DEVELOPING MAINTAINABILITY FOR TOKAMAK FUSION POWER SYSTEMS

Phase II Report Volume I — Executive Summary

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PREFACE
VOLUME I

This report presents the results of the second phase of a study, "Developing Maintainability in Controlled Thermonuclear Reactors" by McDonnell Douglas Astronautics Company - St. Louis for the United States Department of Energy (DOE) under contract number EG-77-C-02-4184.A001. The reporting period covers 1 November 1977 through 31 October 1978.

The overall purpose of the study is to identify design features of fusion power reactors which contribute to the achievement of high levels of maintainability. This executive summary presents the progress achieved toward this objective in this phase and includes a comparison with the results of the first phase study efforts. A series of maintainability design guidelines and an improved maintenance system are defined as initial steps in developing the requirements for a maintainable tokamak fusion power system. The principle comparative studies that are summarized include the determination of the benefits of various vacuum wall arrangements, the effects of unscheduled and scheduled maintenance of the first wall/blanket, some initial investigation of maintenance required for subsystems other than the first wall/blanket, and the impact of maintenance equipment failures.

The executive summary is Volume I of a three volume report. Volume II presents the detailed study results and Volume III presents appendixes which contain the time estimates for the basic scenarios and some of the major maintenance equipment requirement and descriptive definitions.

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1.0 INTRODUCTION

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

This study is an extension of DOE sponsored maintainability analyses initiated in 1977. Earlier studies emphasized scheduled first wall/blanket replacement for five 5000 MW_{th} tokamak fusion power systems. In the 1978 studies we normalized the reference reactor concepts (four in number) to a 3000 MW_{th} size and standardized certain subsystems. The emphasis was on the unscheduled downtime requirements. In addition we defined an improved maintenance system which incorporates many of the desirable features identified in the comparative analyses.

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

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

The characteristics of the reactor which affect maintainability include the reactor size; ease of access; the first wall and blanket module size; the location and number of vacuum walls; the arrangement of critical subsystems such as cryogenic vacuum pumps and neutral beam injectors; divertor design features; the number and construction of toroidal field coils; and the location of poloidal field coils. We have evaluated the influence of these characteristics on the maintainability of the reference reactors as measured by changes in the availability and cost of electricity. This evaluation serves as a base for the formulation of an initial set of maintainability design guidelines and the improved maintenance system. In addition to the summary presented in this volume, further discussion of these evaluations and design guidelines is found in Sections 5.0 and 7.0 of Volume II.

2.0 STUDY OBJECTIVES

To assist in developing the maintainability of tokamak fusion power reactors the study was directed toward evaluating the degree of the maintainability of the reference reactors and thereby determining the features which produced the highest level of maintainability. Since the evaluation parameters are availability and cost of electricity, the two maintenance requirements of greatest significance are maintenance downtime and cost of equipment, spares, facilities and personnel. Therefore, the first study objective is to determine the required maintenance downtime, which is lost time for energy production, arising from significant maintenance actions. Through the evaluation process the desirable maintenance characteristics of the reference reactors are identified and a set of reactor design guidelines for maintainability can be formulated. These selected guidelines and characteristics are then used as a basis for defining a total maintenance system concept.

The achievement of these objectives requires resolution of the following critical questions.

- o Select a desirable size for a first wall/blanket module.
- o Determine the reactor characteristics which provide rapid access to all subsystems for maintenance.
- o Select the arrangement of vacuum zones and location of vacuum walls in the reactor room best suited for low cost maintenance.
- o Identify the maintenance operations which can use contact, i.e., "hands-on", maintenance and those operations where remote maintenance is required.
- o Determine the effect on downtime of scheduled maintenance requirements for reactor subsystems other than first wall/blanket.
- o Identify the effects on downtime of unscheduled maintenance of the first wall/blanket and other subsystems.
- o Identify maintenance equipment characteristics that reduce the effect of equipment failures on total downtime.

While the state of development of fusion power reactor concepts permits only partial resolution of these questions, their impact on availability, maintenance equipment, facilities, maintenance personnel and cost of electricity has been defined insofar as possible.

3.0 APPROACH

Since the original reactor concepts being compared vary significantly in size and performance, it is necessary to bring them to a relatively common performance level to make the comparative base reasonably consistent. Figure 1 shows relative size of the four reactor concepts investigated in this study when designed to a power output of $3000 \text{ MW}_{\text{th}}$ with a major radius and other plasma characteristics that yield a near minimum cost of electricity. The major radius of each reactor is included in Figure 1 to indicate that the unique design concepts differed sufficiently among themselves to preclude normalizing the reactor designs and thus make all characteristics identical. Since overall reactor performance at minimum cost is the selected sizing criterion, it is believed that these reference reactors represent a good base for maintainability comparisons. Wherever possible, subsystems which interface with the reactor, namely, the vacuum, supplementary heating, toroidal field magnet and heat transfer systems, have also been standardized. The unique characteristics of each concept that affect maintainability have been retained in the normalization process.

Figure 2 compares the principal characteristics of the reference reactors when the performance characteristics are as consistent as possible. While the major radius is one of the principal parameters selected, the differences in the

FIGURE 1

FOUR REACTOR CONCEPTS ARE NORMALIZED

	UWMAK-III	GA-DOUBLET	CULHAM	ORNL CASSETTE
PEAK THERMAL POWER, MW _{th}	3000	3000	3000	3000
NET POWER, MW _e	992	902	962	962
MAJOR RADIUS, m	6.5	6.5	7.5	7.5
PLASMA HALF WIDTH, a, m	1.75	1.41	1.92	1.92
PLASMA ELONGATION RATIO	2	3	2	2
NEUTRON WALL LOADING, MW/m ²	2.74	2.36	2.12	2.02
WALL AREA, m ²	781	888	991	1037
NUMBER OF TF MAGNETS	16	16	16	16
NUMBER OF NBI's	12	12	12	12
WALL/BLANKET COOLANT	LITHIUM (OUTER) HELIUM (INNER)	HELIUM	HELIUM	HELIUM

FIGURE 2

design of the inner plasma chamber wall cause the minimum COE design point for this radius to differ slightly for each reactor. Because other characteristics are unique to each concept, such as the plasma cross section of the GA-Douplet, average wall loadings and wall areas also differ. Net electrical power differs because of unique concept characteristics and, therefore, it was deemed best to accept this effect on COE in making comparisons rather than adjusting the reactor size to compensate for this difference. Other significant parameters are the maximum toroidal field strength, which is fixed at 8.66T and thus permits the use of NbTi for all magnets, and a burn time and duty factor of 3600 seconds and 97.3%, respectively. The poloidal beta for all concepts except the GA-Douplet is defined as equal to the aspect ratio. The GA-Douplet uses one half of this value. These normalized designs are believed sufficiently similar in performance and in achieving a minimum COE value that the dissimilarities among the reactors encountered when formulating the various maintenance plans are functions of only the unique maintainability characteristics.

Most of the critical questions delineated in the definition of study objectives are evaluated through investigation of the relative first wall/blanket maintainability for each reactor concept. The range in first wall/blanket module sizes available with the reactor concepts is indicated in Figure 3. These typical modules are shown to the same scale. The relative maintainability over this size range, as measured by the total downtime, is found to differ significantly. The

FIRST WALL/BLANKET MODULES RANGE WIDELY IN SIZE

13-1971

FIGURE 3

Culham module contains all of the first wall/blanket in one sector except for a small divertor module. For UWMAK-III, the "A" module is the largest of the 5 first wall/blanket modules and 3 inner wall panels present in one sector. Both the GA-Doublet module (1808 total in the reactor or approximately 113 per sector) and the ORNL Cassette (37 per sector) are considered small modules. The access to modules over this size range and their handling characteristics vary widely and require different maintenance approaches for each reference reactor.

The maintainability evaluation for each issue to be investigated requires a comparison of maintenance plans generated for each alternative maintenance scenario involved in defining the issue. Figure 4 illustrates the data required for each maintenance plan to define its impact on the COE through use of the TOCOMO system analysis code. Other estimates of maintenance equipment weight and facilities are also provided. The time estimates are based on a detailed functional flow of the maintenance procedure required by each maintenance scenario and reactor design variation. This estimate is at a level of detail that accounts for such items as

**MAINTENANCE PLANS DEFINE TOTAL DOWNTIME,
EQUIPMENT AND PERSONNEL REQUIREMENTS**

22.43 FIGURE 4

the number of bolts or length of weld wherever this is significant. In Figure 4 the total time required for the maintenance action accounts for simultaneous operations on all 8 sectors assuming 24 hour continuous maintenance operation. When used in the TOCOMO analysis the typical downtime of 22.4 days shown in Figure 4 is diluted by a 75% productivity factor to establish more realistic elapsed time estimates. In the case illustrated in Figure 4 the revised downtime becomes 30 days.

