DEVELOPING MAINTAINABILITY FOR TOKAMAK FUSION POWER SYSTEMS

Phase I Report Volume I - Study Results

H. S. Zahn, et.al.

**McDonnell Douglas Astronautics Company
St. Louis, Missouri, 63166**

October - 1977

NOTICE
This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Department of Energy, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

Prepared For

**THE U.S. ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION
UNDER CONTRACT NO. EG-77-C-02-4184**

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

PREFACE
VOLUME I

This report presents the results of the first phase of a study, "Developing Maintainability in Controlled Thermonuclear Reactors" by McDonnell Douglas Astronautics Company - St. Louis for the Energy Research and Development Administration (ERDA) under contract number EG-77-C-02-4184. The reporting period covers 1 February through 31 October 1977.

The overall purpose of the study is to identify design features of tokamak fusion power reactors which contribute to the achievement of high levels of maintainability. In this first phase, the principal emphasis is on scheduled maintenance whose frequency is determined by the life of the reactor first wall/blanket. Remote operations are baselined. Five conceptual reactor designs have been analyzed. Each concept is characterized by the size of the replaceable first wall/blanket module - large, intermediate, small - and whether access to the module was from the outside of the reactor, the inside of the reactor or a combination of both. The study results are expressed in terms of availability (scheduled maintenance downtime), the costs of maintenance (capital and recurring) and the percent effect of maintenance on the cost of electricity.

During this first phase, the study benefitted significantly by the critical review of the feasibility of maintenance functions and the time-to-perform estimates by numerous persons involved in nuclear maintenance and remote operations. The McDonnell Douglas Corporation gratefully acknowledges this help. These persons are named in Appendix H of Volume II. Extensive personnel contacts with many other individuals expert in their respective fields have been made by study personnel. These persons have been very helpful in providing a better understanding of the many facets of specific design and operation concepts and this assistance is also sincerely appreciated. The study personnel and authors of both Volume I and Volume II are listed in Appendix H.

This report contains two volumes. Volume I is the discussion of the study results. Volume II contains appendices which present detailed data on the time estimates, equipment descriptions, additional design definition performed, a description of the systems analysis computer code, TOCOMO and contributors to this report.

TABLE OF CONTENTS

	<u>PAGE</u>
PREFACE	iii
TABLE OF CONTENTS	v
LIST OF FIGURES	viii
LIST OF TABLES	x
1.0 INTRODUCTION	1-1
2.0 SUMMARY	2-1
2.1 REACTOR DESIGN CONCEPTS	2-1
2.2 DEVELOPMENT OF MAINTENANCE PLANS	2-2
2.3 EVALUATION OF DESIGN FEATURES	2-6
2.4 CONCLUSIONS	2-9
3.0 SYSTEM DESCRIPTIONS	3-1
3.1 SUMMARY OF DESIGN CONCEPTS	3-3
3.2 BASELINE LARGE MODULE	3-3
3.3 ALTERNATE LARGE MODULE	3-7
3.4 BASELINE INTERMEDIATE MODULE	3-10
3.5 BASELINE SMALL MODULE	3-15
3.6 ALTERNATE SMALL MODULE	3-17
4.0 MAINTENANCE PLAN DESCRIPTIONS	4-1
4.1 MAINTENANCE APPROACH SUMMARY	4-2
4.1.1 Maintenance Plan Characteristics	4-4
4.1.2 Maintenance Equipment Characteristics	4-7
4.1.3 Maintenance Downtime Requirements	4-8
4.1.3.1 Installed Equipment Impacts	4-10
4.1.3.2 Contact Maintenance Impacts	4-11
4.2 SCHEDULED MAINTENANCE	4-13
4.2.1 Remote Maintenance Approaches	4-13
4.2.1.1 The Large Module Concept (UWMAK-I)	4-15
4.2.1.2 The Alternate Large Module - Culham Mk-II	4-23
4.2.1.3 The Intermediate Module Concept - UWMAK-III	4-31
4.2.1.4 The Small Module Concept - GA-DPR	4-39
4.2.1.5 The Small Module Concept - General Atomic DPR With In-Place Maintenance Equipment	4-47
4.2.1.6 Alternate Small Module - ORNL Concept	4-52

TABLE OF CONTENTS (CONTINUED)

	<u>PAGE</u>
4.2.2 Contact Maintenance Approaches	4-56
4.2.2.1 Large Module - UWMAK-I	4-57
4.2.2.2 Intermediate Module - UWMAK-III	4-62
4.2.2.3 Small Module - GA-DPR	4-66
4.3 UNSCHEDULED MAINTENANCE	4-70
4.3.1 Unscheduled Maintenance Scenario	4-71
4.3.2 Unscheduled Maintenance Impacts	4-76
4.4 OTHER SUBSYSTEM EFFECTS	4-78
4.4.1 Subsystem Maintenance Requirements	4-78
4.4.2 Subsystem Maintenance Plan	4-81
4.4.3 Subsystem Scheduled Maintenance Impacts	4-84
5.0 MAINTENANCE PLAN ANALYSES.	5-1
5.1 APPROACH TO ASSESSMENT	5-1
5.1.1 Cost Assessment	5-1
5.1.2 Availability	5-2
5.1.2.1 Availability Goals	5-3
5.1.2.2 Estimation of Availability	5-4
5.2 ALTERNATE REPLACEMENT FRACTION MAINTENANCE PLAN CHARACTERISTICS	5-6
5.2.1 Downtime Required	5-6
5.2.2 Maintenance Equipment Requirements	5-9
5.2.3 Maintenance Personnel Requirements	5-10
5.3 TOTAL MAINTENANCE COSTS	5-11
6.0 ASSESSMENT	6-1
6.1 DESIGN FEATURES AFFECTING MAINTENANCE	6-1
6.2 FEATURE COMPARISONS	6-13
6.2.1 Comparison of Concepts Differing in First Wall/ Blanket Module Size	6-17
6.2.2 Normalization of Reactor Size	6-20
6.2.3 Effect of Reactor Size	6-22
6.2.4 Effect of In-Place Maintenance Equipment	6-24
6.2.5 Comparisons of Specific Activities and Subsystem Features	6-26

TABLE CONTENTS (CONTINUED)

	<u>PAGE</u>
6.2.5.1 Accessing The First Wall/Blanket	6-26
6.2.5.2 Location of the Poloidal Field Magnets . . .	6-28
6.2.5.3 General Arrangement of the Diverter System	6-29
6.2.5.4 Primary Vacuum Wall Seal Location	6-31
6.2.5.5 Connections Required For First Wall/ Blanket Replacement	6-32
6.2.6 Impact of Contact Operations	6-34
7.0 CONCLUSIONS	7-1
7.1 OBSERVATIONS	7-1
7.2 INTERPRETATION	7-8
8.0 REFERENCES.	8-1

LIST OF FIGURES

<u>FIGURE</u>		<u>PAGE</u>
2-1	DESIGN APPROACHES INCORPORATE A VARIETY OF DESIGN FEATURE CHARACTERISTICS	2-1
2-2	MODULAR MAINTENANCE PLAN ESTIMATES USED AS BASE FOR SYSTEM ANALYSIS	2-2
2-3	MAINTENANCE CAPITAL COSTS MORE SENSITIVE TO WALL REPLACEMENT FRACTIONS FOR LARGE MODULE SIZE	2-4
2-4	AVAILABILITY IS A FUNCTION OF ACCESS TIME	2-5
2-5	COST OF ELECTRICITY INSENSITIVE TO HIGHER WALL REPLACEMENT FRACTIONS	2-5
2-6	SOME SELECTED MAINTENANCE PLANS USE APPROXIMATELY ONE YEAR INTERVALS.	2-6
2-7	TOKAMAK DESIGN CONCEPTS APPROACH ECONOMIC GOALS	2-8
2-8	DESIGN CONCEPTS HAVE WIDE RANGE OF MAINTENANCE EFFECTS . . .	2-10
3-1	PLAN VIEW OF LARGE MODULE CONCEPT REACTOR BUILDING (UWMAK-I)	3-4
3-2	BASELINE LARGE MODULE CONCEPT (UWMAK-I)	3-5
3-3	ALTERNATE LARGE MODULE CONCEPT (CULHAM MK-II)	3-8
3-4	ALTERNATE LARGE MODULE REMOVAL.	3-9
3-5	PLAN VIEW OF INTERMEDIATE LARGE MODULE CONCEPT REACTOR BUILDING (UWMAK-III)	3-11
3-6	BASELINE INTERMEDIATE MODULE CONCEPT (UWMAK-III).	3-12
3-7	BASELINE INTERMEDIATE MODULE CONCEPT (UWMAK-III).	3-13
3-8	BASELINE SMALL MODULE CONCEPT (GA-DPR).	3-15
3-9	BASELINE SMALL MODULE CONCEPT (GA-DPR).	3-16
3-10	ALTERNATE SMALL MODULE CONCEPT (ORNL CASSETTE).	3-19
3-11	ORNL BLANKET CONCEPT - THE FBZ APPROACH	3-21
4-1	MAINTENANCE EQUIPMENT DESIGN APPROACHES	4-7
4-2	UWMAK-I REACTOR MODULE	4-16
4-3	RME-2 OPERATIONAL MAINTENANCE UNIT	4-21
4-4	LARGE MODULE CONCEPT (UWMAK-I) TASK FLOW BASELINE CONFIGURATION	4-23
4-5	LARGE MODULE CONCEPT (REDUCED SIZE UWMAK-I) TASK FLOW	4-24
4-6	ALTERNATE LARGE MODULE CONCEPT (CULHAM MK-II) TASK FLOW . . .	4-31
4-7	MODULE HANDLING MACHINE CONCEPTUAL CONFIGURATION	4-37
4-8	INTERMEDIATE MODULE CONCEPT (UWMAK-III) TASK FLOW BASELINE CONFIGURATION	4-38

LIST OF FIGURES (CONTINUED)

<u>FIGURE</u>		<u>PAGE</u>
4-9	REMOTE MAINTENANCE MACHINE (RMM)	4-44
4-10	IN-CHAMBER MAINTENANCE MACHINE (ICMM) CONCEPT - SIDE VIEW. .	4-45
4-11	SMALL MODULE CONCEPT (GA-DPR) TASK FLOW BASELINE CONFIGURATION	4-47
4-12	MAINTENANCE EQUIPMENT LOCATION FOR BLANKET MODULE REPLACEMENT.	4-50
4-13	SMALL MODULE CONCEPT (GA-DPR) TASK FLOW BASELINE CONFIGURATION WITH IN-PLACE MAINTENANCE EQUIPMENT	4-52
4-14	ALTERNATE SMALL MODULE CONCEPT TASK FLOW - ORNL CASSETTE CONCEPT.	4-56
4-15	LARGE MODULE CONCEPT (UWMAK-I) TASK FLOW BASELINE CONFIGURATION WITH CONTACT MAINTENANCE	4-61
4-16	INTERMEDIATE MODULE CONCEPT (UWMAK-III) TASK FLOW BASELINE CONFIGURATION WITH CONTACT MAINTENANCE	4-65
4-17	SMALL MODULE CONCEPT (GA-DPR) TASK FLOW BASELINE CONFIGURATION WITH CONTACT MAINTENANCE	4-70
4-18	INTERMEDIATE MODULE CONCEPT (UWMAK-III) TASK FLOW - UNSCHEDULED MAINTENANCE	4-74
5-1	AVAILABILITY EXPERIENCE FOR FISSION POWER REACTORS	5-3
5-2	ECONOMIC COMPARISON OF POWER SOURCES	5-4
5-3	UWMAK-I BASELINE	5-14
5-4	ECONOMIC PARAMETERS FOR INTERMEDIATE MODULE BASELINE - UWMAK-III BASELINE	5-15
5-5	GA-DPR BASELINE	5-17
7-1	IMPACT OF MAINTENANCE CONCEPTS ON THE COST OF ELECTRICITY	7-2
7-2	MAINTENANCE EFFECTS FOR NEAR-MINIMUM COST OF ELECTRICITY REACTORS	7-3
7-3	IMPACT OF REACTOR SIZE ON MAINTENANCE COSTS	7-4
7-4	EFFECT OF MAINTENANCE EQUIPMENT CONCEPT	7-5
7-5	IMPACT OF CONTACT MAINTENANCE.	7-7

LIST OF TABLES

<u>TABLE</u>		<u>PAGE</u>
3-1	SUMMARY OF DESIGN CONCEPTS	3-3
3-2	MODULE PHYSICAL PARAMETERS (BASELINE LARGE MODULE, UWMAK-I)	3-6
3-3	REACTOR DESIGN ASSUMPTIONS (BASELINE LARGE MODULE, UWMAK-I)	3-6
3-4	MODULE PHYSICAL PARAMETERS (ALTERNATE LARGE MODULE, CULHAM Mk II CONCEPT)	3-10
3-5	MODULE PHYSICAL PARAMETERS (BASELINE INTERMEDIATE MODULE, UWMAK-III)	3-14
3-6	ASSUMPTIONS AND ADDITIONAL DESIGN DEFINITIONS (BASELINE INTERMEDIATE MODULE, UWMAK-III)	3-14
3-7	MODULE PHYSICAL PARAMETERS (BASELINE SMALL MODULE, GA-DPR)	3-16
3-8	REACTOR DESIGN ASSUMPTIONS (BASELINE SMALL MODULE, GA-DPR)	3-17
3-9	MODULE PHYSICAL PARAMETERS (ALTERNATE SMALL MODULE, ORNL CASSETTE)	3-20
3-10	REACTOR DESIGN ASSUMPTIONS (ALTERNATE SMALL MODULE)	3-20
4-1	FIRST WALL/BLANKET MAINTENANCE APPROACH SUMMARY	4-4
4-2	MAINTENANCE DOWNTIME REQUIREMENTS	4-9
4-3	UNSCHEDULED MAINTENANCE SCENARIO (PROBLEM STATEMENT)	4-72
4-4	REPAIR OF UNSCHEDULED FIRST WALL COOLANT LEAK (GENERAL GROUND RULES AND ASSUMPTIONS)	4-73
4-5	UNSCHEDULED FIRST WALL/BLANKET TIME COMPARISON (CENTRAL WALL MODULE)	4-76
4-6	REACTOR CONCEPT COMPARISON FOR UNSCHEDULED COOLANT LEAK MAINTENANCE	4-77
4-7	UWMAK-III SUBSYSTEMS (LOCATED WITHIN REACTOR BUILDING)	4-79
4-8	MANIFOLD AND LINE MAINTENANCE REQUIREMENTS	4-82
4-9	SUBSYSTEM MAINTENANCE TIME ESTIMATES (INTERMEDIATE MODULE CONCEPT)	4-85
5-1	FISSION PLANT AVAILABILITY (MEDIUM PLANT)	5-5
5-2	FUSION PLANT AVAILABILITY GOALS	5-5
5-3	FIRST WALL/BLANKET REPLACEMENT SCHEDULE	5-7
5-4	MAINTENANCE EQUIPMENT - BASELINE REACTORS	5-8
5-5	NUMBER OF MAINTENANCE SETS	5-10
5-6	MAINTENANCE PERSONNEL REQUIREMENTS	5-10

LIST OF TABLES (CONTINUED)

<u>TABLE</u>		<u>PAGE</u>
5-7	MAINTENANCE SUMMARY LARGE MODULE CONCEPT - UWMAK-I	5-13
5-8	MAINTENANCE SUMMARY INTERMEDIATE MODULE CONCEPT.	5-15
5-9	MAINTENANCE SUMMARY SMALL MODULE CONCEPT (GA-DPR).	5-16
6-1	FUSION REACTOR DESIGN FEATURE CHARACTERISTICS	6-2
6-2	REACTOR CHARACTERISTICS	6-18
6-3	IMPACT OF REACTOR CONCEPT ON MAINTENANCE OPERATIONS.	6-18
6-4	IMPACT OF REACTOR CONCEPT ON MAINTENANCE COSTS (COST OF ELECTRICITY).	6-19
6-5	NORMALIZED REACTOR CHARACTERISTICS	6-20
6-6	MAINTENANCE OPERATIONS FOR NORMALIZED REACTORS - 5000 MW _{th}	6-21
6-7	PERCENTAGE EFFECT OF MAINTENANCE COST OF ELECTRICITY	6-22
6-8	LARGE AND SMALL REACTOR CHARACTERISTICS (TRAPPED ION MODE CONFINEMENT SCALING)	6-23
6-9	IMPACT OF REACTOR SIZE ON MAINTENANCE OPERATIONS	6-23
6-10	IMPACT OF MAINTENANCE ON THE COST OF ELECTRICITY (LARGE MODULE CONCEPT - UWMAK-I)	6-24
6-11	SMALL MODULE REACTOR BASELINE CHARACTERISTICS	6-24
6-12	IMPACT OF IN-PLACE EQUIPMENT ON MAINTENANCE OPERATIONS	6-25
6-13	IMPACT OF MAINTENANCE ON COST OF ELECTRICITY (SMALL MODULE IN-PLACE EQUIPMENT)	6-26
6-14	ACCESSING AND ASSEMBLY TIMES	6-28
6-15	POLOIDAL COIL RETRACTION AND EXTENSION TIMES	6-29
6-16	DIVERTER MODULE EXCHANGE TIME	6-30
6-17	IMPACT OF VACUUM WALL LOCATION	6-31
6-18	CONNECTION REQUIREMENTS (NOT INCLUDING BLANKET ATTACHMENTS)	6-33
6-19	JOINT LENGTHS WORKED IN MODULE REPLACEMENT	6-34
6-20	BASELINE REACTOR CHARACTERISTICS	6-35
6-21	IMPACT OF HANDS-ON (CONTACT) MAINTENANCE ON MAINTENANCE OPERATIONS	6-36
6-22	MAINTENANCE EFFECTS ON COST OF ELECTRICITY (REMOTE AND CONTACT)	6-37

THIS PAGE IS INTENTIONALLY LEFT BLANK

1.0 INTRODUCTION

The maintainability of a tokamak fusion reactor system is a principal factor in establishing this type of system as an economical source of commercial power. In particular, the feasibility of performing the maintenance tasks and the cost of the facilities, equipment, spares, personnel and the loss of generated power when the system is down, require examination to aid in directing design efforts for the achievement of economically maintainable systems. This study has conducted such an examination emphasizing scheduled maintenance activities of the first wall blanket components. The objectives defined include: (1) the establishment of overall maintainability requirements for selected tokamak designs; (2) identification of desirable maintenance design features, and (3) definition of scheduled maintenance approaches.

Fusion reactor conceptual designs for producing commercially economical power have been developed. These designs vary widely in their maintainability characteristics, all of which affect the downtime required to conduct maintenance and, consequently, the availability of the fusion system and the cost of electricity produced by the system. Some of the principal factors affecting downtime are the capability to access the reactor components, the maintenance equipment and facilities provided, and the environment in which maintenance must be conducted.

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 loading and radiation damage. It therefore requires periodic replacement throughout the life of the reactor. Under these circumstances, the characteristics affecting the maintainability of the first wall and blanket become critically important and must be closely analyzed. These characteristics 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; diverter design features; the geometric proportions of the reactor; and, the location of poloidal field coils.

The primary reactor configuration parameter employed in this study to select concepts for study is the replaceable first wall/blanket module size. Three sizes have been selected. These are:

- o Large - representing complete poloidal sectors of the first wall/blanket and shield,
- o Intermediate -- representing poloidal sectors divided into smaller module components (as many as five, for instance),
- o Small - These module sizes are generally small enough so, when removed, relocation of other external systems is not required.

The selected baseline configurations are UWMAK-I (large module), UWMAK-III (intermediate module) and the General Atomic Demonstration Power Reactor (DPR) as the small module baseline. In addition to the baseline, two alternates have been selected - one large module alternate, the Culham MK II and one small module alternate, the ORNL cassette concept.

In order to prevent misleading comparisons, all of the reactor concepts have been normalized to the same thermal power and to those reactor parameters which result in near-minimum cost of electricity for the thermal power of 5000 MW and for a fluence limit at the first wall of 5 MWyrs/m^2

Remote Operations are employed as the baseline approach but maintenance plans were also developed for contact operations (hands-on) with the three baseline reactor concepts.

The impact of an unscheduled failure has been addressed to a limited degree. The example analyzed was the shut-down due to a coolant leak in a diverter first wall/blanket module of the intermediate module concept. Also, to a limited degree, the impact of other subsystem maintenance was analyzed. In this example, the cryovacuum system of the intermediate module concept is one of the critical subsystems considered in some detail.

In the following study phase, emphasis will be placed on other subsystem maintenance impacts, unscheduled failures, contact operations and the configuring of a preferred maintenance approach.

2.0 SUMMARY

Design features of the reactor concepts defined for tokamak fusion power systems vary significantly in their influence on the maintainability of these systems. This study attempts to unravel some of the effects of the more significant features as an aid to the development of configurations in the future. The study establishes scheduled maintenance plans for five of the more thoroughly documented approaches to commercial tokamak fusion reactor designs and evaluates particular features of these designs, especially the first wall/blanket, for their impact on scheduled reactor maintenance.

2.1 REACTOR DESIGN CONCEPTS - The pertinent design features affecting the maintainability of the five selected design concepts are tabulated in Figure 2-1. Since the first wall/blanket module replacement is apt to dominate scheduled maintenance operations, the concepts are categorized according to large, intermediate and small blanket module sizes.

DESIGN APPROACHES INCORPORATE A VARIETY OF DESIGN FEATURE CHARACTERISTICS

FIRST WALL/BLANKET DESIGN CATEGORY	BASLINE LARGE MODULE	ALTERNATE LARGE MODULE	BASLINE INTERMEDIATE MODULE	BASLINE SMALL MODULE	ALTERNATE SMALL MODULE
SOURCE OF DATA	UWMAK-I	CULHAM Mk II	UWMAK-III	GA-DPR	ORNL-FPD
THERMAL POWER, MW	5000	5000	5000	1764	5000
T.F. MAGNET HEIGHT, m	29.6	27.5	26.5	18.2	26.5
REACTOR RADIUS, m	25.9	16.5	17.7	15.3	17.7
PLASMA CROSS SECTION	CIRCULAR	ELLIPTICAL	ELLIPTICAL	DOUBLET	ELLIPTICAL
NO. OF T.F. MAGNETS	12	12	18	16	18
POLOIDAL FIELD MAGNET LOCATION re TF MAGNET	OUTSIDE	OUTSIDE & INSIDE	INSIDE	INSIDE	INSIDE
AUXILIARY HEATERS	NEUTRAL BEAM INJECTOR	NEUTRAL BEAM INJECTOR	R.F. HEATERS	NEUTRAL BEAM INJECTORS	NEUTRAL BEAM INJECTORS
PRIMARY COOLANT	LITHIUM	HELIUM	LITHIUM	HELIUM	MOLTEN SALT
NO. OF MODULES PER REACTOR	12	12	90	2,000	810
PRIMARY VACUUM WALL LOCATION	FIRST WALL/BLANKET	SHIELD	FIRST WALL/BLANKET	FIRST WALL/BLANKET	REACTOR ROOM
MODULE REMOVAL TECHNIQUE	ENTIRE SECTOR REMOVED WITH TF MAGNET	ENTIRE SECTOR REMOVED WITHOUT TF MAGNET	PARTIAL SECTORS WITHOUT TF MAGNET	SMALL MODULES REMOVED FROM INSIDE THE PLASMA CHAMBER	SMALL MODULES REMOVED FROM OUTSIDE THE PLASMA CHAMBER

Figure 2-1

The baseline concepts are UWMAK-I (large module), UWMAK-III (intermediate module) and GA-DPR (small module). The Culham Mk II alternate design concept is placed in the large first wall/blanket module category since a complete poloidal sector comprises each module. (A sector of each reactor plasma chamber is a division of the toroid bounded by or centered on the

toroidal field magnets.) For the purpose of the study analysis, the Culham Mk II first wall/blanket and shield arrangement is adapted to the UWMAK-I reactor concept to provide a complete definition of the plant.

The ORNL blanket/shield concept is placed in the small module category because the number of modules per reactor is the same order of magnitude as the number required by the GA-DPR concept and the handling characteristics are similar. This blanket concept is adapted into the UWMAK-II system definition for the purposes of scaling and costing by use of the TOCOMO systems analysis code.

2.2 DEVELOPMENT OF MAINTENANCE PLANS - The development of the maintenance plans is based on the premise that all scheduled maintenance occurs during the downtime required for the first wall/blanket replacement. This premise has been tested to some extent by examining the influence of scheduled maintenance for other subsystems in the reactor room.

Maintenance plans have been defined for each concept tabulated in Figure 2-2. These plans, in most cases, involved the following stepwise procedure.

- o Definition of scheduled maintenance functions required to remove and replace a first wall/blanket module (including accessing and reassembly activities).

MODULAR MAINTENANCE PLAN ESTIMATES USED AS BASE FOR SYSTEM ANALYSES

DESIGN APPROACH	MAXIMUM THERMAL POWER MW _{th}	MAINTENANCE APPROACH				
		MAINTENANCE MODE ⁽¹⁾	EQUIPMENT CONCEPT	REPLACEMENT ⁽²⁾ MODULES	TOTAL FRACTIONS	DOWNTIME DAYS ⁽³⁾
UWMAK-I, BASELINE	5000	REMOTE	MOBILE	1 MODULE	.083	154
UWMAK-I, BASELINE	5000	CONTACT				88
UWMAK-I,	3000	REMOTE				135
UWMAK-I, ALT. JOINTS ⁽⁵⁾	5000	REMOTE				126
UWMAK-I, MINIMUM COE ⁽⁵⁾	5000	REMOTE				135
CULHAM Mk II	5000	REMOTE	MOBILE	2 MODULES	.083	47
UWMAK-III, BASELINE ⁽⁴⁾	5000	REMOTE	MOBILE	{ 3 MODULES, 1/2 ISSEC }	.046	65
UWMAK-III, BASELINE ⁽⁴⁾	5000	CONTACT				50
UWMAK-III	5000	UNSCHEDULED	MOBILE	1 MODULE		66
GA-DPR, BASELINE	1764	REMOTE	INSTALLED	125	.063	118
GA-DPR, BASELINE	1764	CONTACT				103
GA-DPR, BASELINE	1764	REMOTE				25
GA-DPR, MINIMUM COE ⁽⁵⁾	5000	REMOTE				25
ORNL CASSETTE	5000	REMOTE	MOBILE	15	.046	53

(1) FULLY REMOTE OR CONTACT WHERE POSSIBLE

(2) EQUIVALENT TO 1 REACTOR SECTOR

(3) BASED ON 24 HOUR DAY WITH 75% UTILIZATION

(4) REPLACE ONLY 5/6 OF MODULE AREA PER SECTOR, INCLUDES INSPECTION IN REACTOR.

(5) COE - COST OF ELECTRICITY

Figure 2-2

- o Definition of maintenance equipment required.
- o Estimation of the time required to perform each maintenance function.
- o Description of equipment utilization and personnel utilization required for the fraction of the first wall/blanket replaced during each outage.
- o Development of time-phased sequence of activities.
- o Determination of total downtime required.

For each of these concepts, a separate maintenance plan is developed for each of six different fractions of first wall/blanket replaced per outage. Each fraction represents a different number of reactor sectors or modules. Each fraction for a given concept also produces a different time between scheduled outages. Other parameters that vary with the replacement fraction are the number of sectors or modules worked simultaneously and the resultant manpower, maintenance equipment and facility requirements. All of these are combined to define capital costs, maintenance operations costs, and availabilities for each maintenance plan. The TOCOMO systems analysis and cost code is used to derive this cost data based upon both the reactor and plant design parameters consistent with the design concept and the maintenance plan data.

The following illustrations show the effects on maintenance capital cost, availability and total cost of electricity of replacing different fractions of the first wall/blanket. Data is shown for each of the five design concepts studied. Each design concept is sized to produce 5000 MW_{th} and to those design parameters which resulted in near-minimum cost of electricity. These parameters include plasma cross-section height/width ratio (h/w), toroidal field strength (B_{max}), and neutron wall loading (P_n). For the GA-DPR concept, the in-place equipment maintenance approach developed in this study results in the lowest cost maintenance plans for the GA-DPR and, therefore, the data for this approach is shown with these comparisons.

Figure 2-3 shows the effect of the first wall/blanket replacement fraction on the maintenance capital cost. This includes the cost of facilities for hot cells, storage and maintenance areas, the cost of maintenance equipment and of initial spares. These costs increase almost linearly as the fraction increases. The lowest rate of increase occurs for the small module concept because very little additional maintenance equipment and personnel and no additional facilities are required when the replacement fraction is increased.

MAINTENANCE CAPITAL COSTS MORE SENSITIVE TO WALL REPLACEMENT FRACTIONS FOR LARGE MODULE SIZES

Figure 2-3

Figure 2-4 illustrates the rapid increase in availability as the replacement fraction is increased up to fractions of one third of the total first wall/blanket. The principal cause of this rapid increase is the decrease in the impact of access time either because of the maintenance of multiple sectors in parallel or, as in the case of the GA-DPR, because access time is the same for any number of modules exchanged. This figure also illustrates the non-linearity of such impacts when the replaced fraction requires a deviation from the equipment utilization due to either space or reactor structural constraints. The discontinuity in the curve for the ORNL and UWMAK-I concepts occurs because the replacement of a fraction of 50% is not practical by replacing all sectors simultaneously as is the case for a fraction of 33%. Therefore, fewer sectors are reworked at a time, resulting in a loss in availability shown.

Figure 2-5 illustrates how the cost of electricity is dominated by the effect of availability. The cost of electricity is rapidly reduced as availability increases until the availability levels off at about a replacement fraction of 0.33. At higher replacement fractions there is little, if any, benefit to the cost of electricity.

Figure 2-4

Figure 2-5

2.3 EVALUATION OF DESIGN FEATURES - The maintenance plans used for comparison of design features are chosen from the comparison analyses shown in Figure 2-5 and the other alternatives defined in Figure 2-2. The selected plan from every analysis is that which exchanges the first wall/blanket fraction at the lowest resultant cost of electricity for the design concept and maintenance approach being considered.

The replacement fraction chosen for each alternative is indicated in Figure 2-6 together with the total maintenance interval as measured from the start of one scheduled shutdown to the start of the next. The majority of the plans achieve the minimum cost of electricity at a replacement fraction of 33 percent with all but two falling between 25 to 50 percent.

Maintenance intervals of one year, including both forced outages as well as scheduled shutdowns, are generally common practice in utilities. Both of these types of outage are included in the maintenance intervals shown in Figure 2-6. The maintenance plans selected for the contact maintenance mode of the UWMAK-III design approach and the remote maintenance modes of the ORNL cassette and Culham Mk II design approaches fall close to the annual outage requirement. However, other plans can be selected to meet this requirement,

Figure 2-6

but these other plans result in a penalty in cost of electricity. For instance, in the case of UWMAK-III baseline the wall fraction which results in minimum cost of electricity is 1.00 and the maintenance interval is about 33 months. In order to reduce the maintenance interval to about 1 year, the wall fraction would have to be about one-third. Referring to the data of Figure 2-5 it can be seen that the cost of electricity would increase from 55 mills/kWhr to 57 mills/kWhr. In the case of the GA-DPR, the cost would change but a small amount.

Power plant availability and the cost of electricity have been defined as criteria for use in evaluating the effects of maintenance on plant performance and economic viability. An availability threshold and a nominal availability of 62 and 72 percent, respectively, are established as guidelines. The threshold is based on an economic analysis which uses probable costs of electricity from system analyses reported in Reference 13 and from data in Reference 12 to define the threshold as the cost of electricity breakeven point of a fusion reactor with a coal-fired base load plant in the year 2000. The cost of electricity in 1977 dollars to produce this tradeoff is 38.9 mills/kWhr. The 72% nominal availability goal is based on acceptable fission power plant performance outage distribution data taken from Reference 11.

With these boundaries, the plot shown in Figure 2-7 indicates that the majority of the cases that have been considered fall between the availability threshold and the nominal availability goal but all are above the cost of electricity breakeven point associated with the threshold goal and an implied annual cost. An analysis of maintenance costs shows that significant reduction in these costs may possibly result in the achievement of the economic goals by some of the design concepts and maintenance plans. An improvement, for instance in availability, of 8 points for the Culham concept would result in achieving the cost of electricity goal (38.9 mills/kWhr). This is based on no increase in unit capital cost.

Figure 2-7 also illustrates some of the variations in design and maintenance concepts that can aid in achieving the goals. Going from the baseline GA-DPR with remote maintenance to the in-place maintenance equipment concept increases the availability by more than 10% and reduces the cost of electricity by approximately 8 mills/kW hr. While contact maintenance improves availability for all baseline plans, the influence on the cost of electricity for first wall/blanket maintenance appears relatively small except

SOME TOKAMAK DESIGN CONCEPTS APPROACH ECONOMIC GOALS

(1) COAL PLANT DATA FROM REFERENCE 12. AND FIGURE 5-2, 1977

13-1229

Figure 2-7

for the UWMAK-I concept. The cost benefit here largely results from both an increase in availability and a reduction in capital costs that occur when the replacement fraction selected for the contact maintenance is 25 percent instead of the 33 percent selected for remote maintenance. Other effects that are shown by the plot include the effect of increasing wall loading on the same size reactor. This is shown by the reduction in availability and cost for the 3413 MW_{th} GA-DPR reactor when compared with the 1764 MW_{th} reactor. Also, reactor size effects are shown by comparing the UWMAK-I 5000 MW_{th} baseline and a smaller 3000 MW_{th} reactor using the same design approach. The impact of varying replacement fractions from 100 percent to 50 percent is shown to reduce availability and increase the cost of electricity for the UWMAK-III concept.

In view of the potential improvement in the design and maintenance plans for the various approaches, a group of candidates appear to merit more consideration, based on the data of Figure 2-7. These include the Culham Mk II, the ORNL, the GA-DPR with in-place maintenance equipment, and the UWMAK-III. Contact maintenance also merits further consideration for the Culham and ORNL concepts and for unscheduled maintenance tasks (all concepts).

A review of the maintenance effects on the cost of electricity and a comparison of these costs is used to establish the desirability of several design features. Figure 2-8 shows the percentage effect of maintenance on the cost of electricity (maintenance efficiency) for the maintenance plans derived in the study. These data include the effect of maintenance capital costs, the maintenance operating costs and of availability. The range of cost impacts of these maintenance effects varies widely, but a relatively low cost maintenance plan is found in all module size ranges. From a comparison of these data some tentative conclusions regarding the module size, reactor size, contact maintenance and maintenance equipment are defined.

2.4 CONCLUSIONS - Based on the comparison of the selected maintenance plans, the supporting time estimates and the design definitions, it is possible to present some summary conclusions. For many of the design and maintenance features compared, only trends are indicated since many of the conclusions eventually may be modified by including the effects of maintenance of other subsystems and unscheduled maintenance. However, the results as they presently appear are listed.

DESIGN CONCEPTS HAVE WIDE RANGE OF MAINTENANCE EFFECTS

13-1182

Figure 2-8

- o Maintenance effects expressed as a percentage of the cost of electricity range from 16 to 50 percent for the selected five design concepts before normalizing to common capabilities. When the concepts are normalized for power, confinement physics and minimum cost of electricity (COE) the range is 20 to 77 percent. Four of the normalized concepts have cost percentages between 20 and 31 percent.
- o The four design concepts with low maintenance cost percentages of COE are the Culham Mk II, UWMAK-III, ORNL and GA-DPR (with in-place equipment). A clear trend of module size advantage is not evident for scheduled maintenance operations.
- o The range of availabilities for all design and maintenance concepts is 54 to 76 percent. One concept of each of three module size categories

is equal to or above the 72 percent goal - see Figure 2-7.

- o Maintenance downtime contributes 37 to 80 percent of the maintenance impact on COE. The least effect of downtime was observed in the Culham Mk II concept.
- o Maintenance costs as a percentage of COE average:
 - o Operating costs - 5.2 percent
 - o Capital costs - 7.2 percent
 - o Facilities - 1.6 percent
 - o Capital Equipment Costs - 3.6 percent
 - o Initial Spares - 2.0 percent

The UWMAK-I concept has the largest capital cost percentage (12.3%) and the largest maintenance operations cost percentage (7.7%).

- o Reduction in the UWMAK-I size from 5000 to 3000 MW_{th} reduces maintenance cost percentage of the COE by 21%.
- o The in-place maintenance equipment concept for GA-DPR increases availability 17 percent and decreases maintenance cost impacts on the COE by 59.9 percent to 30.9 percent of the COE. Additional maintenance equipment capability is the largest contributor to this reduction. Therefore, much of this benefit may be achievable by installing the same equipment at the start of the shutdown instead of leaving it in-place during reactor operation.
- o Increasing the module size from the GA-DPR to the ORNL design concept appears to be the major factor in a 37 percent reduction of maintenance effects on COE. Other contributors are removal from outside of the reactor and a bolted instead of welded module connection. The total first wall/blanket for the larger small module (ORNL) concept requires replacement of 270 modules compared to 2000 for the smaller module (GA-DPR) concept.
- o Access through the vacuum wall when the vacuum seal is outside of the shield (Culham Mk II) requires only 19.7 percent of the time for access through the vacuum wall when it is located at the first wall/blanket (UWMAK-I). The seal length for the Culham Mk-II is 42 percent of the length for the UWMAK-I. The time difference is a function of ease of access as well as of seal length.
- o Poloidal diverter modules extend the time to exchange modules from approximately 9 to 29 percent of the replacement time, exclusive of

access and reassembly. The larger effect occurs in the large module concepts where the diverters are a smaller part of the total first wall/blanket.

- o Contact operations reduced the downtime effects on the COE by 37.5 percent in the large module concept and only 8.5 percent and 7.5 percent for the intermediate and small module concepts, respectively, because the percentage of total downtime where contact operations are possible is much greater for the large module concepts than for smaller module concepts.
- o Unscheduled maintenance for a coolant leak in the first wall of the intermediate module can require as much time to replace the faulty module as a scheduled shutdown requires to replace the entire sector. Small modules appear to have an advantage in unscheduled operations due to low access time requirements; however, a valid leak isolation system must be devised to realize this advantage.

3.0 SYSTEM DESCRIPTIONS

The maintenance analysis discussed in this report is conducted for three baseline fusion reactor power system conceptual designs. These three baseline concepts are the UWMAK-I, the UWMAK-III and the General Atomic Demonstration Power Reactor (GA-DPR). The basis for selection of these three concepts is that each of them represents a different approach to the design of the first wall/blanket. The different first wall/blanket approaches are desired as the basis for the analysis because this subsystem appears to impose a major maintenance effort on the tokamak type of fusion reactor as a result of its acknowledged design life limitations. The limited life requires periodic replacement of the first wall/blanket and the apparent magnitude of this task makes the first wall/blanket the most likely subsystem for driving any maintenance analysis. The selection of the three reactor concepts seems appropriate for identifying design features that are beneficial in obtaining a high degree of maintainability.

The principal feature that differentiates the three concepts is that of the size of the replaceable first wall/blanket module. The large module size is represented by the UWMAK-I concept. In this concept the number of replaceable modules is determined by the number of toroidal field magnets employed in the design. Since twelve toroidal field magnets are used, twelve modules are required to make up the total reactor first wall/blanket. Each module is a complete radial sector of the plasma chamber and each module includes one of the toroidal field magnets. The intermediate module size is represented by UWMAK-III. This design employs eighteen radial sectors to make up the plasma chamber. Each sector is divided into an outer wall with three modules, two central wall modules comprising the diverter region, and ISSEC (Internal Spectral Shifter and Energy Converter) panels comprising the inner wall region. The small module baseline is represented by the GA-DPR. This concept consists of sixteen toroidal field magnets, but in this case, the magnets and their location do not form boundaries for defining module size. Rather the modules are of the canister type and their diameter is determined by the size of the vacuum ports through which they must pass when removed from the plasma chamber structural shell. Other features that vary between the concepts are the poloidal field magnet location, the coolant type and the techniques employed to access the module.

In the course of the study, two alternative design concepts have been added to the three baselines. These are the Culham Mark II first wall/blanket/shield concept and the ORNL cassette concept. The Culham Mk II properly belongs to the large module concept since an entire radial sector of the first wall/blanket/shield constitutes the major replaceable module. The ORNL cassette approach has been placed in the small module category because the entire reactor is made up of 810 modules. Of these, 270 are exposed directly to the plasma.

Since the first wall/blanket is the principal reactor subsystem to be investigated in this study, the system descriptions that are provided in the balance of this section, are concerned primarily with the relationship of the first wall/blanket to the other elements of the reactor. Other subsystems are important, of course, but in this phase of study they are considered primarily in the context of what interference they offer in accessing the first wall/blanket modules. In one case, that of the cryovacuum pumps and the particle collector assemblies for UWMAK-III, specific replacement activities have been considered.

In making comparisons on the basis of either maintenance costs or on the basis of time to perform maintenance functions, it is desirable to size all concepts to the same set of requirements. This characteristic, of course, is not satisfied by the design definitions as originally conceived. For instance, the GA-DPR has a thermal power of 1764 MW_{th} whereas the UWMAK-III and UWMAK-I are 5000 MW_{th} machines. It is also desired, as established in Section 5.1.1, that they employ performance and design parameters which result in the minimum cost of electricity for a particular design approach. Hence each of the baselines has been reconfigured, where required, to produce both 5000 MW_{th} and to attain near-minimum cost of electricity. This is accomplished through the use of the McDonnell Douglas systems analysis computer code, TOCOMO. Because of the system design options available in the code (UWMAK-I, UWMAK-III and the GA-DPR), the Culham Mk II first wall/blanket design approach has been incorporated into a UWMAK-I type of reactor design and ORNL cassette blanket design approach has been incorporated into a UWMAK-III reactor configuration.

