MAINTENANCE CONSIDERATIONS OF THE STARFIRE COMMERCIAL TOKAMAK

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Summary

An initial reactor design has been developed for the Starfire Tokamak reactor that incorporates maintenance features to permit reactor and plant operation with a 75% availability.

All components of the reactor can be replaced utilizing highly automated remote maintenance techniques. Provisions for contact maintenance are included but would only be utilized on a contingency basis since it is believed that allowable dose rates will be decreased in future years. A modular design approach is used for the reactor and auxiliary subsystems to permit efficient use of remote maintenance. The modular approach minimizes the number of different maintenance operations required and can result in use of simple tasks such as push, pull, turn, etc., maneuvers for module removal. Fault isolation is provided for each replaceable module. When a reactor component fails the fault isolation system identifies the module that contains the failed component. The module is subsequently removed and replaced with a pretested module. Detailed fault isolation and component replacement or repair is performed in the hot cell where more time and equipment is available.

The reactor design does not require any in-place manufacturing operations such as rewinding magnets in place and minimizes any in-reactor welding operations. No in-reactor welding is required for scheduled maintenance.

An initial allocation of replacement times and the resultant component reliability requirements has been made for the current utility maintenance scenario that utilizes scheduled annual shutdowns of 1 month and a scheduled 4 month shutdown every tenth year. These allocations establish requirements for maintenance equipment and can be used to identify the need for redundancy. The 75% availability goal is believed to be achievable if a four-year replacement cycle for the first wall, blanket, limiter and RF duct assembly can be utilized. Scheduled maintenance operations can not be permitted to shutdown the reactor more than 1 time per year and in-reactor components should be designed so that scheduled replacement is not required more than 1 time in two to four years. Auxiliary subsystem components outside of the reactor will be required to include redundancy that permits operation for at least a year or that permits replacement during reactor operation.

Introduction

The maintenance approach for the Starfire Commercial Tokamak is being developed as part of a DOE funded study to develop a conceptual design for a commercial tokamak reactor and balance of plant.

The primary consideration in maintenance approach selection is the plant availability which is the main driver in determining the cost of power produced. As such, major reactor design decisions are being made based on maintenance considerations. Design approaches permitting rapid replacement of life limited components have been emphasized. All components, including the life-of-plant items such as the TF and EF coils, are designed for replacement within time limits acceptable to the utilities.

Remote maintenance is used for all operations inside the reactor building because of the desire to limit radiation exposure to maintenance workers. Benefits of contact maintenance will be assessed at the end of the study.

The first wall and blanket assembly (including coatings and limiters) is expected to require the most frequent scheduled maintenance since little redundancy can be incorporated. Design studies resulted in selection of a design that permits fault isolation to a toroidal sector and subsequent removal and replacement. Subsequent repairs are made in a hot cell. The shield system is independent of the first wall and blanket and, except for an access door, requires no scheduled maintenance.

This paper presents the maintenance approach, the commercial tokamak design features that enhance maintenance and preliminary repair time and required mean-time-between-failures for major subsystems. Reactor hall building and maintenance equipment requirements including hot cells, coil rewinding and cranes are discussed.

Maintenance Approach

The remote maintenance approach was chosen for in-reactor operations because of the likelihood that current regulatory radiation limits will be significantly reduced and because the reactor hall will be exposed to tritium by permeation and releases during maintenance of the coolant, fueling, vacuum and tritium systems. Some activation may also result from neutron streaming, and particulate matter. Use of remote maintenance equipment will permit maintenance with a minimal cool-down or clean-up period, and may permit some maintenance operations during reactor operation. Other factors influencing the choice of remote maintenance include: 1) remote maintenance will be required for accident conditions, however it would not have to be as sophisticated, 2) remote technology will be available thru currently planned programs (HEF, etc.) and 3) the belief that for a properly designed machine, scheduled maintenance can be performed more rapidly than personnel suited for radiation protection.

The design philosophy being followed is to minimize the radiation levels within the reactor building; to design all components for complete remote maintenance, and to identify contact maintenance operations where personnel can safely be used with significant economic savings. Emphasis is being placed on designing to permit rapid replacement of scheduled maintenance items because Starfire is assumed to exist in a mature fusion economy where development work and operational experience have resulted in a predictable reactor with appropriate redundancy and reasonable component reliability.

