contact and remote timelines the downtime required to shutdown and gain access and the downtime to reassemble, test and startup are constant. With the maintenance equipment concept applicable to these timelines the shutdown, access, reassembly, test and startup functions are highly automated and, therefore, the downtime requirement for these functions is unaffected by the use of contact maintenance. The downtime for remote operations is increased only by the module replacement time increase to a total of approximately 811 hours.

GA-DOUBLET REFERENCE REACTOR MAINTENANCE SCENARIO

FIGURE 4.4-8

4.4.4.2 GA-Doublet Maintenance Equipment Concept - The maintenance equipment concept for scheduled replacement of sizeable first wall/blanket fractions is the same as that employed for unscheduled maintenance. Additional units of support equipment are required for handling and storing the replaced modules. Table 4.4-12 lists the basic and spares equipment set requirements and the total equipment units required for replacing 456 modules (a wall fraction of 1/4). This table gives the weight of the equipment when shielded for contact assisted maintenance.

For remote maintenance operations the shielding for personnel protection is assumed not to be required and Table 4.4-13 defines the equipment sets used for these conditions. The only change required in the quantity of equipment used for remote maintenance is the deletion of 8 large shielded containers. These containers provide personnel protection by shielding the loader racks when removed from the reactor. The major difference in the two sets of equipment is the removal of shielding for remote maintenance which results in the reduction in total equipment weight of 7204 tonnes for a basic set plus spares. This increases to 7459 tonnes when considering the difference in weight of the equipment and spares provided to replace a first wall/blanket fraction of 1/4 (456 modules).

4.5 SUBSYSTEM MAINTENANCE - An analysis of the impacts on availability produced by the unscheduled maintenance required for other reactor subsystems than the first wall/blanket is initiated in this phase of the study. Of the four subsystems directly interfacing with the reactor that are defined in Section 3.2 the unscheduled maintenance of two of the more critical components are selected to

TABLE 4.4-12
GA-DOUBLET CONTACT SHIELDED MAINTENANCE EQUIPMENT SET

ITEM NO.	MAINTENANCE EQUIPMENT ITEMS	ITEM WT (MT)	BASIC EQUIPMENT SET (113 MODULE CAPACITY)**		SPARES EQUIPMENT SET		EQUIPMENT SET FOR 452 MODULES (WALL FRACTION 1/4)	
			QUANTITY	SET WEIGHT	QUANTITY	SET WEIGHT	QUANTITY	SET WEIGHT
1	POLAR CRANE	4980.00	1*	4980.00	0	0.00	1	4980.00
2	OVERHEAD REMOTE MANIPULATOR	1660.00	1	1660.00	0	0.00	1	1660.00
3	REMOTE MAINTENANCE MACHINE (RMM)	383.00	8	3064.00	1	383.00	8	3064.00
4	REMOTE LOADER MACHINE (RLM)	176.00	8	1408.00	1	176.00	8	1408.00
5	LOADER RACK	3.40	23	78.20	2	6.80	90	306.00
6	REMOTE VIEWING MACHINE (RVM)	168.00	8	1344.00	1	168.00	8	1344.00
7	RMM WORKHEADS SET	1.00	8	8.00	1	1.00	8	8.00
8	LOADER RACK DOLLY	13.40	8	107.20	2	26.80	22	294.80
9	TOW UNIT	50.00	4	200.00	1	50.00	5	250.00
10	REMOTE EQUIPMENT DOLLIES	40.00	4	160.00	1	40.00	4	160.00
11	WORKHEAD DOLLIES	3.00	4	12.00	1	3.00	4	12.00
12	BREEDER MODULE CONTAINER	.60	113	67.80	1	.60	456	273.60
13	REMOTE MAINTENANCE EQUIPMENT SPARES DOLLY	2.50	3	7.50	0	0.00	3	7.50
14	SHIELDED CONTAINERS	95.00	8	760.00	1	95.00	8	760.00
			TOTAL SET WT. = 13856.70		TOTAL SET WT. = 950.20		TOTAL SET WT. = 14527.90	
			-4980.00				-4980.00	
			8876.70				9547.90	

* OVERHEAD CRANE NOT INCLUDED IN SET WEIGHT

** BASIC SET IS FOR APPROXIMATELY ONE SECTOR EQUIVALENT NUMBER OF MODULES

TABLE 4.4-13
GA-DOUBLET REMOTE UNSHIELDED MAINTENANCE EQUIPMENT SET

ITEM NO.	MAINTENANCE EQUIPMENT ITEMS	ITEM WT (MT)	BASIC EQUIPMENT SET (113 MODULE CAPACITY)**		SPARES EQUIPMENT SET		EQUIPMENT SET FOR 452 MODULES (WALL FRACTION 1/4)	
			QUANTITY	SET WEIGHT	QUANTITY	SET WEIGHT	QUANTITY	SET WEIGHT
1	POLAR CRANE	4980.00	1*	4980.0	0	0.00	1	4980.00
2	OVERHEAD REMOTE MANIPULATOR	1660.00	1	1660.00	0	0.00	1	1660.00
3	REMOTE MAINTENANCE MACHINE (RMM)	35.00	8	280.00	1	35.00	8	280.00
4	REMOTE LOADER MACHINE (RLM)	10.00	8	80.00	1	10.00	8	80.00
5	LOADER RACK	3.40	23	78.20	2	6.80	90	306.00
6	REMOTE VIEWING MACHINE (RVM)	2.50	8	20.00	1	2.50	8	20.00
7	RMM WORKHEADS SET	1.00	8	8.00	1	1.00	8	8.00
8	LOADER RACK DOLLY	2.50	8	20.00	1	2.50	22	55.00
9	TOW UNIT	50.00	4	200.00	1	50.00	5	250.00
10	REMOTE EQUIPMENT DOLLIES	23.00	4	92.00	1	23.00	4	92.00
11	WORKHEAD DOLLIES	2.50	4	10.00	1	2.50	4	10.00
12	BREEDER MODULE CONTAINER	.30	113	33.90	1	.30	456	136.80
13	REMOTE MAINTENANCE EQUIPMENT SPARES DOLLY	2.50	3	7.50	0	0.00	3	7.50
14	SHIELDED CONTAINERS	0.00	8	0.00	0	0.00	0	0.00
			TOTAL SET WT. = 7469.00		TOTAL SET WT. = 133.60		TOTAL SET WT. = 7885.30	
			-4980.00				-4980.00	
			2489.60				2905.30	

* OVERHEAD CRANE NOT INCLUDED IN SET WEIGHT

** BASIC SET IS FOR APPROXIMATELY ON SECTOR EQUIVALENT NUMBER OF MODULES

exemplify potential impacts to availability. These components are the cryovacuum pumps in the plasma chamber vacuum system and the ion sources in the neutral beam injector. A brief analysis of the exchange of toroidal field magnets has also been conducted and is discussed in Section 4.7.

The vacuum pumps and ion sources are selected because the anticipated design of these units appears to make them more susceptible to unscheduled maintenance than many other components. It is expected, and assumed throughout the study, that most of the scheduled maintenance for subsystem components can be conducted during the major outage for first wall/blanket exchange or, if the wall life is long enough, scheduled maintenance on subsystem components is conducted during the 28 day annual scheduled reactor outage. With scheduled maintenance presumed to be accomplished during either of these periods, the potential effects of unscheduled subsystem component failures is of importance in determining the relative influence of such failures on the ability to satisfy allowable unscheduled downtime goals and meet availability requirements.

Several failure modes can result in a requirement to replace individual plasma chamber vacuum pumps or vacuum system isolation valves used to switch from pump to pump for regeneration. For example, valve operators are servomechanisms and these may fail to operate or valve seals can fail to seat properly and preclude regeneration. Either failure mode is assumed to require valve replacement. Since two types of cryovacuum pumps are used in the four reference reactors, the maintenance plan for each type is defined. For the GA-Douplet, the valve is in the vacuum line

upstream from the pump and is removed separately. For this type of pump, one plan is described for the valve replacement and one for pump replacement. The UWMAK-III cryovacuum pumps, on the other hand, integrate the valves and pumps into several panels. In this case it is assumed that only one panel need be removed and a plan is presented for this maintenance operation.

The ion source replacement is expected to be required frequently because of the potential short life. Whether scheduled, or unscheduled because of failure, the maintenance plan for this task is expected to be the same. The estimated downtime is defined to determine the impact of a potential high frequency item even though replacement is a relatively simple procedure.

4.5.1 Subsystem Maintenance Summary - The estimated downtimes for the four selected subsystem maintenance actions are summarized at the level 1 detail in Table 4.5-1. For each maintenance action both contact assisted and remote maintenance mode operations are estimated. Where different vacuum wall arrangements are defined for the reference reactor, the estimates show the variation in downtime for each arrangement.

These subsystem components are of the type where diagnostic instrumentation which can isolate the failed unit is reasonably assumed to be available. The assumption is also made that a failure of these components will not require an emergency shutdown such as in the case of a first wall/blanket leak, but that a planned shutdown is required to replace the component. With these assumptions the shutdown time is the same as for a scheduled first wall/blanket exchange. This is assumed to be a constant for all reference reactors.

The principal variation in the estimated times occurs during the maintenance actions after shutdown and before startup. As expected, the remote maintenance mode requires additional time in every case. This time is not as great as expected, however, since the GA cryovacuum pump valve, the UWMAK-III cryovacuum pump panel and the NBI ion source are all expected to be radioactive from either contamination or neutron streaming. The vacuum wall arrangement, on the other hand, has no impact on the conduct of the maintenance action directly because the type of joint is the same for all arrangements. Even though seals are employed at these points in the system, bolted sealed attachments are assumed to be adequate.

The startup operations are also the normal verification and startup functions for the reactor. These operations vary with the vacuum wall location, primarily because of increasing vacuum pump downtimes with the larger vacuum secondary chambers.

TABLE 4.5-1

SELECTED SUBSYSTEM MAINTENANCE ACTION DOWNTIME SUMMARY

MAINTENANCE ACTION	ESTIMATED DOWNTIMES (HOURS)*			
	SHUTDOWN	MAINTENANCE	START-UP	TOTAL
GA-DOUBLET CRYOVACUUM PUMP VALVE CONTACT MAINTENANCE REMOTE MAINTENANCE	17:00	34:55 37:55	24:00 24:00	75:55 78:55
GA-DOUBLET CRYOVACUUM PUMP PANEL CONTACT MAINTENANCE REMOTE MAINTENANCE		46:00 60:35	24:00 24:00	87:00 101:35
UWMAK-III CRYOVACUUM PUMP PANEL CONTACT MAINTENANCE				
VACUUM WALL ARRANGEMENT 1		49:40	24:00	90:40
VACUUM WALL ARRANGEMENT 2		↓	28:00	94:40
VACUUM WALL ARRANGEMENT 3			36:00	102:40
REMOTE MAINTENANCE				
VACUUM WALL ARRANGEMENT 1		69:35	24:00	110:35
VACUUM WALL ARRANGEMENT 2		↓	28:00	114:35
VACUUM WALL ARRANGEMENT 3			36:00	122:35
NBI ION BEAM SOURCE CONTACT MAINTENANCE				
VACUUM WALL ARRANGEMENT 1		14:50	24:00	55:50
VACUUM WALL ARRANGEMENT 2		↓	28:00	59:50
VACUUM WALL ARRANGEMENT 3			36:00	67:50
REMOTE MAINTENANCE				
VACUUM WALL ARRANGEMENT 1		27:40	24:00	68:40
VACUUM WALL ARRANGEMENT 2		↓	28:00	72:40
VACUUM WALL ARRANGEMENT 3			36:00	80:40

* TIME ESTIMATES ARE UNDILUTED FOR PRODUCTIVITY

The estimated downtimes are relatively small compared to unscheduled maintenance for the first wall/blanket in all reference reactors except the GA-Douplet. Here, the time for replacement of the cryovacuum pump by remote operations is approximately the same as the time for replacement of one module (see Table 4.3-15). The important facet of the operations shown in Table 4.5-1 is that the shutdown and startup times are a significant part of the total time required for the total maintenance action. As a percentage of the total time for each maintenance action, shutdown and start-up are:

- o 52 to 54% of the GA-Douplet Vacuum Pump Valve replacement,

- o 40 to 47% of the GA-Doublet Cryovacuum pump replacement,
- o 43 to 45% of the UWMAK-III Cryovacuum pump replacement, and
- o 66 to 73% of the NBI Ion Source replacement.

These values indicate that, as the maintenance actions imposing unscheduled outages require less downtime to repair or replace the components, attention must be given either to reducing shutdown and startup time or to providing a design that can delay shutdown until a more significant outage is required. The specific plans for accomplishing each of these maintenance actions on an unscheduled basis is discussed in the following sections.

4.5.2 GA-Doublet Cryovacuum Pump Valve Replacement - The scenario employed for this maintenance action assumes that the valve which isolates one of the sixteen main cryovacuum pumps at the bottom of the GA-Doublet reference reactor has failed, but in a manner that allows the reactor to be shut down in a planned operation. The pumps and valve are located below the NBI's as shown in Figure 3.3-12. Access to the valves is assumed to be through the supports of the NBI units and from a floor below the reactor room floor at the base of the pumps. Both flanges of the valve are secured to the duct and to the cryovacuum pump by through-bolts that disconnect both joints at the same time. The mount for each cryovacuum pump incorporates a jacking device to lower the pump and valve to provide clearance between the seals and the vacuum duct. The regeneration vacuum line which exits the bottom of the pump and other service lines must be flexibly mounted or incorporate a bellows to accommodate this movement. An isolation valve in this regeneration line is closed during the replacement operation. Movement of the valve horizontally out of position is accomplished by the use of rails which raise the valve to clear the lower seal and then allow it to be moved outward to clear the NBI's and then to be picked up by the overhead crane.

Table 4.5-2 lists the sequence of functions performed during this maintenance action. Functions not directly conducted on the pump or valve are performed in parallel operations as noted in the table. The last function shown in the list is to bakeout and regenerate the cryovacuum pump. This work is accomplished automatically and is conducted in parallel with the reactor start-up and verification procedure. Therefore, the time required to conduct this function is not incorporated serially in the total time for the maintenance action.

Some maintenance equipment is required in addition to the listing given for the first wall/blanket replacement contained in Table 4.3-17. This is a mobile, manned, floor operated unit with manipulators capable of operating smaller tools, such as

TABLE 4.5-2
GA-DOUBLET CRYOVACUUM PUMP ISOLATION VALVE MAINTENANCE ACTIVITY

LEVEL 1 ACTIVITY	DETAILED MAINTENANCE ACTIVITIES
GAIN ACCESS	MOVE CRYOVACUUM PUMP MAINTENANCE MACHINE INTO POSITION DISCONNECT POWER LEADS FROM VALVE (2) REMOVE SHIELD SEGMENTS FROM VALVE REMOVE BOLTS (20) LOWER CRYOVACUUM PUMP
REMOVE	ATTACH AND SLIDE VALVE OUTWARD ON RAILS MOVE OVERHEAD CRANE INTO POSITION* ATTACH CRANE TO VALVE LIFT VALVE AND MOVE TO DOLLY
REPLACE	MOVE REPLACEMENT VALVE INTO POSITION ON DOLLY* ATTACH CRANE TO REPLACEMENT VALVE LIFT REPLACEMENT VALVE AND PLACE ON TRACKS MOVE VALVE INTO POSITION
REASSEMBLE	RAISE CRYOVACUUM PUMP AND CHECK ALIGNMENT INSTALL BOLTS (20) REMOVE FAILED VALVE FROM REACTOR ROOM* INSTALL SHIELD SEGMENTS AROUND VALVE CONNECT POWER LEADS CHECK VALVE OPERATION BAKEOUT AND REGENERATE PUMP*

* PARALLEL EFFORT WITH OTHER ACTIVITIES

impact wrenches, in relatively difficult places. The requirement for the maintenance action described in this section is a reach of about 5 meters to get behind the vacuum duct above the valve and the capability to remove segments of shielding from the valve. Minimum lift at the extreme reach is required if the valve body and its extension contains surfaces that can be used for sliding the shield segments in and out of position. The manipulator arms can either provide the motive force for the horizontal motion of the shield blocks and valve or a separate ram type arm can be attached by a manipulator and then provide the required motion. A detailed definition of this machine requires analysis of other maintenance actions at this level of component removal before an integrated concept can be selected.

The time estimates for this maintenance action are found in Tables A-27 and A-28, Appendix A, for the contact and remote maintenance mode alternative operations. The time variation between contact and remote maintenance, i.e., between 34.9 hours and 37.9 hours, respectively, is small primarily because the vacuum duct, pump valve and the cryovacuum pump are assumed to be activated by neutron streaming through the main vacuum ports and all operations must be remotely conducted during the period when the shield blocks are removed.

4.5.3 GA-Doublet Cryovacuum Pump Replacement - The scenario employed for this maintenance action is similar in many respects to that used for the pump valve replacement discussed in Section 4.5.2. The failed pump is a main cryovacuum pump located immediately below the pump valve discussed in the previous section. Access to the pump is assumed to be from a lower floor level but would have to be between supports for the NBI units mounted on the floor above. The pump mount is assumed to provide horizontal mobility which allows the pump and mount to be moved to a position where the pump can be raised by the overhead crane through an opening in the reactor room floor. Auxiliary cranes on tracks in the ceiling of the lower floor may also be used for transport. In this scenario both the cryovacuum pump valve and the pump are removed together. This is feasible because the valve supports are assumed to be attached to the pump structural housing and can tie the valve and pump together even though the attachment bolts are removed. The seal between valve and pump must be replaced each time the pump is disconnected and, therefore, it is necessary to rework both the pump and valve flange faces each time this maintenance action is conducted.

Table 4.5-3 lists the sequence of maintenance functions which are conducted during this maintenance action. Those functions performed as parallel operations in time are noted on the table. The sequence shown in this table is for contact assisted maintenance operations. Since the valve and vacuum line become radioactive during reactor operations, remote maintenance operations must be used as soon as the shield segments are removed. For this reason, as many disconnect functions as possible are conducted before removing the shield segments, and, during reassembly, these reconnecting operations are delayed until after the shield segments are replaced. This sequence is not as critical for remote operations and the service line disconnects are made after the pump and valve are lowered and reconnected prior to mating the valve and main vacuum duct. However, the contact sequence can be used for remote operations and the time difference for this fully remote operation alternative is either small or nonexistent.

TABLE 4.5-3
GA-DOUBLET CRYOVACUUM PUMP MAINTENANCE ACTIVITY

LEVEL 1 ACTIVITY	DETAILED MAINTENANCE ACTIVITIES
GAIN ACCESS	<p> MOVE PERSONNEL INTO REACTOR ROOM MOVE VACUUM PUMP MAINTENANCE MACHINE INTO POSITION* DISCONNECT POWER LEADS FROM VALVE (2) DISCONNECT LN₂ INLET AND OUTLET LINES DISCONNECT LH_e INLET AND OUTLET LINES DISCONNECT REGENERATION HEATER SUPPLY AND RETURN LINE DISCONNECT REGENERATION PUMP-OUT VACUUM LINE MOVE TUG INTO POSITION AT PUMP* </p>
REMOVE	<p> ATTACH TUG TO FAILED PUMP* MOVE NEW PUMP INTO IMMEDIATE AREA* CLEAR AREA OF ALL PERSONNEL REMOVE SHIELD SEGMENTS FROM VALVE (2) REMOVE BOLTS AT VALVE FROM MAIN LINE DISCONNECT (20) MOVE MAINTENANCE MACHINE CLEAR OF PUMP LOWER CRYOPUMP AND VALVE (~ 5 cm) MOVE FAILED PUMP CLEAR OF IMMEDIATE AREA MOVE FAILED PUMP OUT OF AREA OF HOT CELL* </p>
REPLACE	<p> MOVE NEW PUMP INTO POSITION DISCONNECT TUG FROM PUMP MOVE MAINTENANCE MACHINE INTO POSITION RAISE CRYOPUMP AND VALVE AND ALIGN INSTALL BOLTS (20) </p>
REASSEMBLE	<p> INSTALL SHIELD SEGMENTS AROUND VALVE CHECK FOR RADIATION AND MOVE PERSONNEL INTO AREA CONNECT REGENERATION PUMP-OUT VACUUM LINE CONNECT REGENERATION HEATER SUPPLY AND RETURN LINE CONNECT LH_e INLET AND OUTLET LINES CONNECT LN₂ INLET AND OUTLET LINES CONNECT POWER LEADS TO VALVE CHECK VALVE OPERATION MOVE PERSONNEL FROM AREA MOVE MAINTENANCE MACHINE FROM AREA* </p>

* PARALLEL EFFORT WITH OTHER ACTIVITIES

The time estimates for the use of contact assisted or fully remote operations during this maintenance action are shown in Tables A-29 and A-30, Appendix A. These tables define the detailed differences in the functional sequences. The time advantage for contact assisted operations is significant for this maintenance action because of the large number of service connections required for the cryovacuum pump.

The maintenance equipment concept employs the same basic machine that is defined for conducting the cryovacuum pump but a line disconnect tool is also required for the pump service line connections. The tug is used to tow the pump and valve assembly out of position and to position the replacement unit. Both the basic maintenance machine and the tug are manned and require shielded cabs for remote operations. Depending on the space available and the size of each unit, the possibility of combining both unit functions into a single machine should be explored. The tug is included in the maintenance equipment list for the first wall/blanket replacement given in Table 4.3-17, Section 4.3.4, but the mobile manipulator machine must be added.

4.5.4 UWMAK-III Cryovacuum Pump Panel Replacement - The scenario employed for this maintenance action assumes that the cryovacuum pump or valve failure will permit a planned shutdown of the UWMAK-III reactor. This prevents delays in getting equipment and replacement parts into the reactor room and is assumed to permit fault isolation to the failed cryovacuum panel. Since the isolation valves are built into each panel of the pump assemblies in the UWMAK-III configuration, the replacement of the pump assembly and valves is necessary in the event of failure of either the valve or the pump panel itself. Two pump assemblies are installed between each pair of Toroidal Field coils as shown in Figure 3.3-6, Section 3.3.2. One is above the reactor and one below. Each assembly has two panels, one horizontal and one vertical. This scenario selected the horizontal panel of the upper assembly for replacement since the GA-Douplet pump replacement illustrated some of the requirements for systems below the reactor. All cryovacuum pump assemblies are assumed to become radioactive during reactor operation.

Access to the pump assembly is from the maintenance device mounted on the reactor central core above the reactor. This device is essentially a boom with a traveling hoist. It is listed in Table 4.3-8, Section 4.3.2 and the concept is illustrated in Appendix B. A special workhead may be required to remove bolts and/or shield segments from the cryovacuum pump panel. A workhead for disconnecting coolant lines is already provided but may have to be either modified or

additional workheads added to disconnect and reconnect the pump services. All of these service lines are expected to be relatively small except the regeneration vacuum line which is approximately an 8 cm line (per Section 3.2.4). Only the basic requirements have been defined for this equipment. The other special equipment required is a dolly for transporting and storing the heavy panels.

Table 4.5-4 shows the activity sequence used for this maintenance action. The parallel time functions in the sequence are indicated. The sequence shown is for use of the contact assisted maintenance mode and retains personnel in the reactor room to disconnect all pump services. After replacement of the pump and shield segments, personnel reconnect these services. The fully remote operations can resequence these disconnects until after the removal of the shield segments as is discussed for replacement of the GA-Douplet cryovacuum pump.

The time estimates for these maintenance actions are given in Tables A-31 and A-32, Appendix A, for the contact and remote maintenance modes, respectively. These tables define the detailed differences in the functional sequences. The time requirements are essentially the same as those required by the GA-Douplet cryovacuum pump removal. When using the contact maintenance mode only 71% of the remote maintenance downtime is necessary for the pump replacement sequence, exclusive of reactor shutdown and startup requirements. This advantage is so small for the contact maintenance mode because the radiation environment precludes contact operations when shielding is removed.

4.5.5 NBI Ion Beam Source Replacement - The scenario used as the basis for this maintenance action assumes that the ion beam source failure occurs in such a manner that the reactor shutdown is a planned operation. Such a failure is believed possible as a result of many failure modes which do not cause a disruption of other ion sources if some redundancy exists in the NBI system capability to achieve ignition. The capability to remove these ion sources separately is assumed to be desirable even though each NBI is postulated to have 3 beam lines. For scheduled replacement it may be desirable to replace the three beam lines as a unit but this capability has not been included in these estimates. Since the reactor shutdown is a planned operation, the estimated time required is applicable to scheduled or unscheduled maintenance actions. An alternative is to attempt to replace these sources with the reactor in operation. This is especially attractive if the reactor room serves as a secondary vacuum chamber because of the long pump down time required to startup the reactor. Such an alternate has not been considered in this study.

TABLE 4.5-4
UWMAK-III CRYOVACUUM PUMP PANEL MAINTENANCE ACTIVITY

LEVEL 1 ACTIVITY	DETAILED MAINTENANCE ACTIVITIES
GAIN ACCESS	MOVE VACUUM PUMP WORKHEAD INTO REACTOR ROOM* MOVE PERSONNEL INTO REACTOR ROOM MOVE CRANE INTO POSITION USING CRANE ATTACH WORKHEAD TO CENTRAL CORE MAINTENANCE DEVICE DISCONNECT VALVE POWER LEADS FROM PUMP DISCONNECT LN ₂ INLET AND OUTLET LINES DISCONNECT LH _e INLET AND OUTLET LINES DISCONNECT REGENERATION HEATER SUPPLY AND RETURN DISCONNECT PLENUM PUMP-OUT LINE CLEAR AREA OF ALL PERSONNEL REMOVE SHIELD SEGMENTS (3) FROM PUMP
REMOVE	DISCONNECT HORIZONTAL PUMP ASSEMBLY FROM PLENUM (20 BOLTS) ATTACH CRANE TO PUMP ASSEMBLY LIFT PUMP ASSY. BY CRANE AND LOWER TO DOLLY MOVE REPLACEMENT PUMP ASSY. INTO REACTOR ROOM ON DOLLY*
REPLACE	ATTACH CRANE TO REPLACEMENT PUMP ASSEMBLY LIFT REPLACEMENT PUMP ASSY. INTO POSITION CONNECT PUMP ASSEMBLY TO PLENUM (20 BOLTS)
REASSEMBLE	REPLACE SHIELD SEGMENTS (3) ON PUMP CHECK FOR RADIATION AND MOVE PERSONNEL INTO AREA CONNECT PLENUM PUMP-OUT LINE CONNECT REGNERATION HEATER SUPPLY AND RETURN CONNECT LH _e INLET AND OUTLET LINES CONNECT LN ₂ INLET AND OUTLET LINES CONNECT VALVE POWER LEADS CHECK VALVE OPERATION DETACH WORKHEAD FROM CENTRAL CORE MAINTENANCE DEVICE REMOVE WORKHEAD FROM REACTOR ROOM MOVE PERSONNEL FROM AREA

*PARALLEL EFFORT WITH OTHER ACTIVITIES

Table 4.5-5 lists the maintenance activities required to replace a single ion source with the use of as many contact maintenance activities as possible. For this maintenance action it is assumed that the ion source is shielded externally but that the neutron streaming through the NBI port activates the interior of the NBI chamber and makes the reactor room unsuitable for personnel if the NBI chamber is opened. The face of the ion source toward the chamber is also expected to be activated. Casking the ion source to permit contact maintenance throughout this operation is expected to increase rather than shorten the downtime.

TABLE 4.5-5
NBI ION SOURCE MAINTENANCE ACTIVITY

LEVEL 1 ACTIVITY	DETAILED MAINTENANCE ACTIVITIES
GAIN ACCESS	PURGE ION SOURCE OF SF ₆ * CHECK RR FOR RADIATION AND MOVE PERSONNEL INTO RR MOVE HOIST/BOOM INTO POSITION MOVE PERSONNEL ACCESS PLATFORM INTO POSITION EXTEND HOIST/BOOM TO POSITION AT ION SOURCE ATTACH HOIST/BOOM TO ION SOURCE DISCONNECT AND STOW DEUTERIUM LINE DISCONNECT AND STOW SF ₆ LINE DISCONNECT AND STOW H ₂ O SUPPLY/RETURN LINE DISCONNECT AND STOW ELECTRICAL POWER LEADS REMOVE BOLTS AT ION SOURCE ASSY. MAIN FLANGE (10)
REMOVE	REMOVE PERSONNEL FROM RR LOWER ION SOURCE WITH HOIST/BOOM TO FLOOR LEVEL PLACE ION SOURCE ON DOLLY AND DETACH HOIST MOVE NEW ION SOURCE ASSY. ON DOLLY INTO RR* MOVE OLD ION SOURCE ASSY. ON DOLLY FROM RR*
REPLACE	ATTACH HOIST/BOOM TO NEW ION SOURCE ASSY. RAISE ION SOURCE ASSY. WITH HOIST/BOOM AND POSITION CHECK FOR RADIATION AND MOVE PERSONNEL INTO AREA
REASSEMBLE	INSTALL BOLTS AT ION SOURCE ASSY. MAIN FLANGE (10) CONNECT ELECTRICAL POWER LEAD CONNECT H ₂ O SUPPLY/RETURN LINE CONNECT SF ₆ LINE CONNECT DEUTERIUM LINE REMOVE HOIST/BOOM FROM ION SOURCE ASSY. PRESSURIZE AND TEST ALL FLUID LINES FOR LEAKS REMOVE HOIST/BOOM AND PERSONNEL ACCESS PLATFORM FROM AREA VERIFY VACUUM SEAL AT MAIN FLANGE*

* PARALLEL EFFORT WITH OTHER ACTIVITIES

The configuration of the ion source assembly is generally the concept depicted in Figure 3.2-28. Section 3.2.3. This assembly concept requires many less connections than current ion sources. The assembly, with shield, will detach as a unit. It is assumed that the neutralizer is a separate unit which does not need to be detached at the ion source interface.

The detailed time estimates for both the partial contact and the fully remote maintenance sequences are presented in Tables A-33 and A-34, Appendix A. The maintenance action when using fully remote operations requires an extended time which is much larger (87 percent) than the time necessary when using contact operations. The sequence for remote operations is almost identical to that for contact operations. Therefore, the remote operations seem relatively unwarranted unless either a scheduled fully remote first wall/blanket exchange is being conducted or a system for ion source exchange with either the reactor operating or with the reactor room at high vacuum is defined as a desirable alternative.

The maintenance equipment concept for this operation uses three items of equipment of which some may be adaptations of equipment already specified for several of the reference reactor first wall/blanket equipment concepts. These equipment items are:

- o A hoist mounted on a swinging boom arm to lift and transfer the ion source and shielding to a transport dolly,
- o The ion source transport dolly, and
- o A gantry arrangement behind the ion source which will retain the service connections and move them out of the transfer path.

The hoist could readily be a part of the Operational Maintenance Unit provided for the Culham and ORNL Cassette concepts or it could be added to a modified tug. The latter may provide greater maneuverability on the reactor room floor. The dolly may only require an adapter for another dolly since it is anticipated that the ion sources would be stored in bins (racks) to save space and reduce equipment requirements. The apparent complexity of the gantry arrangement may also be reduced with further study. An arrangement must be sought to provide service connections which do not clutter the NBI floor space nor interfere with overhead maintenance equipment movement.

The ion source is the smallest component assessed and indicates the trend toward shorter downtimes with smaller, more accessible components. It also indicates the trend toward greater benefits from contact maintenance operations even on fairly heavy components such as the shielded ion source.

4.6 MAINTENANCE EQUIPMENT MAINTENANCE - Some items of maintenance equipment are quite complex and its failure while conducting a reactor maintenance action will impose additional downtime and reduce availability. The extent of this additional downtime is investigated by selecting maintenance actions for each reference reactor and postulating a failure mode for the maintenance equipment used in each maintenance action.

The maintenance equipment failure modes are selected with the objective of producing the most difficult recovery scenario possible and, thereby, to define the largest potential impact on the downtime. All failures of maintenance equipment are assumed to impact downtime only when the equipment is actively engaged in either a scheduled or unscheduled maintenance action on a reactor subsystem. The selected failure modes are only representative of the potential modes that may occur since a failure modes and effects analysis has not been conducted. However, since many reactor failure modes employ the same maintenance equipment and many equipment failure modes have very similar corrective actions and impacts, the selected examples are believed to have much wider representative application than is apparent from their limited number. While only one failure mode for each item of maintenance equipment is postulated, the failure mode is deemed to be representative of many possible failure modes for that item of equipment. Therefore, the frequency of failure selected for each scenario is considered to be the frequency of failure of that equipment for all of its possible failure modes and not just the particular mode that is considered.