The level of design detail is sometimes not sufficient in the original design concept to permit maintenance equipment definitions or to make time estimates to the desired level of activity; consequently, this detail has

been developed in the study or certain clarifying assumptions have been made. In either case, these are stated in each system description presented in the following subsections.

3.1 SUMMARY OF DESIGN CONCEPTS - The major characteristics of the reactor concepts are summarized in Table 3-1. Both the baseline and alternate concepts are shown. In addition, the characteristics of the UWMAK-I and the GA-DPR after adjustment for thermal power and near-optimum cost of electricity are shown. After this adjustment, the neutron wall loading varies from 2.0 to 2.5 MW/m² among the concepts. Total beta varies between 8 and 16%.

TABLE 3-1
SUMMARY OF DESIGN CONCEPTS

CONCEPTS	LARGE			INTERMEDIATE	SMALL		
	UWMAK-I ORIGINAL	UWMAK-I MIN COE (1)	CULHAM MIN COE (1)	UWMAK-III MIN COE (1)	GA-DPR ORIGINAL	GA-DPR (2)	ORNL
THERMAL POWER, MW _{th}	5000	5000	5000	5000	1764	5000	5000
WALL LOADING, MW/m ²	1.24	1.97	2.18	2.50	1.01	2.31	2.50
BETA (TOTAL) %	6.2	8.9	15.4	8.4	10.9	14.6	8.4
PLASMA h/w	1.0	2.0	2.0	2.0	3.0	3.0	2.0
MAJOR RADIUS, m	13.0	9.4	7.8	8.1	7.0	7.2	8.1
PLASMA MINOR, m	5.0	2.8	3.0	2.7	1.8	2.2	2.7
NO. OF TF MAGNETS	12	12	12	18	16	16	18
MODULES PER REACTOR	12	12	12	90	2000	2000	810
PRIMARY COOLANT	LITHIUM	LITHIUM	HELIUM	LITHIUM	HELIUM	HELIUM	SALT
MODULE REMOVAL TECHNIQUE	ENTIRE SECTOR REMOVED WITH TF MAGNET	ENTIRE SECTOR REMOVED WITH TF MAGNET	ENTIRE SECTOR REMOVED W/O TF MAGNET	PARTIAL SECTORS W/O TF MAGNET	SMALL CAN-ISTERS REMOVED FROM INSIDE CHAMBER	SMALL CAN-ISTERS REMOVED FROM INSIDE CHAMBER	CASSETTE MODULES REMOVED FROM EXTERNAL SIDE
PRIMARY VACUUM WALL LOCATION	BACK OF BLANKET	BACK OF BLANKET	OUTER SHIELD	BACK OF BLANKET	BACK OF BLANKET	BACK OF BLANKET	REACTOR ROOM WALL
PLASMA HEATING	NEUTRAL BEAMS	NEUTRAL BEAMS	NEUTRAL BEAMS	R.F.	NEUTRAL BEAMS	NEUTRAL BEAMS	NEUTRAL BEAMS

(1) COST OF ELECTRICITY (COE)

(2) REVISED SIZE FOR APPROXIMATE MINIMUM COE AND USED COMMON CONFINEMENT LAW (TRAPPED ION MODE -TIM)

3.2 BASELINE LARGE MODULE - The baseline large module reactor is based on the UWMAK-I as defined by the University of Wisconsin. Extensive data on the physics and operational characteristics of this reactor are presented in Reference 1.

A plan view of the plant layout is shown in Figure 3-1. The reactor is surrounded by a reactor room which contains the neutral beam injectors and provides maintenance access to the reactor. The cylindrical reactor room wall contains one or more access hatches and rotates to provide access to selected reactor sectors. Surrounding the reactor room is the reactor building. The reactor hall is the connecting passage between the reactor room and the storage and maintenance areas. Figure 3-1 shows three maintenance hot cells. More may be provided, depending on the maintenance plan used.

**PLAN VIEW OF LARGE MODULE CONCEPT REACTOR BUILDING
(UWMAK-I)**

Figure 3-1

The reactor toroid is divided into twelve radial sectors, equal to the number of toroidal field magnets. All poloidal field magnets are located outside of the toroidal field magnets. All magnets are superconducting.

The UWMAK-I reactor cross section is shown in Figure 3-2. The plasma cross section is circular with a major radius of 13 meters. The first wall/blanket material is 316 stainless steel and the primary coolant is lithium.

The lithium also serves as a breeding material for tritium. Neutral beam injectors are used for auxiliary heating of the plasma.

13-716

Figure 3-2

The basic maintenance technique for replacement of the first wall/blanket is to remove and replace entire reactor sectors as shown in Figure 3-2. Each is accompanied by a toroidal field magnet. The poloidal field magnets are raised/lowered to provide clearance for radial translation of the sectors from the reactor core. Characteristic physical parameters of the removable module are shown in Table 3-2. The maintenance plan for replacement of the first wall/blanket is presented in more detail in Section 4.2.1.1.

The UWMAK-I design as defined in Reference 1 is used in this analysis with as little revision as possible. However, in some areas discrete details are not available. Consequently, certain assumptions concerning the physical make-up and configuration of the reactor have to be made in order to conduct a maintenance analysis. Table 3-3 is a generalized list of the primary assumptions made. Additional detail assumptions concerning particular sub-systems and design features are presented in Appendix F, Section 1.0 and in conjunction with the time estimates in Section 1.0 of Appendix A.

TABLE 3-2
MODULE PHYSICAL PARAMETERS (BASELINE LARGE MODULE, UWMAK-I)

o MODULE WEIGHT	- 3500 TONNES
o MODULE SIZE	- ≈26m X 18m X 12m
o MAJOR COMPONENTS INCLUDED IN MODULE	- o FIRST WALL/BLANKET o SHIELD o T.F. MAGNET o DIVERTERS o MANIFOLDING o MODULE SUPPORT STRUCTURE o NEUTRAL BEAM INJECTOR INTERFACE o VACUUM SYSTEM INTERFACE
o FIRST WALL MATERIAL	- 316 STAINLESS STEEL
o FIRST WALL COOLANT	- LITHIUM
o FIRST WALL CONFIGURATION	- U-BEND
o SHIELD COOLANT	- GASEOUS HELIUM
o VACUUM JOINT CONFIGURATION	- CLAMPED/BOLTED MECHANICAL JOINT AT FIRST WALL

TABLE 3-3
REACTOR DESIGN ASSUMPTIONS (BASELINE LARGE MODULE, UWMAK-I)

o USE 20 NEUTRAL BEAM INJECTORS SIMILAR IN SIZE AND SHAPE TO THE ARGONNE NATIONAL LABORATORY EXPERIMENTAL POWER REACTOR DESIGN.
o THE REACTOR ROOM INSIDE DIAMETER IS INCREASED TO 77 m TO ACCOMMODATE THE NEUTRAL BEAM INJECTORS.
o THE REACTOR ROOM WALL CAN ACCOMMODATE UP TO FOUR HATCHES.
o AN OVERHEAD CRANE IS AVAILABLE ONLY IN THE REACTOR HALL.
o LITHIUM COOLANT LINE JOINTS ARE WELDED. ALL OTHER LINES ARE CONNECTED MECHANICALLY.
o THE VACUUM PUMPS ARE LOCATED OUTSIDE OF THE REACTOR ROOM.
o REACTOR PLUMBING SYSTEMS ARE REARRANGED FOR EASE OF ACCESS TO THE CONNECTIONS AND EASE OF SEPARATION AT EACH SECTOR.
o EACH PAIR OF TOROIDAL FIELD MAGNETS ARE CONNECTED BY 12 CROSS BRACE SUPPORTS.
o THE SHIELD STRIP OVER EACH BLANKET JOINT IS SEGMENTED INTO 12 SECTIONS FOR EASE OF REMOVAL.
o THE BLANKET JOINT/YOKE CONFIGURATION IS MODIFIED FOR DISCONNECTING REMOTELY.

3.3 ALTERNATE LARGE MODULE - The alternate large module reactor is based on the Mk II design approach developed by the Culham Laboratory.

The Culham Mk II approach is presented in References 2 and 3. Design information is not available in as much detail as for the UWMAK-I, UWMAK-III, and GA-DPR. Therefore, as used in this study, the Culham Mk II first wall/blanket approach is adapted to a modified UWMAK-I reactor. This study approach is used to permit scaling the concept and developing the data necessary for maintenance comparisons described in Section 5.0.

The basic configuration of the reactor building, magnets, and neutral beam injectors remain the same as for the UWMAK-I although their size and arrangement is changed slightly as a result of the modifications made to the UWMAK-I reactor. Figure 3-1 shows the principal features of this arrangement.

A cross section of the adaptation of the Culham Mk II concept to the UWMAK-I is shown in Figure 3-3. The resulting configuration is used to evaluate maintenance features, however, considerable additional analysis must be conducted before considering the configuration to be viable as an operating reactor. Figure 3-4 illustrates the major difference between the UWMAK-I and the Culham Mk II module concept. In this figure the access panel and shield door are between the toroidal field magnets. The reactor module and the toroidal field magnet bore is sized to provide space for the reactor module between the toroidal field magnets during replacement operations. The magnets remain in place during these operations.

The UWMAK-I reactor is used to provide some degree of similarity between the alternate and baseline design for comparison purposes. However, the UWMAK-I concept, to which the Culham first wall/blanket design is adapted, is modified to a higher plasma height to width ratio to make it more compatible with the Culham type design. The characteristics used for the modified UWMAK-I are developed by using the TOKOMO reactor sizing program (Reference 7) which defines the minimum cost of electricity for a 5000 MW reactor at an eccentricity of approximately 2.0. This eccentricity is also close to the eccentricity of 1.75 as used in Reference 2 for the Culham Mk II design.

The assumption is made that one single null poloidal diverter is used as defined in Reference 3 and shown in Figure 3-3. Lateral support panels are installed between adjacent toroidal field magnets but are not vacuum tight. The primary vacuum chamber is formed by the outer shield and the

ALTERNATE LARGE MODULE CONCEPT (CULHAM MK II)

Figure 3-3

ALTERNATE LARGE MODULE REMOVAL

13-1180

Figure 3-4

secondary vacuum chamber by the reactor room as in the UWMAK-I. The Culham reference indicates that the primary coolant is helium. Tritium breeding is accomplished by circulating lithium slowly through the first wall/blanket. Details of the Culham Mk II first wall/blanket construction, flow paths and manifolding are not available. Therefore, the assumption is made that each sector of the first wall/blanket is supplied by helium coolant through one supply and one return line located on the lower portion of the reactor. Also, as indicated in Reference 2, lithium is supplied to each module by one relatively small supply line and it returns to the tritium reclamation system through one return line.

The basic scheduled maintenance technique is to remove an entire sector module as one unit from between the toroidal field magnets of any one sector. This is similar to the baseline large module concept, however, the toroidal field magnet is not removed with the module and only a large door in the outer shield and a lateral shear panel between toroidal field magnets is removed. Figure 3-4 shows how the module and T.F. magnets are sized to permit the module to move between the magnets. The small diverter module shown in Figure 3-3 must also be removed as a separate unit. Characteristic physical parameters of the removable module are shown in Table 3-4. The maintenance plan for replacement of the first wall/blanket is presented in more detail in Section 4.2.1.2.

TABLE 3-4
MODULE PHYSICAL PARAMETERS (ALTERNATE LARGE MODULE, CULHAM MK II CONCEPT)

o MODULE WEIGHT	-	~800 TONNES
o MODULE SIZE	-	~16m X 10m X 6m
o FIRST WALL MATERIAL	-	316 STAINLESS STEEL
o FIRST WALL COOLANT	-	GASEOUS HELIUM
o MAJOR COMPONENTS INCLUDED IN MODULE	-	<ul style="list-style-type: none"> o FIRST WALL/BLANKET o INNER SHIELD o MANIFOLDS o MODULE SUPPORT STRUCTURE o NEUTRAL BEAM INJECTOR INTERFACE
o VACUUM JOINT CONFIGURATION	-	BOLTED MECHANICAL JOINT AT OUTER SHIELD
o FIRST WALL CONFIGURATION	-	NOT DEFINED

3.4 BASELINE INTERMEDIATE MODULE - The baseline intermediate module is the UWMAK-III reactor concept as defined by the University of Wisconsin. A detailed description of this reactor design and data on the physics and operational characteristics is presented in Reference 4.

A plan view showing the plant layout is shown in Figure 3-5. The reactor is surrounded by a reactor room with sufficient area for access to the reactor by maintenance equipment. An overhead bridge crane, supported by the central reactor core column and the reactor room wall is capable of moving around the reactor room to aid in the maintenance operations. The hot cells, maintenance areas, storage areas, etc., are located around the outside of the reactor room.

PLAN VIEW OF INTERMEDIATE LARGE MODULE CONCEPT REACTOR BUILDING (UWMAK-III)

13-976

Figure 3-5

The UWMAK-III cross section is shown in Figure 3-6. This reactor is designed to generate a maximum of 5000 MW of thermal power with a net electrical output of 1899 MW. It has a noncircular plasma cross section with a major radius of 8.1 meters and a plasma height to width ratio of two. The first wall/blanket material is a refractory metal alloy, TZM, and the primary coolant is lithium. The lithium also serves as a breeding material for tritium. Twelve RF heaters are used for auxiliary heating of the plasma.

The reactor toroid is divided into eighteen radial sectors, equal to the number of toroidal field magnets. Poloidal field magnets are located both on the inside and outside of the toroidal field magnets. All magnets are superconducting.

In the maintenance concept for this reactor, modules comprising the outer wall, diverter, and graphite ISSEC panels for the inner wall are

BASELINE INTERMEDIATE MODULE CONCEPT (UWMAK-III)

13-709

Figure 3-6

replaced (Figure 3-7). One outer wall sector consists of three modules. An "A" module is centered on the equatorial plane of the outer wall. The "B" modules are located immediately above and below the "A" modules. In addition, diverter (central wall) modules are located in the island region of the diverter between the two diverter passages. Characteristic physical parameters of these modules are shown in Table 3-5. Each of the eighteen sectors contains one "A" module, two each of the "B" modules and diverter modules, and several ISSEC graphite panels. Replacement of modules is accomplished by removal of an "A" module from outside of the toroid and then removing "B" modules, diverter modules, and ISSEC panels from inside the toroid through the "A" module opening. A more detailed maintenance plan for replacement of the first wall/blanket is presented in Section 4.2.1.3.

**BASELINE INTERMEDIATE MODULE CONCEPT
(UWMK-III)**

Figure 3-7

TABLE 3-5

MODULE PHYSICAL PARAMETERS (BASELINE INTERMEDIATE MODULE, UWMAK-III)

o MODULE WEIGHT	-	o "A" MODULE - 50 TONNES o "B" MODULE - 8 TONNES o DIVERTER MODULE - 8 TONNES
o FIRST WALL MATERIAL	-	TZM
o FIRST WALL COOLANT	-	LITHIUM
o FIRST WALL CONFIGURATION	-	U-BEND
o VACUUM JOINT CONFIGURATION	-	WELDED

The UWMAK-III design as defined in Reference 4 is used in this analysis with as little revision as possible. However, in some areas discrete details are not available. Consequently, certain assumptions concerning the physical make-up and configuration of the reactor had to be made in order to conduct a maintenance analysis. Table 3-6 is a generalized list of the primary assumptions made. Additional detail assumptions concerning particular sub-systems and design features are presented in Appendix F, Section 2.0, and in Appendix B, Section 1.0, in conjunction with the time estimates.

TABLE 3-6

ASSUMPTIONS AND ADDITIONAL DESIGN DEFINITIONS
(BASELINE INTERMEDIATE MODULE, UWMAK-III)

- o 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.
- o "B" MODULES ARE BOLTED TO THE SHIELD STRUCTURE WITH A WELDED VACUUM SEAL BETWEEN MODULES.
- o GRAPHITE BLOCKS PROTECT THE STRUCTURAL ATTACHMENTS IN THE SPACE BETWEEN ADJACENT "B" MODULES.
- o THE CARBON CURTAIN IS ATTACHED TO THE OUTER WALL IN REMOVABLE SECTIONS.
- o THE ISSEC IS DIVIDED INTO 6 SEGMENTS PER REACTOR SECTOR.
- o THE RF SYSTEM CAN BE RELOCATED TO THE LOWER PORTION OF THE REACTOR WITH THE RF ROOM EXTERIOR TO THE REACTOR ROOM.
- o THE ARRANGEMENT OF COOLANT MANIFOLDS IS DEFINED TO PERMIT SPECIFICATION OF THE MAINTENANCE ACTIVITY.
- o THE LITHIUM COOLANT MANIFOLD LINE JOINTS ARE MECHANICALLY DISCONNECTED (NOT WELDED).
- o ALL MANIFOLDING AND ELECTRICAL LEADS ARE AT ONE RADIAL LOCATION TO MINIMIZE INTERFERENCE WITH MOVEMENT OF THE CRANE.

3.5 BASELINE SMALL MODULE - The small module baseline is the General Atomic Demonstration Power Reactor (GA-DPR) conceptual design. Extensive data on the physics and operational characteristics of this reactor is presented in Reference 5. Other data from Reference 8 is used to augment this concept when necessary.

The plant layout surrounding the reactor is assumed to be similar to that of the UWMAK-III reactor as shown in Figure 3-5 with a circular reactor room surrounding the reactor and an overhead crane provided to assist in maintenance operations. Sufficient area is provided in the reactor room for access to the reactor and movement of all equipment and reactor components.

The GA-DPR reactor cross section is shown in Figure 3-8. The plasma cross section is a noncircular doublet configuration with a major radius of 7 meters and a plasma height to width ratio of three. The first wall/blanket material is primarily Inconel 718 with gaseous helium as the primary loop coolant fluid. Solid lithium compounds in the blanket modules are used for breeding tritium. Neutral beam injectors are used for auxiliary heating of the plasma.

Figure 3-8

The first wall/blanket consists of 2000 cylindrical modules mounted on the inside of the inner shield. These modules are removable from inside the plasma chamber for replacement of the first wall blanket as shown in Figure 3-9. The modules are 0.7 meter in diameter. The principal first wall material for the module is Inconel 718, however, a circular silicon carbide plate is attached to the plasma side of each module by a single fastener. This plate is cooled only by radiation. Characteristic physical parameters of the module are shown in Table 3-7.

BASELINE SMALL MODULE CONCEPT (GA-DPR)

Figure 3-9

TABLE 3-7

MODULE PHYSICAL PARAMETERS (BASELINE SMALL MODULE, GA-DPR)

o MODULE WEIGHT	- 380 kg
o MODULE SIZE	- .7 m DIAMETER X .36 m
o FIRST WALL MATERIAL	- INCONEL 718/SILICON CARBIDE
o FIRST WALL COOLANT	- GASEOUS HELIUM
o VACUUM JOINT CONFIGURATION	- CLAMPED WITH WELDED SEAL

The basic scheduled maintenance technique is to gain access to the inside of the plasma chamber through the vacuum ports at the top of the plasma chamber. Maintenance devices are installed both on and inside the plasma chamber to remotely accomplish module replacement. A more detailed maintenance plan for replacement of the first wall/blanket modules is presented in Section 4.2.1.4.

The GA-DPR design as described in Reference 5 is used in this analysis with as little revision as possible. However, in some areas details are not available. Consequently, certain assumptions concerning the physical make-up and configuration of the reactor have to be made. An additional study of a similar concept for an Experimental Power Reactor prepared by the General Atomic Company for the Electric Power Research Institute (Reference 8) is used to amplify Reference 5 data where appropriate. A generalized list of primary assumptions is presented in Table 3-8. Additional detail assumptions concerning particular subsystems are presented in Appendix F, Section 3.0, and Appendix C, Section 1.0, in conjunction with the time estimates.

TABLE 3-8

REACTOR DESIGN ASSUMPTIONS (BASELINE SMALL MODULE, GA-DPR)

- o REACTOR SUPPORT STRUCTURE DOES NOT INTERFERE WITH MAINTENANCE.
- o A METHOD OF SHUTTING OFF HELIUM FLOW TO APPROPRIATE GROUPS OF MODULES IS POSSIBLE.
- o THE NEUTRAL BEAM INJECTOR SYSTEM WILL NOT INTERFERE WITH FIRST WALL/BLANKET MAINTENANCE.
- o THE REMOVAL OF VACUUM PUMPS IS NOT REQUIRED FOR FIRST WALL/BLANKET MAINTENANCE.
- o REACTOR SUPPORT STRUCTURE WILL CARRY MAINTENANCE EQUIPMENT LOADS.
- o TWO OVERHEAD POLAR BRIDGES ARE AVAILABLE, ONE FOR CRANES, ONE FOR MANIPULATORS.

3.6 ALTERNATE SMALL MODULE - The alternate small module reactor is based on a first wall/blanket concept developed by the Oak Ridge National Laboratory (ORNL). This first wall/blanket concept, Reference 6, is adapted to the UWMAK-III reactor design. A cross section of this adaptation is shown in Figure 3-10. The resulting configuration is used to evaluate maintenance features. Considerable additional analysis must be conducted before considering the configuration to be viable as an operating reactor. The ORNL concept is adapted to the UWMAK-III so that some similarity to the UWMAK-III

exists for comparison. Also, the scaling and costing codes are available for UWMAK-III which permit simulated costs and scale normalization to be employed for comparison purposes. In adapting the ORNL concept, the ORNL cassette design is arranged to encompass the UWMAK-III plasma shape and size. The poloidal field and diverter magnets are retained in approximately the same general configuration as for the UWMAK-III but they are moved slightly to adapt to the ORNL type first wall/blanket.

The basic concept of the ORNL cassette design is retained but is modified as necessary to conform to the UWMAK-III requirements. One modification is the assumption that diverters are incorporated of the same type as those used in UWMAK-III instead of the bundle diverters. This assumption is made to bring the concept into agreement with the UWMAK-III cost code. The arrangement of the interlocking cassette region sequence has been rearranged as shown in Figure 3-10. However, this has no effect on the manner in which the reactor operates.

A major deviation from the UWMAK-III design is the location of the primary vacuum wall. It is assumed in this concept that the entire reactor room acts as a vacuum chamber. The vacuum barrier at the first/wall blanket is a high impedance connection to separate the plasma chamber from the reactor room. At the pressure levels used, this type of barrier is designed to restrict the flow and permit the plasma chamber vacuum to be maintained at the desired level during operation.

The basic approach to scheduled replacement of the first wall/blanket is to remove cassettes one at a time as depicted in Figure 3-11. A detailed maintenance plan for cassette removal/replacement is presented in Section 4.2.1.6. Characteristic physical parameters of the cassette modules are shown in Table 3-9. A tabulation of primary groundrules and assumptions is shown in Table 3-10. One of the assumptions requires a design deviation from the original concept as it is shown in Figure 3-11. The original ORNL concept results in the removal of one group of cassettes being blocked by another group which must be removed first. For this study, the installation of the blocked group of cassettes is made in the outer wall of the plasma chamber as shown in Figure 3-10 instead of on the floor as shown in Figure 3-11. This change is made to ease the requirements on maintenance equipment and operations by:

- o providing room for exit without any cassettes being moved downward toward the lower diverter, and

ALTERNATE SMALL MODULE CONCEPT (ORNL CASSETTE)

Figure 3-10

- o increasing the efficiency of the operation since the outer cassettes are most likely to be replaced in pairs because they have the same wall loading conditions.

Further detailed assumptions are included with the time estimates in Appendix D, Section 2.0.

TABLE 3-9

MODULE PHYSICAL PARAMETERS (ALTERNATE SMALL MODULE, ORNL CASSETTE)

o MODULE WEIGHT	- 5 TONNES ("A" CASSETTE) 5 TONNES ("B" CASSETTE) 3 TONNES ("C" CASSETTE) 3 TONNES ("D" CASSETTE)
o MODULE SIZE	- 10 m X 1.5 m X .33 m ("A" CASSETTE) 8 m X 1.5 m X .33 m ("B" CASSETTE) 7 m X 1.0 m X .33 m ("C" CASSETTE) 16 m X .7 m X .33 m ("D" CASSETTE)
o FIRST WALL MATERIAL	- STAINLESS STEEL
o FIRST WALL COOLANT	- NITRATE-NITRITE SALT
o FIRST WALL CONFIGURATION	- CASSETTES (SEE REFERENCE 6)
o VACUUM JOINT LOCATION	- REACTOR ROOM WALL

TABLE 3-10

REACTOR DESIGN ASSUMPTIONS (ALTERNATE SMALL MODULE)

- o ENTIRE REACTOR BUILDING IS EVACUATED AS DISCUSSED IN REFERENCE 6. THE FIRST WALL/BLANKET IS NOT A VACUUM SEAL BUT A HIGH IMPEDANCE BARRIER ONLY.
- o DIVERTERS AND VACUUM PUMPS LIKE THOSE USED ON THE UWMAK-III ARE INCORPORATED INTO THE FIRST WALL/BLANKET DESIGN. (DIVERter SLOTS REQUIRED IN CASSETTES.)
- o LATERAL SUPPORT PANELS BETWEEN THE TOROIDAL FIELD COILS ARE REQUIRED FOR STRUCTURAL SUPPORT BUT NOT AS A VACUUM BARRIER. PERMANENT OPENINGS ARE PROVIDED IN SUPPORT PANELS TO ALLOW REMOVAL OF CASSETTES.
- o A FIRST WALL/BLANKET 1.0 METER THICK PLUS SHIELDING IS REQUIRED AT ALL POINTS SURROUNDING THE PLASMA. THE PLASMA MAJOR RADIUS IS INCREASED FROM THAT OF THE UWMAK-III DUE TO ADDED FIRST WALL THICKNESS AT THE INNER WALL REGION. THE PLASMA CROSS SECTION OF UWMAK-III IS RETAINED.
- o AUXILIARY PLASMA HEATING IS BY NEUTRAL BEAM INJECTORS.
- o EACH CASSETTE HAS FOUR CONNECTIONS:
 - o COOLANT SUPPLY AND RETURN (SALT).
 - o TRITIUM RECOVERY SUPPLY AND RETURN.
- o POLOIDAL COILS ARE RELOCATED SLIGHTLY TO ALLOW REMOVAL OF CASSETTES WITHOUT MOVING POLOIDAL COILS.

ORNL BLANKET CONCEPT THE FBZ APPROACH

THIS FIGURE ILLUSTRATES THE REMOVAL OF CASSETTES THAT HAVE BEEN DAMAGED DUE TO RADIATION. THEY ARE IN THE FBZ. WITH THIS ARRANGEMENT THERE WOULD BE A FIVE-STEP SEQUENCE TO REMOVE THE MIDDLE CASSETTES. THE OUTER CASSETTES ARE THEN MOVED TO THE FREE SPACE AND THE SEQUENCE REPEATED.

13-717

Figure 3-11

4.0 MAINTENANCE PLAN DESCRIPTIONS

Maintenance plans that have been developed consider primarily the scheduled maintenance of the first wall/blanket of each design concept. Replacement of this reactor element appears at the outset to be the major scheduled maintenance requirement (and possibly also the major unscheduled maintenance requirement) for a tokamak reactor design. The magnitude of the task is such that the scheduled maintenance on all other subsystems can possibly be performed in conjunction with the replacement of the first wall/blanket. This will be the case only if this replacement is properly scheduled and the maintenance plan concept provides for such parallel operations. Additional discussion of other subsystem maintenance and its impact is presented in Section 4.4.

The maintenance plans for replacement of the first wall/blanket for those design concepts described in Section 3.0 are defined for the baseline large module, intermediate module and small module concepts with one alternative design concept for the large module and one alternative design concept for the small module. An alternative maintenance approach for the small module concept is also included. The initial assumption is made that the possibility of completely preventing the activation of reactor room components or structure by neutron streaming through plasma chamber penetrations may be difficult to achieve. Therefore, the baseline maintenance plans are developed using remote operations to develop a base estimate of the cost of maintenance and to establish the feasibility of maintenance under the most difficult possible environment.

Alternately, for the three baseline design concepts, maintenance plans are developed under the assumption that the activation of reactor room components or structure can be eliminated. Under these conditions, the presence of workers in the reactor room with a minimum of protective clothing can be allowed and contact maintenance, i.e., maintenance by use of personnel in direct contact with the reactor components (except for the use of protective clothing), is utilized to the maximum extent possible.

In all of the maintenance plans except one, almost all of the maintenance equipment, excluding the overhead crane, is mobile enough to be moved from the reactor room during reactor operating periods. The exception is the in-place equipment plan for the GA-DPR. For this approach to GA-DPR

maintenance, the equipment remains installed on the exterior of the reactor in such a manner that it is immediately available for first wall/blanket maintenance.

The maintenance plans defined in the following sections are restricted to scheduled maintenance of the first wall/blanket for the design concepts described in Section 3.0. The plans included in this section are limited in scope and are not intended to be total maintenance plans. In addition to these plans, a total maintenance plan requires additional consideration of unscheduled maintenance, of other reactor and balance of plant subsystems, facility design, utilization of spares, additional maintenance equipment, manpower utilization and the percentage of the reactor maintained or overhauled during a scheduled outage. These subjects are only briefly considered in this analysis.

For more detail of the maintenance plans and the equipment concepts used in this analysis, reference is made to Appendixes A through E in Volume II.

4.1 MAINTENANCE APPROACH SUMMARY - A number of overall assumptions and ground rules defining the conditions under which maintenance is conducted are common to all maintenance approaches. In addition, the major functions required for maintenance of each design concept can be grouped into common blocks of gaining access, removal of the modules, inspection and test, replacement of the modules and reassembly of reactor elements removed or disconnected when providing access to the modules. Shutdown and startup operations are very similar for all concepts and affect the analysis only slightly.

The common assumptions and ground rules include the following.

- o All procedures emphasize the use of state-of-the-art technology.

Some of the technology is applied from other than the usual fission power plant construction techniques and some extensions in technology are included for comparison purposes. The principal cases where such extensions are assumed are the use of laser welding equipment for welding the vacuum seals in the GA-DPR design concept and the use of mechanical joint connections in large liquid lithium lines in the UWMAK-III design concept. The maintenance equipment also can be considered an extension of state-of-the-art, particularly in those areas where manipulator loads exceed current capabilities and where feedback or computerized control is assumed.

- o The radiation environment after shutdown for the various design concepts under consideration is assumed to lie between that defined for the UWMAK-I in Reference 9 and the estimates for the Argonne National Laboratory Experimental Power Reactor made in Reference 10. Based on these calculated estimates the dose rate outside of the reactor but in the reactor room 24 hours after shutdown may vary between 2 mrem/hr and 1165 mrem/hr. The first of the above estimates is outside of the T.F. coils of the ANL Experimental Power Reactor and assumes no penetrations of the plasma chamber. The second estimate is outside of the UWMAK-I shield. For the UWMAK-I calculation this dose rate decays to 870 mrem/hr one month after shutdown. These estimates lead to the assumption that contact maintenance outside of the shield can be made possible in all concepts examined.

The dose rate inside the plasma chamber is estimated at 2×10^9 mrem/hr one day after shutdown, decaying to 1×10^9 mrem/hr in one year. In the central core region the dose rate decays from 6×10^2 mrem/hr to 2×10^2 mrem/hr in the same period (Reference 10). This estimate indicates the impossibility of doing any contact maintenance inside the plasma chamber and the possibility that contact maintenance in the central core region (above or below the reactor) can be made feasible.

With this limited data it has been assumed that contact maintenance can be made feasible everywhere in the reactor room outside of the outer plasma chamber shield by suitable shield design. However, whenever a penetration of the shield is made the maintenance in the reactor room must be conducted remotely.

- o The design concepts are evaluated with minimum change or elaboration to the original concept. Where the characteristics which influence the maintenance plans are undefined, design assumptions have been made. Some of these design assumptions are described briefly in Section 3.0 along with the system descriptions. These and others are defined in more detail in Appendix F.
- o When estimating the time required to accomplish successive tasks it is assumed that no manpower limitations exist. For remote operations the limiting factors for parallel operations are usually equipment performance or equipment quantity limitations. For contact

maintenance, as many men are used simultaneously as deemed reasonable for the operations being conducted. Time phasing of personnel is conducted only to a very limited degree.

4.1.1 Maintenance Plan Characteristics - A brief summary of the critical differences among the concepts is outlined in Table 4-1. The modules replaced have been described in Section 3.0 but the number of modules represented by each maintenance plan and for which replacement estimates are included in Appendixes A through D has been kept to a minimum. This is done to provide an estimate that can be combined or expanded to include additional modules in the same reactor up to the total required to exchange the complete first wall/blanket. In each case, except the GA-DPR and the ORNL concepts, these are the modules to be exchanged in one reactor sector. A tokamak reactor is usually designed to have as many sectors as T.F. magnets. Since this varies - the UWMAK-I has 12 magnets, the UWMAK-III has 18 and the GA-DPR has 16 - the percentage of the reactor exchanged is only roughly comparable.

TABLE 4-1
FIRST WALL/BLANKET MAINTENANCE APPROACH SUMMARY

REACTOR CONCEPTUAL DESIGN (MAINTENANCE MODE)	MODULES REPLACED PER REACTOR SECTOR	ACCESS AND REASSEMBLY			MAINTENANCE OPERATION CHARACTERISTICS
		COMPONENTS REMOVED	JOINTS DISCONNECTED	INSPECTIONS AND TESTS	
LARGE MODULES:					
UWMAK-I - REMOTE	SECTOR INCL. T.F. MAGNET	NBI'S (3) MAGNET BRACES JOINT SHIELDS	COOLANT SHIELD BLANKET VACUUM T.F. MAGNET	VACUUM CONNECTIONS POWER CONNECTIONS COOLANT CONNECTIONS	TF MAGNETS WARM MODULES DRAINED INERT ATMOSPHERES NO CASKS MEN SHIELDED
- CONTACT	SAME AS REMOTE	SAME AS REMOTE	SAME AS REMOTE	SAME AS REMOTE	SIMILAR TO REMOTE EXCEPT: AIR ATMOSPHERE MANUAL OPERATIONS FOR SHIELDED ACCESS
CULHAM MK-II - REMOTE	SECTOR AND DIVERTER	SHEAR PANEL SHIELD DOOR	COOLANT SHIELD	VACUUM CONNECTIONS COOLANT CONNECTIONS	ALL MAGNETS CHILLED AIR ATMOSPHERE NO CASKS MEN SHIELDED
INTERMEDIATE MODULES:					
UWMAK-III - REMOTE	OUTER WALL & 1/2 OF CENTRAL & INNER WALL	SHEAR PANEL WAVE GUIDE MANIFOLDS	COOLANT SHIELD BLANKET VACUUM	VACUUM CONNECTIONS COOLANT CONNECTIONS	ALL MAGNETS CHILLED MODULES FULL INERT ATMOSPHERE MEN SHIELDED NO CASKS
- CONTACT	SAME AS REMOTE	SAME AS REMOTE	SAME AS REMOTE	SAME AS REMOTE	SIMILAR TO REMOTE EXCEPT: AIR ATMOSPHERE MANUAL OPERATIONS FOR SHIELDED ACCESS
SMALL MODULES:					
GA-DPR - REMOTE	INDIVIDUAL (FROM 1 TO 125)	VACUUM PORT COVER	VACUUM	VACUUM CONNECTIONS	ALL MAGNETS CHILLED AIR ATMOSPHERE NO CASKS MEN SHIELDED
- CONTACT	SAME AS REMOTE	SAME AS REMOTE	SAME AS REMOTE	SAME AS REMOTE	SIMILAR TO REMOTE EXCEPT: ALL COMPONENTS IN CASKS ALL OPERATIONS OUTSIDE REACTOR UNSHIELDED
- REMOTE (IN-PLACE EQ.)	SAME AS REMOTE	NONE	VACUUM	VACUUM CONNECTIONS	SAME AS REMOTE
ORNL - REMOTE	INDIVIDUAL MODULES (FROM 1 TO 45)	NBI'S (2)	COOLANT LITHIUM BLANKET VACUUM	VACUUM CONNECTIONS COOLANT CONNECTIONS	ALL MAGNETS CHILLED MODULES FULL AIR ATMOSPHERE NO CASKS MEN SHIELDED

The GA-DPR concept differs in that the modules are not directly related to sectors. Therefore, the estimates are made for one module for each in-chamber maintenance machine but, for the purpose of this discussion, 1/16 of the total number of modules are used (125 or one sector's equivalent).

The ORNL concept differs in that the modules (cassettes) are in three layered zones which requires the removal of a zone only when its operating life is reached. The estimates are made only for replacement of the first blanket zone modules in one sector, i.e., 15 of the total of 45 modules in a sector.

It is noted that the Culham Mk-II and the ORNL concepts are listed with the large and small modules, respectively. The Culham Mk-II concept is most closely related to the UWMAK-I large module since almost the complete sector is removed in one piece, and the ORNL cassette concept is related to GA-DPR small module since many small modules are used in one sector.

For the Culham Mk-II concept, the cost and maintenance data is computed using the UWMAK-I code of the TOCOMO program which assumes that the magnets and sectors are similar to the UWMAK-I. Therefore, the estimates are based on 12 sectors, instead of the 20 defined by Culham. In this case the plasma characteristics are used for the UWMAK-I producing minimum cost-of-electricity which requires a height to width ratio of 2:1 to define wall life, etc. The principles used by Culham to segment the reactor and separate the shield and module are retained since it is these principles that are being evaluated.

Similarly, the ORNL cassette concept cost and maintenance data is defined using the UWMAK-III code of the TOCOMO program. This assumes materials, magnets and weights similar to the UWMAK-III. However, the estimates reflect the maintenance time requirements of the ORNL concept. Therefore, the ORNL concept estimates are for one sector out of the 18 required to make up the UWMAK-III.

These approximate approaches to the Culham Mk-II and the ORNL cassette concepts are used to evaluate maintenance costs and other maintenance parameters. Since the data available is insufficient to create a separate code for these concepts, the data generated must be used only for the limited purpose for which it is intended. It does not represent an evaluation of the total reactor design defined by these two concepts.

Table 4-1 also lists the principal access and reassembly requirements for each design concept. The maintenance plans for contact maintenance are

essentially the same as those used for the respective remote maintenance approaches. The details of the task sequence and time required differ materially between contact and remote maintenance but the same components must be disassembled and disconnected and the same verification tests conducted since each reactor concept is designed for only one basic maintenance approach.

From Table 4-1 it is apparent that the most significant disassembly is required for the large module concept employing the UWMAK-I design approach and the least disassembly is required for the small module concept employing the GA-DPR concept. The effect of the more difficult access requirements imposed by the UWMAK-I approach is directly reflected in the time estimates presented later in this section.

The maintenance operation characteristics in Table 4-1 principally describe the significant environment in which maintenance is conducted. In all cases the energy in the magnets is dumped since scheduled maintenance in a high magnetic field is considered an added constraint that is unnecessary. Other factors dominate shutdown and the added time for charging the magnets during startup preparation is a small percentage of the total outage period. However, only in the UWMAK-I concept does the requirement to remove the T.F. magnet with the sector make it necessary to warm up all T.F. magnets and the reactor core during maintenance.

Among the concepts employing liquid lithium or liquid salt coolants only the UWMAK-I blanket modules and lines are drained. Some reconfiguration of the lines is necessary to provide this capability but, even with this rearrangement, the drainage is required to clear only the feed and return lines. The UWMAK-III concept blanket manifolds are so constrained that drainage appears ineffective in aiding maintenance, and the ORNL concept employs a large number of small lines for which it is assumed that leak-tight quick-disconnects can be developed.

The use of an inert atmosphere is considered whenever liquid lithium is employed. However, while lithium represents a potential fire hazard, the use of an inert environment would impede the operation of maintenance personnel considerably. Therefore, to give contact maintenance the best possible capability, the assumption is made that the fire hazard in an air atmosphere can be overcome and an air atmosphere is used in the reactor room for these concepts. For the GHe coolant systems, purging or drainage has a relatively small effect on maintenance procedures.

The only maintenance operations that use shielded casks are those employed during contact maintenance of the GA-DPR design concept. In all other contact maintenance operations considered, the module access and size is such that the use of casks appears impractical. The employment of casks for remote maintenance is also considered unnecessary since the movement to the hot cells is conducted totally within protected and sealed facilities. All movement to or from storage into these facilities is conducted through an airlock or decontamination chamber.

The previous discussion concerning the radiation assumptions indicates that the use of protective clothing for all personnel employed in contact maintenance is required. This includes the use of a breathing apparatus to prevent tritium ingestion. For all remote operations, the personnel controlling the operations are either outside of the reactor building biological shielded areas or are enclosed in shielded cabs on the mobile equipment.

4.1.2 Maintenance Equipment Characteristics - Figure 4-1 summarizes the principal approaches employed by the maintenance equipment systems. The

MAINTENANCE EQUIPMENT DESIGN APPROACHES

	<p>LARGE MODULE</p>	<p>INTERMEDIATE MODULE</p>	<p>SMALL MODULE</p>
CONCEPT:	EXTERNAL DISCONNECT	EXTERNAL/INTERNAL REMOVAL	INTERNAL REMOVAL
CHARACTERISTIC MODE:	REACH AROUND	BORE IN	HAND OUT
CHARACTERISTIC WEIGHT:	HEAVY	HEAVY	LIGHT
CHARACTERISTIC FUNCTIONS:	ATTACH, BOLT/UNBOLT, LIFT, TRANSLATE	ATTACH, BOLT/UNBOLT, WELD/CUT, TRANSLATE (2 DEGREES)	ATTACH, ROTATE, WELD/CUT, RAISE/LOWER
VIEWING:	DIRECT, TV	DIRECT, TV	TV
HANDLING CAPABILITY:	50 TONNES	150 TONNES	0.5 TONNE
LIMITATIONS:	CRANE ACCESS UNAVAILABLE, MAX. OF 4 HATCHES IN WALL	CRANE ACCESS LIMITED	ACCESS LIMITED BY NUMBER OF VACUUM PORTS

equipment defined for maintenance of the UWMAK-I is characterized by several mobile vehicles which are sized primarily by the requirement to reach above and behind the joints between the reactor sectors and by the weight of shield blocks that must be removed to expose these joints. The weight of some of the shield segments is approximately 50 tonnes. An overhead crane is available only in the reactor hall outside of the reactor room. Thus, all heavy parts must be transported out of the room by the mobile vehicles. Also, the reactor module weight is so great that only floor supported transportation seems practical. For this purpose, the use of air bearings is postulated.