The use of the maintenance plans in evaluating an issue is illustrated by the technique used to determine the optimum fraction of the first wall/blanket to be replaced during a scheduled outage and whether fully remote maintenance or partial contact maintenance results in the lowest COE maintenance plan. Figure 5 is a plot of the results of the TOCOMO analysis for the Culham reference reactor. In this case maintenance plans were derived for the exchange of 25%, 50%, and 100% of the first wall/blanket during a scheduled reactor outage and for the use of sufficient equipment to simultaneously work on two, four or eight sectors at one time, as appropriate for each wall fraction. (Replacement of sixteen sectors simultaneously is considered impractical.) Also, plans were developed for the remote and the partial contact maintenance modes.

**CONTACT MAINTENANCE REDUCES COE AND INCREASES AVAILABILITY
(CULHAM REFERENCE REACTOR)**

13-2051

FIGURE 5

The TOCOMO Code defined the COE and availability for each combination of maintenance mode, equipment and wall fraction replaced. From this data the plot in Figure 5 shows that the replacement of 8 sectors of first wall/blanket while working on 8 sectors at one time and using as much contact maintenance as possible is the optimum maintenance plan for this reference concept. After this data has been generated for all of the reference concepts, either the complete results as shown in Figure 5 or parts of the data are used to develop conclusions concerning each issue to be studied. These analyses are summarized in the following section.

4.0 STUDY RESULTS

This section presents a summary of the overall results identified during this study period and compares them with similar results of the initial study phase. In addition, a summary of the results for each of the maintainability issues examined is presented.

These specific issues include:

- o the determination of the best vacuum wall arrangement for minimum scheduled downtime.
- o the relative impact of contact assisted maintenance and fully remote maintenance on scheduled and unscheduled downtime.
- o the potential for toroidal field magnet maintenance.
- o the scheduled downtime required for first wall/blanket replacement.
- o the allowable failures for first wall/blanket and other subsystem components.
- o the impact of maintenance equipment failures on scheduled downtime.

While the study emphasis is on the unscheduled maintenance required by the subsystems the first four issues were initially resolved, insofar as possible, to establish a maintenance operation data base for the study of the impact of failures on maintainability.

4.1 SUMMARY OF STUDY RESULTS - The operating costs, including maintenance costs, have been defined for each of the reference reactors and combined with plant costs and availability to determine the cost of electricity (COE) for each reactor. The maintenance scenarios used for this determination are selected as the minimum cost maintenance plans which, coincidentally, are also the maximum availability maintenance plans in each case. Figure 6 illustrates the COE and availability of each reactor concept for comparison with the COE and availability goals established in the first study phase as shown in Figure 7 (Reference 1). These goals are defined by the anticipated breakeven COE and availability of coal fired plants and fusion plants brought on line in the year 2000 (Reference 2). The threshold availability of 55% and COE of 57.4 mills/kWh are defined by the breakeven point. The nominal availability of 72% is the mean performance of fission plants surveyed in 1975 (Reference 3).

The results depicted in Figure 6 indicate that the COE variation in the four concepts is relatively small but the availability variation is significant. However, when some of the better maintenance features are applied to the Culham concept, which has the lowest COE and highest availability, to generate an improved maintenance system (IMS) the principal effect is a decrease in COE. About half of

1978 ANALYSES SHOW IMPROVED AVAILABILITY AND COST OF ELECTRICITY

(1) COAL PLANT DATA FROM REFERENCE 2, ADJUSTED TO 1978 DOLLARS
FIGURE 6

this decrease in cost, i.e., 1.9 mills/kWh, is attributable to the reduction in diameter of the reactor room to 85 meters and the other half, 2.1 mills/kWh, is the effect of lower maintenance equipment cost and an increase in availability. Figure 7 is a similar plot generated in the first phase of the study for 5000 MW_{th} reactors. The effects of normalization and smaller size can be seen by comparing Figures 6 and 7. The improved availability with the smaller 3000 MW_{th} reactors is evident. A change in the cost base from 1977 to 1978 dollars increases the costs slightly in the more recent data. It is noted that the UWMAK-I concept has been dropped as a candidate for the study.

The influence of only the scheduled reactor maintenance costs on the COE is illustrated in Figure 8. This is the percent increase in COE over a basic COE

1977 ANALYSES RESULT IN CONCEPTS THAT MEET AVAILABILITY AND COE GOALS

13-1710

FIGURE 7

1978 ANALYSES SHOW THAT MAINTENANCE IMPACTS ARE DECREASED (COMPARISON OF NORMALIZED REACTORS)

FIGURE 8

which incorporates the balance of plant scheduled outage of 28 days per operating year and unscheduled outages of 65 days per operating year. By selective use of better maintainability features, principally achieving a major improvement in access, the impact of scheduled maintenance has been reduced from a maximum of 21.7% of the COE to 9.1% for the IMS. When the scheduled downtime is decreased below the annual allowance for the balance of plant scheduled outage, as is the case for the IMS, the availability cost for reactor maintenance disappears. A comparison with a similar plot from the initial study phase as given in Figure 9 indicates the general effect of the reduction in size to 3000 MW_{th} reactors. The comparison also shows the reduced impact of the availability costs caused by the loss in energy production. Some of the other variations in the two figures are attributable to a better definition of the Culham and ORNL Cassette concept costs.

**1977 ANALYSES RESULT IN SIGNIFICANT IMPACT
OF MAINTENANCE ON COST OF ELECTRICITY
(COMPARISON OF NORMALIZED REACTORS)**

FIGURE 9

The GA-Doublet reference reactor results shown in Figure 8 compare with the in-place maintenance equipment concept shown in Figure 9.

The net effects of both scheduled and unscheduled outages of the five reactor concepts (including IMS) as measured by days of scheduled downtime required and first wall/blanket failures allowed per operating year are illustrated in Figure 10. The data shown in the figure assumes a COE goal of 49 mills/kWh and defines the potential usage of the maintenance days available to meet this goal. The downtime for scheduled maintenance is fixed by the requirement for replacement of the first wall/blanket. The variation in the time to exchange the first wall/blanket at the optimum rate of 1/2 of the wall per outage and the downtime per operating year is based on the wall life of each reactor. The allowable downtime for unscheduled maintenance is then the time remaining to bring the availability cost (loss of energy production cost) to the level permitted by the COE goal constraint of 49 mills/kWh. These data show, for example in the case of the UWMAK-III, that the 44 days required to correct a first wall failure by exchanging a single module is greater than the allowable time per operating year to meet the COE goal. In contrast to the UWMAK-III, the IMS has considerable allowable downtime remaining for use in recovery from other subsystem failures, even if the average failure rate of the first wall is as high as 4 per year. In all cases the unscheduled time is for replacement of a module having the most difficult access requirements.

ALLOWABLE DOWNTIME APPEARS ADEQUATE FOR SOME FIRST WALL/BLANKET FAILURES
COST OF ELECTRICITY GOAL = 49 MILLS/kWh

REACTOR	TIME TO CHANGE 1/2 1ST WALL (DAYS)	TIME TO CHANGE 1 1ST WALL ELEMENT (DAYS)	DOWNTIME FOR SCHEDULED MAINTENANCE (DAYS /OPERATING YR)	ALLOWABLE DOWNTIME FOR UNSCHEDULED MAINTENANCE (DAYS /OPERATING YR)	REMAINING ALLOWABLE DOWNTIME FOR UNSCHEDULED MAINTENANCE	
					ONE 1ST WALL FAILURE (DAYS)	FOUR 1ST WALL FAILURES (DAYS)
CULHAM	30	17	30	53	36	0
UWMAK-III	57	44	63	42	0	0
ORNL CASSETTE	55	31	50	45	14	0
GA-DOUBLET	90	7	85	45	30	17
IMS	20	13	28*	92	79	40

* 28 DAYS/OPERATING YEAR MINIMUM FOR BALANCE OF PLANT OUTAGE

FIGURE 10

By using the COE goal and the availability goal in this manner, the relative limitations of the maintainability requirements on unscheduled maintenance for each reactor concept can be ascertained. From the data given in Figure 10 it can be concluded that the maintainability of tokamak reactor concepts is within acceptable goals and may even be capable of further significant improvement. This conclusion is based on a limited study of the first wall/blanket and a few other potential subsystem failures and replacement requirements. However, the study has indicated that subsystems other than the first wall/blanket can also be made reasonably maintainable.