This assumption allows the scenarios defined in this section to be used as a representative group of failures and the total downtime approaches the unscheduled downtime that may arise from the maintenance equipment. This use of the estimates is discussed further in Section 5.0. Since the most significant failure modes have been selected and because failures of other maintenance equipment, such as that defined for subsystems other than the first wall/blanket, appear relatively insignificant, it is believed that the use of this assumption provides for a reasonable view of the impact of unscheduled maintenance equipment failures.

For each maintenance equipment failure mode the basic scenario is defined and the failure recovery time is derived from an estimate of the time required for each recovery function in the recovery sequence. This time is the net additional time required to conduct the reactor maintenance action and may be the same, less than, or more than the time required for those additional maintenance operations that are

necessary to correct the equipment failure (the failure reaction time). These differences are noted in Appendix C where the more detailed scenario definitions are compiled. All times given in this discussion are undiluted by productivity factors.

Additional scenario definition includes the special equipment requirements, spares requirements, estimated frequency of occurrence and comments on the maintenance equipment potential complexity and reliability.

4.6.1 UWMAK-III Failure Mode Definitions - Three failure mode scenarios have been developed for maintenance equipment used during the UWMAK-III first wall/blanket exchange. The key characteristics of these scenarios are summarized in Table 4.6-1.

TABLE 4.6-1

UWMAK-III MAINTENANCE EQUIPMENT FAILURE MODE ASSESSMENT

FAILURE MODE SCENARIO	FAILURE RESPONSE	BASIC MAINTENANCE MACHINE RELIABILITY	ANTICIPATED FREQUENCY OF FAILURE	SPARE MAINT. SET UTILIZATION REQUIRED	SPECIAL MAINT. EQUIP. REQ'D	ESTIMATED FAILURE RECOVERY TIME	REMARKS
1. The "B" MODULE WORKHEAD, WITH "B" MODULE ATTACHED, BECOMES JAMMED WHILE TRYING TO LOWER AND REMOVE THE "B" MODULE. THE PMH CANNOT BE RETRACTED.	<ul style="list-style-type: none"> o GAIN ACCESS TO ADJACENT SECTOR USING SPARE MAINT. EQUIPMENT o USE SPECIAL WORKHEAD TO ENGAGE "B" MODULE & "B" MODULE WORK-HEAD, CUT FREE FROM BASE, AND REMOVE 	HIGH-SIMPLE, RUGGED, WELL MAINTAINED MACHINES	LOW-ONCE EVERY 10 YRS	<ul style="list-style-type: none"> - PMH - LSAP WORKHEAD - MMH - "A" MOD. W/H - "B" MOD. W/H - AUX. SERVICES W/H - VARIOUS DOLLIES 	<ul style="list-style-type: none"> o SPECIAL SERVICES WORKHEAD o SSW DOLLY o PARTS DOLLY 	363:20	MECHANISM DESIGNS SHOULD BE RELATIVELY SIMPLE, WITH FAIL OPERATIONAL FEATURES BUILT-IN
2. THE "A" MODULE WORKHEAD, WITH "A" MODULE ATTACHED, FAILS IN PLACE WHILE ATTEMPTING TO EXTRACT THE "A" MODULE.	<ul style="list-style-type: none"> o LOWER "A" MODULE BACK INTO INSTALLED POSITION o REINSTALL SEVERAL RESTRAINT BOLTS o RELEASE WORKHEAD & REMOVE o USE SPARE WORK-HEAD TO COMPLETE MODULE REMOVAL TASK 	HIGH-SIMPLE, RUGGED, WELL MAINTAINED MACHINES	LOW-ONCE EVERY 10 YRS	<ul style="list-style-type: none"> - "A" MODULE WORKHEAD - "A" MODULE W/H DOLLY 	NONE	43:30 HR	SIZE & WEIGHT OF "A" MODULE POSTULATES STRUCTURAL PROBLEMS FOR "A" MODULE
3. THE POLOIDAL MAGNET RETRACTION SYSTEM FAILS TO RAISE ONE OF THE MAGNETS BETWEEN THE LSAP'S AND SHIELD DOORS.	<ul style="list-style-type: none"> o ISOLATE THE FAILURE TO A SPECIFIC RETRACTION SYSTEM MECHANISM o REMOVE APPLICABLE LSAP & REPAIR MECHANISM WITH OMU 	MEDIUM- OMU IS A WELL MAINTAINED MACHINE. MAGNET RETRACTION OPERATES IN A RADIOACTIVE ENVIRONMENT	MEDIUM-ONCE EVERY 3 YRS/MAGNET	<ul style="list-style-type: none"> - PMH - LSAP W/H - POLOIDAL MAGNET RETRACTION MECHANISM 	<ul style="list-style-type: none"> o SPECIAL TOOLS WHICH INTERFACE WITH OMU o SUPPORT JACKS o PARTS DOLLY 	73:10 HR	SENSORS SHOULD ISOLATE LOCATION OF MALFUNCTIONING MAGNET RETRACTION MECHANISM

"B" Module Workhead Failure - The failure of the Module Handling Machine (MHM) workhead used to extract the "B" module is selected because the motions required and the area in which its work is performed appear to present some relatively inextricable situations. The sequence of operations is reviewed in Figures B-12 through B-14 in Appendix B. The point at which the MHM and workhead have released the "B" module from the reactor attachment and transferred the load to the MHM appears to present the most difficult situation from which to recover from a workhead jamming failure. The "B" module motion must be closely controlled because the stab end of the coolant line is still surrounded by shielding and the MHM blocks access to the workhead through the area vacated by the "A" module. The scenario assumes that the failure is of a nature that normal backup devices are of no avail.

The response to such a failure is to gain access to the workhead and the "B" module through the adjacent sector by removing the NBI, LSAP and the "A" Module with spare maintenance equipment. A Special Services Workhead (SSW) is then attached to the MHM at the adjacent sector and is used to reach the failed workhead, take up the "B" module load and cut off or detach part of the failed workhead from the MHM. The failed workhead and "B" module is extracted through the "A" module opening in the adjacent sector. The failed workhead and "B" module are moved to a hot cell for dismantling and repair. The MHM with the remainder of the failed workhead is withdrawn from the reactor, the workhead replaced with the next tool in the sequence and work continues. Meanwhile, the adjacent sector is reassembled.

This entire procedure is very lengthy and the total time required for additional maintenance operations (the failure reaction time) is approximately 1044 hours. However, work can continue simultaneously with the failure response on all other sectors and, since the "B" module operation is actually completed and work on the sector with the failure can continue while the adjacent sector is being reassembled, the net lost time (failure recovery time) is reduced to approximately 363 hours. This is the longest recovery time encountered in all of the maintenance equipment failure modes.

The nature of the failure and the capability to build in backup mechanism operations which provide the capability to override a single failure (fail-operational) will make the expected frequency of occurrence of such a failure low. The equipment is rugged and designed for large loads so that the override forces available are large. A frequency of one failure of this type every 10 calendar years is assumed.

Averaged over the number of operational cycles, this amounts to only a few days of unscheduled downtime per year. Section 5.0 compares the downtimes of all equipment failures examined and described in this section.

"A" Module Workhead Failure - Failure of the workhead mounted on the MHM and used to extract the "A" module from the UWMAK-III also presents a difficult situation because of the large loads imposed on it by the "A" module. The workhead is assumed to fail either when the "A" module hangs up in the reactor or during the transfer of the "A" module load to the workhead and the MHM. The failure occurs after all bolts have been removed which hold the "A" module in place but it is assumed that locating pins are still at least partially in place at the "A" module interface with the reactor.

The response to this failure can be twofold, depending on the extent of the "A" module travel before the failure occurred. If the travel is too far to reinstall the attachment bolts then the MHM is assumed to be able to continue movement until the "A" module is free from the reactor. The more difficult situation is where this is not possible but the attachment bolts can be reinstalled. The latter situation is assumed for this analysis.

The attachment bolts are reinstalled in sufficient number to hold the "A" module in place (assumed about 20% of the total). The "A" module is then disengaged from the workhead. A fail-operational or auxiliary capability to accomplish this type of service is a required capability of the workhead. The module handling machine is withdrawn and the workhead replaced to continue the operation.

Under these conditions the additional unscheduled failure recovery time is 43.5 hours. This is measured from the time the removal of the "A" modules in other sectors is completed until the "A" module in the sector with the failed equipment is removed. The total failure reaction time (i.e., the time when additional maintenance tasks are conducted to remedy the failure) is 59.5 hours. The difference is caused by the ability to conduct parallel operations and assume priority for placement of the equipment required to rectify the failure. The expected frequency of occurrence of once every 10 years is the same as that used for the "B" module workhead failure for the same reasons.

Poloidal Magnet Retraction System Failure - The poloidal magnet retraction system is particularly critical to the maintenance downtime since its operation is in parallel with other access operations and, for most first wall/blanket maintenance operations, the retracting mechanisms are not accessible. The failure mode assumed for this scenario is the failure of one of the retractors on a PF coil assembly.

This retractor is situated behind an LSAP and NBI which are not scheduled for removal in the maintenance action during which the retractor fails to operate. The assumption is made that the instrumentation or other fault isolation procedures will determine which retractor has failed without dismantling any reactor sectors other than planned and without waiting for the LSAP's to be removed.

The procedure outlined in Appendix C calls for removal of the NBI and LSAP from the affected reactor sector using spare maintenance equipment. The Operational Maintenance Unit (OMU) is used to work within the sector. Limited contact maintenance is assumed in this scenario because the reactor shielding has not been opened at this time. The maintenance action requires the replacement of the retractor drive unit and does not require jacking of the PF coils to relieve the loads. Once the drive unit is replaced the retraction of the PF coils continues while the LSAP and NBI are being replaced.

For this maintenance action the failure recovery time is estimated at 73.2 hours from the time that the last LSAP scheduled for removal is removed until all PF coils are retracted and work can be resumed. This is less than the failure reaction time of 140.8 hours because the scheduled maintenance action can be continued while access is being provided to the failed retractor and while the affected sector is being reassembled. Since each PF coil requires at least four retractors the frequency of this type of failure for each of the six PF coil retractor assemblies used in this reactor concept is expected to be fairly large. Therefore, it is assumed to occur an average of once every three calendar years. However, this still represents an unscheduled failure downtime of only a few days per operating year. A more detailed conceptual design and failure analysis of this maintenance equipment concept is advisable to define a better estimate of failure frequency and recovery times. This is desirable for most failure modes where multiple units makes the impact very sensitive to any variation in failure rate per unit.

4.6.2 Culham Failure Mode Definitions - Two failure mode scenarios have been developed for maintenance equipment used during the Culham reference reactor first wall/blanket exchange. The key characteristics of these scenarios are summarized in Table 4.6-2.

Reactor Module Transporter Failure - Recovery from the failure of the reactor module transporter at the critical point of initial movement of the reactor module onto the transporter is one of the more difficult maintenance actions caused by a maintenance equipment failure. The failure mode involves failure of the mechanism that pulls the main reactor module onto the transporter. It is assumed that the

TABLE 4.6-2
CULHAM MAINTENANCE EQUIPMENT FAILURE MODE ASSESSMENT

FAILURE MODE SCENARIO	FAILURE RESPONSE	BASIC MAINTENANCE MACHINE RELIABILITY	ANTICIPATED FREQUENCY OF FAILURE	SPARE MAINT. SET UTILIZATION REQUIRED	SPECIAL MAINT. EQUIP. REQ'D	ESTIMATED FAILURE RECOVERY TIME	REMARKS
1. THE REACTOR MODULE TRANSPORTER RETRACTION MECHANISM FAILS WITH THE REACTOR MODULE PARTIALLY RETRACTED. THE MACHINE MUST BE REPAIRED IN-PLACE.	<ul style="list-style-type: none"> o DISCONNECT MECHANISM FROM MODULE WITH OMU o EXCHANGE FAILED RETRACTION MECHANISM WITH SPARE MECHANISM o RECONNECT SPARE MECHANISM TO MODULE 	HIGH-SIMPLE, RUGGED, WELL MAINTAINED MECHANISM	LOW-ONCE EVERY 20 YRS/TRANSPORTER	<ul style="list-style-type: none"> - REACTOR MODULE RETRACTION MECHANISM - OMU - VARIOUS DOLLIES 	NONE	98.00 HR.	RETRACTION MECHANISM PERFORMS A CRITICAL FUNCTION, BUT SHOULD BE HIGHLY RELIABLE.
2. THE MAIN HELIUM COOLANT DUCT SEAL LEAKS UPON REASSEMBLY & TEST FIXED PORTION OF DUCT MUST BE REPLACED. DURING REPLACEMENT, CUTTING/WELDING WORKHEAD FAILS	<ul style="list-style-type: none"> o DISCONNECT & LOWER FIXED DUCT o CUT FIXED PORTION OF SEAL FREE o DRESS DUCT & INSTALL NEW SECTION o REWELD NEW DUCT/SEAL FLANGE INTO POSITION. EXCHANGE FAILED WORKHEADS 	WELDING/CUTTING WORKHEADS ARE SMALL, RELIABLE, STATE-OF-ART MACHINES	MEDIUM-ONCE EVERY 10 YRS PER MANIFOLD CONNECTION	<ul style="list-style-type: none"> - REPLACEMENT DUCT & FLANGE SECTION - SPARE WORKHEADS 	<ul style="list-style-type: none"> - SPECIAL REMOTE WORKHEADS TO CUT & REWELD NEW DUCT SECTIONS 	110.30 HR. INCLUDING 17.15 FOR REACTION TO TOOL FAILURE	DEVELOPMENT PROGRAM SHOULD PRODUCE A FAIRLY RELIABLE, LEAK TIGHT, MECHANICAL SEAL DESIGN. WORKHEADS DESIGNS AVAILABLE.

reactor module motion has been initiated so that the positioning pins cannot be reinserted and the reactor module cannot be moved in either direction.

The reaction to this failure mode requires the positioning of an OMU alongside of the reactor transporter in the space available behind the adjacent sector. Since only 8 of the sectors are being reworked this space should be available. Usually an NBI will not be installed behind one of the two adjacent sectors to interfere with this operation. The OMU installs devices to secure the reactor module and relieve any load on the retraction mechanism. The retraction mechanism is then replaced with a spare and the securing devices removed. The OMU and auxiliary equipment is withdrawn from the reactor room while the movement of the reactor module continues. Figure C-5, Appendix C, illustrates the sequence of these functions.

The failure recovery time estimated for this sequence is 98.0 hours from the completion of retraction of the reactor modules from the other sectors being reworked to the completion of the retraction of the reactor module in the sector affected by the failure. The failure mode reaction time is 107.0 hours because the reactor module movement can be resumed while clean up operations are continued. This type of failure is assumed to occur very infrequently (i.e., once every 20 years) because of the nature of the mechanism and the low stress type of operation. Therefore, the impact is low when computed on the basis of the average per operating year.

Helium Coolant Manifold Replacement Workhead - This is an example of the impact of a double unscheduled failure which shows the impact of a maintenance tool failure on an unscheduled failure. In this scenario the failure of a seal in the joint between the reactor room floor mounted helium coolant manifold and the reactor module helium coolant manifold is the unscheduled reactor maintenance action. The recovery from this failure is delayed by the failure of the welding/cutting workhead which is replacing the manifold flange mounted in the reactor floor.

Since the maintenance action occurs after the reactor modules are replaced and the OMU's are in place for the normal leak check, these maintenance machines are used to install and replace the automatic welding/cutting tool. The welding/cutting tool is assumed to be the type which operates from a track attached to the manifold and replacement involves only removal and installation of a spare tool on the track. It is assumed that the failure did not result in damage to the manifold.

The failure recovery time for the tool failure is estimated at 17.3 hours. In this scenario the failure response time is the same since parallel operations are not feasible. The total response time for the unschedule manifold joint seal failure, including the tool failure, is estimated as 110.5 hours. The frequency of occurrence of this combination of events is assumed to be only once in 10 calendar years for each manifold since such tools are state of the art equipment.

4.6.3 ORNL Failure Mode Definitions - Three scenarios have been developed for failure modes occurring on maintenance equipment that has been defined for exchanging the first wall/blanket cassettes of the ORNL Cassette reference reactor. These scenarios and the resultant maintenance requirements are summarized in Table 4.6-3.

ORNL Cassette Workhead Failure - The failure to retract a cassette after it has been disconnected from the reactor and the coolant lines and the load is transferred to the cassette retraction workhead installed on the Primary Maintenance Machine (PMM) is one of the failure modes requiring a difficult recovery sequence. This scenario is analogous to the retraction failures described for the UWMAK-III and the Culham concepts. For the specific scenario the failure is assumed to occur during the retraction of a cassette from the lower outer wall (the "A" region). The cassette is partially retracted and the retraction mechanism fails. At this point the PMM cannot be moved without damaging the cassette or the reactor.

The most attractive solution appears to be the incorporation of a fail-safe operating system to accommodate this failure mode. This system would provide for a command operated relief valve (if the retraction drive is hydraulic) which is

TABLE 4.6-3

ORNL CASSETTE MAINTENANCE EQUIPMENT FAILURE MODE ASSESSMENT

FAILURE MODE SCENARIO	FAILURE RESPONSE	BASIC MAINTENANCE MACHINE RELIABILITY	ANTICIPATED FREQUENCY OF FAILURE	SPARE MAINT. SET UTILIZATION REQUIRED	SPECIAL MAINT. EQUIP. REQ'D	ESTIMATED FAILURE RECOVERY TIME	REMARKS
1. THE A, B, & C CASSETTE WORKHEAD EXTRACTION MECHANISM FAILS WITH AN "A" CASSETTE PARTIALLY RETRACTED. THE PMM, TO WHICH THE WORKHEAD IS MOUNTED, CANNOT BE RETRACTED.	<ul style="list-style-type: none"> o ACTIVATE EXTRACTION MECHANISM FAIL-SAFE SYSTEM o ALLOW "A" CASSETTE TO SLIDE BACK INTO THE REACTOR RECEPTACLE. o RELEASE WORKHEAD-FREE MODULE o REMOVE PMM WITH WORKHEAD 	MEDIUM-WELL MAINTAINED MACHINE WITH MECHANISM OF MEDIUM COMPLEXITY	LOW-ONCE EVERY 10 YRS	<ul style="list-style-type: none"> o A, B, & C CASSETTE MODULE WORKHEAD o WORKHEAD DOLLY 	- NONE	39:00 HR	<ul style="list-style-type: none"> o MANUAL ASSIST NOT FEASIBLE o MECHANISM DESIGN SHOULD BE SIMPLE, WITH BUILT-IN FAIL-SAFE FEATURES
2. THE DIVERTOR MODULE WORKHEAD FAILS IN-PLACE WHILE ATTEMPTING TO INSTALL A MODULE. DIVERTOR MODULE LOAD HAS NOT BEEN TRANSFERRED TO IT'S SUPPORT STRUCTURE	<ul style="list-style-type: none"> o RETRACT PMM STABILIZATION PADS o RETRACT PMM A DISTANCE OF 14 METERS o OFF-LOAD DIVERTOR MODULE WITH OVERHEAD CRANE o EXCHANGE DIVERTOR MODULE WORKHEADS 	HIGH-MODULE HANDLING ARM IS A RELATIVELY SIMPLE, WELL MAINTAINED MECHANISM	LOW-ONCE EVERY 10 YRS	<ul style="list-style-type: none"> o DIVERTOR MODULE WORKHEAD o WORKHEAD DOLLY o DIVERTOR MODULE DOLLY 	- NONE	50:00 HR	<ul style="list-style-type: none"> o BOOM ARM WHICH HOLDS AND INSERTS DIVERTOR MODULE IS HEAVY DUTY-BUT SIMPLE o MANUAL ASSIST NOT FEASIBLE
3. THE ENVIRONMENTAL CONTROL SYSTEM FOR THE OPERATORS ENCLOSURE ON THE PMM FAILS. MODULE EXCHANGE WORK CEASES AND THE CREW IS EVACUATED.	<ul style="list-style-type: none"> o NORMAL WORK CREW SHUTS-DOWN AND EVACUATES PMM VIA SHUTTLE VEHICLE o SPECIAL CREW IN "SPACESUIT" ATTIRE MAN MACHINE LONG ENOUGH TO FREE WORKHEAD AND MOVE PMM OUTSIDE OF REACTOR ROOM o SPARE PMM & WORKHEAD COMPLETE MODULE EXCHANGE OPERATIONS. 	MEDIUM-CREW SUPPORT SYSTEMS ARE REDUNDANT, BUT SUBJECT TO HIGH DUTY FACTOR	MEDIUM-ONCE EVERY 2 YRS	<ul style="list-style-type: none"> o PMM o A, B, C CASSETTE MODULE WORKHEAD 	- CREW TRANSFER UNIT	33:30 HR	<ul style="list-style-type: none"> o CREW SUPPORT SYSTEMS MAY TEND TO BE COMPLEX, COMPACT, & REQUIRE SPECIAL MAINTENANCE o PMM MAINTENANCE IN RR IS NOT FEASIBLE

designed to meter the flow and allow the "A" region cassette to move back into position in the reactor. Other safety features may have to be added but such a system then permits the cassette to be released and the retraction of the PMM with the workhead to clear the reactor. The workhead is exchanged and reattached to the cassette. Figure C-7 illustrates the sequence of these functions.

The failure recovery time of 39.0 hours is the delay from the completion of the removal of "A" region cassettes in other reactor sectors to the completion of this operation for the affected sector. This time will vary slightly, depending upon when the failure occurs in the "A" region cassette removal sequence. The failure reaction time is also 39.0 hours in this event since concurrent operations are not feasible. The failure frequency for this type of equipment is assumed to be every 10 calendar years for each unit since no highly complex or sensitive mechanisms are apparently involved.

Divertor Module Workhead Failure - The replacement sequence for the divertor module requires withdrawal and insertion of the module through a small access door in the outer shield between the TF coils. The movement is horizontal and is accomplished by a boom arm that attaches to the module and slides it outboard until it is released from supporting tracks. On reassembly the boom arm inserts the module through the door and engages the tracks. The equipment failure postulated is that the workhead will not insert the replacement module into the tracks and cannot be withdrawn on the boom arm.

The procedure to recover from this failure mode is to release the positioning devices of the PMM, on which the boom arm is mounted, and to back the entire PMM away from the reactor. This also backs the divertor module out of the reactor. The divertor module is removed from the failed workhead by use of the overhead crane. The divertor module workhead is also exchanged by use of this crane and the work is continued. These operations are all remotely conducted since the reactor plasma chamber is open at this point. Figure C-8 describes the functional sequence in additional detail.

The failure recovery time and reaction time are equal for this failure mode. The additional time required from workhead failure to the same point in the installation sequence is 50.0 hours. The frequency of failure of this type of equipment is assumed to be once in every 10 calendar years as for the previously investigated failure of the heavy duty, high load, module handling equipment.

PMM Environmental Control System Failure - This failure mode can occur at any point during the replacement of the cassettes in the ORNL Cassette reference reactor. It also can occur for any other maintenance equipment that requires an operating crew. In this scenario the cassette workhead is assumed to be connected to a cassette and installing a replacement cassette. The Environmental Control System (ECS) failure is assumed to be in the atmosphere control system only and does not affect the radiation protection afforded by the cab shielding. A transfer port is available at the rear of the PMM which connects to a similar port in a shielded transport vehicle used to transfer crew members to and from the PMM.

To remedy this failure it is necessary to exchange the PMM for a spare unit. The crew is first exchanged for a crew equipped with self contained ECS suits. The PMM then operates to release the replacement cassette in a safe mode. The PMM is replaced with the spare unit and the activity is continued.

The failure recovery time and failure reaction time are again equal. The time estimated to accomplish this response to the failure is 33.5 hours. Redundancy

will undoubtedly be incorporated in the crew cab ECS, but this is a complex system. Therefore, the frequency of occurrence for failure of the ECS system to require such a delay is assumed at once every 2 calendar years for each PMM unit. The requirement to transfer a crew and replace the PMM may be alleviated by proper design to allow maintenance of the ECS while the PMM continues in use by providing for an additional crew member to do this work.

4.6.4 GA-Douplet Failure Mode Definitions - Two failure mode scenarios have been developed for maintenance equipment used during the GA-Douplet first wall/blanket exchange. The scenarios for these maintenance actions and key characteristics of the expected impact are summarized in Table 4.6-4.

TABLE 4.6-4
GA-DOUBLET MAINTENANCE EQUIPMENT FAILURE MODE ASSESSMENT

FAILURE MODE SCENARIO	FAILURE RESPONSE	BASIC MAINTENANCE MACHINE RELIABILITY	ANTICIPATED FREQUENCY OF FAILURE	SPARE MAINT. SET UTILIZATION REQUIRED	SPECIAL MAINTENANCE EQUIPMENT REQUIRED	ESTIMATED FAILURE RECOVERY TIME	REMARKS
1. AN RMM FAILS WITH THE MANIPULATOR ARM IN THE COCKED POSITION, HOLDING A BREEDER MODULE. RMM CANNOT BE RETRACTED	<ul style="list-style-type: none"> o ENTER ADJACENT PORT WITH SPARE RMM & SPECIAL MANIPULATOR ARM o REMOVE FAILED MANIPULATOR ARM o REPLACE FAILED RMM WITH SPARE RMM 	MEDIUM-COMPLEX, HIGHLY ARTICULATED MACHINERY, BUT WELL MAINTAINED	MEDIUM-ONCE EVERY 10 YRS/ RMM	<ul style="list-style-type: none"> - RMM - RMM WORKHEADS - REMOTE EQUIP. DOLLY 	- SPECIAL RMM MANIPULATOR ARM	143:15 HR.	OPERATOR ERROR MAY CONTRIBUTE MORE TO FAILURE THAN BASIC MECHANISM
2. THE ISOLATION VALVE SEPARATING THE IN-PLACE MAINTENANCE EQUIP. FROM THE PLASMA CHAMBER FAILS TO SEAL. PLASMA CHAMBER CANNOT MAINTAIN A VACUUM	<ul style="list-style-type: none"> o USE O/H CRANE TO REMOVE IN-PLACE MAINT. EQUIPMENT. o USE REMOTE MACHINES TO REPLACE VALVE 	ISOLATION VALVE IS ASSUMED TO BE MAINT. EQUIP. RELIABILITY OF FREQUENT RESEALING MAY BE LOW	HIGH-ONCE EVERY 2 YRS/ VALVE WITHOUT SCHEDULED MAINTENANCE. EVERY 10 YRS/ WITH PREVENTATIVE MAINTENANCE.	- ISOLATION VALVE ASSY	- AUTOMATIC, REMOTE, FLANGE DRESSING TOOL	171:30 HR.	VALVE SEAL SURFACES AND MECHANISM SUBJECT TO EXTREME RADIATION & HEAT

Remote Maintenance Machine Failure - The use of maintenance equipment that replaces the first wall/blanket modules from inside of the GA-Douplet plasma chamber leads to the possibility of failure of this equipment in many awkward positions. The Remote Maintenance Machine (RMM) manipulator arm is assumed to fail in a bent attitude with a breeder module attached for removal. The bend is such that the RMM cannot be removed through the auxiliary vacuum port with the manipulator in this configuration. The scenario assumes that the RMM manipulator arm is designed so that it can be dismantled remotely in as many sections as necessary to be retracted through a vacuum port. However, for this scenario only one joint is disconnected.

The procedure for responding to this failure mode is to replace the Remote Loading Module (RLM) in the sector next to the failed RMM with a spare RMM. The breeder module is transferred to the spare RMM and removed from the plasma chamber.

This RMM then is outfitted to remove a section of the failed RMM manipulator which is also removed from the plasma chamber. The overhead crane and manipulator is used to remove the failed RMM and it is then replaced by moving the spare RMM to that vacuum port. The RLM is reinstalled. Figure C-10 illustrates the general flow assumed for this scenario.

The failure recovery time and the failure reaction time are equal for this scenario. A total recovery time of 143.3 hours is required to exchange all faulty parts and resume operations. While operations can continue on most sectors, the operable RMM in the other sector adjacent to the RLM that is removed must also be shut down during this maintenance action. Therefore, the first wall/blanket work in these two sectors must be completed after recovery from the failure. The maintenance equipment in this concept is quite versatile so that alternative procedures are possible.

The equipment used in this concept is relatively complex and is installed in place on the reactor. However, maintenance on this equipment is conducted between scheduled outages so the frequency of failure of every 10 years per RMM is assumed. Even though 8 RMM's are installed, only a few days per operating year of unscheduled outage is attributed to the failure of this type of equipment.

Isolation Valve Seal Failure - As a part of the GA-Doublet reactor validation and start up procedure a vacuum check is made on the plasma chamber. This check validates the seals at the vacuum ports used for entry of maintenance equipment and replacement components. The scenario for this failure mode assumes that one of the valves which isolates the in-place maintenance equipment from the plasma chamber is leaking and requires replacement. The instrumentation installed on the reactor is capable of isolating the leak to one sector and thus to one valve since there is only one valve in a sector. Since the module seals are tested as the basic replacement procedure progresses, different trace gases can be used to differentiate between a module leak and the isolation valve leak. The conceptual design of this valve requires removal of the in-place maintenance machine to access the valve for removal. In addition, the seal is assumed to be between the flange on the reactor and the valve disc which requires maintenance of the seal seat on the flange.

The procedure used in this scenario, once the leaking valve is isolated and reseating is attempted, is to back out of the verification procedure and remove the remote maintenance equipment. The valve is removed and a spare valve is made ready. First the reactor flange is reworked and the seal assembly installed. The valve is installed and the vacuum check repeated. After the maintenance equipment

is installed, the verification and start-up procedure is again initiated. This functional sequence is illustrated in Figure C-11.

The failure recovery time for this scenario is estimated at 171.5 hours. This is greater than the failure reaction time (163.5 hours) because the validation and start-up procedure must be reinitiated. The frequency of this failure mode is assumed to be high (once every two years per valve) if no scheduled maintenance is conducted on the valve because of the critical seal problems of a mechanical joint. The impact under these conditions is so significant that a valve design which can be maintained on a scheduled basis while other scheduled maintenance operations are continuing is deemed to be a requirement. A second scenario has been postulated with this type of a valve that presumes the use of preventative scheduled maintenance and the assumption is made that the unscheduled failure frequency is reduced to once every 10 years. The result of this change is discussed in Section 5.0.

4.6.5 Reactor Subsystem Failure Mode Definitions - Scenarios are defined for maintenance equipment failure during unscheduled replacement of the GA-Doublet cryovacuum pump isolation valve and the replacement of an NBI ion source. These basic maintenance actions are described in Section 4.5. The maintenance equipment failure scenarios are briefly defined and the critical characteristics presented in Table 4.6-5.