The equipment defined for the UWMAK-III is required to move heavy shear panels and modules from between the T.F. magnets. This access requires floor mounted equipment for the initial motion since the overhead crane is extremely difficult to use for the precise control and motions required. For this equipment a maximum load capability of approximately 170 tonnes is required. This basic concept is also employed for the Culham Mk-II maintenance plan.

The GA-DPR maintenance equipment employs track mounted machines inside of the plasma chamber. These remove the modules and associated components and transfer them to the exterior of the reactor. All access is through vacuum ports near the top of the chamber. The size of these ports limits the size of the equipment and modules that must pass through them. The location of the ports to a degree determines the mass of the maintenance equipment, largely as a result of the precise control requirements necessary to make interface connections with the inside of the reactor.

Detailed definitions of the maintenance equipment employed in the concepts are presented in Appendix E.

4.1.3 Maintenance Downtime Requirements - The downtime estimates for one reactor sector (or its equivalent) for each of the tokamak design concepts is summarized in Table 4-2. These times are combined to estimate the downtime required for exchange of selected fractions of the total first wall/blanket and the expanded estimates are then used in calculating the total plant cost and availability estimates discussed in Section 5.0. The time estimates given in Table 4-2 are based on the estimates presented in the appendixes but a factor of .75 has been applied as the total effect of productivity, shift change and other lost time activities affecting the capability of personnel to accomplish the maintenance functions. This factor is

TABLE 4-2
MAINTENANCE DOWNTIME REQUIREMENTS

REACTOR CONCEPTUAL DESIGN (MAINTENANCE MODE)	DOWNTIME/SECTOR (DAYS) ⁽¹⁾							SECTORS PER REACTOR	
	SHUTDOWN	MAINTENANCE					STARTUP		TOTAL
		ACCESS	REMOVAL	INSPECTION	REPLACEMENT	REASSEMBLY			
LARGE MODULES:									
UWMAK-I									
-REMOTE	1.01	54.91	← 1.27 →			94.20	2.54	153.95	12
-CONTACT	1.01	32.74	← 1.27 →			49.75	2.54	87.32	12
CULHAM MK-II									
-REMOTE	.94	11.14	← 5.19 →			28.19	1.33	46.81	12
INTERMEDIATE MODULES:									
UWMAK-III									
-REMOTE	.94	16.44	9.42	7.22	13.17	15.56	1.33	64.08	18
-CONTACT	.94	7.52	9.42	7.22	13.17	10.13	1.33	49.73	18
SMALL MODULES:									
GA-DPR ⁽²⁾									
-REMOTE	1.33	20.64	24.86	N/A	35.92	32.41	2.06	117.22	16
-CONTACT	1.33	13.31	24.84	N/A	35.89	25.87	2.06	103.30	16
-IN PLACE-REMOTE	1.33	1.29	5.67	N/A	8.89	5.89	2.06	25.13	16
ORNL									
-REMOTE	1.47	5.83	10.78	5.78	11.61	13.07	4.28	52.82	18

(1) TIMES ASSUME 75% UTILIZATION OF 24 HOUR DAY.

(2) THIS IS TIME TO EXCHANGE 1/16 (6.25%) OF TOTAL MODULES IN REACTOR (I.E. 125 MODULES).

used for a three shift, 24 hour day during the maintenance period.

Examination of the estimates for single reactor sectors indicates that the longest periods required are for the large module UWMAK-I and for the small module GA-DPR. However, the time distribution is markedly different. For the large module the time expended to exchange modules is very low while for the small module it represents 51.8% of the total. Part of the cause for this is the necessity for complete testing of the vacuum joints at each small module and cleaning of the interior of the chamber during the replacement operations. On the other hand, the inspection of the large module is accomplished off-line before it is moved into place. The most significant cause, however, is the difference in concepts in which all small module joints are disconnected and remade during replacement while the large module joints are disconnected and remade during access and reassembly. In addition, the inspection of the first wall of adjacent modules conducted between removal

and replacement of the UWMAK-III modules is omitted from the UWMAK-I estimate.

These differences among maintenance plans make the significance of time differences among unlike concepts difficult to evaluate. However, differences among maintenance plans for the same design concept can be related and two significant factors are considered in the following sections.

4.1.3.1 Installed Equipment Impacts - The small module GA-DPR was examined to determine the impact of utilizing in-place maintenance equipment on the downtime required for first wall/blanket replacement. The examination used a revised maintenance equipment concept in that the number of sets of equipment is increased and the basic equipment utilization concept is also changed. These two revisions must be separately examined. The revised plan is described in Section 4.2.1.5.

Table 4-2 shows the effect of the revised concept when replacing the equivalent of one sector of modules (125 modules). The time indicated for removal and replacement of the modules has been reduced to 24% of that required by the initial plan. However, this benefit is gained almost entirely by the use of 8 removal machines instead of the two used in the original plan. The time estimates in Section 1.0 of Appendix C are based on the use of the two machine concept. In addition, the machine utilization concept differs by using externally mounted instead of internally installed equipment. The mounting of this many machines would increase the access and reassembly time if the original concept were retained so the plan was modified to leave them installed on the reactor during operation. The data in Table 4-2 indicates that this approach reduced the access and reassembly time to 13.5% of that required by the original concept and to 28.6% of the total time required to replace the equivalent of one sector of modules (i.e., 125 modules). This reduction in access and reassembly time becomes less significant as the number of modules increases but becomes increasingly significant for a very small number of modules such as may occur in unscheduled maintenance (see Section 4.3).

Some additional considerations are required by the in-place equipment concept. The vacuum vessel must be penetrated by the maintenance equipment. This requires the design of a vacuum port cover that can be rapidly retracted and resealed. The concept also requires no installation or transfer of maintenance equipment as a part of the maintenance operations immediately

before module replacement begins. Examination of the initial concept shows this transfer of equipment to be a time consuming operation.

In summary, the use of in-place equipment primarily reduces access and reassembly time, but the reactor must be designed to permit the maintenance equipment to reach all parts of the chamber without relocating the equipment. This requirement can result in an appreciable increase in the cost of equipment. In this case the number of module removal machines increased to 8 instead of the 2 used with the initial concept. The initial concept, however, is capable of using four machines simultaneously and this is found to be more effective than 2. Therefore, the data contained in the combined analyses defined in Sections 4.2.1.4 and 4.2.1.5 uses four machines instead of the 2 that are used in the basic time estimates given in Appendix C.

4.1.3.2 Contact Maintenance Impacts - Table 4-2 illustrates the impact of employing contact maintenance for replacement of the first wall/blanket of the baseline design and maintenance concepts. This figure shows that the total time for replacement of the modules in any one sector of each reactor concept decreased by 43.3% for the large module, 22.4% for the intermediate module and only 11.9% for the small module when contact operations are employed as much as possible instead of remote operations.

In all cases the plan for contact maintenance follows closely the remote maintenance plan but takes advantage of the time reductions gained through use of manual operations, of possible changes in the functional sequence and of simultaneous operations by several crews. The major decrease in time when working the large module is gained by resequencing the tasks to disconnect all lines and services using contact maintenance before opening the shield. Since the large module reactor concept requires the largest number of external disconnects of the three concepts examined, the reduction in maintenance time is the greatest when using contact maintenance with this concept. The intermediate module sequence of operations requires no significant change and, since fewer external disconnects are required than for the large module, the reduction in time is less. The small module operations gain the least benefit from contact maintenance primarily because the contact operations are conducted in parallel with the remote operations inside of the plasma chamber. When using a totally remote maintenance plan for the small module concept the internal chamber operations control the elapsed maintenance time. Therefore, any reduction in the time required for maintenance

operations external to the chamber will not affect the elapsed time. The significant advantage of contact maintenance for the small module design, concept is the decrease in the access and reassembly time achieved by opening several vacuum ports at the same time and installing several units of external equipment in parallel with each other.

Contact maintenance will demonstrate the most significant time savings when maintaining other subsystems than the first wall/blanket assuming, of course, that they have not been activated by neutron streaming. When considering the maintenance of other subsystems, a qualitative examination indicates that the small module concept will have the shortest overall scheduled maintenance downtime because no interference with the maintenance of other subsystems occurs during the first wall/blanket exchange operations. On the other hand, the larger module concepts with their attendant inability to place the larger modules in casks requires clearing the reactor building of personnel during the remote operations and thus, interference with the contact maintenance of other subsystems occurs during this period.

A complete analysis of the use of scheduled contact maintenance should consider the best mix of contact and remote maintenance. For example, while the small module permits the use of a more suitable environment for contact maintenance of other subsystems than the larger modules, the longer time for the maintenance of the first wall/blanket when using small modules may be more costly than permitting some interference of remote operations with the contact maintenance and accepting the need to clear personnel from the reactor room during some operations. Of course, if in-place equipment concepts for the small module prove more beneficial than for larger modules, then both remote and contact maintenance operations appear to require shorter times for the smaller modules.

This discussion considers only the time effects for the maintenance of a single sector. In Section 6.0 the analysis of the overall maintenance cost, including the capital cost (maintenance equipment, facilities, and initial spares), replenishment spares, personnel costs, and the cost effects of availability is presented. These cost effects provide additional insight to the comparison of contact and remote maintenance benefits when replacing the first wall/blanket.

4.2 SCHEDULED MAINTENANCE - This section describes the maintenance plans and procedures for the scheduled replacement of the first wall/blanket modules in each of the five selected reactor design approaches outlined in Section 3.0.

The maintenance procedures used to exchange one first wall/blanket module or module group for each baseline reactor configuration using fully remote maintenance operations is first defined in Section 4.2.1 for each of the five design approaches. Significant steps in the maintenance procedures and maintenance equipment characteristics are briefly described and explained. A summary of the time estimates to perform the remote maintenance activities is included.

An evaluation of how personal contact with the reactor exterior can affect the overall maintenance time for performing first wall/blanket exchange on the three baseline reactor designs is presented in Section 4.2.2. Maintenance activities performed or assisted by personal contact are restricted to those which can be accomplished without exposing personnel to radiation hazards, assuming that feasible reactor design modifications are undertaken.

4.2.1 Remote Maintenance Approaches - The maintenance and repair of a complex device such as a reactor using remotely controlled and operated machines is a difficult and time consuming task. Operations performed remotely can require up to 30 times as much serial time as the same operation performed manually. The situation is further complicated when the operator does not have direct visual contact with portions of the reactor, except by television or other intermediate aids.

The approach used to accomplish remote maintenance as rapidly as possible is to remove and replace all reactor components and then repair the components, as necessary, off-line in a protected area. This approach should minimize the operations required and the resultant downtime. Maintenance equipment is integrated with the requirements of the reactor design and, correspondingly, the reactor design is modified when the equipment requirements make this necessary. However, reactor design modification is usually used as a last resort in keeping with the approach to use the reactor concepts with as little revision as possible.

The overall maintenance approach is based upon certain ground rules and assumptions. Many of these have been discussed in the introduction to maintenance plans but are reiterated here in summary. These are listed but not necessarily in the order of greatest impact on the maintenance plans.

- o For remote maintenance plans the level of radioactivity of the reactor and its components is such that all maintenance activities conducted in the reactor room must be performed remotely. Reactor shielding is sufficient to protect components, but not personnel.
- o The reactor designs and concepts are modified only if necessary to accommodate maintenance functions.
- o The reactor building designs are modified, if necessary, to accommodate maintenance machine access requirements, logistics, and staging space around the reactor proper.
- o There is no restriction placed upon the number of personnel or the number of machines involved in the maintenance activity.
- o Scheduled maintenance of other reactor subsystems will be accomplished in conjunction with first wall/blanket maintenance activities.
- o Only scheduled maintenance activities are considered in making down-time estimates.
- o Maintenance timelines are developed for the exchange of one module or group of modules.
- o Each maintenance machine is specifically configured to perform a designated function or group of functions
- o Maintenance machine concepts are based upon current state-of-the-art technologies or reasonable extrapolations thereof.
- o Powered mobile units are provided with a self-contained, shielded operator's enclosure where feasible.
- o The manned maintenance machines have to remain in position for extended periods in some cases. A crew transfer unit is required to exchange crews in these vehicles and effect emergency crew recovery operations.
- o Operational visibility of the maintenance activity is provided either by placing the operator in a position to view the activity or through the use of remote TV camera and light units.

- o A remote control room or rooms is available to assist, coordinate, and monitor the maintenance activities.
- o Personnel in maintenance vehicles are in constant contact with personnel in a remote control room by both voice and TV.

4.2.1.1 The Large Module Concept (UWMAK-I) - The maintenance plan for UWMAK-I is based upon the complete exchange of one or more of the 12 modules which comprise the complete reactor torus. Each reactor module consists of a large toroidal field magnet, a shield segment, a blanket module segment, upper and lower diverters, and particle collectors. Each reactor module is installed on its own transporter as shown in Figure 4-2.

Assumptions and Ground Rules - The assumptions defined for the time estimates described in Appendix A are intended, in most cases, to simplify the maintenance tasks. These assumptions are summarized by the following maintenance ground rules.

- o The Reactor Room (RR) environment comes in contact with solid or liquid lithium, primarily in the particle collector systems and in the open coolant lines. Therefore, an inert gas (possibly argon) is used for the RR atmosphere anytime the RR is not at the operational vacuum condition.
- o All maintenance activities inside the Reactor Room (RR) must be accomplished using remotely controlled equipment and/or with operators in shielded cabs, due to the following:
 - o The temperature environment inside the RR may be on the order of 125°C.
 - o The latent radiation and inert environment inside the RR requires that maintenance personnel be restricted to shielded enclosures.
- o The reactor building atmosphere is also an inert gas since the RR hatches will be open to the reactor building during maintenance periods.
- o The low RR ceiling, which supports diverter field coil windings, plumbing, etc., negates the use of an overhead crane in the RR proper. All lifting and hoisting functions must be accomplished from the RR floor level.
- o The RR floor must be flat and lined with stainless steel to present a smooth operating surface for the maintenance equipment. The RR hatch sill is flat and level with the RR floor, such that there is no discontinuity which would impair the use of air bearings.

UWMAK-I REACTOR MODULE

LEGEND

1. REACTOR MODULE AIR CUSHION TRANSPORTER	13. SHIELD SEGMENT COOLANT (GHe) SUPPLY LINE
2. TOROIDAL FIELD MAGNET AND DEWAR	14. PLASMA CHAMBER VACUUM LINES
3. SHIELD	15. TOROIDAL FIELD MAGNET ELECTRICAL POWER LEADS
4. FIRST WALL/BLANKET	16. REACTOR COOLANT (Li) RETURN LINE
5. PARTICLE COLLECTOR PLATE	17. SHIELD SEGMENT COOLANT (GHe) RETURN
6. VACUUM PORT SHIELD	18. TOROIDAL FIELD MAGNET COOLANT (LHe) SUPPLY LINE
7. TOROIDAL FIELD MAGNET COOLANT (LHe) RETURN LINE	19. NEUTRAL BEAM OR FUEL INJECTOR PORT
8. TOROIDAL FIELD MAGNET COOLANT VAPOR (GHe) RETURN LINE	20. BLANKET SEAL FLANGE (PLASMA CHAMBER VACUUM SEAL)
9. TOROIDAL FIELD MAGNET DEWAR VACUUM LINE	21. BLANKET SUPPORT RODS
10. REACTOR COOLANT (Li) SUPPLY LINE	22. MAGNET SHEAR BEAMS
11. DIVERTED PARTICLE COLLECTOR SUPPLY (Li) LINE	23. FRONT MAGNET/DEWAR SUPPORT
12. DIVERTER PARTICLE COLLECTOR RETURN (Li) LINE	24. FRONT SHIELD SUPPORT
	25. REAR SHIELD/MAGNET/DEWAR SUPPORT (PART OF ITEM 1)

13-685

- o The reactor building is outfitted with a large airlock and decontamination chamber to allow ingress/egress of maintenance equipment into the reactor hall from storage or decontaminated maintenance areas.
- o The Power Plant design incorporates up to four (4) hot cells located radially with respect to the reactor. Each hot cell is sized to handle a removable reactor module.
- o If the maximum of four hot cells are used, four spare reactor modules will be on line at all times.
- o Up to four sets of maintenance equipment will be provided.
- o The RR is equipped with adequate numbers of remote TV cameras and lights to provide full coverage viewing of the reactor and maintenance operations.
- o The reactor hall is wide enough to accommodate a reactor module and its tow vehicle in all orientations.
- o The reactor hall is designed with alcoves on the exterior side to store reactor equipment and components removed from the RR during maintenance.
- o The torus seal on either side of a reactor module is a bolted, rather than a welded, joint.
- o The reactor design and design codes are modified as necessary to enhance the timely accomplishment of maintenance functions.
- o All line connections (fluid, gas, electrical, etc.) to the reactor module proper, except lithium coolant lines, are made through the use of some type of mechanical joint. Welded line joints are selected for lithium lines.

Maintenance Procedures - The procedures for replacement of a single large module are briefly described. These procedures apply to the exchange of one large module (the complete sector) of the UWMAK-I. The shutdown and startup procedures are not repeated when more than one module is exchanged.

- o The reactor room environment is adjusted for maintenance operations. Cryovacuum pumps are allowed to warm-up to room temperature; room pressure and plasma chamber pressure are adjusted to near atmospheric pressure using an inert gas; the room temperature is maintained above the melting point of lithium; and, the reactor core with all toroidal

magnets is permitted to heat above the liquefaction temperature of the room atmosphere. This last requirement prevents the formation of frost on the exposed core face when the toroidal magnet is removed.

- o The lithium coolant is drained from all blanket modules and from the particle collector system, clearing the coolant line joints of lithium.
- o The concrete inner cylindrical wall is rotated until the hatch is opposite the sector of the reactor to be removed.
- o The hatch is opened and an Operational Maintenance Unit (OMU) is employed to disconnect the services of up to three neutral beam injectors. (The quantity depends on the particular sector since the injectors are not uniformly distributed around the toroid.) A Tractor Unit (TU) is employed to tow the injectors out of the way (air bearings are used to provide mobility for the injectors).
- o Poloidal field magnets are retracted automatically while the neutral beam injectors are being removed. Service connections to the P.F. magnets are movable so that disconnects are not required.
- o A section is removed from the cross beam supports above the blanket joints between the T.F. magnets.
- o The shield segments covering the blanket joints are removed. The segments adjacent to the core region are lifted vertically from overhead by means of a High Access Maintenance Unit (HAMU).
- o The yoke segments clamping the reactor module blanket seal flanges are removed and the seal flanges retracted for clearance. Special devices are used to accomplish this function.
- o The lithium coolant lines, gaseous helium coolant lines, vacuum lines, liquid helium lines, and instrumentation and power lines are disconnected and moved out of the module egress path as required.
- o The toroidal magnet shear pins are raised to clear the magnet shear beams.
- o The reactor sector is withdrawn and moved to the hot cell for replacement of the first wall. Mobility is provided through the use of an air bearing transporter. A spare module is used for a replacement.
- o Inspection of adjacent modules is conducted at this time.

The replacement of the reactor module employs a procedure which is essentially the reverse of the removal operations. However, a few exceptions are noted. In general, replacement is more time consuming because of the seal dressing, alignment, testing and similar procedures. As soon as the replacement module is in place, the toroidal magnet shear pins are seated and the magnet vacuum and liquid helium services are connected. When this is accomplished for all modules being replaced, the magnet chill down procedure is initiated for the entire reactor.

An additional task is the test for vacuum integrity of the plasma chamber. This is initiated before the shield segments and the neutral beam injectors are in place. Vacuum plugs have been installed at the injector openings. The cryovacuum pumps are not required since the test is for significant leaks with the reactor room at near-atmosphere pressure. After emplacement of the neutral beam injectors, and sealing of the reactor room, another test is conducted. This test includes the "baking out" of the chamber using the lithium coolant as the heat source. This test is conducted at operating pressures and, hence, involves chill down and operation of all cryovacuum pumps with the required regeneration before reactor startup.

Maintenance Equipment - Replacement of an entire sector of the UWMAK-I reactor requires the use of specialized maintenance equipment integrated with the reactor design and the specific function to be performed.

Equipment for this concept must have the capability to reach around the outside of the reactor and disconnect all services and structural joints for the reactor sector. While the functions that the machines must perform to disconnect the sector are relatively straightforward, the access to the reactor core area is very restricted and requires the use of several highly specialized pieces of equipment.

Major equipment items for exchanging the UWMAK-I reactor modules are defined in some detail in Section 1.0 of Appendix E. They tend to be large, mobile, and have a high degree of mechanical dexterity. In the UWMAK-I maintenance scenario, the largest unit to be moved is the 3500 tonne reactor module. The requirement to move this module in the space available in the reactor room and to support the module within the limited space available beneath the reactor results in selecting a gas bearing transporter as the method of support during the actual exchange. This concept requires that the installed moving parts must be limited to a minimum and cannot be subject

to deterioration during reactor operation. The base support concept for the reactor sector, Figure 4-2, is a relatively simple structure controlled from the tractor unit (TU). The tractor unit provides compressed gas for use in the gas bearings and also controls the movement of the entire base/module assembly. This unit also actuates the jacking mechanism for raising the toroidal magnet when the load is to be removed from the shear pins that attach the magnet to the reactor core. A unique feature of the tractor is the individually controlled pendular suspension for each set of wheels to provide for movement in any direction.

An approach to the design of the equipment required to reach the various parts of the reactor module is illustrated by the Operational Maintenance Unit (OMU), Figure 4-3. This unit is similar to the Heavy Maintenance Unit (HMU) and the High Access Maintenance Unit (HAMU). All employ extendable boom/hoist mechanisms to gain access and conduct required manipulative functions. All units must be retractable in order to pass through the hatches in the reactor room wall and through the airlock/decontamination chamber into the maintenance and storage area.

The OMU is used for complex disassembly and requires dual extendable arms plus a low level device that is moved beneath the reactor module and up the narrow space at the core to hold segments of the blanket seal yoke while they are being removed. The HMU and OMU differ from the HAMU by the size and weight of the load that must be handled and the complexity of the operations that are conducted. The HMU is used to lift the heavy shield segments between the toroidal magnets and place them in the reactor hall for temporary storage. The HAMU reaches over the top of the reactor and provides access for removal of shield segments from the core area and for emplacing and operating the magnet shear pin extractor. Further study may demonstrate that these machines can be functionally combined into one.

Special tools are required to disconnect and reconnect the line fittings for the services required by the reactor sector. The design of these fittings will determine the requirements for alignment and mating the joints under varying temperature conditions, and for cleaning, sealing and testing the joints. The use of a double walled vacuum chamber in the UWMak-I concept has eliminated the requirements for a seal weld at the blanket joints and, with this feature, welding, cutting and debris removal operations are not required at the vacuum wall seal.

RME-2, OPERATIONAL MAINTENANCE UNIT

13-670

The use of a rotating inner wall for the reactor room increases the problem of locating the control room for maintenance operations. Direct viewing of the reactor room activities through the wall appears impractical, since the rotating wall must be repositioned at each scheduled outage. Therefore, the main control room is remote from the reactor room or above the reactor room ceiling but primarily equipped with television for viewing maintenance operations. To supplement this, manned cabs on the major mobile equipments are provided. The use of manned cabs is feasible in concept but the increase in design complexity and the requirement for a crew transfer unit for shift change and safety requires further study.

Minimum Cost Maintenance Plan - The exchange of different fractions of the total reactor first wall/blanket have been analyzed by use of the TOCOMO system analysis and cost code. (This code is described in more detail in Appendix G.) The exchange fraction resulting in the lowest cost of electricity is the replacement of four modules during a scheduled outage. (Other alternatives are to replace 1, 2, 3, 6 or 12 modules.) The fraction wherein four modules are exchanged is the selected maintenance plan for the comparative analyses reported in Section 6.0. For this maintenance plan the sequence of maintenance operations for the baseline large module (UWMAK-I) and the time required to accomplish these operations is shown in Figure 4-4. In all cases this time assumes a three shift, 24 hour day and the estimated times defined in Section 1.0 of Appendix A have been adjusted by the 75% manpower utilization factor.

The baseline reactor design used in this maintenance analysis is the design presented in the UWMAK-I report and modified by the assumptions listed both in the detailed task timelines of Appendix A, and in the additional reactor design definition discussed in Section 1.0 of Appendix F. The detailed task timelines are the times shown for the exchange of one reactor module, whereas Figure 4-4 shows an integrated flow for the simultaneous exchange of four modules. This maintenance plan requires four sets of maintenance equipment, four spare reactor modules, four hatches in the reactor room wall, and four hot cells. It is estimated that 154 days are required to exchange the four modules, providing an overall plant availability of about 66%. While this availability is above the level of minimum acceptability discussed later in Section 5.0, it is likely to decrease if the assumptions made concerning the reactor design approach cannot be satisfied.

**LARGE MODULE CONCEPT (UWMAK-I) TASK FLOW
BASELINE CONFIGURATION**

Figure 4-4

In addition to the full size UWMAK-I concept (5000 MW_{th}) an analysis was also conducted for a reduced size large module as exemplified by a 3000 MW_{th} reactor. The detailed time estimates for this reactor are found in Section 3.0 of Appendix D. The maintenance plan for the reduced size large module is identical with that for the full size module except that the maintenance times are reduced and the maintenance equipment is reduced in size. Figure 4-5 shows the sequence of operations for the reduced size large module concept. The total time required for exchange of the four modules is only about 134 days, a reduction of 20 days, or 13%, and the overall availability is approximately 69%. The cost aspects of this increase in availability are discussed in Section 6.0.

4.2.1.2 Alternate Large Module - Culham Mk-II - For the purpose of comparing a different type maintenance approach for a large module concept a maintenance plan for an alternate large module reactor concept has been developed. The alternate large module reactor used for this plan is a concept based on an approach for first wall/blanket removal developed by the

LARGE MODULE CONCEPT (REDUCED SIZE UWMAK-I) TASK FLOW

13-967

Figure 4-5

Culham Laboratory. This approach is scaled up in size from the original Culham Mk-II data and adapted to a modified UWMAK-I basic reactor. A brief definition of the concept, as applied to the UWMAK-I and used in this maintenance plan, is described in Section 3.3. As with the UWMAK-I, an entire radial sector of the first wall/blanket is replaced; however, it differs from the UWMAK-I technique in that the toroidal field magnet is not removed with the blanket module.

Assumptions and Ground Rules - Some basic assumptions and ground rules used in establishing this overall maintenance plan are:

- o The reactor building arrangement is the same as for the UWMAK-I.
- o The reactor is divided into twelve (12) identical sectors.
- o The reactor room diameter can be increased as required.
- o Multiple hatches, up to a maximum of 4, can be incorporated into the reactor room wall.
- o Neutral beam injectors are used for auxiliary heating.
- o Poloidal field magnets are located such that relocation (i.e., raising or lowering) is not required.
- o Maintenance machines are track mounted and similar in nature to those defined for the UWMAK-III design.

- o Manifold disconnects are required only at the lower portion of each sector.
- o No structural connections or vacuum seals are required between adjacent modules.
- o The primary coolant is GHe.
- o The primary GHe coolant manifolds utilize welded connections.
- o The blanket section has a useful life of 2.3 years.

Additional assumptions and ground rules are listed with the time estimates given in Section 1.0 of Appendix D. Most of the reactor room arrangement assumptions made for UWMAK-I apply to the Culham Mk-II concept also. The use of maintenance equipment operating on tracks eliminates the requirement for a smooth floor.

Maintenance Procedure - The procedures involved in the removal and replacement of the modules in a single first wall/blanket sector follow those for the UWMAK-I for shutdown and startup but deviate significantly for disconnect and removal. The procedures for the exchange of the modules included in one sector are briefly described in the following list. For these operations shutdown and startup procedures are not repeated when more than one set of modules is exchanged.

- o The reactor room environment is adjusted for maintenance operations. The cryovacuum pumps are allowed to warm up to room temperature; room and plasma chamber pressures are brought to near atmosphere; the GHe coolant pressure in the module is reduced and the lithium breeder lines are drained at the point of disconnect.
- o The concrete inner cylindrical wall is rotated until the hatch is opposite the reactor sector to be removed.
- o The hatch is opened and the Manipulator Maintenance Machine (MMM) is used to disconnect the neutral beam injector services followed by the Heavy Duty Lift Machine (HDM) which moves the neutral beam injectors out of the reactor room onto a transport dolly in the reactor hall.
- o The structural shear panel between the T.F. magnets at the module sector is unbolted and removed from the reactor room using the HDM. The panel is moved to storage using the reactor hall overhead crane.
- o The door in the outer shield is unbolted and removed in the same manner as the shear panel.

- o The gaseous helium coolant manifolds located below the inner shield at the front of the module are cut using the MMM and a weld cutting tool.
 - o The lithium breeder lines are disconnected in the same area as the GHe coolant lines.
 - o The diverter module coolant lines are disconnected above the T.F. magnets simultaneously with the other line disconnects.
 - o The reactor module is moved from the reactor between the toroidal field magnets on the Module Removal Device (MRD). The MMM tows the module from the reactor room. No disconnect between modules is required.
 - o The reactor module is moved to the hot cell on a transfer carriage in the reactor hall.
 - o The diverter module is structurally disconnected and lowered to the diverter module dolly. This dolly uses the same tracks as the reactor module. The diverter module is detached and the dolly towed by the MMM.
 - o The diverter module is moved to the hot cell by the overhead crane.
- The installation of new modules is accomplished in general by reversing the above procedure with the exception that:
- o Manifold connections are leak tested.
 - o The primary and secondary vacuum chambers are leak tested.
 - o The integrity of neutral beam injectors is verified.

A general discussion of the maintenance plan and the rationale used follows.

The reactor shutdown operations are basically the same as for the baseline large module. For additional discussion refer to the preceding section. The primary reactor coolant is assumed to be gaseous helium as opposed to lithium for the baseline large module reactor; however, this will have no significant effect on the shutdown operations. As with the baseline reactor, the reactor room environment is maintained at slightly less than atmospheric pressure with an inert gas and all magnet currents are reduced to near zero but the magnets are maintained at or near LHe temperature. The lithium breeding material in the blanket modules not being exchanged is maintained at a temperature slightly above the freezing point throughout shutdown to prevent possible module damage and to speed up the startup operations.

Neutral beam injectors of the same size as those used for the baseline reactor must be moved to provide a clear path for module extraction. For this design only two neutral beam injectors must be removed instead of the three required for the baseline large module concept. Access is feasible with the removal of only two modules because the plasma major radius is significantly smaller, resulting in a module sector with a smaller width, thereby allowing it to pass through an area occupied by only two neutral beam injectors. Also, the neutral beam injectors are at a smaller cant angle to the reactor radii than for the baseline large module reactor and present less interference to module removal. The technique for removing the neutral beam injectors is slightly different than for the baseline. Air bearings are not used for support during movement since the track systems assumed for removing the blanket modules make a smooth floor impractical. A Heavy Duty Lift Machine (HDM), track mounted, is used to lift each neutral beam injector and remove it from the reactor hall. The overhead crane in the reactor hall then moves it to the hot cell. The numerous service connections with the neutral beam injectors are disconnected by use of the Manipulator Maintenance Machine (MMM).

Structural shear panels are assumed to exist between adjacent toroidal field magnets. These panels are similar to those described for the UWMAK-III reactor described in Section 3.4, and are removed in basically the same manner (see Section 4.2.1.3). For this reactor the panels do not form a vacuum tight seal as for the UWMAK-III. The Heavy Duty Lift Machine (HDM) is fitted with a lift and storage fixture and is then used to lift and remove the panel to the reactor hall where the panel is picked up with the reactor hall overhead crane.

The outer shield door forms the primary vacuum chamber wall. This door is removed to gain direct access to the blanket module. The door is of such width that it will fit between adjacent toroidal field magnets; yet, when removed, it will also provide a space wide enough for a primary blanket module to pass. Removal of this door is by the same basic procedure that is used for removal of the structural shear panels and uses the same equipment. It is assumed that this door is bolted in position and that bolted joints will provide a sufficiently high impedance to form the primary vacuum joint when the secondary (outer) chamber is maintained at a vacuum of 10^{-1} to 10^{-3} torr. If a welded joint is required, the removal and replacement of this

door becomes more difficult and much more time consuming. The door is assumed to be cooled by gaseous helium which requires that supply and return lines be disconnected prior to removal.

The reactor design utilizes gaseous helium as the coolant for the first wall blanket. Each primary module sector is supplied with sufficient helium coolant through one main supply and one main return manifold. This assumption minimizes the number of manifolds which must be cut for module removal. Additional manifolds to distribute coolant around the module are required. These are removed with the module and do not have to be disconnected. The main supply and return manifolds are located at the lower portion of the module with the disconnect point located inside the outer shield but outside of the inner shield and above the sill of the shield door. These lines utilize welded connections and are cut and welded in the same manner as the primary lithium coolant lines of the baseline large module reactor. Lithium supply and return lines are also required to supply a low rate of flow of lithium for tritium breeding. These lines are located adjacent to the primary gaseous helium coolant lines, but they are probably small enough that mechanical disconnects are feasible and no welding or cutting is required. Helium coolant lines are also required for the small diverter module located at the top portion of the reactor. These lines are also small and it is assumed that mechanical disconnects may be used in place of a welded joint. No tritium breeding takes place in this small module; therefore, no lithium lines are required. All line disconnects are accomplished by using a manipulator maintenance machine (MMM), an automatic line cutter/welder, and a line connector installation/removal tool. These tools are similar in concept to those used to disconnect lines for the baseline large module reactor.

The primary blanket module is positioned in the reactor in such a manner that it is structurally supported from the bottom and is free standing. Adjacent blanket modules are not structurally connected. The module is removed by moving it radially outward on tracks. A section of rails must be installed to bridge the shield door sill; the module support trolley, with wheels, is fixed in place permanently beneath the module. The module weight is supported on structure and locator pins during reactor operation and the trolley is extended mechanically to pick up the load for transferring the module. The module is moved through the reactor room hatch and then to a

reactor module transfer carriage on which it is transported to the hot cell. This carriage runs on a circumferential track in the reactor hall.

In defining the reactor configuration, one single-null poloidal diverter is located at the top of the reactor. This results in the requirement for a small blanket module between the diverter slots; this module must also be removed and replaced. Removal is accomplished by lowering the module vertically to floor level and placing it on a track mounted dolly. Lowering is accomplished by a hoist assembly placed in position above the diverter and operated by the manipulator maintenance machine.

Replacement of blanket modules and reconfiguring the reactor to operating condition is essentially a reverse procedure from that described. However, some additional tooling and validation is necessary. The welding of the main coolant manifolds includes an inspection of the welds. All lines that have been disconnected are also pressurized and checked for leakage. When all shield doors have been reinstalled, a vacuum test is conducted to check for flow at the shield door seals. After reinstallation of the neutral beam injectors a validation procedure is conducted to assure that they are in operating condition. A complete vacuum check at operating pressures in both the inner (plasma) chamber and outer chamber (reactor room) is also conducted after the reactor room hatches are closed and sealed.

A detailed maintenance task breakdown and time estimates for the removal and replacement of a single module are given in Section 1.0 of Appendix D.

Maintenance Equipment - While this maintenance plan utilizes maintenance equipment similar in many respects to the equipment devised for the UWMAK-III, a more detailed examination of this equipment than merely defining the conceptual functional requirements must be undertaken to establish a credible level of feasibility.

The major equipment items are a Manipulator Maintenance Machine (MMM), which will require one or two manipulator tipped booms capable of reaching all parts of the outside of the reactor in much the same manner as the UWMAK-I equipment but moves on a track system and is capable of handling close in operations like the UWMAK-III equipment.

A Heavy Duty Lift Machine with the approximate capability of the larger UWMAK-III maintenance machine described in the next section, 4.2.1.3, is required to lift the shear panels, shield doors and neutral beam injectors by use of fixtures attached to its vertical working face. The weight of

these items is expected to be approximately the same as those similar UWMAK-III components. However, this machine must also rotate to position the working face properly so that it can lift neutral beam injectors which are installed at an angle to any circumferential or radial movement. Similarly, the reactor hall/reactor room concept requires approximately a 90° rotation capability to move large equipment into the reactor hall through the hatch.

The reactor Module Removal Device (MRD) is another concept where the requirements must be examined. The space below the reactor module is limited and the device must be capable of fitting in this space, raising the wheels from the tracks and surviving long reactor operating periods without any breakdown. The interference of the coolant and breeder lines in front of and below the module almost precludes inserting even a collapsible device between the lines that can handle such large loads (estimated for this 5000 MW_{TH} reactor to be approximately 600 to 800 tonnes per sector).

Other equipment includes large and heavy transfer dollies and carriages but these are state-of-art capabilities and serve only to support the aforementioned devices. It may be desirable to man these devices but this maintenance plan considers all of them to be remotely operated.

Minimum Cost Maintenance Plan - The analysis conducted to determine the cost of electricity when using this reactor concept and maintenance plan used fractions of first wall/blanket replacement identical with those examined for the UWMAK-I analysis. Details of this analysis are discussed in Sections 5.0 and 6.0.

The analysis indicates that the minimum cost of electricity is achieved when the maintenance plan is based on replacing the modules in four sectors, using four sets of maintenance equipment, during each scheduled outage. Replacement of these four sectors requires a total elapsed time of approximately forty-seven days. A flow diagram of this replacement operation is shown in Figure 4-6. The individual task times presented in this figure differ from those in Appendix D as the nominal manpower utilization factor of 75% has been applied to the times shown here. The sequencing of events in this flow diagram assumes that all operations are a parallel effort between the four sector locations. The resulting plant availability is approximately 74%.

ALTERNATE LARGE MODULE CONCEPT (CULHAM MK-II) TASK FLOW

13-966

Figure 4-6

4.2.1.3 The Intermediate Module Concept - UWMAK-III - The maintenance plan and time estimates for the exchange of the intermediate size first wall/blanket modules employed by the UWMAK-III design approach are defined in this section. These modules, as described in Section 3.0, are smaller than the module used by the UWMAK-I concept, but much larger than those used by the GA-DPR approach. Hence, the name intermediate is selected.

The UWMAK-III modules comprise the outer wall, diverter, and graphite ISSEC inner wall panels and these modules must be replaced on a regular basis. The structural life of the "A" modules is estimated at two years, whereas the life of the "B" modules and the diverter modules is estimated at 4 years. Hence, during any shutdown for replacement of the "A" module only half of the "B" and diverter modules are replaced. In addition, three of the six ISSEC panels are replaced each two years.

Assumptions and Ground Rules - The principal assumptions on which the maintenance plan and the time estimates are based are given below. Additional detailed assumptions are stated in the level 3 timeline analysis sheets in Section 1.0 of Appendix B.

- o Radiation levels inside the reactor room necessitate that all maintenance must be controlled from remote control rooms arranged around

the reactor room and/or from shielded cabs installed on the major maintenance vehicles.

- o No manpower limitations have been used in developing the time estimates. The time estimates presented assume that the necessary men are available to conduct any prescribed task.
- o The reactor room is large enough to provide space to move reactor components around the reactor room. A hot cell is provided which is large enough to contain any first wall/blanket modules that are removed in addition to other subsystem components or assemblies.
- o A large airlock and decontamination cell is available which provides access for maintenance machines and new modules or other spares into the reactor room.
- o The atmosphere of the reactor room during maintenance operations is an inert gas (possibly argon) at slightly less than atmospheric pressure. Many lithium lines are disconnected in the maintenance process and the inert atmosphere is provided as a safeguard against fires.
- o The lithium is not drained for module removal because no way has been identified for completely draining the modules with this module arrangement.
- o Since it is desired to keep the lithium molten in the modules not being replaced, the atmosphere is maintained at slightly above the temperature of the molten lithium but below the temperature at which damage occurs to the shield.
- o New modules being replaced are assumed to be prefilled with liquid lithium. This reduces the time for startup by removing the need to remelt the lithium in the intricate blanket passages.
- o Lithium in the modules is heated by the room atmosphere, energy input of the circulation pumps, and by auxiliary heaters to keep the lithium molten. Since the lithium must be heated external to the reactor for later "bakeout" operations in the vacuum chamber, additional external heaters will probably be required and their use during shutdown may be a more efficient method to keep the lithium molten than the use of pump power.
- o The lateral support access panel has no penetrations through the

panel to aid removal and any repair of seals on the panel is accomplished when the panels are in storage.

