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Unavailability model for demand-caused failures of safety components addressing degradation by demand-induced stress, maintenance effectiveness and test efficiency

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ABSTRACT

The reliability, availability and maintainability (RAM) modelling of safety equipment has long been a topic of major concern. Some RAM models have focused on explicitly addressing the effect of component degradation and surveillance and maintenance policies, searching for an optimum level of the safety component RAM by adjusting surveillance and maintenance related parameters. As regards the reliability contribution, these components normally have two main types of failure mode that contribute to the probability of failure on demand (PFD): (1) by demand-caused and (2) standby-related failures. The former is normally associated with a demand failure probability, which is affected by the degradation caused by demand-related stress. Surveillance testing therefore not only introduces a positive effect, but also an adverse one, which it compensates by performing maintenance activities to eliminate or reduce the accumulated degradation. This paper proposes a new model for the demand failure probability that explicitly addresses all aspects of the effect of demand-induced stress (mostly test-induced stress), maintenance effectiveness (PAS or PAR model) and test efficiency. A case study is included on an application to a typical motor-operated valve in a nuclear power plant.

1. Introduction

The safety of nuclear power plants (NPPs) depends on the availability of safety-related components that are normally on standby and only operate in the case of a true demand. The probabilistic risk assessment (PRA) of an NPP normally considers a basic unreliability model for these safety-related components, which usually have two main types of failure modes that contribute to the probability of failure on demand (PFD): (1) by demand-caused and (2) standby-related failures. The former is often associated with a demand failure probability (ρ), and the latter with a standby failure rate (λ). Both are generally associated with constant values in a standard PRA, i.e. ρ_0 and λ_0 respectively, which do not take into account the component degradation due to demand-induced stress and ageing.

However, both failure modes are often affected by degradation such as demand-related stress and ageing, which cause the component to degrade and ultimately to fail. Maintenance and test activities are performed to control degradation and the unreliability and unavailability of such components, although this has both positive and negative effects.

Early studies reported in [1,2] have provided a well-organized foundation for the positive and adverse effects of testing these components, accounting for both by demand-caused and standby-related failure modes. Kim et al. (1991) [1] proposed a well-organized foundation to account for ageing and the positive and adverse effects of testing the components in modelling demand failure probability and standby failure rate, which represents a more realistic unreliability modelling of safety components. Kim et al. (1994) [2] later proposed a simplification of the earlier unreliability model, which can be formulated as follows:

$$u_R(n,t') = \rho(n) + \int_{nT}^{nT+t'} \lambda(n,u)\mathrm{d}u \qquad \text{for } t' \in [0,T] \tag{1}$$

being the demand-caused unreliability contribution

$$\rho(n) = \rho_0 + \rho_0 p_1 n \tag{2}$$

and the standby-related unreliability contribution:

$$\lambda(n,u) = \lambda_0 + \lambda_0 p_2 n + \alpha v \qquad \text{for } v \in \left[0,\ nT + t'\right] \tag{3}$$

