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Harmonization of surveillance requirements and maintenance in a context of ageing and obsolescence based on reliability, availability and risk information

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- Risk management technical specifications framework
- Harmonization of surveillance requirements and maintenance
- RAM and risk models in a context of equipment ageing and obsolescence
- Test and maintenance optimization in the context of RMTS philosophy
- Usefully application for the renewal of the licence for operation of the plant

Har[illegible]nd obsolescence based on reliability, availability and risk information

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ABSTRACT:

This paper contains the fundamentals and a comparison of different alternatives in the context of risk-informed surveillance requirements that consider the full effects of implementing the maintenance rule. A case study is included to demonstrate the performance of the different alternatives, which focus on a motor-operated valve and make use of an Ageing PRA to quantify the effect of component ageing, test and maintenance effectiveness on equipment RAM and its impact on risk. The results show that the alternative that simultaneously harmonises surveillance requirements and maintenance activities provides the best results in terms of RAM and risk in a context of equipment ageing and obsolescence. However, they also show that measures other than simply re-adjusting surveillance testing and maintenance intervals should be explored in case of technical obsolescence, as this has a strong impact on maintenance effectiveness, which may require, for example, an obsolescence management program to be applied.

Keywords:
Testing and maintenance, ageing, obsolescence, risk-informed, decision-making, optimization

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LIST OF ACRONYMS

AMP	Ageing Management Program
APRA	Ageing Probabilistic Risk Assessment
BAO	Bad As Old
CDF	Core Damage Frequency
DG	Diesel Generator
FC	Failure Cause
IAEA	International Atomic Energy Agency
IMM	Imperfect Maintenance Model
MA	Maintenance Activity
MDP	Motor Driven Pump
MOV	Motor-Operated Valve
MR	Maintenance Rule
NRC	Nuclear Regulatory Commission
NPP	Nuclear Power Plant
OMP	Obsolescence Management Program
OP	Optimization Problem
PAR	Proportional Age Reduction
PAS	Proportional Age Setback
PRA	Probabilistic Risk Assessment
PSR	Periodic Safety Review
PWR	Pressurized Water Reactor
RAM	Reliability, Maintainability and Availability
RG	Regulatory Guide
RI	Refuelling Interval
RIDM	Risk-Informed Decision Making
RITS	Risk-Informed Technical Specifications
RMTS	Risk Management Technical Specifications
SF	Surveillance Frequency
SFCP	Surveillance Frequency Control Program
SR	Surveillance Requirements
ST	Surveillance Test
SSC	Structures, Systems and Components
TR	Time of Reference for a given time horizon

1 INTRODUCTION

Technical specifications (TSs) [1] are part of the Licensing Basis to operate a Nuclear Power Plant (NPP) [2], which are intended to provide adequate assurance of the availability and reliability of equipment needed to prevent and mitigate NPP accidents in order to keep NPP risk under control. TSs govern plant operations as they dictate the equipment that must normally be in service, how long it can be out of service, compensatory actions and surveillance requirements (SR) to demonstrate equipment readiness. The term *Risk Management Technical Specifications* (RMTS) is used to emphasize the goal of constructing technical specifications that reinforce the pro-active management of the total plant risk. RMTS are intended to bring technical specification requirements into congruence with risk-informed regulation (RG 1.174 [3] and RG 1.177 (Risk Informed Technical Specifications (RITS)) [4]), which make use of Probabilistic Risk Assessment (PRA).

The issuance of the maintenance rule [5] marked the arrival of a regulation with significant implications for constructing technical specifications. The maintenance rule shares the same goal as the TSs but operates at a more fundamental level with a more dynamic and comprehensive process. The maintenance rule specifies a process for monitoring the effectiveness of maintenance [6] for balancing maintenance unavailability and equipment reliability, while it also requires licensees to assess and manage any plant configuration risk that results from maintenance.