- o Poloidal field magnet retraction is a completely automated function requiring no maintenance machinery. This feature precludes removal of lateral support panels at all locations in order to gain access to raise or lower these magnets.
- o The poloidal field magnets are maintained at low temperatures by coolants carried in movable lines which lower or raise with the magnets.
- o The lithium coolant lines utilize mechanically disconnected joints. The joints use ring clamp type connections. The application of this type of disconnect at the temperatures involved may require an advance in the state-of-art for these large lines but their use is desirable because the disconnect/connect time is significantly less than if a welded joint is used.
- o Control rooms are equipped with a viewing window for a panoramic view of the maintenance area near the control room, and with television monitors for remote viewing. Additional viewing capability is provided by placing shielded cabs on the major equipment items where this is feasible. These cabs contain television monitors as well as viewing windows and are equipped with life support systems and emergency egress for rescue operations.
- o The normal crew changeover at shift change is accomplished either by an auxiliary vehicle or by using an overhead crane to transport the cab to an entrance lock. Quick disconnect fittings are used to make or break the cab's attachment to the machine, power supplies and control circuits. Control is transferred from the cab to other control rooms as required.

Maintenance Procedure - The procedure for replacing the UWMAK-III is briefly outlined below:

- o The reactor room environment is purged of tritium; cryopumps are allowed to heat to room temperature; the plasma chamber pressure and the secondary vacuum region are brought to near atmosphere conditions; and the room temperature is maintained above the melting point of lithium. The poloidal magnet support structure latches are disengaged automatically.

- o Those poloidal field magnets which interface with module removal are translated out of the way by vertical power drives. Those magnets outside of the toroidal magnets are retracted before the access panels are removed.
- o Simultaneously, the Primary Maintenance Machine (PMM) is employed to attach strongback fixtures to the access panels which act as shear webs between the toroidal magnets. This machine also removes the bolts which attach the access panels.
- o The RF waveguides and coaxial cable sections at the reactor sector are disconnected and removed by the PMM. The RF power supply room is relocated below the floor of the reactor room and does not interfere with module replacement activities.
- o The lithium coolant manifolds within the secondary vacuum enclosures are disconnected. Freeze plugs and mechanical disconnects are used and the pipe ends are capped after disconnect.
- o At the same time, the lithium coolant manifolds for the diverter modules are disconnected from above or below the reactor.
- o The hinged shield doors are then rotated into the open position with the use of jacks. Thus, access is provided to the "A" module.
- o The Module Handling Machine (MHM) is used to detach the "A" module and withdraw it from the reactor sector between the toroidal magnets (which remain fixed in place). All lithium cooled modules remain filled with lithium.
- o The upper or lower "B" modules are removed from within the chamber using access through the "A" module aperture. Demounting and transport are accomplished by the MHM.
- o The graphite ISSEC inner wall panels are removed from within the chamber in a manner similar to the "B" modules.
- o The diverter module is removed by translating vertically to clear the shield with the rather long vertical coolant pipe stubs, it is then rotated 90° and moved out through the "A" module opening. This procedure is described in more detail for the use of the MHM in Appendix E, Section 2.0.
- o The modules which are not removed are then inspected as required.

The replacement procedures are essentially the reverse of the above operations with the addition of some test activities. The vacuum integrity check is conducted after the lithium manifolds are connected and the lithium is used as a heat source for bakeout of the impurities in the chamber. The replacement of the RF waveguides and the access panels can be accomplished in parallel with the vacuum test. Since all modules are installed full of lithium, there are no fill and drain requirements.

Maintenance Equipment - For the UWMAK-III design concept, the maintenance equipment is required to operate both externally and internally with respect to the reactor plasma chamber. Maintenance equipment is required to remove all reactor components obstructing access to the first wall/blanket modules as well as to disconnect and install all modules.

As with the previously discussed large module concepts, only a few major pieces of equipment are required as indicated in Section 2.0 of Appendix E. Of these equipments, the Primary Maintenance Machine (PMM) and the Module Handling Machine (MHM) are the largest and most complex items required. The PMM is the basic machine for removing and reinstalling the reactor components that obstruct passage of the modules and the MHM removes and installs the modules. Both machines are mounted on rail track to provide for movement about the reactor but most operations are conducted with the machine fixed in place. The basic arrangement was outlined by Bechtel in the UWMAK-III study (Reference 4) and developed in more detail in this study. The MHM is typical of both machines and is illustrated in Figure 4-7. Both machines employ a working-face concept in which the forward vertical face is modified for different major operations. A working-face concept provides flexibility for tooling arrangements as well as a rigid support for heavy loads. The position of the work can be adjusted easily for variations in fit and for precisely distributing the load among the pickup points to ease the removal of panels in the horizontal direction. This flexibility is difficult to attain by use of the overhead crane.

The maximum load for the PMM occurs when the access panel is removed from between the toroidal magnets. The access panel support fixture is attached to the access panel and picks up the load while an impact wrench moves around the fixture on the working-face and removes the bolts. The entire working-face is then retracted to move the access panel under the overhead crane which, in turn, lifts the panel and fixture clear of the PMM.

MODULE HANDLING MACHINE CONCEPTUAL CONFIGURATION

Figure 4-7

Other tools and manipulators are also fitted to the working-face by the transfer crane. These tools are used to attain access to the coolant manifolds, waveguides and shield plugs. Small components such as manifolds may be placed on the MHM's forward platform conveyor and then moved to the rear of the machine through the working face. The conveyor places these components in position for transfer to dollies.

Conceptually, the MHM is essentially the same as the PMM but the size is smaller. This machine moves through the hole prepared by the PMM on an extension of the floor placed in the access panel opening. Figure 4-7 shows the MHM with an "A" module attached. The peripheral welds, which act as vacuum seals around the "A" module flanges, are cut and the bolts removed by tools operating on manipulator arms on the outside track of the working-face. (See Appendix F of Section 2.0 for seal details.) Additional fixtures with elevators and tools are required to outfit the working-face to remove or replace "B" modules and ISSEC panels from the reactor interior and are installed by a transfer crane. These modules are placed directly on the dollies by a crane in this concept since they are much lighter in weight than the "A" module. The transfer crane may be either the overhead crane or an auxiliary crane mounted directly on the MHM (not shown in Figure 4-7).

Two additional machines are required for disconnecting the diverter module coolant lines and for removing the upper and lower cryovacuum pump assemblies. The upper central core maintenance device is a manipulator system emplaced by the overhead crane on a circular track around the core. Several of these may operate at one time, depending upon the number of pumps that must be serviced. The lower central core maintenance device operates on a level below the reactor floor to access lower diverter coolant lines and vacuum pump components. Components removed by this machine are moved to a plug in the reactor room floor and then handled by the reactor room overhead crane.

Control of maintenance operations for the UWMAK-III is a combination of the features used for the General Atomic-DPR and the UWMAK-I. Control rooms around the reactor room wall are equipped with both direct and television viewing and can manage all operations. However, if required, control cabs can be installed on the PMM, MHM, and Tractor units to provide direct viewing of many aspects of the detailed tasks. The cab is omitted on the MHM in Figure 4-7 but it can be located at the counterweight position. The tractor units (tugs) provide the necessary capability to transfer crews for shift change and safety. In addition, the cabs are all demountable from their bases to permit transfer by the overhead crane to airlock entrances in the reactor room wall backup crew egress method. Computer control of some operations may be feasible.

Inspection of the remaining modules is carried out after the plasma chamber has been penetrated. Equipment for inspection and leak detection have been included in the equipment lists in Appendix E. The maintenance equipment concept includes equipment to provide access for such inspection and test operations through appropriate outfitting of the major equipment units.

Minimum Cost Maintenance Plan - The time estimates developed and presented in Section 1.0 of Appendix B are for a remote maintenance operation and cover the removal and replacement of the first wall/blanket modules in one of the 18 sectors. The exchange of different fractions of the first wall/blanket has been analyzed and the exchange fraction resulting in the lowest cost of electricity is the replacement of all 18 modules during a

scheduled outage. (Other alternatives examined included the replacement of modules in 1, 2, 3, 6 and 9 sectors.) The maintenance plan for exchanging modules in all 18 sectors is the plan used in the comparative analyses discussed in Sections 5.0 and 6.0. For this maintenance plan the sequence of maintenance operations for the baseline intermediate module concept (UWMAK-III) and the time to accomplish these operations is shown in Figure 4-8. The time estimates shown in the figure are based on a 24 hour day with the base estimates from Section 1.0 of Appendix B adjusted by a 75% manpower utilization factor.

For the selected maintenance plan six (6) sets of maintenance equipment are used to exchange six sectors at a time. The potential for paralleling certain operations results in the maintenance outage time of about 112 days every 32.9 months, which yields a respectable plant availability of approximately 73%. The alternative of replacing modules in only 9 sectors during an outage but increasing the frequency of the outage may be worthy of consideration since the penalty is only a cost of electricity increase of 1.5%,

and an availability decrease to approximately 70.3%. The maintenance outage duration is then approximately 89 days. The advantage of this alternative arises when considering unscheduled maintenance operations as discussed in Section 4.3.

4.2.1.4 The Small Module Concept - GA-DPR - The basic approach to maintenance of the General Atomic Demonstration Power Reactor is to exchange the 2000 first wall/blanket modules from inside the plasma chamber, rather than attempting to access the modules from the chamber exterior. This approach is required as a result of the doublet plasma geometry and the associated poloidal field magnet configuration. Magnets located in the central outer wall region cannot be translated without interfering with the plasma chamber.

To implement this maintenance approach, remotely controlled and operated machines are installed on the reactor torus at dedicated openings in the upper vacuum ducts. These machines extend into the plasma chamber and perform the necessary operations to exchange the first wall/blanket modules.

The module is a relatively simple device which is filled with a lithium moderator and is cooled by gaseous helium. There are several other components associated with each module, such as the silicon carbide liner plate, a graphite protector ring, a clamp ring, and tricuspid graphite blocks between modules, all of which must be handled and exchanged by remote equipment.

Assumptions and Ground Rules - The generation of an overall maintenance plan for the scheduled exchange of the GA-DPR first wall/blanket modules requires the formulation of certain ground rules and assumptions which are contained in the following list.

- o All modules are exchanged from inside the plasma chamber by unmanned, remotely controlled machines.
- o The modules and related components have a five (5) year operating life based upon a fluence limit of 5 megawatt years/meter².
- o Access to the plasma chamber is through the auxiliary vacuum ducts above the reactor which are permanently modified to have maintenance equipment entry ports.
- o Manned access to the reactor room is not feasible after the vacuum duct ports are opened and the plasma chamber interior is exposed to the reactor room. Therefore, the installation of all maintenance equipment on the reactor at the entry ports of the auxiliary vacuum

ducts is performed remotely by overhead cranes and manipulator devices.

- o The shield and reactor support structure are designed to react loads imposed upon it by the maintenance equipment.
- o The reactor support structure and poloidal coils located above the vacuum duct ports are moved or modified so that they will not interfere with the installation or operation of the maintenance equipment.
- o The current in all magnets is reduced to zero during maintenance. However, the magnets are maintained at liquid helium temperatures at all times.
- o A method of shutting off helium flow to individual blanket modules or groups of modules as required by the maintenance operations is feasible. Afterheat removal is required during maintenance without damage to the modules with whatever shutoff method is used.
- o The neutral beam injection and vacuum pumping systems do not interfere with first wall/blanket maintenance operations.
- o There is sufficient floor area in the reactor room to satisfy logistics and staging requirements for maintenance equipment and first wall/blanket components.
- o Circulation of the reactor room atmosphere and removal of tritium from it is continuous during maintenance operations.
- o The remote maintenance equipment is installed in the reactor room and removed from it at each scheduled outage.
- o Other reactor subsystems are not disturbed by first wall/blanket maintenance operations.
- o There is one remote control console and operator for each maintenance machine. The consoles and operators are stationed in a remote control room.
- o The electrical power and remote control connections for each remote maintenance equipment item is located at the top of the reactor near each vacuum port. The connections are a standardized design and are completed by the overhead manipulator.

Maintenance Procedures - The sequence of activities for exchange of the first wall/blanket modules is briefly outlined. These procedures apply to the installation of the necessary maintenance equipment to replace only a few or all of the 2000 modules in the reactor since the equipment installation is

capable of reaching any part of the interior of the plasma chamber. Therefore, unlike the large and intermediate module concepts, the access procedures for equipment setup are not repeated when additional modules are removed. However, the option to use additional sets of equipment to increase the rate of module removal does exist, as discussed later, and this will require repetition of the access procedures. The procedures outlined below are for a single set of equipment which is the minimum required to conduct the module replacement operations at any point in the reactor.

- o The reactor is shut down and the plasma chamber pressure raised to atmospheric. The reactor cooling system operates during afterheat decay. Air circulation is maintained in the Reactor Room (RR). These actions are initiated from the reactor control room.
- o The vacuum duct port covers are removed by the overhead manipulators and cranes and stored in hot cells.
- o The Remote Maintenance Machine (RMM), Remote Loading Machine (RLM) and Remote Viewing Machine (RVM) are installed at designated vacuum duct ports by the overhead crane, setup, outfitted, and checked out. A minimum of 4 RVM's is required for complete chamber coverage.
- o The RMM removes first wall liner plates and modules at the top and bottom of the plasma chamber and installs adapter modules and track segments below the adjacent auxiliary vacuum port where an RLM is installed.
- o The In-Chamber Maintenance Machine (ICMM) is inserted into the plasma chamber at the adjacent port and erected by the RLM, then outfitted with arms and workheads by the RMM.
- o The installed ICMM completes the process of laying track to access the required blanket modules. (When two or more ICMM's are used each lays a proportional share of track.)
- o The ICMM completes the removal and replacement of the designated blanket modules using special manipulator arms and workheads. Leak tests are performed on the replaced modules. Modules not replaced are inspected before access to them is unavailable.
- o The ICMM removes the track segments and completes the exchange of modules beneath the track. These modules are also tested and inspected.

- o The ICMM is removed from the plasma chamber, leaving one segment of track installed.
- o The RMM removes the last track segment and completes the exchange of modules obscured by the track.
- o The RMM, RVM, and RCM are removed from the vacuum duct ports by the overhead crane.
- o The vacuum port covers are replaced.
- o A vacuum check of the plasma chamber is performed with the helium coolant flow to all modules established. Part of this test includes a bake-out of the chamber to drive off impurities in and on the replaced components.
- o The chamber is validated and the reactor started. After final tests are complete, the reactor is returned to duty.

The detailed procedure for replacing any blanket module by an RMM or ICMM during the process described above involves the following sequence of events:

- o Removal of the first wall silicon carbide liner plate.
- o Removal of a graphite ring around the module body.
- o The cutting of two peripheral welds at flange joints around the vacuum seal ring.
- o Removal of the seal ring.
- o Rotation and freeing the module clamping ring.
- o Extracting the module and clamp ring from the module cavity.
- o Removal of the module and other components from the plasma chamber.

The installation of a new module is accomplished, in general, by reversing the above procedure, with the following exceptions:

- o The structure to which the seal ring is attached must be dressed to remove traces of the original weld and the module cavity cleaned of debris.
- o The new seal ring must be welded in place and the weld leak tested.
- o The intermodule tricuspid graphite blocks must be replaced.

The logistics of moving thousands of reactor components into and out of the plasma chamber may create overhead crane utilization problems. However, the most difficult task appears to be that of removing and rewelding in place the vacuum seal rings. Approximately 8800 linear meters of helium tight welds must be accomplished remotely to exchange 2000 modules. The maintenance

plan is based on the use of laser technology to perform this operation, but the comparative value of the scheme with respect to other methods of welding in confined areas must be defined.

Another aspect of the maintenance plan involves the use of specialized, dedicated workheads to perform the complex functions of handling, installing, and removing the modules and related components. These interchangeable workheads interface with manipulator arms on designated in-chamber maintenance machines and perform all required tasks. Design configurations of the laser system and workheads remain to be defined.

Additional details of the maintenance procedures and of the estimated time to conduct them is provided in Section 1.0 of Appendix C.

Maintenance Equipment - The foregoing maintenance functions are accomplished using four basic maintenance machines, identified as:

- o The Remote Maintenance Machine (RMM)
- o The In-Chamber Maintenance Machine (ICMM)
- o The Remote Loading Machine (RLM)
- o The Remote Viewing Machine (RVM)

Each machine attaches to the reactor at an auxiliary vacuum duct port. The RMM, as shown in Figure 4-9, is used to remove modules on the vertical centerline of the plasma chamber and install upper and lower track segments for support of the ICMM. The ICMM is a mobile device which traverses track installed in the plasma chamber to gain access to modules around the torus. The ICMM, Figure 4-10, performs the basic module exchange function, using various manipulator arms and workheads in the proper sequence. The RLM performs the function of transferring reactor components and track segments into and out of the plasma chamber by means of a loader rack. The RLM also installs and erects the ICMM in the chamber. The RVM performs the functions of providing the interior lighting and TV coverage in the plasma chamber, power for the ICMM and the entry path for the laser system beam.

A summary of these and other identified maintenance equipment items required by this maintenance plan and their characteristics is presented in Section 3.0 of Appendix E. The significant characteristics of the four basic machines is that they are remotely controlled, highly automated, interface with a common vacuum duct flange configuration, fit a 1.0 meter diameter vacuum duct opening, and are installed by an overhead crane and overhead manipulator.

REMOTE MAINTENANCE MACHINE (RMM)

- RMM CONFIGURATION FOR EXCHANGING BLANKET MODULES UNDER TRACK SEGMENTS – SIDE VIEW

IN-CHAMBER MAINTENANCE MACHINE (ICMM) CONCEPT **-SIDE VIEW-**

13-718

Figure 4-10

There are aspects of this maintenance concept which merit further consideration:

- o The design of the maintenance equipment defined in Section 3.0 of Appendix E, requires advances in the state-of-the-art for remote control devices. The feasibility of designing workheads, manipulator arms, and the basic RMM and ICMM with the required performance capability to fit the envelope and weight constraints is unknown at this time.
- o The RMM, RLM, and RVM equipment items tend to be long and heavy. The capability of the vacuum ducts and reactor support structure to react these loads has to be established.
- o The feasibility of computerizing many of the repetitive functions, as was considered in the time estimates, has to be investigated, as does the effect of wall growth and distortion on preprogrammed operations.
- o The feasibility of adapting laser technology to cut and perform welds automatically on the blanket module vacuum seal ring must be investigated in greater depth. The laser mirror system and computer controlled optics which direct and collimate the energy beam and the design of a workhead to receive and focus the beam are undefined at this time. Also, while control of the effect of background vibration on overall system performance appears feasible upon brief examination, the extent of the problem and viability of potential solutions should be examined more thoroughly.

Minimum Cost Maintenance Plan - The selection of an overall maintenance plan based on minimum cost of electricity involves a tradeoff of the number of modules to be replaced per outage and the number of sets of equipment required. This tradeoff is discussed in Section 5.0. The exchange of different fractions of the first wall/blanket have been analyzed. The fractions considered include the replacement of 1/6, 1/5, 1/4, 1/3, 1/2 and all of the 2000 modules in the reactor. The approach which produces the lowest cost of electricity is to exchange 660 modules (33.3% of the 2000 modules) and to use four sets of maintenance equipment. This sequence requires approximately 214 days, as shown in Figure 4-11, and provides a plant availability of approximately 64%.

SMALL MODULE CONCEPT (GA-DPR) TASK FLOW
BASELINE CONFIGURATION

13-965

Figure 4-11

The task times shown in Figure 4-11 differ from those shown in the detailed timeline of Appendix C because of the use of four, rather than two, sets of maintenance equipment. Four sets result in a lower cost-of-electricity from the plant when all factors are considered. The use of four sets doubles equipment installation time because installation is dependent upon overhead crane utilization and four additional vacuum port covers must be removed. However, this increase is more than compensated for by the time savings realized during the exchange of 660 modules. These time estimates are based on a 24 hour day with the baseline estimates from Section 1.0 of Appendix C adjusted by a 75% manpower utilization factor.

4.2.1.5 The Small Module Concept - General Atomic DPR with In-Place Maintenance Equipment - The maintenance analysis of Section 4.2.1.4 indicates that several features tend to limit further reductions in the maintenance outage time. The use of one or more ICMM's necessitates the laying of track to gain access to the blanket modules. Also, the installation of the maintenance machines saturates the overhead crane utilization capacity. Therefore, an entirely different GA-DPR maintenance plan is formulated.

This approach to GA-DPR maintenance provides a major reduction in maintenance time by leaving the maintenance equipment installed on the exterior of the reactor during reactor operation so that it is immediately available for first wall/blanket maintenance. The time savings occur because the vacuum port cover design is changed to provide for rapid access and reassembly and the cumulative time for installing and removing equipment at each of the 16 ports and within the plasma chamber is eliminated. This approach can be used and still retain the ability to maintain or overhaul the maintenance equipment during reactor operation almost as readily as mobile equipment. Each item of in-place equipment can be remotely removed and replaced in a very short time to permit its maintenance or overhaul off-line. To accomplish such an exchange the reactor must be shut down during removal and replacement operations but these can occur at the same time as almost any short duration outage.

Assumptions and Ground Rules - The assumptions and ground rules defined for the baseline GA-DPR maintenance plan are also applicable to the in-place equipment plan, with the exception that:

- o The maintenance equipment is in-place at the beginning of the scheduled outage.
- o The maintenance functions will be conducted through the auxiliary vacuum ports in a similar manner to that used for the baseline small module maintenance plan, but without the use of in-chamber maintenance machines.
- o The maintenance equipment mounted at the vacuum ports for the baseline small module maintenance plan (RMM, RLM and RVM) are used but with the following modifications.
 - The RMM has the added capability to reach any module within four module diameters of a vacuum port instead of just the modules on the top and bottom rows of the plasma chamber.
 - The RLM and RVM appendages which extend into the plasma chamber must be retractable past the vacuum duct cover and shield.

Maintenance Procedures - The sequence of events for module exchange utilizing in-place maintenance equipment is as follows:

- o The reactor is shut down in the same manner as for the baseline small module maintenance plan.

- o The vacuum duct port shields and covers are retracted automatically and simultaneously from all vacuum ports. This operation is controlled from the remote control room.
- o The RMM, RVM, and RLM machines are extended by remote control into the plasma chamber.
- o Preparations are completed for in-chamber maintenance. The RVM lighting and remote TV systems are activated and checked out. The RMM is outfitted with the proper workhead. Loader racks and dollies are staged around the reactor to remove exchanged reactor components to hot cells. New components are available in the reactor room in other loader racks on dollies. Computer control and feed back systems are calibrated. The laser beam system is aligned. A trial operational check of all maintenance equipment is conducted.
- o The RMM's remove and replace the designated blanket modules using the same sequence for module component removal and replacement, including the same special manipulator arms and workheads, that are used for the baseline maintenance plan. Leak tests are performed on replaced modules. Modules not replaced are inspected.
- o The plasma chamber is prepared for a vacuum check. The maintenance equipment is retracted and the vacuum duct port valves are automatically closed.
- o A plasma chamber vacuum check is performed, validation tests and bakeout are completed and the reactor start tests are conducted in the same manner as for the baseline maintenance plan.

Section 4.0, Appendix D, presents additional details of the functional flow and a detailed time estimate for this maintenance plan.

Maintenance Equipment - This maintenance plan utilizes installed equipment to reduce or eliminate those serial time drivers apparent in the baseline maintenance plan as follows:

- o Semipermanently install the maintenance equipment on the vacuum duct ports. The maintenance equipment is physically isolated from the chamber by automated, shielded, slide valves on each port. The maintenance equipment can be removed from its installed position for overhaul and repair during the reactor operational cycle and replaced without creating a serial time impact.
- o Utilize all vacuum ports simultaneously to optimize module replacement times.

- o Eliminate the use of the In-Chamber Maintenance Machines (ICMM's) and the time consuming task of installing and removing track segments.
- o Utilize 8 Remote Maintenance Machines (RMM's) in lieu of the 4 RMM's and 4 ICMM's used in the baseline case. The utilization of the Remote Loading Machine (RLM's) and Remote Viewing Machines (RVM's) remain the same. This scheme is shown in Figure 4-12, where an RMM is installed, as shown in Figure 4-9, at every other vacuum duct port, and each group of 2 RMM's is supported by one RLM and one RVM.
- o Modify the RMM performance requirements to give the RMM manipulator arm the capability to access any blanket module in the plasma chamber within four module diameters of a vacuum duct port instead of just the top and bottom rows of modules.

MAINTENANCE EQUIPMENT LOCATION FOR BLANKET MODULE REPLACEMENT

- o Place the various RMM workheads in a turret mechanism attached to the RMM. The turret automatically indexes the desired workhead to the manipulator arm, positions the workhead for quick attachment, and stores the workheads not in use. This greatly reduces the burden on the overhead manipulator by eliminating the need to constantly transfer workheads to the RMM.

The problem areas identified for the baseline small module maintenance plan are also applicable to the in-place equipment maintenance plan. One additional problem involves the feasibility of designing a remotely operated, vacuum tight, reuseable, replaceable, 1.5 meter diameter vacuum port cover and seal suitable for use in a severe radiation environment. The operation and maintenance of this seal is essential to the validity of the in-place maintenance equipment concept. Seals of this type without the shield have been installed as valves in smaller vacuum lines and the use of a larger vacuum valve may be only a minor extension of the state-of-art.

This equipment concept also provides the opportunity to reduce the moments imposed by the maintenance equipment on the reactor structure by placing the maintenance machine axis on the chamber vertical axis. This also makes the maintenance equipment easier to install in the vacuum ports. Since track is not installed in the chamber, the machine axis need not be offset relative to the chamber axis, unless excessive interference with poloidal field magnets, the vacuum ducts, or reactor structure results from this arrangement. The vertical installation should be investigated further before being incorporated into the concept.

Minimum Cost Maintenance Plan - The maintenance procedure associated with the plan that utilizes in-place maintenance equipment is much simpler than the baseline small module maintenance procedure and produces significant outage downtime reductions when compared with the baseline procedure. The analysis of the replacement fraction of the total first wall/blanket for the baseline small module reactor with in-place maintenance equipment that produces minimum cost of electricity results in selecting the replacement of only 400 modules per scheduled outage as shown in Figure 4-13. The range of replacement fractions analyzed is identical with the baseline analysis (i.e., 1/6, 1/5, 1/4, 1/3, 1/2 and all modules). These analyses are discussed in Section 5.0. This plan increases the small module plant availability to 75%. Figure 4-13 indicates that the downtime required to exchange 400 modules

**SMALL MODULE CONCEPT (GA-DPR) TASK FLOW
BASELINE CONFIGURATION WITH IN-PLACE MAINTENANCE EQUIPMENT**

13-970

Figure 4-13

is only 53 days over a maintenance interval of 474 days and the sequence shown indicates that the module replacement time occupies the majority of the outage duration. All times shown are based on a 24 hour workday with a 74% manpower utilization factor.

4.2.1.6 Alternate Small Module - ORNL Concept - For the purpose of comparison, a maintenance plan for a first wall/blanket concept using an alternate approach to a small module configuration has been developed. This maintenance plan is based on the reactor design described in Section 3.6, which utilizes and ORNL cassette concept (Reference 6).

Assumptions and Ground Rules - In developing this maintenance plan the following ground rules and assumptions are used:

- o The reactor is divided into eighteen (18) sectors.
- o The first blanket zone (FBZ) approach is used. Only the inner cassettes (first blanket zone) are removed and replaced. The other cassettes in the second and third blanket zones are not replaced since their life is expected to be much longer than the life of the first blanket zone cassettes.
- o The first wall life of the FBZ is 2.0 years.
- o The first wall life is the same at all poloidal and toroidal locations for the first blanket zone (FBZ).
- o The FBZ contains 15 cassettes per sector or 270 per reactor. Total number of cassettes per reactor is eight hundred ten 810 in all three blanket zones.
- o The first/wall blanket connections at the back of the shielding are not vacuum seals but provide only a high impedance barrier between the plasma chamber and the reactor room.

- o Lateral support panels between toroidal field magnets have openings to allow removal of cassettes.
- o Neutral beam injectors are used for auxiliary heating.
- o Poloidal field magnets are located such that their movement is not required for cassette removal.

Maintenance Procedures - The basic steps involved in the removal of cassette modules is:

- o Reactor shutdown
- o Remove neutral beam injectors
- o Disconnect manifolds
- o Remove cassettes
- o Inspect cassettes not removed

The installation of new modules is accomplished, in general, by reversing this procedure.

The reactor shutdown operations are the same as for the baseline intermediate size module reactor (UWMAK-III) that is used as the basis for integrating this first wall/blanket design approach into a reactor concept. The primary coolant is different in that it is a nitrate-nitrite molten salt; however, this has little effect on the type of shutdown operations involved. The cassettes also contain lithium for tritium breeding and the temperature is maintained such that the coolant and lithium remain molten throughout reactor shutdown to reduce the possibility of module damage caused by solidification and the time required to remelt the coolant prior to startup. The magnet current is reduced to zero throughout shutdown but the magnet temperatures are maintained at or near LHe temperature.

It is assumed that the cassettes are removed without draining the coolant salt or lithium. Therefore these fluids are circulated during shutdown operations to remove as much tritium and contaminants as possible prior to disconnecting the manifolds.

Neutral beam injectors of the same size as those used for the baseline large module reactor described in Section 3.2 must be removed to allow clearance for cassette removal. Two injectors must be moved at each sector location. A manipulator type maintenance machine similar to the MMM concept used for the Culham Mk II approach, Section 4.2.1.2, is used for disconnecting the service lines. The overhead crane then removes the injectors.

Prior to cassette removal, four manifolds must be disconnected from each cassette. These consist of a coolant supply and return line and a lithium supply and return line. These lines are relatively small and it is assumed that quick disconnect type connections can be used. The manipulator maintenance machine is used to make these disconnects.

At each sector region (see Figure 3-10) cassettes are removed one at a time. The cassettes do not form a vacuum boundary but provide a high impedance molecular flow joint and must be structurally disconnected. Once disconnected, the internal structural support provides for the removal of the cassettes without further interference with the motions required. The exact way in which cassettes are structurally supported and how they can be moved from side to center positions for removal requires additional definition to verify this assumption. The removal sequence first requires removal of the center cassette of the first blanket zone (FBZ) in the "A" region. (See Figures 3-10 and 3-11, Section 3.6.) Then the cassettes on each side are moved in sequence to the center cassette position and removed through the opening left by the removal of the center cassette. For the "A" region the center cassettes for the second and third zones must also be removed to allow a passage for the "B" region first blanket zone cassettes. For the other regions the same technique is used but only first blanket zone cassettes are removed.

The cassette removal technique utilizes a cassette handling machine which pulls each cassette out and slides it onto a support fixture. This support fixture with the cassette is then moved to the hot cell by use of the overhead crane.

Areas which appear to present major problems are (1) the incorporation of a diverter into the cassette design, (2) structural support of the relatively long slender cassettes, and (3) moving the cassettes sideways to the center removal position.

A detailed maintenance task breakdown and time estimate for the removal and replacement of the fifteen first blanket zone cassettes for one reactor sector location is presented in Section 2.0 of Appendix D.

Maintenance Equipment - The maintenance equipment concept used for this alternate small module design approach is similar to that described for the intermediate module approach (UWMAK-III) as described in Section 4.2.1.3

7

and typified by the Module Handling Machine (MHM) shown in Figure 4-7. However, some modifications to that maintenance equipment approach are necessary and include the following:

- o The use of a Manipulator Maintenance Machine (MMM) similar to that used for the Culham Mk II maintenance equipment concept (an adaptation of the MHM) as described in Section 4.2.1.2. The heavy duty lift machine described for the Culham Mk II concept is not required since the overhead crane can access the heavy units directly in this alternate small module concept.
- o The use of a device or devices that are emplaced on the radial tracks between the MMM and the reactor to hold the module support fixtures for regions "A," "B" and "C" identified in Figure 3-10.
- o It is planned that the upper central core maintenance device used for the UWMAK-III can be modified to withdraw the inner wall modules (Region "D" in Figure 3-10).

Minimum Cost Maintenance Plan - To develop an overall maintenance plan, a tradeoff was conducted to determine the first wall/blanket fraction which should be replaced during a scheduled shutdown to produce minimum plant cost of electricity. This tradeoff examined the same range of first wall blanket fractions used for the intermediate size module analysis (i.e., 1, 2, 3, 6, 9 and 18 sectors) and is discussed in Section 5.0. The tradeoff indicated that replacing all cassettes at six sector locations using six sets of maintenance equipment during each shutdown produces the minimum cost of electricity. Replacement of these six sectors requires a total elapsed time of approximately fifty-three days. A flow diagram of this replacement sequence is shown in Figure 4-14. The individual task times presented in this figure differ from those in Section 2.0 of Appendix D since the manpower utilization factor of 75% has been applied to the times. The sequencing of events in this flow diagram assumes that all operations are conducted as parallel efforts at the six sector locations. The resulting plant availability is approximately 72 percent. A discussion of the characteristics of this and a comparison with other plans is found in Section 6.0.

ALTERNATE SMALL MODULE CONCEPT TASK FLOW
ORNL CASSETTE CONCEPT

13-971

Figure 4-14

4.2.2 Contact Maintenance Approaches - The approach to contact maintenance is to make the general assumption that the reactor and shielding design provide radiation and thermal levels which permit personnel to enter and work inside the reactor room after shutdown. These radiation levels and the requirements involved to achieve them are discussed in Section 4.1. The following constraints are applied to all personnel working in the reactor room.

- o A breathing apparatus and protective clothing must be worn at all times for protection against ingestion of tritium from the atmosphere.
- o At any time that the plasma shield is opened or a part of it is removed either personnel move out of the reactor room or shielding must be provided.

With these constraints the tasks developed for the three baseline maintenance plans have been examined and tasks that can be done with the shield completely closed have been reevaluated and time estimates made utilizing manual operations wherever possible to accomplish the tasks.

The time has been estimated for conducting each individual task either manually or using personnel to directly assist in the task. Time differences between performing a task manually instead of remotely have been evaluated based on the particular functions of each task. The ability to perform contact maintenance does not in all cases reduce the time by a large amount. Small tasks which require many operations, such as removing small bolts,

disconnecting small lines, etc., are done much faster manually because of the greater dexterity of man than remotely operated equipment and also because of the ability to accomplish these tasks in parallel by using multiple personnel. The time for removal of a large heavy object is reduced less than for the smaller tasks because heavy machinery is still required to accomplish the task even with manual assistance. The time for this type of task (i.e., movement of heavy objects) is reduced only because personnel can be used to accomplish those parts of the task where manual assistance or direction is useful, i.e., attaching slings, etc.

In establishing the time estimates it was assumed that personnel are available as needed and that moving personnel into work positions is a parallel effort except where other constraints exist. It is also assumed that rotation of personnel who have reached their radiation limit is accomplished as a parallel effort with no effect on task times.

4.2.2.1 Large Module - UWMAK-I - A maintenance plan was developed utilizing maintenance where feasible for the baseline large module concept - UWMAK-I.

The objective of this plan is to utilize maintenance personnel to the greatest extent possible to perform, assist, or augment the required maintenance task. The maintenance approach is basically the same as that defined in Section 4.2.1.1 for the baseline large module, except where modifications or different sequencing of tasks aids in performing contact maintenance.

Assumptions and Ground Rules - For contact maintenance, the following changes and additions to assumptions and ground rules are made to those established for the baseline large module concept.

- o The reactor is designed with sufficient shielding to allow personnel to work at any position within the reactor room up to the primary shield and remain within allowable radiation dosage limits.
- o The neutral beam injectors are shielded on 5 sides such that each group of two neutral beam injectors is completely shielded.
- o All radioactive subsystems are shielded where necessary to prevent direct radiation into the reactor room after shutdown. This may include some parts of the vacuum lines and possibly coolant lines.
- o Personnel are not allowed in the reactor room when any portion of the unshielded side of the neutral beam injectors is exposed.

- o Personnel are not allowed in the reactor room when air bearings are in operation.
- o Rigorous contamination control of the reactor room environment is required.
- o The temperature environment is maintained at approximately 30°C to 40°C.
- o The atmosphere in the reactor room is air instead of the inert gas used for the baseline maintenance plan.
- o Maintenance equipment is capable of positioning personnel at various locations on the reactor.
- o Work platforms are permanently installed at locations on the reactor as required.
- o Adequate personnel are available to conduct work tasks in parallel at multiple locations when possible.
- o Adequate personnel are available to replace work crews who have reached their radiation dosage limit.

Additional detail assumptions and ground rules for this maintenance plan are included in the Maintenance Task Breakdown and Time Estimates in Section 2.0 of Appendix A.

Maintenance Procedures - The tasks for replacement of a single first wall/blanket module are essentially the same as those described in Section 4.2.1.1 except for a change in sequence in which the removal of the shield segments at sector joints is delayed until after all instrumentation and power leads and manifolds are disconnected and the T.F. magnet shear pins are removed. This change in sequence allows as many tasks as possible to be performed by contact maintenance prior to removal of a shield segment.

The revised procedures for replacement of the large UWMAK-I module are briefly described. These procedures apply to the exchange of one module (a complete reactor sector) and, with the exception of shutdown and start-up, they are repeated for each module removed.

- o The shutdown is accomplished in the same manner as for remote maintenance. The lithium is drained from those modules which are to be replaced and the reactor wall is rotated to align the hatch with the module. The hatch is opened and the reactor room tested to determine if radiation levels are satisfactory.

- o The service lines to the three neutral beam injectors to be removed are disconnected using three work crews operating in parallel.
- o The work crews leave the reactor building and the tractor units move the three neutral beam injectors to the hot cells, emplace a shield block at the exposed side of a remaining neutral beam injector, and install shield plugs in the neutral beam injector connecting ports.
- o The reactor room is checked for contamination and work crews move in to assist in removal of the toroidal field magnet cross-brace center members. Two crews and the Operational Maintenance Unit (OMU) are used.
- o The crews disconnect the upper and lower T.F. magnet services in parallel with disconnecting the reactor module coolant and vacuum lines.
- o The crews then disconnect shield GHe lines and primary vacuum lines.
- o The work crews assist in withdrawing the T.F. magnet shear pins using the OMU, the High Access Maintenance Unit (HAMU) and the Module Transporter. The crews then move from the reactor room.
- o The shield segments around the blanket joints are removed as a fully remote operation.
- o The blanket joints are remotely disconnected.
- o The module is removed with the tractor unit and the replacement module is put in position.

This same change in sequence is incorporated during module replacement, that is, the shield segments are installed as soon as possible to allow effective use of contact maintenance. Maintenance personnel again resume contact maintenance and are interrupted when the neutral beam injectors are emplaced. The reactor room is checked for contamination after every remote operating period. The procedures used for vacuum and system verification checks are the same as during totally remote operations.

While these procedures are similar to the large module replacement operations using remote maintenance, the requirement to maintain cooler temperatures in the work area may necessitate allowing the remaining modules to cool and solidify the lithium or add the requirement for lithium heaters and additional reactor room air coolers. The ventilation requirements for the reactor room will increase significantly over those applicable to remote maintenance.

Ventilation may be required to remove afterheat in addition to the shield coolant system, which is kept operating during shutdown. If the lithium coolant solidifies, the startup times must be increased over those estimated for this maintenance plan.

The interspersal of remote and contact maintenance delays operations slightly when replacing several sectors during one outage since the work must be completed on all sectors being worked simultaneously before going to a remote operating mode or visa versa. This requirement, however, imposes little constraint since parallel operations are planned at all times for both maintenance modes. The only delay is the necessity to await reactor hall crane availability which is a delay that applies to either contact or remote maintenance.

Maintenance Equipment - The maintenance equipment required is basically the same since many of the major tasks must still be performed remotely. In some cases the equipment will be simplified because it does not need to perform as many intricate functions. The use of hand tools to loosen bolts and smaller connections is required, but these have little effect on cost. One additional item that tends to increase cost and add extra tasks is the requirement that the neutral beam injectors be completely shielded. This requirement may size the lifting capability of the heavy unit that puts the shield block in place. The use of air bearings, as with the remote concept, imposes no constraint on contact maintenance since these are only operated during tasks that must be performed by remote techniques in any event.

Work platforms and ladders are permanently installed on the reactors, but the remote equipment units are used to assist in placing personnel at work stations instead of elevators. Some special design and safety provisions are necessary to provide this capability, but the use of maintenance equipment to move personnel is more suitable than the use of elevators since it is more easily accessed for maintenance.

All major equipment items are still required since the size and weight of removed components is unchanged, but no additional major items are needed for contact maintenance. The shielded cabs for operating personnel are still required since the design of the major equipment items is still governed by the remote maintenance requirements.

Minimum Cost Maintenance Plan - The analysis of the cost to maintain the large module reactor when replacing various fractions of the first wall/blanket and using the contact maintenance plan has been conducted. The replacement fraction that produces the minimum cost of electricity is 1/4, or the exchange of 3 modules. While this differs from the 4 modules selected for the totally remote maintenance plan, the difference in cost of electricity between 3 and 4 modules is very small. The other replacement fractions investigated are the same as those chosen for the baseline large module maintenance plan.

The maintenance flow when exchanging 3 modules using contact maintenance is shown in Figure 4-15. The impact of using contact maintenance techniques to disconnect and reconnect the coolant and service lines is readily apparent from the figure. The time required is very close to the same whether one or three modules is being replaced. Replacement of the three modules requires a total elapsed time of approximately eighty-eight days. The resulting

LARGE MODULE CONCEPT (UWMAK-I) TASK FLOW
BASELINE CONFIGURATION WITH CONTACT MAINTENANCE

Figure 4-15

plant availability is approximately 71 percent. The time increments used in this analysis are based on a 24 hour day using a 75% manpower utilization factor.

For contact maintenance operations on the large module reactor design approach, the overall replacement time is much shorter than for the remote maintenance period of approximately 154 days discussed in Section 4.2.1.1. The time increments are reduced principally in disconnecting and connecting the many fluid and electrical lines external to the shield to separate all services, etc. from the reactor module. This type of task is not only accomplished more quickly when using the contact maintenance mode, but it also can be accomplished in parallel with similar tasks. Such parallel operations are not as readily available with fully remote maintenance operations because of space limitations for maintenance equipment. Considerable use is made of parallel efforts within each task listed in Figure 4-15, but the parallel operation of the tasks can possibly be increased still further if manpower is really unlimited. A more detailed consideration of manpower scheduling may indicate some savings in cost since labor costs become significant for contact maintenance operations.

