Availability improvement of ITER blanket remote handling system

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1. Introduction

The ultimate goal of fusion engineering is to make fusion energy available on the power grid, thus fusion power plants must have availabilities comparable to those of existing power plants. As fusion reactors are complex systems, they inevitably require dedicated analyses and engineering to achieve high availability [1,2]. Demonstrating fusion power production with high availability is one of the most important objectives of the ITER project. Accordingly, the ITER Organization has defined a detailed process to assess availability, known as RAMI analysis, and requires all ITER systems to be assessed through this process [3].

Demonstrating the feasibility of remote handling is also an important objective of the ITER project. The National Institutes for Quantum and Radiological Science and Technology is developing the blanket remote handling system (BRHS), one of the remote-handling systems of ITER. The BRHS will be deployed into the vacuum vessel to replace the blanket modules. RAMI analyses and improvements in availability are a must for the BRHS. In addition, the BRHS is specifically required to replace all 440 blanket first wall panels within two years.

In this paper, first we study the characteristics of fusion reactor remote-handling systems and methods to improve their availability, reaching our conclusion that preventive maintenance is a powerful method to improve availability (Section 2.1). Second, we propose a procedure to optimise the parameters of preventive maintenance (Section 2.2). Finally, we show how by using this procedure, the availability of the BRHS improved (Section 3).

2. Methods

2.1. Approach for fusion reactor remote-handling systems

The most important characteristic of fusion reactor remote-handling systems is the radiation environment in which they operate. Because of this 1) the lifetimes of components whose failures are caused by radiation, typically the insulation material, are shorter than those in normal environments; 2) preparations for system maintenance are time-consuming as humans cannot access the system because of the radiation and thus the systems must be withdrawn from their work spaces for maintenance and must also be decontaminated beforehand; 3) failures during operation may cause a situation where the failed system cannot be recovered as humans cannot access the system, which may cause the entire plant to be shut down. In summary, we need to consider failures caused by radiation, optimise the timing of maintenance, and reduce failures as much as possible. In addition, the dimensions of the ITER remote-handling systems are limited to the dimensions of the ports and configuration of the magnets, a characteristic common to both fusion reactor remote-handling systems and radiation environments.

Failures caused by a harsh environment such as radiation are categorized as ‘common cause failures’ [4] because radiation leads to failures of various components, even though the effect of radiation is different across the components. General defensive tactics to avoid common cause failures are listed in [5]. Tactics applicable to radiation...
are barriers, redundancy, preventive maintenance, and monitoring. Using barriers would prove difficult for remote-handling operations of fusion devices because the dimensional increases to shield from gamma rays would be impossible. Making a system redundant allows it to be withdrawn without a dedicated recovery operation in the case of failure, however, the system cannot continue with the remote-handling operation even if it has redundancy because the redundant components will have been irradiated up to the same cumulative dose as the failed component and will most likely fail in the same manner. Monitoring components for damage caused by radiation is an effective tactic, however, it is difficult to quantify and detect the degradation of insulation materials, which are typically damaged by radiation. Preventive maintenance, on the other hand, can be universally applied to all fusion reactor remote-handling systems.

2.2. Finding optimised parameters of preventive maintenance

The following parameters need to be defined when designing a preventive maintenance policy:

- Frequency of preventive maintenance;
- Components to be replaced;
- Numbers of spare parts.

The most straightforward target to optimise these parameters is minimising the number of failures. Since the number of failures does not take the differences in downtime of each failure into account, we propose that maximising inherent availability also be considered [6]. Inherent availability only considers downtime caused by failures, and thus maximising inherent availability clearly minimises downtime caused by failures. In addition, the ITER project requires each plant system to achieve target availabilities. However, minimising the number of failures and maximising inherent availability do not consider downtime for preventive maintenance. We propose introducing completion probability, which is the probability that the remote-handling system will complete a task within the required duration. Completing the required operation within the allocated duration so as not to affect the overall schedule and availability of the plant is a strict requirement of the ITER remote-handling systems. Preventive maintenance should be performed and inherent availability improved as long as completion probability does not decrease and remains at virtually 100%. In summary, we propose adopting the following targets to optimise the preventive maintenance parameters:

- Minimising failures;
- Maximising inherent availability;
- Maximising completion probability.

