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MAINTENANCE AND AVAILABILITY CONSIDERATIONS FOR MFTF-B UPGRADE*

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Abstract: The upgrade of the Mirror Fusion Test Facility (MFTF-B) tandem mirror device incorporates the operation of advanced systems plus the requirement for remote maintenance. To determine if the operating availability goal of this device is achievable, an assessment of component lifetimes was made, along with estimates of device downtime. Key subsystem components were considered from the magnet, heating, impurity control, pumping, and test module systems. Component replacements were grouped into three categories, and a lifetime operating plan, including component replacements, was developed. It was determined that this device could achieve a 10% operating availability.

Introduction

The MFTF-α+T is an upgrade of the MFTF-B which will incorporate a deuterium-tritium (D-T) axicell design, negative-ion beamlines, a direct converter system, and remote maintenance operations. Incorporating these advanced features into the existing tandem mirror device necessitates an assessment of maintenance and availability in order to effectively influence the configuration development of the MFTF-α+T. An availability goal of 10% for machine operations has been established for the α+T. To develop a maintenance program for scheduled operations which meets the availability requirement, an assessment of component lifetimes was made. The focus of this work is on replacement of limited-life components. Key subsystem components of each major system were considered either by extrapolating the work of previous lifetime estimates or by assuming lifetimes based on the judgement of the component designers. Due to the lack of real operating data for D-T fusion systems, this compilation is largely subjective, but it does establish a starting point for a maintenance plan.

Operating Availability and Component Lifetimes

Plan of lifetime operations: Table 1 is the plan of operations for the 10-year lifetime of α+T. The 10 years of device operation are divided into four phases. The first phase occurs during the first year and is essentially an integrated systems checkout to verify the performance characteristics of all of the systems and subsystems and to establish operating capabilities. It is envisioned that active operations on the device will be scheduled for 6 d/week at two shifts per day. No distinction is made here between maintenance activities and device operation, since this shakedown phase implies an intermingling of both. The operating availability goal is expected to be about 1% (7 h/month) to evaluate performance of the systems. It should be noted that certain systems will be operational for considerably longer periods, such as the turbomolecular pumps and the cryogenic magnets.

Phase II occurs during the second year and consists of high-performance deuterium plasma operations. The operating schedule is the same as that of Phase I, except the availability is expected to be at 3%. During this phase, remote maintenance equipment is in place and tested on the device. Earlier development and testing of this equipment is accomplished on the device mockups.

Table 1. Plan of Operations for MFTF-α+T

Phase	Duration (years)	Description	Operating schedule[a]	Full-power operation (h/month)	Average availability (%)
I	0–1	Integrated systems checkout	6 d/week 2 shifts/day	7	1
II	1–2	High-performance deuterium operation & checkout	6 d/week 2 shifts/day	22	3
III	2–3	High-performance D-T operation & checkout	5 d/week 2 shifts/day Down 2 weeks/month	22	3
IV	4–10	High-availability nuclear testing	5 d/week 2 shifts/day Down 2 weeks/month (on average)	72	10

[a]During Phases I and II, there is no scheduled down time since the device is expected to be operational for less than an hour during any shift; during Phases III and IV, the device has 12 weeks per month of scheduled down time.

Phase III occurs in the third year and represents high-performance D-T operations and checkout. At this point, the device is activated; and subsequent operations will routinely require remote handling equipment. Device operations are envisioned to be scheduled for 5 d/week, two shifts per day. Two weeks out of every month, the device is down for scheduled operations. This amount of downtime is assumed adequate to allow for several 24-h waiting periods prior to personnel access and one vacuum vessel pumpdown. If the superconducting coils require thermal cycling, 2 weeks down is not sufficient. On the other hand, if the device operates without major problems, it should be assumed that such operations would be continued, and "scheduled" downtime would be waived. A 3% availability is assumed to be an achievable goal, since this translates to approximately 1 h of D-T operation during each shift when the device is not shut down; this is 22 h/month of full-power operations (Table 1).

