DEVELOPMENT OF ADVANCED SURVEILLANCE REQUIREMENTS OF NUCLEAR POWER PLANTS USING RISK INFORMATION

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This paper presents the fundamentals and example of application of an approach for the development of the RITS-5b accounting for the effects of NPP aging and the maintenance rule. This approach makes use of an Ageing PSA as it allows ac-counting for the RAM and risk impact of ageing, maintenance activities and surveillance tests in an integrated manner. This approach can help in equipment testing and maintenance planning in NPP time horizon 2020.

I. INTRODUCTION

Safe operation of Nuclear Power Plants (NPP) depends on Technical Specifications (TS) [1], so that TS are part of the Licensing Basis (LB) to operate a NPP [2]. In particular, attention is paid to the role of the Surveillance Requirements (SR) as part of TS. The goal of these SR is to provide adequate assurance of the availability and reliability of equipment needed to prevent and, if necessary, mitigate NPP accidents.

In August 1995, the US Nuclear Regulatory Commission (NRC) adopted a final policy statement on the expanded use of Probabilistic Risk Assessment (PRA) methods in nuclear activities. Since then, the risk-informed process introduced in RG 1.174 [3] and RG 1.177 (particularly for Risk-Informed Technical Specifications (RITS)) [4] has evolved into a suite of regulatory guides and methods that define an integrated approach to risk-informed regulation.

Before issuance of the maintenance rule, 10 CFR 50.65, in July 1991 [5], technical specifications primarily governed plant operations. They dictated what equipment must normally be in service, how long equipment can be out of service, compensatory actions, and surveillance testing to demonstrate equipment readiness. The maintenance rule marked the advent of a regulation with significant implications for the evolution for technical specifications. The goal of these technical specifications is to provide adequate assurance of the availability and reliability of equipment needed to prevent and, if necessary, mitigate accidents and transients.

In addition to specifying a process for monitoring the effectiveness of maintenance [6], including performance and condition monitoring, and for balancing maintenance unavailability and equipment reliability, the maintenance rule requires licensees to assess and manage plant configuration risk that results from maintenance.

The U.S. NRC approved initiatives and the associated Technical Specifications Task Force travelers (TSTFs) for fundamentals improvements to the Standard TS of light water reactor. In particular, initiative RITS-5b (TSTF-425) [7], with an aim at enabling utilities to relocate surveillance frequencies to licensee control, thus allowing utilities to change these frequencies by using an approved risk-informed approach, which is applicable to all reactor types.

This initiative has been addressed, for example in STS [1]. Thus, section SR of STS requires the Surveillance Frequency (SF) could be performed either adopting a fixed value, given there for each particular condition, or in accordance with the Surveillance Frequency Control Program (SFCP) implemented ant the NPP.

Nuclear Industry has produced a guidance document on a Risk-Informed Method that can help in the implementation for a SFCP [8]. The approach for changing Surveillance Frequencies uses existing Maintenance Rule implementation guidance (NUMARC 93-01, Rev. 3) [9], combined with elements of NRC In-service Testing Regulatory Guide (RG) 1.175 [10], to develop risk-informed test intervals for SSCs having Technical Specification Surveillance Requirements.

This initiative opens the way to explore solutions for achieving above synergy between more flexible SF now and dynamic MR. The challenge is even more important in the context of 2020 horizon to maintain fission technologies competitiveness, where many NPP will be operating close to the end of their design life. In this context, maintenance activities are crucial for ageing management of NPP. So that, maintenance policies implemented at NPP must be re-analyzed in the light of the risk-impact of NPP ageing in this time horizon and SF in TS must be adjusted consequently.

This paper presents the fundamentals and example of application of an approach for the assessment of safety criteria in the context of the RITS-5b accounting for the effects of NPP ageing and the maintenance rule in an integrated manner. This approach makes use of the Ageing PRA proposed in [11] as it allows accounting for the RAM and risk impact of ageing, maintenance activities and surveillance tests in an integrated manner.

