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Optimization of Allowed Outage Time and Surveillance Test Intervals

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1. Introduction

Technical Specifications (TS) are safety rules which define the limits and conditions to assure that the plant is operated in a manner that is consistent with the analyses and evaluations in the plant's Safety Analysis Report (SAR). TS requirements for a plant include the Limiting Conditions for Operation (LCOs) and Surveillance Requirements (SRs) to assure safety during operation [1].

LCOs define the Allowed Outage Time, or called down time, (D) for which a component or a train in a safety system can remain inoperable before an action is required, i.e., typically, plant shutdown. In another words, the plant is required to be brought into a safe operational state if faulty equipment cannot be restored within its D. The allowed outage time is used to repair or replace a failed or a degraded component, and sometimes, also to carry out scheduled maintenances. The intent of D is to provide adequate time to repair a failed component without incurring undue risk because of loss of function of the component.

The SRs prescribe periodic tests for detecting faults and verifying the operability of safety equipment. The interval between two consecutive tests is called the Surveillance Test Interval (T) [2]. The primary purpose of surveillance testing is to assure that the components of standby safety systems will be operable when they are needed in an accident. By testing these components, failures can be detected that may have occurred since the last test or the time when the equipment was last known to be operational [1].

The probability a system or system component performs a specified function or mission under given conditions at a prescribed time is called availability (A). Unavailability (U) as a risk measure is just the complementary probability to A(t). The increase of U means the risk is increased as well.

D and T have an important impact on components, or systems, unavailability. The extension of D impacts the maintenance duration distributions for at-power operations, making them longer. This, in turn, increases the unavailability due to maintenance in the systems analysis. As for T, overly-frequent surveillances can result in high system unavailability. This is because the system may be taken out of service often due to the surveillance itself and due to the repair of test-caused failures of the component. The test-caused failures include those incurred by wear and tear of the component due to the surveillances. On the other hand, as the surveillance interval increases, the component's unavailability will grow because of increased occurrences of time-dependent random failures. In that situation, the component cannot be relied upon, and accordingly the system unavailability will increase. Thus, there should be an optimal component surveillance interval in terms of the corresponding system availability.

This paper aims at finding the optimal T and D which result in minimum unavailability which in turn reduces the risk. The optimization of TS requirements is carried out based on minimal risk (unavailability). Three elements that contribute to component unavailability are integrated in one model. These contributors are failure on demand, failure during test, and unavailability due test and maintenance. Beside the optimization, this paper also discusses the interaction between D and T.

The organization of the paper will be as follows: Section 2 addresses the problem formulation where the objective function is derived. Application of two cases is provided in section 3. Applying the methodology in section 2 to find the values of optimal T and D for two components, i.e., safety injection pump (SIP) & turbine driven aux feedwater pump (TDAFP). Section 4 is addressing interaction between D and T. Finally, section 5 presents our discussion and conclusion.

2. Method

To model the unavailability of periodically tested stand-by components at time τ , the following model is used [3].

$$U_s = q_o + \left(1 - e^{-\lambda_S(\tau-\tau_l}\right) \quad (1)$$

Where q_o is failure probability per demand, λ the failure rate, and τ_l the last test moment. When $\Delta\tau = 0$ then the unavailability is equal to the time independent part q_o immediately after a test. By integrating equation 1 over a complete test cycle (T) this yields the mean unavailability as in Eq. 2

$$U_{s,mean} = q_o + 1 - \frac{1}{\lambda T}\left(1 - e^{-\lambda T}\right) \quad (2)$$

The expression 2 is addressing the unavailability due failure on demand for a standby component.

The unavailability of a component is dependent on the length of the test interval. Short test intervals lead to reducing unavailability at an actual demand, but the tested component may fail during the test which leads to that the component then becomes unavailable due to repair [3]. The unavailability due to maintenance for a periodically tested component is approximated by the following formula:

$$U_{\mathrm{t}} = (q_o + \lambda T)\left(\frac{D}{T}\right) \quad (3)$$

Where T is the test interval, and D the allowed outage time (maximum time for repair).

Maintenance activities lead to increasing in component unavailability. Two types of maintenance contribute to unavailability. Preventive maintenance activity which include surveillance test intervals. Another type is corrective maintenance due to observed failures. Corrective maintenance is a function of outage (repair) time. Formula below presents unavailability due to both maintenance types.

$$U_m = \frac{t}{T} + \lambda D \quad (4)$$

Where t is the test duration.

Quantification of the different contributions to the component unavailability is needed to derive the final function. The component unavailability U includes the contribution from equations 2, 3, and 4.The accumulation of these contributors gives the general description of total component unavailability as below

$$U = U_s + U_t + U_m \quad (5)$$

The key element of the mathematical modeling of the problem is a general unavailability model as a function of test interval and allowed outage time. The model will be developed by combining equations 2, 3 and 4 in one formula.

$$\mathrm{U} = q_o + 1 + \frac{1}{T}\left[q_o D + t + (2\lambda)DT - \frac{(1-e^{-\lambda T})}{\lambda}\right] \quad (6)$$

Using formula 6 we can calculate the optimal values of test interval and outage time.