where,

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Acronyms and notation

BAO	bad as old
GAN	good as new
MOV	motor operated valve
NPP	nuclear power plant
PAR	proportional age reduction
PAS	proportional age set-back
PFD	probability of failure on demand
PSA	probabilistic safety analysis
RAM	reliability, availability, maintainability
α	linear ageing rate
t	chronological time
t'	time elapsed since the last test
t_D	chronological time at which the initial component unreliability is doubled
v	time elapsed since the last overhaul point
T	test interval
η	test efficiency
M	preventive maintenance interval
m	preventive maintenance number m
m_D	preventive maintenance at which the initial component unreliability is doubled
m*	preventive maintenance at which the component is replaced by a new one
ε	preventive maintenance effectiveness
L	replacement interval (overhaul maintenance)
$n(t)$	accumulated number of demands at time t
$n_{TD}(t)$	number of surveillance test performed up to time t
ρ_0	residual demand failure probability
p_1	test degradation factor associated with demand failures
p_2	test degradation factor associated with standby failures
$f(t)$	degradation function associated with demand-related stress
$f_m(t)$	time-dependent evolution of the degradation function of the component over the period between maintenance m–1 and m
f_m^+	time-dependent degradation function immediately after maintenance m
f_m^-	time-dependent degradation function immediately before maintenance m
$\rho(f)$	time-dependent demand failure probability
$\rho_m(f)$	time-dependent evolution of the demand failure probability over the period between maintenance m–1 and m
ρ_m^+	time-dependent demand failure probability immediately after maintenance m
ρ_m^-	time-dependent demand failure probability immediately before maintenance m
ρ_m	averaged demand failure probability between maintenance activities m–1 and m
ρ^*	averaged demand failure probability over the component useful life, i.e. over the renewal period L
τ	downtime for testing
σ	downtime for preventive maintenance
μ	downtime for corrective maintenance or repair
θ	downtime for replacement or renewal
$u_R(t)$	time-dependent unreliability of the component
$u_{R,\,m}(t)$	time-dependent evolution of the component unreliability over the period between maintenance m–1 and m
$u_{R,m}^+$	time-dependent component unreliability immediately after maintenance m
$u_{R,m}^-$	time-dependent component unreliability immediately before maintenance m
$u_{R,\,m}$	averaged unreliability over the period between maintenance m–1 and m
u_R	unreliability contribution to the component averaged unavailability over the component useful life, i.e. over the renewal period L
u	total averaged unavailability
u_T	averaged unavailability contribution due to testing
u_M	averaged unavailability contribution due to performing preventive maintenance
u_C	averaged unavailability contribution due to performing corrective maintenance
u_O	averaged unavailability contribution due replacement or component renewal

n = number of test performed on the equipment at chronological time t
T = test interval
t’ = time elapsed since the last test
v = time elapsed since the last overhaul point
ρ_0 = residual demand failure probability
p_1 = test degradation factor associated with demand failures
p_2 = test degradation factor associated with standby failures
λ_0 = residual standby time-related failure rate
α = aging factor associated with ageing alone

Eqs. (1) to (3) represent the unreliability model that can estimate the probability of failure on demand (PFD) of a safety component, considering both failure modes on demand, i.e. by demand and standby-related, and at the same time integrates component degradation due to test-induced stress and linear ageing. It also addresses the positive effect of testing, i.e. whether the test is one hundred per cent effective in detecting both demand-caused and standby-related failures.

However, this model does not take into account other important positive and negative effects on the component unreliability, such as: (1) the positive effect of maintenance activities as a function of their effectiveness in managing component degradation due to demand-induced stress and ageing, (2) the negative effect of test inefficiency in detecting failures, (3) demand-induced stress other than that due to testing, e.g. real demands.

As regards the standby-related failure mode, some studies have found that the standby failure rate of a safety component is affected by both demand-induced stress and ageing. Thus, Martorell et al. (1999) [3] provided an age-dependent reliability model associated only with standby-related failures that explicitly takes into account the effect of equipment ageing and the positive and negative effects of maintenance activities founded on imperfect maintenance modelling. Martón et al. (2015) [4] recently proposed an approach to modelling the unavailability of safety-related components associated with standby-related failures that explicitly addresses all aspects of the effect of ageing, maintenance effectiveness and test efficiency. These models do not take into account the explicit degradation effects due to demand-induced stress. Other authors have proposed alternative approaches to modelling the effect of ageing and test and maintenance activities [5-8].

As regards the demand-caused failure mode, this probability of a safety component is normally considered to be mainly affected by demand-induced stress, e.g. due to true demands, proof tests and others. The demand-induced stress is therefore modelled with a stochastic degradation jump in Refs. [9-12], without accounting for test-induced degradation. These studies consider that random shocks occur according to a Non Homogeneous Poisson Process, leading to the immediate failure of the component. Torres Echeverría et al. (2009, 2011) [13,14] provided a model to address the effects of test strategies on the probability of failure on demand for safety instrumented systems. And Sung Min Shin (2015) [15] recently proposed an age-dependent model that considers among others, the effect of “test stress” and maintenance effects.