II. SAFETY PRINCIPLES FOR CHANGING SURVEILLANCE FREQUENCIES

RG 1.174 identifies five key safety principles to be met for all risk-informed applications and to be explicitly addressed in risk-informed plant program change applications. Principles 4 and 5 are the only two being considered in this paper.

Principle 4 establishes that when changes result in an increase in core damage frequency (CDF) or risk, the increases should be small. Normally, the overall impact of the changes are assessed and compared to the quantitative risk acceptance guidelines of RG 1.174, i.e. CDF and LERF (Large Early Release Frequency). The former is obtained using a Level 1 PRA while the latter is obtained using a Level 2 PRA.

Principle 5 establishes that the impact of the proposed change should be monitored using performance measurement strategies. Then, a performance monitoring strategy is required to provide confidence that the change is not degrading the equipment performance, for example, the reliability and availability of such equipment. For certain cases, existing performance monitoring required by the Maintenance Rule is adequate for equipment whose Surveillance Frequencies is controlled under the SR in Technical Specifications. The output of the performance monitoring can be periodically re-assessed, and appropriate adjustments made to the Surveillance Frequencies (and maintenance frequencies also).

III. ADVANCED RAMS MODEL

RG 1.174 requires quantifying CDF and LER measures. Current PRA models and data do not contain the level of detail necessary for the type of PRA application proposed in this paper, so that, PRA must be first adapted to address explicitly the impact of both surveillance and maintenance on risk measures.

In this paper, the adaptation of the original PRA available to an Ageing Probabilistic Risk Assessment (APRA) is considered as proposed in [11], since it allows quantifying the Core Damage Frequency (CDF) as a function of equipment ageing, testing and maintenance frequency and their associated effectiveness.

In addition, maintenance rule requires quantifying equipment RAM (reliability, maintainability and availability) contributions as part of the equipment performance monitoring.

This APRA includes basic models representing equipment unavailability contributions due to both independent failure modes and downtimes contributions due to testing and maintenance, i.e. downtime effect of testing, corrective and preventive maintenance. Such model contributions allow quantifying the equipment performance in terms of RAM as a function of equipment ageing, testing and maintenance frequency and their associated effectiveness.

Then, APRA models and data allow making predictions of the equipment RAM and NPP CDF in any time horizon as they enable to simulate the impact of ageing, testing and maintenance planning, so that, they can be used for testing and maintenance frequency planning and control.

III.A. Age-dependent RAM model

As proposed in Ref. [11], the age-dependent unavailability contribution as a function of time *t* of a single equipment *i*, normally in stand-by, can be divided into the following two categories:

$$u_i(t) = u_i^{unrel}(t, TI, \lambda_i^D(t), RI, \lambda_i^{UD}(t), L, \lambda_i^{UU}(t)) + u_i^{down}(t) \tag{1}$$

Where $u_i^{unrel}(t)$ is the equipment age-dependent unavailability due to failures, i.e. unreliability effect, and $u_i^{down}(t)$ is the equipment age-dependent unavailability contribution due to testing and maintenance downtimes, named the downtime effect. $u_i^{unrel}(t)$, as established in Ref. [11], depends on:

TI_i = surveillance test interval corresponding to surveillance test of equipment *i*,
TR_i = functional test interval or refueling interval corresponding to functional test of equipment *i*,
L = equipment life (or NPP design life),
ρ = cyclic or per-demand failure probability.

In addition, parameter $\lambda_i^D(t)$ represents the age-dependent failure rate associated with detected failures by testing, $\lambda_i^{UD}(t)$ represents the age-depended failure rate contribution associated with undetected failures only after the refueling functional test, while $\lambda_i^{UU}(t)$ represents the age-dependent failure rate contribution associated with failures that remain undetected even after the refueling functional test, which are given by:

$$\lambda_i^D(t) = \eta \cdot \lambda_i^m(t) \tag{2}$$

$$\lambda_i^{UD}(t) = \eta_{RI} \cdot (1-\eta) \cdot \lambda_i^m(t) \tag{3}$$

$$\lambda_i^{UU}(t) = (1-\eta_{RI}) \cdot (1-\eta) \cdot \lambda_i^m(t) \tag{4}$$

where , η is the surveillance test efficiency and η_{RI} is the test efficiency of the refueling functional test, both ranging in the interval [0, 1]. Often, functional test involves testing of full performance of the equipment capacity, so that it performs very close to real conditions in case of emergency and its effectiveness may be assumed to be equal to 1.