All components within the reactor building are replaceable. Some are replaced on a scheduled maintenance basis while others are designed for the life of the plant and are replaced only in the event of failure. Items designed for the life of the plant include the overhead crane, TF coils, EF coils, coolant piping, reactor support structure and radiation shielding. The blanket assembly, impurity control components, rf launchers, pumps, valves, fueling mechanism, power supplies, etc. are replaced on a scheduled basis. Spares are provided for all components with expected high failure rates, so that as one part is removed a pretested replacement is available so reactor operation can commence while repairs to the damaged components are being made. The spares for the superconducting EF coils trapped below the TF coils are stored in place so reactor disassembly is unnecessary in event of a failure. These coils are designed for life of plant but the consequence of their failure suggests in place spares are prudent.

The number of different maintenance operations planned in the reactor building are minimized by using a component "remove and replace" approach. This permits each maintenance action to be preplanned and designed for use with simple push, pull, etc., operations. This approach increases the confidence in the speed of maintenance operations and simplifies maintenance equipment design requirements. Once the damaged or end-of-life components are removed from the reactor they are transported to a hot cell where more time is available for checkout, repair or disposal. The hot cell will have extensive maintenance capability for testing, component replacement, cutting, welding, machining, pinpoint leak location, and low-Z coating repair.

Redundancy is planned for reactor auxiliary subsystems to permit continued operation of the plant until a scheduled maintenance period or until the component can be replaced in-service. The particular components where redundancy is planned will be defined as the design progresses; however, current plans include redundant power supplies, vacuum pumps, rf launchers, some valves, pumps and fueling mechanisms.

Availability goals have been established as 75% for the complete plant including the reactor. This results in a 91 day per calendar year downtime. Allocations of permissible time-to-repair and time-between-failures have been made for major subsystems to serve as a basis for design of the components and maintenance equipment. The maintenance scenario incorporates the current utility practice of scheduling shutdowns annually for one month of maintenance and a 4 to 5 month shutdown every 5 to 10 years for turbine repair.

The Starfire reactor is being designed to conform with this current utility practice, however, the major shutdown is assumed to occur only every 10 years and last for 120 days (3 months). The combination of the annual and ten year shutdowns requires that 39 days of downtime be allocated to scheduled maintenance. Current utility experience with the balance of plant indicates that failures result in approximately 21 days of unscheduled outage annually. This leaves 31 days of unscheduled downtime that can be allowed for reactor subsystems. These allocations assume that both the balance of plant and reactor scheduled maintenances are performed in parallel while no overlap in scheduled and unscheduled maintenance is planned. A summary of these allocations is given below in Table I. It should be noted that a total of 52 days per calendar year is allocated to unscheduled maintenance while only 39 days is used for scheduled maintenance even though we have stated that most outages will be the result of scheduled shutdowns. This is in agreement with the fact that, in general, unscheduled failures will take longer to locate and repair. Convenient preventative maintenance and repair of redundant components is scheduled as part of the maintenance scenario during these unscheduled outages.

Table 1. Maintenance Scenario

Outage Type	Balance of Plant		Reactor*	
	Scheduled	Unscheduled	Scheduled	Unscheduled
Total Downtime Allocation (da/yr)	39	21	39	31

*Includes maintenance equipment and auxiliary reactor systems.

Reactor Maintenance Features

The reactor design configuration is shown in Figure 1. The design was developed so all components could be replaced in the event of failure and fault isolation is provided to the replacement level so that minimal time is required for identifying a failed component.

The design is being developed to keep the top and sides of the reactor clear for access by maintenance equipment. Components are also being combined where practical to minimize the number of assemblies and improve access. Examples of combined components include; the TF coil room-temperature dewar provides structural support for the EF coils and shield; and the shield provides the anti-torque frame and vacuum boundary.

The blanket is replaceable in 1/24 sectors of the torus. Each 1/24 sector incorporates an integral first wall, limiter, rf duct and air bearing pad that is removed with the blanket. The coolant is manifolded through separate loops for each 1/24th of the blanket to permit leak isolation to individual sectors. The helium coolant lines and the water coolant lines to the rf duct and limiter utilize mechanical disconnects. The life goal for limiter and rf duct is 4 years and the blanket life goal is 8 years. After four years the blanket sector is replaced. The used sector is refurbished in the hot cell by replacing the limiter, rf duct and low-Z coating. Periodic in-situ replacement of the low-Z coating may also be required.