In view of this common goal, achieving synergy between the static technical specifications and the dynamic maintenance rule should be included in creating risk management technical specifications. Thus, for example, the Nuclear Regulatory Commission (NRC) approved initiatives and the associated Technical Specifications Task Force travellers for fundamentals improvements to the Standard TS of light water reactors. For example, initiative RITS-5b [7], with the aim of enabling utilities to relocate surveillance frequencies to licensee control, thus allowing utilities to change these frequencies by using an approved risk-informed approach applicable to all reactor types. This initiative has been addressed, for example in TS [1]. Thus, section SR of the STS requires the Surveillance Frequency (SF) to be performed either by adopting a fixed value for each particular condition, or in accordance with the Surveillance Frequency Control Program (SFCP) implemented at the NPP. The Nuclear Industry has produced a guidance document on a risk-informed method that can help in the implementation of an SFCP [8]. The approach for changing SF 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 Systems, Structures and Components (SSCs) with TSs.

Achieving this synergy imposes a challenge on the way to exploring an optimal solution for a common surveillance testing and maintenance policy, which is even more important in the context of the 2030 Horizon to m eir design life and when NPP ageing and obsolescence will be an issue.

The International Atomic Energy Agency’s (IAEA) Safety Guide entitled ‘Ageing Management for Nuclear Power Plants (NPP)’ is mainly focused on managing the physical ageing of systems, structures and components (SSCs) important to safety, but it also provides recommendations on safety aspects of managing obsolescence, especially technical obsolescence management [11]. The IAEA safety guide lays down that SSC technical obsolescence important to safety must be managed proactively and within a program of obsolescence management. Due to these requirements and their respective national regulations, several licensees have implemented an obsolescence management program (OMP) as a part of their ageing management program (AMP) [11-13]. However, many of these programs are still in their initial or developmental stages as it is difficult to determine how obsolescence issues may affect plant safety or how the proposed action plans for ageing and obsolescence management will positively influence it in the long term.

AMP and OMP programs also share similar objectives to other ongoing programs at NPPs, such as Reliability Centered Maintenance, the Life Management Program, Maintenance Rule Implementation, Long Term Operation, RMTS, etc [14]. The common objective of these programs is to reach and maintain a high intrinsic reliability target, reducing equipment failure probability to the minimum, especially for equipment important to NPP safety. The second objective is to reduce equipment downtime for testing and maintenance as far as possible. Equipment out of service for preventive or corrective maintenance cannot perform its intended function and thus may not be available for accident prevention or mitigation. Both equipment reliability and downtime issues are affected by ageing and obsolescence, so that surveillance and maintenance planning has a great influence on all of them.

In this context, establishing a maintenance and test plan based on obsolescence and aging would be useful to maintain the reliability margins and component availability to ensure safe long-term operations. In this document, the harmonisation of surveillance and maintenance requirements is therefore considered in a context of ageing and obsolescence in the framework of the extended design life of nuclear plants, and compares several optimization criteria in the context of changes in TS and the maintenance rule. To achieve this objective, surveillance and maintenance policies implemented in the nuclear power plant are re-analysed according to NPP ageing and obsolescence, considering their impact on RAM and the risk assessed on a time horizon. This includes verifying that the proposed harmonised surveillance and maintenance policy is in agreement with the fulfilment of reliability, availability and risk targets, which act as decision-making criteria imposed by regulatory safety goals or as targets by the ongoing programs cited above.

This paper is structured as follows: Section 2 introduces the RMTS context. Sections 3 and 4 propose the formulation of the age-dependent RAM and risk models, respectively, based on a physical model of the safety-related equipment performance. Section 5 establishes the RAM and risk-informed decision-making crite nd risk models introduced previously. In Section 6 the multi-criteria decision-making is formulated in the form of three objective optimization problems (OPs), adopting each one of the above criteria as either an objective to be optimized or a constraint to the decision-making problem. The case study in Section 7 provides a comparison of the results obtained for the optimization of the surveillance and maintenance intervals under each of the three OP formulated and accounts for the effect of ageing and technical obsolescence. Section 8 provides some concluding remarks.