We created a procedure to survey for parameters that satisfy these three targets. This procedure defines the frequency of preventive maintenance based on the weakest components, which is necessary to minimise failures. To maximise completion probability, no additional preventive maintenance is introduced for the other components, and thus they are replaced only in the preventive maintenance defined by considering the weakest components. Our procedure is as follows.

[Step 1] Create a reliability block diagram (RBD) and perform an RBD analysis with no preventive maintenance and unlimited spare parts to identify the weakest components. Perform a parameter survey of preventive maintenance frequency for the weakest components and define their frequency.

[Step 2] Perform an RBD analysis with preventive maintenance only for the weakest components with the frequency defined in Step 1. Define other components to be replaced for preventive maintenance. Perform a parameter survey of preventive maintenance frequency of those components and define their frequencies.

[Step 3] Perform an RBD analysis with preventive maintenance for the defined components and estimate the operation times necessary to complete the required tasks. Perform an RBD analysis for the estimated duration with preventive maintenance and define the number of spare parts based on the expected numbers of failures.

The details of this procedure with respect to the BRHS are presented in Section 3.

3. Results

3.1. Reliability block diagram

The conditions of the analysis in this section are essentially the same as those of our previous analysis performed in [7], but failure distribution of the internal wiring has been changed to normal distribution with 25600-h MTBF as a result of irradiation tests [8]. The BRHS is required to replace all 440 blanket first wall panels within 2 years. To this end, the BRHS needs to achieve a 227-day uptime within the maximum operation time, 690 days, which is the simulation duration of Steps 1 and 2 performed in Section 3.2. All the simulations were performed using BlockSim based on the Monte Carlo method. In each analysis, a 690-day simulation was repeated 1000 times, and availability and number of failures were obtained as averages of 1000 simulation results. Completion probability was obtained based on the number of simulations in which the BRHS achieved a 227-day uptime during a 690-day simulation.

The RBD was created based on the functional breakdown of the BRHS as shown in Table 1 of [7]. The functions consist of physical components. Every component of the BRHS is assigned to a function. According to their failure mode, the components have reliability parameters: failure distribution function, Mean Time Between Failures (MTBF) and Mean Time To Repair (MTTR). Details of the reliability parameters are described in Table 2 of [7]. There are four failure modes: radiation, mechanical, electrical and software. The most dominant failure modes are applied to each component. Components that have radiation failure mode are cameras, umbilical cables, internal wirings, grease-containing components (bearings and reduction gears), motors and slip rings. The MTBF of the components are defined based on radiation tests, specifications provided by vendors, engineering judgement and ITER’s database. Applied distribution functions are the normal, lognormal and exponential distributions. The early failures, which can be found in the bathtub curve, are not considered because those failures should be found in the commissioning phase before operation, which all fusion remote-handling systems must undergo. Note that if the fresh components are not less likely to fail than older components, preventive maintenance will not improve the availability as much as presented in this chapter.

3.2. Applying proposed procedure

Here we apply our procedure proposed in Section 2.2 to the BRHS. [Step 1] The initial scenario, in which no preventive maintenance is performed and spare parts are unlimited, was analysed. Fig. 1 shows the expected number of failures of each component in the 690-day operation. The ReliaSoft’s Failure Criticality Index (RS FCI) is also shown. The RS FCI can be obtained from RBD analysis using BlockSim, and represents the percentage of times that a failure of a component caused a system failure [9]. Since a failure of every single component would cause the system to be down, the number of failures and the RS FCI indicate the same trend. The component having the largest expected failure is the umbilical. Fig. 2 shows the reliability of the operation. Reliability decreases rapidly after 4 months of operating time. Failures of the umbilical are considered to be the cause of the decrease in reliability since a 4-month operation time corresponds to the lifetime of the umbilical. Therefore, we ascertained that the weakest component is the umbilical and should be a target of preventive maintenance. The optimised frequency of preventive maintenance can be estimated to be
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