Blanket module leak detection will be accomplished by sequentially reducing the pressure in individual blanket sectors and monitoring the change of the partial pressure of helium in the plasma chamber with a gas analyzer. This technique requires valves that isolate sectors from the primary coolant loop. Leak detection of the limiter first wall and rf launcher water system will also rely on reducing the system pressure of each sector sequentially and denoting changes in the detected leak rate. Leak detection of the shield system to the plasma chamber system will be accomplished by injecting helium into a cavity between redundant seals. The blanket leak detection system is dependent on the particular design that is developed and will be modified as necessary.

The shield is designed to last the life-of-plant and will be replaced only in event of unscheduled failures. A shield door is provided that permits access to the blanket. The door is sealed with redundant seals with intermediate pumping, that are shielded locally to reduce the radiation damage. The seals are replaced each time the door is opened. The basic shield consists of sectors welded together to form the vacuum boundary. Cutting and rewelding the poloidal seals is required if shield sector replacement is required. Access to the welds is from the shield interior and a permanent welder/cutter track is

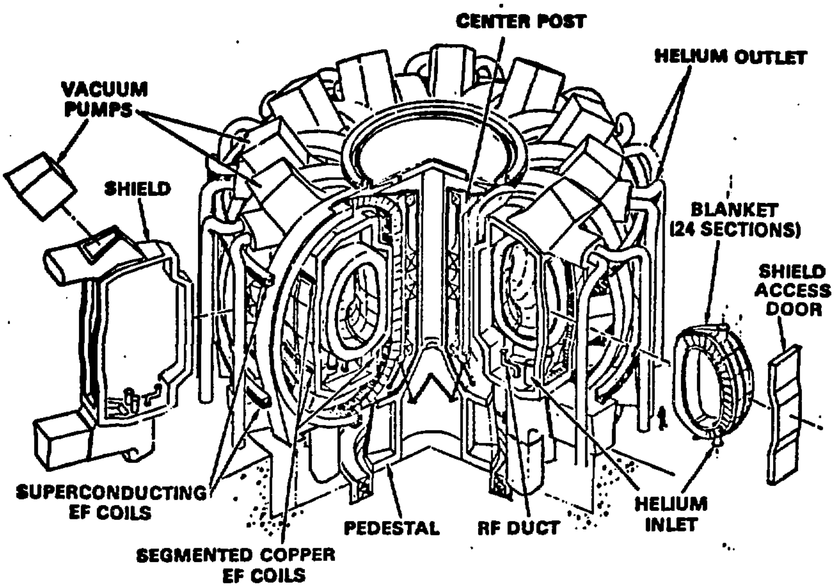

Figure 1. Starfire Reactor Design

installed at each joint. The modular design of the shield is shown in Figure 2. Redundant seals are provided at each joint to permit leak testing.

The TF coils are also life-of-plant components. They utilize a common welded dewar in the center post region. Coil replacement time is not significantly impacted by the welded dewar. A permanent welder/cutter track is also installed at this joint. Annealing of the TF coil is planned every 10 years to reduce the effects of radiation damage in the stabilizer.

The EF coils are also life-of-plant. EF coils inside the TF coil are copper and are segmented to permit removal. An elevation system is rovided to raise and lower the outer coils for access to the blanket. The external EF coils are superconducting. Those on the top and sides of the reactor can be removed for replacement. Spare EF coils are provided for those trapped below the TF coils. In event of failure the coil is cut out and the spare raised into position.