Phase IV encompasses the blanket testing program during the last 7 years of operation. The operating schedule is the same as Phase III, except that the availability is up to 10%; and the 2-week downtime per month is an average for scheduled maintenance activities. In a month when test module replacement or ion source replacement is not scheduled, the device will be kept in operation.

The availability in Table 1 is defined as the time when the device is actually operated (to create plasmas) divided by the total calendar time (including planned shutdowns). For example, in Phase IV, 72 h of operation is planned over the total 720 h in a typical month in order to achieve 10%. This translates into ~2 h of device operation in an 8-h shift.

Scheduled operations and component lifetimes: One of the major missions of α+T is to successfully complete a blanket testing program. These results will become the basis for future devices which will have full-scale breeding blanket designs for use in future devices. The total program requires six blanket module replacements during the last 7 years of operation, and the downtime for each of these is expected to vary according to the particular module being installed. A brief discussion related to device downtime follows and is also described in Fig. 1.

During years 4 and 5, two different liquid metal (LM) modules will be tested, followed by two different solid breeders in years 6 through 8. The evaluations of the test results for these four designs will be used to develop and test one prototype for each concept which is to be operated during years 9 and 10.

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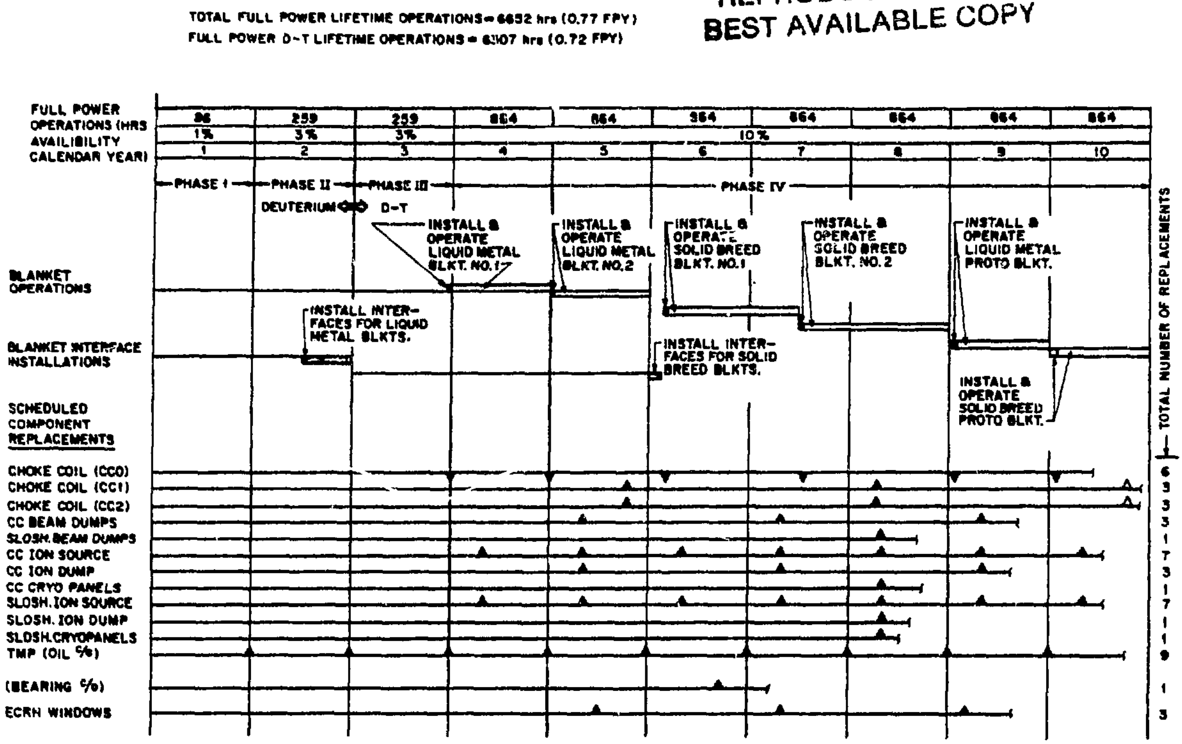

Fig. 1. Lifetime plan for scheduled operations.