4.2 VACUUM WALL ARRANGEMENT SELECTION - Three similar vacuum wall arrangements have been defined for each reactor concept except the GA-Doublet. For the GA-Doublet no measurable advantage is foreseeable when using arrangements other than the basic concept. Figure 11 illustrates the general vacuum wall arrangements.

Arrangement 1 uses the plasma chamber blanket or shield as the primary wall except in the Culham concept where the outer shield is used as the primary wall. For each concept the assumption is made that this joint must use a welded seal. With this arrangement the UWMAK-III and the ORNL Cassette reactors have only one vacuum zone but the Culham design still results in two zones with only a high impedance joint at the blanket and inner shield.

In arrangement 2 the principal vacuum barrier is formed by sealing the lateral support access panels (LSAP's) which react the magnet loads in the region of the toroidal field magnets. This arrangement is assumed to require no welded seals and results in two vacuum zones for the UWMAK-III and ORNL Cassette concepts and three zones for the Culham design.

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

FIGURE 11

Arrangement 3 uses the reactor room wall as the primary vacuum wall and results in the same number of zones as arrangement 2.

The downtimes required to replace the modules in one sector of each reference reactor have been defined. The percent difference in downtime for each vacuum wall arrangement from the downtime required by the vacuum wall arrangement which approximates the basic reactor concept is shown in Figure 12. For the UWMAK-III concept, estimates have been made for both scheduled and unscheduled maintenance, for remote or contact maintenance operations, and for all three vacuum wall arrangements. Arrangement 1 involves the welded joint as in the original concept. The most significant change in downtime occurs when using arrangement 3 and, where possible, contact maintenance operations. Unscheduled maintenance results in the shortest downtime because only one module has failed and is replaced. It is believed that the trends shown exist for the other concepts. Therefore, only the unscheduled contact operations were examined for the Culham and ORNL Cassette concepts.

The Culham concept showed improvement for arrangement 3 comparable in magnitude to that achieved by the UWMAK-III. However, arrangement 1 shows a time

CHANGE IN MAINTENANCE DOWNTIMES FOR DIFFERENT VACUUM WALL ARRANGEMENTS

REFERENCE REACTOR CONCEPT	PERCENT CHANGE FROM ARRANGEMENT OF ORIGINAL CONCEPT		
	ARRANGEMENT #1	ARRANGEMENT #2	ARRANGEMENT #3
CULHAM			
UNSCHEDULED MAINTENANCE CONTACT OPERATIONS	-2.5	0	-11.2
UWMAK-III			
UNSCHEDULED MAINTENANCE CONTACT OPERATIONS	0	-8.7	-13.5
REMOTE OPERATIONS	0	-4.4	-11.0
SCHEDULED MAINTENANCE CONTACT OPERATIONS	0	-9.9	-15.2
REMOTE OPERATIONS	0	-4.8	-12.1
ORNL			
UNSCHEDULED MAINTENANCE CONTACT OPERATIONS	+7.0	-.6	0

NOTE: A NEGATIVE NUMBER IS A REDUCTION IN DOWNTIME FROM BASIC ARRANGEMENT.

FIGURE 12

reduction from arrangement 2 even when using a welded joint primarily because the neutral beam injector (NBI) duct removal is considerably simplified. The ORNL Cassette concept shows relatively no change between arrangement 3 as originally proposed and arrangement 2. However, both arrangements require approximately 7% less time than arrangement 1.

These results indicate the desirability of using the reactor room wall as a primary vacuum barrier from the standpoint of maintenance requirements. Analysis of the vacuum pumping requirements for such a large chamber have been made and indicate a feasible pump down time within the allowed startup period if the room design and maintenance operations reduce restart outgassing and leakage at the doors to a negligible amount. Since other large rooms have been designed to satisfy similar requirements (Reference 4) this is considered to be a feasible assumption.

4.3 UTILIZATION OF CONTACT ASSISTED MAINTENANCE - The comparison of the maximum use of contact maintenance operations with maintenance conducted by fully remote techniques used the replacement of the first wall/blanket as the maintenance action for establishing preliminary conclusions. This maintenance operation is the most time consuming considered in the study but, because of the high radiation levels that preclude contact operations for a considerable portion of the total downtime, greater benefits for contact maintenance may be defined later for other maintenance actions. For this comparison all operations up to the removal of plasma chamber shielding and subsequent to its replacement use contact maintenance to assist the operation wherever possible, but even here the assistance from contact maintenance is limited because the large size of the components being handled requires the use of heavy machinery.

Figure 13 defines the difference in COE resulting from the contact and remote maintenance scenarios for each reference reactor. Wherever contact operations are applied without a significant change in maintenance equipment requirements, a cost savings is realized. However, the attempt has been made to allow contact assisted maintenance throughout the GA-Doublet first wall/blanket replacement operation by adding shielding to the maintenance equipment. This equipment revision, coupled with the fact that contact assistance resulted in very little reduction in elapsed time, caused the COE to increase for this concept. The lack of time savings occurs because the critical time operations are those conducted remotely inside of the plasma chamber and contact operations are limited to the outside of the plasma chamber. Therefore, these operations have only a minor effect on the total elapsed time for first wall/blanket replacement.

CONTACT ASSISTED MAINTENANCE IS GENERALLY BENEFICIAL TO COE

FIGURE 13

The magnitude of the time spent in performing contact assisted operations during first wall/blanket replacement is relatively large as shown in Figure 14. The fraction of the total downtime required to replace a single sector expended by those functions that can employ contact assisted maintenance operations varies from 42% to 72% for the ORNL Cassette, Culham and UWMAK-III reactors and is 100% for the GA-Douplet as discussed in the preceeding paragraph. When contact assisted maintenance is used these functions are shortened and expend only 28.9% to 56.7% of the revised total downtime. When replacing the optimum wall fraction of 8 sectors during one outage of the ORNL Cassette, Culham and UWMAK-III reactors, the reduction in the total outage downtime realized by employing contact assisted

SUMMARY OF PARTIAL CONTACT MAINTENANCE DOWNTIME IMPACTS

	UWMAK-III	GA-DOUBLET	CULHAM	ORNL CASSETTE
PERCENT OF TOTAL DOWNTIME DURING WHICH CONTACT MAINTENANCE CAN BE USED(1)	72.0	100	61.2	42.0
PERCENT REDUCTION IN TOTAL DOWNTIME IF CONTACT MAINTENANCE IS USED(2)	27.4	3.6	19.5	14.3

NOTES:

- (1) DATA FOR SINGLE SECTOR FIRST WALL/BLANKET REPLACEMENT
- (2) DATA FROM OPTIMUM SCHEDULED FIRST WALL/BLANKET MAINTENANCE PLANS

FIGURE 14

maintenance techniques varies from 14.3% to 27.4% with only a 3.6% time reduction achieved by the GA-Douplet system. This latter reduction is small because the only reduction possible is the reduced time for traffic delays on the reactor room floor.

The potential for time savings may be greater when using contact assisted maintenance for other maintenance actions, such as cryovacuum pump or ion source replacement, but some remote operations are required for these operations also unless casks can be efficiently used. When the maintenance of all subsystems is considered the need for downtime in addition to that required for first wall/blanket maintenance may exist if contact maintenance is used on these subsystems. The time for this contact maintenance may be limited because of the long time during which a radiation environment exists in the reactor room during the first wall/blanket replacement operation. In this situation the ability of the GA-Douplet to allow 100% of the time for contact maintenance could possibly reverse the COE effects shown in Figure 13. The answer to this question should be considered further.

For this study it is shown that the reference reactors can be maintained by fully remote means for those maintenance actions investigated. This has been done primarily to establish the feasibility of maintaining the tokamak concepts in the event that the assumption of a low level of radiation in the reactor room becomes invalid or in the event of a failure that imposes a high radiation level during maintenance operations.

4.4 TOROIDAL FIELD MAGNET MAINTENANCE - One of the greatest concerns regarding maintainability of tokamak reactor is the ability to replace a toroidal field magnet in the event of a failure. A brief examination of this type of maintenance action was conducted on Ignition Test Reactor (ITR) concepts to determine the impact of one type of demountable magnet on the estimated downtime. ITR's were chosen because the magnet installations are better defined but the results cannot be applied to the analysis of the four reference reactors being used in this study.