4.2.2.2 Intermediate Module - UWMAK-III - A maintenance plan has been developed utilizing contact maintenance, to the greatest extent possible, for the intermediate size module concept - UWMAK-III.

The purpose of this plan is to utilize maintenance personnel to the greatest extent possible to perform, assist, or augment the required maintenance tasks. The maintenance approach is basically the same as for the baseline intermediate module, Section 4.2.1.3. The task definitions and sequencing of these tasks is the same as for the baseline. The primary difference is that contact maintenance is utilized in all tasks until the reactor shield segments are opened.

Assumptions and Ground Rules - For contact maintenance the following changes and additions to assumptions and ground rules are made to those established for the baseline intermediate module concept.

- o The radiation dosage levels are low enough that personnel can work at any position within the reactor room up to the primary reactor shield.
- o All radioactive systems are shielded where necessary to prevent increasing the radiation dosage after shutdown. This may include the vacuum plenum chamber, RF waveguide and possibly, coolant lines.

- o Personnel are not allowed in the reactor room when any portion of the primary shield is opened or other shielding is removed.
- o Rigorous contamination control of the reactor room environment is required.
- o The atmosphere in the reactor room is air instead of the inert gas used for the baseline maintenance plan.
- o The temperature of the environment is maintained at approximately 30°C to 40°C.
- o Maintenance equipment is available for positioning personnel at various locations on the reactor.
- o Work platforms are permanently installed at locations on the reactor as required.
- o Adequate personnel are available to conduct work tasks in parallel at multiple locations when possible.
- o Adequate personnel are available to replace work crews who have reached their radiation dosage limit.

Additional detail assumptions and ground rules for the maintenance plan are included in the Maintenance Task Breakdown and Time Estimate in Section 2.0 of Appendix B.

Maintenance Procedures - The sequence of second level tasks are the same as described in Section 4.2.1.3. Contact maintenance is applied to the functions indicated in the following tasks:

- o Removing the lateral support access panels. While the panel must be supported and lifted by the Primary Maintenance Machine, two crews are used to assist in attaching the fixture to the panel and in positioning and operating the large wrenches to remove the bolts.
- o Removing the RF heater waveguide/coax section inside the outer panels. The lift fixture is attached and the disconnects are made. However, contact maintenance is restricted during removal of the RF heater waveguide/coax during the time when the waveguide is disconnected and removed and prior to installation of shield plugs in the primary shield opening left by the waveguide removal.
- o Removing the lithium manifolds. Two crews are used to attach the hoist to the manifolds, disconnect the joints, assist in moving the manifolds and capping the ends. Two manifolds are worked at one time.
- o Disconnecting the central wall module manifolds. Crews conduct this disconnect simultaneously with the other coolant manifold removal.

- o Raising or lowering the shield segments. Personnel assist in placing the jacks before the shield is opened.
- o In addition work crews also assist in retooling and controlling the major machine operations.

Contact maintenance cannot be employed in the following tasks:

- o Opening/closing of the shield.
- o Module removal/replacement.
- o ISSEC removal/replacement.
- o Inspection of modules not being removed.
- o Vacuum check of the plasma chamber.
- o Leak testing of the lithium manifolds.

Most of the above tasks cannot utilize contact maintenance since direct exposure to the opened plasma chamber occurs during the execution of these tasks. However, during the vacuum check of the plasma and leak testing of the lithium manifolds, contact maintenance is not used because the requirement to raise the lithium lines and modules to a high temperature is expected to raise the room temperature above that suitable for manned operations.

Maintenance Equipment - The maintenance equipment required is essentially the same as the equipment used for remote maintenance except that it can be simplified where intricate tasks are performed or aided by personnel. In particular, the Primary Maintenance Machine (PMM) and the tools, or fixtures used with it may be simplified since this machine is used with contact operations only for this maintenance concept. An additional requirement imposed on the PMM is to move personnel to their work stations on the reactor.

Also, some radioactive components such as the RF heater waveguides are placed in casks to increase the opportunity for contact maintenance.

While many of the tasks are conducted with the assistance of contact maintenance, there are still a significant number of tasks that require remote maintenance. Therefore, much of the equipment and control systems required for the fully remote maintenance concept are still necessary and savings in equipment costs are difficult to attain. Contact maintenance opportunities may be enhanced if the modules are placed directly in casks. However, the modules are large and the removal operations are complex enough to preclude conducting these operations through any reasonable cask design conceived at this point.

Minimum Cost Maintenance Plan - The analysis of the cost to maintain the intermediate size module reactor when replacing different fractions of the first wall/blanket and using the contact maintenance plan has been conducted. The replacement fraction that produces the minimum cost of electricity is the replacement of the modules in six sectors out of the 18 in the reactor during a scheduled outage. The modules in six sectors are replaced simultaneously. The replacement fractions investigated are the same as those analyzed for the baseline intermediate size module reactor.

Figure 4-16 indicates that the downtime of 50 days out of a maintenance interval of 330 days is required to replace the modules for minimum cost of electricity. This results in an availability of approximately 73 percent. The time increments used in this analysis are based on a 24 hour day with a manpower utilization factor of 75%.

The flow diagram for replacement of modules in six sectors shown in Figure 4-16 indicates one of the principal difficulties arising from the use of contact maintenance with the baseline intermediate size module reactor. When using contact maintenance all tasks must be conducted in parallel to permit all contact operations at the same time. Contact operations cannot be conducted on one sector when the shield is open on another sector. When the fully remote plan is used, tasks can be overlapped since no constraints exists. This constraint tends to increase the cost of electricity when

using contact instead of fully remote maintenance plans because the advantages of staggered operations when replacing modules in more than six sectors cannot be realized for contact maintenance plans.

The savings in time for the intermediate module concept when using contact maintenance instead of fully remote maintenance only occurs during access and reassembly. This results in a time reduction per sector reworked from 65 days for the remote maintenance plan to 50 days. These system analyses are discussed more fully in Sections 5.0 and 6.0.

4.2.2.3 Small Module - GA-DRP - A maintenance plan for integrating contact maintenance with the GA-DPR baseline maintenance plan has been formulated. The objective of this plan is to utilize maintenance personnel to the greatest extent possible to perform, assist, or augment the required maintenance tasks. The maintenance approach is basically the same as for the baseline small module, section 4.2.1.4, except that the remote maintenance equipment is shielded to allow personnel to access the reactors during maintenance operations.

Assumptions and Ground Rules - The contact maintenance plan necessitates the following changes in the baseline maintenance plan ground rules and equipment characteristics:

- o The reactor and reactor subsystem designs incorporate sufficient shielding to allow personnel to work around the reactor for long periods after shutdown without receiving more than the allowable radiation dose.
- o Rigorous contamination control of the reactor room environment is maintained.
- o The maintenance machine interface with the vacuum port incorporates seals to isolate the plasma chamber from exterior environment.
- o A negative pressure differential is maintained in the plasma chamber with respect to the reactor room environment to reduce contaminant leakage to an absolute minimum.
- o The maintenance machines are shielded and will be equipped with closure seals at the exposed end. The shielding increases the machine weight significantly. The reactor structure is redesigned to accommodate these weights.
- o Shielded containers, which attach to the exposed end of the Remote Loading Machines, are used to encase all loader racks, maintenance

equipment and other items removed from the plasma chamber. The end of these containers which interface with the RLM are also equipped with closure seals.

- o In addition to thicker shielding and a heavier support structure, the reactor vacuum port ducts are equipped with retractable, shielded duct covers encased in a shielded enclosure. The maintenance machines are attached to this enclosure. The duct cover enclosure provides radiation protection for personnel during maintenance machine installation and duct cover removal operations.
- o Work platforms are installed in the vicinity of the auxiliary vacuum ports as required for personnel. An elevator is available to move personnel to the top of the reactor.

Unless otherwise specified in the detailed maintenance timelines found in Section 2.0 of Appendix C, the maintenance equipment functions exactly as described for the baseline small module remote maintenance plan.

Maintenance Procedures - The maintenance plan sequence and tasks for contact maintenance are the same as those conducted for fully remote maintenance, except that the time required to conduct the tasks employing contact maintenance is reduced.

Contact maintenance is employed in each task as indicated below. The sequence covers operations for two sets of equipment. The sequence will vary slightly when using four sets of equipment to allow for installing more equipment simultaneously.

- o Vacuum port cover removal employs a special shielded removal machine and a vacuum cover cask. These are emplaced and operated by work crews stationed on the work platforms. As many removal machines as necessary are provided to work almost simultaneously on all vacuum port covers that must be removed. Delays in overhead crane availability require some staggering of these operations.
- o Two Shielded Remote Maintenance Machines (RMM's) and two Remote Loading Machines (RLM's) are installed in parallel operations. Work crews control crane operations, assist in placing the machines on the mounts and fastening them to the mounts. Shielded workhead turrets are installed by the work crews on each machine using the overhead cranes.

- o Four Remote Viewing Machines (RVM's) are installed in a similar manner. Work crews checkout all equipment from the work platform at the viewing machine ports.
- o Internal track is installed by the RMM's. Work crews control overhead cranes and install shielded casks on the RLM's to feed and withdraw track and module components in and out of the plasma chamber. All slide closures in casks and machines are operated by manual control.
- o Two In-Chamber Maintenance Machines (ICMM's) are installed. Work crews install the shielded ICMM casks on the RLM's and control the installation operations.
- o The in-chamber track installation is completed. These operations are controlled from the remote control room, but work crews assist by aiding in the installation and removal of track and component casks and in controlling the exchange of workheads. Workhead turrets are replaced by the work crews and overhead cranes if workhead failures occur.
- o Blanket modules are replaced. Again, work crews assist by emplacing the module component casks on the RLM's.

The replacement operations employ essentially the reverse sequence. The plasma chamber vacuum check is controlled from a remote control room and requires no work crews in the reactor room. The room temperatures may rise during this check because of the high temperatures required.

Task time reductions for maintenance equipment installation and removal accrue primarily because certain operations can be performed more quickly. Personnel assist in attaching the crane hooks to loads, guiding suspended equipment into place, installing attachment fasteners, positioning and aligning equipment to installation interfaces, etc. Also, many of the maintenance equipment attachment functions can be performed in parallel by teams of personnel, with machine placement and installation governed by overhead crane utilization. However, while these external functions aid in reducing time during maintenance equipment placement and checkout, the plasma chamber internal operations establish the time required to conduct these fully remote operations. Therefore, reduction in the time required for concurrent external operations by use of contact maintenance techniques will not affect the elapsed time required for the internal operations.

The principal effect of this concept is that all radioactive equipment is placed in casks, including maintenance equipment, and contact maintenance

operations other than first wall/blanket replacement can be conducted without being restricted by the presence of radiation in the reactor room. For all other module sizes, except possibly the ORNL cassette concept, for which contact maintenance is not considered in this study, periods of radiation exposure in the reactor room hamper the scheduling of other maintenance activities.

Maintenance Equipment - Maintenance equipment requirements increase over those required by fully remote maintenance when using contact maintenance for the small module first wall/blanket replacement. While the quantity of each maintenance equipment item remains the same, all external equipment is shielded or contained in casks. This adds to the equipment weight, the reactor structural support requirements and the equipment instrumentation requirements. Auxiliary control of all equipment is required at the work platforms.

To avoid delays caused by overhead crane availability, the lower bridge employed for remote operations may be revised to use crane trolleys instead of or in addition to the manipulators. A traffic analysis is necessary to determine the best mix for hoist requirements.

One additional shielded maintenance machine is required to remove the vacuum covers and place them in casks. This machine is mounted above a double ended cover cask and works through the cask to remove the cover. The cover is withdrawn into the cask and detached from the machine which then retracts into its own cask. The ends of both casks and the vacuum port are closed before removal of the machine and cover from the reactor.

Decontamination facilities and operations become more complex unless maintenance of the maintenance equipment is accomplished in hot cells. Since this procedure is not usually advisable, the equipment must be decontaminated before maintenance can be conducted.

Minimum Cost Maintenance Plan - An analysis of the cost to replace different fractions of the first wall/blanket of the baseline small module concept when employing contact maintenance as much as possible has been conducted. Figure 4-17 illustrates the maintenance flow for the selected replacement fraction that produces the minimum cost of electricity. For the contact maintenance analysis, the selected fraction is 1/4, or 500 modules, of the total reactor wall. The replacement fractions used are the same as those used for the remote maintenance analysis (Section 4.2.1.4). The selected remote maintenance fraction is 660 modules, or 1/3 of the total wall. For

**SMALL MODULE CONCEPT (GA-DPR) TASK FLOW
BASELINE CONFIGURATION WITH CONTACT MAINTENANCE**

13-972

Figure 4-17

contact maintenance, the time required to replace the modules is approximately 155 days out of the maintenance interval of 684 days for an availability of about 66 percent. The time increments used in these analyses are based on a 24 hour day and a manpower utilization factor of 75%.

Figure 4-17 shows that the time saving occurs principally during access or reassembly operations and that the module replacement operations are the same per module for contact as for remote maintenance. The data in Section 5.0 shows that for replacing 1/3 of the wall (660 modules) the contact maintenance requires 196 days in contrast with the 214 days shown in Figure 4-11 for remote maintenance and availability increases from 64% for remote to 65.2% for contact maintenance. These analyses are discussed more fully in Sections 5.0 and 6.0.

4.3 UNSCHEDULED MAINTENANCE - The maintenance plans that have been developed for use in the evaluation of maintainable design features consider only scheduled maintenance. The total maintenance approach, however, must also include consideration of the impact of unscheduled maintenance plans. In fact, the results of the brief analysis conducted to this point indicate that the impact of unscheduled maintenance on the selection of design

features for a maintainable fusion reactor may be greater than the impact of scheduled maintenance requirements.

The impact of unscheduled maintenance is reflected in the selection of design features which provide the ability to replace or repair the failed component, or which permit continued operation without the failed component, as quickly as possible and thus reduce the cost effects of the particular failure. Short downtimes for unscheduled (forced) outages are imperative because of the uncertainty of occurrence and the resultant possible major impacts on the power network.

A brief scenario for a single unscheduled outage has been prepared. The impact of this outage on the fusion reactor system is defined in terms of its relative duration compared with scheduled outages on the same subsystem.

4.3.1 Unscheduled Maintenance Scenario - The failure mode chosen to illustrate the potential impact of unscheduled maintenance on the fusion reactor system is a small, pinhole sized, coolant leak in the first wall/blanket of a UWMAK-III type reactor. The assumed conditions of the failure are listed in Table 4-3. These conditions define the problem facing the maintenance personnel at the inception of the outage. The assumption is also made that, while the reactor instrumentation will determine the mode of failure, the determination of the precise location and size of the leak is dependent upon other test procedures.

Other ground rules and assumptions which reflect maintenance policies that must be established by the operating plant maintenance staff prior to the outage are listed in Table 4-4. Whenever defining the impact of the unscheduled maintenance which can result from a wide range of potential failure modes, a consistent set of maintenance policies is required. The impact on cost of electricity will vary with the set of policies adopted. By examining a number of different policy sets appropriate to each design approach, the most effective maintenance plan can be eventually adopted for each approach.

The paramount objective of the procedure selected to repair the failure under consideration is to minimize the cost of the shutdown. This requires optimizing the cost of repair, including cleanup, and the cost of the lost time. The initial procedure considered for this scenario undoubtedly can be

TABLE 4-3
UNSCHEDULED MAINTENANCE SCENARIO
(Problem Statement)

- o REACTOR - UWMAK-III TYPE
- o MAINTENANCE SYSTEM - REMOTE SYSTEM
- o FAILURE MODE - LITHIUM COOLANT LEAK, PLASMA QUENCHED
- o OPERATING MODE BEFORE FAILURE - REACTOR IN PLASMA BURN
- o REACTOR ROOM - SEALED AT TIME OF FAILURE
- o MAINTENANCE EQUIPMENT - ONE SET ON STANDBY AND CHECKED, LOCATED
ON DOLLIES IN STORAGE, DECONTAMINATED
- o BALANCE OF PLANT - OPERATING BUT SHUTDOWN AUTOMATICALLY ON
FAILURE DETECTION
- o FAILURE DETECTION - BY PLASMA QUENCH
- o FAILURE IDENTIFICATION - BY VACUUM PORT SPECTROMETRIC ANALYSIS
- o FAILURE ISOLATION TO REACTOR SECTOR - BY COMPARATIVE ANALYSIS
OF VACUUM PORT SPECTRO-
METER OUTPUTS
- o FAILURE ISOLATION TO MODULE - ACCOMPLISHED AFTER OPENING SUSPECT
SECTOR, METHOD TBD
- o SPARES - ONE SET READY, IN STORAGE, ON FIXTURE, BUT NOT HEATED
OR FILLED WITH COOLANT

improved but it serves to illustrate an approach to defining unscheduled maintenance estimates.

To achieve the foregoing objective the maintenance policies assumed for use in the event of a coolant leak in the UWMAK-III plasma chamber are defined as follows. The operating instrumentation will be able to sense the presence of lithium and its concentration in the exhaust from the segments of the reactor plasma chamber (cause of failure). By comparing the concentration in the exhaust from all sectors, the sector in which the leak occurs can be determined (general location). However, another technique is required to locate the particular poloidal position in the sector at which

TABLE 4-4
REPAIR OF UNSCHEDULED FIRST WALL COOLANT LEAK
(GENERAL GROUND RULES AND ASSUMPTIONS)

- o FAILED MODULE WILL BE ISOLATED AFTER REACTOR SECTOR IS OPENED.
- o REMOVE FIRST WALL/BLANKET MODULES OF SAME SIZE AS EXCHANGED IN SCHEDULED SHUTDOWN, I.E., FULL SIZE MODULES WILL BE REMOVED AND REPLACED, NOT JUST SECTIONS.
- o MODULE REPAIR WILL BE DONE OFF-LINE. FAILED MODULE WILL BE REPLACED WITH A SPARE.
- o MAINTENANCE PROCEDURES WILL BE IDENTICAL TO THOSE USED FOR SCHEDULED SHUTDOWN EXCEPT WHERE REVISIONS ARE NECESSARY.
- o FIRST WALL LEAK IS A PIN SIZED HOLE. CONTAMINATION OF MODULE SURFACES BELOW LEAK DOES NOT OCCUR WITH PROCEDURES USED IN SHUTDOWN.
- o CONTAMINATION BY LITHIUM FROM LEAK IS DEPOSITED ONLY IN VACUUM PLENUM OR ON CRYOVACUUM PUMPS AND IT IS REMOVED WITHOUT DISMANTLING THE PUMPS OR VACUUM DUCTWORK. (SEE PROCEDURE DEFINED IN ASSUMPTIONS OF TASK 1.01, SECTION 5.0, APPENDIX D.)

the leak occurs. This technique can only be used after the first wall and blanket are opened (specific location).

The immediate problem for the maintenance crew is to limit the damage due to the leak. It is assumed that a large leak can be determined by terminating or restricting flow in the suspected sector and watching pressure and flow in all lines as the pressure is reduced. Also, monitoring of the lower vacuum system plenum chamber for the presence of liquid lithium may be helpful. (Obviously, this only a brief review of the very difficult problem of isolating a leak.) Drainage is initiated to prevent excessive spillage of lithium which may possibly cause more damage to the system than the effect of afterheat on the first wall blanket structure since cleanout and repair of the lower vacuum system and other contaminated areas can be extremely time consuming.

In the assumed case, the foregoing procedure does not detect the presence of liquid lithium and, therefore, the leak is assumed to be small. Coolant flow is immediately reinitiated in the blanket and afterheat is removed before shutting down the coolant flow. Coolant temperatures and pressures are regulated to minimize or eliminate dripping. Lithium will vaporize at reactor operating temperatures and pressures and will probably condense in the vacuum plenum or on the cryovacuum pumps. It is desirable to have this occur in the plenum where it will not interfere with the vacuum pump operation. The lithium condensation area may be minimized by shutting down vacuum pumps except in the affected reactor sector and, even there, the cryovacuum pumps may be shut off as quickly as possible. A bypass system may be required to bypass the cryovacuum pumps in order to reduce possible damage.

These procedures and other damage limiting operations that are required are largely conducted during afterheat removal and reduction of magnet currents. Since the policy is to remove the affected module, the nominal shutdown for all other sectors must be automatically initiated with possibly some additional precautions such as the vacuum system shutdown already mentioned. The flow of operations for this unscheduled maintenance event is illustrated in Figure 4-18.

INTERMEDIATE MODULE CONCEPT (UWMAK-III) TASK FLOW
- UNSCHEDULED MAINTENANCE -

The procedures for gaining access to the leaking sector are identical with those used for a scheduled maintenance shutdown. The access sequence requires the following steps. (See Figure 3-6 for arrangement details of the UWMAK-III design concept.)

- o Remove the lateral support access panel between the T.F. magnets at the affected sector.
- o Retract the poloidal magnets which interfere with access to the major outer wall module (the "A" module).
- o Remove the RF heater coax cable and waveguide connection to the reactor shield.
- o Remove the lithium coolant manifolds connecting the "A" module and upper and lower adjacent modules ("B" modules) to the lithium supply and return system.
- o Disconnect and open the upper and lower doors in the plasma chamber shield.

The removal of the modules also follows the procedures used for scheduled maintenance. However, the isolation of the leak and detailed assessment of the extent of the damage occurs in this phase. The procedures to accomplish this objective differ from the scheduled removal procedures. The sequence for removing modules is as follows.

- o Remove the "A" module and transport it to a hot cell. The module is inspected for leakage in the hot cell.
- o A complete inspection of the suspect sector and its adjacent sectors is conducted by the inspection machine used during scheduled maintenance. (The inspection technique and tools may differ from those used during scheduled maintenance when conducting this inspection.) The total first wall area remaining in the reactor sector and the two adjacent sectors are inspected to locate any additional leaks or to determine if any additional damage occurred in the vicinity of the leak.
- o The upper "B" module and ISSEC panel are removed in the same sequence used for scheduled maintenance. The sequence of maintenance machine usage, however, must vary because of the foregoing inspection task and removal of only one ISSEC panel.
- o The upper central wall module (the leaking module) is disconnected simultaneously with the removal of the "B" module and ISSEC panel

by using the central core maintenance unit above the reactor.

- o The central wall module is then removed. (No further inspection is necessary except as prescribed for the assembly procedures.)

Replacement and reassembly operations are identical with the scheduled procedure. These are slightly shorter than the time required for scheduled maintenance since only one ISSEC panel has been removed.

A detailed presentation of the unique procedures used for the unscheduled tasks and the estimated time for each function is defined in Section 5.0 of Appendix D.

4.3.2 Unscheduled Maintenance Impacts - The total shutdown time for unscheduled replacement is compared with the time required for replacement of the modules in the reactor sector during a scheduled shutdown in Table 4-5.

TABLE 4-5
UNSCHEDULED FIRST WALL/BLANKET TIME COMPARISON
(Central Wall Module)

LEVEL 1 TASK (SUBDIVISION)	ESTIMATED TIME DURATION				TIME DIFFERENCE	
	UNSCHEDULED REPLACEMENT		SCHEDULED REPLACEMENT			
	HOURS	PERCENT OF TOTAL	HOURS	PERCENT OF TOTAL	HOURS	PERCENT CHANGE
	SHUTDOWN	29:00	2.5	17:00	1.5	+12:00
MAINTENANCE	569:00	48.4				
(ACCESS)	52:00	4.4	296:00	25.6	0:00	0.0
(REMOVAL)			169:30	14.7	+156:00	
(INSPECTION)	0:00		130:00	11.3	-130:00	+8.7
(REPLACEMENT)	85:00	7.2	237:00	20.6	-14:00	-5.9
(REASSEMBLY)	418:30	35.5	280:00	24.2	0:00	0.0
STARTUP	24:00	2.0	24:00	2.1	0:00	0.0
TOTALS	1178:00		1153:00		+25:00	+2.2

The unscheduled maintenance mode was chosen to illustrate the replacement of the most difficult potential source of the leak, i.e., the most difficult module to access. The time required is actually longer than the scheduled maintenance time for the sector. If the "A" module were the leaking module the time would be reduced, but only by approximately 14%.

The comparison shows that, for this single failure and this particular design and maintenance approach, a single unscheduled failure would result in a downtime approximately as long as the scheduled downtime. While this represents one of the more difficult and time consuming failure modes to correct, the impact on outage time, and consequently on operating cost, can

be severe. As discussed further in Section 5.0, the experience in fission plant operation indicates acceptable outage times in which scheduled outages are of about the same order of magnitude in duration as unscheduled outages. If this is the case, it can readily be seen that a single outage of the type postulated could utilize the total time allocated for unscheduled outage within an operating period.

For similar failure modes in other reactor concepts a qualitative assessment of the effect of unscheduled maintenance is indicated by the comparison shown in Table 4-6. Access time is the key to total replacement time. For this parameter the GA-DPR is superior along with the other small module concept - the ORNL cassette concept. When the reactor sector containing the leak can be determined without examining each module, tracks are not required in the GA-DPR and access time is short. The time to locate the leak, however, can be long for all concepts. However, here too, the small module concepts have the advantage since the pinpointing of the leak is either more of a probabilistic problem of inspecting the correct module than a matter of requiring a large time for access or the coolant loop manifolding may permit isolating groups of modules and testing them, thereby isolating the failure to a relatively small area.

TABLE 4-6
REACTOR CONCEPT COMPARISON FOR UNSCHEDULED COOLANT LEAK MAINTENANCE

REACTOR CONCEPT (MAINTENANCE MODE)	UNSCHEDULED FAILURE			ALLOWABLE FAILURES/OPERATING PERIOD
	REPLACEMENT TOTAL TIME ⁽¹⁾	LEAK LOCATION TIME	PERCENT OF SCHEDULED MAINTENANCE TIME	
UWMAK-III REMOTE CONTACT	HIGH MODERATE	FAIR FAIR	VERY HIGH HIGH	LOW LOW
ORNL REMOTE: MODE 1 ⁽²⁾ MODE 2 ⁽²⁾	LOW MODERATE	FAIR GOOD	MODERATE MODERATE	LOW MODERATE
UWMAK-I REMOTE CONTACT	VERY HIGH VERY HIGH	POOR POOR	VERY HIGH VERY HIGH	VERY LOW VERY LOW
CULHAM MK-II REMOTE	MODERATE	FAIR	VERY HIGH	LOW
GA-DPR REMOTE CONTACT BUILT-IN	LOW LOW VERY LOW	GOOD GOOD GOOD	VERY LOW VERY LOW LOW	MODERATE MODERATE HIGH

(1) Replacement time does not include leak location time.

(2) Mode 1 removes 1 cassette then locates leak.
Mode 2 removes all modules necessary and inspects as removed.

The other parameters included in Table 4-6 indicate the possibility of using procedures for the various design concepts which vary from the scheduled maintenance procedures. These parameters also indicate the potential effect on the reactor economics of unscheduled failure modes of this type. In the first instance, the capability to use unique procedures to perform unscheduled maintenance permits the time for these outages to be shortened considerably and a more satisfactory rating is given in the table where this is possible. Also, the capability to access any module rapidly provides the small module concepts with an advantage. As for the impact on economics, the larger the number of failures that may be absorbed within a given operating period, without exceeding the downtimes estimated for unscheduled failures, the smaller will be the impact of each failure. The advantages for small module concepts when considering the first three factors in the table result in a potentially low relative economic impact.

The overriding consideration influencing the comparison toward small modules is the ability of these concepts to provide relatively rapid access to the first wall/blanket. However, the large number of modules to be examined for leaks and the difficulties in conducting this examination may influence the evaluation against small modules unless a viable leak location method is provided.

In view of these considerations, the selection of the design characteristics for a fusion reactor must be such that failures of this type are corrected in a very short time or that the probability of occurrence is very remote. Both approaches must be considered for any study of the impact of unscheduled failure modes on the economics of the maintainability of fusion power reactors.

4.4 OTHER SUBSYSTEM EFFECTS - A brief investigation has been conducted of the maintenance requirements and the effects on scheduled maintenance efficiency imposed by subsystems in the reactor room other than the first wall/blanket. This investigation used the UWMAK-III design concept as an example for defining the potential impacts on the total reactor maintenance resulting from these subsystems.

4.4.1 Subsystem Maintenance Requirements - The principal reactor related subsystems which are installed at least partly in the reactor room are listed in Table 4-7. (This table is reproduced from Reference 14.) The

TABLE 4-7
UWMAK-III SUBSYSTEMS
(LOCATED WITHIN REACTOR BUILDING)

SYSTEM	LOCATION	SIZE	MOST PROBABLE FAILURE MODE	REDUNDANCY	METHOD OF MAINTENANCE
1ST WALL/BLANKET (OUTER)	OUTER RADIUS OF PLASMA CHAMBER	9M X 3.5M MODULES	<ul style="list-style-type: none"> o VACUUM AND COOLANT LEAKS DUE TO FATIGUE CRACK GROWTH o STRUCTURAL FAILURE DUE TO EMBRITTLEMENT 	NONE	REPLACE MODULES
1ST WALL/BLANKET (INNER)	INNER RADIUS OF PLASMA CHAMBER	13M HEIGHT BY 5M RADIUS	<ul style="list-style-type: none"> o LEAKS IN HELIUM COOLANT LINES o RADIATION AND THERMAL DAMAGE 	NONE	DESIGNED TO LAST LIFE OF PLANT
ISSEC	1ST WALL COVERING OF INNER WALL	25 CM THICK GRAPHITE 13M HEIGHT BY 5M RADIUS	RADIATION AND THERMAL DAMAGE	NONE	REPLACE DURING SCHEDULED OUTER 1ST WALL/BLANKET REPLACEMENT
CARBON CURTAIN (OUTER WALL)	COVERS OUTER 1ST WALL/BLANKET (PLASMA SIDE)	THIN FLEXIBLE CARBON CURTAIN (APPROX. .2 CM THICK)	RADIATION DAMAGE	NONE	REPLACED DURING SCHEDULED OUTER 1ST WALL/BLANKET REPLACEMENT
SHIELD	SURROUNDS ENTIRE PLASMA CHAMBER	OUTER - 8000 TONNES CENTRAL - 1300 TONNES INNER - 3000 TONNES	<ul style="list-style-type: none"> o LEAKS IN HELIUM COOLANT LINES o RADIATION AND THERMAL DAMAGE (STRUCTURAL FAILURE) 	NONE	DESIGNED TO LAST LIFE OF PLANT
CRYOVACUUM PUMPS, (PLASMA CHAMBER)	UPPER AND LOWER PORTIONS OF PLASMA CHAMBER BETWEEN T.F. COILS CONNECTED TO DIVERTER SLOTS	GREATER THAN TWICE THE VOLUME OF THE PLASMA CHAMBER	<ul style="list-style-type: none"> o THERMAL FATIGUE o VALVE MALFUNCTION o VALVE SEAL LEAKAGE o CYROGENIC LEAKAGE (LN₂ OR LH₂) o ACCESS PLATE LEAKAGE o RADIATION DAMAGE 	REDUNDANCY POSSIBLE BY OVERSIZING PUMPS TO ALLOW OPERATION WITH PERCENTAGE OF PUMPS DOWN	REPLACE SECTIONS OF PUMPS WITH REACTOR SHUTDOWN
PARTICLE BOMBARDMENT PLATES	INSIDE OF VACUUM PUMPS NEAR DIVERTOR	1M X 3M AT 36 LOCATIONS	<ul style="list-style-type: none"> o PERIODIC REPLACEMENT REQUIRED o MECHANICAL MALFUNCTION o LEAK IN SODIUM COOLANT LOOP o FROZEN LITHIUM SEAL 	REDUNDANCY POSSIBLE BY OVERSIZING PLATES TO ALLOW OPERATION WITH PERCENTAGE OF PLATES INOPERATIVE	REMOVE ACCESS PANEL ON CYROPUMP AND REMOVE UNIT. REQUIRES REACTOR SHUTDOWN.
R.F. HEATERS	AROUND TORUS OUTSIDE OF T.F. COILS	7M X 3M X 5M	<ul style="list-style-type: none"> o R.F. GENERATOR (KLYSTRONS OR TETRODES) o VACUUM WINDOW IN WAVEGUIDE o RADIATION DAMAGE TO WAVEGUIDE AT PLASMA CHAMBER PORT o ARCING IN WAVEGUIDE o VACUUM LEAK IN WAVEGUIDE o WAVEGUIDE VACUUM PUMPS 	REDUNDANCY POSSIBLE IF DESIGNED TO OPERATE WITH PERCENTAGE OF HEATERS INOPERATIVE	<ul style="list-style-type: none"> o POSSIBLY CAN REPLACE R.F. TUBES WITHOUT PLANT SHUTDOWN o REPLACE ENTIRE R.F. ROOM o REPAIR IN PLACE DURING PLANT SHUTDOWN
NEUTRAL BEAM INJECTORS (ALTERNATE FOR R.F. HEATERS)	AROUND TORUS AS NEAR TO PLASMA AS POSSIBLE	VERY LARGE.	<ul style="list-style-type: none"> o ION SOURCE o ACCELERATOR (ARCING) o MAGNETS o NEUTRALIZER o COLLECTOR/CONVERTOR o CRYOPUMPS/VACUUM CHAMBER o CONTROL SYSTEM o RADIATION DAMAGE o LEAKS o DIELECTRIC BREAKDOWN o RADIATION DAMAGE 	<ul style="list-style-type: none"> o REDUNDANCY POSSIBLE IF DESIGNED TO OPERATE WITH PERCENTAGE OF HEATERS INOPERATIVE o SOME REDUNDANCY IN INTERNAL COMPONENTS IS PROBABLY POSSIBLE. 	<ul style="list-style-type: none"> o REPLACE ENTIRE UNIT AND REPAIR o SOME SYSTEMS COULD POSSIBLY BE REPAIRED IN PLACE
FUEL INJECTORS	AROUND TORUS AS NEAR TO PLASMA AS POSSIBLE	NOT DEFINED		o REDUNDANCY APPEARS QUITE FEASIBLE BY LOCATING EXTRA INJECTORS AROUND TORUS	o REPLACE UNITS AT SCHEDULED SHUTDOWN
SUPERCONDUCTING MAGNETS (T.F. AND POLOIDAL)	AROUND PLASMA CHAMBER OUTSIDE OF SHIELD		<ul style="list-style-type: none"> o RADIATION DAMAGE TO INSULATION o VACUUM LEAKS o LH₂ LEAKS o STRUCTURAL FATIGUE OF O.H. COIL SUPPORTS o GOES NONSUPERCONDUCTING o OVERPRESSURIZED RUPTURE 	NONE	<ul style="list-style-type: none"> o DESIGNED TO LAST LIFE OF PLANT o FAILURES IN CRYOSTAT REPAIRED IN PLACE o A FAILURE WITHIN MAGNET COULD CAUSE REWINDING COIL. (MAJOR SHUTDOWN)
DIAGNOSTIC INSTRUMENTATION	THROUGHOUT ENTIRE REACTOR BUILDING. PRIMARILY IN 1ST WALL COOLANT CHANNELS, SUPERCONDUCTING MAGNETS, AND PLASMA HEATERS	TENS OF THOUSANDS OF UNITS	<ul style="list-style-type: none"> o RADIATION DAMAGE o MAGNETIC FIELD INTERFERENCE 	POSSIBLE IN ALMOST ALL CASES	RELY ON HIGH REDUNDANCY AND REPLACE AT SCHEDULED SHUTDOWN.
MANIFOLDING	THROUGHOUT REACTOR BUILDING CONCENTRATED NEAR 1ST WALL	LARGE AMOUNT OF MANIFOLDING REQUIRED	<ul style="list-style-type: none"> o LEAKS o CORROSION o EXPANSION JOINTS o VALVES 	PROBABLY NOT FEASIBLE IN MOST CASES	o REPAIR IN PLACE IF POSSIBLE OR REPLACE SECTIONS
ELECTRICAL CABLES AND CONDUITS	THROUGHOUT REACTOR BUILDING				
MAINTENANCE EQUIPMENT		TRACKS, CRANE, ETC.	o MECHANICAL	NONE	DURING SCHEDULED SHUTDOWN
STRUCTURE	POLOIDAL COIL SUPPORTS/RAISING EQUIPMENT		<ul style="list-style-type: none"> o COIL LIFTING DEVICES o SHEAR PANEL SEALS 	NONE	

facility systems such as lighting and ventilation are omitted. The table indicates the potential failure modes for these subsystems. Most of these failure modes would be infrequent occurrences within the life of the reactor. Periodic inspection is used as a scheduled preventative maintenance procedure that determines incipient failures. These potential failure areas are then corrected as a part of a scheduled maintenance outage. Where inspection capability is insufficient or the repair penalties extreme, design is such as to reduce the probability of failure to acceptable limits so that an unscheduled occurrence is unlikely. Therefore, the scheduled maintenance procedure used for most of these subsystems is inspection and repair as needed.

Some of the subsystems listed in the table have specific components which must be replaced periodically. These subsystems include the coolant loops, cryovacuum pumps, particle bombardment plates, R.F. heater waveguide, neutral beam injectors (an alternate for RF heaters), fuel injectors, and diagnostic instrumentation. A number of these replacement components are removed from the reactor room during the first wall/blanket scheduled replacement and can be repaired in the hot cell or other maintenance areas. These include the RF heater waveguides or neutral beam injectors, whichever is used, and the fuel injectors. If these are to be replaced or repaired during the scheduled shutdown, the presumption is that sufficient spares are available. The assumption is also made that the nominal time between replacement for each item is as long as the time between replacement of the first wall/blanket modules. If, on the other hand, the life of each component is only as long as the period between shutdowns, then all of these components must be replaced or repaired during every scheduled outage.

The maintenance of the cryovacuum pumps, the particle collection plates and the inaccessible instrumentation is considered as additional scheduled maintenance. The maintenance of permanently installed maintenance equipment, such as overhead cranes and poloidal magnet retraction mechanisms, must ultimately be considered but this equipment is included in this investigation only as supporting equipment for other maintenance. Most of the maintenance equipment is removed from the reactor room and maintained during the reactor operating period. In addition to maintenance of the permanently installed maintenance equipment, the scheduled inspection requirements of the remaining reactor subsystems remain to be defined. These subsystems

include both toroidal field magnets and poloidal field magnets, all fluid lines and manifolds, power and instrumentation cables, radiation shielding and structure. Inspection of these systems is expected to be feasible as a parallel operation with the replacement of other subsystems since the interference with other component replacement operations is a minimum. A summary of the fluid lines to be inspected with each subsystem is listed in Table 4-8.

The potential interference of the replacement of cryovacuum pumps, particle collection plates and instrumentation with first wall/blanket maintenance is considered in this analysis. This interference arises because the maintenance of the cryovacuum panels and particle bombardment plates require use of the overhead crane. Instrumentation maintenance interference occurs because the instrumentation at the inner wall can only be accessed (in the UWMAK-III design concept) while the ISSEC panels are removed. The anticipated wearout components in each of these units include the shuttle valve seals in the cryovacuum pumps, the plate material in the particle collection plates and the end instruments in the shield behind the ISSEC as well as in various fluid lines throughout the reactor room. Instrumentation in the first wall/blanket modules being replaced will be repaired off-line in a hot cell area. However, instruments in permanently installed lines must be replaced during shutdown.

These maintenance requirements are used to establish a replacement maintenance plan for concurrent replacement of the scheduled items. In formulating this plan the assumption is made that the required component replacement will be conducted during the scheduled outage for first wall/blanket replacement.

4.4.2 Subsystem Maintenance Plan - The principal assumptions used to develop the maintenance plan for subsystems other than the first wall/blanket include:

- o A second overhead crane is available to provide for continuous use of one crane. Maintenance on one crane is conducted while the other is being used.
- o The cryovacuum pump panels can be separately disconnected and reassembled in two units. One unit is the panels at the top of the plenum chamber and one is the end panels. These panels will be capable of supporting themselves without additional backup structure

TABLE 4-8
MANIFOLD AND LINE MAINTENANCE REQUIREMENTS

SUBSYSTEM	FLUID LINES, MANIFOLDS, POWER CABLES ⁽¹⁾	SCHEDULED MAINTENANCE MODES ⁽¹⁾
FIRST WALL/BLANKET	LITHIUM FIRST WALL COOLANT GHe INNER WALL COOLANT LN ₂ FREEZE PLUG LINES	INSPECTION & TEST INSPECTION & TEST INSPECTION & TEST
REACTOR SHIELD	GHe COOLANT	INSPECTION & TEST
PRIMARY CYROVACUUM PUMPS	LN ₂ PLATE COOLANT LHe PLATE COOLANT GHe REGENERATION FLUID VACUUM	INSPECTION & TEST INSPECTION & TEST INSPECTION & TEST TEST
SECONDARY VACUUM CHAMBER	VACUUM	TEST
MAGNETS (PF AND TF)	POWER CABLES LN ₂ THERMAL SHIELD COOLANT LHe PRIMARY COOLANT VACUUM JACKETS	INSPECTION & TEST INSPECTION & TEST INSPECTION & TEST TEST
RF HEATERS	RF GENERATOR COOLANT WAVEGUIDE VACUUM LN ₂ VACUUM PUMP COOLANT LHe VACUUM PUMP COOLANT POWER CABLES	TEST TEST INSPECTION & TEST INSPECTION & TEST INSPECTION & TEST
NEUTRAL BEAM INJECTORS (ALTERNATE TO RF HEATER)	VACUUM LN ₂ VACUUM PUMP COOLANT LHe VACUUM PUMP COOLANT H ₂ (OR D ₂) SUPPLY POWER CABLES	TEST INSPECTION INSPECTION INSPECTION & TEST INSPECTION & TEST
DIVERTERS	LITHIUM LINES	INSPECTION & TEST
FUEL INJECTORS	LN ₂ VACUUM PUMP COOLANT LHe VACUUM PUMP COOLANT VACUUM	INSPECTION & TEST INSPECTION & TEST TEST
LHe LINES	VACUUM JACKET LN ₂ THERMAL SHIELDING	TEST INSPECTION & TEST

⁽¹⁾ INSTRUMENTS INSTALLED IN THE LINES AND CABLES REQUIRE TESTING IN ADDITION TO THE INSPECTION OF THE LINES. WHERE TEST IS INDICATED THIS REFERS TO INSTRUMENTATION TESTING. IF FAULTY, REPLACEMENT WILL BE SCHEDULED.

when being removed. The panels are shown in Figure 3-6 above (or below) and at the ends of the vacuum plenum chambers. Additional details are defined in Reference 4.