Figure 1 shows the four phases of device operation and the relationship to the blanket tests. The following assessment of device downtimes for blanket changeouts is a postulation based on estimating the requirements for these blanket installations.

LM Blanket 1 is estimated to require 2 weeks of around-the-clock remote operations. This period is based on the assumption that prior to beginning D-T operations (the last 6 months of year 2), the interface connections, piping, valves, and any necessary device modifications are carried out using contact operations. These modifications are envisioned to be sufficient for LM Blankets 1 and 2. Consequently, the installation of these modules appears reasonable at 2 weeks each at year 3 and the beginning of year 5.

Similarly, the solid breeder (SB) test phase has an interface modification period which is assumed to be 6 weeks of around-the-clock operations. These will essentially be fully remote and will benefit from the use of the full-scale mockup system prior to actual operations. Following these changes, both SB modules are assumed to require 2 weeks for installation and checkout early in year 6 and in the middle of year 7.

The prototype modules presumably utilize some of the original interface equipment and should be designed to require minimal device modifications for their installation. One month of downtime for each module appears reasonable at the beginning of years 9 and 10.

Table 2. Estimated Component Lifetime for α+T

System/subsystem	No. of modules	MTBF (h)	MTTR (days)	Lifetime (FPY)
Test modules				
LM #1	1	—	—	.10
LM #2	1	—	—	.10
SB #1	1	—	—	.15
SB #2	1	—	—	.15
LM Prototype	1	—	—	.10
SB Prototype	1	—	—	.10
Test module coil (CCO)	1	>>8800	>47	L
Solenoid coils (CS)	2	>>8800	>>47	L
Choke coils (CC1)	2	~2200	47	.25
Solenoid coils (S)	10	>>8800	>>47	L
Choke coils (CC2)	2	~2200	47	.25
Cee coils	12	>>8800	>>47	L
D.C. coils	2	>>8800	>47	L
Drift pump coils	4	>>8800	47	L
Halo scraper	2	~8800	47	1 (L)
Direct converter	2	~8800	47	1 (L)
C.C. beamlines				
Ion source	16	<900	10**	<.1
Ion dump	2	~1800	47	.2
Cryopanels	2	~4400	47	.5
Bending magnets	2	>>8800	47	L
Sloshing beamlines				
Ion sources	8	<900	10**	<.1
Ion dump	2	~4400	47	.5
Cryopanels	2	~4400	47	.5
C.C. beamdumps	2	~1800	47	.2
Sloshing beamdumps	2	~4400	47	.5
ECRH windows	4	~1600	47	.25
ICRH	8	>>8800	>47	L
Turbomolecular pumps	4			
oil changeout		~4000	2	—
bearing changeout		~25000	3	—

*Replace all sources.

Component lifetimes: Ideally, scheduled replacements should coincide with the mandatory downtimes for the blanket installations. To determine the impact that limited-life components may have on the test program and the device operating availability, an estimate of component lifetimes has been compiled. Table 2 is a listing of system and subsystem components on the device island. Related items such as power supplies, refrigerators, and radio frequency (RF) drivers outside the vault have not been considered. In addition, because of the modular nature of many of the components, such as the halo scraper, subunits like the leading edge of the scraper are not considered separately, because their failure requires removing the entire scraper module. The same is true for the direct converter, the beamline dumps, and the test module (which contains a high-field resistive coil).

It should be pointed out that the component lifetime *estimates* in the table are indeed estimates, since no precedent exists for the device components in the operating environment of a D-T fusion reactor. Many of these numbers are taken from the estimates derived for the Tandem Demonstration Facility (TDF) design [1].