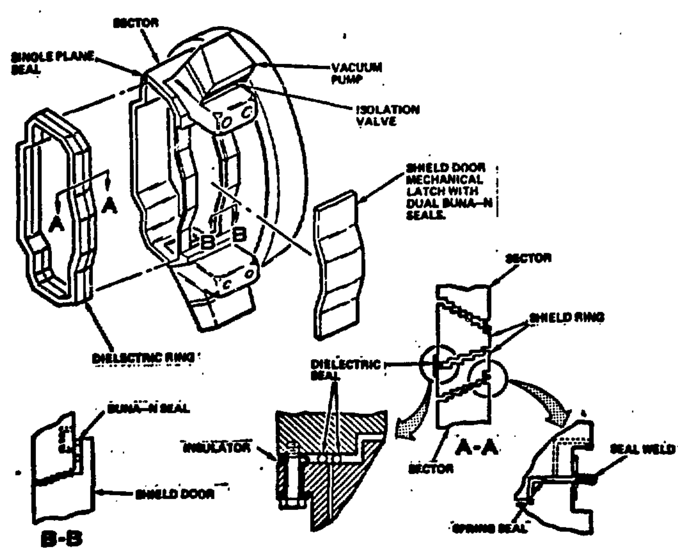

Figure 2. Shield Design

The vacuum system utilizes redundancy to improve the probability of continuous operation between scheduled maintenance periods. Twenty-four cryosorption pumps with isolation valves are provided of which approximately 20 are required for operation. External valves and pumps leading to the tritium processing system utilize redundancy.

The power supplies are assumed fully redundant and include a replacement capability during operation. The power supply systems are located outside the primary confinement building and can be repaired during plant operation.

Failed redundant heat transport system components, with exception of a few in-line valves, can be replaced during reactor operation using remote/hands-on maintenance equipment.

Reactor Building Maintenance Functions

A preliminary listing of scheduled maintenance functions is provided in Table 2. The number of scheduled actions at the reactor island have been held to a minimum. The scheduled maintenance functions of the auxiliary systems can, in part, be done during reactor operations.

The planned unscheduled maintenance functions include all component assemblies making up the reactor. The unscheduled items are shown in Table 3. Both tables 2 and 3 will be updated as the design progresses and the subsystems are better defined.

Table 2. Scheduled Maintenance Functions

Reactor Island

- o Shield door seal replacement
- o rf wave guide window replacement
- o Blanket sector replacement
- o Vacuum pump/isolation valve replacement
- o Fueling system replacement
- o TF coil annealing

Auxiliary Reactor Subsystems

- o Coolant loops
  - valve replacement
  - pump replacement
- o Power systems
  - electrical switch replacement
  - electrical energy storage component replacement
  - power conversion system replacement
- o Maintenance equipment replacement
- o Tritium processing

Table 3. Unscheduled Maintenance Functions (excluding scheduled maintenance functions)

- o Power lead replacement
- o Coolant line replacement
- o Heat exchanger replacement
- o EF coil replacement
- o TF coil replacement
- o Shield replacement/repair

Hot Cell Operations

The functions planned in the hot cell are listed in Table 4.

Table 4. Hot Cell Functions

- o Component testing
  - vacuum integrity
  - electrical function
  - configuration
  - leakage
- o Repair
  - cutting
  - welding
  - machining
  - cleaning
- o Reactor retrofit
  - blanket
    - o limiter replacement
    - o rf launcher replacement
    - o low-Z coating replacement
    - o module replacement
  - tritium processing system
  - vacuum system
  - coolant systems
  - cryogenic systems
  - power system
- o Maintenance equipment
- o Decontamination/disposal

Maintenance Time Allocations

A preliminary listing of the scheduled maintenance actions is shown in Table 5. The assumed critical path is shown with the presumption that all other maintenance actions can be accomplished in parallel operations. This listing will be updated as the program progresses. An increase in the number of items in the critical path can have significant impact on achieving our scheduled maintenance goals and would require a decrease in the replacement time. If subsequent analysis of the life of blanket module components (i.e., limiters) indicate lives less than 4 years, other maintenance concepts which permit replacement without blanket removal will be required.

The unscheduled maintenance item listing is shown in Table 6. The values shown for Mean-Time-To-Replace (MTTR) are assumed values based on past studies. The average downtime per year is then assigned to each subsystem based on the perceived relative reliability and complexity of each subsystem. The result is a permissible failure rate per calendar year. These values can then be used by subsystem designers to define the redundancy and design margin requirements for the subsystems. An accurate assessment of the actual failure rates can only be derived after subsystems are defined as to the number of components, redundancy provisions, the types of failure modes and failure rate per failure mode have been established. Our program will utilize historical data where possible to assess feasibility of meeting the requirements of Table 6. A conclusion that can be drawn after review of the table is that the time required for shutdown and startup must be kept to a minimum (2 days or less) to prevent using a large percentage of the unscheduled downtime simply to restart the burn.