- o The cryovacuum pumps are attached to the plenum with bolted flanges and mechanical seals.
- o The central core of the reactor includes two circumferential tracks, permanently installed, which support a boom hoist and manipulator that can be moved radially and circumferentially, independent of the overhead crane. This hoist provides access to all vacuum systems above the reactor.
- o The particle bombardment plate assemblies are accessed through the opening left by removal of the top cryovacuum pump panel unit above the reactor, or the bottom pump below the reactor. A complete assembly is removed in one piece and taken to a hot cell for replacement of the bombardment plate material.
- o Instruments are replaced in manifolds and fluid lines when no other activity is occurring in that sector area.
- o Instruments are replaced in the inner wall during the inspection period. (See Figure 4-8 and Section 4.2.1.3 for a definition of this period.) A detailed analysis is expected to show an extended time for the inspection period because of this function.
- o All operations must be remotely conducted during and after opening the plenum. For this analysis all operations even before and after opening the plenum are assumed to be conducted remotely. As an alternative, contact maintenance may be used for the initial and final steps when detaching or attaching the vacuum pumps and for replacement of instrumentation outside of the reactor shield.

The removal of the cryovacuum pump panels and the particle bombardment plate assemblies above the reactor are conducted in the following sequence.

- o Install the reactor core mounted maintenance device by use of the overhead crane and manipulators.
- o Unbolt the top cryovacuum panel and disconnect all ducts and fluid lines to it.
- o Pick up the cryovacuum panel with the overhead crane and transfer it to a dolly on the reactor room floor for movement to the hot cell.

- o Remove the end cryovacuum panels using the same procedure.
- o Detach the particle bombardment plate assembly using the core mounted device and transfer to a dolly with the overhead crane.

The reassembly is conducted in the same manner but with the principal steps reversed.

Removal of the pump panels and plates installed below the reactor will be conducted at the same time as removal of the same components installed above the reactor, using a comparable sequence but with a machine that operates on the floor below the lower cryovacuum pump plenum chamber. The removal of components from the machine operating on the floor below the lower plenum chamber is by use of the overhead crane working through a hole in the reactor room floor.

The instrumentation replacement requires use of equipment which can access the inner wall and fluid lines. The access to the specialized instruments mounted in the reactor room floor area, such as the neutron monitor, can be conducted using the smaller tugs with an auxiliary manipulator. Access to the inner wall will use the inspection machine. Access to the manifolds will require either the core mounted device or overhead manipulators for manifolds external to the T.F. magnets. The primary maintenance machine defined in Section 4.2.1.3 and Section 2.0 of Appendix E is used for inspection of manifolds between the shield and the outer vacuum wall, i.e., the walls between the T.F. magnets.

The time estimates for accomplishing these tasks are summarized in Table 4-9. More detailed estimates are presented in Section 6.0 of Appendix D. These estimates are for replacing the plenum chamber components either above or below one reactor sector and for replacing the instrumentation for the inner wall of one sector.

4.4.3 Subsystem Scheduled Maintenance Impacts - The impact of the scheduled maintenance time required for the assemblies in the cryovacuum pump plenum chambers and the instrumentation in the reactor room on the overall scheduled maintenance time requirements determined for the first wall/blanket exchange of the intermediate module concept has been examined. The purpose is to determine whether any extension is necessary in the time already required for the exchange of the first wall/blanket modules.

The costs associated with the exchange of varying quantities of first wall/blanket modules and the resultant availabilities are found in

TABLE 4-9
SUBSYSTEM MAINTENANCE TIME ESTIMATES
(INTERMEDIATE MODULE CONCEPT)

TASK NO.	LEVEL 1 TASK (SUBDIVISION)	LEVEL 2 TASK	DURATION/SECTOR	
			PER TASK HOURS	CUMULATIVE HOURS
2.0 2.30 2.31 2.32 2.33	Maintenance (Vacuum Pump)	Cryovacuum Pump Removal Particle Bombardment Plate Removal Particle Bombardment Plate Replacement Cryovacuum Pump Replacement TOTAL:	40:00 24:00 23:00 70:30	157:30***
2.40 2.41 2.42	(Instrumentation)	Inner Wall Instruments External Manifolding Neutron Monitor TOTAL:	45:30 28:30* 13:00**	
				45:30***

* Conducted in Parallel With First Wall/Blanket. Only 20% of Estimated Instruments/Sector Replaced.

** Conducted in Parallel. Only One Replaced/Maintenance Period.

*** Conducted in Parallel with First Wall/Blanket Replacement.

Table 5-8, Section 5.5. The cost of electricity resulting from replacement of the modules in either 9 sectors or in 18 sectors is almost equal. Both plans (i.e., 9 or 18 sectors reworked) are compared with the capability to exchange the plenum chamber assemblies, that is, the two cryovacuum pump panels and the particle bombardment plate assemblies, to determine whether either has the advantage.

The exchange of 18 sectors of first wall/blanket modules is accomplished after a two year operating period. The plan for this exchange includes a 28 day annual balance of plant scheduled maintenance period. If the plenum chamber assemblies can be exchanged within these 28 days, then this maintenance can be conducted almost independently of the first wall/blanket maintenance.

The time estimate for maintenance of a single set of upper plenum chamber assemblies is 157:30 hours (from Table 4-9). This time becomes an elapsed time of 8.75 days when adjusted to account for personnel utilization and shift change time losses and when assuming a three shift operation. To maintain all 18 sets of plenum chamber assemblies in series requires 157.5 days. It is assumed that the lower 18 sets of plenum chamber assemblies can be maintained during the same time period. If these are to be maintained in 28 days, it is necessary to work on six sectors at a time. This would require six reactor central core maintenance devices and would probably saturate the overhead crane availability causing significant delays.

Therefore, it seems impractical to exchange these assemblies in the required 28 days and the plan for exchange of 18 first wall/blanket module sectors requires additional maintenance time.

When considering the impact of the maintenance of the upper plenum chamber assemblies on the plan for exchange of 9 sectors of first wall/blanket modules it is found that the maintenance of two sets of plenum chamber assemblies simultaneously can be accomplished within the 89 days required for first wall/blanket exchange. In this plan the outage for first wall/blanket exchange is required after approximately a one year operating period. Since the plenum chamber assembly maintenance requirement is estimated to occur after the same period and the elapsed time required for exchange of 18 plenum chamber assemblies two at a time is 78.75 days, this appears to be an acceptable plan with no impact on overall maintenance time requirements.

A brief analysis has been conducted to determine the impact on crane operations when exchanging the 18 upper cryovacuum pump and bombardment plate assemblies in conjunction with 9 sectors of first wall/blanket modules. This analysis assumes that two reactor core maintenance devices are available to work on two sets of plenum chamber assemblies at one time. The total delay required to provide crane availability is estimated to be approximately 1 to 2 days. The use of two central core maintenance devices and maintenance equipment to exchange 5 sectors of first wall/blanket at one time appears to provide the best balance of time and equipment required for both maintenance operations. The cost data in Table 5-8 will be revised slightly if the vacuum plenum assembly requirements are added to the spares, equipment and manpower costs.

The impact of instrumentation maintenance on overall maintenance time requirements results primarily from the exchange of the plasma chamber inner wall instruments. This operation must be conducted serially with the first wall/blanket exchange and increases the time required by approximately 2.5 days for the inspection phase of the operations for each sector. However, the phasing of these inspection operations, as shown in Figure 4-8, Section 4.2.1.3, indicates that this additional inspection phase time does not add to the total exchange time when reworking the first wall/blanket modules in 18 sectors during a scheduled outage of 112 days. The same result is achieved when exchanging 9 sectors in 89 days.

Since all other instrumentation work is expected to be accomplished in parallel and can use existing equipment except, possibly, an additional central core maintenance device, this will have little impact on the maintenance cost.

The impact of the subsystems examined to this point on the maintenance costs appears to be small. Some additional spares, maintenance equipment and manpower will be required, as expected, but there is little or no increase in elapsed maintenance time during a scheduled outage for first wall/blanket maintenance of the UWMak-III design concept if the plan for replacement of the modules in 9 sectors after a one year operating period is used.

5.0 MAINTENANCE PLAN ANALYSES

The principal contents of this section are the data developed for the comparisons made in Section 6.0. Only those types of data are presented which are used directly in the comparisons. These types are defined in Section 5.1.

The major effort in this study has been directed toward scheduled replacement operations for the first wall/blanket. This region of the reactor is probably the most difficult to access and may also have the most critical life limitations. The impact of other subsystems on maintenance operations is discussed briefly in Section 4.4.

5.1 APPROACH TO ASSESSMENT - The approach which was employed to make the comparative assessments was to determine the effect of maintenance on the cost of electricity. This parameter is defined as:

$$COE = \frac{(C_C)(ROI) + C_F + C_{O\&M}}{(P_C)(A_F)(D_F)}$$

where:

- COE = cost of electricity
- C_C = capital cost (direct plus indirect)
- ROI = return on investment
- C_F = annual fuel costs
- $C_{O\&M}$ = annual cost of operations and maintenance
- P_C = plant generating capacity
- A_V = plant availability
- D_F = plant duty factor

The numerator of the above expression is the total annual cost for producing electricity and the denominator is the net energy produced per year.

5.1.1 Cost Assessment - The capital cost of the fusion plant is influenced by three maintenance related costs. These are the facility costs, the cost of initial spares and the maintenance equipment costs.

The facility costs include hot cells, maintenance buildings, overhead cranes, storage areas, airlock passage ways, check stations, and mock-up rooms.

The fuel costs are, of course, quite small and are only indirectly related to maintenance requirements.

The operations and maintenance costs are recurring costs and include labor and materials. From a maintenance standpoint they are affected by the labor required to replace the first wall/blanket and by the materials which are required in the refurbishment of the first wall/blanket modules.

5.1.2 Availability - Availability is defined in this report as the period of time the fusion plant is available for generating electricity at full capacity divided by the time occupied by one scheduled maintenance cycle. The maintenance cycle is the time from the beginning of a scheduled outage to beginning of the next scheduled outage. This definition may be written in equation form as:

$$A = \frac{t_{ut}}{t_{mc}} = \frac{t_{ut}}{t_{ut} + t_{dt}} = \frac{1}{1 + \frac{t_{dt}}{t_{ut}}}$$

where:

A = availability
 t_{mc} = scheduled maintenance cycle
 t_{ut} = uptime (available time)
 t_{dt} = downtime (unavailable time)

The expression for t_{ut} may be written as:

$$t_{ut} = t_{wl}(f)$$

where:

t_{wl} = first wall life
 f = fraction of first wall replaced per outage

hence:

$$A = \frac{1}{1 + \frac{t_{dt}}{(t_{wl})(f)}}$$

For a total power plant:

$$t_{dt} = t_{dt_{BOP}} + t_{dt_{A\&R}} + t_{dt_{FUS}} + t_{dt_{FUU}}$$

where:

$t_{dt_{BOP}}$ = downtime for balance of plant, scheduled & unscheduled
 $t_{dt_{A\&R}}$ = downtime for administrative and regulatory outages
 $t_{dt_{FUS}}$ = scheduled downtime for first wall/blanket replacement and other scheduled fusion unique maintenance
 $t_{dt_{FUU}}$ = unscheduled downtime for all fusion unique equipment

5.1.2.1 Availability Goals - Availability goals have been established to provide a sense of what availability is required to make the fusion plant competitive with existing power producers. Two of the goals are based on the data of Figure 5-1. These data are obtained from Reference 11 and are based on the maintenance histories of 33 fusion power plants with service lives greater than one year. The median availability from these data is approximately 72% and is described as "respectable" performance. This value has been chosen for this study as a "nominal" goal and is considered a desirable objective.

The second goal defined is the "mature" goal and corresponds to the highest level of availability from Figure 5-1, i.e., 87%. This is a level considered achievable by a second, or later, generation plant.

The third goal defined in this study is the "threshold goal" and is based on a somewhat different rationale. It is that level of availability which is expected to result in the same cost of electricity for a fusion plant as that expected to occur for a coal-fired plant in the year 2000. The data employed in this analysis is shown in Figure 5-2. The oil-fired, coal-fired, and fission fueled data shown in this figure are based on 1975 costs from Reference 12. The fusion costs are from McDonnell Douglas studies, Reference 13. The threshold availability required to achieve the breakeven with coal is 62%.

It was helpful in this study to clarify how the fission plant availability experience is distributed between the fission reactor and the balance of plant

AVAILABILITY EXPERIENCE FOR FISSION POWER REACTORS

Figure 5-1

and between forced outages and scheduled outages. The data that is used from Reference 11 is shown in Table 5-1 and corresponds to the nominal total plant availability goal selected for this study (72%). The distribution of these outage data is shown in Table 5-2.

5.1.2.2 Estimation of Availability - The fusion plant availability is computed for use in this study by estimating the downtime required for the scheduled maintenance and adding an allowance for unscheduled downtime based on the proportionate distribution experienced in fission plants. This distribution is shown in Table 5-2 for the three goals. However, some modifications have been made to these data. For instance fission plants expend a large part of the scheduled downtime for refueling. Fusion plants do not have to shut down for refueling but do require an extensive shutdown for first wall/blanket replacement. This may not occur every year as it often does for fission plants but may be every two or three years depending on the most economical replacement fraction used and the wall life of each particular reactor. However, the balance-of-plant will probably require scheduled maintenance every year. Hence, for the estimation of availability in this study, an allowance of 28 days of downtime has been made for balance-of-plant scheduled maintenance for every operating year in addition to one year in a given maintenance cycle.

Figure 5-2

TABLE 5-1
FISSION PLANT AVAILABILITY
(MEDIAN PLANT)

	OUTAGES PERCENT OF AVERAGE SERVICE LIFE	DISTRIBUTION PERCENT OF TOTAL AVERAGE OUTAGE*
FORCED OUTAGES	10.0*	35.5
REACTOR AND NSSS	(4.0)	(14.2)
BALANCE OF PLANT	(6.0)	(21.3)
SCHEDULED OUTAGES	17.1	60.6
REACTOR AND NSSS	(15.4)	(54.4)
BALANCE OF PLANT	(1.7)	(6.2)
REGULATORY	<u>1.1</u>	<u>3.9</u>
	28.2	100.0

AVERAGE FISSION PLANT AVAILABILITY = $100 - 28.2 = 71.8\%$

*REFERENCE NO. 11

TABLE 5-2
FUSION PLANT AVAILABILITY GOALS
(ALL VALUES IN PERCENT)

	TOTAL OUTAGE (UNAVAILABILITY)					AVAILABILITY		
	SCHEDULED		FORCED		REGULATORY	REACTOR SYSTEMS ⁽¹⁾		TOTAL AVAILABILITY
	REACTOR SYSTEMS ⁽¹⁾	BOP	REACTOR SYSTEMS ⁽¹⁾	BOP		SCHEDULED ONLY	SCHEDULED & FORCED	
MATURE AVAILABILITY	6.5	0.7	1.7	2.5	1.1	93.5	91.8	87.5
NOMINAL AVAILABILITY	15.4	1.7	4.0	6.0	1.1	84.6	80.6	71.8
THRESHOLD AVAILABILITY	21.0	2.3	5.4	8.2	1.1	79.0	73.6	62.0

(1) INCLUDES OUTAGES FOR REACTOR AND NSSS

In addition to the allowance for scheduled balance-of-plant maintenance, 65 days per operating year is allowed for forced outages due to both the balance-of-plant and to the fusion unique equipment.

5.2 ALTERNATE REPLACEMENT FRACTION MAINTENANCE PLAN CHARACTERISTICS -

The maintenance plans for replacing the modules in one sector of each design concept serve as the base for the generation of data which define alternative maintenance plans for replacement of different fractions of the first wall/blanket for each concept. The base data used for this purpose has been established during the study and is discussed in Section 4.0. The data that must be generated to define each plan includes the downtime, the maintenance equipment, and the manpower requirements.

The characteristics of these data are discussed in this section.

5.2.1 Downtime Required - The scheduled downtime for replacement of first wall/blanket modules has been estimated and incorporated in the maintenance plans described in Section 4.0. These downtimes are shown in Table 5-3 as a function of the reactor concept and the number of modules replaced per outage.

The lowest downtime per outage for the large module concept is realized with the Culham Mk II concept when using remote operations. Contact operations for this concept have not yet been assessed.

For the intermediate concept, contact operations result in lower downtimes for the smaller number of modules replaced per outage. However, at the higher fractions of all replacement, the reduction in downtime is nonexistent.

Both of the small module concepts, the ORNL and the GA-DPR with in-place equipment showed low downtimes. The ORNL showed some lower downtimes at higher fractions of the wall replaced per outage. For each design concept the variation in downtime is determined individually for the replacement fractions analyzed. A maintenance plan is defined which utilizes the maintenance equipment, personnel, facilities and maintenance characteristics of the design concept to the best possible advantage within the limitations imposed by that concept.

For example, the maintenance plan for replacement of one sector of the UWMAK-I uses one set of maintenance equipment as it is defined in Table 5-4. Only one reactor room wall hatch and one hot cell are required, and only the manpower to operate one set of equipment is used. As the plans are evolved to require replacement of more sectors, through a total of four sectors, these

TABLE 5-3
FIRST WALL/BLANKET REPLACEMENT SCHEDULE
(DAYS/OUTAGE)

NUMBER OF MODULES REPLACED - LARGE MODULE CONCEPT	1	2	3	4	6	12
BASELINE (UWMAK-I)	154	154	154	154	246	354
CONTACT (UWMAK-I)	88	88	88	88	127	158
SMALL (UWMAK-I)	135	135	135	135	237	303
CULHAM	47	47	47	47	84	128

NUMBER OF MODULES REPLACED - INTERMEDIATE SIZE CONCEPT	1	2	3	6	9	18
BASELINE (UWMAK-III)	65	65	65	65	112	112
CONTACT (UWMAK-III)	49	49	49	49	111	113

NUMBER OF MODULES REPLACED - SMALL SIZE CONCEPT GA/ORNL	330/1	400/2	500/3	660/6	1000/9	2000/18
BASELINE (GA-DPR)	133	149	175	214	296	558
CONTACT (GA-DPR)	113	130	156	196	284	544
IN-PLACE (GA-DPR)	45	53	64	80	114	216
ORNL	52	52	52	52	139	131

NOTE: NUMBERS SELECTED ON BASIS OF LEAST COST MAINTENANCE PLAN OPTIONS.

TABLE 5-4
MAINTENANCE EQUIPMENT - BASELINE REACTORS

LARGE MODULE			INTERMEDIATE MODULE			SMALL MODULE		
	TOTAL UNITS			TOTAL UNITS			TOTAL UNITS	
	1*	4*		1*	6*		1*	4*
1. HEAVY MAINT. UNIT	2	5	1. PRIMARY MAINTENANCE MACHINE	2	7	1. SHIELDED CAB, O/H CRANE	1	1
2. OPERATIONS MAINT. UNIT	2	5	2. MODULE HANDLING MACHINE	2	7	2. SHIELDED CAB, REM./MANIP.	1	1
3. REACTOR MISSILE TRANSPORTER	15	18	3. INSPECTION MACHINE	2	7	3. REMOTE MAINT. MACHINE	2	5
4. TRACTOR UNIT	2	5	4. SCREWJACKS	6	28	4. IN-CHAMBER MAINT. MACHINE	2	5
5. HI ACCESS UNIT	2	5	5. LATERAL SUPPORT PANEL WORKHEAD & STORAGE FIXTURE	2	7	5. REMOTE LOADER MACHINE	2	5
6. SHIELD SEGMENT SUPPORT	3	10	6. "A" MODULE WORKHEAD & STORAGE FIXTURE	2	7	6. SHIELDED TOWMOTOR	2	2
7. BLANKET SEAL/YOKE	4	11	7. "A" MODULE & FIXTURE DOLLY	2	7	7. LOADER RACK	2	5
8. MAGNET SHEAR PIN EXTRACTOR	2	5	8. RF WAVEGUIDE DOLLY	2	7	8. ICM/INSTAL. ADAPTER	2	5
9. LINE JOINT ALIGNMENT TOOL	4	14	9. LITHIUM MANIFOLD DOLLY	2	7	9. REMOTE VIEWING UNIT	2	5
10. LINE CONNECTION & INSTALLATION TOOL	3	7	10. SCREWJACK TRANSPORT DOLLY	2	7	10. LASER BEAM SYSTEM	1	1
11. IMPACT WRENCH	5	15	11. B MODULE TRANSPORT & STORAGE DOLLY	2	7	11. BLK MODULE CONTAINER	24	24**
12. LINE CUTTER & INSPECTION TOOL	6	20	12. ISSEC TRANSPORT & STORAGE DOLLY	2	7	12. IN CHAMBER TRACK SET	1	1
13. CREW TRANSFER UNIT	2	2	13. "B" MODULE WORKFACE	2	7	13. VACUUM PORT COVER DOLLY	2	3
			14. LITHIUM LINE FREEZE UNITS	432	432	14. REMOTE EQUIPMENT DOLLY	2	5
			15. SHIELDED TUG	2	7	15. TRACK SUPPORT ADAPTER SET	1	1
			16. ISSEC PANEL WORKFACE	2	7	16. LOADER RACK DOLLY	2	5
			17. LATERAL SUPPORT PANEL DOLLY	2	7	17. HOIST FIXTURE	2	3
						18. RME WORKHEADS SET	2	5
						19. RME MANIPULATOR SET	2	5
						20. MANIPULATOR DOLLY	2	5
						21. WORKHEAD DOLLY	2	5
						22. TRACK AND ADAPTER DOLLY	2	3
						23. WASTE DOLLY	2	5

*NUMBER OF SETS

** DEPENDENT ON NUMBER OF MODULES REMOVED

quantities are increased because the maintenance approach is to conduct replacement of all sectors in parallel operations. However, when six sectors are replaced, the limitation on the number of hatches in the reactor room wall (only a maximum of four are available) requires that the sectors be replaced in two groups, replacing only three sectors at a time per group. This increases the time, but it is not doubled as expected, because the number of neutral beam injectors removed per sector decreases when this large number of sectors is replaced. Also, shutdown, testing, and startup are only conducted once. The equipment, facilities, manpower, and spares are all adjusted to this revised maintenance approach. Similarly, the replacement of 12 modules is accomplished by replacing three groups, four sectors at a time. The data illustrates that this general approach is followed for all large module concepts.

For the intermediate module design concepts the maintenance plan discussed in Section 4.2.1.3 indicates that the overlapping of different functions are used extensively for the totally remote operation approach. For the replacement of modules in one through six sectors, the most efficient technique

is to work on all sectors simultaneously. Alternate groupings have been tested to determine if more efficient (i.e., lower cost of electricity) groupings are possible but such has not been the case. For the replacement of modules in nine sectors when using contact maintenance techniques, the parallel operation of different functions is not possible, as discussed in Section 4.2.2.2. Therefore, the downtime estimates increase at a different rate than when using totally remote operations.

For the small module concept the downtimes increase uniformly for all of the different GA-DPR maintenance approaches as the replacement fraction increases because the four sets of equipment are installed for all replacement fractions. The comparison of two and four sets was tested and four proved to be more efficient approach. However, for the ORNL concept the equipment requires that each sector is worked individually and the time increases with replacement fraction in the same manner as for the UWMak-III.

5.2.2 Maintenance Equipment Requirements - The maintenance equipment quantity requirements were estimated as a function of the maintenance plan and the unique requirements for each concept. In Table 5-4 is listed the number of each type of equipment as a function of the three baseline concepts and of the number of parallel operations (sets of equipment) required by the selected maintenance plan. Examples shown are for one and four sets for the large and small module reactor concepts and for one and six sets for the intermediate module concept. The Culham Mk II approach employs equipment similar to the complement of equipment shown for the intermediate size module maintenance equipment. The ORNL concept also uses a similar complement of equipment to that used for the intermediate module. The similarities for the major equipment units are described in Section 4.2.

The fraction of equipment sets required for each concept as a function of the amount of wall replaced per outage is shown in Table 5-5. All equipment descriptions are found in Section 4.2 or in Appendix E.

It is seen from Tables 5-4 and 5-5 that, as the number of sectors increase the equipment sets increase, but not as complete sets. In keeping with the approach of determining the requirements of each maintenance plan individually, as defined in Section 5.2.1, the required number of additional equipment items of each type are determined for each replacement fraction maintenance approach. The equivalent number of complete sets are computed by estimating the total weight of all equipment items for each replacement fraction and comparing this weight to the weight of one set.

TABLE 5-5
NUMBER OF MAINTENANCE SETS

NUMBER OF MODULES REPLACED FOR LARGE MODULE CONCEPT	1	2	3	4	6	12
BASELINE	1	1.19	1.35	1.60	1.48	1.96
CONTACT	1	1.44	1.79	2.15	2.08	2.57
SMALL	1	1.21	1.43	1.65	1.56	1.99
CULHAM	1	1.41	1.83	2.24	2.25	2.84

NUMBER OF MODULES REPLACED FOR INTER- MEDIATE MODULE CONCEPT	1	2	3	6	9	18
BASELINE	1	1.47	1.94	3.39	3.23	6.21
CONTACT	1	1.47	1.95	3.40	3.24	6.24

NUMBER OF MODULES REPLACED FOR SMALL MODULE CONCEPT	330/1	400/2	500/3	600/6	1000/9	2000/18
BASELINE	1.67	1.71	1.75	1.80	2.00	2.49
CONTACT	1.50	1.60	1.75	1.99	2.50	3.86
INPLACE	1.09	1.11	1.13	1.17	1.26	1.53
ORNL	1.0	1.55	2.09	3.74	3.07	5.03

5.2.3 Maintenance Personnel Requirements - The number of maintenance personnel primarily affect the operations and maintenance cost account. These manpower demands were estimated for each reactor type, for each module removal option (quantity replaced per outage) and whether contact or remote. The manpower per shift is based on the people required for the first wall/blanket maintenance functions with four support persons allocated for each person actually performing the function. The cost of manpower is computed only for

the downtime period required by each replacement option and, consequently, the work period as well as the number of personnel vary with each option (replacement fraction).

The manpower requirements are shown in Table 5-6. The Culham Mk II approach requires the fewest personnel for the large module concept. Personnel requirements are the highest for the UWMAK-III concept when using contact operations for removing more than 20% of the modules per outage. The GA-DPR baseline and the GA-DPR with in-place maintenance equipment require the fewest personnel when using remote operations.

Manpower requirements also vary with the first wall/blanket fraction replaced on each design concept as seen in Table 5-6. The number of personnel are made consistent with the sets of equipment and the number of reactor sectors being worked at one time. The method used is illustrated for the downtime in Section 5.2.1 and this method is extended for estimating personnel requirements also.

5.3 TOTAL MAINTENANCE COSTS - The output of the TOCOMO system analysis code is summarized in this section to illustrate how costs vary with concept and with the fraction of the first wall/blanket replaced during each scheduled outage. The data is summarized according to large, intermediate and small module categories. No attempt has been made in this section to select the most preferable design features and characteristics or to identify best suited maintenance methods or scenarios. These discussions are found in Sections 6.0 and 7.0. The trends derived and cost optimization analyses conducted with the help of the TOCOMO program are presented with a brief discussion of the more apparent results.

The tables presented in this section list pertinent maintenance data for each design concept and maintenance approach discussed in Section 6.0 and 7.0. The data for each replacement fraction for each concept is included. From the data for all replacement fractions within a concept the fraction resulting in the lowest cost of electricity is chosen as the maintenance plan to be used in the analyses. These maintenance plans, including the specific flow of the maintenance sequence for each plan, are discussed in Section 4.0.

Large Module Concepts - Table 5-7 summarizes the maintenance effects for the large module concepts. This summary includes (1) the UWMAK-I baseline design concept using remote maintenance operations, (2) the UWMAK-I baseline with contact maintenance operations, (3) a 3000 MW_{th} UWMAK-I with features

TABLE 5-6
MAINTENANCE PERSONNEL REQUIREMENTS
(MANPOWER/SHIFT)

NUMBER OF MODULES REPLACED FOR LARGE MODULE CONCEPT	1	2	3	4	6	12
BASELINE	74	120	202	286	202	286
CONTACT	154	300	447	594	447	594
SMALL	74	120	202	286	202	286
CULHAM	67	114	160	207	160	207

NUMBER OF MODULES REPLACED FOR INTERMEDIATE MODULE	1	2	3	6	9	18
BASELINE	100	173	233	440	233	440
CONTACT	167	300	434	834	434	834

NUMBER OF MODULES REPLACED FOR SMALL SIZE MODULE	330	400	500	660	1000	2000
BASELINE	107	107	107	107	107	107
CONTACT	227	227	227	227	227	227
IN-PLACE	107	107	107	107	107	107
ORNL	47	74	100	180	100	180

NOTE: NUMBERS SELECTED ON THE BASIS OF LEAST COST MAINTENANCE PLAN OPTIONS.

TABLE 5-7
MAINTENANCE SUMMARY-LARGE MODULE CONCEPT - UWMK-I
(FLUENCE LIMIT = 5 MW-YR/M²)

	MODULES REPLACED/ OUTAGE	MAINT. SETS	MANPOWER/ SHIFT	DAYS/ OUTAGE	DIRECT COST \$S	INDIRECT COST \$S	TOTAL MAINT.	COST/ KW HR	AVAILABILITY
BASELINE	1	1.00	74	154	174.64	132.53	307.17	105.32	.4107
	2	1.19	120	154	243.12	184.50	427.62	80.93	.5536
	3	1.35	202	154	310.21	235.42	545.63	74.33	.6260
	4	1.60	286	154	379.38	287.91	667.29	72.78 ←	.6614
	6	1.48	202	246	497.97	377.91	875.88	77.63	.6446
	12	1.96	286	354	880.89	668.51	1549.40	85.37	.6773
CONTACT	1	1.00	154	88	175.92	133.51	309.43	83.78	.5274
	2	1.44	300	88	254.26	192.96	447.22	70.55	.6506
	3	1.79	447	88	328.17	249.05	577.22	67.45 ←	.7052
	4	2.15	594	88	401.81	304.93	706.74	67.64	.7261
	6	2.08	447	127	521.36	395.66	917.02	70.72	.7197
	12	2.57	594	158	903.03	685.92	1589.75	78.38	.7445
3000 MW _{TH}	1	1.00	74	135	80.93	61.23	142.16	78.77	.4634
	2	1.21	120	135	109.19	82.61	191.80	62.69	.5995
	3	1.43	202	135	137.45	103.99	241.44	58.93	.6606
	4	1.65	286	135	165.52	125.22	290.74	53.11 ←	.6901
	6	1.56	202	237	208.65	157.85	366.50	61.92	.6633
	12	1.99	286	303	354.83	268.44	623.27	65.23	.7036
BASELINE MINIMUM COE	1	1.00	74	135	82.66	62.73	145.39	88.98	.3413
	2	1.21	120	135	111.77	84.82	196.59	64.13	.4869
	3	1.43	202	135	140.92	106.94	247.86	56.90	.5675
	4	1.65	286	135	169.85	128.90	298.75	53.64 ←	.6188
	6	1.56	202	237	214.71	162.94	377.65	57.37	.5859
	12	1.99	286	303	366.09	277.83	643.92	56.94	.6443
CULHAM	1	1.00	67	47	63.68	48.14	111.82	55.59	.5403
	2	1.41	114	47	91.10	68.87	159.97	46.46	.6603
	3	1.83	160	47	118.22	89.37	207.59	43.84	.7131
	4	2.24	207	47	144.87	109.52	254.39	42.85 ←	.7428
	6	2.25	160	84	186.56	141.04	327.60	45.24	.7203
	12	2.84	207	128	319.22	241.03	560.55	48.45	.7278

← SELECTED MAINTENANCE PLAN

configures to produce near-minimum cost of electricity, (4) a 5000 MW_{th} UWMK-I reconfigured to produce near-minimum cost of electricity, and (5) the Culham Mk II which is also proportioned to near-minimum cost features for 5000 MW_{th}.

The highest availability for the UWMK-I concepts results from the use of contact operations. The lowest cost of electricity for these concepts results from the optimized 5000 MW_{th} machine.

The Culham Mk II design concept with remote operations results in lowest cost of electricity of any of the large module concepts and availabilities are comparable to UWMak-I with contact operations.

The availability, cost of electricity and maintenance capital cost trends are shown in graphic form in Figure 5-3 for the UWMak-I baseline.

Intermediate Module Concept - The intermediate module concept cost summary is presented in Table 5-8. This concept is based on the UWMak-III with all remote operations as the baseline approach. Contact operations are also analyzed and these data are included in the table. The minimum cost of electricity for remote operations is realized for case where all 18 sectors are replaced during one outage. These data are also plotted in Figure 5-4. It is also clear that very little penalty would be paid by replacing either 6 or 9 sectors at one time.

When contact operations are performed the minimum cost of electricity does occur for the case of replacement of 6 modules per outage. For the 6 module replacement the availability with contact operations is about 5 points higher than with all remote activities.

Small Module Concepts - Table 5-9 summarizes the maintenance effects for the small module concepts. This table includes (1) data for the GA-DPR base-

Figure 5-3

TABLE 5-8
MAINTENANCE SUMMARY-INTERMEDIATE MODULE CONCEPT
(FLUENCE LIMIT = 5 MW-YR/M²)

	MODULES REPLACED/ OUTAGE	MAINT. SETS	MANPOWER/ SHIFT	DAYS/ OUTAGE	DIRECT COST MS	INDIRECT COST MS	TOTAL MAINT.	COST/ KW HR	AVAILABILITY
BASELINE	1	1.00	100	65	42.21	32.03	74.24	104.18	.3596
	2	1.47	173	65	56.21	42.66	98.87	75.57	.5052
	3	1.94	233	65	69.46	52.71	122.17	66.03	.5840
	6	2.59	233	89	95.72	72.52	168.24	59.73	.6477
	9	3.23	233	112	121.08	91.73	212.81	57.88	.6734
	18	6.21	440	112	205.31	155.81	361.12	55.38	.7300
CONTACT	1	1.00	167	49	44.98	34.14	79.16	91.12	.4191
	2	1.47	300	49	59.94	45.49	105.43	69.52	.5611
	3	1.95	434	49	74.27	56.36	130.63	62.50	.6326
	6	3.40	834	49	101.66	77.15	178.81	56.00	.7249
	9	3.24	434	115	128.07	97.19	225.26	59.77	.6697
	18	6.24	834	111	217.01	164.69	381.70	56.87	.7307

← SELECTED MAINTENANCE PLAN

ECONOMIC PARAMETERS FOR INTERMEDIATE MODULE BASELINE
UWMAK III BASELINE
FLUENCE LIMIT = 5 MW-YR/m²

Figure 5-4

TABLE 5-9
 MAINTENANCE SUMMARY-SMALL MODULE CONCEPT (GA-DPR)
 (FLUENCE LIMIT = 5 MW-YR/M²)

	MODULES REPLACED/ OUTAGE	MAINT. SETS	MANPOWER/ SHIFT	DAYS/ OUTAGE	DIRECT COST MS	INDIRECT COST MS	TOTAL MAINT.	COST/ KW HR	AVAILABILITY
BASELINE 1764 MW _{TH}	330	1.67	107	133	66.55	50.50	117.05	86.72	.6178
	396	1.71	107	149	68.59	52.05	120.64	85.17	.6291
	495	1.75	107	175	71.05	53.92	124.97	84.68	.6331
	660	1.80	107	214	74.69	56.68	131.37	83.89 ←	.6398
	989	2.00	107	296	84.68	64.26	148.94	83.93	.6447
	1978	2.49	107	558	111.23	84.41	195.64	85.88	.6461
BASELINE 5000 MW _{TH}	330	1.67	107	144	72.33	54.89	127.22	76.30	.4397
	396	1.71	107	161	74.77	56.74	131.51	73.83	.4546
	495	1.75	107	189	77.82	59.06	136.88	71.81	.4679
	660	1.80	107	231	82.39	62.53	144.92	69.23	.4860
	989	2.00	107	320	94.43	71.66	166.09	67.57 ←	.5000
	1978	2.49	107	603	126.79	96.22	223.01	68.33	.5037
CONTACT 1764 MW _{TH}	330	1.50	227	109	72.19	54.78	126.97	85.84	.6497
	396	1.60	227	130	76.51	58.06	134.63	86.06	.6506
	495	1.75	227	155	82.90	62.91	145.81	85.77 ←	.6542
	660	1.99	227	196	93.01	70.59	163.60	86.67	.6523
	989	2.50	227	280	113.50	86.14	199.64	88.17	.6522
	1978	3.86	227	544	166.38	126.27	292.65	92.91	.6494
INPLACE 1764 MW _{TH}	330	1.09	107	45	55.07	41.79	96.86	68.71	.7535
	396	1.11	107	53	56.68	43.01	99.69	68.67 ←	.7551
	495	1.13	107	64	58.72	44.56	103.28	69.28	.7495
	660	1.18	107	80	62.54	47.46	110.00	69.82	.7457
	989	1.26	107	114	69.95	53.09	123.04	70.78	.7408
	1978	1.53	107	216	92.45	70.16	162.61	72.87	.7360
INPLACE 5000 MW _{TH}	330	1.09	107	49	60.72	46.08	106.80	51.02	.6447
	396	1.11	107	58	62.71	47.59	110.30	50.92	.6468
	495	1.13	107	70	65.32	49.57	114.89	50.55	.6522
	660	1.18	107	88	70.10	53.20	123.30	50.00	.6609
	989	1.26	107	125	79.43	60.28	139.71	49.84 ←	.6661
	1978	1.53	107	238	107.70	81.73	189.43	51.29	.6570
ORNL	1	1.00	47	52	28.47	21.61	50.08	90.03	.4065
	2	1.55	74	52	38.65	29.33	67.98	67.32	.5497
	3	2.09	100	52	48.21	36.59	84.80	59.85	.6229
	6	3.74	180	52	78.01	59.20	137.21	52.77 ←	.7185
	9	3.07	100	139	85.9	65.19	151.09	59.01	.6415
	18	5.03	180	131	140.15	106.36	246.51	54.16	.7164

← SELECTED MAINTENANCE PLAN

line when using remote operations, (2) the same reactor concept using contact operations, (3) the GA-DPR baseline with a modified maintenance equipment concept (in-place equipment), (4 and 5) two examples of the GA-DPR concept resized to 5000 MW_{th} (one with baseline maintenance equipment and one with in-place equipment) and (6) the ORNL concept adapted to a 5000 MW_{th} reactor performance.

The highest availabilities result from the GA-DPR (1764 MW_{th}) with in-place equipment. The lowest cost of electricity is produced by the GA-DPR scaled to 5000 MW_{th} and using in-place equipment. The lower availability for the plant with higher thermal power is the result of the higher optimum wall loading and shortened wall life.

The data for the GA-DPR is shown graphically in Figure 5-5. These data illustrate the insensitivity of the GA-DPR concept to the number of modules replaced per outage.

Figure 5-5

6.0 ASSESSMENT

This section discusses the reactor design and operating features in two parts. The first part, Section 6.1 contains a description of the design features and the second part, Section 6.2 presents the quantitative effect of those features on the maintenance costs.

The design features examined in this section are the first wall/blanket module size and other features related to the maintenance of the first wall/blanket. The principal variations in the maintenance characteristics resulting from module sizes, module access, reactor size, diverters, poloidal field magnet locations and vacuum seal locations are defined and the impacts on maintenance cost or maintenance time are assessed. The data on which the impacts are based are the downtimes for the selected maintenance plans (discussed in Section 4.0 for each design concept) and the cost of electricity as defined in Section 5.0.

The potential impact of the coolant type and significant plasma cross section parameters is also discussed but the impact can only be assessed qualitatively at this time. Impacts resulting from normalizing the reactor design concepts to common size and cost parameters are also presented.

In addition, the influence of several maintenance plan variations and reactor design characteristics have been assessed. The data permits comparison of an in-place equipment concept with installed equipment for the small module baseline reactor concept (the GA-DPR) and the determination of some effects of contact maintenance when compared with remote operations. The influence of the number and type of fluid connections and the length of joints required is also compared among the design concepts.

6.1 DESIGN FEATURES AFFECTING MAINTENANCE - Table 6-1 lists the design features that have a significant effect on maintenance and some of the descriptive characteristics of these features for each of the selected design approaches. These features are discussed in more detail in this section. Summary costs and maintenance time characteristics for complete reactor system analyses are further presented in Section 5.0.