Figure 15 summarizes two of the maintenance scenarios considered and the resultant downtimes. These two scenarios were selected because they show the shortest downtimes. However, in addition to the difference in downtime caused by the TF magnet designs, another cause is the greater number of vertical field coils in the GA-ITR design which requires almost half of the total downtime shown in Figure 15 for disassembly and reassembly.

Two scenarios were examined in addition to that defined in Figure 15 for the High Field Ignition Test Reactor (HFITR). These scenarios require much more disassembly of the reactor to provide access to the lower inboard leg of the segmented hexagonal TF magnet. Failure mode assumptions requiring replacement of an entire TF magnet also increase the downtime significantly. Another scenario examined the use of nonsegmented vertical field coils in the GA-ITR. This scenario significantly increased the access time for the GA-ITR.

The conclusion to be drawn from this brief analysis is that demountable magnets appear necessary to avoid unacceptably long downtimes in the event of a magnet failure. However, differences in magnet reliability for different demountable magnet designs can have a major impact on selecting a specific design approach.

MAGNET MAINTENANCE SCENARIOS

MAGNET TYPE/REACTOR CONCEPT	MAINTENANCE ACTION	PRINCIPAL DESIGN ASSUMPTIONS	TOTAL DOWNTIME DAYS(3)
SEGMENTED SUPERCONDUCTING TF MAGNET/HFITR ⁽¹⁾	REPLACE LOWER INBOARD TF MAGNET SEGMENT	PLASMA CHAMBER CAN BE RAISED WITHOUT DISASSEMBLY TO CLEAR MAGNET LOWER INBOARD LEG	40
UNITARY SUPERCONDUCTING TF MAGNET/GA-ITR ⁽²⁾	REPLACE COMPLETE TF MAGNET	ALL VERTICAL FIELD COILS ARE SEGMENTED AND NORMAL	285

(1) REFERENCES 5,6; DEALS MAGNET APPLIED TO A HIGH FIELD IGNITION TEST REACTOR

(2) REFERENCE 7; GA-ANL TNS SCOPING STUDIES

(3) ALL TIMES DILUTED BY .75 PRODUCTIVITY FACTOR AND BASED ON A 3 SHIFT OPERATION.

FIGURE 15

4.5 SCHEDULED DOWNTIME REQUIREMENTS - The optimum scheduled downtime for first wall/blanket replacement in the four reference reactors has been developed and compared for remote and contact maintenance operations. Figure 16 summarizes the optimum scheduled downtime requirements and identifies the selected maintenance modes. Those wall fractions replaced during each scheduled outage which result in the minimum COE are 1/2 for the Culham, UWMak-III and ORNL Cassette but only 1/4 for the GA-Doublet. The data in Figure 16 represents replacement of the first wall/blanket modules concurrently in 8 sectors during an outage for a wall fraction of 1/2, and a total of 456 modules for 1/4 of the GA-Doublet first wall/blanket. The Ga-Doublet analysis was limited to a maximum wall fraction of 1/4. For the Ga-Doublet, however, a fraction of 1/2 is expected to result in approximately the same COE as for 1/4 because of the short access time and the small amount of additional maintenance equipment required to replace 1/2 of the wall when using the in-place maintenance equipment concept.

Since the first wall/blanket is assumed to be the driver in defining the reactor scheduled downtime and all other scheduled maintenance is conducted during this period, the scheduled downtime per outage given in Figure 16 is an estimate of the total scheduled downtime for the reactor at intervals determined by the wall life and the replacement fraction. For example, the 30 day outage for the Culham concept occurs every 1.18 operating years but for the GA-Doublet the 45 day outage occurs every .53 operating years. When these downtimes are normalized

SCHEDULED DOWNTIME REQUIREMENTS

CONCEPT	WALL LIFE (YR)	MAINTENANCE MODE	WALL FRACTION	SCHEDULED DOWNTIME PER OUTAGE ⁽¹⁾ (DAYS)	SCHEDULED DOWNTIME ⁽¹⁾ (DAYS PER OPERATING YEAR)
CULHAM	2.36	CONTACT ⁽²⁾	1/2	30	30
UWMAK-III	1.82	CONTACT ⁽²⁾	1/2	57	63
GA-DOUBLET	2.12	REMOTE	1/4	45	85
ORNL	2.47	CONTACT ⁽²⁾	1/2	55	50

(1) WALL REPLACEMENT ONLY INCLUDING .75 PRODUCTIVITY FACTOR AND 3 SHIFT OPERATIONS

(2) TO MAXIMUM DEGREE POSSIBLE OUTSIDE OF REACTOR AND WITH REACTOR "CLOSED UP" - OTHERWISE REMOTE

FIGURE 16

to an operating year base the relative scheduled downtime requirements for a given energy production are identified. A fixed allowance of 28 days for the balance of plant annual scheduled outage is included in the computation of this time. The time for the GA-Douplet is largest, even though the time for one outage is low, because the wall life is about the same as for the other reactors and two outages are required to replace the same amount of the first wall/blanket as that replaced during a single outage of the other reference reactors.

The optimum wall fractions determined during the first study phase were all at a replacement fraction of 1/3 of the first wall/blanket per outage. While this fraction is not feasible with 16 sector reactors, it could be the optimum fraction if the number of reactor sectors permitted its use. This wall fraction is included in defining the design guidelines identified in Section 6 of this Volume.

4.6 ALLOWABLE SUBSYSTEM FAILURES - The evaluation of unscheduled downtime impacts is emphasized in the study but this analysis first requires determination of the optimized scheduled downtime for each reactor to provide a consistent minimum COE base. The principal subsystem investigated is the first wall/blanket but some of the requirements for the cryovacuum pumps, vacuum pump valves and Neutral Beam Injector (NBI) ion sources are also identified.

A comparison of the scheduled downtime to replace the entire first wall/blanket for each reference reactor with the downtime to replace one failed module in each reactor is shown in Figure 17. In all cases the time required for a single module replacement as a result of failure far exceeds the average time per module for scheduled replacement. The principal reason for this difference is the time required to access the module. Fault isolation requirements also add to the time required to correct failures. Figure 17 clearly shows that the use of unscheduled maintenance as the sole means for replacing the first wall/blanket is inefficient. The ratio of the time per module for replacement after a failure to the average time per module for scheduled replacement varies from 9 for the Culham to about 75 for the GA-Douplet or ORNL Cassette. This infers that the large module reactor (Culham) can replace large modules after a failure with less penalty per unit area than the small module reactor (GA-Douplet or ORNL Cassette). However, if a failure involves only a small area and the fault isolation technique can isolate to a small module, then the small module reactor has less total time penalty.

Further analysis of the impact of failures on maintenance downtime was conducted by setting availability or COE goals and then determining the allowable unscheduled downtime for each reference reactor. Using this allowable downtime,

UNSCHEDULED WALL/BLANKET REPLACEMENT DOWNTIME IS SIGNIFICANT

FIGURE 17

the allowable number of subsystem failures that will just meet the goal is determined. The number of failures which each reactor can absorb then indicates which reactor concept has a higher degree of maintainability. All values are normalized to an operating year in the manner shown in Figure 18 to compare the allowable number of failures over the same operating period.

The curves defined in Figure 19 illustrate how the allowable number of days for unscheduled downtime per operating year vary among the reactor concepts if either a fixed availability or COE is chosen as a goal. These curves also illustrate the sensitivity of the allowable days of unscheduled downtime to the selection of availability and COE goals. The relative displacement of the availability curves is caused by the difference in the scheduled outage downtime required by each reactor concept. For the COE curves, differences in capital costs tend to reduce this displacement. Differences in slopes of the COE curves are caused by variations in the capital cost/net power ratios among the reference reactor plants.

The examples given in Figure 19 show how the allowable days of unscheduled downtime is determined for the Culham reactor for goals of 72% availability and 52 mills/kWh. With constant values set as goals for each of these parameters, it is apparent that the allowable days of downtime will vary for each reactor.

ALLOWABLE FAILURE RATES ARE DEFINED PER OPERATING YEAR

13-1974A

FIGURE 18

ALLOWABLE UNSCHEDULED DOWNTIME IS DEPENDENT UPON GOALS

13-1974A

FIGURE 19

Figure 20 illustrates the relative ability of each reference reactor to satisfy an availability goal of 72% if only first wall/blanket failures are considered. The scheduled downtimes required per operating year shown in Figure 20 are the same as defined in Figure 16. The recovery downtime for each failure is also given. Since in Figure 20 the same availability applies to all reactors the sum of scheduled and allowable unscheduled downtimes per operating year is a constant. From this example the Culham reactor has not only the greatest allowable unscheduled downtime, but, because of its relatively short recovery time, more downtime remains for other failures, even after four failures per year, than for any other reactor. On the other hand, the GA-Doublet can absorb a maximum of 8.0 failures per year compared to 6.6 for the Culham.