2 RISK MANAGEMENT TECHNICAL SPECIFICATIONS FRAMEWORK

The risk-informed decision-making (RIDM) framework described here requires a physical model of safety-related equipment performance with the appropriate level of detail to explicitly address the impact of equipment ageing (including technical obsolescence) and maintenance activities on the real age of the equipment. This means developing age-dependent RAM and risk models that explicitly address these impacts.

Figure 1 provides an overview of the proposed physical model for safety-related equipment, which would be appropriate with, for example, motor-operated valves (MOV), motor-driven pumps (MDP), diesel generators (DG), etc. The physical model assumes that safety-related equipment is normally on standby and ready to perform its intended safety function in an emergency. At least two equipment failure modes must be considered: standby-related failure and failure-on-demand. Since the equipment is normally on standby, hidden failures can occur while it is on standby and its unavailability due to undetected downtimes should be controlled by surveillance testing (ST1, ST2, etc.) as required by the Technical Specifications. However, some surveillance tests require the equipment to start and run, which could degrade the equipment performance and could impact the probability of the occurrence of all failure modes. Some components may require surveillance tests during NPP refuelling, whose interval test ranges between 12 and 24 months and often involves testing the full performance of the component capacity.

The probability of all failure modes occurring at the same time could increase with the equipment's age, not only because of functional tests, but also due to the equipment ageing associated with the dominant failure causes (FC1, FC2, etc.) or failure mechanisms acting on it. Maintenance activities (MA1, MA2, etc.) are performed on the equipment to keep the dominant failure causes under control and in this way keep the equipment's age as low as possible. The maintenance rule imposes requirements on the effectiveness of the maintenance that needs to be monitored.

Implementing the requirements of both the TS and the maintenance rule within an NPP allows the collection of historical data in relation to functional tests and maintenance activities, i.e. corrective and preventive maintenance, which can be used to fit the most appropriate age-dependent RAM model for each particular piece of safety equipment, depending on the physical model adopted. However, the level of detail of the physical model must be carefully selected to suit the historical data available; for example, it would be impossible to fit detailed RAM models with many parameters when the available data is scarce.