First Wall/Blanket Module Size - The first wall/blanket module size is defined primarily by the relative size of the module to the poloidal dimensions of the reactor chamber and by the mass of the module. The number of modules in each reactor sector and the number of sectors in each reactor

TABLE 6-1

FUSION REACTOR DESIGN FEATURE CHARACTERISTICS

FEATURE	CHARACTERISTIC	TOKAMAK REACTOR DESIGN CONCEPTS				
		LARGE MODULE		INTERMEDIATE	SMALL MODULE	
		UWAK-I (BASELINE)	CULHAM-TK-II (ALT.)	UWAK-III (BASELINE)	GA-DPR (BASELINE)	ORNL CASSETTE (ALT.)
FIRST WALL/BLANKET	ARRANGEMENT T.F. MAGNETS/REACTOR ATTACHMENT VACUUM SEAL, TYPE COOLANT WALL LIFE, YRS. (MATERIAL) WEIGHT, TONNES.	1/SECTOR 12 CLAMPED BELLOWS MECHANICAL LITHIUM 4.03 (316SS) 3500	2/SECTOR 12 WEIGHT ONLY MECHANICAL GHe 2.30 (316SS) 800	11/SECTOR 18 BOLTED WELDED LITHIUM 2.00 (TZM) 50 AND 8	125/SECTOR 16 CLAMPED WELDED GHe 4.96 (INCONEL 718) .38	45/SECTOR 18 BOLTED HIGH IMPEDANCE HITEC 2.00 (TZM) 3-5
FIRST WALL/BLANKET ACCESSIBILITY	DIRECTION OF ACCESS COMPONENTS REMOVED CONNECTIONS, LINES/SECTOR BOLTS/SECTOR COOLANT JOINT TYPE	EXTERNAL NBI'S, COIL CROSS BRACES SHIELD SEG., SEAL CLAMPS 81 668 WELDED	EXTERNAL NBI'S, SHEAR PANEL, SHIELD DOOR 34 210 WELDED	EXTERNAL & INTERNAL SHEAR PANEL, MANIFOLDS, SHIELD DOOR, WAVE GUIDE 68 96 MECHANICAL	INTERNAL VACUUM PORT SHIELDS VACUUM PORT COVERS 32 280 WELDED	EXTERNAL NBI'S, VACUUM PORT SHIELDS & COVERS 94 17 MECHANICAL
REACTOR SIZE	THERMAL POWER, MW _{TH} T.F. MAGNET HEIGHT, m T.F. MAGNET OUTER RADIUS, m	5000 29.6 25.9	5000 27.5 16.5	5000 26.5 17.7	1764 18.2 15.3	5000 26.5 17.7
DIVERTERS	TYPE NUMBER COLLECTOR TYPE COOLANT	DOUBLE NULL POLOIDAL 2 LITHIUM TRAPS LITHIUM	SINGLE NULL POLOIDAL 1 PLATES GHe	DOUBLE NULL POLOIDAL 2 TZM PLATES LITHIUM	FLOWING PLASMA BOUNDARY - - -	DOUBLE NULL POLOIDAL 2 PLATES LITHIUM
POLOIDAL MAGNET LOCATION	POSITION re T.F. COILS MODULE INTERFERENCE MODULE SIZE, m	OUTSIDE MOVEABLE 29.6, HIGH	OUTSIDE & INSIDE NONE 15.7, HIGH	INSIDE MOVEABLE 16.0, HIGH	INSIDE NONE .7, DIA.	INSIDE NONE 16.0, LONG
COOLANT	BLANKET, TYPE , DISCONNECT SHIELD, TYPE , DISCONNECT ROOM ATMOSPHERE ROOM TEMPERATURE	LITHIUM WELDED GHe MECHANICAL INERT 125°C	GHe MECHANICAL GHe MECHANICAL AIR NEAR AMBIENT	LITHIUM MECHANICAL GHe MECHANICAL INERT >183°C	GHe WELDED GHe MECHANICAL AIR NEAR AMBIENT	HITC MECHANICAL HITEC MECHANICAL AIR >183°C
VACUUM SEAL LOCATION	VACUUM ZONES SEAL LOCATION, ZONE 1 , ZONE 2 SEAL TYPE, ZONE 1 LINE CONNECTION, ZONE 1 SEAL LENGTH/SECTOR, m	2 FIRST WALL REACTOR ROOM WALL MECHANICAL BOLTED 102	2 OUTER SHIELD REACTOR ROOM WALL MECHANICAL NOT DISCONNECTED 43	2 BLANKET SHEAR PANELS WELDED NOT DISCONNECTED 47	1 BLANKET - WELDED BOLTED 550	2 SHIELD REACTOR ROOM WALL HIGH IMPEDANCE NOT DISCONNECTED 164
PLASMA CROSS SECTION	MAJOR RADIUS, m MINOR RADIUS, m HEIGHT/WIDTH RATIO ASPECT RATIO	13.000 5.000 1.0 2.6	7.812 3.000 2.0 2.604	7.000 2.700 2.0 3.0	7.000 1.800 3.0 3.89	8.100 2.700 2.0 3.0

are independent of reactor size. Therefore, the impacts of module size can be normalized by categorizing module size through use of these parameters. This permits the range of reactor size variations found in the selected concepts to be classified in a straightforward manner. The impact of module size relative to the reactor size on the tasks and resources required to replace the modules is influenced by several other variables in the reactor design approach. These other variables and the manner in which they influence the module maintenance are also discussed. The other variables include the method of attachment of the module to the reactor, the type and location of the vacuum seal, the type of coolant, and the first wall material. This latter variable, in conjunction with the plasma characteristics of each reactor concept, determines the effective wall life of the reactor.

First wall/blanket module sizes are defined with respect to a reactor sector. The "large" module category includes those concepts which have only one module per sector or, at the most, one major module with small auxiliary modules, such as at the diverters. The "intermediate" module category includes those modules which have several modules per sector. For the intermediate module design concept used, the UWMAK-III, five lithium cooled modules and the inner wall ISSEC are required in each reactor sector. The "small" module size is almost independent of reactor sectors, relying on other design characteristics to define the category. The principal characteristic is that the modules are small enough with respect to the reactor that a very large number are required to make up the first wall/blanket. The concepts selected for analysis (the GA-DPR and the ORNL Cassette) employ 2000 and 810 modules, respectively.

Each reactor has the same number of sectors as the number of T.F. magnets. At this stage of conceptual design definition, the replacement of the first wall/blanket in any one sector may be considered as typical of all other sectors. One exception is the GA-DPR. For this concept the module arrangements are independent of the T.F. magnets. However, the number equivalent to one sector ($1/16$ of 2000, or 125) is used for comparative purposes. A more detailed design of the modules is illustrated for each design approach in Section 3.0.

For this analysis, the percentage of the modules in a sector that is replaced during an outage varies in some reactors because of variations in wall life within the sector. For the UWMAK-III concept, only six of the

eleven modules are exchanged. Three of these constitute 1/2 of the inner wall graphite (ISSEC) panels. (The total number of graphite panels was undefined in reference material and is assumed to be six.) The large UWMAK-III "A" module is always replaced and 1/2 of the 4 "B" modules and central wall modules (one of each type) are exchanged. For the ORNL cassette concept only the 15 first blanket zone modules in each sector are replaced since the life of the 30 modules in the second and third zones is much longer. While a wall life variation also exists for the modules in the GA-DPR concept (depending upon the module poloidal location) this variation is not generally considered in replacement analyses.

A significant impact of wall life on the module size analysis is its effect on the frequency of the outages. The variations in wall life shown in the table are caused primarily by the variation in wall loading as a function of the selected plasma shape and by the variation of reactor sizing parameters. When determining first wall life, the fluence limit was assumed to be constant at 5 MW-Yrs/m^2 for all approaches. Sensitivity to selecting other values of fluence limit is defined in the analysis of reactor size effects.

The remaining design characteristics which influence the variation in the impact of module size on maintenance involve the module attachment technique, vacuum seals and wall coolant type. These characteristics influence maintainability but their impact is only qualitatively evaluated in this discussion.

The maintenance time impacts for the different attachment techniques on different module sizes are large. The clamped bellows between the reactor sectors which are used in the UWMAK-I require a long time to disconnect and reconnect. On the other hand, the Culham Mk-II modules are not attached to each other and only rest on supporting pads or locator pins. Automatic pad latches to react magnetic field loads also may be used if required. This technique requires almost no attachment time. Another attachment concept is illustrated by the UWMAK-III modules which are bolted to each other to form the torus. Module removal is limited to every other module unless additional temporary braces are added. These braces are necessary when exchanging modules in all sectors during a single outage unless the existence of additional structure to support the torus is assumed. Since the selected maintenance plan for the UWMAK-III requires exchange of all 18 sectors, the existence of this additional permanent structure is implied. The GA-DPR and

ORNL cassette concepts attach the modules directly to reactor structure.

The vacuum seals also influence the maintenance time requirements and, indirectly, the module size evaluation since vacuum seals are integral with the modules in several concepts but completely separated from the modules in others. Also, the plasma chamber design concepts have varying degrees of vacuum integrity. While the UWMAK-I uses a clamped seal joint at the first wall and Culham Mk-II uses a bolted flange and seal at the outer shield, the UWMAK-III and GA-DPR design concepts use welded seals at the blanket zone. The use of welded seals is considered unnecessary with a secondary vacuum zone if the secondary zone pressure is on the order of 10^{-3} torr. This pressure is assumed to exist for the Culham Mk-II and ORNL concepts. The UWMAK-I concept uses 10^{-1} torr in the secondary region but this can conceivably be reduced to the 10^{-3} torr with minor revisions in the concept. UWMAK-III, on the other hand, uses a pressure of 75 torr in the secondary vacuum zone and requires a welded seal at the blanket to maintain the plasma chamber vacuum integrity with this pressure differential. The GA-DPR concept also requires a welded seal since the module removal exposes the coolant passages to the plasma chamber interior. In operation, the GA-DPR seal must then provide the barrier between the plasma chamber vacuum and the gaseous helium coolant at a pressure of 50 atmospheres. The ORNL cassette approach utilizes the more advanced concept of only a high impedance joint between the two vacuum zones. This joint is located outside of the shield. Its use requires that all vacuum chamber validation be conducted after the reactor room is sealed. These sealing arrangements affect the module exchange times and, consequently, the evaluation of module size impacts on maintenance efficiencies.

The blanket coolant type used for each design concept also influences the blanket module size analysis by affecting the blanket module disconnect times. These disconnect times depend on both the type of joint and the environment required by the coolant. Liquid metal coolants may require freezing of the lines before a disconnect can be made since draining the complex module coolant passages may not be possible. This freezing may be accomplished either by allowing the coolant in the entire module to solidify or by use of frozen sections of coolant in the lines at the joints as has been assumed for the UWMAK-III concept. Large modules may be unable to use frozen sections of the lines and solidification may result in damage to the module. Hence, limited drainage may be used as has been assumed for the UWMAK-I. This variation in-

indicates that the method of handling the coolant is a function of both module and reactor size. The time estimates vary widely among the several disconnect methods assumed for the liquid lithium lines. The use of gaseous helium coolant, on the other hand, requires relatively little preparation for disconnect, and the time estimates, particularly for large modules, vary considerably from the estimates for liquid cooled modules, especially if the liquid coolants cannot be drained. Reassembly also shows a variation in time between liquid metal coolants and gaseous helium in the event that the liquid metal filled modules are installed with coolant in the modules. For this analysis these variations are reduced by assuming that the large modules with liquid metal coolants can be drained and filled while installed in the reactor (UWMAK-I). Under these conditions the comparison with the alternate gaseous helium cooled concept (Culham Mk-II) is not influenced but the comparison with the UWMAK-III intermediate module is influenced by the shorter times required for preparation to disconnect coolant lines in the UWMAK-I.

First Wall/Blanket Accessibility - Accessibility of the first wall/blanket modules is measured by the preparations required to begin removal of the modules and to make the reactor ready for operation after module replacement. These preparations are evidenced both by the downtime required and the cost of equipment, facilities, spares and manpower that must be provided.

The direction of access to the first wall/blanket is critical in determining the amount of preparation required. For the large module design approaches the access to the first wall/blanket is through the plasma chamber ends of each sector which join with the ends of the adjacent sector. To access these ends requires removal of the sector from the toroid. Provisions for access from other points is not a part of the design concept. Removal of the sector from the toroid requires that it be translated horizontally away from the core. It is characteristic of all large and intermediate size modules that they are moved from the reactor in this direction. While vertical movement of the modules may be feasible, initial motion must be horizontal to provide the clearance necessary. Also, horizontal removal from the reactor requires less change in the facilities concept.

The arrangement of the intermediate size modules provides for access through the outer peripheral wall of the torus with subsequent removal of smaller modules through the access opening. The intermediate module concept

requires removal of less of the reactor for access than does the large module concept.

Even fewer reactor components are removed for access to the small modules than for access to the intermediate modules. The GA-DPR access is enhanced by the use of the flowing plasma boundary approach for removal of plasma residue which permits access through the auxiliary vacuum ports near the top of each sector and subsequent removal of modules through the port. The other small module concept, the ORNL cassette, provides for direct access to all modules from the periphery of the toroidal chamber, i.e., from the top, bottom and outer wall. This design concept postulates the use of bundle diverters but, in the absence of specific data for bundle diverters, diverters similar to the UWMAK-III are used for estimating purposes. Other assumptions have been made that support structure will exist for the modules and for the diverter section of the modules and that this structure provides for the best possible access to the modules. This assumption is used as the basis for estimates made in this initial examination of the concept. More details of the components removed are found in Section 3.0 and 4.0.

Additional accessibility parameters are used as a measure of the time and effort required for access and reassembly. These parameters include the number of connections both for service lines (fluid, power and instrumentation) and for structure (measured by the number of bolts). While service lines are of many sizes, each requires access and some movement to prevent interference with module removal. The methods of connection are equally varied, ranging from welding inserted sections of pipe into the line to the use of quick disconnect fittings (for the smaller lines). Some connection methods use state-of-the-art techniques while others will require advanced development, if feasible at all. The relative maintenance advantages are compared by estimating maintenance time and equipment for this variety of techniques. The welded coolant joints for UWMAK-I indicated in Table 6-1 are the supply and return GHe manifolds; and for the GA-DPR, the welded joints are the nonstructural seals between the gaseous helium coolant and plasma chamber. The mechanical joints for the UWMAK-III concepts are assumed for use primarily because of the constricted line lengths available and difficult access for cutting and welding pipe sections. Since the ORNL cassettes require many smaller connections with a relatively inactive coolant, quick disconnect fittings are postulated.

An alternate method for connecting the UWMAK-I coolant lines has been examined to provide a basis for comparison of the impact on maintenance time. The use of mechanically clamped fittings was assumed as an alternate to welded pipes to determine the relative effort required to break and remake the coolant line connections.

Reactor Size - The approximate overall size of Tokamak fusion power reactors is indicated by the thermal power output, the T.F. magnet overall height and the horizontal radius from the reactor core centerline to the outer limit of the T.F. magnets. These dimensions and the power output are directly related to plasma parameters but are also a function of the basic reactor design approach. Also, they indicate the relative maximum size required for facilities, maintenance equipment and the power conversion systems, including the coolant lines at the reactor.

The design approaches included in Table 6-1 vary in size not only because of the reactor arrangement but also because of the plasma parameters used to size the thermal output. The UWMAK-I uses a circular plasma and a relatively large T.F. magnet. Two additional versions of this reactor concept have been defined for the purpose of indicating the effects on reactor size and on maintenance of both an optimized (i.e., near minimum cost of electricity) plasma using a 2:1 height to width ratio with a 5000 MW_{th} output and the same shape plasma with a 3000 MW_{th} output. Both of these versions markedly reduced the reactor size.

The Culham Mk-II blanket/shield concept is incorporated in a UWMAK-I system for the purposes of using the UWMAK-I TOCOMO sizing and costing code. The T.F. magnet and core dimensions are resized to provide space for the module and diverter based on a plasma height to width ratio of 2.0.

The UWMAK-III dimensions are the same as given in the reference baseline design. The ORNL cassette concept also uses the UWMAK-III characteristics and is essentially the same reactor frame size as the UWMAK-III.

The GA-DPR design approach uses the doublet plasma configuration with an effective height to width ratio of 3.0. The thermal power of the baseline configuration is 1764 MW_{th} but when the same plasma confinement law that is used for the other reactor concepts is used, i.e., the trapped ion mode (TIM),

the thermal power of this size reactor is estimated at 3414 MW_{th}. Another larger version has been defined for a 5000 MW_{th} output to provide a basis for comparison with other concepts and also to illustrate the effects of varying the thermal outputs and size on the maintenance efficiency of the concept.

Diverters - The impact of diverters on the maintainability of reactors has been only partially assessed since the diverter arrangements included in the design concepts considered in the study use a limited number of variations. In general, diverters always require special provisions in the first wall/blanket design in the vicinity of the diverter and, therefore, add to the maintenance requirements.

The use of double null poloidal diverters, as in the UWMAK-I and the UWMAK-III design approaches, requires removal of a diverter or central wall module at each diverter. For the UWMAK-I concept, this removal is integral with the sector removal, but additional coolant line disconnects must be made which increase the number of lines in the disconnect areas above and below the reactor. The UWMAK-III concept requires replacement of an additional module at each diverter in addition to making coolant disconnects above and below the reactor which are difficult to access.

The use of a single null poloidal diverter, as in the Culham Mk-II approach, is another option. This concept eases the disconnect requirements and reduces maintenance effort. Conversely, the requirement for at least one diverter is still complicated. The exchange of the diverter module in this concept will require some internal operations.

The GA-DPR flowing plasma boundary approach has eliminated diverters as a consideration for module removal in this reactor and, consequently, has provided a highly simplified approach to access.

In addition to the diverter modules themselves, the type of particle collector system used influences the maintenance requirements. The liquid lithium traps used in the UWMAK-I concept adversely affect the module removal requirements by increasing the number of fluid connections required and by increasing the potential hazard from exposed lithium. This collector system is the only one removed with the first wall/blanket module. However, an examination of the maintenance required for the particle collector plates of the UWMAK-III has been conducted and is briefly discussed in Section 4.4.

The effect of diverters on maintainability is most readily defined by comparing the requirements for maintenance in design approaches with diverters, i.e., the UWMAK-I and the UWMAK-III, and in design approaches without the diverters, namely, the GA-DPR. One of the effects of diverters is caused by the requirement for poloidal magnets to shape the diverter field. The resultant interference of these magnets adversely affects the access to the diverters as well as to other subsystems such as the first wall/blanket modules. This impact is considered by the comparisons presented in Section 6.2.

Poloidal Magnet Location - The variation of poloidal magnet locations in the design concepts listed in Table 6-1 influences both the maintenance requirements of the first wall/blanket modules and the maintenance of the T.F. magnets. The arrangements examined are categorized as (1) poloidal magnets outside of the T.F. magnets (UWMAK-I approach); (2) poloidal magnets within the T.F. magnet bore but with the T.F. magnet bore large enough to permit raising and lowering the poloidal magnets to gain access to the plasma chamber (UWMAK-III approach); (3) poloidal magnets inside the T.F. magnet bore and constrained from moving by either the T.F. magnets on the plasma chamber (ORNL or GA-DPR approaches); and (4) the hybrid approach with poloidal magnets both inside and outside of the T.F. magnet and with the inside magnets constrained from moving but arranged for no interference (Culham Mk-II approach).

If maintenance efficiency is controlled by first wall/blanket replacement, as assumed for this analysis, then the module size appears to be limited for those arrangements in which poloidal coils are inside of the T.F. magnet bore. Whether an advantage lies with the ability to move these magnets or merely to constrain their installation to provide for movement of the larger modules will be determined by the size of the module selected as having the best maintenance characteristics when considering both scheduled and unscheduled maintenance.

The poloidal magnet impact on maintenance of the T.F. magnets or elements of the plasma chamber other than the first wall/blanket remains to be investigated.

Coolant Type - The parameters of importance which affect the impact of the first wall/blanket and shield coolants on the maintenance efficiency of the reactor design approaches are the number and type of connections and the environmental requirements imposed on maintenance because of coolant safety or first wall/blanket module handling constraints. The principal types of coolant

considered are molten lithium, the molten salt (HITEC) employed in the ORNL cassette approach and gaseous helium.

The impact of welded or mechanical connections for use with molten lithium is examined for the UWMAK-I. While mechanical connections are considered beyond the state-of-art for such temperatures and pipe diameters, an assessment is made of the improvement in maintenance with their use. This assessment of mechanical vs. welded connections also applies to the welded GHe module connections used in the Culham Mk-II concept. Time and equipment requirements are expected to vary only slightly, especially since the UWMAK-I connections are drained of lithium and require no freezing of the coolant.

Two types of mechanical coolant connections are used for the reactor approaches listed in the table. The larger connections required for the UWMAK-I, Culham Mk-II and UWMAK-III are of the clamped flange type using two bolts to make the connection. The smaller connections required by the ORNL cassette approach use quick disconnect fittings.

The type of coolant used for a reactor concept also imposes environmental conditions on maintenance operations. Whenever lithium is exposed to the atmosphere, it is assumed that an inert gas atmosphere is required. If this is actually necessary, the use of contact maintenance periodically during an outage may require an atmosphere change to air which will increase downtime. For remote maintenance, the inert atmosphere will impose additional design requirements for the maintenance equipment and facilities. These are expected to include special lubricant requirements and airlock type transfer facilities.

An additional assumption used in the time estimates is that atmospheric temperatures are maintained at a level that will keep the lithium or salt molten unless it is drained prior to the first wall/blanket exchange and filled after the module has been installed and the reactor preheated. Unless such temperatures are maintained, either special heaters are required when installing modules full of liquid metal or salt coolant over a long period is required to melt the coolant after installation. The design of modules for drainage and refilling in place appears impractical in some concepts but may be more practical with smaller and simpler modules like the ORNL cassettes. For these cassettes the atmospheric temperature is retained at the level for molten lithium since a molten lithium core is used in this system for breeding tritium and transferring it to a tritium reclamation system.

Vacuum Seal Location - The influence of the vacuum seal location on the maintenance of the design concepts included in Figure 6-1 is primarily a function of the variation in the number of vacuum zones, the location of the vacuum wall for each zone and the type of seal for the plasma chamber zone. Some aspects of the variations in the type of seal have been previously discussed in the consideration of first wall/blanket module size.

In all design concepts the location of the seal for the first vacuum zone, i.e., the plasma chamber, is at or near the first wall/blanket. The seal location farthest removed from the plasma is just outside of the plasma chamber shield in the Culham Mk-II and the ORNL cassette concepts. The next closest location to the plasma for this seal is at the outside of the blanket in the UWMAK-III concept. This location also approximates the GA-DPR case, even though access is from within the chamber for the GA-DPR, because the GA-DPR seal is protected by a graphite ring approximately 12 cm deep. In the UWMAK-I concept, the seal is located between the blankets of adjacent sectors where it is exposed directly to the plasma. In this concept the seal flanges are actively cooled. These locations have varying requirements for radiation damage and varying life expectancy. The least vulnerable seal location, as well as seal design, seems to be the high impedance joint used for the ORNL cassette concept.

The outer vacuum zones are all at the reactor room wall except for the UWMAK-III concept, which uses the shear panel (lateral access panel) between the T.F. magnets as the vacuum wall, and possibly the Culham Mk-II concept which considers a double seal at the shield door. The seals at these locations have not been defined.

When removing the first wall/blanket modules, vacuum lines to the pumps are disconnected in only two of the design approaches. These are the UWMAK-I lines which are disconnected to permit moving the entire reactor sector and the GA-DPR vacuum port cover in the auxiliary vacuum line at the top of the reactor. This cover is removed to gain access. Both line connections use bolted flanges since the space around the flanges appears relatively uncluttered. When evaluating the influence of vacuum wall locations these line connections are of little significance and are omitted.

The impacts of vacuum wall location on the maintenance efficiency are expected to vary with the volume of the evacuated zones and the amount of

outgassing expected. In addition, the length of the seals defines the duration of the maintenance tasks and the probability of leakage. The large module approach (UWMAK-I) has the longest seal around a single module but the GA-DPR seals are longer per sector than any other approach because of the large number of modules. The shortest seals are on those required for the Culham Mk-II approach or for the UWMAK-III. The seals around the reactor room are longest for the UWMAK-I because of the rotating wall and probably the shortest for the GA-DPR or ORNL cassette approaches because the smaller modules and the smaller equipment required to maintain these reactors can use smaller openings in the wall.

Plasma Cross Section - Comparison of the relative maintainability of each design concept with variations in plasma characteristics is primarily a function of those characteristics which affect the reactor size and the wall life of the first wall/blanket. The parameters affecting size are given in Table 6-1 and indicate a rather narrow range of differences in plasma dimensions for the concepts examined except for the UWMAK-I approach. The plasma characteristics selected for the Culham Mk-II are based on an optimized UWMAK-I reactor configuration previously defined in the discussion of reactor size. The plasma major radius of 7.81 meters requires a small diameter core when the Culham Mk-II approach is fitted to this plasma size because of the thickness requirements of the shield and blanket. A higher aspect ratio is required to enlarge the core but, since the maintenance requirements have been relatively insensitive to aspect ratios in the range of the design approaches considered in this study such refinement is unwarranted. The ORNL cassette approach is applied to a plasma with the same characteristics as the UWMAK-III. The only alteration required is a small adjustment in the location of the poloidal field coils. By using plasma characteristics with the same thermal power, the physical size of the design approaches under consideration are normalized for comparison purposes.

The wall life effects on the maintenance requirements have been discussed previously under the first wall/blanket module size considerations.

6.2 FEATURE COMPARISONS - In this section quantitative comparisons are made between selected design features. The features included in this discussion are:

- o First wall/blanket replaceable module size,

- o Normalized comparison,
- o Reactor size,
- o Permanently installed maintenance equipment,
- o Technique for accessing the first wall/blanket,
- o Magnet locations,
- o Vacuum vessel location,
- o Diverter type,
- o Connections,
- o Effect of contact (hands-on) operations.

Some of the comparisons of design features and maintenance operations that are derived from the maintenance concepts are based on the overall concept effects. Other comparisons require a detailed examination of the number of functions and the time required for specific operations. Those that permit comparisons of overall effects are:

- o First wall/blanket replaceable module size (original reactor definition),
- o First wall/blanket replaceable module size (normalized to uniform reactor thermal power),
- o Reactor size (varying thermal power with same design concept),
- o Impact of permanently installed maintenance equipments,
- o Effect of contact (hands-on) operations.

Each of these overall comparisons is presented by using three tables. The first table summarizes the reactor physical characteristics including:

- o Thermal power,
- o Net electrical power,
- o Major radius,
- o Plasma minor radius (half-width),
- o Reactor room height,
- o Reactor room diameter,
- o Neutron wall loading.

The second table presents and summarizes the operating conditions for maintenance such as:

- o Fraction of the wall replaced per outage,
- o Wall life,
- o Scheduled downtime (threshold and nominal),
- o Estimated downtime for scheduled replacement of first wall/blanket

- modules,
- o Estimated total cycle time,
- o Estimated availability.

The wall life presented in the second table is determined by:

$$\text{Wall Life} = \frac{\text{Fluence Limit}}{\text{Wall Loading}}$$

For these analyses the fluence limit is set at 5 MW-yrs/m².

The scheduled downtime goals are derived for both the nominal and threshold availability goal percentages defined in Section 5.1.2. Hence the scheduled downtime goals are defined as follows:

$$t_{dt_G} = t_{mc} - t_{dt_U} = \frac{t_{ut}(f)}{A_G} - t_{dt_U}$$

where:

t_{dt_G} = scheduled downtime goal for fusion unique equipment,

t_{mc} = scheduled maintenance cycle

t_{ut} = operating time (up time)

f = fraction of first wall replaced per outage

A_G = availability goal

t_{dt_U} = unscheduled downtime

The assumptions involved in the above relationship are as follows:

- o The scheduled downtime for balance of plant maintenance will be accomplished during the downtime for scheduled first wall/blanket replacement.
- o The allowance for unscheduled downtime is for the entire plant.
- o The scheduled maintenance for fusion unique equipment other than the first wall/blanket can be accomplished during the downtime for first wall/blanket replacement.

The allowances for unscheduled downtime are based on the overall availability goals as derived in Section 5.1.2. These allowances are 65 days per operating year for the nominal goal and 88 days per operating year for the threshold goal.

The estimated scheduled downtime is based on the definition of scheduled maintenance functions, the time to perform those functions and the time phased plan for maintenance operations (fraction of wall replaced, equipment utilization, etc.) developed in Section 4.0.

The estimated scheduled maintenance cycle time is based on the summation of the operating time, an allowance for unscheduled downtime (65 days per operating year), and allowance for balance-of-plant scheduled shutdown which exceeds 28 days in a given cycle (based on $t_{dt_{BOP_S}} = (t_{ut}/365) \times 28-28$)

and the estimated downtime for scheduled wall replacement. The estimated availability is, therefore:

$$A = \frac{t_{ut}}{t_{ut} + t_{dt_{BOP_S}} + t_{dt_U} + t_{dt_S}}$$

where:

$$t_{ut} = t_{wl} (f)$$

$$t_{wl} = \text{first wall life}$$

$$f = \text{fraction of first wall replaced per outage}$$

$$t_{dt_{BOP_S}} = \text{scheduled balance of plant downtime}$$

$$t_{dt_U} = \text{unscheduled downtime}$$

$$t_{dt_S} = \text{estimated scheduled downtime for wall replacement}$$

The third table employed in these comparisons is the percentage effect on the cost of electricity of maintenance capital expenditures, recurring maintenance costs (Operations and Maintenance accounts) and downtime. All percentages are based on the ratio of a cost increment to the base cost of electricity that is realized for a particular concept if no scheduled wall replacement activities are performed. The first three columns in the table are maintenance capital investment including facilities (hot cells, etc.), initial spares, and the special maintenance equipment. These capital costs are then converted to annual costs and include both direct and indirect costs. The assumed rate of return on investment used to make this conversion is 15

percent per year. This annual capital cost increment is added to the recurring annual maintenance costs to obtain the total annual cost increment for maintenance. The fifth and sixth columns are the recurring annual maintenance costs and include labor costs directly related to regularly scheduled wall replacement and the replacement wall material costs. The relationship for determining the maintenance cost of electricity increments is as follows:

$$\Delta\text{COE} = \frac{\Delta \text{ Annual Cost}}{(\text{Net electrical output}) (\text{Availability}) \times 8760}, \text{ (mills/kw-hr)}$$

The availability used in the above relationship is that which is realized if there is no scheduled wall replacement.

The eighth column in the third table is the incremental cost of electricity resulting from the delta availability caused by scheduled wall replacement downtime. The final column is the total maintenance effect.

6.2.1 Comparison of Concepts Differing in First Wall/Blanket Module Size - Six reactor concepts have been examined to determine the effect of first wall/blanket module size on maintenance operations and costs. These six concepts are:

- o UWMAK-I (large module baseline),
- o Culham Mk-II (large module alternate),
- o UWMAK-III (intermediate module baseline),
- o General Atomic DPR (small module baseline),
- o General Atomic DPR with in-place maintenance equipment,
- o Oak Ridge (ORNL) (small module alternate).

The reactor physical characteristics are summarized in Table 6-2. All of the reactors are 5000 MW_{th} machines except the small module GA-DPR rated at 1764 MW_{th}. In addition, three of the reactors, the two GA-DPR's and the UWMAK-I are non-optimum with respect to minimum cost of electricity. In Section 6.2.2, these reactors are adjusted to produce 5000 MW_{th} at optimum or near optimum size based on trapped electron mode confinement assumptions.

The maintenance operations are characterized in Table 6-3. The GA-DPR concept with in-place maintenance equipment results in the highest availability of any of the concepts (0.755). This availability corresponds to an estimated scheduled maintenance downtime of 53 days, which is better than the nominal scheduled maintenance downtime goal of 77 days.

It should be pointed out that in this particular comparison, the reactor concepts are analyzed in their original size (i.e., original thermal power).

Hence, there are differences in physical size as well as in wall loading (first wall life). Later on in this discussion the concept comparison is made based on the same (5000 MW_{th}) size and wall loadings which are in the 2.0 to 2.5 MW/m² range.

TABLE 6-2
REACTOR CHARACTERISTICS

CONCEPT	THERMAL POWER MW _{th}	NET ELECT. POWER MW _E	MAJOR RADIUS R m	PLASMA MINOR RADIUS a m	REACTOR ROOM		NEUTRON WALL LOADING P _n MW/m ²
					HEIGHT m	DIAMETER m	
LARGE MODULE							
UWMAK-I	5000	1504	13.0	5.0	50.3	134.5	1.24
CULHAM	5000	1524	7.8	3.0	31.3	82.7	2.18
INTERMEDIATE MODULE							
UWMAK-III	5000	1899	8.10	2.7	57.1	77.7	2.50
SMALL MODULE							
GA-DPR	1764	541	7.00	1.80	42.9	67.3	1.01
GA-DPR (IN-PLACE EQUIP.)	1764	541	7.00	1.80	42.9	67.3	1.01
ORNL	5000	1899	8.10	2.70	57.1	77.7	2.50

TABLE 6-3
IMPACT OF REACTOR CONCEPT ON MAINTENANCE OPERATIONS

CONCEPT	FRACTION OF WALL REPLACED PER OUTAGE	SCHEDULED DOWNTIME GOAL THRESH/NOM DAYS	ESTIMATED SCHEDULED DOWNTIME DAYS	ESTIMATED TOTAL CYCLE TIME DAYS/YR	ESTIMATED AVAILABILITY	WALL LIFE YR
LARGE MODULE BASELINE (UWMAK-I)	0.333	182/104	154	741/2.04	0.661	4.03
LARGE MODULE ALTERNATE (CULHAM)	0.333	104/59	47	377/1.03	0.743	2.30
INTERMEDIATE MODULE BASELINE (UWMAK-III)	1.000	271/154	112	1000 (2.75)	0.730	2.00
SMALL MODULE BASELINE (GA-DPR)	0.333	224/128	214	943/2.58	0.640	4.96
SMALL MODULE BASELINE WITH IN-PLACE EQUIP.	0.200	135/77	53	479/1.31	0.755	4.96
SMALL MODULE ALTERNATE (ORNL)	0.200	135/77	53	479/0.93	0.755	2.00

The two other reactor concepts produce availabilities better than the nominal goal (0.72). These are the large module Culham Mk-II concept (0.743) and the intermediate module UWMAK-III concept (0.730).

The effect of maintenance capital investment and operations and maintenance recurring costs are shown in Table 6-4 along with the effect of downtime. UWMAK-I maintenance effects are dominated by both capital costs (19.7%) and availability (25.6%). The capital cost effect is predominantly due to initial spares (shield plus blanket plus large toroidal magnet). For the Culham Mk-II reactor nothing dominates. For the intermediate module concept, UWMAK-III, the capital costs (9.3%) and availability (10.5%) contribute about equally. In the case of the small module concept, GA-DPR, the capital costs are made up largely of equipment costs (7.7% out of 8.7%), but the dominant effect is downtime (27.9%). The use of in-place equipment with the GA-DPR results in a reduction of downtime effects of 21.8 percent. The alternate small module concept (ORNL cassette) maintenance effect is dominated by the contribution of downtime but the total effect is below 20%.

TABLE 6-4

IMPACT OF REACTOR CONCEPT ON MAINTENANCE COSTS (COST OF ELECTRICITY)

CONCEPT	MAINTENANCE CAPITAL INVESTMENT				MAINTENANCE OPERATIONS			DOWN- ¹ TIME %	TOTAL MAINT. EFFECT.
	FACILITY	INITIAL SPARES	MAINT. EQUIP.	TOTAL	LABOR	MAT'LS	TOTAL		
LARGE MODULE CONCEPT									
BASELINE (UWMAK-I)	5.9	9.9	3.9	19.7	3.7	1.0	4.7	25.6	50.0
ALTERNATE (CULHAM)	4.0	3.5	3.0	10.5	2.2	1.2	3.4	8.3	22.2
INTERMEDIATE MODULE CONCEPT									
BASELINE (UWMAK-III)	1.3	2.6	5.4	9.3	2.6	2.9	5.5	10.5	25.3
SMALL MODULE CONCEPT									
BASELINE (GA-DPR)	0	1.0	7.7	8.7	3.4	1.4	4.8	27.9	41.4
GA-DPR IN-PLACE	0	0.6	6.1	6.7	1.7	1.7	3.4	6.1	16.2
ALTERNATE (ORNL)	0.6	0.9	2.0	3.5	1.5	2.9	4.4	11.7	19.6

¹ SCHEDULED FIRST WALL/BLANKET REPLACEMENT

It seems possible, from this data, that concepts can be configured in each of the module size categories to keep maintenance effects in the 20-30% range subject to correction for size as discussed later. The major leverage to maintaining low total maintenance effects is the downtime required.

6.2.2 Normalization of Reactor Size - It is believed that since some of the reactor concepts are of different sizes (MW_{th}) and have not been defined at near optimum design parameters, i.e., the design parameters such as wall loading and maximum toroidal field strength have not been adjusted to yield near-minimum cost of electricity, the percentage effect of availability on cost of electricity based on the data for the unadjusted concepts might be misleading in the comparisons of maintenance effects. Consequently, each of the reactors has been examined through the use of our TOCOMO systems analysis code to redefine the size and other characteristics necessary to minimize the cost of electricity for a 5000 MW_{th} machine. These characteristics are summarized in Table 6-5. It is observed that they all produce about the same net electrical power except UWMAK-III and ORNL which employ the UWMAK-III helium gas cycle thermal conversion system with somewhat higher efficiencies. They all have plasma height to width ratios of 2.0 except the GA-DPR which is a doublet configuration with a height to width ratio of 3.0. The wall loadings vary from about 2.0 to 2.5 MW/m^2 . Included in this comparison is the GA-DPR with the in-place maintenance equipment concept.

TABLE 6-5
NORMALIZED REACTOR CHARACTERISTICS

$MW_{TH} = 5000$

CONCEPT	NET ELECTRICAL POWER MW_e	MAJOR RADIUS R m	PLASMA MINOR RADIUS a m	REACTOR ROOM		NEUTRON WALL LOADING P_D MW/m^2
				HEIGHT m	DIAMETER m	
LARGE MODULE CONCEPT						
UWMAK-I	1496	9.40	2.75	30.9	92.4	1.97
CULHAM MK-I	1524	7.81	3.00	31.3	82.7	2.18
INTERMEDIATE MODULE CONCEPT						
UWMAK-III	1899	8.10	2.70	57.1	77.7	2.50
SMALL MODULE CONCEPT						
GA-DPR (BASELINE MAINT. EQUIP.)	1541	7.23	2.15	47.6	72.1	2.32
GA-DPR (IN-PLACE MAINT. EQUIP.)	1541	7.23	2.15	47.6	72.1	2.32
ORNL CASSETTE	1899	8.10	2.70	57.1	77.7	2.50

A comparison of the maintenance operations for the six concepts is provided in Table 6-6. When the design parameters are adjusted to near optimum, the fraction of the wall replaced per outage ranges from 0.333 to 1.000. Three concepts have availabilities which are close to or better than the nominal availability goal (0.72). These are the large module concept (Culham Mk-II), the intermediate concept (UWMAK-III) and the small module concept (ORNL).

TABLE 6-6

MAINTENANCE OPERATIONS FOR NORMALIZED REACTORS - 5000 MW_{TH}

CONCEPT	FRACTION OF WALL REPLACED PER OUTAGE	SCHEDULED DOWNTIME GOAL THRESH/NOM. DAYS	ESTIMATED SCHEDULED DOWNTIME DAYS	ESTIMATED TOTAL CYCLE TIME DAYS/YR.	ESTIMATED AVAILABILITY	WALL LIFE YR.
LARGE MODULE CONCEPT						
UWMAK-I (5000 MW OPTIM.)	0.333	115/65	135	498/1.37	0.619	2.53
CULHAM (5000 MW OPTIM.)	0.333	104/59	47	377/1.04	0.743	2.30
INTERMEDIATE MODULE CONCEPT						
UWMAK-III (5000 MW)	1.000	271/154	112	1000/2.74	0.730	2.00
SMALL MODULE CONCEPT						
GA-DPR (5000 MW OPTIM.)	0.500	146/83	320	726/1.99	0.501	2.16
GA-DPR (5000 MW OPTIM.) (IN-PLACE MAINT. EQUIP)	0.500	146/83	125	591/1.62	0.666	2.16
ORNL (5000 MW)	0.333	90/52	52	338/0.93	0.719	2.00

The percentage effect of scheduled maintenance on the cost of electricity is compared in Table 6-7 for each of the six concepts. In terms of the overall effect, the small module ORNL concept has the least effect (19.6%) with the large module Culham Mk-II and the intermediate module UWMAK-III fairly close (22.3% and 24.9%, respectively). The use of in-place maintenance with the small module concept shows a dramatic improvement in maintenance effect (reducing the baseline from 77.1 to 30.9%).

It is clear that, from a scheduled maintenance standpoint, at least one concept from each of the large, intermediate and small concepts have maintenance procedures which produce effects on the cost of electricity in the 20-30% range. Therefore, these concepts are candidates for additional analysis of

unscheduled operations. It seems, intuitively, that the smaller module concepts should offer certain advantages from an unscheduled failure of a blanket module since, in this situation, it will probably be desirable to replace only the faulty module. Hence, the smaller the module, the smaller the removal time if, of course, the removal time is shown to be proportional to module size.