Table 2 is intended to be a representative listing of components which comprise many of the key α+T systems. Of these, approximately half are expected to require at least one replacement during the operating life of the machine. The remainder are primarily lifetime components, such as the superconducting coils, which would be expected to operate for many full-power years (FPY) and limited-life components with lifetimes greater than that of the full-power operating life of the device. Examples of this category are the halo scraper and the direct converter, which have expected operating lifetimes of approximately 1 FPY.

From the availability listing in Table 1 for the four phases of operation, the full-power operations in the device lifetime are derived by multiplying the availability for each year by the number of hours in a year. N corresponds to the number of years in each phase. The total full-power lifetime operations (TFPLO) equation is:

$0.01(8640)N_1 + 0.03(8640)N_2 + 0.03(8640)N_3 + 0.10(8640)N_4$, where $N_1 = 1$, $N_2 = 1$, $N_3 = 1$, $N_4 = 7$, so that TFPLO = 6652 h (0.77 FPY). To derive full-power operations for D-T, the first two terms are omitted.

The D-T full-power operations (DTFPO) equation is:

$0.03(8640)N_3 + 0.10(8640)N_4$, so that DTFPO = 6307 h (0.72 FPY).

The column that lists the number of modules indicates the component replacement in its modular form. For example, the Electron Cyclotron Resonant Heating (ECRH) system is listed as 4. In fact, the ECRH is made up of 14 waveguides (7 in each end cell), but they are installed as modules, with one module consisting of six waveguides and another consisting of one waveguide for each cell. Hence, replacing the ECRH (because of damaged windows) requires four separate removals, not 14.

The mean time between failures (MTBF) is the number of hours that the component is expected to operate. From this and the availability distribution components, replacements can be converted to calendar time in order to develop the replacement schedule. For example, the 18-T choke coil (CC2) has an FPY of 0.25, which corresponds to 2160 h of operation. Using the availability from Table 1, annual hours of operation for the device are:

Years	1	2	3	4	5	6	7	8	9	10
Operating hours/yr	86	259	259	864	864	864	864	864	864	864
Replace CC2					↑		↑			↑

Consequently, coil CC2 requires the first changeout after 4.8 CY and every 2.5 years after that, as shown above and in Fig. 1.

The turbomolecular pumps (TMP) are a slightly different example. Their scheduled maintenance operations are not for component replacement due to failure. Nevertheless, these operations require shutting down the device; hence, they are included. Two operations have been identified: (1) an oil changeout after ~4,000 h of operation and (2) replacement of bearings after ~25,000 h of operation [2]. For these, the FPY calendar-time equivalents are not applicable, since the pumps are expected to operate whenever the machine is not down for maintenance; this is to sustain the vacuum environment in the device. From Table 1, this time is assumed to be 2 weeks/month (24 h/day), according to the column for operating guidelines. Therefore, the 4,000 h corresponds to ~1 CY and the 25,000 h to 5.7 CY, as shown in Fig. 1.

The MTBF for the choke coils has an indirect relationship with several other components. The test module coil (CCO) is an integral part of the test module, and even though it is estimated to be a lifetime component, it will be removed when blanket tests are changed. This occurs six times in the 10-year life of the device. It could be postulated that the same coil will be used for each blanket module; that is, it can be remotely removed from the used blanket module and installed into the new module in the hot cell. This may increase the downtime estimated for blanket installation because of the extra handling and integrity testing operations required; and, in addition, it may compromise the design features and reliability of the blanket design. It appears more reasonable at this time to assume that the CCO will be fabricated into each blanket module at the manufacturer's facility, where it becomes an integral part of a test module. This approach is based on the modularity concept, which is the basis for the development of the α+T device configuration. Therefore, in the 10-year lifetime, seven CCO coils are required: one for initial operations during the first 3 years, and six to be furnished to the manufacturers of the test blankets. Figure 1 indicates these replacements using upside-down triangles to indicate that they are not required by component failures. Also, the location of these triangles conveniently aligns them with the blanket installations for the purpose of discussion here. Clearly, these components must be delivered to the blanket manufacturer many months prior to completing a test module assembly.