TABLE 4.6-5
REACTOR SUBSYSTEM FAILURE MODE ASSESSMENT

REACTOR CONCEPT	FAILURE MODE SCENARIO	FAILURE RESPONSE	BASIC MAINTENANCE MACHINE RELIABILITY	ANTICIPATED FREQUENCY OF FAILURE	SPARE MAINT. SET UTILIZATION REQUIRED	SPECIAL MAINT. EQUIP. REQ'D	ESTIMATED FAILURE RECOVERY TIME	REMARKS
GA-DOUBLET VACUUM PUMPING SUBSYSTEM	1-A. A CRYOVACUUM PUMP ISOLATION VALVE FAILS TO CLOSE. THE REACTOR IS SHUTDOWN TO ALLOW UNSCHEDULED REPLACEMENT OF THE VALVE. DURING VALVE CHANGEOUT, A MAINTENANCE MACHINE ALSO FAILS.	<ul style="list-style-type: none"> o STOP WORK ON VALVE REPLACEMENT o PREP. SPARE MAINT. MACHINE IN MAINT. STAGING AREA o EXCHANGE MAINT. MACHINES 	HIGH-MAINT. MACHINES SHOULD BE WELL MAINTAINED	LOW-ONCE EVERY 5 YRS	- CRYOSORPTION PUMP VALVE MAINTENANCE MACHINE	- NONE	10:00 HR	<ul style="list-style-type: none"> o MAINT. MACHINE DOES NOT HANDLE VALVE o ONLY TIME LOST IS TO EXCHANGE MAINT. MACHINES
ALL	1-B. ONE ION SOURCE OF THREE IN AN NBI EXPERIENCES A FAILURE. AN UNSCHEDULED MAINTENANCE OUTAGE IS REQUIRED TO REPLACE THE ION SOURCE. DURING REPLACEMENT, THE OMU, USED TO EXCHANGE THE SOURCE, ALSO FAILS.	<ul style="list-style-type: none"> o STOP WORK ON ION SOURCE REPLACEMENT o PREP. OMU FROM ANOTHER "ON-LINE" SET o REMOVE FAILED OMU FROM RR o EMPLACE ALTERNATE OMU WITH NEW CREW 	HIGH-OMU SHOULD BE WELL MAINTAINED	LOW-ONCE EVERY 8 YRS	- NONE-USE OMU FROM ANOTHER "ON-LINE" SET	- NONE	6:00 HR	<ul style="list-style-type: none"> o ONLY TIME LOST IS TO EXCHANGE OMU'S

GA-Doublet Cryovacuum Pump Valve Maintenance Machine Failure - The scenario for this maintenance action deals with the general purpose maintenance machine used on the reactor room floor, or on the floor below, to conduct remote maintenance on activated or contaminated components such as the main cryovacuum pump isolation valve. This machine is equipped with manipulator arms and the scenario postulates the failure of one of these arms. Since the machine conducts only light load attachment or disconnect operations and the heavy operations are conducted by transporters or the overhead crane, the problem is reduced to extricating the machine either by automatically disconnecting it from the component or just leaving the tool on the component. The maintenance machine is then moved or towed to a repair area and replaced with a spare.

The failure recovery time for such an operation is estimated at approximately 10 hours with most of the time required to prepare a substitute machine. The frequency of this type of failure is expected to be low (once in 5 years for each machine) since these machines are kept in a repair or storage area when not in use and are assumed to be well maintained.

Operational Maintenance Unit Failure During Ion Source Replacement - For this scenario the failure of the OMU occurs as it is conducting an unscheduled replacement of a failed NBI ion source. Therefore, operational maintenance equipment can be made available for replacement of the OMU without using the spare equipment. It is assumed that one of the OMU manipulators failed but the OMU remains mobile. The OMU is further assumed to be operating disconnect mechanisms and not in the act of lowering the ion source to the transport dolly. Therefore, freeing the OMU from its task is similar to that of freeing the GA-Doublet general purpose maintenance machine in the scenario described above. The recovery procedure is to replace the OMU with another machine which is "on line" and ready to operate. This is a different maintenance approach than is used for replacement of the GA-Doublet maintenance machine and results in a shorter downtime.

The failure recovery time is estimated as only the six hours required to replace the OMU. The frequency of occurrence of failure of this equipment is expected to be low and is assumed at once every 8 years for each OMU.

4.7 DEMOUNTABLE MAGNET MAINTENANCE - Magnet features important to maintainability include the intertwined geometry of toroidal and poloidal field magnets, the centrally located ohmic heating coils and the use of superconducting magnet elements. Current techniques for superconducting element design employ continuous winding of the conductors with the result that disassembly and reassembly at the

reactor site is extremely difficult. Analysis of the maintenance requirements of the magnet subsystem for tokamak reactors, particularly the maintenance of the toroidal field (TF) magnets, is treated separately from the other subsystems since the impact on the economics of the reactor can be so significant. An objective of magnet design is to eliminate the need for maintenance but because failure can occur the design must enable repair at minimum cost.

The use of demountable magnets which provide for replacement without rebuilding the magnet is a potential solution. These are generally of two types. One is demountable as a unit (i.e., a unitary design) and, in the case of the TF magnets, a demountable design requires that either the poloidal field (PF) magnets all be outside of the TF magnet bore or that the PF magnets be segmentable. The segmented magnet is the second type and may be either a segmented TF magnet or a segmented PF magnet and also either a normal or a superconducting magnet.

Recently, a concept of a segmented demountable superconducting TF magnet design, the DEALS concept, has been proposed, References 4-7 and 4-8. This approach employs a polygonal shape with straight legs, Figure 4.7-1, and provides the capability of disassembly in situ and the replacement of any one or more of the individual legs.

DEMOUNTABLE TOROIDAL MAGNET ARRANGEMENT

FIGURE 4.7-1

This assessment will treat only the maintainability of the segmented demountable magnet concept. It will not address, for example, the magnet performance, reliability or its basic design feasibility.

The maintainability analysis compares the downtime required to exchange a TF coil of the segmented demountable superconducting magnet design, as represented by the DEALS concept, with the downtime required to exchange a unitary design TF magnet. Since the total impact on economics is so dependent upon reliability and because the reactors used in this analysis differ significantly from the reference reactor designs, this analysis is not integrated in the subsystem tradeoffs discussed in Section 5.0.

4.7.1 Segmented Demountable TF Magnet Replacement - The unscheduled downtime resulting from a failure of a DEALS type of magnet is examined as it applies to the High Field Ignition Test Reactor (HFITR) concept defined in Reference 4-8. This design arrangement is illustrated in Figures 4.7-2 and 4.7-3 taken from the reference. For this analysis three failure modes of the TF magnet are examined. These are summarized in Table 4.7-1. For the first case the conductor fails in the inner lower leg of the magnet and no damage occurs in the adjacent joints or

DEALS MAGNET APPLICATION IN HFITR REACTOR

REFERENCE 4-8

FIGURE 4.7-2

DEALS MAGNET APPLICATION IN HFITR REACTOR—PLAN VIEW

REFERENCE 4-8

FIGURE 4.7-3

TABLE 4.7-1

DEMOUNTABLE TOROIDAL FIELD COIL FAILURE SCENARIOS

MAINTENANCE ACTION NO.	REACTOR	FAILURE	CONSEQUENCE	DESIGN ASSUMPTION
1	HFITR	SHORT IN TF COIL CONDUCTOR	NO DAMAGE TO ADJACENT JOINTS	PLASMA CHAMBER CAN BE RAISED TO PROVIDE CLEARANCE AT INNER LEG OF MAGNET.
2	HFITR	SHORT IN TF COIL CONDUCTOR	JOINT BETWEEN INNER LOWER LEG AND INNER VERTICAL LEG ARE WELDED TOGETHER	SAME AS MAINTENANCE ACTION NO. 1
3	HFITR	SHORT IN TF COIL CONDUCTOR	NO DAMAGE TO ADJACENT JOINTS	NO CLEARANCE IS AVAILABLE TO RAISE PLASMA CHAMBER

the support structure. For the second case the conductor fails in the inner lower leg and the inner lower joint is welded so that simple disassembly is not feasible. Both of these cases assume that the plasma chamber can be raised enough, without dismantling any of the reactor, to provide clearance for removal of the magnet leg between the supporting structure after the joint at the inner leg is disconnected. The third case is similar to the first. In this case no clearance is available to raise the plasma chamber until the reactor is disassembled to the point where the completed torus, including the TF coils, can be raised to provide this clearance.

To estimate the downtime a number of design assumptions are made. These are listed in Table 4.7-2 for the HFTR design. The functional sequences used for the three maintenance actions are listed in Tables 4.7-3, 4.7-4 and 4.7-5. The design assumptions make maintenance action number 1 the simpler of the three cases. Therefore, the downtime is estimated for this case to determine the minimum possible time that can be expected for such an outage. This time is approximately 417 hours of maintenance time, not including warmup and cooldown of the TF magnets. Since part of the TF magnet warmup operation (approximately 5 days) and part of the cooldown operation (approximately 7 days) can overlap the initial disassembly and the final reassembly of the reactor, the total time required when using a time dilution factor for only the maintenance time is approximately 40 days. All operations during this outage are conducted using contact operations since the shielding is not opened at any time. The assumption that this type of maintenance is feasible is one of the chief reasons for the relatively short downtime estimates.

A number of cautions are necessary regarding the assumptions and the procedures outlined in making this downtime estimate. Several of the design assumptions in Table 4.7-2 are quite optimistic. These are discussed in the following paragraphs.

The best estimate of the clearance between TF coils at the vertical leg joints is approximately 10 cm based on the sketches shown in Reference 4-8. This is insufficient space for manual access. However, the assumption that a tool can be built to perform the welding and cutting functions in this space is optimistic since present designs of this type of equipment require more space.

The design of the joint to allow disassembly and reassembly by moving one of the magnet segments along its axis may require additional study. This operation requires the capability to insert the insulation blocks and avoid increasing the joint height and width dimensions significantly. Also, the method of cooling the joint is not clear but the assumption of dewar around the joint is made to allow

TABLE 4.7-2
HFITR MAINTENANCE DESIGN ASSUMPTIONS

- TF COIL JOINTS MUST BE DESIGNED FOR SUPERCONDUCTING TEMPERATURES.
- THE 10 CM CLEARANCE BETWEEN TF COILS AT THE VERTICAL INNER LEG JOINTS IS SUFFICIENT FOR WELDING/CUTTING TOOL AT EACH JOINT. IT IS FEASIBLE TO REACH INTO THE 10 CM X 1 m SLOT A DISTANCE OF 1 m.
- ALL MAINTENANCE OPERATIONS USE CONTACT MAINTENANCE.
- ALL SERVICE CONNECTIONS TO THE PLASMA CHAMBER CAN MOVE APPROXIMATELY 5-10 CM WITHOUT DISCONNECTION REQUIRED. THIS INCLUDES NBI'S, COOLANT LINES, OTHER VACUUM AND REFRIGERANT LINES.
- CLEARANCE BETWEEN TF COILS AND/OR PF COILS AND THE PLASMA CHAMBER TORQUE SUPPORT STRUCTURE IS AT LEAST ~5-10 cm.
- TF COIL JOINT PRESSURES CAN BE OBTAINED WITHOUT THRU BOLTS.
- BOTH OUTER DEWAR AND TF COIL CASE MUST BE WELDED.
- INDIVIDUAL LEGS OF TF COIL ARE INDIVIDUALLY COOLED BECAUSE OF LONG FLOW PATH THAT MAY RESULT IN GAS POCKETS (THEREBY PRODUCING HOT SPOTS) AND BECAUSE NO FLOW CHANNELS ARE SHOWN THROUGH JOINTS.
- FOR MAINTENANCE ACTION #2, THE FACT THAT THE JOINT IS WELDED IS DETERMINED DURING STEP #10 OF MAINTENANCE ACTION #1.
- OUTER STRUCTURAL SUPPORT WILL HOLD COILS IN PLACE WHEN THE UPPER LEGS OF THE COIL ARE DISCONNECTED AND WHEN THE COIL SUPPORT STRUCTURE IS DISCONNECTED FROM THE UPPER COLLAR AND IS SUPPORTED BY RETRACTABLE WHEELS.
- SUFFICIENT CLEARANCE EXISTS BETWEEN THE INBOARD VERTICAL LEG OF THE TF COIL AND THE CHAMBER OUTER SHIELD TO ALLOW VERTICAL WITHDRAWAL OF THE VERTICAL LEG TO A POSITION CLEAR OF THE CHAMBER AND BUCKING STRUCTURE.
- THE VERTICAL LEG OF THE TF COIL IS SUPPORTED BY LEDGES IN SUPPORT STRUCTURE CHANNEL WHICH SURROUNDS THIS LEG OF COIL AND IS HELD VERTICALLY BY THE UPPER TORQUE PLATE AND THE COLLAR BY BEARING ON THE BEARING BLOCKS.
- THE REACTOR IS COOLED TO ROOM TEMPERATURE BEFORE MAINTENANCE IS STARTED TO INCREASE CLEARANCES WITH TF COILS, IF POSSIBLE.
- INSULATION INSERTS IN THE LOWER INBOARD LEG JOINT MUST BE IN PLACE BEFORE JOINING BECAUSE THERE IS NO ROOM TO INSERT THEM FROM ABOVE OR BELOW. (ONLY MAINTENANCE ACTION #3 PROVIDES THE CAPABILITY FOR SUFFICIENT VERTICAL CLEARANCE AND THEN MANY LINES HAVE TO BE DISCONNECTED.) ASSUME THAT THE DESIGN ALLOWS PROGRESSIVE MATING OF EACH TURN DURING THE JOINING OPERATION TO ALLOW FOR ALIGNING ONE INSULATION INSERT AT A TIME.
- THE FAILURE MODE IS SUCH THAT THE TF COIL CASE IS NOT RUPTURED SUFFICIENTLY TO STRUCTURALLY DEFORM THE MAGNET AND CAUSE BINDING AGAINST SUPPORTING STRUCTURE WHEN THE MAGNET IS WITHDRAWN.
- FOURTEEN DAYS ARE REQUIRED TO WARMUP TF COILS AND ALSO TO CHILL THEM DOWN AGAIN AT STARTUP.

TABLE 4.7-3
HFITR TF MAGNET REPLACEMENT PROCEDURE
(MAINTENANCE ACTION NUMBER 1)

MAINTENANCE ACTION:

REMOVE LOWER INBOARD LEG OF A DEFECTIVE TF COIL.

ASSUME:

WEIGHT OF REACTOR CAN BE RAISED OFF OF INBOARD LOWER LEG. (ASSUME TOLERANCES FOR LINES AND VACUUM CHAMBER/SHIELD ALLOW THIS WITHOUT DISASSEMBLY.)

PROCEDURE IS AS FOLLOWS:

1. INSERT JACKS UNDER PADS ALONG LOWER OUTBOARD AND INBOARD TORQUE SHELL BETWEEN ALL TF COIL BOTTOM SECTIONS; RAISE STRUCTURE TO CLEAR BOTTOM LEG.
2. REMOVE OUTBOARD STRUCTURE ASSEMBLY AT FAILED MAGNET LOCATION. (ASSUME NO SUBSYSTEM OBSTRUCTIONS)
3. REMOVE TF COIL INTERCOSTAL SUPPORTS AROUND BOTH SIDES OF DEFECTIVE COIL.
4. SUPPORT LOWER OUTBOARD LEG WITH CRADLE OR DOLLY.
5. DISCONNECT DEWAR AND LOWER OUTBOARD LEG JOINTS.
6. DISCONNECT SERVICES TO LOWER OUTBOARD AND INBOARD LEGS.
7. REMOVE OUTBOARD LEG OF TF COIL.
8. SUPPORT LOWER INBOARD LEG WITH RETRACTION MECHANISM OR DOLLY.
9. DISCONNECT DEWAR AND LOWER INBOARD LEG JOINT.
10. RETRACT INBOARD LEG OUTWARD AND DOWNWARD, REMOVE FROM AREA.
11. INSTALL REPLACEMENT LOWER INBOARD LEG OF TF COIL.
12. ATTACH INBOARD JOINT OF LOWER INBOARD LEG OF TF COIL.
13. INSTALL LOWER OUTBOARD LEG OF TF COIL.
14. CONNECT JOINTS FOR LOWER OUTBOARD LEG OF COIL.
15. REMOVE DOLLY AND CRADLE.
16. CONNECT SERVICES TO BOTH LOWER LEGS.
17. TEST DEWAR, LHe AND LN₂ CHANNELS FOR LEAKS.
18. LOWER SUPPORT STRUCTURE TO REST ON LOWER TORQUE PLATE AND/OR SUPPORT BLOCKS.
19. INSTALL INTERCOSTAL SUPPORTS BOTH SIDES OF TF COIL.
20. INSTALL OUTBOARD STRUCTURAL SUPPORT ASSEMBLY.
21. PRELOAD OUTBOARD STRUCTURE JOINTS IN TENSION, REMOVE JACKS.
22. CHILL DOWN AND ELECTRICALLY TEST REPAIRED COIL.

NOTE: IF SUPPORT STRUCTURES REST ON LOWER TORQUE PLATE - MAY NOT NEED TO RAISE STRUCTURE.

TABLE 4.7-4
HFITR TF MAGNET REPLACEMENT PROCEDURE
(MAINTENANCE ACTION NUMBER 2)

MAINTENANCE ACTION:

REMOVE LOWER INBOARD LEG OF A DEFECTIVE TF COIL.

ASSUME:

FAILURE CAUSED INNER JOINT TO BE WELDED TO THE INNER VERTICAL LEG.

PROCEDURE IS AS FOLLOWS:

1. CONDUCT FIRST 9 STEPS OF MAINTENANCE ACTION #1.
2. ATTEMPT TO RETRACT LOWER INBOARD LEG OF TF COIL.
3. CUT THROUGH INBOARD JOINT OF LOWER INBOARD LEG OF TF COIL.
4. REMOVE LOWER INBOARD LEG OF TF COIL.
5. TAKE UP WEIGHT OF ALL GOOD COILS, STRUCTURE, SHIELD, AND PLASMA CHAMBER ON RETRACTABLE STRUCTURE WHEELS.
6. DISCONNECT 15 JOINTS BETWEEN UPPER COLLAR AND OUTER STRUCTURAL SUPPORTS.
7. REMOVE UPPER RETAINING RING.
8. REMOVE UPPER COLLAR ASSEMBLY.
9. REMOVE UPPER TORQUE PLATE.
10. DISCONNECT SERVICES TO UPPER INBOARD LEG OF TF COIL.
11. DISCONNECT DEWAR AND JOINTS OF UPPER INBOARD LEG OF TF COIL.
12. REMOVE UPPER INBOARD LEG OF TF COIL.
13. DISCONNECT SERVICES TO INBOARD VERTICAL LEG OF TF COIL.
14. REMOVE VERTICAL INBOARD LEG OF TF COIL FROM REACTOR.
15. INSTALL REPLACEMENT VERTICAL INBOARD LEG IN REACTOR.
16. CONNECT SERVICES TO VERTICAL INBOARD LEG OF TF COIL.
17. INSTALL REPLACEMENT LOWER INBOARD LEG.
18. ATTACH INBOARD JOINT OF LOWER INBOARD LEG OF TF COIL.
(RETAIN SUPPORT IN PLACE UNTIL OUTBOARD LEG ATTACHMENT IS COMPLETED.)
19. INSTALL UPPER INBOARD LEG OF TF COIL.
20. CONNECT JOINTS FOR UPPER INBOARD LEG OF TF COIL.
21. CONNECT SERVICES TO UPPER INBOARD LEG OF TF COIL.
22. INSTALL UPPER COLLAR ASSEMBLY.
23. INSTALL UPPER RETAINING RING.
24. CONNECT 15 JOINTS BETWEEN UPPER COLLAR AND OUTER STRUCTURAL SUPPORTS.
(STEPS 13 THROUGH 20 OF MAINTENANCE ACTION #1 CONDUCTED IN PARALLEL WITH STEPS 19 THROUGH 24 ABOVE AS FOLLOWS: STEPS 13 THROUGH 16 OF MAINTENANCE ACTION #1 IN PARALLEL WITH STEPS 19 THROUGH 21 ABOVE. STEPS 17 THROUGH 20 OF MAINTENANCE ACTION # 1 IN PARALLEL WITH STEPS 22 THROUGH 24 ABOVE.)
25. COMPLETE INSTALLATION OF LOWER OUTBOARD LEG OF TF COIL.
26. PRELOAD ALL STRUCTURAL SUPPORT JOINTS IN TENSION.
27. RETRACT WHEELS TO TRANSFER LOADS TO OUTER STRUCTURAL SUPPORTS.
28. CHILL DOWN AND ELECTRICALLY TEST REPAIRED COIL.

TABLE 4.7-5
HFITR TF MAGNET REPLACEMENT PROCEDURE
(MAINTENANCE ACTION NUMBER 3)

MAINTENANCE ACTION:

REMOVE LOWER INBOARD LEG OF A DEFECTIVE TF COIL.

ASSUME:

NO CLEARANCE IS AVAILABLE TO RAISE TORUS INSIDE OF TF COILS.

GENERAL PROCEDURE:

DISASSEMBLE REACTOR TO THE POINT WHERE COMPLETE TORUS AND TF MAGNET ASSEMBLY CAN BE RAISED 5-10 CM ON INNER OHMIC HEATING (OH) COIL RING ASSEMBLY AND BUCKING COLUMN/INNER TORQUE RING ASSEMBLY TO GAIN ACCESS TO LOWER INBOARD LEG OF DEFECTIVE MAGNET.

PROCEDURE IS AS FOLLOWS:

1. INSTALL JACKS UNDER TORQUE SUPPORT STRUCTURE BETWEEN ALL TF COILS AT APPROXIMATE CENTER OF TORUS (ASSUMED TO BE C.G. OF TOROIDAL CROSS SECTION.)
2. REMOVE 16 OUTER STRUCTURAL SUPPORTS.
3. REMOVE UPPER RETAINING RING.
4. REMOVE UPPER COLLAR.
5. ATTACH CRANE TO OH COIL AND TO BUCKING CYLINDER ASSEMBLIES.
6. RAISE COMPLETE TORUS AND ALL TF MAGNETS 5-10 CM FOR ACCESS TO DEFECTIVE LOWER INBOARD MAGNET LEG BY COORDINATED USE OF CRANE AND JACKS. (A LOAD AND DISPLACEMENT MEASURING SYSTEM MUST BE USED FOR CRANE AND JACKS.)
7. CONTINUE MAINTENANCE ACTION #1 STARTING WITH STEP #3 AND OMITTING STEPS 18 AND 20 THROUGH 22.
8. LOWER COMPLETE TORUS AND ALL TF MAGNETS TO REST ON LOWER TORQUE PLATE AND/OR SUPPORT BLOCKS.
9. INSTALL UPPER COLLAR.
10. INSTALL UPPER RETAINING RING.
11. INSTALL 16 OUTBOARD STRUCTURAL SUPPORT ASSEMBLIES.
12. PRELOAD OUTBOARD STRUCTURAL SUPPORT JOINTS IN TENSION, REMOVE JACKS.

such cooling. Time is allowed to remove the dewar in addition to the time to remove welds around the casing through which pressure is applied to the contact pressure plates and which seals the magnet casing. Additional coolant connections may be required but these are not included.

The influence of the lateral pressure of the structural bearing blocks shown in Figure 4.7-2 on the TF magnet in restricting the axial movement of the segment being removed is not considered. Design of the structural slot nesting the segment must include the capability to retract bearing blocks or supporting surfaces to allow its withdrawal by the technique postulated.

The failure of a segmented magnet is assumed to require the replacement of only one segment, or two segments if a joint is involved. However, the replacement of all segments may be required to assure safety, the effectiveness of the repair, and the interchangeability of segments after a disruptive failure. This will increase the time requirements significantly.

A final caution is that the assumption of contact maintenance feasibility is dependant upon the activation level of equipment and walls in the reactor room. If neutron streaming through such openings as NBI ducts and vacuum ducts is significant, the use of personnel in the reactor room may be restricted. Such a situation will increase the estimated downtime.

4.7.2 Unitary Design TF Magnet Replacement - For examination of the maintenance requirements invoked by replacement of a unitary design TF magnet the General Atomic Ignition Test Reactor (GA-ITR) is selected. This design concept is well defined in Reference 4-9. Figure 4.7-4 and 4.7-5 illustrate the significant features of the design.

Two scenarios are defined for replacement of a TF magnet in the GA-ITR. One assumes that the PF magnets are also unitary normal coils and the other makes the assumption that the PF magnets are segmented normal magnets divided into 6 equal segments. Table 4.7-6 summarizes the principal points of these scenarios. The use of the doublet shape illustrates one of the more difficult configurations for replacement of a TF magnet because of the numerous PF magnets. These include 26 field shaping (F) coils and 10 stabilization (S) coils installed within the bore of the TF magnet. However, the design is such that these coils and the plasma chamber can be disassembled and rebuilt in place.

The assumptions made regarding the GA-ITR design are listed in Table 4.7-7. These assumptions define the data sources and details of assembly and disassembly necessary to estimate the downtime required for each scenario. The functional sequences used in both of these scenarios are listed in Tables 4.7-8 and 4.7-9 for maintenance actions number 1 and number 2, respectively. The principal difference in these two scenarios is that the segmenting of the PF magnets allows the failed TF magnet to be removed with the disassembly of only three sectors while the unitary PF magnets require the disassembly of all sectors for replacement of one TF magnet.

Downtime estimates are presented for both scenarios. When segmented PF magnets are used, the total downtime required is approximately 5130 hours. Since disassembly and reassembly operations are so extensive these are in process while the TF magnets are being warmed up before being disconnected and cooled down after

GENERAL ATOMIC IGNITION TEST REACTOR

FIGURE 4.7-4

installation. Therefore, additional time is not required for this procedure as is the case for the segmented TF magnet scenarios. Most of the maintenance activity must be conducted by remote techniques since the shielding is open during most of the disassembly and reassembly operations. Only about 160 hours of contact maintenance operations can be conducted. The total elapsed time required for this scenario, assuming a 3 shift operation and a productivity factor of .75, is 285 days.

For the scenario employing unitary PF magnets the total time is increased to approximately 17,300 hours or 962 days. Of this time approximately 530 days or 55 percent of the total downtime is required to disassemble and rebuild the PF magnets. This compares with 81 days or 28 percent of the total downtime with segmented PF magnets.

PLAN AND PROFILE VIEW OF GENERAL ATOMIC IGNITION TEST REACTOR

FIGURE 4.7-5

TABLE 4.7-6
UNITARY TOROIDAL FIELD COIL FAILURE SCENARIOS

MAINTENANCE ACTION NO.	REACTOR	FAILURE	CONSEQUENCE	DESIGN ASSUMPTION
1	GA-ITR	SHORT IN TF COIL CONDUCTOR	COMPLETE MAGNET MUST BE REPLACED	UPPER, LOWER AND INNER "F" COILS ARE NOT SEGMENTED
2	GA-ITR	SHORT IN TF COIL CONDUCTOR	COMPLETE MAGNET MUST BE REPLACED	UPPER, LOWER AND INNER "F" COILS ARE SEGMENTED

TABLE 4.7-7
GA-ITR TF MAGNET MAINTENANCE DESIGN ASSUMPTIONS

- FOLLOW DESIGN IN REFERENCE 4-9 INsofar AS POSSIBLE.
- GA REPORT INDICATES THAT INNER, UPPER AND LOWER F COILS ARE NOT SEGMENTED (LIKE DOUBLET III). FOR MAINTENANCE ACTION #1 ASSUME THAT THESE COILS ARE NOT SEGMENTED. FOR THE ALTERNATE MAINTENANCE ACTION #2 ASSUME THAT THESE COILS ARE SEGMENTED.
- PROCEDURES OUTLINED IN REFERENCE 4-9 VOLUME VII ARE USED INsofar AS THEY ARE DEFINED.
- ASSUME REMOVABLE SHIELD SEGMENTS INCLUDE ALL SHIELDING FOR COMPLETE SECTOR INCLUDING THE BOTTOM SHIELDING. WHEN ALL SHIELDING IS REMOVED A COMPLETE TOROIDAL RING IS CONTINUOUSLY ACCESSIBLE FOR REWINDING THE INDUCTION COILS.
- TF COILS ARE SUPPORTED FROM FLOOR ONLY AND WILL MOVE OUTWARD FROM CORE OF REACTOR WITHOUT FURTHER DETACHMENT FROM CORE.
- OVERHEAD CRANE CAPACITY WILL BE SUFFICIENT TO HANDLE ONE TF COIL.
- EACH INDUCTION (E) COIL IS WOUND IN A HORIZONTAL POCKET AND HELD IN PLACE BY THE TF COILS. VERTICAL MOVEMENT OF INDUCTION COILS IS NOT POSSIBLE BETWEEN POCKETS. SEE REFERENCE 4-9 FOR ELECTRICAL CONNECTION OF COILS IN PARALLEL.
- CRYOGENIC COOLING OF SUPERCONDUCTORS IS BY POOL BOILING OF LHe. COOLING CHAMBER FOR TF COILS IS SEPARATED FROM INTERCOSTAL SUPPORT INSULATION TO ALLOW TESTING OF COIL COOLANT AND CIRCUITRY BEFORE ALL INTERCOSTALS ARE INSTALLED.
- NO ADDITIONAL STRUCTURE IS REQUIRED TO SUPPORT REACTOR WHICH WILL INTERFACE WITH OPERATIONS AS DEFINED.
- THE VACUUM SYSTEM IS CONNECTED THROUGH THE NEUTRAL BEAM INJECTORS. IF NOT, ADDITIONAL TIME IS REQUIRED TO DISCONNECT THE VACUUM SYSTEM.
- A MACHINE CAN BE DESIGNED TO CONSTRUCT THE CONTINUOUS (NOT DEMOUNTABLE) F COILS INSIDE OF THE BORE OF THE TF COILS AND CLEARANCE IN THE BORE IS SUFFICIENT TO CONSTRUCT THE OUTBOARD COILS WHEN THE PLASMA CHAMBER IS IN PLACE. IF SUCH CLEARANCE DOES NOT EXIST THESE OUTBOARD COILS MAY HAVE TO BE DEMOUNTABLE.
- TF COIL OUTBOARD LEGS ARE SUFFICIENTLY DISTANT FROM THE SHIELD AND PLASMA CHAMBER TO ALLOW REMOVAL OF COMPLETE SECTORS OF THESE COMPONENTS BETWEEN THE COILS. IF THIS SPACE IS LIMITED, DOUBLING OF THE NUMBER OF SEGMENTS FOR REMOVAL IS REQUIRED.
- VACUUM CHAMBER ASSEMBLY EQUIPMENT IS AVAILABLE FOR WORKING 4 SECTORS AT A TIME BUT ONLY ONE CRANE IS AVAILABLE. SO, PLACEMENT OPERATIONS ARE CONDUCTED ONLY ONE AT A TIME.
- ALL OPERATIONS INCLUDING AND SUBSEQUENT TO REMOVAL OF UPPER SHIELD SEGMENTS AND BEFORE THESE ARE REINSTALLED ARE CONDUCTED REMOTELY.
- COMPLETION OF THE INSTALLATION OF EACH SET OF COMPONENTS REQUIRING COOLING IS FOLLOWED BY A TEST OF THE COOLANT SYSTEM FOR LEAKS.
- DEMOUNTABLE F COILS ARE ALL IN 60° SECTIONS WITH THE JOINTS LOCATED APPROXIMATELY IN THE CENTER OF ALTERNATE SECTORS. ALL COIL JOINTS WILL BE IN THE SAME SECTORS.
- INNER WALL COOLANT TANK JOINTS ARE DISCONNECTED FROM THE PLASMA CHAMBER SIDE ONLY.
- TF COIL REMOVAL, WHEN F COILS ARE SEGMENTED, IS BASED ON A TOROIDAL LOCATION WHICH REQUIRES THE REMOVAL OF ONLY 1 NBI UNIT.
- ASSUME THAT ALL 10 OUTBOARD F COILS ARE SEGMENTED.
- ASSUME THAT THE 3.8 m ITR IS USED WHICH SHOWS NO S COILS WHICH REQUIRE SEPARATE REMOVAL.