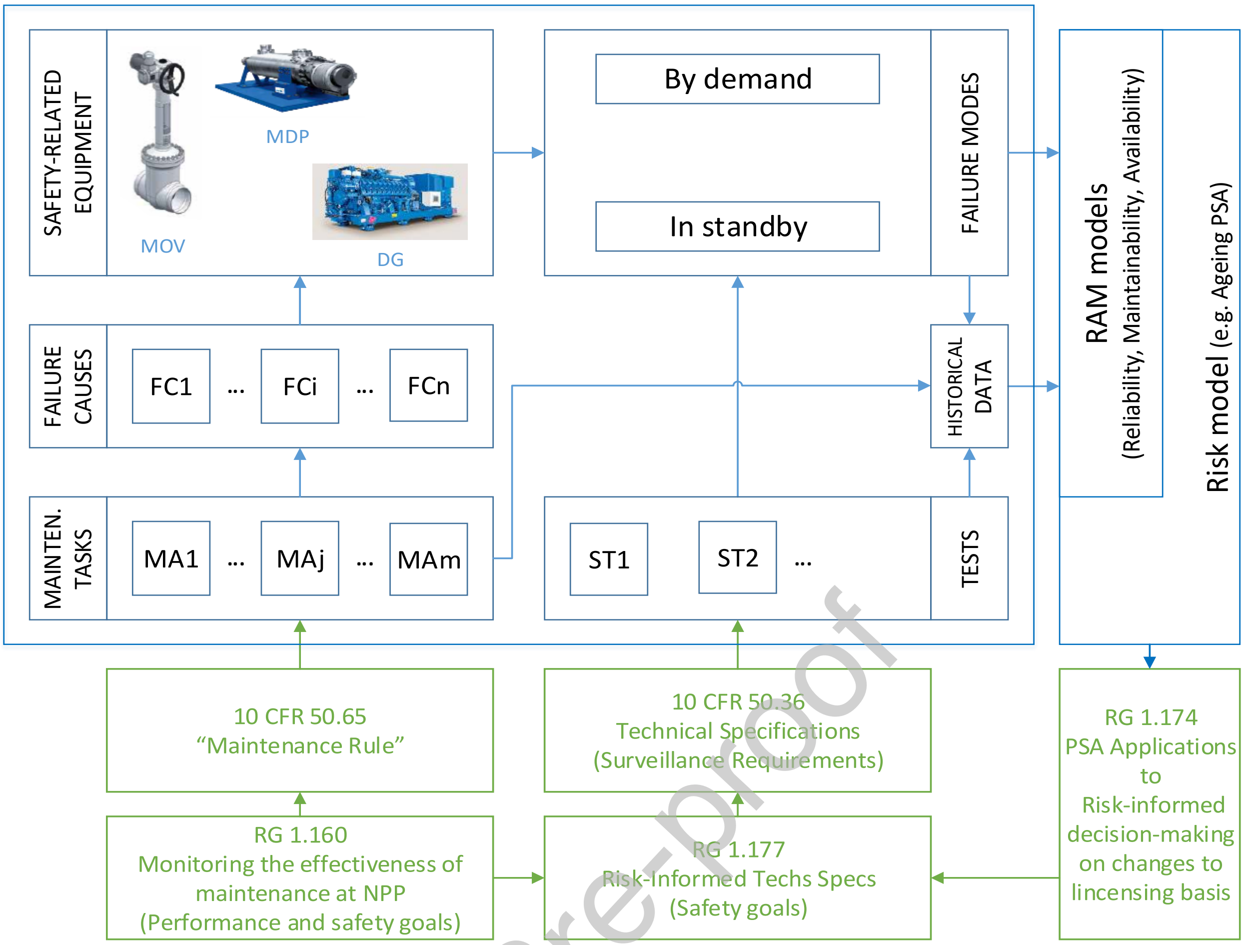

Figure 1. Physical model of the safety-related equipment performance in a RMTS context

The simplified physical model shown in Figure 2 is adopted in the following sections. In spite of being a simplification, this is a generalization of the particular model adopted for MOV and MDP in the case study included in reference [15], in which for example an MOV is considered to consist of two items: an electrical actuator and a mechanical body. Each item is exposed to one group of failure causes or mechanisms that are controlled through the performance of an electrical and a mechanical maintenance activity, respectively. It is assumed that degradation mechanisms and maintenance activities only have an impact on the failure mode of the equipment on standby and is not considered in the demand-caused failure mode. A single surveillance test is considered to control the equipment's downtime due to the occurrence of hidden failures while the equipment is on standby. However, in the present paper it is assumed that ageing, testing and maintenance activities have an impact on both the standby-related and the demand-related failure modes of the safety-related equipment consisting of one single item.