The use of a COE goal brings the capital cost into the evaluation and produces slightly different results. Figure 21 illustrates these impacts. Here the difference

MEETING AN AVAILABILITY GOAL
AVAILABILITY GOAL = 72%

CONCEPT	SCHEDULED DOWNTIME (DAYS/OPERATING YEAR)	TOTAL ALLOWABLE UNSCHEDULED DOWNTIME ⁽¹⁾ (DAYS/OPERATING YEAR)	REMAINING ALLOWABLE UNSCHEDULED DOWNTIME	
			ONE WALL BLANKET FAILURE/YEAR ⁽²⁾	FOUR WALL/BLANKET FAILURES/YEAR ⁽²⁾
CULHAM	30	112	95	44
UWMAK-III	63	80	36	<0
ORNL	50	92	61	<0
GA-DOUBLET	85	56	49	28

(1) AVERAGE VALUE

(2) DOWNTIME FOR AN UNSCHEDULED WALL/BLANKET FAILURE

CULHAM 17 DAYS
UWMAK-III 44 DAYS
ORNL 31 DAYS
DOUBLET 7 DAYS

MEETING A COST OF ELECTRICITY GOAL
COE GOAL = 52 MILLS/kWhr

CONCEPT	SCHEDULED DOWNTIME (DAYS/OPERATING YEAR)	TOTAL ALLOWABLE UNSCHEDULED DOWNTIME ⁽¹⁾ (DAYS/OPERATING YEAR)	REMAINING ALLOWABLE UNSCHEDULED DOWNTIME	
			ONE WALL BLANKET FAILURE/YEAR ⁽²⁾	FOUR WALL/BLANKET FAILURES/YEAR ⁽²⁾
CULHAM	30	81	64	13
UWMAK-III	63	71	27	<0
ORNL	50	74	43	<0
GA-DOUBLET	85	76	69	48

(1) AVERAGE VALUE

(2) DOWNTIME FOR AN UNSCHEDULED WALL/BLANKET FAILURE

CULHAM 17 DAYS
UWMAK 44 DAYS
ORNL 31 DAYS
DOUBLET 7 DAYS

in allowable unscheduled downtime is much less than for a constant availability since capital cost variations act to bring the relative COE of the reactors closer together as seen in Figure 19. The result is that, even though the Culham reactor has the greatest allowable downtime for unscheduled maintenance, one failure per year leaves the GA-Douplet with 5 more days remaining than Culham. This evaluation shows the GA-Douplet much more capable of absorbing failures than the other reactors

with a maximum of 10.9 failures allowed. Culham is again ranked high with a maximum of 4.8 failures allowed, but the UWMAK-III and ORNL Cassette require too long a recovery time to allow for four failures. Since the failure mode for the ORNL Cassette is chosen as a failure in the third blanket zone, this requires removing a total of 9 cassettes to replace the failed cassette. This selection may unduly penalize this concept even though the recovery times for Culham and UWMAK-III also are defined for the module with the most difficult access.

The impact of failures of several other components is indicated in Figure 22. These components are all at the outside of the reactor and access is simple compared to first wall/blanket modules. However, contact maintenance is limited because removal of shielding is necessary with the resultant exposure to radiation levels assumed to be too high. Therefore, failure recovery times, though short because of ease of access, are greater than would be expected with total contact maintenance. For these component failures the allowable unscheduled downtime is the same as available for first wall/blanket maintenance but, because of the shorter recovery time, the maximum number of failures allowed is much greater than for the first wall/blanket. It is apparent that the first wall/blanket failures can represent a potentially more serious situation than the failures of other subsystems examined to date.

4.7 MAINTENANCE EQUIPMENT FAILURE IMPACTS - The failure of maintenance equipment during any maintenance action, whether scheduled or unscheduled, will extend

**MEETING A COST OF ELECTRICITY GOAL
(WITH SUBSYSTEM FAILURES)
COE GOAL = 52 MILLS/kWh**

SUBSYSTEM FAILURE	FAILURE RECOVERY TIME (DAYS)	TOTAL ALLOWABLE UNSCHEDULED DOWNTIME (1) (DAYS/OPERATING YEAR)	REMAINING ALLOWABLE UNSCHEDULED DOWNTIME, (DAYS)		FAILURES PER OPERATING YEAR (2)
			ONE FAILURE PER OPERATING YEAR	FOUR FAILURES PER OPERATING YEAR	
GA-DOUBLET CRYOVACUUM PUMP	5.6	76	70	53	13.6
GA-DOUBLET CRYOVACUUM PUMP VALVE	4.3	76	71	58	17.7
UWMAK-III CRYOVACUUM PUMP PANEL	5.2	71	65	50	13.7
NBI ION SOURCE					
CULHAM	3.7	81	77	66	21.9
UWMAK-III	3.3	71	67	57	21.5
ORNL CASSETTE	3.7	74	70	59	20.0
GA-DOUBLET	3.1	76	72	63	24.5

(1) AVERAGE VALUE

(2) FAILURES CONSUMING TOTAL ALLOWABLE UNSCHEDULED DOWNTIME

FIGURE 22

the downtime. An estimate of the seriousness of this extension has been made and a synopsis of the results is shown in Figure 23. For each reference reactor some of the more critical maintenance equipment failures that could occur during first wall/blanket scheduled replacement operations have been examined and a downtime estimated for recovery from each failure. Failures producing the most difficult foreseeable recovery modes are selected. In addition, recovery from maintenance equipment failures during replacement of vacuum pumps and ion sources is also evaluated to determine the relative impact of maintenance equipment failure during these less critical operations.

To estimate the magnitude of the impact, the frequency of each type of failure is estimated and the total downtime is computed. Figure 23 illustrates the total for each of the reactors. These examples do not allow a comparison of the maintenance equipment concepts because of the limited number of failure modes examined.

ADDITIONAL ALLOCATED MAINTENANCE DAYS DUE TO MAINTENANCE EQUIPMENT FAILURE

FIGURE 23

However, the conclusion can be drawn that techniques are available to permit recovery from the most difficult failure modes examined.

One particularly high impact failure mode is the failure of the isolation valve that separates the in-place remote maintenance machine (RMM) mounted on the GA-Doublet auxiliary vacuum duct from the plasma vacuum. The recovery time for a single failure is estimated at approximately 9 days, and, if maintenance is conducted only when a failure occurs, the failure frequency of one every 2 calendar years per valve is assumed. Since 16 of these valves are used the resultant downtime from this source alone becomes approximately 120 days per operating year. The value of approximately 22 days per operating year shown in Figure 23 is obtained by requiring scheduled maintenance on this valve during each outage. This procedure is assumed to reduce the failure frequency to one every 10 calendar years. The valve design must be such that this maintenance can be conducted concurrently with first wall/blanket operations. This example illustrates the importance of designing maintainability into the maintenance system as well as into the reactor.

The longest outage examined is the recovery from the "B" module workhead failure when replacing this first wall/blanket module on the UWMAK-III. Figure 24 illustrates the maintenance equipment concept used for UWMAK-III and the difficulty that can arise when access for module removal is from within the plasma chamber.

"B" MODULE REMOVAL SEQUENCE

- INSTALL THE "B" MODULE WORK HEAD ON BASE FRAME OF MHM USING OVERHEAD CRANE
- EMPLACE RADIAL TRANSLATION CARRIAGE
- MOVE BASE FRAME CROSSSLIDE TO FULL IN-BOARD POSITION
- EXTEND "B"-MODULE WORK HEAD INTO POSITION BENEATH MODULE
- REMOVE GRAPHITE INSERTS BETWEEN ADJACENT MODULES
- EXTEND LOAD ARMS TO ENGAGE PICK-UP POINTS ON "B"-MODULE
- REMOVE "B"-MODULE EMPLACEMENT BOLTS
- TRANSFER "B" MODULE LOAD FROM STRUCTURE TO "B" MODULE WORKHEAD

FIGURE 24

The failure is assumed to be a seized workhead mechanism occurring just after the "B" module load is transferred to the workhead. The recovery technique is to use a specialized workhead mounted on a spare module handling machine (MHM), like that illustrated, and to disassemble the "B" module workhead from the adjacent sector. A total recovery time of 20 days is required, and since 8 "B" module workheads are used and a failure frequency of one every 10 years is assumed, the net downtime per operating year is about 23 days.