TABLE 4.7-8
GA-ITR TF MAGNET REPLACEMENT PROCEDURE
(MAINTENANCE ACTION NUMBER 1)

<p>MAINTENANCE ACTION: REMOVE FAILED TOROIDAL FIELD (B) MAGNET AND REPLACE.</p> <p>ASSUME: UPPER, LOWER AND INNER F COILS ARE NORMAL BUT NOT SEGMENTED.</p> <p>GENERAL PROCEDURE: IT IS NECESSARY TO REMOVE ALL OF THE REACTOR INSIDE OF THE TF COILS TO REWIND THE INNER, UPPER AND LOWER F COILS AFTER REPLACEMENT OF THE FAILED TF COIL. THEREFORE, A SYSTEMATIC STRIPPING OF THE REACTOR SHIELD, COILS AND PLASMA CHAMBER IS NECESSARY AS FOLLOWS:</p> <ol style="list-style-type: none"> 1. DRAIN AND DISCONNECT SERVICES TO UPPER 6 E COILS. 2. DETACH AND REMOVE UPPER E COILS AND SUPPORTING STRUCTURE, STORE. 3. REMOVE VACUUM JACKETED AND INSULATED B COIL INTERCOSTAL ABOVE PLASMA CHAMBER FOR 12 SECTORS. 4. DISCONNECT UPPER SHIELD COOLANT LINES. 5. DETACH AND REMOVE UPPER SHIELD SEGMENT FOR ALL 12 REACTOR SECTORS. 6. DISCONNECT SERVICES TO ALL 6 NEUTRAL BEAM INJECTOR (NBI) ASSEMBLIES. 7. DISCONNECT AND RETRACT THE SIX NBI UNITS (2 NBI'S PER UNIT) AWAY FROM REACTOR APPROXIMATELY 2 METERS. 8. DISCONNECT AND REMOVE SWING VALVE MODULES AND NBI DRIFT DUCT SHIELDING FOR ALL 6 NBI UNITS. 9. DISCONNECT OUTER SHIELD SEGMENT COOLANT LINES FOR ALL 12 SECTORS. 10. REMOVE TANK CAP FOR INNER WALL SHIELDING AND FIELD SHAPING COILS. 11. REMOVE INNER WALL SHIELDING FOR ALL 12 SECTORS. 12. REMOVE OUTER SHIELD SEGMENTS FOR ALL 12 REACTOR SECTORS. 13. DISCONNECT SERVICES AND DEMOUNT THE 6 OUTER F COILS INTO 6 SECTIONS EACH, REMOVE FROM REACTOR. 14. DISCONNECT SERVICES AND DEMOUNT THE REMAINING 4 OUTER F COILS INTO 6 SECTIONS EACH (2 UPPER AND 2 LOWER COILS). REMOVE FROM REACTOR. 15. DISCONNECT SERVICES FROM REMAINING 3 UPPER AND 3 LOWER F COILS OUTBOARD OF LIMITER ACTUATORS. CUT EACH COIL INTO 6 SECTIONS AND REMOVE FROM REACTOR. 16. DISCONNECT COOLANT LINES FROM PLASMA CHAMBER. 17. DISCONNECT LIMITER DRIVE UNITS. 18. INSTALL MAINTENANCE EQUIPMENT IN CHAMBER PORTS. (INSTALL 4 UNITS.) 19. REMOVE LINER AT PLASMA CHAMBER JOINTS. 20. INSTALL SPREADER BARS INSIDE PLASMA CHAMBER SECTOR. 21. CUT WELDED SEALS AT PLASMA CHAMBER JOINTS AND SEPARATE. 22. REMOVE MAINTENANCE EQUIPMENT FROM CHAMBER. 23. REMOVE 12 CENTER INTERCOSTAL MEMBERS BETWEEN TF COILS. 24. REMOVE 4 SECTORS OF PLASMA CHAMBER (4 IN SEQUENCE). 25. REPEAT 18 THROUGH 22 FOR REMAINING 8 SECTORS. 26. DISCONNECT AND REMOVE PANELS CONSTITUTING THE WALL AND BOTTOM OF THE INNER SHIELD AND F COIL TANK. 27. DISCONNECT SERVICES FROM 8 F COILS (4 UPPER AND 4 LOWER) AND CUT INTO 6 SECTIONS EACH. REMOVE FROM REACTOR. 	<ol style="list-style-type: none"> 28. DISCONNECT SERVICES FROM THE SIX INNER F COILS. CUT INTO 6 SECTIONS EACH AND REMOVE FROM REACTOR. 29. DISCONNECT COOLANT FROM BOTTOM SHIELD SEGMENT ON EITHER SIDE OF DEFECTIVE TF COIL. 30. DETACH AND REMOVE BOTTOM SHIELD SEGMENT ON EITHER SIDE OF DEFECTIVE TF COIL. 31. DRAIN DEFECTIVE TF COIL COOLANT AND DISCONNECT SERVICES FROM COIL. 32. ATTACH CRANE TO TF COIL TO BE REMOVED. 33. DISCONNECT AND REMOVE LOWER INTERCOSTAL MEMBER ON EITHER SIDE OF DEFECTIVE TF COIL. 34. CUT DEWAR AT INNER LEG OF DEFECTIVE TF COIL ON EITHER SIDE FOR FULL HEIGHT OF DEWAR AND ACROSS TOP AND BOTTOM OF TF COIL. 35. DETACH DEFECTIVE TF COIL FROM FLOOR AND MOVE OUTWARD FROM CORE, THEN VERTICALLY TO CLEAR REACTOR. USE OVERHEAD CRANE. 36. MOVE REPLACEMENT TF COIL INTO POSITION WITH OVERHEAD CRANE AND ATTACH TO FLOOR SUPPORTS. 37. WELD DEWAR ON EACH SIDE OF VERTICAL INNER LEG OF REPLACEMENT TF COIL AND ACROSS TOP AND BOTTOM OF TF COIL. 38. INSTALL THE LOWER INTERCOSTAL MEMBER ON EITHER SIDE OF REPLACEMENT TF COIL, RELEASE CRANE FROM COIL. 39. RECONNECT SERVICES TO TF COIL. 40. TEST REPLACEMENT COIL VACUUM, COOLANT FLOW AND CIRCUITRY FOR LEAKS, OBSTRUCTIONS OR CONTINUITY AS APPROPRIATE. 41. REPLACE BOTTOM SHIELD SEGMENTS AND ATTACH TO STRUCTURE. 42. CONNECT COOLANT LINES TO REPLACED BOTTOM SHIELD SEGMENTS. 43. RECONSTRUCT THE SIX CONTINUOUS INNER WALL F COILS. 44. RECONSTRUCT THE EIGHT CONTINUOUS F COILS (4 UPPER AND 4 LOWER) WHICH ARE INBOARD OF THE LIMITER ACTUATORS. 45. REPLACE THE INNER SHIELD AND F COIL TANK BOTTOM AND WALL. 46. INSTALL THE PLASMA CHAMBER ONE SECTOR AT A TIME BY REVERSING THE SEQUENCE DESCRIBED IN STEPS 16 THROUGH 25 ABOVE. 47. RECONSTRUCT THE SIX CONTINUOUS F COILS (3 UPPER AND 3 LOWER) OUTBOARD OF THE LIMITER ACTUATORS. 48. INSTALL THE TEN OUTER WALL DEMOUNTABLE F COILS. 49. INSTALL THE 12 OUTER SHIELD SEGMENTS AND COOLANT LINES. 50. INSTALL THE INNER WALL SHIELDING BLOCKS. 51. INSTALL THE INNER WALL COOLANT TANK COVER. 52. INSTALL THE SIX NBI SWING VALVE MODULES. 53. INSTALL THE SIX NBI UNITS (2 NBI'S PER UNIT) 54. INSTALL THE 12 UPPER SHIELD SEGMENTS. 55. INSTALL THE VACUUM JACKETED INTERCOSTAL MEMBERS BETWEEN THE 12 TF COILS ABOVE THE UPPER SHIELD SEGMENT. 56. INSTALL 6 UPPER E COILS (3 ASSEMBLIES) AND CONNECT. 57. CONDUCT TEST OF ALL COILS, VACUUM, AND COOLANT SYSTEMS FOR CONTINUITY AND LEAKS.
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These estimates are very preliminary and, as seen from Table 4.7-7, many assumptions are used in deriving them. Some of the design assumptions are particularly critical and additional cautions regarding them are considered in the following paragraphs.

Of particular importance is the assumption that the PF coils are to be discarded and rebuilt from new material. This allows the removal of these coils quite rapidly by cutting them into segments rather than by the slower process of unwinding and saving the conductor and coil cases. If the conductor can be readily reprocessed the material cost saving may be significant, depending on the reprocessing required, but the increase in downtime may also be very costly.

TABLE 4.7-9
GA-ITR TF MAGNET REPLACEMENT PROCEDURE
(MAINTENANCE ACTION NUMBER 2)

MAINTENANCE ACTION:

REMOVE FAILED TOROIDAL FIELD (B) MAGNET AND REPLACE

ASSUME:

ALL F COILS ARE NORMAL AND SEGMENTED.

GENERAL PROCEDURE:

REMOVE THE REACTOR SECTORS ON EITHER SIDE OF THE DEFECTIVE TF COIL ONLY AS FAR AS NECESSARY TO CLEAR THE BORE OF THE DEFECTIVE COIL. THIS WILL REQUIRE THE REMOVAL OF THREE SECTORS OF THE PLASMA CHAMBER SINCE THE F COILS ARE SEGMENTED IN 60° SECTIONS WHICH WILL SPAN 2 COMPLETE REACTOR SECTORS (NOTE, ONE SECTOR IS THE REACTOR BETWEEN 2 TF COILS). IT IS ASSUMED THAT A THIRD SECTOR MUST BE REMOVED TO GAIN ACCESS TO THE OVERLAP IN THE F COIL JOINTS AND THAT, THEREFORE, IT IS BEST TO PLACE THESE JOINTS IN THE CENTER OF THE SECTORS IN WHICH THEY ARE LOCATED.

PROCEDURE IS AS FOLLOWS:

FOLLOW PROCEDURE OF GA-ITR MAINTENANCE ACTION #1 EXCEPT THAT:

- WHERE 12 UNITS OF A COMPONENT ARE CALLED OUT, ONLY 3 ARE AFFECTED IN THIS PROCEDURE.
- WHERE F COILS ARE DISCONNECTED AND CUT INTO 6 SECTIONS, ONLY 2 JOINTS WILL BE DISCONNECTED AND ONE SECTION REMOVED. SERVICES WILL NOT BE DISCONNECTED SINCE THE PROBABILITY OF THIS REQUIREMENT IS LOW.
- ONLY 3 SECTIONS OF THE INNER WALL TANK ARE REMOVED FOR ACCESS TO THE INNER WALL F COILS.
- ONLY 1 NBI UNIT WILL BE DISCONNECTED AND 1 SWING VALVE MODULE REMOVED.
- WHERE SEGMENTED F COILS ARE REMOVED, ONLY ONE SECTION WILL BE REMOVED.

The use of normal PF coils for a commercial reactor has been considered for commercial concepts but most concepts take advantage of the plant operating efficiency increase attained by the use of superconducting PF coils. If superconducting PF coils are used then reconstruction is even more expensive and time consuming, or if these coils are segmented then the same questions of joint feasibility, economy, etc. arise as when the segmented superconducting concept is used for the TF coil. The best answer to this problem is to conduct a relatively complex tradeoff study involving capital cost, design feasibility, development risk, operating costs and maintainability for several design concepts.

Additional capital cost is imposed on the plan by the need to disassemble large parts of the reactor when the PF coils are not segmented because of the

larger facility necessary to store this amount of activated material. Therefore, the advantage lies with the use of segmented PF coils where less of the reactor is disassembled and the facilities required are smaller.

Some time saving is realized by assuming that each S coil and its companion F coil at the outer wall of the GA-ITR are disassembled and rebuilt as a single physical unit. This may not be the intent of the postulated design. However, it effectively reduces the number of coils to be rebuilt from 36 to 30.

A final caution concerns the assumption that space exists in the bore of the GA-ITR TF magnets to install the tooling required to rebuild the magnets and that rebuilding is feasible by use of remote equipment. The design concept of this equipment remains to be defined and the feasibility of containing it in the limited space available, especially for rebuilding the large outer wall F coils, should be further investigated.

4.8 REFERENCES

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- 4-5. "A Tokamak Reactor with Servicing Capability," by Mitchell, J. T. D., Culham Laboratory, Abingdon, UK and Hollis, A., Research Reactor Division, UKAEA, AERE Harwell, UK from proceedings of the 9th Symposium on Fusion Technology, Garmish-Partenkirchen, 1976.
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- 4-7. "DEALS: A Demountable Externally Anchored Low Stress Superconducting Magnet System for Fusion Reactors," by Powell, J., Hsieh, D., and Lehner, J., Brookhaven National Laboratory, Upton, N.Y., Report No. BNL 50616, January 1977.
- 4-8. "A Niobium-Tin DEALS Toroidal Magnet System for A High Field Ignition Test Reactor," by Powell, J., et al., Brookhaven National Laboratory and Grumman Aerospace Corporation for the U.S. Department of Energy, Draft Report, December 1977.
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5.0 DESIGN FEATURE TRADEOFF ANALYSIS AND EVALUATION - TASKS 8 AND 9.

The purpose of the tradeoff analysis and evaluation tasks is to develop both general and specific conclusions regarding the maintainability of Tokamak Fusion Power Systems by examination of the reference reactor systems defined in Task 6 and the Maintenance Plans defined in Task 7.

5.1 FIRST WALL/BLANKET MODULE TRADEOFFS - These tradeoffs are intended to assess the differences between the reference reactor first wall/blanket module concepts, but the incorporation of the various module concepts into an actual reactor design entails the use of a complete reactor design concept to conduct such an evaluation. Consequently, the tradeoff of first wall/blanket concepts really becomes an evaluation of reactor concepts. To elaborate further, a first wall/blanket design dictates a given coolant, manifolding clearances, toroidal magnetic field on axis (given a specific B_m) and power level of reactor. Additionally, the module concept design features prescribe a maintenance technique which impacts reactor design, maintenance equipment and confinement building philosophy. Since these factors must be considered, this task utilizes the reference reactor system definitions as delineated in Section 3. The reference reactor concepts have been normalized as much as possible to eliminate spurious conclusions. The principal normalized parameters are listed below in Table 5.1-1. For most concepts, this normalization process did not require a major change from the original reactor concept and this process is discussed in detail in Section 3. Table 5.1-2 is reproduced from Section 3 as a convenient reference for the discussion of this task.

TABLE 5.1-1
NORMALIZED REACTOR PARAMETERS

PARAMETER	VALUE
THERMAL POWER	3000 MW
NUMBER TF MAGNETS	16
MAXIMUM TF STRENGTH (B_m)	8.66T
BURN AND REJUVENATION TIME	3600 AND 100 SEC
PLASMA CONFINEMENT LAW	TRAPPED ION MODE
SUPPLEMENTAL HEATING	NEUTRAL BEAM INJECTORS
PLASMA HEIGHT/WIDTH	2 (3 FOR DOUBLET)

TABLE 5.1-2

REFERENCE REACTOR CONCEPT CHARACTERISTICS

	UWMAK-III	GA-DOUBLET	CULHAM	ORNL
* POWER, MW_{th}	3000	3000	3000	3000
* NET ELECTRICAL POWER, MW_e	992	902	962	962
* FIRST WALL/BLANKET CONFIGURATION	UWMAK-III	CANISTER	CANISTER	CASSETTE
* FIRST WALL COOLANT	LITHIUM (OUTER WALL) HELIUM (INNER WALL)	HELIUM	HELIUM	HELIUM
* DIVERter COOLANT	LITHIUM	-	LITHIUM	LITHIUM
* AUXILIARY HEATING	NBI	NBI	NBI	NBI
* VACUUM SYSTEM	UWMAK-III	GA-DPR	UWMAK-III TYPE	UWMAK-III TYPE
* DIVERter	UWMAK-III (DOUBLE NULL)	FLOWING PLASMA BOUNDARY	SINGLE NULL	UWMAK-III TYPE (SINGLE NULL)
* T. F. MAGNETS, NUMBER	16	16	16	16
* MAX. TOROIDAL FIELD STRENGTH (B_{max}), TESLA	8.66	8.66	8.66	8.66
FIELD STRENGTH ON AXIS (B_0) TESLA	4.109	4.616	3.871	3.882
* PLASMA STABILITY FACTOR	2.5	2.5	2.5	2.5
* PLASMA BURN TIME, SEC	3600	3600	3600	3600
* PLASMA REJUVENATION TIME, SEC	100	100	100	100
* PLASMA ECCENTRICITY	2	3 (DOUBLET)	2	2
* PLASMA MAJOR RADIUS, m	6.5	6.5	7.5	7.5
PLASMA MINOR RADIUS, m	1.75	1.405	1.924	1.924
PLASMA VOLUME, m^3	785.87	796.98	1096.0	1096.0
WALL AREA, m^2	781.02	888.04	990.8	1037.3
POLOIDAL BETA	3.714(A)	2.315(A/2)	3.906(A)	3.906(A)
NEUTRON WALL LOADING, MW/m^2	2.74	2.364	2.121	2.026
ION TEMPERATURE, T_i , KeV	12.8	15.8	12.9	13.0
ELECTRON TEMPERATURE, T_e , KeV	13.8	15.8	13.8	13.9
DENSITY, n_i PARTICLES/ m^3	1.57×10^{20}	1.22×10^{20}	1.31×10^{20}	1.31×10^{20}
CONFINEMENT TIME τ_p , SEC	2.32	2.90	2.72	2.70
$n_i \tau_p$ PARTICLE-SEC/ m^3	3.64×10^{20}	3.54×10^{20}	3.57×10^{20}	3.57×10^{20}
FUSION REACTION RATE, $\langle \sigma v \rangle$ m^3/SEC	2.0×10^{-22}	3.11×10^{-22}	2.05×10^{-22}	2.05×10^{-22}
THRUPUT, TORR-L/SEC	2127	5143	2116	2128
CRYO PANEL AREA, m^2 (OPERATING FACE AREA)	425	1027	423	426
WALL LIFE, YRS.	1.8	2.1	2.4	2.5

* INDEPENDENT SELECTED PARAMETERS

A = ASPECT RATIO

To develop the data required for the tradeoff studies, maintenance plans for each reactor concept have been defined and are discussed in Section 4. A summary of the parameters for these maintenance plans is presented in Table 5.1-3. For each reactor concept, maintenance plans have been formulated for both partial contact maintenance operations and fully remote maintenance. Contact maintenance utilizes as much "hands on" maintenance as possible until the reactor shielding is physically opened up and protection is no longer afforded to the maintenance personnel. It assumes that the radiation levels are low enough in the reactor room when the reactor shielding is in place to permit "hands-on" maintenance operations. Remote maintenance is completely accomplished without any "hands on" operations. For these reactor concepts the primary vacuum wall may be located in three generic locations. These are: (1) the first wall or blanket, (2) the lateral support access panel (LSAP) or outer shield, or (3) the reactor room wall. These location numbers are used to designate the vacuum wall arrangements when describing the maintenance scenarios. More detail on the specific vacuum wall arrangements is shown in Figure 3.2-32 of Section 3.2.4.

Table 5.1-3 defines the possible maintenance scenarios for each reactor concept. For each scheduled wall blanket maintenance period, a fraction of the wall may be removed and replaced with the fraction varying from one eighth to complete replacement (2 to 16 sectors respectively). For each replacement fraction chosen, maintenance plan options exist which range from having a few sets of maintenance equipment operating simultaneously on a few modules up to many maintenance sets operating simultaneously on all modules to be replaced. The GA-Douplet is somewhat different because the modules may be located anywhere in the 16 sectors with the fraction of the first wall/blanket removed varying from 1/6 (304/1808) up to 1/4 of the total modules in the reactor. The number of equipment sets is an equivalent number based on the ratio of the weight of the maintenance equipment required to accomplish the particular maintenance scenario to the weight of the maintenance equipment required to remove one module. Following this item in Table 5.1-3 is the weight of the maintenance equipment set required to accomplish the removal of one module. The next column lists the number of personnel required to accomplish the scheduled first wall/blanket maintenance per shift. The expected outage time is given for each scenario including cooldown and startup times. The times shown are based on a 24 hour day, 3 shift operation and are diluted in the ratio of 4 to 3 in order to account for unproductive utilization of time.

TABLE 5.1-3
SCHEDULED MAINTENANCE CASE SUMMARY

REACTOR CONCEPT	TYPE OF MAINT. EQMT.	VACUUM WALL LOCATION	NO. SECTORS WORKED	REACTOR MODULES REPL. SIMLT.	NO. EQUIP. SETS	WEIGHT OF MAINT. EQUIP. SET -Kg X 10 ⁶	NO. PERSONNEL REQUIRED	OUTAGE TIME W/DILUTION - DAYS	PLANT AVAILABILITY	COST OF ELECT. -MILLS/KWH
UWMAK-III	CONTACT	2 (AT LSAP)	8	8	4.427	2.5826	146	57	.7410	✓ 51.37
			8	4	3.044		74	85	.6975	53.07
			8	2	2.416		72	161	.6016	60.72
			4	4	2.325		70	48	.6818	53.50
			4	2	1.795		38	79	.6049	59.44
			4	1	1.458		20	149	.4821	73.74
			2	2	1.469		38	43	.5899	60.47
			2	1	1.133		20	74	.4835	72.87
	REMOTE	2 (AT LSAP)	16	8	5.100	2.5826	50	131	.7094	53.83
			16	4	3.789		26	226	.6441	59.53
			8	8	4.412		50	78	.7079	53.10
			8	4	3.098		26	126	.6423	57.16
			4	4	2.443		26	68	.6301	57.45
			4	2	1.787		14	120	.5364	67.74
GA-DOUBLET	CONTACT	1 (AT BLANKET)	16	304	1.033	9.8269	24	31	.7047	53.77
			16	360	1.045		24	35	.7103	53.40
			16	456	1.068		24	43	.7138	53.25
	REMOTE	1 (AT BLANKET)	16	304	1.076	2.6232	12	32	.7008	51.30
			16	360	1.100		12	37	.7037	51.15
			16	456	1.158		12	45	.7086	✓ 50.93
CULHAM	CONTACT	3 (REACTOR ROOM WALL)	16	8	3.273	3.3108	116	47	.7832	52.23
			16	4	2.788		44	69	.7678	52.64
			8	8	2.620		82	30	.7940	✓ 50.28
			8	4	2.135		44	50	.7657	51.55
			4	4	1.760		44	26	.7666	50.78
			4	2	1.446		22	45	.7208	53.50
	REMOTE	3 (REACTOR ROOM WALL)	16	8	3.265	3.3108	50	63	.7719	52.84
			16	4	2.788		26	103	.7452	54.18
			8	8	2.618		50	38	.7824	50.94
			8	4	2.134		26	65	.7458	52.83
			4	4	1.759		26	34	.7484	51.93
			4	2	1.445		14	59	.6885	55.92
ORNL	CONTACT	3 (REACTOR ROOM WALL)	16	8	4.376	1.1368	68	99	.7498	53.00
			16	4	3.033		44	176	.7047	55.73
			8	8	4.220		76	55	.7606	✓ 51.01
			8	4	2.721		44	100	.7069	54.08
			4	4	2.502		44	51	.7120	52.92
			4	2	1.617		22	93	.6285	59.22
	REMOTE	3 (REACTOR ROOM WALL)	16	8	4.916	1.1368	74	113	.7412	53.93
			16	4	3.026		38	205	.6890	56.97
			8	8	4.478		74	64	.7492	51.94
			8	4	2.714		38	115	.6906	55.33
			4	4	2.495		38	60	.6923	54.40
			4	2	1.613		26	112	.5969	62.47

The scenario data listed in Table 5.1-3 is necessary to evaluate reactor and maintenance system impacts on the cost of electricity through the use of the TOkamak Systems Analysis and COst MOdel (TOCOMO) code. For more information see References 5-1, Appendix A and Reference 5-2, Volume II, Appendix G. The last two columns of data in Table 5.1-3, i.e., plant availability and cost of electricity (COE), are outputs of the code and are used extensively in the following sections to highlight significant conclusions. All costs are presented in constant 1978 dollars which show approximately 6-1/2% increase over the 1977 dollars shown in Phase I Report, Reference 5-2. The availability is calculated as defined in Reference 5-3.

$$\text{Availability} = \frac{\text{Operating Time}}{\text{Operating time} + \text{Maintenance Time}}$$

The maintenance time consists of reactor scheduled maintenance period for replacing a fraction of the first wall and blanket, a scheduled annual maintenance period for balance of plant (28 days) and allowable outage time for unscheduled maintenance of the reactor and balance of plant (nominally 65 days/operating year). The scheduled maintenance periods for the reactor and balance of plant are frequently accomplished simultaneously. The extent of simultaneous maintenance is dependent upon the duration and frequency of the respective scheduled maintenance periods.

To visualize the output data shown in Table 5.1-3, Figure 5.1-1 displays the cost of electricity (COE) and availability for the UWMAK-III design concept. Data for both the contact and remote maintenance plans are presented. Only the lowest COE (and the highest availability) points are connected but the results from other maintenance plans are presented. In general, working on the maximum number of modules being replaced results in the lowest COE. Also the curves connecting the points have no significance and, therefore, are shown as straight lines, i.e., only discrete fractions of the wall may be replaced (1/16, 1/8, 1/4, 1/2, 1). It can be seen in Figure 5.1-1 that partial contact maintenance results in a lower cost of electricity than does remote maintenance. Removal of one half of the first wall/blanket yields the lowest cost of electricity for both the contact and remote maintenance scenarios.

The COE and availability for the GA-Douplet is shown on Figure 5.1-2. The cost advantage of contact over remote has been reversed in this instance because the GA-Douplet concept is configured basically for remote operation. The use of contact maintenance insofar as feasible has very little advantage because the functions governing the downtime are all conducted within the reactor and must use remote operations. Increasing the fraction of the wall replaced to 1/2 might show some improvement in the COE and availability.

COE AND AVAILABILITY FOR UWMAK-III

NOTE: THIS COMPARISON OF CONTACT AND REMOTE MAINTENANCE INCLUDE CONSIDERATION OF FIRST WALL/BLANKET REPLACEMENT ONLY. NO ESTIMATES OF TIME TO REMOVE OTHER EQUIPMENT IN REACTOR HALL HAVE BEEN INCLUDED. CONSIDERATION OF THESE OTHER MAINTENANCE REQUIREMENTS WOULD PROBABLY INCREASE BENEFITS OF CONTACT MAINTENANCE.

FIGURE 5.1-1

COE AND AVAILABILITY FOR DOUBLET

FIGURE 5.1-2

The COE and availability for Culham and ORNL are shown in Figures 5.1-3 and 5.1-4, respectively. For both of these configurations, the use of partial contact maintenance is shown to have a lower COE with the minimum COE occurring with one-half of the wall being replaced at each scheduled replacement outage. Figure 5.1-5 combines the contact maintenance plots shown on Figures 5.1-1 through 5.1-4 while Figure 5.1-6 shows the combined remote maintenance plots. The lowest cost of electricity is achieved with the Culham reference reactor when using the contact maintenance scenario. The minimums for all concepts fall within very tight limits with the COE ranging from 50.3 to 51.0 mills/kWh. There is more variation in COE with a variation in the fraction of the walls removed or between the contact and remote maintenance scenarios than there is between design concepts at the optimum design point. Another point of interest is that, although the costs of electricity for the reference reactors are very similar, the availabilities show a large variance and the capital cost also exhibits some diversity. All of the variations tend to compensate and yield a set of COE values that are very similar. There is no reason to believe that the COE is invariant and it is expected that another set of initial circumstances could yield dissimilar COE values.

5.2 VACUUM WALL LOCATION - The effect of the potential vacuum wall arrangement on the downtime requirements for replacement of the first wall/blanket of the reference reactors has been examined and is reported in detail in Section 4.2. Since the downtime requirements appear to have the greatest impact on the COE, based on the data presented in Table 5.1-3, the vacuum wall arrangement with the minimum downtime required is expected to result in the minimum COE. Similarly, the maintenance scenario that results in the minimum downtime for a single sector in any reference reactor concept also achieves the minimum overall downtime for the various first wall/blanket fractions. Therefore, the vacuum wall arrangements selected for the maintenance scenarios discussed in Section 4.2 are also expected to be the arrangements that result in the optimum replacement wall fractions (minimum COE) selected for each reference reactor. The conditions imposed by these vacuum wall arrangements are summarized in Figure 5.2-1. The GA-Douplet has been analyzed for only the basic wall location specified for the original concept because access of the first wall/blanket from the interior of the plasma chamber is unaffected by vacuum wall location. The use of the reactor room wall as the primary vacuum wall for the GA-Douplet reference reactor is expected to increase rather than decrease the time for first wall/blanket replacement.

COE AND AVAILABILITY FOR CULHAM

FIGURE 5.1-3

COE AND AVAILABILITY FOR ORNL

FIGURE 5.1-4

SUMMARY OF COE AND AVAILABILITY CONTACT MAINTENANCE

FIGURE 5.1-5

SUMMARY OF COE AND AVAILABILITY REMOTE MAINTENANCE

FIGURE 5.1-6

VACUUM WALL LOCATION ARRANGEMENTS

FIGURE 5.2-1

The effect of the variation in the vacuum wall arrangements is indicated in Table 5.2-1. This table shows the percentage change in maintenance time among the wall combinations tested from the vacuum wall arrangement most closely approximating the arrangement for the original concept. From these comparisons the shortest time for the Culham and the UWMAK-III reference reactors occurs when using the reactor room wall as the primary vacuum barrier. For the ORNL Cassette concept the shortest time occurs when using the lateral support access panel (LSAP) between the TF coils as the primary vacuum wall, although, this time differs little from that required when the primary vacuum barrier is at the reactor room wall. From this data the optimum wall locations for the reference reactors are expected to be with the primary vacuum wall located at the reactor room wall for all reference reactors except for the GA-Doublet.

5.3 SYSTEM IMPACTS OF COOLANT SELECTION - The selected reactor design concepts also afford the opportunity for a comparison of the primary coolant selection. The UWMAK-III utilizes helium for cooling the inner wall of the plasma chamber and lithium for the outer wall while the remaining reactor concepts used helium for the entire blanket coolant. Table 5.3-1 defines the coolant used for each concept and the resultant incremental power requirements. Although the maximum thermal power from the fusion reaction is normalized at 3000 MW, the continuous thermal power available to the conversion cycle varies from 2860 for the GA-Doublet up to 2972 for the Culham and the ORNL Cassette reference reactors. The continuous thermal power takes into account the reactor duty factor, the heat lost in the shields, the heat lost through the openings in the wall and additional heat gained from pumping the coolant throughout the coolant loop. The GA-Doublet results in the lowest net thermal power (2860 MW) because of the neutrons lost through the large openings for the flowing plasma boundary outlet ducts. The UWMAK-III is the intermediate case at 2918 MW because the pumping power of helium and lithium is lower, hence less heat is transferred to the coolant fluid. The coolant pumping power is largest for the pure helium case represented by the GA-Doublet. The pumping power is also comparatively large for the ORNL Cassette and the Culham reference reactors. The pumping power required for helium at 50 atmospheres and at high flow rates is approximately twice that of the pumping power required for lithium in the lower magnetic field regions, such as in the case of UWMAK-III. However, if lithium is required in the high field areas in the inner portions of the blanket, then the pumping power of lithium also becomes high. After accounting for thermal to electrical conversion efficiencies and subtracting the pumping power as well as the other required auxiliary powers, Table 5.3-1 shows that the UWMAK-III has the highest net electrical power output at 992 MW and the GA-Doublet has the lowest at 902 MW.

TABLE 5.2-1
CHANGE IN MAINTENANCE DOWNTIMES FOR DIFFERENT VACUUM WALL ARRANGEMENTS

REFERENCE REACTOR CONCEPT	PERCENT CHANGE FROM ARRANGEMENT OF ORIGINAL CONCEPT		
	ARRANGEMENT #1	ARRANGEMENT #2	ARRANGEMENT #3
CULHAM			
UNSCHEDULED MAINTENANCE CONTACT OPERATIONS	-2.5	0	-11.2
UWMAK-III			
UNSCHEDULED MAINTENANCE CONTACT OPERATIONS	0	-8.7	-13.5
REMOTE OPERATIONS	0	-4.4	-11.0
SCHEDULED MAINTENANCE CONTACT OPERATIONS	0	-9.9	-15.2
REMOTE OPERATIONS	0	-4.8	-12.1
ORNL			
UNSCHEDULED MAINTENANCE CONTACT OPERATIONS	+7.0	-.6	0

TABLE 5.3-1
COMPARISON OF THERMAL AND ELECTRICAL POWERS

PARAMETER	UWMAK-III	GA DOUBLET	CULHAM	ORNL
COOLANT	Li (OUTER), He (INNER)	He	He	He
MAX. THERMAL POWER (MW)	3000	3000	3000	3000
CONTINUOUS THERMAL POWER TO CONVERSION CYCLE (MW)	2918	2860	2972	2972
GROSS ELECTRICAL (MW)	1137	1098	1141	1141
PUMPING POWER (MW)				
LITHIUM	33	----	9	9
HELIUM	15	82	70	70
CIRCULATING POWER DURING BURN (MW)	146	196	179	179
NET ELECTRICAL POWER (MW)	992	902	962	962

Another aspect of the coolant selection is the additional volume required for helium manifolding in contrast with lithium manifolding. The additional thickness required in the inner blanket region causes a reduction in the average toroidal field strength, B_0 , when using the same maximum field strength, B_m , for all concepts and since fusion power is proportional to B_0^4 , this has a powerful impact on reactor sizing. For this reason both Culham and ORNL Cassette reactors have a major radius of 7.5 meters as opposed to 6.5 meters for UWMAK-III which does not use manifolding for the ISSEC. The GA-Douplet still retains a major radius of 6.5 meters because it has a plasma height to width ratio of 3 that results in a higher B_0 and because of smaller manifolding used with the small modules.