The 12-T choke coils (CC1) have a limited life and are mounted to their supporting shield segments, which are lifetime components. The two coil/shield modules are replaced as units through the blanket access hatch. A new coil is mated to its shield segment in the hot cell for reinstallation. The 18-T choke coil set (CC2) is composed of two subassemblies. One is the outer superconducting coil, a lifetime component, and the second is the inner normal conducting insert coil, which has a limited life. The two coils will be lifted out as a single module, and the insert coil will be replaced in the hot cell. These two situations are the only exceptions to the modular independence of components which have different lifetimes. The removal of the two 12-T coil/shield modules and the two 18-T coil sets will have an additional impact on device downtime since their replacement requires more than the installation of spare choke coils. Additional remote handling operations are required in the hot cell, as well as an integrated system checkout prior to reinstallation into the device.

The mean time to repair (MTTR) for each scheduled component replacement is the number of hours required to remove and replace a module and includes the following general procedures: 24-h device shutdown period; remove/replace operations; repair time, where applicable (choke coils, TMP); thermal cycling of the superconducting coils, where applicable; testing and checkout; and vacuum pumpdown, except for TMP and ion source replacements. Except for blanket module replacements, which assume around-the-clock maintenance operations, MTTRs are based on two 8-h shifts per day.

Availability and Maintenance

Down time: Four major activities impact on the total time during which the device is shut down: (1) initial shutdown to reduce activity to levels which allow personnel access; (2) maintenance operations during which components are removed and replaced using both contact and remote means; (3) thermal cycling of the superconducting coil systems if maintenance activities require in-vessel operations or coil replacements; and (4) pumpdown of the vessel and possible reconditioning of the internal surfaces.

Shutting down the device to begin maintenance-related operations requires two approaches, depending upon the nature of the activities. If a maintenance activity can be accomplished remotely, then the 24-h waiting period after shutdown can be waived, and only the time required to de-energize the coils is required prior to introducing remotely operated equipment. This scenario is not considered here, since α+T is based on contact operations for initiating many of the maintenance-related activities.

Thermal cycling of the coil systems represents the most significant potential impact to device downtime, since it is estimated to require approximately 2 to 3 weeks each for coil warmup and cooldown. It should be pointed out that these numbers are estimates based on extrapolating from the experience of the Large Coil Program (LCP), and even though they essentially duplicate the experience at Lawrence Livermore National Laboratory (LLNL) for the technology demonstration for yin-yang coils, a detailed analysis which includes the economic consideration of refrigeration has not been done. Where it is appropriate to do so, 6 weeks are assumed to be required for any operations which affect coil replacements, as discussed in the next subsection.

Similarly, the pumpdown time required for the plasma chamber after extended maintenance operations has not been analyzed to any detail. Under ideal conditions, it has been estimated that ~10 h of pumping using the TMPs in the end cells and the cryopanels in the beamline drift tubes may be sufficient to achieve the base operating vacuum. In light of this uncertainty, a more appropriate number may be in the range of 3 to 6 d, for two reasons. First, the operating experience for the Tandem Mirror Experiment (TMX) indicates that a 3-d pumpdown is achievable but often becomes 6 d due to numerous unforeseen problems in operating large, complex vacuum systems. It appears reasonable to assume (at least for the time being) that α+T will be similar. Second, the experience for tokamaks indicates again that days of pumpdown are required, particularly if the vessel is open to atmospheric conditions for extended periods (days to weeks) and if replacement components such as limiters have not been "conditioned" prior to installation. In Dylla's article [3] on conditioning techniques for tokamaks, three methods are discussed: bakeout, discharge cleaning, and gettering. In one example, he cites 100 h (4 d) of glow discharge conditioning for the Poloidal Divertor Experiment (PDX) to achieve acceptable levels of cleanliness for operation. While it is not clear that any of these will be required for α+T, it seems prudent to assume pumpdown may have an impact on downtime. Of the three techniques stated above, gettering may be the most efficient; however, because of tritium inventory buildup, it does not appear appropriate in a D-T device. Hence, in light of the uncertainty for pumpdown, 6 d is assumed to be the requirement.

