Nuclear Engineering and Design 246 (2012) 128–135

Contents lists available at SciVerse ScienceDirect

Nuclear Engineering and Design

journal homepage: www.elsevier.com/locate/nucengdes

Uncertainty and sensitivity analyses for age-dependent unavailability model integrating test and maintenance

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ARTICLE INFO

Article history:
Received 4 April 2011
Received in revised form 1 September 2011
Accepted 3 October 2011

ABSTRACT

The interest in operational lifetime extension of the existing nuclear power plants is growing. Consequently, plants life management programs, considering safety components ageing, are being developed and employed. Ageing represents a gradual degradation of the physical properties and functional performance of different components consequently implying their reduced availability. Analyses, which are being made in the direction of nuclear power plants lifetime extension are based upon components ageing management programs. On the other side, the large uncertainties of the ageing parameters as well as the uncertainties associated with most of the reliability data collections are widely acknowledged.

This paper addresses the uncertainty and sensitivity analyses conducted utilizing a previously developed age-dependent unavailability model, integrating effects of test and maintenance activities, for a selected stand-by safety system in a nuclear power plant. The most important problem is the lack of data concerning the effects of ageing as well as the relatively high uncertainty associated to these data, which would correspond to more detailed modelling of ageing.

A standard Monte Carlo simulation was coded for the purpose of this paper and utilized in the process of assessment of the component ageing parameters uncertainty propagation on system level. The obtained results from the uncertainty analysis indicate the extent to which the uncertainty of the selected component ageing data set influences the performed unavailability calculations on system level, as well as they present sensitivity insights on the equipment. Sensitivity analyses were additionally conducted. The obtained results indicate sensitivity insights associated to the coded Monte Carlo simulation itself as well as component ageing effects sensitivity judgements related to the selected system unavailability calculation.

1. Introduction

The unavailability reduction of safety systems and consequently the nuclear power plant (NPP) itself, by utilizing the probabilistic safety assessment (PSA) methodology, is one of the prime goals in the nuclear industry. Thus, improving NPP safety is achievable through improvement of the reliability and availability of its components, which, on a deeper resolution level, is a function of their age throughout plant operational life (Martorell et al., 1999). Ageing represents a gradual degradation of the physical properties and functional performance of different components consequently implying their reduced availability. Components ageing depend strongly on the test and maintenance (T&M) activities they are subjected to.

An ever-increasing number of NPPs and their safety-related equipment are approaching their initially intended lifetime deadline. Therefore, the equipment ageing phenomena, seen as a safety-related issue in the nuclear industry, is being paid a great deal of importance in the last two decades. It is reasonable to expect that the ageing phenomena, exhibited as availability and reliability reduction of specific SSCs, may impact the general plant safety. The loss or even a functional capability reduction of some of the most risk-important SSCs can cause some of the multiple levels of protection, defined by the defence-in-depth strategy to deteriorate and by that reduce plant safety. In order to maintain the originally defined NPP safety margins, the ageing-related impact on it must be properly addressed and managed (IAEA, 1990). A lot of scientific work has been done on the subject of studying the effects of ageing NPP equipment. Studies on degradation of various safety-related

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doi:10.1016/j.nucengdes.2011.10.002

equipment such as different containment and concrete structures, piping, instrumentation and control equipment, different stainless steel components, etc., due to ageing-related effects as well as methods for assessment of ageing and ageing management programs are just a part of wide set of researches and studies associated to the NPP equipment ageing (Blahoianu et al., 2011; Cicero et al., 2009; Hashemian, 2010; Kobayashi, 2002; Michel et al., 2001; Naus et al., 1996, 1999; Scott et al., 1992; Vesely and Walford, 1988; Volkanovski, 2011; Wang et al., 2010).

For that purpose, NPPs equipment ageing programs were commenced by the US Nuclear Regulatory Commission (USNRC). One of them was the Nuclear Plant Aging Research (NPAR) Program (USNRC, 1991). The NPAR program was conducted by the Office of Research of Nuclear Regulatory Commission (Vesely, 1992). The explicit consideration of the risk effects of ageing, by allowing component failure data to be evaluated for ageing effects and associated risk implications, has been an important feature of the NPAR. By the explicit consideration of the implications the component ageing might have on plant safety, different ageing contributors can be prioritized respective to their risk importance. Ageing of single components and simultaneous ageing of multiple components exhibited in data can be and should be evaluated for their risk effects. Since the risk effects of ageing are not necessarily additive, the risk effects of ageing of a single component can be insignificant, but the same ageing exhibited by several components can be highly risk significant. The risk significant ageing effects exhibited in data are of high priority and their causes need to be evaluated to assure that research programs and ageing management programs focus on these causes. On the other hand, the lack of equipment ageing data as well as the uncertainty associated with them is widely acknowledged problems. Ageing data uncertainty may implicate under- and/or overestimation of the unavailability of a system in the process of risk-informed decision-making (RIDM), e.g. risk-informed T&M optimization (Kancev and Cepin, 2011a,b). Consequently, the need of incorporating ageing data uncertainties arises in the context of the mentioned RIDM process, as it is important for the decision-maker to be able to estimate how uncertain the results are and how the uncertainty associated with these ageing data is propagated in the model.