Still other cost considerations are the additional building floor space required for helium intermediate heat exchangers, pumps and piping and the maintenance requirements for handling high pressure (50 atmosphere) helium, primarily those involving leaks and leak detection. Tritium handling and detection and problems with liquid metal corrosion may impose additional maintenance requirements that affect coolant selection.

5.4 CONTACT VERSUS REMOTE MAINTENANCE - A limited comparison of contact and remote maintenance can be made from the data presented in Figures 5.1-1 through 5.1-6 and Table 5.1-3. The analysis is limited because it is based only on first wall/blanket replacement operations. The use of contact ("hands-on") maintenance during replacement of the first wall/blanket is limited to those periods before the shielding around the plasma chamber is opened and after it is closed. Also, in the case of the GA-Douplet first wall/blanket replacement, contact maintenance is of limited advantage because the time controlling operations must be conducted remotely inside of the plasma chamber. The use of contact operations for maintenance of other equipment in the reactor hall are expected to increase the benefits of contact maintenance discussed in this section. These operations should be more fully explored.

Even though the use of contact maintenance is limited in the development of the data presented in Section 5.1, the use of contact techniques instead of remote for only a few operations resulted in a lower COE and higher availability at all wall fractions examined for all reference designs except the GA-Douplet. The results of the comparison are summarized in Figure 5.4-1. For the UWMAK-III, Culham and ORNL-Cassette reactors the maintenance equipment cost is essentially unchanged between contact and remote maintenance scenarios and the small increase in cost because of the need for additional personnel is offset by the additional production

COMPARISON OF CONTACT AND REMOTE MAINTENANCE

FIGURE 5.4-1

of energy attained with the higher availabilities. However, for the GA-Douplet the slight reduction in downtime realized because of faster handling of maintenance equipment is offset by the larger cost of shielding used to protect the personnel during contact operations.

The comparison with the GA-Douplet on a purely cost basis must eventually consider all maintenance in the reactor room because the addition of the shielding, while costly, permits contact maintenance operations during almost all maintenance operations. Such shielding seems infeasible for the larger modules used in the UWMAK-III and Culham reactors. With such a potential capability for overlap of maintenance operations the net increase in total downtime caused by maintenance

operations other than replacement of the first wall/blanket is expected to be much less for the GA-Doublet reactor than for the other concepts. Table 5.4-1 summarizes the differences in scheduled maintenance downtime and cost of electricity among the four reactor concepts caused by the use of contact or partial contact maintenance operations instead of fully remote operations. The limited capability to conduct contact operations is indicated by the percentage of the total fully remote time which can be devoted to contact activities. This varies from 42% to 72% for the UWMAK-III, Culham and ORNL Cassette reactors. The GA-Doublet is a special case since the use of shielding can make 100% of the time available for contact maintenance operations outside of the reactor shield but this results in an increase in the

TABLE 5.4-1
SUMMARY OF PARTIAL CONTACT MAINTENANCE DOWNTIME IMPACTS

	UWMAK-III	GA-DOUBLET	CULHAM	ORNL CASSETTE
TOTAL DOWNTIME (HRS.) ⁽¹⁾				
PARTIAL CONTACT MAINTENANCE	1023.4	781.3	546.4	988.6
FULLY REMOTE MAINTENANCE	1408.7	810.8	679.4	1154.0
PERCENT REDUCTION WITH CONTACT	27.4	3.6	19.5	14.3
DOWNTIME FOR FUNCTIONS CAPABLE OF USING CONTACT MAINTENANCE ⁽²⁾				
DOWNTIME IF USING REMOTE MAINTENANCE, HRS.	756.8	110.3 ⁽³⁾	301.8	418.3
PERCENT OF TOTAL	72.0	100	61.2	42.0
DOWNTIME IF USING CONTACT MAINTENANCE, HRS.	385.5	110.3 ⁽³⁾	172.3	234.3
PERCENT OF TOTAL	56.7	100	47.4	28.9
TOTAL COST OF ELECTRICITY, MILLS/kWh ⁽¹⁾				
PARTIAL CONTACT MAINTENANCE	51.37	53.25 ⁽⁴⁾	50.28	51.01
FULLY REMOTE MAINTENANCE	53.10	50.93	50.94	51.94
PERCENT SAVINGS WITH CONTACT	+ 3.2	- 4.3	+ 1.3	+ 1.7

NOTES:

- (1) DATA FROM OPTIMUM SCHEDULED FIRST WALL/BLANKET MAINTENANCE PLANS.
- (2) DATA FOR SINGLE SECTOR FIRST WALL/BLANKET REPLACEMENT ONLY.
- (3) DATA FOR 8 MODULES ONLY.
- (4) COST INCREASE BECAUSE OF ADDITIONAL SHIELDING COST.

COE because of the increased shielding cost and no significant savings in downtime are achieved.

The maximum decrease in COE resulting from the use of partial contact operations is 1.73 mills/kWh in the case of the UWMAK-III reactor. For this reactor the decrease in total downtime achieved by contact operations is the largest for the reference reactors at 27.4 percent. For those functions where contact maintenance can be used a saving in downtime of 35 percent is achieved. This appears to be less than is expected from experience in smaller component repair but the size of the components being handled or replaced and the difficulty of gaining access with the heavy equipment necessary to handle these components leads to the reduced time savings. A more detailed design and analysis may develop techniques which increase the time savings and the functions to which contact operations can be applied.

5.5 DEMOUNTABLE MAGNETS - If a unitary design superconducting toroidal field magnet ever fails when it is installed as shown in any of the reference reactors a prolonged repair period is required to put the reactor back into service. An exact estimate of the time and effort required is highly speculative, with many options possible. One of the design options which may hold some promise, is the segmented demountable superconducting toroidal field magnet known as the DEALS magnet. This magnet concept is described in Reference 5-4 and maintenance of this type of magnet is discussed in Section 4.7. Figure 5.5-1 is a pictorial representation of a possible configuration with five joints that was considered for the Improved Maintenance System discussed in Section 6.1. While this configuration shows 5 joints, as few as 2 to 4 joints could be selected. At present the joints must be normally conductive with a large cross section. Advantages of the segmented magnet include the fact that it may be manufactured and transported more easily. Also, as defined in Section 4.7, the repair times of the two systems, unitary and segmented, are quite dissimilar. The unitary design is expected to have a long time between failure (MTBF) and a long time to repair (MTTR). The segmented magnet is expected to have a lower value of MTBF and a much lower MTTR. On the other hand the joints impose a requirement for additional hardware since the magnet is no longer a constant tension configuration. This requires additional structure as shown in Figures 4.7-2 and 4.7-3. To assess the impact of the segmented magnet, or more generally, any readily demountable magnet, an analysis has been conducted by parametrically varying the MTBF and MTTR over a range of anticipated values and observing the results. Figure 5.5-2 shows the operating cost for a range of failures and MTTR. The cost of operation associated with a failure does not

**TYPICAL SEGMENTED DEMOUNTABLE TF MAGNET
(CONFIGURATION EXAMINED FOR USE IN AN
IMPROVED MAINTENANCE SYSTEM)**

(REFERENCE 5-3)

FIGURE 5.5-1

exceed 10% unless the number of failures during the plant lifetime exceeds 3 for a MTTR of 1 year, or 2 for a MTTR of 2 years. These MTTR's are typical for a unitary design toroidal field magnet as reflected in the data presented in Section 4.7. If the segmented toroidal field magnet has a probable MTTR of about 45 days as indicated in Section 4.7, more than 20 magnet failures would be allowed during the plant lifetime and the criterion of less than a 10% increase in cost would still be satisfied. If the MTTR is 3 months, 10 failures are allowed. Figure 5.5-2 will allow evaluation at any limiting value of COE for the Culham reference reactor, given any assumed MTTR or number of magnet failures.

To consider a typical comparison, if the unitary design magnet fails once in the plant lifetime and has a MTTR of one year, the allowable number of segmented demountable magnet failures, having a typical MTTR of 45 days is somewhat above 8 failures per plant lifetime. Considering the 5 joints for the magnet shown in Figure 5.5-1 and the leads for each of 16 magnets, the limitation of 8 failures per plant lifetime may be a difficult reliability to achieve. If the unitary design

COST OF ELECTRICITY SENSITIVITY TO NUMBER OF FAILURES CULHAM REACTOR CONCEPT

FIGURE 5.5-2

magnet failures are assumed to be as many as 2 per plant lifetime, the segmented demountable magnet system is allowed almost 12 failures. If the unitary design magnet MTTR is 2 years, failures of 1 and 2 per plant lifetime yield allowable segmented, demountable magnet failures of 16 and 24 per plant lifetime, respectively.

5.6 UNSCHEDULED MAINTENANCE - During the Phase I of this study a nominal availability goal was established at 72% (see Reference 5-2, Section 5.1.2.1) based on a representative performance of fission power reactors. If the availability goal is established at 72%, and the scheduled reactor maintenance times are as stated in the reference cases of Table 5.1-3, the remaining factors to be defined are the unscheduled reactor and plant maintenance times.

To determine these factors, optimum maintenance plans for each of the reference reactors were evaluated using TOCOMO for a range of unscheduled maintenance times from 0 to 100 days per operating year, encompassing the nominal value of 65 days used in the Phase I study. Figure 5.6-1 presents the results of this analysis. If these reactors are constrained to have a fixed availability, the COE changes significantly. Table 5.6-1 compiles the baseline data and the data for two constant

EFFECT OF UNSCHEDULED MAINTENANCE ON COE AND AVAILABILITY

FIGURE 5.6-1

TABLE 5.6-1
COST COMPARISONS AT FIXED AVAILABILITIES AND COE'S

	UWMak-III	DOUBLET	CULHAM	ORNL
<u>BASELINE DATA</u>				
UNSCHEDULED MAINT. DAYS	65	65	65	65
AVAILABILITY	.7410	.7086	.7940	.7606
COE - MILLS/kWh	51.37	50.93	50.28	51.01
<u>72% AVAILABILITY</u>				
ALLOWABLE UNSCHD. MAINT. DAYS	80	56	112	92
COE - MILLS/kWh	52.9	50.2	55.3	53.8
<u>80% AVAILABILITY</u>				
ALLOWABLE UNSCHD. MAINT. DAYS	29	7	62	41
COE - MILL/kWh	47.7	45.3	49.9	48.4
<u>49 MILLS/kWh COE</u>				
ALLOWABLE UNSCHD. MAINT. DAYS	42	45	53	45
AVAILABILITY	.777	.736	.815	.794
<u>52 MILLS/kWh COE</u>				
ALLOWABLE UNSCHD. MAINT. DAYS	71	76	81	74
AVAILABILITY	.732	.693	.768	.748

availability examples and two constant cost of electricity examples. The baseline availability of the reference GA-Doublet reactor is less than 72%. If the availability is increased to 72% the costs of electricity will decrease slightly. All the other reactors have nominally a higher availability, and therefore, a reduction to 72% will result in an increase in the COE. As shown in Table 5.6-1, for a fixed availability of 72% the days of unscheduled maintenance vary from 56 to 112 days with costs ranging from 50 to 55 mills/kWh. At 80% availability, it is doubtful if there is enough time remaining to accomplish unscheduled maintenance on the UWMAK-III and certainly not enough time to accomplish unscheduled maintenance on the GA-Doublet. When constant COE values are used, the unscheduled maintenance days and availabilities shown in Table 5.6-1 cover a significantly smaller range of values among the four reference reactors.

To evaluate the impact of an unscheduled first wall or blanket failure, the previous data for fixed availabilities of 72% and 80% from Table 5.6-1 are used in conjunction with the data generated in Section 4.3. Figure 5.6-2 illustrates the variation in the number of unscheduled first wall/blanket failures that can be accommodated by each reference reactor and attain the availability goals for which the plots are made. The allowable unscheduled maintenance days are the days remaining after the required scheduled maintenance days are subtracted from the total number of allowable days of downtime per operating year. The number of days of outage required by each unscheduled failure for each reference reactor defines the slope of the curves in Figure 5.6-2. With Figure 5.6-2, the allowable unscheduled maintenance time for the remainder of the reactor and plant may be determined as a function of the anticipated unscheduled first wall/blanket failure rate. For example, for more than one failure per year, the UWMAK-III has the least time remaining for other unscheduled maintenance because of the long time to replace a first wall/blanket module (44 days). In contrast to this, the Culham concept intrinsically has the highest availability and, therefore, the largest number of days allowed for unscheduled downtime of all the concepts. The Culham concept also has a low unscheduled replacement time. These factors result in the Culham concept having the highest allowable maintenance times. Although the GA-Doublet also has a very low replacement time, its low availability keeps it in the midrange of allowable unscheduled maintenance times unless a large number of module failures are experienced. A maintainability figure of merit (FOM) appropriate for unscheduled failures is the number of allowable failure at zero days remaining for unscheduled maintenance. This is the abscissa intercept of Figure 5.6-2. These FOM's are summarized in

**ALLOWABLE UNSCHEDULED MAINTENANCE DAYS PER OPERATING YEAR EXCLUDING
UNSCHEDULED WALL AND BLANKET FAILURES
AVAILABILITY GOAL DATA**

FIGURE 5.6-2

Table 5.6-2. For a 72% availability, the GA-Doublet has the highest FOM With UWMak-III the lowest. If the value of availability is chosen to be 80% as shown in Figure 5.6-2, different values of allowable days for unscheduled maintenance are obtained and, thusly, new FOM's are obtained for the 80% availability case. The ranking remains the same except for the GA-Doublet which moves from the first to the third position. The reason for change in position is that, although the modules may be replaced quickly, the inherent low availability of the GA-Doublet reference reactor severely constrains the allowable days of unscheduled maintenance which is available to recover from unscheduled failures.

If the basis of comparison is changed from an availability goal to a COE goal, as shown in Figure 5.6-3 the figure of merit is changed significantly. However, the rankings of the concepts remain the same with the UWMak-III being the lowest and the

TABLE 5.6-2
WALL/BLANKET UNSCHEDULED MAINTENANCE FIGURE OF MERIT

CONCEPT	FIGURE OF MERIT	
	72% AVAILABILITY	80% AVAILABILITY
UWMAK-III	1.82	.66
DOUBLET	8.00	1.00
CULHAM	6.59	3.65
ORNL	2.96	1.32

ALLOWABLE UNSCHEDULED MAINTENANCE DAYS PER OPERATING YEAR
EXCLUDING UNSCHEDULED WALL AND BLANKET FAILURES
COE GOAL DATA

FIGURE 5.6-3

GA-Doublet ranking the highest for the first wall/blanket unscheduled maintenance action.

The same analysis approach may be followed on different subsystems. Figure 5.6-4 evaluates the allowable unscheduled maintenance times for a 72% availability goal considering vacuum system failures. The estimated failure recovery times are shown as the slopes of the respective curves with the abscissa intercept indicating the FOM's. Figure 5.6-5 is a similar plot for the ion source failures. Failures in both the vacuum subsystem and the ion sources will not have a significant total system impact if the failure rate is held to a reasonable value. The GA-Doublet is more severely constrained by failures in these subsystems.

5.7 SENSITIVITY OF SCHEDULED MAINTENANCE PARAMETERS - To evaluate the scheduled maintenance times for the replacement of the first wall/blanket modules, the following data must be defined.

ALLOWABLE UNSCHEDULED MAINTENANCE DAYS PER OPERATING YEAR EXCLUDING VACUUM SUBSYSTEM FAILURES

ALLOWABLE UNSCHEDULED MAINTENANCE DAYS PER OPERATING YEAR EXCLUDING ION SOURCE FAILURES

FIGURE 5.6-5

- o The number and weight of the maintenance equipment sets required.
- o The maximum number of direct maintenance personnel required specifically for this task.
- o The downtime to accomplish the maintenance and return the plant to an operating state.

These data are defined in Section 4.4 and are summarized in Table 5.1-3. To assess the sensitivity of the COE to a variation in these parameters, each of these parameters are adjusted from the nominal values given for the Culham reference reactor and the observed changes in COE are shown in Figure 5.7-1. For changes of ± 10 percent in the number and weight of maintenance sets required and the days required per first wall/blanket maintenance outage, the COE varies ± 0.2 to 0.25 mills/kWh (± 0.4 to 0.5%). This represents a relatively weak impact on the COE.

COE SENSITIVITY TO MAINTENANCE PARAMETERS

FIGURE 5.7-1

Even if the estimates are in error by 50%, the impact on COE would be in the range of one mill/kWh. The COE sensitivity to the number of personnel required to accomplish the maintenance function is an order of magnitude less than the other input parameters and it can be concluded that a significant increase in personnel can be used to offset downtime and maintenance equipment costs. It was found during the conduct of this portion of the study that if the number of days required per scheduled outage is less than the annual balance of plant scheduled maintenance outage (28 days) and the frequency of wall replacement is less than a year, then the sensitivity of the "days per outage" parameter becomes a weak function on the order of the sensitivity exhibited by the number of maintenance personnel. This effect occurs because the scheduled outage for the first wall/blanket then can be conducted during the annual scheduled outage for BOP maintenance and, therefore, it imposes no additional penalty on the plant availability.

Since the impact of these parameters is very weak, the sensitivity studies of the other reactors have not been conducted. It is anticipated that the results would have been similar.

5.8 COE IMPACT OF UNSCHEDULED MAINTENANCE EQUIPMENT FAILURES - In all of the prior analyses, the reactor and plant maintenance equipment is expected to have a limited life and thus it will be replaced on a regularly scheduled basis if that life is less than the life of the plant. Additionally, some reactor and plant maintenance equipment will fail unexpectedly and the allowance for unscheduled maintenance is provided and its impact has been evaluated. This trade study evaluates the impact of failures of the maintenance equipment during maintenance periods. The most predictable failures of maintenance equipment will occur during the scheduled first wall/blanket replacement periods since this equipment has been defined in more detail, and these equipment failures appear to have the largest impact on the availability of the reactor. Table 5.8-1 summarizes those maintenance equipment failures that are included in the analysis. These failures are chosen as those which can cause significant impact on the outage time for each of the reference reactors. The maintenance equipment component that fails is listed in Table 5.8-1 along with equipment unit expected failure frequency, the failure recovery time and the number of units in operation which could experience this failure. For more information on these failures modes, see Section 4.6. The failure frequency, recovery time and number of units is applied over the interval of time between failures. This results in an average downtime that should be added to the scheduled maintenance time to insure adequate scheduled downtime to recover from unscheduled maintenance equipment failures. Also listed is the average number of each component and the total of these maintenance equipment failures expected per scheduled outage. From the above information the overall availability and COE is computed. From this analysis the UWMAK-III is expected to have an average of approximately 5 maintenance equipment failures per outage requiring an additional downtime of 35 days. The GA-Doublet scenario Number 1 has a very high failure rate of 8.7 failures per outage which is caused by the frequency of isolation valve failures (once every two years) each of which require 9 days for recovery. This yields an unacceptable cost, so it was assumed that this component could be replaced on a regular schedule which is expected to reduce the failure rate to perhaps once every 10 years. This assumption is shown in Scenario No. 2 for the GA-Doublet, which results in only approximately 2 failures and an additional 17 days of downtime per outage. The Culham and ORNL Cassette reference reactors are estimated to require additional maintenance days of 23 and 20, respectively, which fall between the other two reactors. The system impact of these failures is graphically shown on Figure 5.8-1. In this figure the baseline conditions for all four reactors are shown both

TABLE 5.8-1
MAINTENANCE EQUIPMENT FAILURE ANALYSIS DATA

REACTOR	COMPONENT	FAILURE FREQUENCY -YR ⁻¹	FAILURE RECOVERY TIME-DAYS	NUMBER OF UNITS*	OPTIMUM * MAINTENANCE INTERVAL-MO	ADDITIONAL * MAINTENANCE TIME-DAYS	FAILURES* PER OUTAGE	AVAILABILITY	COST OF* ELECT. MILL/KWH
UWMAK-III	"B" WORKHEAD	1/10	20.2	8		21.27	1.06		
	"A" WORKHEAD	1/10	2.4	8		2.52	1.06		
	P.F. RETRACT.	1/3	4.06	6		10.6	2.59		
	VAC. VLV. MNT. EQ.	1/5	.555	1		.15	.26		
	ION SOURCE OMU	1/8	.333	1		.05	.16		
	TOTAL:				15.8	35	5.13	.690	55.55
DOUBLET SCENARIO 1	RMM	1/10	7.96	8		6.0	.76		
	ISOLATION VALVE	1/2	9.07	16		68.8	7.61		
	VAC. VLV. MNT. EQ.	1/5	.555	1		.1	.19		
	ION SOURCE OMU	1/8	.333	1		.04	.12		
	TOTAL:				11.42	75	8.68	.556	64.89
SCENARIO 2	RMM	1/10	7.96	8		5.15	.63		
	ISOLATION VALVE	1/10	9.07	16		11.73	1.27		
	VAC. VLV. MNT. EQ.	1/5	.555	1		.09	.16		
	ION SOURCE OMU	1/8	.333	1		.03	.10		
	TOTAL:				9.51	17	2.16	.667	54.10
CULHAM	MODULE	1/20	5.944	16		7.43	1.52		
	TRANSPORTER								
	COOLANT	1/10	6.127	16		15.33	3.02		
	CONNECTIONS								
	VAC. VLV. MNT. EQ.	1/5	.555	1		.17	.38		
	ION SOURCE OMU	1/8	.333	1		.07	.24		
	TOTAL:				18.57	23	5.16	.762	52.56
ORNL	CASSETTE W/H	1/10	2.166	8		2.90	1.33		
	DIVERter W/H	1/10	3.33	8		4.46	1.33		
	ECS	1/2	1.85	8		12.38	6.70		
	VAC. VLV. MNT. EQ.	1/5	.555	1		.19	.33		
	ION SOURCE OMU	1/8	.333	1		.07	.21		
	TOTAL:				20.13	20	9.90	.736	52.85

*THESE DATA MAY BE DEPENDENT UPON NUMBER OF WALL/BLANKET MODULES REPLACED PER OUTAGE.
VALUE SHOWN IS BASED UPON OPTIMUM REPLACEMENT SCHEDULE AS DETERMINED BY LOWEST COE.

SYSTEM IMPACT OF MAINTENANCE EQUIPMENT FAILURES

FIGURE 5.8-1

with and without maintenance equipment failures. The additional cost incurred by these failures is 4 mills/kWh for the UWMAK-III, 3 mills/kWh for the GA-Douplet, slightly over 2 mills/kWh for the Culham and less than 2 mills/kWh for the ORNL reference reactor. Based on this data, the final COE is highest for the UWMAK-III at 55 mills/kWh followed by the GA-Douplet at 54 mills/kWh with the Culham and ORNL reference reactors at 52.5 and 52.8 mills/kWh, respectively. Inclusion of the maintenance equipment failure data opens up the COE spread between the high and low values for the reference reactors from 1 mill/kWh to almost 3 mills/kWh, but the relative ranking of the reactor concepts remains the same.

The input parameter with the lowest confidence level is the estimated failure frequency. To assess the impact of this parameter, composite failures per outage have been varied from 2 to 12. Figure 5.8-2 displays the results of this analysis using the values in Figure 5.8-1 as the nominal data points. The days required per outage increase uniformly with the number of failures. The GA-Douplet and the UWMAK-III have the greatest total number of maintenance days per outage over the

SENSITIVITY TO MAINTENANCE EQUIPMENT FAILURES PER SCHEDULED OUTAGE

FIGURE 5.8-2

range of failures investigated. Likewise these two reactors experience the greatest rate of change on availability over the range of failures even though they achieve consistently lower availabilities than the ORNL Cassette and the Culham concepts. The analysis of the COE shows that the ORNL Cassette and the Culham remain the lowest in cost and the least sensitive to the failure rate, while the GA-Doublet has the highest cost over the range of failures and is most sensitive to the failure rate. The impact on the GA-Doublet rate of increase in the COE per failure would be approximately halved if a replacement wall fraction of 1/2 is used as for all other reference reactors instead of the value of 1/4 used in the baseline scenario.

Although the list of maintenance equipment failures is incomplete, it does cover the components which are expected to require the most time to recover. To help visualize the impact of the various maintenance items, Figure 5.8-3 displays the additional maintenance days required for the nominal maintenance equipment failure

ADDITIONAL ALLOCATED MAINTENANCE DAYS DUE TO MAINTENANCE EQUIPMENT FAILURE

FIGURE 5.8-3

scenario normalized to days per operating year. For the UWMAK-III the "A" module workhead produces a relatively minor impact while the poloidal magnet retraction mechanism and the "B" module workhead are approximately equal. The "other" category includes the vacuum valve on the GA-Doublet cryovacuum pumps and the NBI ion source exchange. These are considered typical of smaller component maintenance, and therefore, are included for all 4 concept scenarios. The cutting and welding workhead on the Culham main helium coolant manifold connection has a much larger impact than the reactor transporter retraction mechanism. For the ORNL Cassette examples three failures are significant. These include the environmental control system failure on the primary maintenance machine which dominates the divertor workhead and the cassette workhead extraction mechanism recovery time requirements.

Combining these data for maintenance equipment failures with the presented data in Section 5.6 for unscheduled maintenance days per operating year with a fixed

COE yields the data shown in Figure 5.8-4. The higher COE of 52 mills/kWh was chosen for this example because a COE of 49 mills/kWh with maintenance equipment failures yields unacceptably low allowable unscheduled maintenance times. Even at 52 mills/kWh the allowable unscheduled maintenance time remaining for other than first wall/blanket failures appears marginal at failure rates of less than one per year and probably not acceptable above one first wall/blanket failure per year.

5.9 OPTIMUM REACTOR COST COMPARISONS - One of the principal normalization assumptions used in the study is that the reactor geometries will yield the chosen thermal power of 3000 MW. There exists a continuum of possible combinations of plasma major and minor radii which can give the desired power. The values of radii chosen for the four reactors in Table 5.1-2 and discussed in Section 3.1 are selected to be in the minimum COE region based on prior system analyses. To test this premise, the

**ALLOWABLE UNSCHEDULED MAINTENANCE DAYS PER OPERATING YEAR EXCLUDING
UNSCHEDULED WALL AND BLANKET FAILURES
COE GOAL = 52 MILL/kwh**

FIGURE 5.8-4

6.0 IMPROVED MAINTENANCE SYSTEM - TASK 10

The purpose of this task is to define an improved maintenance system based on the tradeoff analysis and evaluation of tasks 8 and 9, on the reference reactor systems defined in task 6 and on the maintenance plans developed in task 7.

6.1 IMPROVED MAINTENANCE SYSTEM (IMS) - Based on the evaluation of maintenance plans and techniques developed for the four reference designs a configuration for a reactor with improved maintenance characteristics is developed. This reactor concept incorporates features from the reference reactors which have been found to improve maintainability and it also incorporates several additional maintenance concepts. The reactor concept which has resulted is not by any means the optimum reactor design. However, it does attempt to incorporate features which will lower the time required to perform maintenance tasks.

Prior to developing the concept a number of desirable maintainability design guidelines have been formulated. These guidelines are presented in Section 7.0. Since the design of a reactor for good maintainability characteristics must also result in a reactor which provides efficient and dependable operation, only some of the guidelines are incorporated into the design. Engineering judgement is relied upon when incorporating some features where in-depth tradeoffs for each of the subsystems and of each desirable feature are beyond the scope of this study. Further investigation is required to determine which features are more desirable from both a reactor operations and a maintainability standpoint.

Of the reference reactors investigated and reported in Section 3.0 and evaluated in Task 9 the Culham concept has an attractive arrangement for first wall/blanket maintenance and appears to allow the use of improved maintenance concepts. It also attains the lowest cost of electricity. Therefore the Culham concept is used as the basic concept from which the IMS reactor is derived. The primary changes from the Culham reference reactor are in the area of; 1) accessing the primary first wall/blanket module, 2) cryovacuum pump arrangement, 3) arrangement of the transformer coils in the central core, and 4) the use of individual removable canisters for the first wall/blanket.

Maintenance plans have been developed for this reactor and are presented for scheduled and unscheduled maintenance of the first wall/blanket in Section 6.2.

6.1.1 Reactor General Arrangement - The general arrangement of the reactor as configured for improved maintenance is shown in Figure 6.1-1. The basic reactor parameters are the same as those used for the Culham reference reactor and are presented in Table 3.1-1 of Section 3.0. The reactor uses helium as the primary

optimum maintenance plan and equipment have been selected for each of the reference reactors and a series of TOCOMO runs have been conducted with the geometry of all four reactor concepts depicted in Figure 3.1-8 varying from a large minor radius and small major radius point up to a large major radius and small minor radius point and determining the variation in COE along the curve for each concept. These data are presented in Figure 5.9-1, which repeats Figure 3.1-8 insofar as showing the combination of major radius (R) and minor radius (a) for the given thermal power, wall/blanket/shield thickness, plasma height to width ratio, maximum toroidal field, poloidal beta limit and the confinement law is concerned. The COE values are also included. The distinguishing features among the various reactor concepts is the thickness of the wall/blanket/shield combination, the plasma height to width ratio and the poloidal beta. The geometries of the ORNL and the Culham concepts are virtually identical and are represented as a single line. The actual minimum COE point is found to be either the chosen baseline value or very close to the baseline. Thus it is concluded that the initial geometry choices were well founded and no changes are required.

COST OF ELECTRICITY FOR A RANGE OF REACTOR SIZES

THERMAL POWER = 3000 MW
TIM CONFINEMENT
h/w = 2; DOUBLET h/w = 3

β_p = ASPECT; DOUBLET RATIO
 $\beta_{pe} = A/2$
★ BASELINE VALUES

FIGURE 5.9-1

Since the baseline cases of the candidate reactor have been evaluated for the optimum maintenance scenario, the final costs of electricity are very similar. However, the elements which comprise the COE, have a sizable variance as shown in Figure 5.9-2. The total annual plant cost is subdivided into the fixed charge for borrowed capital, the operations and maintenance (O&M) costs and the fuel cost. The latter is not shown since the fuel cost is expected to be insignificant for fusion reactors. The maintenance related capital is usually 8 to 9 percent of the total capital. It is to be noted that the GA-Doublet and the ORNL Cassette reference reactors have slightly lower O&M costs and the UWMak-III has the highest. The total annual plant cost is highest for Culham and lowest for the GA-Doublet reactor. However, there are other factors included in the COE equation as shown below.

$$COE = \frac{(\text{Constant}) (\text{Annual Plant Cost})}{(\text{Net Electrical Power}) (\text{Plant Availability})}$$

Since the net power is in the denominator, the higher values of power are advantageous to the COE. In this regard the UWMak-III is the best at 992 MW and the GA-Doublet is lowest at 902 MW. The third factor is the plant availability for which the Culham reference reactor achieves the highest at .794 and the GA-Doublet the least at .7138. The fourth chart on Figure 5.9-2 shows the combination of all of these factors in the COE which is almost identical for all concepts.

Specifically evaluating the elements of the first wall/blanket maintenance reveals differences between the various reactor concepts and maintenance scenarios. Figure 5.9-3 graphically displays the most significant cost elements. The UWMak-III and the ORNL Cassette reactors require the largest number of equivalent maintenance sets to remove one half the wall per maintenance outage. The GA-Doublet uses the least personnel since maintenance of the first wall/blanket is largely accomplished with remote manipulators. The outage time to accomplish the optimum first wall/blanket replacement is longest for the UWMak-III and the ORNL Cassette, and shortest for the Culham for one half the wall, while the GA-Doublet time required is an intermediate value when replacing one quarter of the first wall/blanket modules at a time. The maintenance facility capital cost (hot cells, maintenance and storage areas) is least for the GA-Doublet because the GA-Doublet modules are the smallest and require the least area per module. The GA-Doublet also has the lowest cost maintenance equipment when the shielding for contact maintenance is omitted. This is reflected in the annual fixed charge for the total maintenance capital equipment where all concepts are very similar except for the GA-Doublet which is lower. The annual

ELEMENTS OF COST OF ELECTRICITY

REACTOR WALL/BLANKET SCHEDULED MAINTENANCE DATA

FIGURE 5.9-3

maintenance personnel costs are low for all concepts except for the UWMAK-III. The annual replacement first wall/blanket cost is highest for the GA-Douplet and the Culham reactors. All of these costs are directly attributable to the reactor design concept, the maintenance scenario or the design of the maintenance equipment for each reference reactor.