It should be noted here that pessimistic estimates for coil cycling and pumpdown are used in order to test their impact on achieving the 10% operating availability of the device. Clearly, if the availability objective can be achieved under these conditions, the uncertainties above will not be a factor. This is shown to be the case for achieving 10% availability.

Scheduled replacements: The chart of Fig. 1 simplifies general operating data for the device and compares it to blanket test operations, blanket installations, and scheduled component replacements. Full-power operations are shown in annual hours for both hydrogen and D-T phases, along with the assumed availability for the four operating phases. The blanket testing during Phase IV is also shown in conjunction with the expected blanket installations. Scheduled component replacements taken from Table 2 are also plotted in a time-line manner. These replacements comprise 14 components for this preliminary investigation.

It is not surprising to note that virtually all of the replacements occur during the D-T phases of operations, which in general require the use of remote handling equipment. The first operation shown is an oil replacement for the TMPs at the end of Phase III. Since the opportunity to accomplish this remotely (as a learning process) is likely during Phases I and II, oil changeouts should not present any unforeseen problems. In fact, this task is one that may be easily automated, considering its frequency. Therefore, the initial challenge is expected to be replacement of the central cell and sloshing beamline ion sources. These replacement scenarios, as well as all of the other scheduled replacements, will be done in a routine manner, since the maintenance equipment and the operators will have had ample opportunities for development and learning using the mockup systems.

To assess the impact of all of the scheduled replacements on the device operating availability, each of the 14 replacements was studied with regard to required down times. Figures 2 and 3 are time-line charts for these components, which show (to first order) the stepwise procedures and an estimate of the time required. Three group categories for components were established.

Group I consists of components that exhibit similarities regarding the procedures for replacement. In addition, replacing these requires bringing the vessel up to atmospheric pressure, which also entails warming the superconducting coils. Figure 2 shows that these operations require 47 d of device shutdown, primarily as a result of thermally cycling the superconducting coils.

Group II consists of the beamline ion sources. Their replacement does not affect the vacuum of the plasma chamber since each source will have a vacuum-tight valve. Replacement of Group II components is estimated to require 9.5 d of device down time.

Group III consists of the two maintenance activities for the TMPs. Because of the vacuum valves, these do not affect the vacuum of the plasma chamber. Oil changeouts are annual but only require 1.5 d of down time. The bearing changeout after 5.7 years can be accomplished either by hot cell repair, which will be time consuming because of remote operations, or simply by pump replacement. The latter is assumed to be the maintenance mode.

Using the downtime required for each group from Figs. 2 and 3 applied to Fig. 1, a compilation of the down time for each calendar year can be derived using the very conservative assumption that no component replacements are done in parallel. This approach can be used to establish an upper bound on achieving device availability and acts as a test for the feasibility of attaining a 10% operating availability. The results of this compilation are shown below.

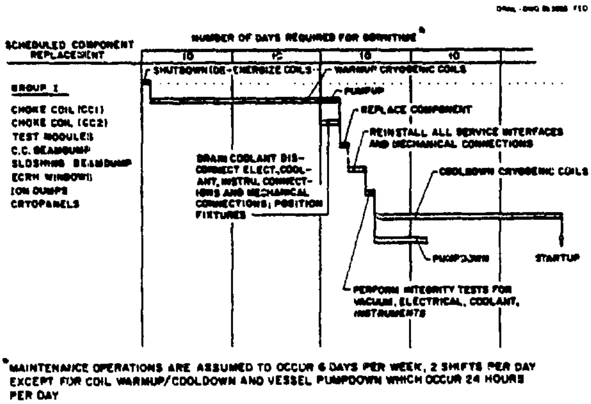

Fig. 2. Group I component replacements.