Most of the work encountered in the literature on risk-informed optimization problems does not consider ageing data uncertainty analysis. Typical uncertainties to be considered are different parameter and model uncertainties associated with system design, which define the system reliability allocation (Marseguerra et al., 2005; Martorell et al., 2007; Painton and Campbell, 1995; Rocco et al., 2003; Volkanovski and Cepin, 2011) as well as uncertainties associated with T&M activities that govern the system availability and maintainability characteristics (Bunea and Bedford, 2002; Marseguerra et al., 2004a,b; Rocco et al., 2000).

This paper addresses the consideration of ageing data uncertainties in an age-dependent unavailability model. This model, which was previously developed (Kancev and Cepin, 2011a) and substantially improved (Kancev and Cepin, 2011b), was utilized herein in its improved form. The model presents an analytical approach for calculating system unavailability with simultaneous consideration of component ageing, testing strategy and effects of T&M activities. The analytical system unavailability is derived as a function of the surveillance test interval (STI) of the case study equipment. A standard safety system of a commercial nuclear power plant is selected as a case study. The objective of the work is to assess the implications of the selected ageing data uncertainty on the system unavailability calculations. For that purpose, a Monte Carlo (MC) simulation is used in order to study and assess uncertainty propagation on system level. Given the analytical system unavailability model is a function of the test interval, two specific cases are considered and compared. In the first case, the system unavailability is calculated for the test interval specified in the surveillance requirements (SRs), which are defined within the technical specifications (TSs) associated to the studied case study system. The second case comprises system unavailability calculation for a test interval derived as an optimal one in the course of a previous study (Kancev and Cepin, 2011b). Probability density functions (PDFs) of the mean system unavailability for these two relevant cases are calculated and compared. The results gained are indicating higher uncertainty impact on the calculated system unavailability in the first case. Additionally, three different sensitivity analyses are performed. The results obtained from the sensitivity analyses identify sensitivity insights related to the application of the MC simulation code itself as well as sensitivity understandings regarding the ageing effects on the case study equipment in the process of calculating system unavailability.

2. The analytical age-dependent unavailability model and its case study application

Components are the smallest functional parts comprising a system. For the unavailability analysis herein, each component is seen as an entity which is not further subdivided. Analysis starts with the identification of a component, its critical failure modes, and collecting component data, which has to correspond to selected probabilistic models for calculation of component unavailability.

The key element of the mathematical modelling of the problem is a general unavailability model as a function of STI, calculating the mean standby component unavailability including contributions of test and repair (Cepin, 2002; Cepin and Mavko, 1997; Martorell et al., 2000; Vaurio, 1980):

$$Q_{\text{mean}} = \rho + \frac{1}{2}\lambda_0 T_i + \frac{T_t}{T_i} + (\rho + \lambda_0 T_i)\frac{T_r}{T_i} \tag{1}$$

where Q_{mean} is component mean unavailability; T_t is test duration; T_r is mean time to repair; ρ is failure probability per demand; λ_0 is standby failure rate; and T_i is surveillance test interval (STI).

Eq. (1) addresses the non-ageing scenario where the failure rate λ is constant and small. It is assumed that $\lambda_0 t < 0.1$, where t is the time since the last test (Kancev and Cepin, 2011b; Samanta et al., 1994). The first term on the right-hand side of Eq. (1) addresses the contribution of the failure probability per demand in the mean component unavailability. The third term stands for the contribution of testing activities in the mean unavailability. The component is supposed to be inoperable with probability equals to unity, herein. The fourth term stands for the contribution of repair in the mean component unavailability. It represents the unavailability contribution due to detected component downtimes. The model assumes that the maintenance activities are chronologically placed immediately after the test in case a component failure is detected. The second term on the right-hand side of Eq. (1) comprises the failure rate contribution. It represents the average unavailability contribution due to undetected component downtimes and is derived in the utilized form as a result of certain assumptions (Samanta et al., 1994). Namely, if we assume negligible T_t and T_r in comparison with T_i, any repair is carried out immediately after a test, as well as negligible test inefficiencies in a way that the component unavailability at the end of the test is zero (repair same-as-new is considered herein), the time-dependent probability for a random failure, $q(t)$, then rises according to the formula:

$$q(t) = 1 - e^{-\lambda_0 t} \approx \lambda_0 t \quad \text{assuming} \quad \lambda_0 t < 0.1 \tag{2}$$

where t is the time since the last test.