5.10 MAINTENANCE EQUIPMENT DEVELOPMENT RISK - The equipment required to accomplish the maintenance must be developed specifically for each reactor concept. Although these machines or their component parts are expected to be similar to, or extensions of, existing and developed equipment, some development risk is anticipated. There exists no generally accepted definition of development risk. In this analysis, risk is defined as (1) the probability of encountering the need for additional effort to correct either programmatic or technical discrepancies arising during development of the equipment and (2) the additional funds required to correct these discrepancies. A risk ranking for each definition is developed among the reactor concepts. The probability factor defined above is related to the complexity of the maintenance system and to the portion of the system requiring advances in state-of-art technology. The degree of technology advance for the different elements of equipment is also important in evaluating the state-of-art required.

The relative complexity and advances in the state-of-art required to evaluate the first definition of development risk given above have been reviewed for the maintenance equipment associated with each reference reactor. This evaluation is based on the percentage of the weight of each system which is considered to be high complexity or high technology equipment. For the purpose of risk analysis, the system weight is based on one unit of each type of equipment. The percentage of the GA-Douplet system considered to be high technology and high complexity equipment is greater than for any other system. The GA-Douplet system weight used to compute this percentage excludes the weight of the overhead remote manipulator support structure. However, all equipment items in the GA-Douplet system except minor support equipment, such as dollies and containers, must be capable of computerized remote control and capable of using refined feedback and orientation systems. These capabilities are necessary to operate the maintenance equipment as an integrated system in a radiation environment. Such equipment elements account for a significant portion of the weight of equipment developed (on the order of 80%).

The aforementioned requirements for the high technology capabilities also apply to some of the maintenance equipment used by the other reference reactors,

i.e., Culham, UWMak-III and the ORNL Cassette. These capabilities are necessary for all remotely controlled equipment if the estimated maintenance times used in this study are to be achieved. In addition, the load capacity required for remote manipulative mechanisms in some of the Culham, UWMak-III and ORNL equipment elements far exceeds current equipment design. For each of these reactors this type of equipment is classified as complex, high technology equipment but the portion of the total system classified in this manner is only on the order of 40% of the weight of equipment developed. This implies that the probability of encountering the need for additional effort during system development is less for the Culham, UWMak-III and ORNL reactors than for the GA-Doublet because the percentage of the total system involving complex, high technology equipment is the percentage of the system most likely to experience difficulties during development. Table 5.10-1 indicates the relative rankings of the reactor systems for risk parameter.

On the other hand, the penalty associated with the second definition of development risk requires evaluation of the potential requirement for additional development effort, namely, the estimated additional development cost. This penalty defines a different ranking for the four systems than the ranking derived from the first risk definition. Table 5.10-1 indicates that the relative cost penalties are greatest for the UWMak-III and least for the GA-Doublet.

TABLE 5.10-1
RELATIVE DEVELOPMENT RISK FOR MAINTENANCE EQUIPMENT

REFERENCE REACTOR CONCEPTS	CULHAM	UWMak-III	ORNL CASSETTE	GA-DOUBLET
PROBABILITY OF REQUIRING ADDITIONAL DEVELOPMENT:				
COMPLEXITY RANKING	4	4	3	7
STATE-OF-ART ADVANCE RANKING	3	2	2	6
RISK PENALTY				
ADDITIONAL DEVELOPMENT COST RANKING	4	5	3	2

- o VALUES GIVEN FOR EACH PARAMETER INDICATE RELATIVE VARIATION OF RANKING PARAMETER FOR EACH REACTOR CONCEPT
- o LOW VALUES DEFINE LEAST COMPLEX, LEAST ADVANCE IN SOA AND LEAST COST PENALTY.

The estimated additional development cost is taken as the difference between the likely development cost of maintenance equipment and a base development cost. The base development cost considers a minimum successful testing program with no redesign required. For a first order approximation, this will be estimated as equal to the first unit cost. The rationale for computing these two costs is described in the following paragraphs.

The size and number of individual maintenance equipment items varies for each maintenance concept. To assess the first unit cost, the individual equipment weights (one of a kind) are used as a base. These values are shown in the tables of Section 4.4. To account for additional failsafe or fail-operational capabilities required on some of the maintenance equipment, a failsafe factor is applied to the weight of each appropriate equipment item. Utilizing this revised weight along with a weight-based cost estimating relationship, yields a base first unit cost for all of the equipment required to maintain each reference reactor.

There exists a large diversity of size, weight, complexity and advancement of the state-of-art among the equipment items required for each reactor. To define an adjusted likely development cost, each equipment item is categorized by the advancement of the state-of-art required and its degree of design complexity. Its weight is then adjusted for these factors and added to the adjusted weight of all other equipment items. If a maintenance machine has a low complexity and is within the current state-of-art, it may be assumed that it can be developed for approximately the same cost as the first unit cost, hence a development cost factor of approximately one is assigned. On the other hand, if the equipment is complex and/or requires an advancement of the state-of-art, the likely development cost could be significantly higher.

When examining the maintenance system concepts for development risk as measured by the possible additional development costs, the GA-Douplet is found to be the minimum risk concept. This minimum risk evaluation occurs principally because the majority of the weight included in deriving costs are the supporting beams for the overhead remote manipulator. This overrides the effect of the relatively light weights for the complex equipment items even though the adjustment for complexity and state-of-art advance is severe for these items. The UWMAK-III maintenance equipment set has the highest risk and the ORNL Cassette and the Culham have intermediate risk. The ORNL Cassette has the lower development cost because the equipment weight required is the lightest for all concepts. In summary, while complexity and state-of-art advances are factors in determining these costs the smaller size

of the complex equipment required by the GA-Douplet concept dominates the estimate and results in the least cost penalty for this system.

5.11 REFERENCES

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- 5-3 "Fusion Reactor First Wall/Blanket Systems Analysis Tokamak Concepts, Interim Report," by Fuller, G. M., McDonnell Douglas Astronautics, St. Louis, EPRI Report No. EPRI 472-1, October 1977.
- 5-4 "DEALS: A Demountable Externally Anchored Low Stress Superconducting Magnet System for Fusion Reactors," by Powell, J., Hsich, D., and Lehner, J., Brookhaven National Laboratory, Upton, N.Y., Report No. BNL 50616, January 1977.

IMPROVED MAINTENANCE SYSTEM

A-A FIGURE 6.1-1

coolant, is sized for an output of 3000 megawatts thermal power and has a plasma major radius of 7.5 meters.

The vacuum conditions in the reactor and reactor room are the same as those described in Section 3.2.4 for vacuum wall location number 3. That is, the entire reactor room is evacuated to 1×10^{-4} torr, the area between the shield and the first wall/blanket module is evacuated to 1×10^{-6} torr and the plasma chamber is evacuated to 1×10^{-8} torr.

The primary changes in reactor configuration from the reference reactor occur in the design of the shield door, the lateral access panel and the neutral beam injector. Effort was concentrated on changing the configuration of these items since they highly influence the access to the plasma chamber for first wall/blanket changeout. Table 6.1-1 shows the tasks and associated times for the scheduled changeout of the first wall/blanket for one sector of the reference reactor (discussed in Section 4.4). It can be seen that gaining access to the first wall/blanket and reassembly contribute significantly to the overall time. In fact, the six tasks of removal and reinstallation of the neutral beam injector, TF magnet lateral support access panel (LSAP), and shield door, designated by the arrows in Table 6.1-1, account for 249:00 hours or 51 percent of the total time. When using the partial contact maintenance scenario indicated in Table A-17, Appendix A, these same functions require 119:20 hours or 32.8 percent of the total time. This indicates a potential for significant time reductions in these areas and the approach is to combine and automate these accessing functions.

The selected approach is shown in Figure 6.1-1. Several alternate methods have been devised for removal of the neutral beam injectors. These are shown in Figure 6.1-2. Two of these concepts show movement of the neutral beam injector radially outward and then displacing it to the side but not removing it from the reactor room. This type of motion can be automated but the displacement is such that disconnect of fluid and electrical lines is still required. Another method shown is to disconnect the beam duct and lower the neutral beam injector by elevator to a lower level. This can possibly be accomplished without disconnecting all fluid and electrical lines. Tracks mounted on top of the neutral beam injector would cover the floor opening and provide support for the LSAP, shield door and first wall/blanket module removal. Another concept, as shown in Figure 6.1-1, is that of combining the shield door, LSAP and neutral beam injector into one integral unit and pivoting the entire assembly to a position below the main reactor room floor. This is the concept chosen for the IMS reactor. Other concepts

TABLE 6.1-1
CULHAM REFERENCE REACTOR

SCHEDULED REMOTE MAINTENANCE OF FIRST WALL/BLANKET

LEVEL 1 TASK	LEVEL 2 TASK	DURATION (HRS.)
SHUTDOWN	REACTOR SHUTDOWN	17:00
ACCESS	→ MOVE NBI	28:40
	POLOIDAL MAGNET RETRACTION	31:00*
	→ LATERAL SUPPORT PANEL REMOVAL	31:40
	→ REMOVE SHIELD DOOR	35:30
	DISCONNECT MODULE COOLANT MANIFOLD	7:00
REMOVAL	REMOVE REACTOR MODULE	17:00
	DISCONNECT DIVERTOR MODULE MANIFOLD	9:50*
	REMOVE DIVERTOR MODULE	22:00
INSPECTION	INSPECTION OF REMAINING MODULE	76:35
REPLACEMENT	REPLACE DIVERTOR MODULE	29:00
	REPLACE REACTOR MODULE	16:15
REASSEMBLY	CONNECT DIVERTOR MODULE MANIFOLD	11:10*
	CONNECT MODULE COOLANT MANIFOLD	7:50
	PRESSURIZE COOLANT MANIFOLD AND TEST	15:30
	→ REPLACE SHIELD DOOR	41:00
	→ LATERAL SUPPORT PANEL REPLACEMENT	58:55
	REPOSITION POLOIDAL MAGNETS	42:45*
	→ REINSTALL NBI	53:15
STARTUP	VALIDATION AND STARTUP	36:00
TOTAL:		493:00

* PARALLEL EFFORT, NOT INCLUDED IN TOTAL TIME.

→ CANDIDATE ITEMS FOR POTENTIAL TIME IMPROVEMENT

considered include connecting the shield door and LSAP and then removing them from the reactor room as a single unit; combining the shield door with the first wall/blanket module; raising the shield door to an overhead position; using the shield door for lateral support of the TF magnets; mounting the shield door and/or lateral support on permanently mounted overhead rails; and designing the TF magnets such that lateral support in the access area is not required.

ALTERNATE ACCESS CONCEPTS

FIGURE 6.1-2

For the concept chosen for the IMS the lateral support panel and shield door are combined into a single structure and the neutral beam injector is mounted to this assembly. The inside periphery of this assembly serves as a vacuum barrier. Vacuum seals are located around the periphery on the inside of the assembly. Tracks are permanently mounted on the inside face of the shield such that when the assembly is rotated to the open position the shield forms the floor of the reactor room with tracks in position for module removal. A segment of tracks must be added in the area above the pivot point where permanent tracks are not possible. The separation point of the neutral beam injector duct is located at the tracks and a segment of the duct remains with the first wall/blanket module. Separation is made at this point such that the duct need not be removed to allow movement of the module over the tracks without a separate task for duct removal. Lowering of the entire assembly is accomplished by hydraulic jacks or mechanical screw jacks. The weight of the entire assembly is approximately 650 tonnes. Since motion of the neutral beam injector is minimized the majority of the fluid and electrical lines may be designed to pivot or flex about the assembly rotation point, thereby eliminating the requirement for disconnect of these lines. Further investigation is required to determine which connections can be retained. It is assumed that large lines such as the vacuum regeneration duct will require disconnect. Maintenance of the neutral beam injector is conducted from below the main reactor room floor and can be done in parallel with first wall/blanket maintenance. In addition, this could possibly permit contact maintenance on the neutral beam injector. Maintenance of the neutral beam injector can also be conducted from the main reactor room in a conventional manner if access to the first wall/blanket and rotation of the door assembly is not required.

It has been assumed that fastening the assembly into the reactor operating position can be accomplished by the use of multiple tapered pins driven into position and retracted by a central driving source. This is an alternative to using multiple singly engaged bolts. Further study is required to determine the feasibility of such a latch design. Another area for further investigation is the feasibility of emplacing the shield door/LSAP as an integral unit and effecting a good vacuum seal and structural support for the TF magnets at the same time.

The sectors which contain no neutral beam injectors are opened in the same way and maintenance can be performed from the lower level on other items such as instrumentation and fuel injectors.

The first wall/blanket modules are the same as those used in the reference

reactor with the exception that the first wall/blanket is assumed to consist of canisters similar to those defined for the GA-douplet reference design in Section 3.2.1.2. The primary reason for this assumption is to allow the possibility of single canister removal for unscheduled failures. The divertor first wall/blanket utilizes the same type canisters therefore replacement of this area is done by individual canister removal vs. lowering of the entire divertor module as is done for the reference reactor. This avoids disturbing the vacuum boundary at the divertor coolant lines and the disconnecting of these coolant lines.

The configuration of the magnet system is the same as that described for the Culham reference reactor in Section 3.2.2. This consists of sixteen superconducting toroidal field (TF) magnets and fifteen superconducting poloidal field (PF) magnets. Nine of the PF magnets are located inside of the TF magnets. The PF magnets located outside of the PF magnets are retractable to provide clearance for maintenance of the first wall/blanket and particle bombardment plates. The retraction of these magnets is an automated function and no maintenance machines are required inside of the reactor room to accomplish this task. With PF magnets inside of the TF magnets the problem of replacement of either the TF magnets or the inside PF magnets remains. This problem has not been resolved in this study. To make replacement of these magnets at all reasonable either the magnets should be segmented or the PF magnets should be located outside of the TF magnets. Relocation of the PF magnets outside of the TF magnets would be highly desirable, but the determination of the design and cost characteristics of such a configuration is beyond the scope of this study. The use of segmented magnets has been briefly investigated to determine if this type concept is compatible with the basic improved maintenance approach.

Segmented magnets can utilize either normal PF magnets inside of the TF magnets, segmented superconducting PF magnets or segmented superconducting TF magnets. An ideal situation from a maintenance standpoint would be for both the TF magnets and the PF magnets to be segmented. However, it is not known if segmented superconducting magnets are feasible from a reliability standpoint and the use of normal magnets for commercial reactor is generally considered unacceptable. A layout of a reactor using segmented TF magnets has been constructed and is shown in Figure 6.1-3. This reactor uses the same features as the IMS reactor except for the magnet configuration. The configuration shown utilizes TF magnets constructed of five segments. The inner leg is slightly curved such that the inner joints are made accessible for disconnect without increasing the major radius of

IMPROVED MAINTENANCE SYSTEM WITH SEGMENTED TF MAGNETS

A-A
FIGURE 6.1-3

the reactor. Supporting structure for the segmented magnets is shown located primarily inside of the magnets. An exterior structural support may be required for the top leg to react radially outward loads. The layout indicates that it appears feasible to incorporate segmented TF magnets without any major changes in the reactor however the feasibility of making the segmented magnet and the load capability of the interior structure remain to be established.

The transformer coils located at the central core of the reactor have been rearranged from that shown for the Culham reference reactor. The coils have been located inside of the central core TF magnet structural bucking cylinder. This arrangement is desirable because the transformer coils can be removed without dismantling the bucking cylinder. The coils are accessed by first removing the top of the dewar and then removing the coils from the top. This will still not be a simple task when electrical and fluid interconnections are considered. The central core support does not extend to the top of the reactor room as has been shown in some reactor designs. This is to allow removal of the transformer coils. Such a design, however, results in an overhead crane arrangement that requires total overhead support from the reactor room. This crane arrangement is discussed in Section 6.1.2.

The possibility of using fewer TF magnets and also the use of saddle coils between TF magnets are areas worthy of investigation but have not been considered at this time.

The cryovacuum pump arrangement is changed from that shown in the reference reactor. The configuration shown utilizes twenty cylindrical shaped pumps located on a common plenum above the divertor. Cylindrical pumps were chosen as they are better suited for individual removal and replacement than the flat sided pumps as shown on the reference reactor. Each pump has an isolation valve located at the base of the pump between the pump and the plenum. This valve is used to shutoff the pump during its regeneration cycle and to isolate the pump for removal and replacement. More detailed study of this arrangement could consider the removal and replacement of a pump during reactor operation. The common plenum provides the capability for the reactor to operate with a failed pump. In the event of a failed pump the isolation valve is closed, fluid lines are disconnected from the pump and the pump is disconnected from the top of the isolation valve and removed. A disconnect is also provided at the base of the isolation valve such the valve itself can be removed during reactor shutdown. The disconnects between the valve, plenum, and pump should be as rapid as possible.

Areas which will require further investigation to indicate feasibility are the impedance of flow through the TF magnets, plenum, and isolation valve; the ability to effect quick disconnects at the pump interfaces; and the ability to remove a pump in the presence of a high magnetic field.

The divertor bombardment plates are shown basically the same as for the reference design. The details of a bombardment plate have not been defined but, it is anticipated that removal and replacement on a regular basis will be required. Access doors in the vacuum pump plenum between the TF magnets are provided. The bombardment plates are supported by structure attached to the TF magnets.

An alternate configuration which locates the bombardment plates outside and above the TF magnets has been considered. This location provides for better access to the plates but, the feasibility of shaping the particle flow to this location and the configuration of the poloidal field magnets to accomplish this remains to be defined. If frequent replacement of the bombardment plates is required as indicated in Section 3.2.5, it would be desirable to replace or replenish them without reactor shutdown.

The reactor is supported by pillars extending between the TF magnets, by the center bucking column, and by the TF magnet support struts. Since the bucking column and the TF magnet both operate at the superconducting temperature they are enclosed in a dewar and thermal isolation is required in the supports.

During the study several design or tradeoff studies were identified but not pursued because of the time limit of the present study. Some of these studies are listed below.

- o The feasibility of flexible or rotating joints in mechanical and electrical connections to the neutral beam injector such that disconnect is not required during access tasks.
- o The feasibility of combining vacuum sealing capability and load carrying capability into a single shield door/lateral support panel assembly.
- o The feasibility of using segmented, normal magnets and determining whether this approach or locating all poloidal field magnets outside of the toroidal field magnets is more economical.
- o The economics of using fewer toroidal field magnets.
- o The ability to accomplish and the economics of conducting limited maintenance tasks without reactor shutdown.
- o The arrangement and maintenance requirements of the divertor particle bombardment plates.

- o The feasibility of reliable cryovacuum pump valves.
- o The arrangement of the retractable structure for the poloidal magnets.
- o The extent that manifolding and instrumentation affect maintenance access.

6.1.2 Reactor Facilities - Reactor maintenance has not only an impact on the design of the reactor itself but also on the reactor building. Figure 6.1-4 shows a plan view for an arrangement of the surrounding facility for the IMS reactor. An elevation view for the reactor is shown in Figure 6.1-5.

The reactor is housed in a cylindrical wall, domed roof building. This area serves as the primary vacuum building and as a primary confinement building. Immediately surrounding the reactor room is another circular shaped building which serves as a secondary confinement building. Located to one side of the cylindrical building are the hot cells, the maintenance equipment storage, repair and training area, and the new component receiving, inspection, and checkout room. On the other side is located the turbine-generator building.

The reactor room which surrounds the reactor is an 85 meter diameter cylindrical concrete/steel building with a domed roof. This structure is designed to withstand pressure and seismic loads to prevent any leakage from the reactor to the environment. The inside of the building is lined with steel to provide a vacuum barrier and to lower outgassing. It is desirable to maintain the diameter of this building as small as possible. The 85 meter diameter is determined by the clearance required during maintenance for extraction of a first wall/blanket module and its associated maintenance equipment and by the space required to provide a circumferential path to move the module and equipment around the reactor to the reactor room exit. A circumferential track is provided in the reactor room floor for transfer of equipment around the room. The reactor room extends below the reactor main floor level and includes the area into which the neutral beam injectors are rotated during first wall maintenance.

The overhead portion of the reactor room contains a large truss structure to provide overhead support of the primary cranes so that a center column support is not required. A center support column interferes with access and replacement of the reactor central core transformer coils. A single crane spanning the entire reactor room diameter results in a very large cross-section of the crane bridge and only one crane is possible. By providing an overhead center support the crane bridge span is cut in half and two, or more, cranes can be utilized adding maintenance versatility.

Surrounding the reactor room is an annular shaped building of lower height

IMPROVED MAINTENANCE SYSTEM REACTOR FACILITY
(PLAN VIEW)

FIGURE 6.1-4

IMPROVED MAINTENANCE SYSTEM REACTOR FACILITY
(ELEVATION VIEW)

FIGURE 6.1-5

which serves as a secondary confinement building. This area is divided into various rooms containing reactor support systems such as the primary coolant system, etc., and decontamination area and transfer locks to the hot cells and maintenance equipment storage area. The outside diameter of this area is 165 meters. This results in a 40 meter wide annular building which provides sufficient area for the reactor subsystems as established for the reference reactors described in Section 3.3.5.

A lower level is also provided beneath the main reactor floor. This lower level is required as a result of the maintenance technique of pivoting the neutral beam injector, lateral support panel and shield door. The lower level is used for scheduled maintenance of the neutral beam injector and pivoting door assembly. The neutral beam injector is maintained as a parallel effort during scheduled replacement of the first wall/blanket. The neutral beam injector transfer hall is an annular area extending completely around the lower reactor area and incorporates a track for transporting neutral beam injectors to a transfer lock located at one circumferential location. This transfer lock interfaces with a lower level hot cell which is used for neutral beam injector maintenance and storage. The lower level hot cell is connected to the upper level hot cell by elevator. Space is also available in the lower level for reactor ancillary equipment.

Transfer of reactor components and maintenance equipment to and from the hot cell and maintenance equipment storage area at the upper level is accomplished through either of two transfer locks. One transfer lock leads directly to the hot cell and the other to the maintenance equipment storage, repair and training area. Between the transfer locks is a decontamination area which can be reached from either transfer lock.

The general flow of traffic is for maintenance equipment to be moved to the reactor room through transfer lock No. 1. On return to the storage area the equipment is moved to the transfer lock and then into the decontamination area, where it is cleaned prior to return to the clean storage area. Used reactor components are moved from the reactor room through transfer lock No. 2 to the hot cell. If decontamination is required it can be diverted to the decontamination area. Movement of refurbished components from hot cell to reactor room is done in a reverse manner. Two transfer locks are desirable to reduce traffic congestion during major scheduled maintenance. The arrangement shown, with a decontamination area between the two transfer locks, provides alternate paths from the reactor room to the hot cell or storage area by way of the decontamination area in the event of

a failure or mishap in one transfer lock. This also provides a path between the maintenance equipment storage area and hot cell without entering the reactor room such that transfer of equipment can be accomplished during reactor operation. The plant arrangement shown for the reference reactors in Section 3.3.5 shows a different arrangement in that the hot cell and maintenance equipment storage areas are located on opposite sides of the reactor. This arrangement has the advantage of reduced traffic congestion by locating the transfer locks further apart, however, it has the disadvantage of requiring movement through the reactor room to move maintenance equipment from the storage room to the hot cell.

Transfer of a reactor component to the hot cell is accomplished by moving the component outward from the reactor on radial tracks and onto a carriage located on the reactor room circumferential tracks. It is moved on the carriage circumferentially around the reactor to the transfer lock into the hot cell. The transfer locks, decontamination area, hot cell and equipment storage areas also have overhead cranes for positioning and movement of equipment. Track turntables may also be required for placement of components.

The hot cell shown is for refurbishment and storage of activated components, in particular the first wall blanket modules. The hot cell shown is sized for the scheduled replacement of eight first wall blanket modules per reactor shutdown. Ten refurbishment bays are shown. One extra is used for storage of a spare module and the other for placement of a removed module during changeout. Additional area is also provided for maintenance and storage of items such as neutral beam injectors, vacuum pumps and particle bombardment plates. Area is also provided for long term storage of activated hardware although provisions are also made for disposal of activated hardware from the hot cell.

During reactor operation all maintenance equipment is kept in the storage area. A complete repair facility is provided in this area for total repair and maintenance of the maintenance equipment. In this area is also provided a reactor mockup for training of personnel, and development of new maintenance techniques.

Adjacent to the maintenance equipment storage area is an area for new reactor components. This area is not required to handle activated or contaminated equipment. Any new equipment received in this area is inspected, assembled, if required, and subjected to an operational checkout prior to movement to the reactor room through the maintenance equipment storage area.

6.2 IMS FIRST WALL/BLANKET MAINTENANCE PLAN - Maintenance plans for the removal and replacement of the first wall/blanket have been formulated and are

presented here. Three cases are considered.

- 1) Scheduled replacement of one half of the first wall/blanket modules.
- 2) Unscheduled replacement of one canister in the divertor because of an unscheduled failure using access by primary module removal.
- 3) Unscheduled replacement of one canister in the divertor because of an unscheduled failure using access through divertor access ports.

Since the IMS reactor is based on the Culham reference reactor design the approach to scheduled first wall/blanket maintenance is somewhat similar to that used for the Culham reference design as described in Section 6.1. However, the preferred design has been changed from the reference design so that a number of maintenance actions required to gain access to the first wall/blanket modules are eliminated. This has been accomplished by incorporating the pivoting door which combines the removal/replacement of the neutral beam injector, the toroidal field magnet support panel and the shield door into a single function.

The scheduled maintenance case considers the scenario in which eight of the sixteen first wall/blanket modules are exchanged by use of eight sets of maintenance machines working in parallel at eight module locations. This scenario is found to be the minimum cost arrangement in the reference cases studied in Section 4.4. The first unscheduled case considered assumes that a single failed canister is replaced by accessing the canister in the same manner as used for the scheduled maintenance case. The second unscheduled case considered assumes that the single failed canister is replaced utilizing maintenance equipment accessing the canister through the divertor ports.

6.2.1 Scheduled First Wall/Blanket Replacement - A maintenance plan for the scheduled removal and replacement of the first wall/blanket at eight of the sixteen sectors has been developed. This maintenance plan is presented along with the assumptions and ground rules used, the maintenance tasks involved, and the maintenance equipment used.

Assumptions and Ground Rules - The general assumptions and ground rules used are as follows:

- o Radiation levels inside the reactor room necessitate that all maintenance must be controlled remotely from control rooms or from shielded cabs installed on the major maintenance vehicles. (Contact maintenance operations have been deleted or automated by the redesign.)
- o The entire reactor room is evacuated to 1×10^{-4} torr during reactor operation.

- o A leak tight vacuum seal at the shield door/lateral support access panel is not required because the reactor room is evacuated. However, a high impedance joint is required.
- o The high impedance joint and structural attachment of the shield door/lateral support access panel can be accomplished by a centrally controlled locking latch mechanism vs. individual bolts.
- o The area between the first wall/blanket modules and the shield door is vacuum pumped separately from the plasma chamber, however, this system does not interfere with first wall/blanket maintenance.
- o No structural connection or vacuum seal between adjacent first wall/blanket modules is required when in the installed position.
- o The main supply and return helium manifold to the first wall/blanket module utilizes a mechanical disconnect that requires no welding.
- o The neutral beam injector duct disconnects such that the duct remains with and is removed with the first wall/blanket.
- o No unplanned failures occur during the maintenance period.
- o All times, except in Section 6.3, are without productivity.

Maintenance Procedure - The procedure involved in the removal and replacement of the first wall/blanket modules follow those for the Culham reference reactor described in Section 4.4 except for the steps in gaining access to the first wall/blanket and in reassembling these items. The maintenance tasks and associated time estimate for each task is shown in Table 6.2-1. The times presented here are for the removal and replacement of the first wall/blanket primary module and divertor canisters at one sector location using one set of maintenance equipment. The time to replace a single first wall/blanket module is 300:40 hours. This is a reduction of 192:20 hours or 39 percent from that of the reference reactor when using fully remote maintenance or 62:50 hours (17 percent) from that of the reference reactor when using as much contact maintenance as possible. The difference between the IMS downtime and that required for the contact maintenance scenario is relatively small because the functions affected by the IMS revision are all amenable to contact maintenance. In addition, to take full advantage of the IMS downtime reduction, the poloidal field coils are retracted and extended all at one time instead of serially as in the reference reactor scenarios.

The basic tasks involved in using this technique are elaborated below:

- o Reactor shutdown involves the same functions as described for the Culham reference reactor in Section 4.4.

TABLE 6.2-1
IMPROVED MAINTENANCE SYSTEM
SCHEDULED REMOTE MAINTENANCE OF FIRST WALL/BLANKET

LEVEL 1 TASK	LEVEL 2 TASK	DURATION (HRS)
SHUTDOWN	SHUTDOWN REACTOR	17:00
ACCESS	RETRACT POLOIDAL 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	17:00
	REMOVE DIVERTOR CANISTERS (6)	26:15
INSPECTION	INSPECT REMAINING MODULE	76:35
REPLACEMENT	REPLACE DIVERTOR CANISTERS (6)	27:45
	REPLACE REACTOR MODULE	16:15
	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 POLOIDAL MAGNETS	6:00
STARTUP	VALIDATION AND STARTUP	36:00
*PARALLEL EFFORT. NOT INCLUDED IN TOTAL TIME		TOTAL: 300:40

- o Poloidal magnet retraction is the same as for the Culham reference reactor. It is not possible to accomplish this task totally in parallel with other tasks as it was on the reference reactor and, therefore, this task controls the total downtime.
- o The cryovacuum pump regeneration line is disconnected from the neutral beam injector prior to rotation of the neutral beam injector/door assembly. It is assumed that this is the only line that requiring disconnect from the neutral beam injector because of its size and rigidity. All other fluid and electrical service lines either rotate or otherwise move with the door and require no disconnect. This task is conducted as a parallel function with retraction of the poloidal magnets.

- o Rotation of the neutral beam injector/door assembly is the largest deviation from the procedure used for the reference reactor described in Section 4.4. This single task replaces removal of the neutral beam injector, removal of the lateral support panel and removal of the shield door. The maintenance equipment utilized for removal of these three items is also eliminated. The rotation of this assembly is basically an automated function. It is assumed that the structural disconnect can be effected by inserting multiple tapered pins which fasten the door in position with a single operation. The assembly is lowered by hydraulic or mechanical screw jack to a position such that the shield door, with rails permanently attached, aligns with the radial floor tracks.
- o Installation of a segment of track is required to fill a gap left after door assembly rotation is complete. This gap is immediately above the rotation point of the door assembly. This segment of track is stored outside of the reactor room and placed into position by a piece of maintenance equipment.
- o The disconnect of the primary module coolant manifold and removal of the reactor module utilize basically the same procedure as described for the Culham reference reactor in Section 4.4. The manifold disconnect utilizes a mechanical disconnect and the floor end of the manifold is retracted and covered. The module is removed by connecting a tug vehicle to the module, moving the module radially outward and then circumferentially around to the reactor room exit. It is assumed the module is supported from side-ward tipping during transport by the wheel/track arrangement and that no external support is required. This type arrangement simplifies the maintenance equipment required for movement of the module.
- o The reactor utilizes a removable canister type first wall/blanket, therefore the divertor first wall/blanket is removed as six individual canisters rather than one large module as in the case of the Culham reference reactor. This procedure requires more operations. It eliminates the need to disconnect the manifolding and support structure overhead of the reactor in the area of the vacuum pumps and the requirement to withdraw them through the vacuum plenum.
- o Inspection of remaining modules is the inspection of the modules not being replaced during the scheduled shutdown. This task is the same as that used for the reference design.

The installation of new modules is accomplished in general by reversing the above procedure with the exception that validation testing is added.

As with the reference reactors the time to conduct a scheduled first wall/blanket changeout at eight of the sixteen sector locations has been made. A compilation of these times is presented in Figure 6.2-1. The total elapsed time, not including any manpower dilution factor, is 14.85 days.

For this maintenance plan the direct operating personnel required are a maximum of 50 when conducting all remote operations. This is estimated to increase only to a maximum of 66 personnel when partial contact operations are employed. The automated access provisions of the IMS limit the opportunity for contact maintenance operations since it is the functions which could utilize contact maintenance that have been automated. The number of personnel are based on the estimates presented in Section 4.1, Figure 4.1-11. Because of the reduced contact maintenance requirements the floor crew has been reduced from a maximum of 6 per sector to only 2 per sector for a total of 16 additional personnel when conducting contact maintenance.