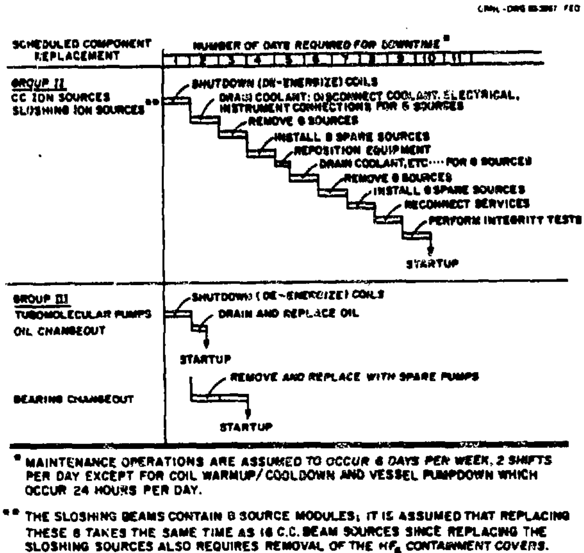

Fig. 3. Groups II and III component replacements.

From the plan of operations (Table 1), down time was scheduled for 2 weeks per calendar month. For any year, this is equivalent to 144 d, assuming maintenance is accomplished for 6 d/week. In the previous chart, years 5, 7, 8, and 9 exceed this annual value. However, an investigation of year 8 with the most-scheduled, serial down time (302.5 d) still shows that α+T could exceed the 10% availability requirement. For year 8, the operating availability could be 17%. Although this theoretically demonstrates that the upper bound for achieving 10% availability has not been reached, the assumption of serial component replacements is unreasonable for several reasons: it places unnecessary cycling on the cryogenic structures, requires an inefficient use of manpower and equipment, and uses up time which could be allocated for unscheduled occurrences. Consequently, component replacements are scheduled as parallel operations whever possible.

As an example, the scheduled replacements during year 8 can be accomplished as follows:

Calendar year	1	2	3	4	5	6	7	8	9	10
Total downtime (days)	1.5	1.5	15.5	34.5	255.5	37.5	175.5	302.5	161.5	127

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	Weeks
Shutdown and coil warmup	~3
Serial replacement of all Group I components (8 operations at 1 week each)	~8
Coil cooldown and vessel pumpdown	~3
Total down time	14 (~100 d)

Therefore, ~200 d are gained for other activities.

Spares: An analysis for a spares inventory was not undertaken for this study; however, it appears that a minimum requirement for spare components is necessary so that device operations are not unduly impacted. Figure 1 lists the total number of replacements for components over the device lifetime, and this represents the total number of spares. Clearly, these do not have to be stored in inventory at one time since components are cycled in intervals of one to several years.

Unscheduled maintenance operations: Considerations for unscheduled replacements have been factored *into the configuration development*, and it appears that there is ample time in the operating schedule to accommodate a limited number of such occurrences. The unscheduled replacements which potentially have the greatest impact on device availability are for the superconducting coils. Although time studies for unscheduled replacements were not developed, some judgements can be made with regard to their impact on the operating availability of the device. During the 10-year device lifetime, ~1100 d were estimated for total down time resulting from scheduled component replacements (from the previous subsection). Also, 2 weeks per month were assumed to be devoted to scheduled shutdowns, which is ~1700 d in 10 years. The difference between these two numbers is potentially scheduled down time, which can be allocated to unscheduled component replacements and is ~600 d. Clearly, a limited number of unforeseen component replacements can be accommodated during the device lifetime.

References

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