An overall impact of maintenance equipment failures on the allowable unscheduled downtime for reactor failures can be estimated if the failures indicated in Figure 23 are assumed to be representative of all maintenance equipment failures. Since these are the most difficult and time consuming failures, there is some credibility to the relative ranking of the effects of each equipment concept on reactor downtime. By adding these additional days to the scheduled downtime, the remaining downtime allowable for forced outages caused by other subsystems in order to meet a 52 mills/kWh COE goal is shown in Figure 25. In this comparison of the reference reactors the ranking is similar to that obtained without including maintenance equipment failure impacts as shown in Figure 21. The GA-Doublet can accommodate the greatest total number of failures and is the only reactor that can accommodate as many as 4 first wall/blanket failures per operating year. However, with a first wall/blanket failure rate of one per year the Culham reactor now has the greatest number of days (45) remaining in which to recover from forced outages caused by other subsystems.

**MEETING A COST OF ELECTRICITY GOAL
(WITH MAINTENANCE EQUIPMENT FAILURES)
COE GOAL — 52 MILLS/kWh**

CONCEPT	SCHEDULED DOWNTIME (DAYS PER OPERATING YEAR)	TOTAL ALLOWABLE UNSCHEDULED DOWNTIME WITH EQUIP. FAILURES ⁽¹⁾ (DAYS/OPERATING YEAR)	REMAINING ALLOWABLE UNSCHEDULED DOWNTIME	
			ONE WALL BLANKET FAILURE/ YEAR ⁽²⁾	FOUR WALL/ BLANKET FAILURES/ YEAR ⁽²⁾
CULHAM	30	62	45	<0
UWMAK-III	63	33	<0	<<0
ORNL	50	58	27	<0
GA-DOUBLET	85	44	37	16

(1) AVERAGE VALUE

(2) DOWNTIME FOR AN UNSCHEDULED WALL/BLANKET FAILURE

CULHAM 17 DAYS

ORNL

31 DAYS

UWMAK-III 44 DAYS

DOUBLET

7 DAYS

FIGURE 25

5.0 IMPROVED MAINTENANCE SYSTEM CAPABILITY

The maintenance trade studies have identified several design attributes of a maintainable tokamak fusion power reactor. These include 1) the need to access any replaceable element as simply and rapidly as possible; 2) the use of the reactor room as a primary vacuum barrier with multiple vacuum zones; 3) the use of large, easily accessed first wall/blanket modules to reduce scheduled downtimes; 4) the desirability for easily accessed and replaceable small modules to aid unscheduled maintenance; and 5) the use of contact or contact assisted maintenance wherever possible.

With these requirements foremost, a preliminary version of an improved maintenance system (IMS) has been defined which primarily improves the maintainability of the first wall/blanket. Some maintainability aspects of other subsystems such as the access and removal of the cryovacuum pumps and NBI's have also been improved. A cross section and plan view of the IMS design arrangement are shown in Figures 26 and 27, respectively.

FIGURE 26

FIGURE 27

Since the Culham concept was found to provide the more desirable characteristics for scheduled maintenance of the first wall/blanket the general arrangement and cross section of this reactor is selected as a base. In the Culham concept the functions required to provide access for removal of the sector module account for 51% of the total downtime to replace the modules in one sector. Removal and reinstallation in each sector of the outer shield door, the lateral support access panel (LSAP), and the NBI are combined into one operation. This reduces access time to 32.8% of the total downtime. In addition, the NBI is moved to a room below the floor for access at the same time that the first wall/blanket maintenance is conducted. The interior of the outer shield forms the floor and it appears that sufficient beam depth between the door and the LSAP exists for this floor to support the first wall/blanket module as it is removed. With this concept the reactor floor level can be raised from the level required to remove the LSAP and shield door, as is necessary with the Culham concept, to the floor level of the outer shield. This floor level and the use of the outer shield door as a bridge

eliminates requirements for much of the heavy maintenance equipment. The cryo-vacuum pumps are relocated in the IMS concept for easier access and removal but more analysis is required to locate all coolant, vacuum and service lines, instrumentation, and supporting structure, and to establish arrangements of other subsystems that will result in a valid maintainability concept. Designs for demountable toroidal field magnets and interior poloidal field magnets are also required. Nevertheless, the approach taken has illustrated a capacity for improvement of reactor maintainability that could result in even greater savings in downtime and COE.

A brief review of the facility requirements for maintenance of the IMS reactor resulted in the overall approach to a reactor building arrangement as shown in Figure 28. The reactor room has been reduced to a diameter of 85 meters. Twin polar cranes are supported from the roof truss which also is required to react vacuum loads during reactor operation. A 40 meter annular secondary confinement area surrounds the reactor room, although it is not as high. Detailed layouts indicate that the coolant primary and secondary loops and steam generators can be

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MAINTENANCE FACILITIES ARE IDENTIFIED

FIGURE 28

housed in this volume where indicated in the figure. Vacuum systems can be housed in this ring and the tritium reclamation system is planned for this location. The dual transfer lock system provides redundancy and rapid in-out traffic to hot storage and repair areas as well as maintenance equipment, mockup and other non-radiating areas. These are sized for operations requiring replacement and rework of 1/2 of the first wall/blanket and for other maintenance during a scheduled shutdown.

The effectiveness of the IMS in satisfying the COE goal of 52 mills/kWh has been defined by establishing a maintenance plan for replacement of 1/2 of the first wall/blanket and comparing the requirements of this plan with Culham reference reactor capabilities. Figure 29 tabulates the maintainability performance of the IMS and the comparable values for the Culham reference reactor. Comparison of the two designs shows the IMS able to accommodate more failures of other components within the 65 day allowable downtime period. Even when including maintenance equipment failures and using either a 52 mills/kWh COE goal or a 72 percent availability goal the IMS can absorb 4 failures of the first wall/blanket with a minimum of 43 days remaining for recovery from other failures. This compares favorably with the maximum time of 25 days attained by the Culham concept which is the maximum time remaining for any other reference reactor.

IMPROVED MAINTENANCE SYSTEM CAPABILITY TO MEET COE GOAL

CONCEPT (1)	COST OF ELECTRICITY MILLS/kWh	AVAILABILITY	SCHEDULED DOWNTIME DAYS/OPERATING YR.	ALLOWABLE UNSCHEDULED DOWNTIME DAYS/OPERATING YR.	REMAINING ALLOWABLE (2) UNSCHEDULED DOWNTIME	
					1 WALL/BLANKET FAILURE/OPER. YR.	4 WALL/BLANKET FAILURES/OPER. YR.
IMS-FIXED UNSCHEDULED DOWNTIME	46.25 (50.28)	.797 (.794)	28 ⁽³⁾ (30)	65 (65)	52 (48)	13 (<0)
IMS-COE GOAL (WITHOUT EQUIPMENT FAILURES)	52.0	.71 (.77)	28 ⁽³⁾ (30)	122 (81)	109 (64)	70 (13)
(WITH EQUIPMENT FAILURES) (4)	52.0	.71 (.77)	28 ⁽³⁾ (30)	103 (62)	90 (45)	51 (<0)
IMS-AVAILABILITY GOAL (WITHOUT EQUIPMENT FAILURES)	51.2 (55.4)	.72	28 ⁽³⁾ (30)	114 (112)	101 (95)	62 (44)
(WITH EQUIPMENT FAILURES) (4)	51.2 (55.4)	.72	28 ⁽³⁾ (30)	95 (93)	82 (76)	43 (25)

(1) CULHAM DATA IN PARENTHESES

(2) DOWNTIME REQUIRED FOR UNSCHEDULED WALL/BLANKET FAILURE
IMPROVED MAINTENANCE SYSTEM = 13 DAYS (MAXIMUM)
CULHAM = 17 DAYS

(3) DETERMINED BY BALANCE OF PLANT SCHEDULED DOWNTIME ALLOWANCE

(4) DOWNTIME FOR EQUIPMENT FAILURES IS THE SAME FOR CULHAM AND FOR IMS (19 DAYS)

FIGURE 29

A unique situation develops as the first wall/blanket replacement time is reduced below the 28 day balance of plant scheduled maintenance downtime requirement. The IMS requires only 20 days per outage. The scheduled downtime is no longer driven by the first wall/blanket replacement requirement and the scheduled maintenance requirements for other reactor components must be considered. Conducting additional scheduled maintenance requirements for these components may no longer be feasible during the first wall/blanket outage. Further investigation is required to determine this impact on the total maintenance costs or on the reactor availability.