It has been assumed that contact maintenance is possible only after reactor shutdown and prior to opening any reactor shielding. For the IMS concept the only tasks which lend themselves to contact maintenance are disconnect/connect of the NBI regeneration duct and possibly the initial steps of shield door rotation.

IMPROVED MAINTENANCE REACTOR MAINTENANCE SCENARIO

FIGURE 6.2-1

Disconnect of the NBI regeneration duct is a parallel function with poloidal magnet retraction, therefore a time savings here does not result in a savings in the total time. Contact maintenance could possibly save a slight amount of time by aiding with unlatching the shield door assembly. However, since this action is automated very little direct time could be saved.

Maintenance Equipment - The maintenance equipment used to accomplish the tasks listed in Table 6.2-1 are presented in Table 6.2-2. Many of the equipment items are the same as or similar to the items used on the Culham reference reactor. However, because of the different maintenance techniques the requirement for several of the larger maintenance items has been eliminated. The major functions not required by the maintenance equipment are disconnect and removal of the neutral beam injectors and disconnect and transport of lateral support access panels and shield door. Another change in equipment concept results from the assumption that the first wall/blanket module can be stabilized against tipping loads without moving the entire module onto a transporter. The Overhead Remote Manipulator is also not required since disconnect of the divertor manifolding is not required. The items listed in Table 6.2-2 are items required for first wall/blanket exchange only. Maintenance of other subsystems will require additional equipment.

6.2.2 Unscheduled First Wall/Blanket Maintenance - Unscheduled maintenance of the first wall/blanket was considered. The ground rules and assumptions are basically the same as presented for the Culham reference reactor in Section 4.3.1. One major difference from the reference design is the assumption that the reactor first wall/blanket is composed of individual canisters. For this type of design it is assumed that the unscheduled failure is a pinhole size coolant leak in one of these canisters in the divertor area. The use of canisters allows for either of two possible techniques to be used when accessing the failed canister. One method is to remove the primary module and gain access to the divertor area from inside the plasma chamber in the same manner as the Culham reference reactor. The other technique is to enter through the area above the divertor with an extendable manipulator and remove the failed canister without disturbing the primary first wall/blanket module and removing the neutral beam injector, lateral support panel and shield door assembly. This technique is somewhat similar to that used on the GA-Douplet reference reactor described in Section 4.3.4.

The tasks and associated times required for the case in which the primary first wall/blanket module is removed to gain access to the divertor area is shown in Table 6.2-3. The tasks in this case are basically the same as those for

**TABLE 6.2-2
IMPROVED MAINTENANCE SYSTEM
MAINTENANCE EQUIPMENT SUMMARY**

ITEM DESIGNATION	MAJOR FUNCTION	OPERATING LOCATION	LIFTING CAPABILITY	SIZE (L X W X H)	WEIGHT (KG)
POLOIDAL CRANE	REMOVE/INSTALL CRYOPUMPS AND OTHER REACTOR COMPONENTS DURING INITIAL ASSEMBLY.	REACTOR ROOM OVER REACTOR.	170 TONNES	100 m X 6.0 m X 12.0 m	4980 TONNES
TUG VEHICLE	PROVIDES MOTIVE POWER TO MOVE SMALL EQUIPMENT SUCH AS MANIFOLD COVERS, DIVERTOR MODULE CANISTERS, AND TRACK SEGMENTS.	REACTOR ROOM, HOT CELL, AND STORAGE AREAS.	N/A	4.0 m X 4.0 m X 1.5 m	8 TONNES
OPERATIONAL MAINTENANCE UNIT (OMU)	DISCONNECTS NBI REGENERATION DUCT, INSTALLS TRACK SEGMENT, DISCONNECTS COOLANT MANIFOLD, INSTALLS MANIFOLD COVERS, REMOVES DIVERTOR CANISTERS, INSPECTS.	REACTOR ROOM.	1.25 TONNES	14.0 m X 6.5 m X 4.5 m	77.5 TONNES
REACTOR MODULE REMOVAL MACHINE	PROVIDES MOTIVE POWER TO TRANSLATE REACTOR MODULE AND ADD STABILITY, IF REQUIRED.	REACTOR ROOM, HOT CELLS AND STORAGE AREA		9.45 m X 6.0 m X 4.0 m	80 TONNES
IMPACT WRENCH	AUTOMATED DEVICE WHICH REMOVES/INSTALLS LARGE FASTENERS, USED IN CONJUNCTION WITH OMU.	REACTOR ROOM BETWEEN T.F. COILS.	N/A	70 cm X 24 cm X 33 cm	.4 TONNES
AUXILIARY SERVICES WORKHEAD	INSTALLS/REMOVES H ₂ MANIFOLD AND H ₂ MANIFOLD DUCT COVER.	REACTOR ROOM BETWEEN T.F. COILS.	10 TONNES	4.0 m X 3.7 m X 5.0 m	13 TONNES
AUXILIARY SERVICES WORKHEAD DOLLY	TRANSLATES THE AUXILIARY SERVICES WORKHEAD BETWEEN THE STAGING AREA AND THE REACTOR ROOM.	REACTOR ROOM, MAINTENANCE EQUIPMENT STAGING AREA.	SUPPORTS 13 TONNES	4.0 m X 4.0 m X 1.0 m	4 TONNES (EMPTY) 17 TONNES (LOADED)
HELIUM COOLANT MANIFOLD COVER	COVERS AND SEALS THE LARGE DIA. H ₂ COOLANT DUCT WHICH MUST BE DISCONNECTED TO REMOVE THE REACTOR MODULE SECTOR.	REACTOR ROOM, BETWEEN T.F. COILS.	N/A	1.5 m DIA. X .25 m THICK	3.5 TONNES
H ₂ MANIFOLD COVER DOLLY	TRANSLATES THE H ₂ MANIFOLD COVER BETWEEN THE STAGING AREA AND THE REACTOR ROOM.	REACTOR ROOM, MAINTENANCE EQUIPMENT STAGING AREA.	SUPPORTS 3.5 TONNES	1.0 m X 2.0 m X .50 m	1.0 TONNE
DIVERTOR MODULE WORKHEAD	MULTI-FUNCTIONAL TO REMOVE AND REPLACE ALL SEGMENTS OF A DIVERTOR CANISTER INCLUDING GRAPHITE RING, GRAPHITE BLOCKS, PRESSURE VESSEL, BREEDING MODULE, SEAL CLEANING, AND LEAK DETECTION.	REACTOR ROOM, INSIDE PLASMA CHAMBER AREA.		14.0 m X 2.5 m X 12.0 m	9 TONNES (EMPTY) 12 TONNES (LOADED)
DIVERTOR MODULE WORKHEAD DOLLY	TRANSLATES THE DIVERTOR MODULE WORKHEAD BETWEEN THE MAINTENANCE EQUIPMENT STAGING AREA AND THE REACTOR ROOM	REACTOR ROOM, MAINTENANCE EQUIPMENT STAGING AREA.	SUPPORTS 12 TONNES	14.0 m X 3.0 m X 1.0 m	3 TONNES (EMPTY) 15 TONNES (LOADED)
DIVERTOR MODULE TRANSPORTATION AND STORAGE DOLLY	TRANSFERS NEW DIVERTOR CANISTERS INTO REACTOR ROOM AND USED DIVERTOR MODULES INTO HOT CELL.	REACTOR ROOM, HOT CELL, STAGING AREA.		4.0 m X 2.0 m X 1.0 m	2 TONNES (EMPTY)
INSPECTION WORKHEAD	USED TO INSPECT REACTOR MODULES ADJACENT TO REMOVED MODULE.	REACTOR ROOM IN PLASMA CHAMBER AREA.	N/A	8.0 m X 2.5 m X 6.0 m	60 TONNES
INSPECTION WORK-HEAD DOLLY	TRANSLATES INSPECTION WORKHEAD BETWEEN STAGING AREA AND REACTOR ROOM.	REACTOR ROOM, MAINTENANCE EQUIPMENT STAGING AREA.	SUPPORTS 60 TONNES	9.0 m X 3.0 m X 1.0 m	20 TONNES (EMPTY) 40 TONNES (LOADED)
LEAK TEST WORK-HEAD	USED TO CHECK FOR LEAKS AROUND THE H ₂ COOLANT MANIFOLD.	REACTOR ROOM.	N/A	.50 m X .30 m X .30 m	.3 TONNES

TABLE 6.2-3
IMPROVED MAINTENANCE SYSTEM
UNSCHEDULED REMOTE MAINTENANCE OF FIRST WALL/BLANKET
(ACCESS BY PRIMARY MODULE REMOVAL)

LEVEL 1 TASK	LEVEL 2 TASK	DURATION (HRS.)
SHUTDOWN	SHUTDOWN REACTOR	29:00
	ISOLATE LEAKING MODULE	18:00
ACCESS	RETRACT POLOIDAL MAGNET	5:00*
	DISCONNECT NBI REGENERATION DUCT	3:35*
	ROTATE SHIELD DOOR, LSAP AND NBI	12:45
	INSTALL TRACK SEGMENT	4:15
REMOVAL	DISCONNECT MODULE COOLANT MANIFOLD	10:00
	REMOVE REACTOR MODULE	17:00
	REMOVE DIVERTOR CANISTER (1)	12:00
REPLACEMENT	REPLACE DIVERTOR CANISTER (1)	8:20
	REPLACE REACTOR MODULE	16:15
	CONNECT MODULE COOLANT MANIFOLD	7:50
	PRESSURIZE COOLANT MANIFOLD AND TEST	15:30
	REMOVE TRACK SEGMENT	8:30
REASSEMBLY	ROTATE SHIELD DOOR, LSAP AND NBI	14:00
	CONNECT NBI REGENERATION DUCT AND TEST	7:45*
	REPOSITION POLOIDAL MAGNETS	6:00
STARTUP	VALIDATION AND STARTUP	36:00
* CONDUCTED IN PARALLEL. NOT INCLUDED IN TOTAL TIME.		TOTAL: 220:25

scheduled maintenance. Differences from the scheduled case are that additional time is required for determination of the type of failure and isolation of the failure to its specific location. The conditions assumed for this is that the leak is isolated to a specific sector and to the divertor prior to any accessing tasks taking place. This requires the use of built-in diagnostic equipment. After the primary first wall/blanket is removed the leak is then isolated to an individual canister. Only the one leaking canister is removed and replaced. It is assumed that inspection of adjacent sectors is not required.

The tasks and times for the case in which access is made through the divertor is shown in Table 6.2-4. Figure 6.2-2 depicts the concept considered. In this case the primary first wall/blanket module is not disturbed but three canister

TABLE 6.2-4
IMPROVED MAINTENANCE SYSTEM
UNSCHEDULED REMOTE MAINTENANCE OF FIRST WALL/BLANKET
(SINGLE CANISTER REPLACEMENT)

LEVEL 1 TASK	LEVEL 2 TASK	DURATION (HRS.)
SHUTDOWN	SHUTDOWN REACTOR ISOLATE LEAKING MODULE	29:00 18:00
ACCESS	RETRACT POLOIDAL MAGNET REMOVE ACCESS PORT COVERS (3) INSTALL REMOTE MAINTENANCE MACHINE INSTALL REMOTE VIEWING MACHINE INSTALL CANISTER REMOVAL MACHINE ISOLATE LEAKING CANISTER (TO ONE CANISTER)	5:00* 21:15 13:45 7:30 10:30 5:00
REMOVAL	REMOVE LEAKING CANISTER	6:10 14:15
REPLACEMENT	INSTALL CANISTER	
REASSEMBLY	REMOVE MODULE REMOVAL MACHINE REMOVE REMOTE VIEWING MACHINE REMOVE REMOTE MAINTENANCE MACHINE INSTALL ACCESS PORT COVERS (3) REPOSITION POLOIDAL MAGNETS	4:15 4:15 4:15 25:15 6:00
STARTUP	VALIDATION AND STARTUP	36:00
TOTAL:		205:25

*PARALLEL EFFORT. NOT INCLUDED IN TOTAL TIME.

removal machines as shown in Figure 6.2-2 are installed at and adjacent to the sector containing the failed module. These machines are similar in function and design to those described in Section 4.3.4 for the GA-Douplet reference reactor design. The machines are installed on the reactor structure at the sector in question and at the sectors on each side after the leak has been isolated to one sector. A permanent installation alternative would require that these maintenance machines be installed permanently at all eighteen sectors. This arrangement requires a much longer maintenance machine than shown in Figure 6.2-2 to allow for complete retraction of the machines. Such an arrangement results in restricted overhead crane usage. The selected arrangement using only three machines is used for unscheduled maintenance only and is not intended for usage during scheduled first wall/blanket

CANISTER REMOVAL MAINTENANCE DEVICE

FIGURE 6.2-2

replacement. The assumption has been made that the reactor divertor design can provide for enlargement of the divertor slot to approximately 80 cm to allow insertion of the maintenance arm. If this is not possible, an alternate procedure would be to raise the entire divertor prior to installation of the maintenance machines. The basic maintenance procedure used is:

- o Shut down the reactor and isolate the leak to within one sector and determine that it is in the divertor. This step is identical to that used in the case where the primary module is removed.
- o Lower the one poloidal magnet which interferes with installation of the canister removal machines.

- o Remove the access covers to the divertor area and install the three maintenance machines. It is assumed that three of these machines are required, one for providing lighting and viewing coverage, one for actual removal of the canisters from the wall, and one to remove the canister and associated parts from the reactor chamber.
- o Isolate the leak to an individual canister. The divertor contains six canisters therefore this involves scanning each of the six canisters to determine which is leaking. If the initial fault isolation has determined that the leak is in the primary module this task could be lengthy since 169 canisters would have to be scanned unless the leak can be isolated to a segment of the module without use of the internal maintenance machines.
- o Remove the leaking canister. This involves several steps including removal of a graphite ring surround the canister, removal of the canister pressure vessel and removal of the reactor breeding module.
- o Canister replacement, reassembly, and startup are performed in the reverse order of the above.

The above cases consider only totally remote maintenance. Contact maintenance does not directly contribute any significant time savings for these cases. Nevertheless, a contact maintenance capability is still a desirable feature to allow for maintenance of unforeseen events.

6.3 COST AND AVAILABILITY EVALUATION - The purpose of investigating the Improved Maintenance System (IMS) is to arrive at a power plant that is easier to maintain and cheaper to operate. The rationale for the proposed design revisions incorporated in a tokamak reactor have been discussed in the preceding sections and descriptions of the proposed improvements for the reactor, maintenance equipment and maintenance plans have been presented. Incorporating all of these changes, the IMS is compared with the optimum Culham concept selected in Section 5 using data generated by the TOCOMO code.

With the IMS concept, the distinction between contact and remote maintenance fades with the outage time being identical for both (see Section 6.2.1 for a timeline). On the basic Culham reactor, the manpower requirements for contact and remote maintenance are 82 and 50 respectively but for the IMS, the requirements are 66 and 50 as discussed in Section 6.2.1. On the baseline Culham case with contact maintenance, the advantage of shorter outage times more than offsets the disadvantage of additional maintenance personnel so the contact maintenance has the more favorable Cost of Electricity (COE). With IMS having no difference in outage times

between contact and remote maintenance, the remote maintenance has a slight cost advantage with a smaller maintenance crew required. Although the remote maintenance is used when evaluating the IMS, the cost is virtually the same for either remote or contact maintenance.

The proposed changes are evaluated in two steps to visualize the relative impacts. The baseline condition is the Culham design with contact maintenance of 8 modules replaced at a time. Step 1 evaluates the IMS with reduced maintenance equipment, maintenance personnel and downtime for scheduled wall/blanket replacement, but without a smaller confinement building size. Step 2 includes the reduction in confinement building size from 100 to 85 meters diameter to incorporate all IMS changes. Table 6.3-1 illustrates the changes and their resultant availability and cost impacts. Some reactor design features are modified from the baseline Culham, but they are not significant enough to change the basic reactor costs. One of the most significant changes to the maintenance equipment requirements for the operations involved in exchange of the first wall/blanket is the elimination of the Overhead Remote Manipulator which weighs 1.66×10^6 kg. This is one of the factors that contributes to the reduction of maintenance equipment total weight. The number of maintenance personnel required are also reduced but this does not have a strong impact on COE. The scheduled wall/blanket replacement time is reduced from 30 to 20 days but the availability shown in Table 6.3-1 shows only a very slight improvement. Figure 6.3-1 illustrates how the availability changes with the scheduled maintenance outage times for the baseline Culham data. Availability does not improve with outages below 28 days because the scheduled maintenance for the wall life occurs after approximately one year of operation and can be accomplished simultaneously with the annual balance of plant (BOP) scheduled maintenance period of 28 days. Figure 6.3-1 illustrates the role of various factors, by showing the effect of computing the availability for twice the estimated wall life, for a decrease of 4 days in annual BOP scheduled maintenance time and for a reduction of 10 days in the unscheduled maintenance period for the entire plant. The doubled wall life reduces the slope of the availability curve, the reduction in unscheduled maintenance increases the magnitude of the availability approximately 1.4% and reduction in the annual BOP maintenance requirement increases the availability a maximum of 17% and moves the breakpoint of the curve to 4 days less than the breakpoint of the baseline. The direct cost comparisons of the IMS with the baseline system are illustrated in Table 6.3-1. The maintenance facilities increased slightly to accommodate the larger number (but smaller weight) maintenance equip-

TABLE 6.3-1
IMPROVED MAINTENANCE SYSTEM COMPARISON

CONCEPT	BASELINE CULHAM	IMS WITHOUT REDUCED CONFINEMENT BLDG.	IMS WITH REDUCED CONFINEMENT BLDG.
WT. MAINT. EQUIPMENT SET (kg X 10 ⁶)	3.31	.48	.48
EQUIVALENT NO. OF MAINT. SETS	2.62	4.58	4.58
TOTAL WT. MAINT. EQUIP. (kg X 10 ⁶)	8.67	2.2	2.2
MAINT. PERSONNEL REQUIRED	82	50	50
SCHEDULED WALL/BLANKET TIME/ OUTAGE (DAYS)	30	20	20
CONFINEMENT BLDG. DIAMETER (m)	100	100	85
DIRECT COST (M\$)			
MAINT. FACILITIES	16.3	21.5	21.5
MAINT. EQUIPMENT	102.6	48.8	48.8
CONFINEMENT BLDG.	182.9	182.9	132.2
DIRECT COST CHANGE FROM BASELINE (M\$)	0	-48.6	-100.3
TOTAL INVESTMENT COST CHANGE (M\$)	0	-80.4	-166.2
TOTAL INVESTMENT COST (M\$)	2150.0	2069.6	1983.8
ANNUAL RETURN ON CAPITAL (M\$)	322.6	310.4	297.6
ANNUAL WALL REP. PERSONNEL COST (M\$)	1.5	.7	.7
TOTAL ANNUAL COST (M\$)	336.6	323.6	310.7
AVAILABILITY	.7940	.7969	.7969
COST OF ELECTRICITY (MILL/KWH)	50.28	48.17	46.25

ment. The maintenance equipment direct cost decreases to less than one half the former value. The confinement building cost is reduced by fifty million dollars. The maintenance equipment change reduces the direct cost by $\$48 \times 10^6$ (indirect $\$80 \times 10^6$) and the confinement building removes another $\$52 \times 10^6$ direct cost ($\$86 \times 10^6$ indirect). Both of these changes individually reduce the COE approximately two mills/kWh with a resultant COE of 46.25 mills/kWh. The impact of a

SENSITIVITY OF AVAILABILITY TO WALL REPLACEMENT TIME

FIGURE 6.3-1

reduced outage time from 30 to 20 days has only a slight effect on availability (and COE) as shown in Figure 6.3-1. This result varies and with a shorter annual BOP scheduled maintenance period a more significant availability change occurs.

The fact that the reduction of the size of the confinement building is as

important in reducing the COE as the improved maintenance plan and equipment is significant. The confinement building is a very expensive structure which is costed on a volume basis. Thus the cost is proportional to the square of the building diameter, yielding a 28% reduction for a 15% diameter change. The COE of 46.25 mills/kWh should not be construed as the cost of electricity postulated for an optimum power plant because system studies indicate that the selection of other values for basic design parameters will define reactors with a lower COE, exclusive of maintenance, than that achieved by those selected for the baseline in this study. In this comparison, however, the change in COE from the baseline is indicative of the possible improvements that may be accomplished with proper planning and design of a maintenance oriented power reactor.

By using the technique developed in Section 5.6 the allowable unscheduled maintenance days per operating year for the IMS has increased, for an availability goal of 72%, from 112 days to 114 days. Similarly, for the cost of electricity goal of 49 mills/kWh, the allowable unscheduled maintenance days increased from 53 to 92 days. The baseline Culham reference reactor can accomplish an unscheduled wall replacement in 17 days while the IMS can accomplish a primary module removal in 12.2 days and a single canister replacement in 11.4 days. Figure 6.3-2 shows these times as a function of unscheduled failures to arrive at the figure of merit (FOM) for this system. Table 6.3-2 tabulates the FOM for the baseline and the IMS, illustrating the improvement possible with the IMS.

TABLE 6.3-2
WALL/BLANKET UNSCHEDULED MAINTENANCE FIGURE OF MERIT

CONCEPT	FIGURE OF MERIT	
	72% AVAILABILITY	49 MILL/kWh
CULHAM-BASELINE	6.6	3.1
IMS-PRIMARY MODULE REMOVAL	9.3	7.5
IMS-SINGLE CANISTER REPLACEMENT	10.0	8.1

IMS ALLOWABLE UNSCHEDULED MAINTENANCE FOR COST AND AVAILABILITY GOALS

FIGURE 6.3-2

7.0 CONCLUSIONS

The conclusions for this study are presented as a series of design guidelines for tokamak demonstration or commercial reactors. The definition and rationale for selection of these guidelines is provided in this section together with some illustrations of their application to tokamak reactors. In addition, some observations which are extraneous to the guideline discussion but which concern the maintainability of tokamak reactors are included in this section.

7.1 SUGGESTED MAINTAINABILITY GUIDELINES - These maintainability guidelines are defined only for tokamak fusion power reactors and are found to be of two types. One type is a broad, high level statement that is very general in its application to the reactor design. The other type is a statement that applies to a specific subsystem or class of components required by the reactor design. The guidelines are separated and presented in accordance with this general classification.

7.1.1 General Guidelines - The guidelines for broad application to tokamak design for maintainability are summarized in the following list. Each guideline is then discussed in more detail.

- o Design to minimize unscheduled maintenance.
 - Use preventative replacement.
 - Design for concurrent maintenance operations.
 - Design for ease of access and short replacement time.
 - Unscheduled replacement to be primary mode only for very long life, costly replacement components.
 - Design for one year minimum life or one year minimum between scheduled outages.
- o Design for unscheduled maintenance by incorporating modular replacement to the smallest economically justifiable component or assembly.
 - Design for minimum cost and maximum dependability of fault isolation and for low cost of spares.
 - Design for unscheduled replacement of one small component instead of an assembly of multiple identical or larger components because of generally more rapid access.
- o Make operations during maintenance shutdowns as simple as possible.
 - Design to minimize the complexity and the total number of operations conducted in the reactor room.

- Design remote operations to be simple in order to minimize procedural error and downtime.
- o Employ contact maintenance when cost of electricity is minimized.
 - Design for simultaneous maintenance functions.
 - Conduct contact operations when reduced downtime offsets shielding costs.
- o Design for minimum operations to access assemblies being replaced.
- o Design maintenance equipment to conduct remote maintenance.
 - Design common support equipment for contact and remote operations.
 - Design for unscheduled combinations of events which require changing contact to remote operations.
- o Make maintenance equipment accessible during maintenance operations.
 - Design for maintenance equipment removal and replacement if failure occurs during maintenance operations when equipment is accessible.
 - Design maintenance equipment for dismantling and/or fail-operational redundancy during maintenance operations when entire equipment unit cannot be removed and replaced.

The meaning and application of these broad statements to tokamak reactor design is discussed in more detail in this section.

Design to Minimize Unscheduled Maintenance - While the maintenance of any equipment item is always minimized within reasonable cost bounds, the decision as to the dominant maintenance mode to be employed (either replacement on a predetermined schedule or awaiting an actual or incipient failure before replacement) can be a critical cost decision. This guideline is applied by defining the design and installation of any component to economically provide for scheduled maintenance instead of unscheduled maintenance whenever the life of the component is significantly less than the reactor design life. The measure of the breakeven point between scheduled replacement of such items and allowing the item to remain in service until it fails is the cost of replacement, including downtime. The design should be such that this cost will be as low as possible. The study has shown that the cost of an unscheduled failure in lost electricity sales can far exceed the cost of scheduled replacement of units if a reliable inspection procedure or the unit life data is used to indicate that replacement is required. The cost of inspection should also be included in the evaluation of whether to design for scheduled or unscheduled maintenance.

This guideline emphasizes directing decisions toward scheduled replacement where the economics of the tradeoff are uncertain. An example requiring scheduled

replacement is found in the comparison of two scenarios for replacing a maintenance equipment isolation valve in the GA-Doublet reference reactor (Section 5.8). When scheduled maintenance is assumed to decrease the unscheduled failure rate from every 2 years to every 10 years the average downtime per operating year decreases from about 130 days to about 22 days. The large number of these valves (16) increases the impact of this failure rate. The design of the components and their assembly must be such that this scheduled maintenance (inspection and selective replacement) can be conducted concurrently with the first wall blanket replacement otherwise the advantage of scheduled maintenance is diminished, although not completely lost. The foregoing example assumes that repair of this particular valve requires reactor shutdown when unscheduled maintenance is required. The design guideline applies only to those unscheduled maintenance actions which do require shutdown or loss in energy production.

The alternative of designing some components for unscheduled maintenance is exemplified by maintenance of the TF magnets. Here the magnet design life is expected to approach the reactor design life. The cost of scheduled replacement is shown to be unfavorable by the large downtime required which ranges from 42 days to 962 days. In this case the life of the magnets is expected to be so great that a method for determining incipient failure is necessary to make scheduled replacement practical. Such a method that gives sufficient lead time has not been examined in the study. Also, the economics conclusion is reached by examining the trends of the first wall/blanket economics study which indicate that the impact of downtime (loss of production) is greater than other maintenance cost impacts and the reduction of this downtime, in this case by avoiding scheduled maintenance, can justify considerable capital expenditure to design for increased life. The impact of downtime is significant only if the total exceeds the balance of plant outage period. This is expected even though the Culham and IMS downtimes are less when only the first wall/blanket outage is considered. Therefore, while this guideline is appropriate for many less costly maintenance operations on multiple component system elements, some limitations must be considered in its application.

The design for scheduled maintenance requires design for low failure rates and a useful life of one or more operating cycles. An operating cycle includes the period between scheduled outages for first wall/blanket replacement; unscheduled downtime during this period, and the scheduled outage downtime. The application of the usual techniques of degraded performance factors, redundancy and reduced complexity or number of components is feasible for many reactor subsystems and,

for this study, the assumption is made that sufficient life can be developed to span the operating cycle determined by either the first wall/blanket replacement or the annual balance of plant maintenance shutdown.

Another example of the penalties of unscheduled maintenance is found in the subsystem unscheduled maintenance downtimes discussed in Section 4.5. For these maintenance operations the shutdown and startup times are a significant part of the total time required for the total maintenance action. As a percentage of the total time for each maintenance action, shutdown and startup are:

- o 52 to 54% of the GA-Doublet Vacuum Pump Valve replacement,
- o 40 to 47% of the GA-Doublet Cryovacuum pump replacement,
- o 43 to 45% of the UWMAK-III Cryovacuum pump replacement, and
- o 66 to 73% of the NBI Ion Source replacement.

These values indicate that, the design for unscheduled outages must give attention to reducing shutdown and startup time or a design must be defined that can delay shutdown until replacement can be scheduled during some other required outage.

Design for Unscheduled Maintenance by Incorporating Modular Replacement to the Smallest Economically Justifiable Component - The necessity of conducting unscheduled maintenance must be considered for all components since all components have a finite failure rate even when using the most thorough preventative scheduled maintenance and diagnostic procedures. This principle again is a broad statement that indicates the desire to make all components replaced in an unscheduled maintenance action as small as can be economically justified. The result may be that, for a given subsystem, the scheduled maintenance may call for replacement of a major unit to achieve the shortest downtime and lowest cost, while, for various failure modes, the unscheduled maintenance will replace the smallest component or subassembly of this major unit that contains the failed part in order to achieve the shortest unscheduled downtime and/or the lowest cost. In other designs this is common practice but the study has indicated that it is desirable for fusion reactors also. This guideline is based on the assumption that as the component or module size is reduced there is usually an accompanying reduction in total downtime to access and replace a single module. This is highly dependent on the specific reactor design employed. Sometimes as the component or module size is reduced the accessing time may be increased and thereby make the replacement of such a component economically inappropriate.

One example is found in the analysis of the modules replaced in the first wall/blanket of the reference reactors. The Culham concept, a large module, is

established as the most economical for scheduled maintenance in Section 5.1. A major cause of this minimum cost (50.28 mills/kWh) is that this concept also achieves the maximum availability (.794). Spare module costs per unit area are similar for all concepts and have little influence on the evaluation because all except the GA-Douplet achieve minimum cost of electricity at a replacement wall fraction of 0.5. The optimum wall fraction for the GA-Douplet appears to occur near 0.25.

The other part of this example is that, for unscheduled first wall/blanket failures, the reactor concept with the largest allowable number of failures is the GA-Douplet. This also has the smallest replaceable module. While the GA-Douplet concept also employs in-place maintenance equipment which reduces the access time, it is generally believed that the smaller components can be designed to have smaller access times. Both the ORNL Cassette concept and the GA-Douplet access times (26.3 and 18.2 hours, respectively) are less than the Culham concept access time of 55.6 hours (all times are for unscheduled contact maintenance). Therefore, in this example the minimum unscheduled maintenance cost (equating this to loss of production through downtime) is for the smaller component. The Improved Maintenance System (IMS) concept explored the possibility of replacing smaller first wall/blanket modules for unscheduled maintenance and this may be feasible even for the first wall/blanket subsystem in this concept.

Another aspect of reducing replacement of failed components to the smallest economically replaceable units, however, is the requirement to provide appropriate sensors for performance monitoring and fault isolation. The feasibility of isolating the fault to the smallest replaceable component determines, in some subsystems, the minimum assembly or component that can be replaced. For the first wall/blanket, the methods of leak detection must be further examined to assure the feasibility of fault isolation to the selected module being replaced.

Make Operation During Maintenance Shutdowns as Simple as Possible - This general principle is particularly appropriate for remote operations in a radiation environment. In this study its application is found necessary to achieve the availability levels required to approach the 72 percent goal.

At the level of availability attained by the maintenance plans for first wall/blanket replacement, downtime is the critical parameter. This is evidenced by the fact that the cost in lost revenue for each hour of downtime is approximately 50,000 dollars (Section 4.3) and the minimum cost of electricity is achieved with the maximum equipment and spares cost that is feasible as indicated by the optimization studies reported in Section 5.1. Therefore, the operations should be defined

to reduce the downtime to the lowest possible level.

To achieve minimum downtime for a maintenance task, the policy of replacement of a component instead of repair in place has resulted because, in every case examined, the disassembly to repair the part in the component assembly appears to require more time and more complex equipment than replacing the assembly. In general, the minimum number of functions required to accomplish a maintenance action requires the minimum time; fewer functions are required to replace than to repair.

Scheduled maintenance operations on the reference reactors are simplified by replacing the component assemblies instead of individual components since fewer functions and less complex motions are required. This objective is achieved because assemblies can be replaced by using bolts instead of welds and, where feasible, latches instead of bolts. Line connections are simplified for maintenance of assemblies since the lines to assemblies can be manifolded together for fewer connections. Also, disconnects require less time by using quick disconnect fittings where feasible on small lines instead of bolted connections, or by using clamped fittings on large lines instead of welded joints at those points where repeated maintenance is necessary. These considerations may appear to contradict the guideline to replace the smallest economically justifiable component for unscheduled maintenance. However, they should rather serve to define a larger assembly for replacement during scheduled operations with smaller parts of the same assembly replaced during unscheduled operations, i.e., a dual replacement policy for scheduled and unscheduled operations. They can also define the best economic compromise of assembly or component size for replacement during either scheduled or unscheduled operations.