TABLE 6-7
PERCENTAGE EFFECT OF MAINTENANCE ON COST OF ELECTRICITY

$$MW_{TH} = 5000$$

CONCEPT	MAINTENANCE CAPITAL COSTS				O&M COSTS			DOWN-TIME EFFECT %	TOTAL MAINT. EFFECT %
	FACILITY %	INITIAL SPARES %	MAINT. EQUIP. %	TOTAL %	LABOR %	MAT'LS %	TOTAL %		
LARGE MODULE CONCEPT									
UWMAK-I (5000 MW OPT.)	4.2	4.3	3.8	12.3	6.7	1.0	7.7	34.5	54.5
CULHAM (5000 MW OPT.)	4.3	3.0	3.1	10.4	2.4	1.2	3.6	8.3	22.3
INTERMEDIATE MODULE CONCEPT									
UWMAK-III	1.3	2.6	5.4	9.3	2.6	2.9	5.5	10.5	25.3
SMALL MODULE CONCEPT									
GA-DPR (5000 MW OPTIM.)	0	1.2	4.9	6.1	3.3	1.9	5.2	65.8	77.1
GA-DPR (5000 MW OPTIM.) IN-PLACE MAINT. EQUIP.	0	1.2	3.9	5.1	1.7	2.6	4.3	21.5	30.9
ORNL (5000 MW OPTIM.)	0.6	0.9	2.0	3.5	1.5	2.9	4.4	11.7	19.6

6.2.3 Effect of Reactor Size - The previous comparison of reactor concepts raises the question of the effect of reactor physical size on the equipment requirements, the time to perform the maintenance functions, the frequency of maintenance operations and, in fact, the overall maintenance approach. To make this evaluation it has been decided to compare these effects for two reactor thermal power levels, 5000 MW_{th}, and 3000 MW_{th}, and for near minimum cost of electricity design conditions at both power levels. The baseline UWMAK-I is first resized to incorporate trapped ion mode confinement scaling and a plasma height to width ratio of 2.0. A maximum toroidal field strength of 7.0 tesla is selected. The resized baseline reactor parameters are shown in Table 6-8. When the reactor is then resized to 3000 MW_{th} the maximum field strength is changed to 6.0 tesla. As a result, the scale

dimensions of both reactors are almost equal. The wall loading, however, for the 5000 MW_{th} case is almost twice that for the 3000 MW_{th} reactor.

TABLE 6-8
LARGE AND SMALL REACTOR CHARACTERISTICS
(TRAPPED ION MODE CONFINEMENT SCALING)

CONCEPT	B _{MAX} TESLA	THERMAL POWER MW _{th}	NET ELECT. POWER MW _E	MAJOR RADIUS R m	PLASMA MINOR RADIUS a m	REACTOR ROOM		NEUTRON WALL LOADING P _n MW/m ²
						HEIGHT m	DIAMETER m	
LARGE REACTOR UWMAK-I	7.0	5000	1496	9.4	2.75	30.9	92.4	1.97
SMALL REACTOR UWMAK-I	6.0	3000	872	9.2	3.0	32.5	93.0	1.10

¹ PLASMA CROSS SECTION HEIGHT/WIDTH = 2.0

The effect of this scaling is to conclude that both the scheduled maintenance downtime and the equipment requirements remain the same for both thermal power levels. However, the availability, shown in Table 6-9, is significantly lower for the larger machine due almost entirely to the difference in neutron wall loading.

TABLE 6-9
IMPACT OF REACTOR SIZE ON MAINTENANCE OPERATIONS

CONCEPT	FRACTION OF WALL REPLACED PER OUTAGE	WALL LIFE YR	SCHEDULED DOWNTIME GOAL THRESH/NOM DAYS	ESTIMATED SCHEDULED DOWNTIME DAYS	ESTIMATED TOTAL CYCLE TIME DAYS	ESTIMATED AVAILABILITY
LARGE REACTOR SIZE - 5000 MW _{th}	0.333	2.53	115/65	135	498/1.37	0.619
SMALL REACTOR SIZE - 3000 MW _{th}	0.333	4.53	205/116	135	798/2.18	0.690

The percentage effects of maintenance on the cost of electricity are shown in Table 6-10. The effect of maintenance on the cost of electricity is reduced by 13.6% by reducing the thermal power from 5000 MW_{th} to 3000 MW_{th}. This is largely caused by the reduction in the frequency of wall replacement outages related to the neutron wall loading.

TABLE 6-10
IMPACT OF MAINTENANCE ON THE COST OF ELECTRICITY
(LARGE MODULE CONCEPT - UWMAK-I)

CONCEPT	MAINTENANCE CAPITAL INVESTMENT				MAINTENANCE OPERATIONS			DOWN- ¹ TIME %	TOTAL MAINT. EFFECT. %
	FACILITY	INITIAL SPARES	MAINT. EQUIP.	TOTAL	LABOR %	MAT'LS %	TOTAL %		
LARGE REACTOR - 5000 MW	4.2	4.3	3.8	12.3	6.7	1.0	7.7	34.5	54.5
SMALL REACTOR - 3000 MW	6.3	5.4	5.4	17.1	6.0	0.9	6.9	19.2	43.2

¹ SCHEDULED FIRST WALL/BLANKET REPLACEMENT

6.2.4 Effect of In-place Maintenance Equipment - Evaluation of the small module concept (the GA-DPR baseline), which involves the installation of internal remotely operated equipment, suggests an alternate concept whereby this equipment is installed on a permanent basis as an integral part of the reactor. In order to derive the maximum benefit from this approach, it is desirable to be able to reach all modules with the manipulator arm of the remote maintenance machine without the necessity of laying track (see Sections 4.2.1.4 and 4.2.1.5) and without the use of the in-chamber maintenance machine normally employed during the maintenance of the small module baseline reactor.

In Table 6-11 the basic reactor characteristics are summarized. These features are kept constant in the comparison.

TABLE 6-11
SMALL MODULE REACTOR BASELINE CHARACTERISTICS

CONCEPT	THERMAL POWER MW _{th}	NET ELECTRICAL POWER MW _E	MAJOR RADIUS R m	PLASMA MINOR RADIUS a m	REACTOR ROOM		NEUTRON WALL LOADING P _n MW/m ²
					HEIGHT m	DIAMETER m	
GA-DPR (WITH EITHER BASELINE OR IN-PLACE MAINTENANCE EQUIPMENT)	5000	1541	7.23	2.15	47.6	72.1	2.32

The maintenance operations for the baseline approach (see Section 4.2.1.4 for a description) are compared to those required when using the in-place equipment maintenance concept (see Section 4.2.1.5) in Table 6-12. The optimum fraction of the first wall/blanket replaced per outage is 0.50 for both the baseline and the in-place concept. It is interesting for this concept that the cost of electricity is relatively insensitive to the fraction of the wall replaced per outage (see Section 5.3). This occurs because the scheduled downtime for this concept is approximately proportional to the fraction of the wall replaced per outage. The actual module replacement time is almost all related to internal operations and is, in fact, related directly to the number of modules replaced. The time required to set up and remove the maintenance equipment before and after replacement operations is a constant for any fraction of the wall replaced in this analysis.

TABLE 6-12
IMPACT OF IN-PLACE EQUIPMENT ON MAINTENANCE OPERATIONS

CONCEPT	FRACTION OF WALL REPLACED PER OUTAGE	SCHEDULED DOWNTIME GOAL THRESH/NOM DAYS	ESTIMATED SCHEDULED DOWNTIME DAYS	ESTIMATED TOTAL CYCLE TIME DAYS	ESTIMATED AVAILABILITY	WALL LIFE YR
SMALL MODULE BASELINE WITH MAINTENANCE EQUIP. INSTALLED ON DEMAND	0.500	146/83	320	726/1.99	0.501	2.16
SMALL MODULE BASELINE WITH IN-PLACE MAINTENANCE EQUIP.	0.500	146/83	125	591/1.62	0.666	2.16

The improvement in downtime resulting from the use of in-place concept is dramatic. It results in a change in availability of 0.16. This is achieved by elimination of the vacuum duct removal and reassembly operations, of the installation and removal of the remote maintenance machine, of the track laying and removal operations, and of the installation and removal of the in-chamber maintenance machine.

The effects on the cost of electricity caused by using the in-place concept are shown in Table 6-13. The reduction in maintenance capital investment effects are small, only about one percent. The reduction in maintenance operations effects is also small, about one percent. The big effect is from the improved availability and this impact on cost of electricity is about 44.3%. The total reduction in the effect of maintenance on cost of electricity is 46.2%. It should be pointed out, however, this approach has not, at

this time, been evaluated for unscheduled shutdowns caused by failures in the maintenance equipment. Accounting for this factor may have a significant effect on the desirability of this approach.

TABLE 6-13
IMPACT OF MAINTENANCE ON COST OF ELECTRICITY
(SMALL MODULE IN-PLACE EQUIPMENT)

CONCEPT	MAINTENANCE CAPITAL INVESTMENT				MAINTENANCE OPERATIONS			DOWN-TIME %	TOTAL MAINT. EFFECT. %
	FACILITY %	INITIAL SPARES %	MAINT. EQUIP. %	TOTAL %	LABOR %	MAT'LS %	TOTAL %		
GA-DPR BASELINE	0	1.2	4.9	6.1	3.3	1.9	5.2	65.8	77.1
GA-DPR WITH IN-PLACE MAINTENANCE EQUIPMENT	0	1.2	3.9	5.1	1.7	2.6	4.3	21.5	30.9

¹ SCHEDULED FIRST WALL/BLANKET REPLACEMENT

6.2.5 Comparisons of Specific Activities and Subsystem Features - In addition to the overall comparisons of maintenance effects associated with various reactor concepts, it is possible to identify some of the desirable and some of the less desirable specific design features. It is difficult in many cases to isolate maintenance effects to a specific design feature. They are usually related to a blend of design features which make up the total design approach. The cases that have been chosen illustrate distinctively different design features related to the following:

- o Accessing the first wall/blanket modules,
- o Location of the poloidal field magnet system,
- o General arrangement of the diverter system,
- o Location of the primary vacuum wall.

6.2.5.1 Accessing the First Wall Blanket - Each of those previously described concepts which have been categorized according to the first wall/blanket module size also represents a unique approach to accessing the first wall/blanket. The concepts included in this particular discussion are:

- o UWMAK-I,
- o Culham Mk II,
- o UWMAK-III,
- o General Atomic DPR,
- o General Atomic DPR with in-place maintenance equipment,
- o ORNL Cassette.

Specifically, an estimate has been made of the time required for each of the above concepts to get to the point where the joint of the first wall/blanket can be unfastened to permit its removal. In addition the time required to reassemble the reactor after the replacement first wall/blanket module has been installed and any joint reconnections have been made is estimated. The activities for accessing and reassembly include (where appropriate to a given design):

- o Movement or repositioning of neutral beam or RF heater components,
- o Removal of any toroidal field coil structural support members,
- o Disconnection or reconnection of fluid lines (coolant and vacuum),
- o Disconnection or reconnection of instrumentation and diagnostics,
- o Removal and reinstallation of shield blocks.

The times required for performing these activities for each of the concepts are summarized in Table 6-14. The major time requirements for UWMAK-I are those necessary to access one of the twelve sectors. These times are primarily determined by neutral beam injector removal, fluid line connections and shield block removal and reinstallation. For the Culham design the longest time requirement (also for one sector) involves moving the neutral beam injectors, removing the toroidal field magnet shear panels and removing the outer shield door. The Culham design requires about two-thirds less time than the UWMAK-I design for accessing and reassembly of a comparable fraction of the first wall/blanket. For the UWMAK-III design, removing the toroidal field coil shear panels and the lithium manifolds account for a high percentage of the accessing time. This time is based on accessing one sector or one eighteenth of the reactor. A major part of the accessing time for the GA-DPR baseline is the installation of the remote maintenance machines and in laying track for the in-chamber maintenance equipment. When the in-place equipment is employed, the total accessing time is small and is made up of those activities associated with deployment of the equipment into the plasma chamber. Most of the accessing time for the ORNL concept is divided between removing the neutral beam injectors and disconnecting coolant manifolds. The time quoted for the ORNL concept is also for one sector or one eighteenth of the reactor.

TABLE 6-14
ACCESSING AND REASSEMBLY TIMES

CONCEPT	ACCESS TIME HRS	REASSEMBLY TIME HRS	TOTAL TIME HRS
UWMAK-I	781	1406	2187
CULHAM MK 2	200	507	708
UWMAK-III	296	280	576
GA-DPR	371	555	926
GA-DPR (IN-PLACE MAINTENANCE EQUIPMENT	23	106	129
ORNL CASSETTE	105	209	314

6.2.5.2 Location of the Poloidal Field Magnets - The poloidal field magnets are located either inside or outside of the toroidal field magnets (or both). From the standpoint of their effectiveness in positioning and stabilizing the plasma the closer they are located to the plasma, the better. As a result, in those concepts where the accessing is principally external, some vertical translation of these magnets is required. (The ORNL concept is an exception to this.)

At this point in time in tokamak concept definition there exists no definition of either the structural support and attachment of these magnets or of the manner in which they are translated out of the way of modules being removed from the first wall/blanket. Hence, we have assumed that the magnet release and reattachment to the support structure and the vertical translation mechanisms, where required, are operated remotely and automatically.

The estimated times required to move these magnets out of the way are summarized in Table 6-15 for the five concepts. It should be emphasized that these magnet translations are accomplished in parallel with other tasks whose time requirements are dominant. Hence, there is no net effect on the total downtime requirements. The longest time requirement is for UWMAK-III which

has 11 poloidal field magnets arranged in 8 sets. Seven of these sets are inside the toroidal field magnets and because of possible interference with each other, they are translated individually.

TABLE 6-15
POLOIDAL COIL RETRACTION AND EXTENSION TIMES

CONCEPT	COIL RETRACTION HRS	COIL EXTENSION HRS	TOTAL HRS
LARGE MODULE (UWMAK-I)	5	5	10
ALTERNATE LARGE MODULE (CULHAM MK 2)	NONE	NONE	NONE
INTERMEDIATE MODULE (UWMAK-III)	43	57	100
SMALL MODULE (GA-DPR)	NONE	NONE	NONE
ALTERNATE SMALL MODULE (ORNL CASSETTE)	NONE	NONE	NONE

In the case of the small module concept, the GA-DPR, all module replacement is conducted internally so there is no need to move poloidal coils. In the alternate small module concept (ORNL), the first wall/blanket cassettes with shield block (see Section 3.6) are slipped between adjacent coils. Hence, no translation is necessary.

The necessity for the remote automatic feature of magnet translation must be recognized as an important design requirement. This requirement has a major influence in the development of a maintenance plan. If, for some reason the requirement cannot be satisfied, there would be a serious impact on down-time especially for the case of an unscheduled failure of a single module.

6.2.5.3 General Arrangement of the Diverter System - One of the most troublesome and time consuming elements to maintain is the diverter system. The diverter systems employed in the concepts under consideration in this study (except the GA-DPR) feature single or double null poloidal configurations which include a first wall/blanket component bounded by the diverter

passages that follow the separatrix lines to the particle collection plates (see Section 3.0 for design arrangements). This first wall/blanket component is subjected to intense neutron activity as are other portions of the first wall/blanket and, hence, must be periodically replaced. The location close to the core and in the proximity of poloidal field magnets makes access difficult for maintenance operations.

The estimated time to disconnect, remove, replace and connect the diverter modules for each concept is presented in Table 6-16. Both contact and remote operations are included. The times generally represent additional downtime over and above that required to disconnect, remove, replace and reconnect the other wall/blanket modules in that particular sector, although the UWMAK-III and the Culham Mk-II diverter modules can be disconnected and reconnected in parallel with other operations.

TABLE 6-16
DIVERTER MODULE EXCHANGE TIME

CONCEPT	REMOTE OR CONTACT	TYPE OF DIVERTER	NO. OF DIVERTERS IN TIME ESTIMATE	TIME TO DISCONNECT HR	TIME TO REMOVE HR	TIME TO REPLACE HR	TIME TO CONNECT HR	TOTAL TIME HR
LARGE MODULE BASELINE (UWMAK-I)	REMOTE	DOUBLE NULL POLOIDAL	2	50	NONE	NONE	173	223
LARGE MODULE (UWMAK-I)	CONTACT	DOUBLE NULL POLOIDAL	2	9	NONE	NONE	46	55
LARGE MODULE REDUCED SIZE (UWMAK-I)	REMOTE	DOUBLE NULL POLOIDAL	2	43	NONE	NONE	147	190
LARGE MODULE ALTERNATE (CULHAM)	REMOTE	SINGLE NULL POLOIDAL	1	10	22	29	11	72
INTERMEDIATE MODULE (UWMAK-III BASELINE)	REMOTE	DOUBLE NULL POLOIDAL	2	31	25	40	51	147
INTERMEDIATE MODULE BASELINE (UWMAK-III)	CONTACT	DOUBLE NULL POLOIDAL	2	8	25	40	12	85
SMALL MODULE BASELINE (GA-DPR)	REMOTE	FLOWING PLASMA BOUNDARY	N.A.	NONE	NONE	NONE	NONE	NONE

For UWMAK-I, the diverter module is withdrawn and replaced as a part of the first wall/blanket and shield sector. Hence, the times shown are only for disconnecting the reconnecting the lithium lines. These line connections

are welded joints. In the case of the UWMAK-I contact operations, two crews work simultaneously and the times shown are net elapsed times.

For the UWMAK-III intermediate module only one diverter module is removed in the sector for each scheduled outage. This concept would probably benefit the most from any improvements in diverter design.

6.2.5.4 Primary Vacuum Wall Seal Location - In comparing the baseline large module concept (UWMAK-I) with the alternate large module concept, part of the effect of vacuum wall location can be observed. In UWMAK-I, the vacuum wall is at the first wall and the blanket joint is between the sector modules. For the Culham Mk-II design the primary vacuum wall is the outer shield structural shell.

Table 6-17 shows the vacuum seal lengths for each concept and the disconnect and reconnect times. Both the seal lengths and the times are for one sector. Also shown is the effect of reduced module size for the large module concept. There is no benefit from contact operations for the UWMAK-I concept since the shield blocks are removed, exposing the radioactive joint when the vacuum seals are disconnected. Hence, contact operations cannot be employed.

TABLE 6-17
IMPACT OF VACUUM WALL LOCATION

CONCEPT	SEAL LENGTH m	TIME TO OPEN SEAL HR	TIME TO RESEAL HR	TOTAL TIME HR
LARGE MODULE CONCEPT - REMOTE (UWMAK-I)	102	207	290	497
LARGE MODULE CONCEPT REDUCED SIZE - REMOTE (UWMAK-I)	66	174	243	417
LARGE MODULE ALTERNATE CONCEPT - REMOTE (CULHAM - MK II)	43	43	55	98

The significantly smaller door seal length for the alternate large module concept results in an 80% reduction in time from the baseline UWMAK-I concept. The other part of the tradeoff, which should ultimately be included, is the

change in vacuum pumping requirements which result from changing the vacuum wall location.

6.2.5.5 Connections Required for First Wall/Blanket Replacement - The total connections that must be made and unmade (per sector) in the process of a first wall/blanket replacement are presented in Table 6-18. The connections are grouped according to structure, heaters, plasma chamber, toroidal field magnets and the totals for each sector and for the total reactor.

UWMAK-I has the largest number of bolted connections with the GA-DPR having the least. The UWMAK-I requires bolts for disconnecting the bracing between the toroidal field magnets, shield segments, vacuum seal clamps and vacuum lines whereas the GA-DPR uses bolts primarily to fasten vacuum port seals. The largest number of fluid line connections belong to the ORNL concept with the GA-DPR again having the least. UWMAK-I also has a large number of fluid line connections to contend with and many of these are very large when compared to those required for the ORNL cassettes. Therefore, the size of the connection must be considered when making comparisons of this type although, disconnect setup time is required for each connection so quantity is also important. Therefore, the data presented here can only give a qualitative understanding of the relative degree of difficulty involved for each concept.

In Table 6-19 the blanket module joint lengths which must be worked for each sector and for the total reactor are shown. In this case, the longest length of joint worked per reactor is for the GA-DPR with the Culham Mk-II and UWMAK-III about tied for the least with 43 meters and 47 meters, respectively. The joint lengths shown are for connecting the modules only and do not include connections required to gain access. While joint length is an indicator of the relative disconnect and reconnect tasks for replacing the first wall/blanket in a sector, the design of the joints must also be understood to define the relative degree of difficulty. For example, the UWMAK-I joint length given in the table is the length of the blanket joint at only one end of a sector. If a sector is removed by itself, two of these joints must be disconnected. The Culham Mk-II joint length is the length around the vacuum joint at the shield and the total length is disconnected for each sector. On the other hand, the UWMAK-III joint is between two sectors which, if modules in both sectors are removed, requires the joint between sectors to be disconnected only once. Also, the Culham Mk-II joints are bolted while the UWMAK-III joints are structurally bolted with welded seals. The ORNL

TABLE 6-18

CONNECTION REQUIREMENTS
(NOT INCLUDING BLANKET ATTACHMENTS)

CONCEPT	STRUCTURE		HEATERS (NB's & RF)					CHAMBER				MAGNETS			TOTAL/ SECTOR		TOTAL/ REACTOR	
	SHEAR STRUCT. (BOLTS)	SHIELD (BOLTS)	POWER	FLUID	INSTR.	VACUUM	INJECTOR LINE	VACUUM	BLANKET COOLANT	DIVERTER COOLANT	SHIELD COOLANT	POWER	VACUUM	COOLANT	BOLTS	LINES	BOLTS	LINES
LARGE MODULE (UWMAK-I)	10 (24)	224 (2)	3 (3)	5 (3)	2 (3)	2 (3)	1 (3)	4	6	4	20 (2)	2	1	5	688	81	8256	972
LARGE MODULE ALTERNATE (CULHAM)	120	90	3 (2)	5 (2)	2 (2)	2 (2)	1 (2)	-	4	3	2	-	-	-	210	34	2520	408
INTERMEDIATE MODULE (UWMAK-III)	84	12	3	-	-	-	-	-	60	5	-	-	-	-	96	68	1728	1224
SMALL MODULE (GA-DPR)	-	35 (8)	-	-	-	-	-	-	-	-	4 (8)	-	-	-	280	32	280	32
SMALL MODULE ALTERNATE (ORNL)	-	17	3 (2)	5 (2)	2 (2)	2 (2)	1 (2)	-	68	-	-	-	-	-	17	94	306	1692

TABLE 6-19
JOINT LENGTHS WORKED IN MODULE REPLACEMENT

CONCEPT	JOINT LENGTH PER SECTOR m	JOINT LENGTH PER REACTOR m
LARGE MODULE - UWMAK-I	51	612
LARGE MODULE ALTERNATE - CULHAM MK II	43	516
INTERMEDIATE MODULE UWMAK-II	47	846
SMALL MODULE BASELINE - GA-DPR	550 ¹	8800 ¹
SMALL MODULE ALTERNATE - ORNL	164	2952

¹ TWO WELDS PER MODULE

Joint length is large because the total periphery around each module at the shield connection is included in the joint. Some designs can significantly reduce this length.

6.2.6 Impact of Contact Operations - Contact or hands-on operations are examined for the three baseline concepts. These are the large module concept (UWMAK-I), the intermediate module concept (UWMAK-III) and the small module concept (GA-DPR). It should be emphasized that contact operations are not employed when the reactor is opened up, i.e., where maintenance operations involve direct exposure to the radioactive first wall/blanket components. Hence, contact activities are confined to those operations prior to and subsequent to the first wall/blanket replacement activities including accessing and reassembly functions.

The baseline reactor concept sizes are repeated for easy reference in Table 6-20. No significant modification of the reactor is assumed in the analysis of the contact activities.

TABLE 6-20

BASELINE REACTOR CHARACTERISTICS

Concept	Thermal Power MW _{th}	Net Electrical Power MW _E	Major Radius R m	Plasma Minor Radius a m	Reactor Room		Neutron Wall Loading P _n MW/m ²
					Height m	Diameter m	
Large Module Concept (UWMAK-IO)	5000	1504	13.00	5.00	50.3	134.5	1.24
Intermediate Module Concept (UWMAK-III)	5000	1899	8.10	2.70	57.1	77.7	2.50
Small Module Concept (GA-DPR)	1764	541	7.00	1.80	42.9	67.3	1.01

Maintenance operation comparisons are presented in Table 6-21. Generally speaking, the minimum cost of electricity occurs at different fractions of the wall replaced per outage for contact and remote operations. The change in the optimum wall replacement fraction (i.e., the fraction which provides minimum cost of electricity) for the large module baseline is related to the improvement in availability (from 0.66 to 0.70) when the contact operations are employed (reduced downtime). This results largely from the fact that fluid line disconnect activities can be conducted in parallel with each other because the fluid line geometry and arrangement permits the necessary personnel to be placed at each line simultaneously. The capability to perform the tasks more rapidly is also a factor. Remote operations require serial line disconnect and reassembly operations because of limited boom and manipulator clearances. These conditions are not encountered in other concepts and the reasons for the change in the optimum fraction for remote and contact operations is rather complex because of the large number of contributing factors. Since the optimum is based on minimum cost of electricity, changes in maintenance facilities, initial spares, maintenance equipment, labor for maintenance operations and materials for first wall/blanket replacement all influence the selection of the fraction replaced per outage.

In the case of the intermediate module concept (UWMAK-III) the improvement is much less dramatic. The larger number of modules and the attendant equipment cost prevents operating on all of the modules simultaneously. For remote operations where the optimum fraction is 100% the best equipment mix results in working 6 sectors simultaneously and then the next six sectors. While

TABLE 6-21
IMPACT OF HANDS-ON (CONTACT) MAINTENANCE ON MAINTENANCE
OPERATIONS

CONCEPT	SEQUENCE OF SECTORS (MODULES) WORKED	FRACTION OF WALL REPLACED PER OUTAGE	SCHEDULED DOWNTIME GOAL THRESH/NOM DAYS	ESTIMATED SCHEDULED DOWNTIME DAYS	ESTIMATED TOTAL CYCLE TIME DAYS	ESTIMATED AVAILABILITY	WALL LIFE YR
Large Module Baseline Remote	4 Together	0.333	182/104	154	741	0.661	4.03
Contact	3 Together	0.250	136/77	88	522	0.705	4.03
Intermediate Module Baseline Remote	6 Together	1.000	271/154	112	1000	0.730	2.00
Contact	6 Together	0.333	90/52	49	335	0.725	2.00
Small Module Baseline Remote	4 at a time	0.500	337/191	296	1403	0.645	4.96
Contact	4 at a time	0.250	169/95	152	693	0.654	4.96

working on accessing the second six sectors, module replacement activities on the first six can begin. (The reactor is thus open and this technique cannot be used for contact activities.) When contact activities are considered all accessing must be completed before replacement functions can begin. Hence, the maintenance plan for contact operation is optimized on a 0.333 fraction (6 sectors) and with equipment to do all 6 sectors simultaneously.

In the case of the small module, the design concept inherently minimizes the amount of accessing required external to the plasma chamber. Hence, the benefit from contact activities, though such exists, is fairly minimal when considering scheduled first wall/blanket replacement.

The percentage effect of maintenance operations on the cost of electricity is shown in Table 6-22. The major effect for the large module concept is seen to be the effect on downtime with the resulting reduction in cost of electricity attributable to downtime of from 25.6% to 16.0%. For the small module concept the small improvement in downtime, about 2%, is offset by penalties in scheduled maintenance labor of about 3.6% resulting in a net increase in maintenance effect on cost of electricity of 2.5% for contact maintenance.

In summary, the effects of contact operations in replacing the first wall/blanket for the baseline concepts appear relatively small except for the case

of the large module concept. As has been noted earlier, the effect on availability for the large module concept is significant.

TABLE 6-22
MAINTENANCE EFFECTS ON COST OF ELECTRICITY (REMOTE AND CONTACT)

CONCEPT	FACILITY %	INITIAL SPARES %	MAINT. EQUIP. %	TOTAL %	LABOR %	MAT'LS %	TOTAL %	DOWN- TIME %	TOTAL MAINT. EFFORT %
Large Module Concept (UWMAK-I) Remote	5.9	9.9	3.9	19.7	3.7	1.0	4.7	25.6	50.0
Contact	4.7	7.9	4.3	16.9	4.7	1.1	5.8	16.0	38.7
Intermediate Module Concept (UWMAK-III) Remote	1.3	2.6	5.4	9.3	2.6	2.9	5.5	10.5	25.3
Contact	0.6	0.9	3.7	5.2	6.5	2.9	9.4	11.9	26.5
Small Module Concept (GA-DPR) Remote	0	1.0	7.7	8.7	3.4	1.4	4.8	27.9	41.4
Contact	0	0.8	8.8	9.6	7.0	1.5	8.5	25.8	43.9

There are several aspects of this comparison that suggest additional study on the subject of contact operations. One is the benefit associated with the large module concept. Only the baseline could be examined (UWMAK-I in this phase). In the next phase the maintenance of the Culham Mk-II concept will be addressed by using contact techniques. In the case of the intermediate and small module concept, the benefit of contact activities for unscheduled operations, particularly in those cases where the plasma chamber does not need to be opened up, is expected to be significant. In the case of the GA-DPR with in-place equipment and with casking of the blanket modules, external contact operations can be conducted with an anticipated strong benefit to reactor availability in the event of unscheduled shutdowns.

7.0 CONCLUSIONS

This section presents the highlights of the quantitative results of the maintenance analyses and some discussion of these highlights. It is the intent of this section to provide guidance on what design approaches offer a potential for achieving viable tokamak fusion power system maintainability.

7.1 OBSERVATIONS - The comparisons discussed in previous sections are summarized here in a set of conclusions. These conclusions are, of necessity, incomplete because the study has addressed, primarily, scheduled replacement of the first wall/blanket. The impacts of unscheduled maintenance, or other subsystem maintenance, and of contact operations for alternate concepts (scheduled and unscheduled) remain to be accomplished in the next study phase. The conclusions which are appropriate at this time are presented in the following discussion.

- o The total scheduled maintenance effects from each of the five reactor concepts plus the GA-DPR with in-place equipment on the cost of electricity are shown in Figure 7-1. In these data, there has been no attempt to normalize the reactor size or other operating characteristics. The effects range from 16.1 percent for the GA-DPR concept with in-place equipment to 50.0 percent for the UWMAK-I baseline. The availabilities range from 0.64 (GA-DPR baseline) to 0.76 (GA-DPR with in-place equipment).
- o When the six concepts are normalized in size ($5000 \text{ MW}_{\text{th}}$) and adjusted in terms of other system parameters (B_{max} , P_n) to produce a near-minimum cost of electricity, the effect of scheduled maintenance on the cost of electricity is as shown in Figure 7-2. The range in effect is now from 19.6 percent (ORNL) to 77.1 percent (GA-DPR). The availability ranges from 0.50 for the baseline GA-DPR to 0.74 for the Culham concept.
- o The downtime effect is the largest single contributor to the effect of scheduled maintenance on the cost of electricity. From Figure 7-2 it can be seen that these effects range from 8.3 percent for the Culham concept to 65.8 percent for the GA-DPR baseline.
- o Four of the six concepts depicted in Figure 7-2 have maintenance plans whose total effect on the cost of electricity is in the range of 20-30 percent. Since these four concepts (Culham, UWMAK-III, ORNL and the

Figure 7-1

GA-DPR with in-place maintenance equipment) represent all three module size categories, this feature cannot, in itself, be employed as a design guideline for scheduled maintenance operations.

- o Total maintenance capital effects on the cost of electricity range from 3.5 percent for the small module ORNL to 12.3 percent for the UWMAK-I. The sizeable effect for UWMAK-I results from the cost of initial spares which are influenced to a large degree by the fact that each replaceable sector includes one large toroidal field coil.
- o Maintenance equipment costs (included in the maintenance capital effects) raise the cost of electricity from 2 percent (ORNL) to 4.9 percent for the GA-DPR baseline.

MAINTENANCE EFFECTS FOR NEAR-MINIMUM COST OF ELECTRICITY REACTORS

13-983

Figure 7-2

- o The operations and maintenance (recurring) cost increases the cost of electricity from 3.4 percent (Culham) to 7.7 percent (UWMAK-I) due to wall replacement labor and materials.

- o Reducing the size of the large module concept (UWMAK-I) from 5000 MW_{th} to 3000 MW_{th} reduces the effect of maintenance on the cost of electricity by 21.0 percent, Figure 7-3. The availability is increased from 0.62 (5000 MW_{th}) to 0.69 (3000 MW_{th}). A similar effect is noted for the GA-DPR concept.
- o The incorporation of in-place equipment in the GA-DPR results in a dramatic increase in availability (from 0.50 to 0.67) and a corresponding reduction in the total maintenance effect on the cost of electricity from 77.1 to 30.9 percent, Figure 7-4. This improvement

Figure 7-3

EFFECT OF MAINTENANCE EQUIPMENT CONCEPT

13-980

Figure 7-4

is due to the elimination of the following: (1) vacuum duct removal and reassembly operations; (2) the installation and removal of the remote maintenance machine; (3) the installation and removal of internal track; and, (4) the installation and removal of the in-chamber maintenance machine.

- o The two concepts employing small modules differ in the manner of accessing the first wall/blanket modules. The GA-DPR employs the internal technique. The ORNL cassette is accessed from the outside of the reactor. The significant difference in the effect of maintenance approach on the cost of electricity is that resulting from downtime. The availability of the GA-DPR is 0.67 (with in-place equipment) and for the ORNL concept it is 0.72. The increment in the cost of electricity caused by the downtime is 22 percent for the GA-DPR and 12 percent for the ORNL. This is almost all due to module replacement differences coupled with a module size effect. There are 270 ORNL modules to be removed and 2000 GA-DPR modules, the latter

number being large as a result of the vacuum port diameter limitation on the size of the module. The ORNL modules are bolted in whereas each GA-DPR module requires two peripheral welds at module mid-height. There are design uncertainties with both concepts. With the ORNL concept, the uncertainty is in the definition of the structural support of the long slender module and in the mechanism for translating the module in and out and sideways during reactor installation. Also the effect of diverter design requirements on module removal operations is, as yet, not defined. With the GA-DPR concept the uncertainty is with the reliability of (1) the in-place equipment subjected to prolonged exposure to the reactor environment, and (2) the module welded joints (2 per module) with a large pressure differential across the joint, 50 atmospheres.

- o In comparing two large module concepts having different vacuum wall locations, it is found that opening and resealing the outer shield door in the vacuum wall of the Culham concept requires only 39 percent of the time required to open and reseal a single poloidal joint of the UWMAK-I reactor. The Culham concept seal length is about 17 percent less than the UWMAK-I seal (one joint) and accessibility is much better. All operations are on the outer wall whereas, with UWMAK-I, the joint must be accessed around the complete poloidal periphery.
- o The use of poloidal diverters presents special maintenance problems. The removal and replacement of just the first wall/blanket elements of these systems is found to take from approximately two days to over nine days depending on the concept and whether contact operations can be used. In three concepts (UWMAK-I, Culham and UWMAK-III) the diverter first wall/blanket module cannot be replaced without removing the entire poloidal sector of first wall/blanket modules.
- o Contact operations have been investigated for the three baseline concepts. The effect on the cost of electricity is shown in Figure 7-5. Contact operations are limited to those activities which can be conducted while the reactor chamber is closed and sealed. There is a significant effect in only one of the concepts, UWMAK-I. In this case the effect of downtime on the cost of electricity is reduced from 25.6 percent to 16.0 percent through the use of contact operations. It should be emphasized that only scheduled wall replacement maintenance has been investigated at this time. It is highly possible

IMPACT OF CONTACT MAINTENANCE

13-982

Figure 7-5

that more significant benefits can be realized for unscheduled contact maintenance. This is particularly true of the GA-DPR concept, since, with this approach, casking of the modules is possible; hence, at no point is the reactor room exposed to the radioactive modules or to maintenance equipment.

- o Unscheduled maintenance has been analyzed in this study phase for only one reactor concept, UWMak-III, and for only one failure mode --

a coolant leak in the diverter first wall/blanket module. It is found that the downtime is slightly greater (2%) than the time required to replace all of the modules in a sector on a scheduled basis. The 2 percent increase is due to the time it takes to isolate the leak to the diverter module. For this concept, 84 percent of the total downtime is required for access independent of the number of modules removed. The amount of access time for the small module concepts is a significantly lower fraction of the total downtime. Hence, in future studies it is expected that the unscheduled maintenance per failure for the small concepts will be a smaller fraction of scheduled requirements in the wall/blanket region.

7.2 INTERPRETATION - During the development of the maintenance plans and the system analyses those characteristics of the design concepts that affect their maintainability have been observed. These general observations aid in interpreting the foregoing specific results and lead to the following series of qualitative interpretations of the data developed by the study.

- o There does not appear to be any reason for scheduled maintenance effects to prevent achieving nominal availability goals (0.72).
- o Concepts exist which employ first wall/blanket module sizes in each of the three categories - large, intermediate and small and which are capable of achieving nominal availability goals.
- o Unscheduled maintenance requirements will probably determine proper module size (based on a tradeoff of module attachment simplicity, leak isolation capability and ease of access).
- o The percent effect of maintenance on the cost of electricity seems to be smaller for small thermal power reactors ($3000 \text{ MW}_{\text{th}}$) than for larger thermal powers ($5000 \text{ MW}_{\text{th}}$).
- o The Culham Mk-II design concepts and the ORNL cassette have the most attractive vacuum seal locations - at the outer shield. They have good accessibility and should permit relatively low vacuum pumping requirements.
- o An internal maintenance approach (GA-DPR small module concept) has good accessibility but requires development of a simple reliable module attachment technique.
- o In order for internal maintenance activities with small modules (such as the GA-DPR) to have high availability, there should be techniques

developed to minimize or eliminate internal preparations for actual removal (such as laying track). One of these techniques has been investigated in the study and appears feasible.

- o An external maintenance approach (ORNL cassette small module concept) has good accessibility but requires development of module support and installation techniques. Therefore, small modules with either internal or external maintenance approaches appear to provide greater ease of access with attendant potential advantages for unscheduled maintenance.
- o If diverters are required in the ultimate design, a focused attempt should be made to simplify the configuration. For instance, a single null poloidal diverter has fewer connections and can be made more accessible than its double null counterpart. A bundle diverter may offer additional advantages.
- o Contact (hands-on) operations are difficult to employ with any benefit to scheduled maintenance of first wall/blanket components. This is due to the large size of the components, the type of operations required, and the fact that these operations are precluded when the plasma chamber is open to the reactor room. Only the baseline reactor concepts were explored with contact activities. The alternate Culham concept may show a benefit from contact operations due to the relatively large number of activities performed when the plasma chamber is closed. The principal benefit from contact operations will probably result when unscheduled maintenance is required in the reactor room. or when scheduled maintenance of other subsystems is required concurrently with first wall/blanket replacement. Under these conditions, the advantages of being able to place small modules and their handling equipment in casks becomes apparent.

8.0 REFERENCES

1. "UWMAK-I, A Wisconsin Toroidal Fusion Reactor Design" by the University of Wisconsin Fusion Feability Study Group, Nuclear Engineering Department, University of Wisconsin, Madison, Wisconsin, sponsored by the Wisconsin Electric Utilities Research Foundation and the U.S. Energy Research and Development Administration, Report No. UWFDM-68, Vol. I and Vol. II, May 1975.
2. "A Tokamak Reactor with Servicing Capability," by Mitchell, J. T. D., Culham Laboratory, Abingdon, Oxon, United Kingdom, and Hollis, A., Research Reactors Division, UKAEA, AERE Harwell, United Kingdom, from proceedings of the 9th Symposium on Fusion Technology, Garmish-Partenkirchen, 1976.
3. "The Impact of Servicing Requirements on Tokamak Fusion Reactor Design," by Mitchell, J. T. D., Culham Laboratory, Abingdon, Oxon, United Kingdom, September 1976.
4. "UWMAK-III, A Noncircular Tokamak Power Reactor Design," Nuclear Engineering Department, University of Wisconsin, sponsored by the Electric Power Research Institute, Report UWFDM-150, July 1976.
5. "Conceptual Design Study of a Noncircular Tokamak Demonstration Fusion Power Reactor," by the Fusion Engineering Staff, General Atomic Company, prepared for U.S. Energy Research and Development Administration, General Atomic Report BA-A13992, November 1976, ERDA Contract E(04-3)-167.
6. "ORNL Fusion Power Demonstration Study," Interim Report by Steiner, D., Oak Ridge National Laboratory, Report No. ORNL/TM-5813, March 1977.
7. "Fusion Reactor First Wall/Blanket System Analysis," McDonnell Douglas Astronautics Company - St. Louis, Annual Report, 1977 (to be published).
8. "Experimental Fusion Power Reactor Conceptual Design Study," by Baker, C. C., et al; General Atomic Company, EPRI Report ER289, December 1976, EPRI Contract 323-1.

9. "Radioactivity and Associated Problems in Thermonuclear Reactors," by Vogelsang, W. F., University of Wisconsin, Proceedings of the Second ANS Topical Meeting on the Technology of Controlled Nuclear Fusion, Richland, Washington, September, 1976.
10. "Tokamak Experimental Power Reactor Conceptual Design," by Stacey, W. M., et al; Argonne National Laboratory, Argonne, Illinois, Report No. ANL/CTR-73-3, Vol. I and Vol. II, August 1976.
11. "Use of Nuclear Plant Operating Experience to Guide Productivity Improvement Programs," by Lapides, M. E., and Zebroski, E., Electric Power Research Institute, Report No. EPRI SR-26, November 1975.
12. "The Economics of Nuclear Power," Energy Research and Development Administration, Pamphlet No. EDM-068 (3-76).
13. "Impact of Confinement Physics on Fusion Reactor Design and Economics," Electric Power Research Institute, Report No. EPRI PP 547-1, June 1977.
14. "Fusion Reactor First Wall/Blanket System Analysis," McDonnell Douglas Astronautics Company - East, Final Report No. 472-1, October 1976.