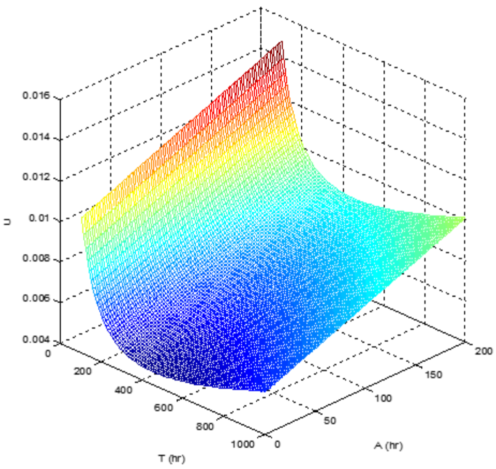

Fig. 1. Unavailability as a function of T and A.

By drawing Eq.6 in 3 dimensions, U as a function in D and T, we find that the unavailability decreased then increased which implies that there is an optimum value, herein the minimum unavailability as a measure for minimal risk. In the following section, calculations are carried out to find optimal T and D.

3. Application

The methodology described in Section 2 is applied herein for the optimization of the test intervals and allowed outage time of two safety systems components which are safety injection pump (SIP) and turbine driven auxiliary feedwater pump (TDAFP).

Table.1 Component unavailability parameters

	λ (h^{-1})	q_o	$MTTR$ (hr)	t (hr)
SIP	$5 * 10^{-5}$	10^{-3}	21.6	1
TDAFP	$3 * 10^{-4}$	$1.5 * 10^{-2}$	20.9	1

The mean time to repair (MTTR) is based on the Ulchin unit 3&4 allowed outage time extension report. Failure probability per demand (q_o) and failure rate (λ) are based on Ulchin unit 3&4 PSA report.

3.1 Surveillance test intervals optimization

To find the optimal test intervals using expression in formula 6, outage time is considered constant. In other words, Eq.6 is used as a function of T. Repair time used for calculation is given based on the historical record of the SIP and TDAFP operation and performance of Ulchin power plant. The MTTR of the SI pumps is 21.6 hours and MTTR of AF pumps is 20.9 hours. With the original D of 72 hours, this MTTR is about 30% of the allowed outage time.

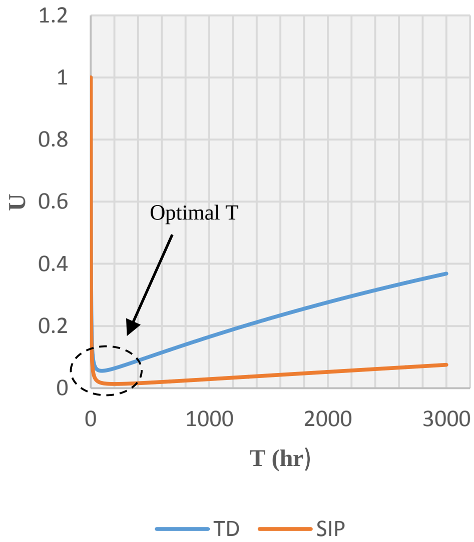

Fig. 2. Unavailability as a function of T.

From the risk based optimization point of view, the optimal test interval will be correlated with the minimum unavailability as a risk measure. Figure 2 presents the optimal values of test interval for SIP (T=203 hr) and TDAFP (T=94 hr).

3.2 Allowed outage time optimization

During an outage time, the risk level generally increases because of the loss of function of the component. The increase in risk level is the cause of the outage time risk contribution, as shown in Figure 3. Whenever a component goes down, there is an associated D risk contribution that needs to be controlled [1].

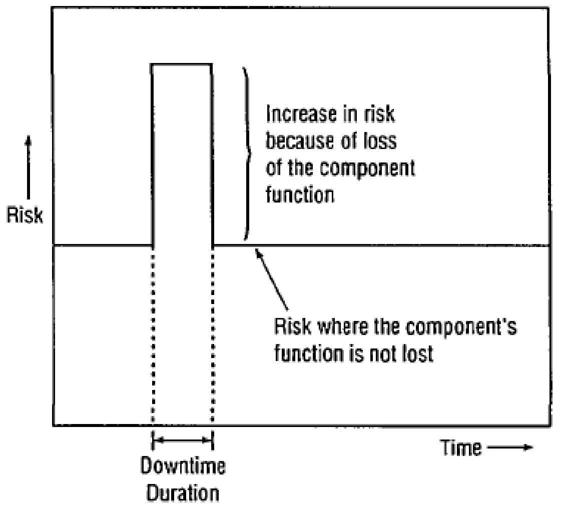

Fig. 3. The risk contribution associated with an allowed outage time [NUREG/CR-6141].