Note, Eq. (2) to (4) depend also on $\lambda_i^m(t)$, which represents the age-dependent failure rate of equipment *i* after *m*-maintenance.

Based on Refs. [12, 13], this failure rate can be formulated considering a linear ageing model and PAR and PAS imperfect maintenance models respectively as follows:

$$\lambda_i^m(t) = \lambda_{0,i} + \alpha_i \cdot \frac{M}{2} + \alpha_i \cdot (t - \varepsilon_i \cdot M \cdot m) \tag{5}$$

$$\lambda_i^m(t) = \lambda_{0,i} + \alpha_i \cdot \frac{M}{2} + \alpha_i \cdot (t - \varepsilon_i \cdot M \cdot \sum_{k=0}^{m-1} (1-\varepsilon_i)^k \cdot (m-k)) \tag{6}$$

where $\lambda_{0,i}$ is the baseline failure rate when the equipment i is new, M which is the maintenance interval, α_i which represents the linear ageing rate, ε_i which is the maintenance effectiveness ranging in [0, 1], *t* which represents the chronological time ($t > t_m$), t_m is equal to the product *M*m*, which represents the time in which the last maintenance m was performed.
As described in Refs [12, 13], in the PAR approach, each maintenance activity is assumed to reduce proportionally the item age gained from the previous maintenance. However, PAS model considers that the maintenance activity reduces proportionally, in a factor of ε, the age that the item has immediately before it enters maintenance.

The Downtime contribution (u_{down}) can be split into at least the following downtimes contributions based on Ref [11]:

$$u_{down} = u_i^T(t,\tau,TI) + u_i^M(t,\sigma,M) + u_i^C(t,\mu,\lambda_i^D(t)) + u_i^O(t,\Gamma,L) \tag{7}$$

where, $u_i^T(t)$ represents the unavailability contribution due to testing, $u_i^M(t)$ is the unavailability contribution due to preventive maintenance, $u_i^C(t)$ is the unavailability contribution due to corrective maintenance, and $u_i^O(t)$ is the contribution due to replacement of the item, if any, where the following notation is used:

τ = downtime for testing,
σ= downtime for preventive maintenance,
M = time-directed preventive maintenance interval,
μ = downtime for repair when there are no time limitations on conducting such a repair,
Γ= downtime for replacement.

III.B. Age-dependent Risk model

RG 1.174 establishes two risk metrics are necessary to evaluate the risk impact of whatever change to the licensing basis, which can be evaluated using a PRA, for example, adopting the approach proposed in Refs. [14, 15].

The PRA used in this paper to support the analysis of changes addresses CDF for power operation and internal events only, since a Level 1 PRA of a PWR NPP for power operation and internal events is available.

As said, the original PRA available is adapted to an APRA following the approach proposed in [11] and the age-dependent equipment RAM-model introduced in the previous section, which allows quantifying the age-dependent CDF as a function of equipment ageing, testing and maintenance frequency and their associated effectiveness.

Thus, using this APRA, the required risk metrics are the annual average baseline CDF before and after the change, which can be used to formulate the following increase in the age-dependent CDF as follows:

$$\Delta CDF(t) = CDF_a\,(t) - CDF_b(0) \qquad (8)$$

where CDF_b (0) is the initial CDF before (b) the change and CDF_a (t) is the age-dependent CDF after (a) the change.