Maintenance Facility

The selection of the "remove and replace" and "fully remote" maintenance approaches results in a rather large maintenance facility. The first iteration in a facility layout to sustain the needs of normal maintenance has resulted in a facility that

Table 5. Scheduled Maintenance

Action	Frequency (yr)	Replaced/ Outage (%)	Time-to-Replace (days)	Critical Path
Reactor shutdown and startup	Annual	N/A	2	*
Shield door seal replacement	Annual	25	2	*
RF wave guide window replacement	4	25	6	*
Blanket replacement (2 sectors)	Annual	25	20	*
Vacuum pump replacement	Annual	16	6	*
Fueling system replacement	Annual	25	6	
TF coil anneal	10	100	<120	(1)
Coolant loop component replacement	Annual	25	14	
Power system component replacement	Annual	50	14	
Maintenance equipment repair	Annual	N/A	N/A	

* These operations must be done sequentially, other operations are assumed to be performed during the critical path time frame.

(1) Compatible with 10-yr shutdown for 16 to 20 weeks for turbine repair.

covers some 2000 to 2500 m^2 of floor area. The major features of the facility are described as follows:

2 – Large component disassembly cells,
12 m tall x 12 m x 6 m
2 – small component repair cells,
4 m tall x 10 m x 6 m
1 – Storage bay (3 levels deep),
16 m wide x 18 m long x 20 m deep
2 – Reactor hall service entrances,
10 m tall x 6 m wide

These facilities are supplemented with interconnecting corridors, shielded walls and doors, equipment staging areas, equipment storage and repair, and hot cell operational areas. Additionally these facilities are equipped with cranes, hot cell windows and manipulators, lighting service/repair equipment and decontamination equipment. Scheduled functions covered with these facilities are:

1. Blanket Sector, including servicing of component connectors, seals, support structure and sensors. The major components are:
   - Limiters
   - First wall panels
   - Low Z coating
   - Blanket modules
   - RF grills and extensions
2. Vacuum pumps (scheduled replacement)
3. Shielding Sections (Unscheduled replacement)

Other components such as Klystrons (generator/launcher), coolant piping, vacuum, cryogentic and electrical connectors, structural members, etc. are of a lesser radiation problem and are handled in a second order maintenance category with separate equipment.

Major unscheduled maintenance operations have been considered for shield section, EF coil and TF coil replacement. Equipment will be provided even though they are designed for the life-of-plant.

A proposed maintenance facility layout is shown in Figure 3.

The layout shows the dual entrance to the reactor building through which the blanket sectors will travel. Each will have an ante-chamber for decontamination/isolation. Corridors connect the entrance with the two main disassembly cells, storage vault and outer equipment area. The smaller hot cells for first wall, blanket module, RF grille and vacuum pump maintenance are also attached to the corridor network to attain a smooth flow during multiple maintenance operations.

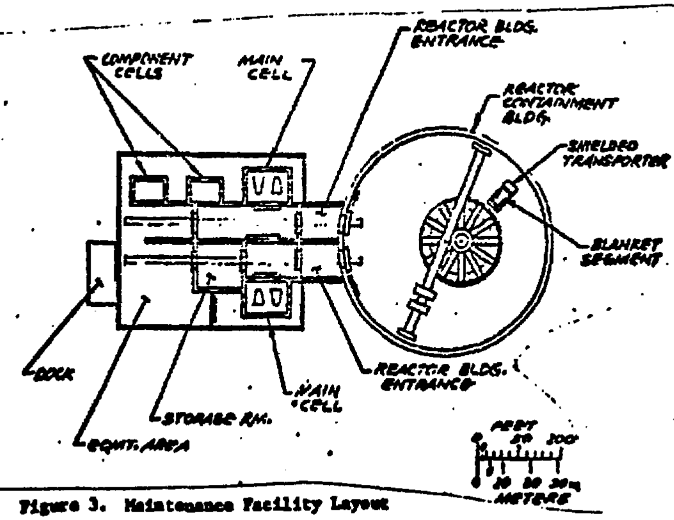

Figure 3. Maintenance Facility Layout