6.0 CONCLUSIONS

Solutions to the critical maintenance questions identified in Section 2.0 have, for the most part, been identified. These solutions are summarized as a series of recommended design features and design guidelines and are presented in broad terms in Figures 30 and 31. A more detailed discussion is found in Section 7 of Volume II.

Several of the more significant conclusions resulting from the trade studies conducted during the study are listed below. These conclusions affect both the selection of the design features and the design guidelines collected in Figures 30 and 31.

- o Ease of access can be attained independently from the selection of large or small first wall/blanket modules. This objective can be achieved by design of the reactor, as in the case of IMS (large module) where reactor redesign reduced scheduled maintenance to 20 days from the 30 days required by Culham. The use of a large module composed of small heat cells (either being replaceable) for the IMS only resulted in a reduction of the 12.2 days to replace a single large module in an unscheduled maintenance action to 11.4 days to replace a small heat cell because the access for the large module is improved so greatly over the Culham concept. Ease of access can

DESIRABLE MAINTAINABILITY FEATURES

- o EMPLOY LARGE MODULES WITH MINIMUM ACCESS OPERATIONS FOR SCHEDULED MAINTENANCE (CULHAM)
- o EMPLOY SMALL MODULES WITH MINIMUM ACCESS OPERATIONS FOR UNSCHEDULED MAINTENANCE (GA-DOUBLET)
- o USE A SINGLE COOLANT CONNECTION PER MODULE (CULHAM, GA-DOUBLET)
- o USE MULTIPLE VACUUM CHAMBER ZONES (CULHAM, ORNL)
- o MINIMIZE PLASMA CHAMBER WELDED OR SEALED JOINTS BETWEEN MODULES (CULHAM, ORNL)
- o MINIMIZE REPETITIVE MAINTENANCE WELDING (CULHAM, ORNL)
- o USE MAXIMUM CONTACT MAINTENANCE WHILE MINIMIZING ADDED SHIELDING REQUIREMENTS (UWMAK-III)
- o CONSTRAIN REMOTE MAINTENANCE TO SIMPLE OPERATIONS (CULHAM)

FIGURE 30

DESIGN GUIDELINES FOR MAINTAINABILITY

GENERAL

- o PREVENTATIVE MAINTENANCE REPLACEMENT SHOULD BE USED WHERE ECONOMICALLY JUSTIFIED.
- o ONE YEAR MINIMUM OPERATING LIFE, INCLUDING REDUNDANCY, FOR ALL SUBSYSTEMS.
- o USE MINIMUM SIZE ECONOMICALLY REPLACEABLE COMPONENTS FOR UNSCHEDULED MAINTENANCE.
- o MINIMIZE ACCESS OPERATIONS FOR REPLACEABLE COMPONENTS.
- o MAKE MAINTENANCE OPERATIONS AS SIMPLE AS POSSIBLE.
- o USE CONTACT MAINTENANCE WHEREVER RADIATION LEVEL IS LOW ENOUGH.
- o DESIGN MAINTENANCE EQUIPMENT WITH THE CAPABILITY TO CONDUCT ALL OPERATIONS REMOTELY.
- o MAKE MAINTENANCE EQUIPMENT ACCESSIBLE DURING ITS OPERATION.

DESIGN APPROACH

- o USE MAXIMUM FIRST WALL/BLANKET MODULE SIZE FOR SCHEDULED REPLACEMENT.
- o USE MINIMUM HEAT CELL SIZE FOR FIRST WALL/BLANKET UNSCHEDULED REPLACEMENT.
- o DESIGN MAGNETS TO BE REPLACEABLE AFTER REACTOR IS RADIOACTIVE.
- o DESIGN DIVERTOR, NEUTRAL BEAM AND VACUUM COMPONENTS FOR EASY REPLACEABILITY.
- o LOCATE FLUID LINES AND INSTRUMENTATION FOR MINIMUM INTERFERENCE WITH ACCESS.
- o DESIGN FOR UNRESTRICTED TRAVEL OF THE OVERHEAD CRANE.
- o HELIUM (GASOUS) COOLANT PREFERRED OVER LITHIUM (LIQUID METAL) FOR MAINTAINABILITY. (CONCEPTS DID NOT INCLUDE OTHER COOLANTS).
- o MULTIPLE ZONED VACUUM WALL ARRANGEMENT IS PREFERRED.
- o USE MINIMUM NUMBER OF CONNECTIONS FOR COMPONENT REPLACEMENT, PARTICULARLY FLUID CONNECTIONS.
- o DESIGN FOR CONCURRENT REPLACEMENT OF SUBSYSTEM COMPONENTS.
- o DESIGN FOR FIRST WALL/BLANKET REPLACEMENT FRACTION OF 1/3 OR GREATER.

FIGURE 31

also be achieved by a maintenance equipment concept, as exemplified by the use of in-place maintenance equipment on the small module GA-Douplet. In this latter case the unscheduled downtime is only 7 days in comparison with the 11.4 days required by the IMS when using similar equipment to replace the small heat cells in the IMS but installing the equipment during each outage.

- o The use of large first wall/blanket modules for scheduled maintenance and small modules for unscheduled maintenance is also desirable. The Culham large module concept requires a scheduled downtime of only 30 days to replace 1/2 of the wall/blanket area, while the GA-Douplet small module concept requires 90 days. However, Culham requires an unscheduled downtime of 17 days to exchange a single module, compared with only 7 days for the GA-Douplet. The scheduled maintenance advantage of the large module arises because of the short replacement time required after access

is attained. The large modules have fewer joints to be broken and fewer operations to be conducted than small modules covering the small wall area. However, access to individual small modules is generally more rapid than to large modules as indicated by the foregoing comparison of Culham and GA-Doublet. The advantage of replacing an individual small module is not so great in the case of the IMS because the IMS access functions are only 11% of the total downtime compared to 32% for the Culham reactor. Therefore, the conclusion to recommend the use of small modules for unscheduled maintenance is dependent on the detailed access provisions provided in any specific design and the minimum size module or group of modules for which fault isolation is feasible.

- o The use of the reactor room wall as the primary vacuum wall and the use of multiple vacuum zones results in the lowest scheduled downtimes for first wall/blanket replacement. Time reductions provided by this arrangement from the time required for the arrangement using only one zone with welded seals (two zones for Culham) are 13.5 percent for UWMak-III, 7.0 percent for the ORNL Cassette and 11.2 percent for Culham concepts. These reductions are for unscheduled replacement of single modules. The GA-Doublet considered only the single vacuum zone basic design arrangement because no measurable improvement is anticipated with multiple zones.
- o Welding is generally a time consuming operation because of setup requirements, particularly for repeated operations. Comparative time estimates generated in the first study phase indicate the desire to avoid welding operations for scheduled maintenance actions. This consideration increases the desirability of such design features as mechanically connected fluid, power and instrumentation lines and the use of multiple vacuum zones.
- o Contact maintenance operations are desired wherever possible. These operations are limited for first wall/blanket maintenance because of plasma chamber wall activation. However, even for this maintenance operation, from 29 percent to 100 percent of the downtime can be available for partial contact operations in the reference reactor concepts studied. The net downtime reduction from contact operations, however, only ranges from 3.6 percent to 27 percent of the total outage time. This relatively small time reduction occurs either because remote operations must be conducted in parallel with contact operations and the time reduction per operation does not affect the total elapsed time, as for the GA-Doublet, or because

the large size of the equipment being handled only allows limited exploitation of manual operations. It is anticipated that much greater time savings can be achieved when using contact operations for other reactor room maintenance. Caution must be exercised in the use of this conclusion since the emplacement of auxiliary shielding and/or its cost can overshadow the time and cost savings of contact maintenance.

