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Time-dependent unavailability of equipment in an ageing NPP: Sensitivity study of a developed model

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ABSTRACT

A previously developed model for assessing time-dependent unavailability of ageing safety equipment is briefly presented at the beginning of this paper. One of the essential features of this model is that it simultaneously considers the effects of ageing, testing, preventive and corrective maintenance and overhaul.

The main focus of this paper is aimed towards performing sensitivity analysis of the developed model. A component level resolution is selected as the basis for performing the analysis. Investigation of the influence of different component-relevant input parameters on the calculated equipment unavailability is the goal of the analysis. The dependency of the calculated component unavailability on the corresponding surveillance test interval is of a particular interest. The focus is being given to one of the specifics of the developed model – the aggregation approach, i.e. the aggregation limiter that copes with the breach of computational memory.

The results show that a relatively low value of the aggregation limiter implicates discrepancies in the shape of the component unavailability as a function of the surveillance test interval in some cases. These discrepancies are being substantially reduced with the increase of the value of the limiter. Consequently, longer computational time and higher memory requirements are directed.

1. Introduction

Reducing the unavailability of safety systems in nuclear power plants (NPP) by utilizing the merits of the probabilistic safety assessment (PSA) methodology is one of the prime goals in the nuclear industry. By developing and applying equipment time-dependent unavailability models different phenomena can be described in more details. Hence, the higher accuracy of such time-dependent models which implicate the provision of more realistic NPP risk modelling [1–4]. In that sense, test and maintenance (T&M) activities in NPPs are acknowledged as an important potential of risk [5]. The number of NPPs that are approaching the end of their life cycle is increasing. About 20% of all the power reactors operating worldwide have been in operation for more than 30 years, and almost 50% have been in operation for 20–30 years [6]. Moreover, a rather limited number of new NPPs are being put into operation. In view of this trend, many countries are giving a high priority to extending the operation of NPPs beyond the operational deadline originally anticipated [6]. Explicit consideration of ageing effects within the NPP equipment unavailability modelling would suit to more detailed risk modelling and would identify, qualitatively and quantitatively, the effects the ageing might have on the general plant risk profile [4].

The issue of modelling of time-dependent unavailability of certain equipment and consequently, the optimization of the related T&M activities is especially important in the nuclear industry. Most of the work encountered in the literature on this issue [7–18] does not address component ageing. The impact of component ageing in the T&M optimization policies is considered in [19–24].

The essential feature of the previously developed model [4] is that it integrates the effects of performing surveillance tests, preventive maintenance (PM), and corrective maintenance (CM), i.e. repair, as well as absolute overhaul, i.e. component replacement. Simultaneously, the model incorporates the effects of ageing on the calculated time-dependent unavailability.

Sensitivity analysis of the model, presented within this paper, is performed on component level. Firstly, the time-dependent component unavailability of selected equipment is calculated using the model. Then, the calculated unavailability is analysed as a function

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of the corresponding surveillance test interval (STI). The partially non-convex, non-smooth shape of this function for some components, which is associated with local extremes, is discussed. In that sense, one of the specifics of the time-dependent unavailability model is the aggregation approach which applies for coping with the potential breach of the computational memory constraints. Namely, the model incorporates the provision of introducing multiple failure rates, existing simultaneously, each one with its probability of existence. The number of these failure rates rises exponentially with time. After a certain extent, controlled by an aggregator parameter, the corresponding simultaneously existing failure rates are being aggregated. Thus, the "discrepancies" of the dependency of the calculated unavailability on its STI for a specific component is reasoned via the value of this aggregator parameter and sensitivity analysis is being performed. The results implicate the effect which the assignment of the aggregator limiter value might pose on the calculated component unavailability.

2. Model

As it was discussed in the introduction, this chapter presents the outline of the previously developed time-dependent unavailability model [4], for which the sensitivity analysis, which is the objective of this paper, is performed in Section 3.

The time-dependent failure rate $\lambda(t)$ is of interest herein for the purpose of modelling the ageing effects on equipment unavailability. The linear ageing model:$\lambda(t) = \lambda_0 + \alpha \cdot t$ is assumed for modelling equipment ageing, where λ_0 is the initial failure rate, and α is the ageing rate. As discussed earlier, technical specifications (TSs) require surveillance testing to assure certain level of safety systems availability. Besides the positive effects in terms of detecting equipment failures, the surveillance tests may adversely impact safety due to their undesirable side effects, such as wear-out due to frequent testing. The test-caused component degradation, seen as a progressive wear-out due to frequent testing, is modelled by defining the equipment demand failure probability as a function of number of tests performed n, i.e. $\rho = \rho(n,t) = \rho_0 + n(t) \cdot \beta = \rho(t)$, where ρ_0 is the initial demand failure probability, $n(t)$ is the number of tests performed on the equipment under consideration until time t and β is a test degradation factor [25,26]. Therefore, the time-dependent unavailability on component level $Q_{comp}(t)$ is modelled with the following expression:

$$Q_{comp}(t) = \underbrace{\rho_0 + n(t) \cdot \beta}_{first\ term\ =\ \rho(t)} + \underbrace{(1-\rho(t)) \cdot \left(1 - e^{-\int_0^t \lambda(\tau) d\tau}\right)}_{second\ term},$$
$$\text{such that} \quad T_i > t \geq 0\ (within\ one\ STI), \tag{1}$$

where T_i is the duration of one STI. The first term on the right-hand side of Eq. (1) models component probability of failure to start upon demand. The second term models the probability of failure due to random failure at a time t of successfully started equipment. In its form, Eq. (1) models the time-dependent component unavailability as a function of the number of tests performed on the component and their adverse effect along with the inclusion of ageing effects. By setting $Q_{comp}(t) = 1$ for $T_t > t \geq 0$ (withinoneSTI), a provision is made to account for the test-caused risk contributor associated with the downtime T_t needed to perform the test.