Eq. (8) can be simplified for the case of a single component i, assuming linear dependency between ui(t) and CDF(t), as follows:

$$\Delta CDF(t) = \left\lfloor u_i^a(t) - u_i^b(0) \right\rfloor \cdot B_i \qquad (9)$$

where $u_i^b(0)$ is the initial unavailability of component i before the change and $u_i^a(t)$ is the age-dependent component unavailability after the change. Both unavailability can be obtained using Eq. (1). In addition, B_i represents the Birnbaum importance measure of equipment *i*.

Eq. (9) has been shown for sake of simplicity to show the relationship between the age-dependent risk model and the age-dependent RAM model in the previous section. However, the linear dependency assumed is not true for many cases, such as the one being considered in this work, where $u_i(t)$ must be developed as a function of maintenance interval (M) and testing interval (TI) and, therefore, CDF(t) is a polynomic function, e.g. quadratic or cubic function, of such intervals because of those intervals TI and M not only affect equipment *i* but also other equipment overtaken same test strategy and maintenance plan. So that, Eq. (8) will be considered from now on and in the example of application.

Note, Eq. (8) and (9) account simultaneously for the risk impact of both the change and equipment ageing between an initial or departing situation (t=0) and the NPP age at a given chronological time *t*. So that, this equation allows projecting the risk impact of a given testing and maintenance policy accounting for NPP ageing in a given time horizon.

In addition, one could be interested in quantifying the risk impact of the effect the change only, therefore, disaggregating the effect of NPP age as a consequence of the chronological time evolving from t=0 to a given t. The following expression is proposed:

$$\Delta CDF(t)_{wa} = CDF_a\,(t) - CDF_b(t) \qquad (10)$$

where CDF_b (t) and CDF_a (t) are the age-dependent CDF before (b) and after (a) the change, respectively, at a given chronological time, *t*.

Now, Eq. (10) accounts only for the risk impact of the change at a given chronological time *t*. As expected, this impact will depend on the NPP age at this chronological time, so that, this equation allows projecting the risk impact of a given testing and maintenance policy at a NPP age in a time horizon.

IV. CASE STUDY

This section presents an example of application of the APRA for assessing equipment RAM and NPP risk accounting for equipment ageing and testing and maintenance frequency changes in an integrated manner. Such a type of APRA application could be useful in the context of the RITS-5b initiative.

IV.A. Safety-related equipment

In this work, equipment ageing, maintenance activities and surveillance testing of a motor-operated valve (MOV) of the Auxiliary Feed Water System (AFWS) is considered. This MOV has been selected because of it is one of the most critical equipment with respect to the CDF according to the standard PRA available. Besides, equipment ageing, maintenance and surveillance requirements are also important for this MOV.

IV.B. RAM data

Table 1 shows data used for modelling the MOV based on the information provided in Ref. [11] and [13].

TABLE I. Data used for MOV

Parameter	**Description**	**Data**
ρ	Probability of failure on demand	1,82·E-3
λ_0 (h^{-1})	Initial failure rate	Gamma (4,45·E-08, 0.5)
α (h^{-2})	Ageing factor	4,11·E-10
M (h)	Maintenance interval (initial)	8760
ε	Maintenance effectiveness	0,6
σ (h)	Downtime for preventive maintenance	1
μ (h)	Downtime for corrective maintenance	2,6
TI (h)	Test interval (initial)	4320
η	TI efficiency	0,6
τ (h)	Downtime for surveillance testing	1
RI (h)	Functional test interval (refueling interval)	13140
η_{RI}	Test efficiency of the functional test	1
L(h)	Equipment design life (10 years)	87600
Γ(h)	Downtime for replacement	6

IV.C. Results

The advanced RAMS model introduced in section three allows making predictions of the age-dependent equipment unavailability and NPP risk in any time horizon as it enables to simulate the impact of equipment ageing and testing and maintenance policies.

This section presents the results of quantifying Eq. (1), (8) and (10) using the data presented in the previous section for several maintenance and surveillance test intervals in a five years horizon.