- o In determining that contact assisted maintenance is desired wherever possible, it was also determined that all maintenance functions appear to be feasible by remote operations. The impact of total downtime on maintenance costs is expected to be of major importance when considering all maintenance operations. Therefore, the extension of the remote equipment capability to provide for conducting any foreseeable maintenance function in the event of some types of unscheduled failures which impose radiation hazards should reduce the total downtime for recovery from these failures. This feature should be economically viable in reducing the impact of radiation hazards.
- o The minimum cost of electricity for the reference reactors and the IMS all fall between 46.25 mills/kWh for the IMS and 51.37 mills/kWh for the UWMAK-III which is well below the 57.4 mills/kWh defined as a breakeven goal. This COE is based on a fixed allowance for unscheduled outages of 65 days per operating year. All reference reactor availabilities are above the nominal goal of 72% except the GA-Douplet which is approximately 71%. Therefore, it can be concluded that these goals appear achievable by tokamak reactors.
- o When comparing allowable unscheduled downtime at a fixed cost of electricity of 52 mills/kWh (selected at a value above the optimums for all reactors) the GA-Douplet and the Culham reference reactors have the greater allowable downtimes of 76 and 81 days per operating year, respectively. These downtimes do not include the effects of maintenance equipment failures. Both of these reference reactor downtimes are exceeded by the IMS at 122 days per operating year. However, the ability of the GA-Douplet to recover from a first wall/blanket failure in 7 days gives this concept the greatest capability to handle first wall/blanket failures (10.9). On the other hand, the greatest capability to handle other failures is available with the IMS since 109 days remain after one first wall/blanket failure compared to 69 days for the GA-Douplet (Figure 21). These time differences

provide only a relative measure of merit of the reactor concepts until additional failure modes are analyzed.

- o Maintenance equipment failures can result in a significant reduction in allowable unscheduled downtime. A sampling of these failures identified 16 to 38 days per operating year as representative recovery downtimes. This time must be taken directly from the total allowable unscheduled maintenance days identified above. That is, the 122 total days available for the IMS are reduced to 103 days to allow for the 19 days of forced outages estimated for maintenance equipment in the IMS concept. If, in addition, one first wall/blanket failure occurs per year the remaining allowable downtime for additional forced outages becomes 90 days. This compares favorably to the 37 days for the GA-Douplet and 45 days for Culham. The large additional downtimes resulting from maintenance equipment failures are partly caused by the difficulty in accessing the failed maintenance equipment components. Access to maintenance equipment can be as time consuming as access to the reactor components unless particular attention is given to this requirement in the design of the equipment concept.

To summarize the design guidelines delineated in Figure 31, the reactor should be designed for ease of access to all components for which maintenance operations are anticipated. The use of preventative maintenance is to be emphasized but only at intervals determined by the balance of plant or scheduled first wall/blanket scheduled outages. Therefore, the reliability must be high over this period and the use of redundancy and other reliability improvement techniques will likely be necessary.

Unscheduled maintenance is to be expected and planned for during the design of the reactor by the use of small components with simple access. Maintenance equipment should be designed for unscheduled remote operations even though the nominal maintenance mode uses contact operations. Maintenance equipment failures also require specific design for remote replacement during reactor maintenance operations.

Replacement is the selected method for scheduled maintenance, and also for unscheduled maintenance when feasible. This mode is selected instead of in situ repair because it tends to simplify and standardize the maintenance functions required in the reactor room. The complex and diversified repair operations can better be handled in a hot cell or other area where time is not as critical and access to failed parts and specialized tools is more open or observable.

Wherever possible, contact maintenance should be used but the option to use remote maintenance must be provided. Therefore, maintenance equipment should be designed to take advantage of the best features of both modes of operation. The economics of contact maintenance should consider shielding and its handling time and cost. The maintenance system should be analyzed prior to operation to determine all maintenance that can be conducted by contact operations and how they may be conducted alternatively by use of remote operations.

An economic analysis should be the deciding factor to determine those maintenance actions which use scheduled maintenance and those solely conducted with unscheduled maintenance. Economics also determines the size of component or sub-assembly to be replaced for scheduled or unscheduled operations. Similarly, the choice of the use of contact or remote operations for scheduled or unscheduled maintenance, the design of connections and connecting operations and the design of access techniques should all be based on economic analyses.

The most serious unknown impact is the potential requirement for recovery from failure modes not yet analyzed, the impact of additional preventative maintenance, and design for reliability. Many failure modes must remain undefined at this time and the use of contact maintenance is desired to provide the flexibility to accommodate them with a minimum requirement for on the spot remote tool design. However, the best insurance against this uncertainty is a thorough failure modes and effects analysis similar to those conducted for some fission facilities or space vehicles.

The ultimate objective of the study is to determine whether a tokamak design can be defined which is maintainable when the economics of both scheduled and unscheduled maintenance of all reactor peculiar subsystems are considered. In this context a maintainable system is defined as one which can attain or better the nominal availability and the COE goals. As seen in Figure 6, the IMS availability and COE are significantly better than the selected goals. The capability of tokamaks to handle maintenance operations, as represented by the IMS concept, is further summarized in Figure 32.

For the IMS tokamak reactor the downtime required by the most critical first wall/blanket subsystem is less than the currently accepted annual shutdown of 28 days for balance of plant operations. Preliminary investigations of other subsystem maintenance, except for magnet replacement, indicates that their maintainability is also within acceptable limits. The best achievable availability estimate is currently almost 80% with an accompanying COE of 46.25 mills/kWh.

IMS MAINTAINABILITY CHARACTERISTICS

	FIXED UNSCHEDULED DOWNTIME	FIXED AVAILABILITY
COST OF ELECTRICITY, MILLS/kWh	46.25	51.19
AVAILABILITY, %	79.7	72
WALL LIFE, YEARS (AT 5.0 MW-YRS/m ²) ⁽¹⁾	2.36	2.36
REPLACEMENT WALL FRACTION/OUTAGE	1/2	1/2
SCHEDULED DOWNTIME/OPERATING YEAR, DAYS ⁽²⁾	28 (20)	28 (20)
ALLOWABLE UNSCHEDULED DOWNTIME/OPERATING YEAR, DAYS	65 ⁽³⁾	114
MAINTENANCE EQUIPMENT FAILURES		
ESTIMATED DOWNTIME/OPERATING YEAR, DAYS	19	19
DOWNTIME REQUIRED FOR 1 FIRST WALL/BLANKET FAILURE, DAYS	13	13
DOWNTIME REMAINING FOR OTHER SUBSYSTEM FAILURES, DAYS ⁽⁴⁾	33	82

(1) ASSUME CULHAM REFERENCE REACTOR WALL LIFE.

(2) 28 DAYS ALLOWED FOR BALANCE OF PLANT MAINTENANCE OF WHICH 20 DAYS IS REQUIRED FOR FIRST WALL/BLANKET. FIRST WALL/BLANKET TIME BASED ON MINIMUM COE MAINTENANCE PLAN.

(3) 65 DAYS BASED ON AVERAGE EXPERIENCE IN CURRENT FISSION POWER PLANTS.

(4) THIS DOWNTIME IS TOTAL ALLOWABLE FOR UNSCHEDULED OUTAGES LESS DOWNTIME FOR MAINTENANCE EQUIPMENT OUTAGES AND ONE FIRST WALL/BLANKET OUTAGE.

FIGURE 32

These values compare favorably with the 72% nominal availability goal and the breakeven COE of 57.4 mills/kWh discussed in Section 5.1 of this volume. Therefore, tokamak systems appear to be maintainable under the conditions defined for the study.

To resolve the additional questions raised during the study which affect the conclusion that tokamaks are maintainable further investigation of the following issues is recommended.

- o Determine the economics of magnet replacement using several demountable magnet concepts. This study would include defining the system costs to place poloidal field magnets outside of the bore of the toroidal field magnets insofar as possible. The impact on system costs of varying plasma parameters, height to width ratio, recirculating power cost and capital cost of magnets as the poloidal field magnet locations are varied should be evaluated.

- o Define the total scheduled downtime required, including traffic impacts, when considering all reactor subsystems. The downtime requirement for maintenance of the first wall/blanket is currently estimated at 20 days per outage. This short downtime may reduce the assumed ability to overlap the maintenance of other subsystems with the first wall/blanket maintenance. Therefore, an analysis of the scheduled maintenance required for all subsystems may indicate the necessity to increase the estimated downtime per scheduled outage.
- o Designs of the first wall/blanket are being defined which tend to increase the life of the first wall significantly. An analysis of the influence of this increase in life on the assumption that this subsystem is the scheduled maintenance driver should be included with the preceding additional subsystem analysis. It is expected that one or more other reactor subsystems such as divertors, vacuum valves or coolant loop components may become the scheduled maintenance drivers.
- o The use of various divertor designs to reduce the surface heat flux on the particle bombardment plates, and to increase the access to these plates, should be examined. Alternative designs for achieving impurity control should be examined to include bundle divertors, limiters and getters.
- o The impacts of the instrumentation subsystem on the maintainability of the reactor should be included.

7.0 REFERENCES

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