The PM, suggests that the incline of the equipment failure rate $\lambda(t)$ is being gradually reduced following a predetermined PM schedule with fixed periodicity $\widehat{T_M} = T_{M_{(i+1)}} - T_{M_i}$ where $T_{M_{(i+1)}}$ and T_{M_i} are time points at which two consecutive PM activities take place. Given the linear ageing model considered herein and assuming constant ageing rate reduction factor $\chi:\ \mathbb{R}, \in [0,\ 1]$ the component failure rate $\lambda_{PM_n}(t)$ after the n^{th} PM, i.e. for $t \in [T_{M_n}, T_{M_{(n+1)}}]$, will be:

$$\lambda_{PM_n}(t) = \lambda_{PM_{n-1}}(T_{M_n}) + (1-\chi)^n \cdot \alpha \cdot (t - T_{M_n})$$
$$= \lambda_{PM_0}(T_{M1}) + \sum_{j=1}^{n-1} (1-\chi)^2 \cdot \alpha \cdot \widehat{T_M} + (1-\chi)^n \cdot \alpha \cdot (t - T_{M_n}). \tag{2}$$

Eq. (2) presents the expression for calculating the time-dependent failure rate on component level, incorporating the PM effect together with the ageing effects (the linear ageing model). The preventive maintenance within this model is assumed to be an imperfect maintenance, i.e. which brings the equipment under consideration into a "better" condition than bad-as-old (BAO) PM policy and "worse" condition than good-as-new (GAN) PM policy. It is modelled via the factor $\chi:\ \mathbb{R}, \in [0,\ 1]$ which is seen as an ageing rate reduction factor due to preventive maintenance.

The CM activities are modelled as imperfect. The component is considered to undergo imperfect repair immediately after the surveillance testing, provided the considered component has experienced a failure in the last STI. The main idea behind the CM model herein is the assumption that the repair reduces the failure rate for a constant factor $\xi:\ \mathbb{R}, \in [0,\ 1]$ proportionally to the current failure rate $\lambda_{T^+_{CM,n}}$ at the moment the repair is finished after the n^{th} STI ($T^+_{CM,n}$) and relatively to the initial failure rate λ_0, i.e.:

$$\lambda_{T^+_{CM,n}} = \left(\lambda_{T^-_{CM,n}} - \lambda_0\right) - \xi \cdot \left(\lambda_{T^-_{CM,n}} - \lambda_0\right) + \lambda_0 = (1-\xi) \cdot \left(\lambda_{T^-_{CM,n}} - \lambda_0\right) + \lambda_0$$
$$\text{such that } T_{CM,n} = [T_F + (n-1) \cdot T_i + T_t + T_r], \tag{3}$$

where, T_t is the testing time, T_F is the time to first surveillance test, and T_r is the repair time, i.e. the time needed to perform CM. Fig. 1 depicts, as an example, the effects of the PM solely and the combined effect of PM and CM on a selected sample component. The red line represents the time-dependent failure rate $\lambda_{max}(t)$ not considering any PM or CM while the blue line presents the time-dependent failure rate $\lambda_{min}(t)$ given the effects of the PM activity solely. The grey line presents the time-dependent failure rate $\lambda_{min}(t)$, given the simultaneous effects of the PM and CM activities, such that the CM is applied in each STI (i.e. under assumption that the considered equipment experiences failure in each STI). The ageing effect is, of course, considered in all three cases as well. The probability, whether given component will experience failure during certain STI, is also modelled [4]. Two (2^1) different failure rate time-dependent functions are possible after the first STI for a given equipment, 2^2 after the second STI,..., 2^n after the n^{th} STI, as presented as an example on Fig. 2. The probability $\varepsilon_{i,j}$ whether the equipment will experience failure solely due to a random failure during certain STI $[T_{i,(n)}, T_{i,(n+1)}]$, i.e. $[T_{CM,i},\ T_{CM,i+1}]$ is considered within the model in accordance with Eq. (1). Thus:

$$\varepsilon_{i,j} = 1 - e^{-\int_{T_{CM,n}}^{T_{CM,(n+1)}} \lambda_{i-1,j}(t) dt} \quad j = 1, 2, \ldots, 2^n. \tag{4}$$

where $\varepsilon_{i,j}$ is the probability of existence of the j^{th} failure rate function after the i^{th} STI, i.e. $\lambda_{i,j}(t)$.

The probabilities of occurrence $\varepsilon_{i,j}$, i.e. existence of the specific failure rate $\lambda_{i,j}(t)$ are calculated at the end of each preceding STI, i.e. after the first CM:

$$\varepsilon_{1,2} = 1 - e^{-\int_0^{T_{CM,1}} \lambda_{0,1}(t) dt},$$
$$\varepsilon_{1,1} = 1 - \varepsilon_{1,2}, \tag{5}$$

such that $\varepsilon_{1,1} + \varepsilon_{1,2} = 1 \varepsilon_{1,1} + \varepsilon_{1,2} = 1$.

Then, after the second CM, 2^2 different failure rates $(\lambda_{2,1}(t); \lambda_{2,2}(t); \lambda_{2,3}(t); \lambda_{2,4}(t))$ with their corresponding probabilities of occurrence $(\varepsilon_{2,1}; \varepsilon_{2,2}; \varepsilon_{2,3}; \varepsilon_{2,4})$ are possible:

$$\varepsilon_{2,2} = \varepsilon_{1,1} \cdot \left(1 - e^{-\int_{T_{CM,1}}^{T_{CM,2}} \lambda_{1,1}(t) dt}\right),$$