When Eq.6 (as a function of D) is applied to find the optimal value of allowed outage time, we find from Fig. 4 that there is no optimal value of D. The unavailability will keep increasing as D is getting increased. So, the best value of allowed outage time is the minimum as much as possible considering the adequate time for maintenance.

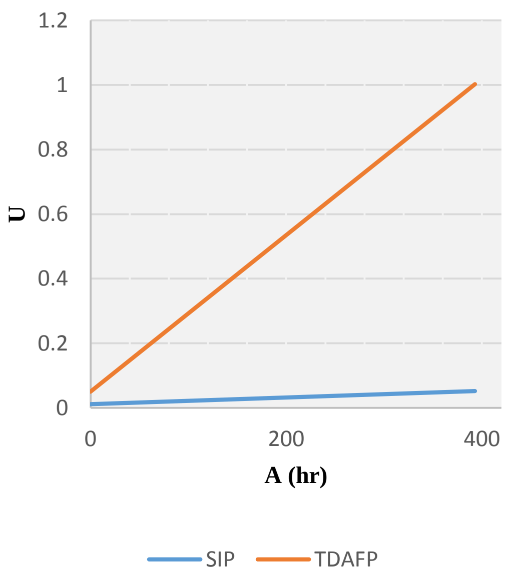

Fig. 4. Unavailability as a function of A.

4. The interaction between outage time and test interval

As discussed in section 3 that the relationship between unavailability and D is linear while the T relationship with unavailability is letter U shape. The relationship or interaction between D and T is addressed in this section.

The risk criterion set forth that the component's average unavailability should remain constant when D or T modification is required [4]. That criterion means for a given risk level U, T and D are tied in the sense that if D or T modification is studied, their contributions must be traded off to keep the same level of risk. Thus, an increase in D, that increases the U_t contribution, must be balanced by decreasing T to an appropriate U_s level to keep the risk level U_r constant.

$$U_r = U_s + U_t \quad (7)$$

From a mathematical point of view above relation can be expressed in terms of the D and T relation for a given U_r , which is obtained by simplifying and rearranging terms, to yield:

$$D = [U_r - \left(q_o + \tfrac{1}{2}\lambda T\right)/(q_o + \lambda T)]T \quad (8)$$

Expression (8) is known as the interaction function at component level and it depends on the risk level U_r and component characteristics (q_o, λ). Expression (8) is represented for a component (SIP) in illustration 5 for a constant risk level (U_r value).

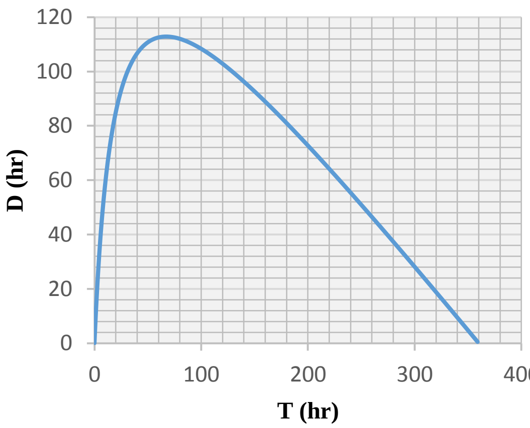

Fig. 5. Interaction function at component level.

Above expression (8) as shown in Fig. 5 can be used to find pairs (T,D) on the trade-off criteria, which satisfy that the risk is kept constant when one requirement in a couple (T,D) - set up by Technical Specifications - is intended to be modified. In addition, expression (8) can be used to optimize D and T requirements, given by TS, at least in the component level. Here, optimization means to change the surveillance test intervals requirement in order to minimize the risk level for an allowed outage time given. Thus, the top of the curve represents a couple (T, D) which minimize the risk for a D value given [5].

5. Discussion and conclusion

The methodology which was carried out in previous sections did not include some parameters which would affect the results.

A long allowed outage time implies a relatively larger risk to be incurred, but a shorter D may result in inadequate repair and/or unnecessary plant shutdown, both of which have risk implications. Also, test intervals may even have an adverse impact on safety because of their undesirable effects (e.g., test errors causing plant transients, or wearout of the equipment due to testing). In general, these undesirable effects will be reduced if the T is increased, because then fewer tests will be conducted. By extending the T, we also can obtain the additional benefit of reducing resources on testing. However, an important disadvantage of T extension is that the fault-exposure time, i.e., the time during which the component will be subject to failures during standby (standby time-related failures), will correspondingly increase as the T increases.

For above reasons, the results we got of T e.g. (203 hr ≈ 0.3 month) is too small when compared with the current T (3 months). So the extension of D and T is desired by utilities and regulators.

Further study on optimization can address the impact of some factors such as cost and human errors. Another study would be carried out at system level.

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