Fig. 1, 2 and 3 presents the results of quantifying Eq. (1), (8) and (10) respectively as a function of both variables surveillance test interval (TI) and maintenance interval (M).

These figures could be used to obtain different couples of test and preventive maintenance intervals that both manage equipment ageing and satisfies the acceptance criteria for SF changes according to RG 1.174.

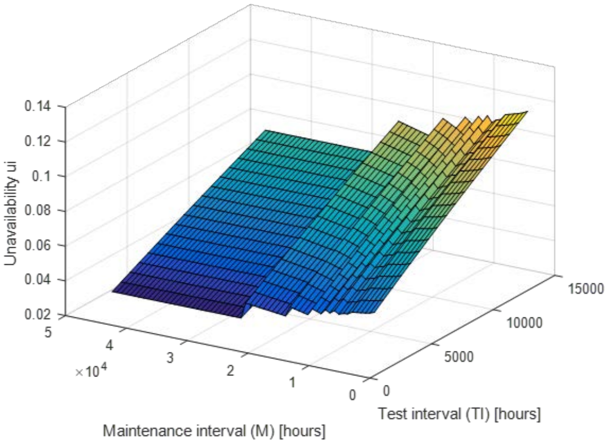

Fig. 1. Equipment unavailability (t=43200 hours)

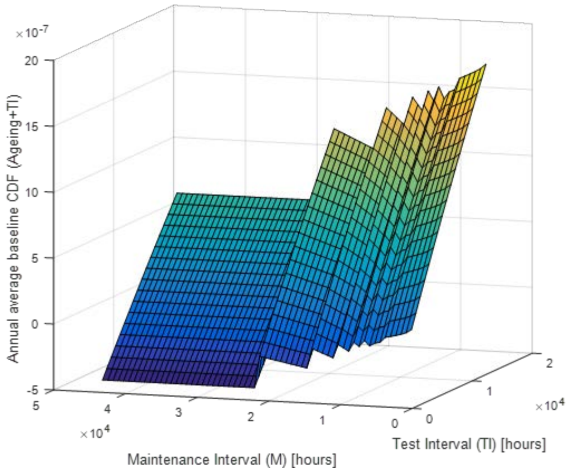

Fig. 2. ΔCDF (t=43200 hours)

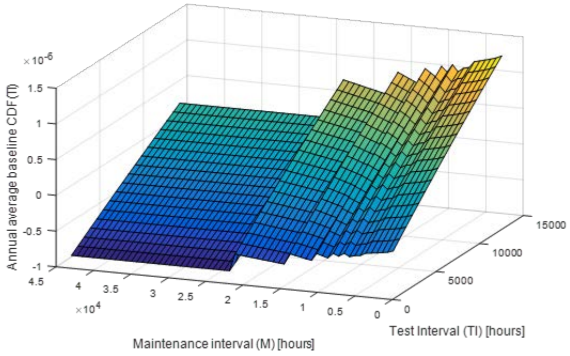

Fig. 3. ΔCDF_{wa} (t=43200 hours)

V. CONCLUSIONS

A real challenge nowadays is to develop RISR (Risk-Informed Surveillance Requirements) within NPP Technical Specifications in scope of RMTS initiatives, in particular RITS-5b, by providing tools to allow exploring solutions for achieving synergy be-tween more flexible surveillance requirements and dynamic maintenance rule.

This challenge is even more important in the context of 2020 horizon, where NPP will face the problem of guaranteeing safe operation in presence of equipment ageing, where NPP owners and regulatory bodies will be responsible for implementing an appropriate SFCP in good agreement with the necessary adjustment of maintenance programs implemented currently at NPP to achieve appropriate levels of safety in the operation of NPP in a time horizon involving the end of its operational design life or beyond.

This paper presents an approach that makes use of an Ageing PRA model for quantifying the RAM and risk impacts of ageing, maintenance activities and surveillance tests in an integrated manner. The ex-ample of application demonstrate this tool could be used for testing and maintenance frequency planning and control.

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