When operations during maintenance shutdowns are simplified this results in relegating the more complex repair operations to a hot cell or other repair locations. In the hot cell time is not as critical, the environment can be controlled to allow more complex operations, and the penalties resulting from failures that occur during the repair process are more easily controlled. This type of complex repair operation includes welding, brazing, soldering, routing service lines, testing and inspection.

Design for Contact Maintenance When Cost Effective - The application of contact maintenance is limited during first wall/blanket replacement in tokamak reactors since it cannot be used if the reactor plasma chamber is open. Even so, when compared with fully remote operations, a reduction in cost of electricity up

to 1.7 mills/kWh (3.3%) is achieved for the UWMAK-III reference system as discussed in Section 5.1.

The principal advantages of contact maintenance over remote maintenance result from the reduction in time achievable when conducting a particular function and also in the ability to conduct more functions simultaneously. The time reduction is estimated to be less significant than when comparing contact operations with other types of remote operations, such as many of the current hot cell activities, because in a fusion reactor, the replaced components and attaching mechanisms are large and frequently cannot be manhandled but must use auxiliary equipment. However, the ability to conduct multiple maintenance actions in parallel, as postulated with contact maintenance, is necessary to realize the assumption that all other scheduled maintenance can be conducted during first wall/blanket maintenance. Examples of the advantages of such parallel contact operations are derived principally from the ability to place men in more positions than can be occupied by the large maintenance machines. The use of manual operations permits removal of several bolts at one time in the doors and access panels and permits the use of multiple crews to disconnect fluid lines when the control and access would otherwise be limited to one machine. This capability is used extensively in first wall/blanket access and reassembly operations.

Excessive application of contact maintenance can result in a decrease in cost effectiveness. One of the GA-Doublet reference reactor maintenance plans employed contact maintenance throughout the first wall/blanket activities by shielding the maintenance equipment and the activated first wall/blanket modules. The cost of shielding caused the contact maintenance scenario to be more costly since the time saving with contact maintenance is offset by the shielding costs. In the GA-Doublet case, automation cannot be reduced significantly since the time controlling operations are all conducted in the radiation environment inside the plasma chamber. This result may also be expected in the other reference systems as more contact maintenance is employed since the shielding costs for casking the modules and protecting equipment is likely to be very large.

Another implication of the use of contact maintenance during a first wall/blanket exchange outage is that the portion of the outage required for remote maintenance must be reduced to a minimum if the total downtime for maintenance of other subsystems is to fit within the time available for contact maintenance. The impact of the maintenance of these subsystems can be significant as discussed in Section 4.5 where a cryovacuum pump panel replacement is estimated to require

approximately 6.8 days. Conducting this maintenance in parallel with the first wall/blanket exchange may present serious traffic problems if remote maintenance is required.

Design for Minimum Operations for Access - This principle is related to making the downtime operations simple and few in number. The significance of access time compared with the total time is illustrated by the Culham optimum contact maintenance plan where access and reassembly is 57% of the total downtime; the GA-Doublet, however, is designed for ease of access and reassembly, and these functions are only 10% of the total downtime (Section 4.4). Access time is also significant for apparently accessible subsystems such as the ion source where the data summarized under the first guideline discussed in this section indicates access is 73% of the total time. With replacement of components and assemblies instead of repair in situ being used to reduce the number of maintenance operations, the number of operations for access to the detailed part that is to be replaced also tend to be minimized. These access operations are reduced because the detailed access for replacement of the faulty part are eliminated. For example, replacement of worn out seals in a cryovacuum pump panel valving system requires disassembly of the pump panel. These numerous operations are reduced by replacing the entire panel.

Access operations can also be reduced by combining major equipment elements of the reactor and thereby reducing the downtime necessary to access the assembly being replaced. This approach is used in defining the Improved Maintenance System discussed in Section 6.0. The resultant effect is a decrease in downtime from 30 days to 20 days for replacing 50% of the first wall/blanket in the reactor.

Design Maintenance Equipment to Conduct Remote Maintenance - All tokamak fusion reactor concepts examined in this study require remote maintenance for at least some part of the replacement of the first wall/blanket and for other subsystem failure modes. The equipment to conduct these operations must be designed for remote operation or operation from a shielded enclosure on the equipment. However, since some operations use contact maintenance, equipment designed for these operations could conceivably be designed for less rigorous requirements. The principle defined by this guideline is intended to assure that equipment will be available to conduct even these contact operations by remote techniques when required. The equipment concepts defined in this study are capable of meeting this requirement.

The advantages of complying with this guideline include the following:

- o Equipment will be available at all times to conduct the contact operations in a remote operating mode when a failure occurs which results in a radiation environment.

- o The heavy equipment required for remote operations is also required to aid access during contact operations, so, therefore, the additional equipment requirements may be relatively small.
- o Maintenance equipment failure modes during contact operations can require remote operations for recovery from the failure, e.g., contact operations to replace lights may become remote in the event of a failure of a light during remote operations, or the tugs normally employed in contact operations may be used to move failed maintenance equipment during remote operations.
- o General purpose equipment requires less storage space and possibly fewer maintenance facilities.
- o The cost of accommodating those unplanned failure modes which present radiation or other hazards requiring remote operations is expected to be minimized.

General concern exists about relying on remote operations for maintenance but a thorough system analysis has been effective in preplanning for contingencies in other nuclear facilities such as the Hot Fuel Examination Facility and in other inaccessible complex systems such as space vehicles.

Make Maintenance Equipment Accessible During Maintenance Operations - The ability to access the maintenance equipment at all times during its operation is essential. For failures of this equipment which render it inoperable fail-operational techniques cannot be relied upon completely. Therefore, this guideline must be followed to permit rescue of failed equipment by other maintenance equipment.

In this study some failure modes for maintenance equipment permit recovery but require considerable downtime. This guideline also implies that the reactor design will not require the maintenance equipment to operate in such a location that it is difficult and time consuming to conduct a rescue. The UWMAK-III module handling machine becomes so buried in the reactor when replacing the interior modules that rescue is difficult, requiring approximately 20 days, whereas the Culham transporter is exposed at all times and requires only approximately 5.4 days to recover from a similar failure.

A corollary to this principle is that maintenance equipment should be remotely maintainable. In most of the failure modes examined, remote maintenance is required to retrieve the failed equipment unit and replace it with a spare machine. The need to dismantle the equipment in its failed position arises when the equipment becomes inaccessible such as with the failures examined for the UWMAK-III and the GA-Doublet first wall/blanket replacement equipment. Repair of the failed units

will also require remote maintenance in many cases, even though decontamination is possible, because many failure modes can occur with an activated component attached.

7.1.2 Reactor Subsystem Design Approach Guidelines - Those maintainability guidelines which are more specifically applicable to the design of various subsystems and features of tokamak fusion power reactors including the following.

- o Maximize the first wall/blanket module size for scheduled replacement.
- o Use the smallest removable first wall/blanket element size for unscheduled replacement.
- o Magnetic field coils must be replaceable after reactor is radioactive.
- o Divertor and NBI components must be easily replaced.
- o Minimize interference to access by fluid lines and instrumentation.
- o The overhead crane operating envelope should be unrestricted.
- o Helium coolant is preferred over lithium for maintainability.
- o A design for minimum number of connections is cost effective.
- o Design for first wall/blanket scheduled replacement fraction of one third or greater.
- o Design for concurrent maintenance of other subsystems during first wall/blanket replacement.
- o A multiple zoned vacuum wall arrangement is preferred for maintainability.

A more detailed description of the meaning and application of these guidelines is presented in the following paragraphs.

Maximize First Wall/Blanket Module Size for Scheduled Replacement - The examination of the four reference reactor concepts includes examination of first wall/blanket modules ranging in size from almost a complete reactor sector in the Culham concept to a small heat cell in the GA-Douplet. The maintenance plans for replacement of the entire first wall/blanket range in total scheduled downtime from 60 days for the Culham to 180 days for the GA-Douplet with the other reactors ranging between these values. These downtimes result in availabilities between .794 and .709, respectively. Both of these concepts, however, produce near minimum cost of electricity at 50.28 and 50.93 mills/kWh, respectively. The UWMak-III and ORNL Cassette concepts have a slightly higher cost of electricity. When using both the cost of electricity and availability as criteria, the Culham concept is the more suitable for scheduled maintenance.

The large module of the Culham concept possesses inherent advantages and some potential disadvantages. The access to the module and its exchange are simple, requiring significantly fewer operations than for the small module. For the IMS

they are simplified even further for an additional cost reduction of 2.11 mills/kWh. Fault isolation is expected to be simplified and thereby more rapid when using a large module because it need only isolate to the reactor sector and differentiate between the sector module and the divertor module. Maintenance equipment is accessible most of the time in the event of failure. On the other hand, spares cost are significantly increased and contact operations are greatly limited.

Use the Smallest Removable First Wall/Blanket Element Size for Unscheduled Replacement - The examination of the plans for unscheduled maintenance of the first wall/blanket modules of the four reference reactors clearly indicates that the downtime for replacement of a single module is a minimum for the GA-Douplet concept when using in-place maintenance equipment. Such an equipment concept appears more practical with reactors employing small modules. The downtimes for the four reactor concepts to replace a failed module ranged from 41.3 days for the UWMAK-III to 7.1 days for the GA-Douplet with the Culham requiring 17.5 days. This low replacement time for the GA-Douplet, when coupled with approximately the same allowable number of unscheduled days of outage per operating year for a fixed COE goal of 52 mills/kWh (Figure 5.6-3) results in more allowable failures per operating year for the GA-Douplet (11) than for the Culham (5). The ORNL is also a relatively small module concept but the longer time required to access a third zone module as selected for unscheduled maintenance scenario makes this concept appear less attractive.

The fault isolation techniques remain to be defined, but if a pressurization and search technique as postulated for the small module or some equally rapid fault isolation is feasible then the low replacement times indicated above may be realized. Multiple failures may also occur in the GA-Douplet but these can be approximately twice the total number allowed for the Culham reference reactor before the advantage of the small module is nullified.

Magnetic Field Coils Must be Replaceable After Reactor is Radioactive - The probability of failure of a field coil in the reactor is finite and the capability to replace one of the coils has been examined briefly in the study. It is estimated that the cost of dismantling and rebuilding a reactor designed without provision for coil replacement in the event of failure of one of the coils appears prohibitive. One of several techniques may be employed to relieve this situation. These include:

- o Segmented toroidal field (TF) coils.
- o Poloidal field (PF) coils mounted outside of TF coil bore.

- o Segmented PF coils inside of TF coil bore.
- o Ohmic heating coils structurally decoupled from TF coils inside of reactor core.

The mounting of PF coils outside of the TF coil bore is the simplest solution but may penalize reactor performance too severely. Of the two other techniques the demountable TF coil appears to require less downtime since only about 40 days is estimated to replace a single leg. The replacement of the entire coil takes much longer. However, the reliability of a joint in such a coil must be very high to make the coil failure rate equivalent to that of a unitary design coil.

A suggested technique for structurally decoupling the ohmic heating coils has been incorporated in the IMS concept. Other techniques should also be investigated.

Divertor and NBI Components Must be Easily Replaced - Two of the major sub-systems that require extensive downtime to replace components are the divertor and the NBI. In each of these, as presently designed, some components are predicted to have short operating lives. These are the particle bombardment plates in the divertors and the ion sources in the NBI's. Other components also required periodic replacement such as the divertor first wall/blanket module and the NBI isolation valve. Sections of the divertor slot walls are also subject to neutron streaming and subsequent radiation damage.

The divertor problem is principally one of access. Special equipment is required to access the poloidal divertor module and, in the case of the Culham reference reactor, the replacement of this module adds 14% of the downtime required per sector over that required to replace only the sector module. The ORNL Cassette reference reactor utilizes a 3 layered (zoned) blanket but this concept appears infeasible for the divertor first wall/blanket because there appears no way to connect the coolant lines to the 3 blanket zones. Therefore, a single module is used, but even with this coolant connections are awkward and difficult to reach. For the ORNL Cassette concept the divertor module replacement requires 7% of the downtime compared to an average of 3% of the downtime per cassette.

Divertor bombardment plates outside of the toroidal field coils require removal of cryovacuum pumps for access as in the UWMAK-III. When these plates are placed within the TF coil bore a special shield door is required. These plates have thermal wall loadings estimated at about twice that of the first wall/blanket and are expected to require replacement as frequently as every 17 operating hours (UWMAK-III). Even with internal storage and automatic replacement, resupply at every annual shutdown becomes a major maintenance task because of access difficulty.

Insufficient data is available to include bundle divertors or flowing blanket zone limiters in the examination.

The ion source of the NBI's as currently defined is considered exceedingly difficult to replace because of the many power and service connections. Reducing these connections to five as postulated in Section 3.2.3 appears reasonable. Access to ion sources is good but replacement at intervals less than the annual shutdown period is undesirable. The replacement interval may be extended, however, by using redundancy. As an alternative, remote techniques may be used to replace the ion source during reactor operation, but maintenance equipment designed for operation in the reactor room environment during reactor operation is likely to be very costly. Replacement of other NBI components during reactor operation requires access by remote equipment without displacing other equipment, preferably through the back or top of the NBI.

Minimize Access Interference by Fluid Lines and Instrumentation - All time estimates made in the study assume routings of lines that do not interfere with replacement of reactor components. Separate operations to move these lines increase the complexity of the specialized remote maintenance equipment and increase downtime if this must be done serially. Routing of lines must be above or below the first wall/blanket access area since in the UWMAK-III and Culham concepts space to the side is extremely limited. The GA-Douplet and ORNL Cassette concepts inherently allow more space for line routing.

Overhead lines also restrict access to the maintenance equipment by the overhead crane. If overhead lines are unavoidable, specialized design and operation of the overhead crane can possibly reduce the adverse influence on maintainability. However, the best solution is to eliminate such interference.

Overhead Crane Operating Envelope Should be Unrestricted - Replacement of the first wall/blanket modules and other components at the same time requires minimum interference with overhead crane operations in all reactor concepts. The ability to use the crane, or cranes, to relieve direct serial operations of other maintenance equipment is assumed for transporting replacement units and maintenance equipment from any reactor location to the reactor room exit by the shortest possible route. Overhead lines or insufficient overhead clearance of the reactor or its associated subsystems which prevents movement by the shortest direct route to and from the reactor room exits must be restricted to an absolute minimum. From the estimates made in this study, overhead crane traffic requirements may prove to be the most restrictive time requirement. For this reason concepts are chosen which provide for more than one crane in the reactor room.

Helium Coolant is Preferred over Lithium for Maintainability - For ease of maintenance the use of helium is less contributory to downtime than lithium (the only alternative examined) if it is assumed that the larger line sizes for helium can be developed with high reliability. The use of liquid metals requires filling the blanket before installation to avoid voids in the complex first wall/blanket flow paths. Installation then necessitates preheating and the use of continuous heating during installation or slow heating after installation. The avoidance of voids in connecting lines requires additional precautions. Purging with a gaseous coolant after installation of the blanket is a simpler and less time consuming task.

Helium also is of less concern in the event of a leak or rupture since cleanup is not required. The potential for an exothermic reaction with moisture also does not exist in the event of a line rupture or spill, thereby making this a safer fluid. The use of a sodium coolant in the secondary coolant loop is of less concern because of the more benign environment. However, the use of sodium or lithium as a particle bombardment plate coolant may be necessary because of the higher heat transfer rates available. However, this design in the divertor should also be avoided if at all possible for the reasons given above.

The use of water as a coolant may also possess advantages but none of the concepts studied included this as a coolant. If a design for commercial reactors is feasible the state of the fluid used in the primary loop (whether liquid or gaseous) may influence maintainability because of the possible absence of corrosion products in a cleanup operation with steam instead of water. The presence of tritiated water vapor would also require protective clothing and breathing equipment during a cleanup operation using contact maintenance but this requirement is expected for contact maintenance in the confinement building for other tasks.

Design for Minimum Number of Connections is Cost Effective - The effect of the number of connections required by a maintenance action on the maintainability of a reactor is exemplified by the replacement of the first wall/blanket. This guideline is particularly applicable to fluid line connections. Only one major fluid line connection is broken and remade for replacement of the sector module in the Culham reference reactor. The divertor coolant lines must be disconnected also but this is a parallel operation. The total time required by the helium coolant line connection is 4.0% of the replacement time for a total of 14.8 hours per sector. On the other hand, the GA-Doublet must disconnect 113 modules per sector with a pressure vessel seal on each module. The disconnect, reconnect and test time is 28.6% of the replacement time per sector and the total time is 404.9 hours. The

ORNL Cassette concept requires disconnect of three relatively small lines for each cassette for a total of 51 for each sector. The disconnect, reconnect and test time is only 7.3% of the replacement time per module but the total time is 58.8 hours. The reduction in total time per sector for the one large connection in contrast with the time required for the many small connections is illustrative of the impact of reducing the number of connections as much as possible. This conclusion requires that the design of the larger connection is of comparable reliability and does not incur other problems.

Design for First Wall/Blanket Scheduled Replacement Fraction of One Third or Greater - The examination of maintenance plan alternatives for the four reference concepts indicated that the minimum cost of electricity and maximum availability for each concept is at or near a replacement fraction of $1/2$ for each outage. This is the optimum replacement fraction for the Culham, ORNL Cassette and UWMAK-III reference reactors and the GA-Doublet appears to be close to optimum at this value. These values are summarized in Table 5.1-3. The optimum wall fraction may be even greater if more than 8 reactor sectors can be replaced in simultaneous operations but the traffic problems expected if more than 8 sectors are replaced at one time has limited the maximum number of sectors to be worked at one time to 8 even when using a replacement wall fraction of 1, i.e., 16 sectors. At this rate, the spares required for a replacement wall fraction of 1 override other factors, leading to the optimum fraction of one half.

In the previous study phase, the reactor concepts were evaluated for replacement of a first wall fraction of $1/3$, when applicable, and the maintenance plans were found to optimize at this fraction for the UWMAK-I with 12 sectors, for the UWMAK-III with 18 sectors and for $1/3$ of the GA-DPR modules. The $1/3$ fraction is not feasible with the current 16 sector reference reactors and is not evaluated in this phase. Nevertheless, in view of the data previously developed, the minimum cost of electricity appears to be attained with a minimum replacement wall fraction of $1/3$, or possibly greater, depending on the number of sectors in the reactor.

Design for Concurrent Maintenance of Other Subsystems During First Wall/Blanket Replacement - This guideline has been cited as a major assumption in several of the foregoing explanations. The achievement of the availability goals for scheduled and unscheduled maintenance is very sensitive to the ability to schedule most subsystem maintenance during the first wall/blanket replacement which is, in turn, scheduled for one of the regular maintenance periods. The

principal is stated again to collect the specific applications previously outlined as an important guideline for the design of not only the reactor but also of the maintenance equipment.

Scheduled maintenance of reactor subsystems other than first wall/blanket can expend extensive downtime. The downtime required per unit replaced for the four subassemblies discussed in Section 5.6 ranged from 3.1 days to 5.7 days, including reactor shutdown and startup, or .8 days to 2.8 days if the reactor is shutdown for other causes and maintenance is concurrent with the shutdown. Since the subassemblies examined include the cryovacuum pumps and ion sources for the NBI's, activated radiation sources are exposed during the replacement operation and much of the downtime is expended for remote maintenance operations.

A Multiple Zoned Vacuum Wall Arrangement is Preferred - The analysis described in Section 4.2 illustrates the advantages of multi-zoned vacuum chamber systems for maintainability of the reference reactor concepts. Maximum reduction in downtime for first wall/blanket replacement for each concept when using multiple zones are as follows:

- o 11.2% for Culham when using the reactor room as the outer zone.
- o 15.2% for UWMAK-III when using the reactor room as the outer zone.
- o 7.6% for ORNL Cassette when using the LSAP as the outer zone.

Multiple zones are deemed to have negligible effect on the GA-Doublet downtimes and are not evaluated.

The principal advantage of the multiple zones arises from the assumed capability to eliminate welded vacuum joints with some advantages for eliminating some disassembly functions. The additional vacuum pump capacity and pump down time does not override these advantages. Other advantages such as the reduced impact of seal failures on internal vacuum barriers remain to be evaluated against the potential disadvantages of reduced accessibility for contact maintenance to subsystems other than the first wall and blanket.

7.2 OBSERVATIONS - A number of specific conclusions have been reached during the course of the study which fall outside of the realm of guidelines but provide important insight of desirable maintainability characteristics of the reference reactors. These are defined as critical maintainability characteristics of tokamak fusion reactors and some desirable maintainability features.

7.2.1 Critical Maintainability Characteristics - The maintainability characteristics that are found to be critical in achieving an economical commercial

design of a tokamak reactor other than those characteristics involving the scheduled first wall/blanket maintenance include:

- o Unscheduled maintenance of reactor subsystems.
- o Scheduled maintenance of reactor subsystems other than first wall/blanket.
- o Unscheduled maintenance of maintenance equipment.
- o Failure rates of components employed in large quantities in the reactor.
- o Magnet failures.

While these characteristics have been discussed to some extent when defining the foregoing guidelines some additional observations are cited below.

The total time required for unscheduled maintenance of reactor subsystems other than first wall/blanket is found to be potentially quite large. The critical subsystems whose failure causes shutdowns include the field magnets, cryovacuum pumps, primary coolant loops and supplementary heating systems. Unscheduled failures of only a few components of these subsystems at the rate of 10 to 15 per operating year for the GA-Douplet will use all of the 56 days of unscheduled downtime allowed for this reference reactor if an availability goal of 72% is to be achieved. Similarly, the 112 days of allowable unscheduled downtime available for the Culham reference reactor to achieve the 72% availability goal permits only 30 failures of components similar to the 36 ion sources used in the design before the 112 days is expended. When the possible failures of all components are considered the failure rates must be low to achieve availability goals at the 72% level.

The failure of maintenance equipment during maintenance operations can also be a major source of unscheduled downtime. The time to recover from a single failure of maintenance equipment varied from 8 hours to 18.6 days. A trend exists that the larger, more inaccessible equipment generally requires more recovery time than the small, accessible maintenance tool. If the set of failures examined for each reference reactor is assumed to be representative of an average set of failures during an operating cycle at the failure rates postulated, this equipment alone accounts for additional unscheduled downtime ranging from 17 to 35 days for the GA-Douplet and UWMAK-III reactors, respectively. The fact that failures are more frequent when multiple sectors are being worked on at one time and many pieces of maintenance equipment are in use accounts for a significant amount of this downtime. Since several pieces of equipment may fail during the same period, some of the time stated above may be spent while conducting operations on more than one piece of equipment at a time and thus reduce the total recovery time required below that estimated.

The impact of the frequency of failure of multiple reactor components on unscheduled downtime is illustrated by the 16 maintenance equipment isolation valves required by the GA-Douplet reference reactor. The assumed failure mode is discussed in detail in Section 7.1.1 but the example serves to emphasize the fact that a large number of units requires lower failure rates per unit to achieve satisfactory downtimes. Wherever possible, the number of units must be reduced. For many components this is achievable by a reduction in the number of reactor sectors or increasing unit capacities. However, as pointed out in the definition of the smallest economically justifiable component for use in unscheduled replacement, an economic tradeoff exists between unit size and access time. Another consideration in this tradeoff is component reliability. As the size of the component is made smaller, such as for first wall/blanket modules or fluid line connectors, the smaller components also require a relatively large number of components to perform the function for the entire reactor. The cost and feasibility of obtaining the required increased reliability to keep the frequency of failure at an acceptable level must also be included in this tradeoff in order to determine the optimum size, and therefore the optimum number, of this kind of component.

Toroidal field (TF) magnets or poloidal field (PF) magnets within the TF magnet bore are found to generate the most time consuming maintenance actions. The occurrence of a failure of either of these types of magnets has been found to require repair times in excess of those needed to achieve the desired availability goals unless the reactor design specifically provides for readily demountable magnets. While the example examined in this study is for normal PF coils in an Ignition Test Reactor the downtime to replace an average nondemountable PF coil requiring removal of the plasma chamber is on the order of one year. If an average failure rate per magnet is once during the reactor life of 30 years and assuming 4 PF magnets in the TF magnet bore and 16 TF magnets requiring a repair time of an average of one year per magnet and assuming no concurrent failures the downtime per operating year becomes 243 days. From this source alone the availability becomes approximately 60%. Demountable coils requiring approximately 40 days of downtime per failure reduce this time to the order of 27 days per operating year.

7.2.2 Desirable Maintainability Features - The reactor features that are most desirable include:

- o Minimum access maintenance operations.
- o Small components for unscheduled maintenance.

- o Large components for scheduled maintenance.
- o Minimum maintenance line connections.
- o Minimum routine maintenance welding.
- o Multiple zoned vacuum chambers.
- o Maximum contact maintenance without excessive shielding.

These features have been combined to some degree through use of relatively simple variations in the reference concepts into one Improved Maintenance System (IMS).

By combining six major access and reassembly operations for the first wall blanket into one access and one reassembly operation the time is reduced from 32% of the downtime for these operations to 11% of the downtime. Improved access and reassembly of the cryovacuum pumps through use of a simplified arrangement and pump design is also an objective of the IMS.

The use of individually replaceable heat cells similar to the GA-Doublet concept is employed by the IMS for use in repair of unscheduled first wall/blanket failures. These heat cells are combined into one major sector module similar to that used by the Culham concept for scheduled replacement operations on the first wall/blanket. Potential access to the small modules through an adjustable divertor slot and the divertor access door remains to be investigated further. This concept also minimizes the line connection problem by individually replacing the six heat cells in the divertor region of each sector and thus avoiding the difficult connection access problem for the divertor module. The single connection for each sector module in the Culham concept is retained.

The disassembly and reassembly process is aided by use of multiple vacuum chambers with the primary seal at the reactor room wall. This arrangement decreases the seal requirements at the main shield doors, the divertor shield doors, the NBI connection and the cryovacuum pump connections to a requirement for only high impedance joints. The probability of requiring rework of these joints and also the time required to reassemble the joints is reduced below that required if the primary vacuum seal is made at the joint.

The IMS arrangement simplifies the shielding requirements for the cryovacuum pumps if additional contact maintenance is desired. However, while as much contact maintenance as possible is desired, the contact maintenance opportunities are reduced when replacing the first wall/blanket in the IMS because almost all access and reassembly functions that are amenable to contact maintenance in the Culham concept have been automated. Thus, the contact maintenance performed on the

IMS subsystems other than the first wall/blanket can be conducted concurrently within only a very short period of the first wall/blanket exchange. Additional downtime for this contact maintenance will extend the required downtime for first wall/blanket replacement.

7.2.3 Tokamak Maintainability - The maintainability of tokamak fusion power reactors appears to be economically and technically feasible. Examination of the Improved Maintenance System (IMS), when developed even to the limited extent defined in this study, indicates that economic and availability goals, based upon existing and anticipated coal fired and fission power plant performance, can be attained and probably exceeded.

Table 7.2-1 lists key maintainability parameters of the IMS as they have been defined in this study. The anticipated COE of 46.25 mills/kWh is well below the goal of 57.4 mills/kWh (1978 \$) estimated as a requirement to break even with coal fired plants in the year 2000. The maximum availability of 79.7% is well above the availability goal of 72% derived from the average performance of fission plants surveyed in 1975. The wall life estimate of 2.357 years (at $5.0 \text{ MW}\cdot\text{Yr}/\text{m}^2$) when coupled with the optimum replacement wall fraction of 1/2 gives an operating period of 1.179 years which coincides well with the current utility practice of an annual plant shutdown.

To achieve these COE and availability goals the study emphasized the estimate of scheduled and unscheduled downtime impacts. The scheduled downtime required per outage for first wall/blanket exchange is estimated at only 20 days for the IMS which is well within the assumed annual 28 day plant shutdown period. An allowance of 65 days has been made for unscheduled downtime for these COE and availability calculations and all comparable calculations in the study. This division of time is based on current experience in fission plants when achieving a nominal 72% availability.

Since failure rates are unknown for these tokamak fusion power systems the reasonableness of the 65 day allowance must be judged by the unscheduled failures that can be accommodated within this period. The longest downtime for such failures is assumed to be the time required to recover from a first wall/blanket failure. Other subsystems have been investigated for reference reactors other than the IMS and generally appear to verify this assumption. The only exception is the failure of either a PF or TF magnet. Such a failure should be infrequent. Table 7.2-1 shows that as many as 5.7 failures/operating year of the first wall/blanket can be accommodated if no maintenance equipment failures are experienced and as many as

TABLE 7.2-1
IMS MAINTAINABILITY

COST OF ELECTRICITY, MILLS/KWH	46.3
AVAILABILITY, %	79.7
WALL LIFE, YEARS ⁽¹⁾	2.4
REPLACEMENT WALL FRACTION/OUTAGE	1/2
SCHEDULED DOWNTIME/OPERATING YEAR, DAYS ⁽²⁾	28 (20)
UNSCHEDULED DOWNTIME/OPERATING YEAR, DAYS	65
ALLOWABLE FAILURES/OPERATING YEAR ⁽³⁾	
(WITHOUT MAINTENANCE EQUIPMENT FAILURES)	
FIRST WALL/BLANKET SECTOR MODULE	5.3
FIRST WALL/BLANKET CANISTER	5.7
(WITH MAINTENANCE EQUIPMENT FAILURES) ⁽⁴⁾	
FIRST WALL/BLANKET SECTOR MODULE	3.7
FIRST WALL/BLANKET CANISTER	4.0
NBI ION SOURCE	12.4

(1) ASSUMED CULHAM REFERENCE REACTOR WALL LIFE.

(2) BASED ON A BALANCE OF PLANT ANNUAL OUTAGE
OF 28 DAYS AND ON A CONCURRENT IMS DOWNTIME PER
SCHEDULED OUTAGE OF ONLY 20 DAYS FOR AN OPERATING
PERIOD OF 1.179 YEARS

(3) FORCED OUTAGE DOWNTIME PER FAILURE IS:
 ○ FIRST WALL/BLANKET SECTOR MODULE = 12.2 DAYS
 ○ FIRST WALL/BLANKET CANISTER = 11.4 DAYS
 ○ NEUTRAL BEAM INJECTOR ION SOURCE = 3.7 DAYS

(4) MAINTENANCE EQUIPMENT FAILURE DOWNTIME
ASSUMED THE SAME AS CULHAM REFERENCE REACTOR
AT 19 DAYS/OPERATING YEAR.

4.0 failures/operating year if an allowance of 19 days per operating year is made for maintenance equipment failures. This 19 day allowance is for a potentially representative group of failures assumed for the Culham reference reactor maintenance equipment. Similarly, the number of NBI ion source failures that can be accommodated above the allowance for maintenance equipment failures is approximately 12.4.

At this early stage in the definition of tokamak power reactors it is to be expected that many questions remain. For example, if only one failure per reactor operating year per ion source is an allowable allocation for this assembly the required reliability of each ion source per operating year would have to be at least 0.97. This requires an average MTBF of 1 year per source for a system using 36 ion sources. Such reliabilities are achievable for other equipment and, therefore, the allowable downtime appears reasonable. In addition, a considerable extension in the allowance from 65 days to a total of 114 days is possible if an availability of 72% is sufficient. This increases the COE to 51.2 mills/kWh which is still below the breakeven goal. Allocation of failure rates to all subsystems, assemblies and components and the examination of the effects of redundancy in some components will better illustrate the feasibility of attaining the allowable unscheduled downtimes for the complete reactor.

Other points of concern lie in the validity of the more significant assumptions that may alter the results. These are principally the assumptions that affect maintenance time estimates, and costs of maintenance equipment and personnel. The assumptions of simultaneous scheduled maintenance operations, of demountable magnets with high reliability and of the representative nature of the maintenance equipment failure scenarios are typical assumptions affecting downtime. Any change in the assumption that the remote equipment elements cited represent all major items required is typical of revisions that will have an impact on cost. Any change in the impact on maintenance from revisions required in these and many similar assumptions must continue to be evaluated as reactor concepts and designs become increasingly specific.

Considerable improvement in the maintainability of tokamak reactors may also be achieved. The concepts for an improved maintenance system have only scratched the surface of the potential revisions. A typical change in groundrules that may be effective for external subsystem maintenance, particularly of those subsystems where redundancy can be used, is to design maintenance equipment and define scenarios for replacement of components in high magnetic and electrical fields, a vacuum environment, and/or with the reactor operating. The cost of electricity impacts of these and other revisions appear worthy of consideration.

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