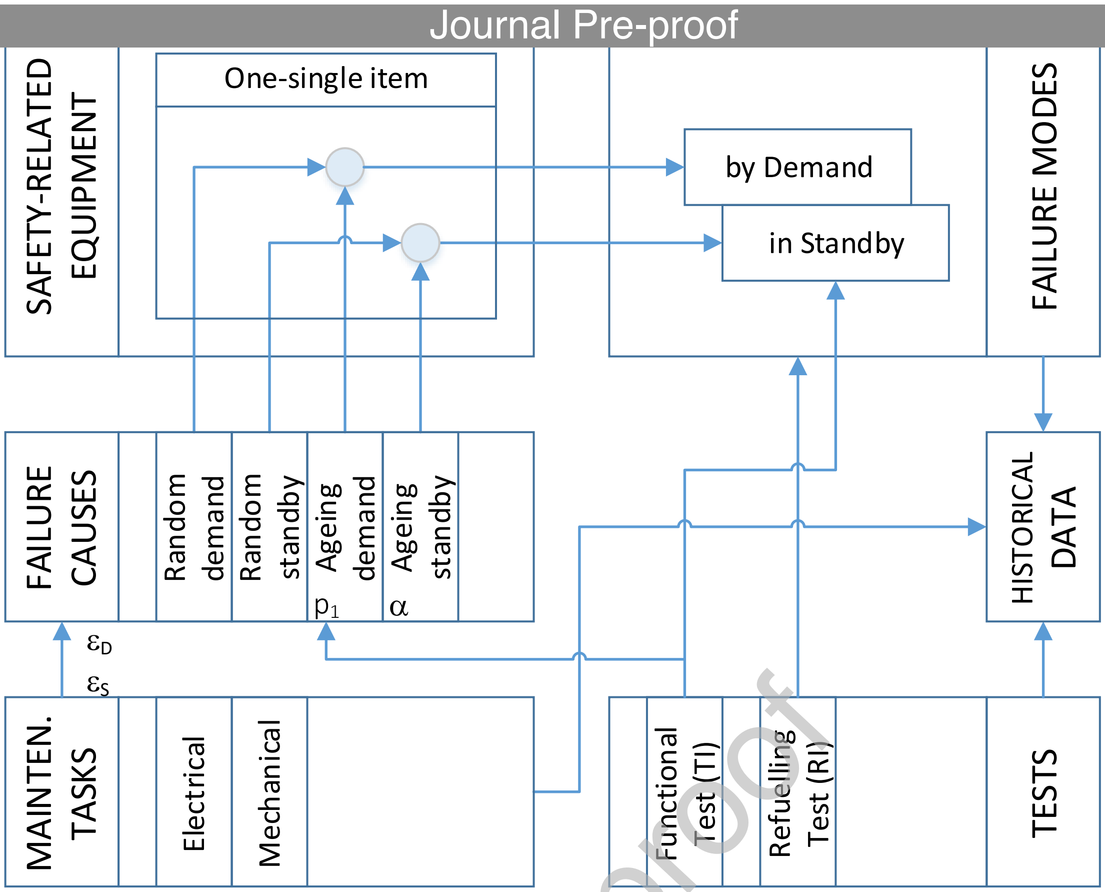

Figure 2. Simplified physical model of the safety-related equipment performance

3 AGE-DEPENDENT RAM MODEL

The first studies on the problem of modelling and assessing equipment ageing and the positive and adverse effects of testing for developing RAM models of safety-related equipment [13, 16-18] were carried out in the 90s. Since then, many other studies have been published in this area of research that also dealt with the problem of modelling and assessing the positive and negative effects of maintenance activities according to their effectiveness in managing equipment reliability degradation [19-28].

In this paper, as the physical model adopted is that shown in Figure 2, an imperfect maintenance model is proposed based on the models introduced in Ref. [19, 23] to formulate the standby failure rate of the equipment that explicitly accounts for the impact of degradation and test efficiency and maintenance effectiveness. The probability of the equipment's failure on demand will be formulated in a similar way and based on the modelling introduced in [26]. Both the stand-by failure rate and the per-demand failure probability models are then used to develop the age-dependent RAM model. The RAM model parameters can be fitted using the available historical data, for example by following the method proposed in [28].

3.1.1 Standby failure rate model

The standby failure rate of the equipment depends on its age, which is a function of the chronological time elapsed since its installation and the effectiveness of the maintenance activities performed on it. The failure rate of the equipment in the period between maintenance activities *m-1* and *m* considering an imperfect maintenance model and a linear model can be formulated as proposed in [19]:

$$\lambda_m(t) = {\lambda_{m-1}}^+ + \alpha \cdot (t - t_{m-1}) \qquad t_{m-1} < t < t_m \tag{1}$$

where ${\lambda_{m-1}}^+$ is the failure rate function for the time immediately after performing the m-1 preventive maintenance activity, α is the linear ageing factor and t represents the chronological time in which the failure rate is evaluated.

Imperfect maintenance models (IMM) consider that each maintenance activity reduces the age of the component to some extent, according to its effectiveness. We here consider the Proportional Age Reduction (PAR) model and the Proportional Age Setback (PAS) model proposed in [19] to model the effect of maintenance activities. The most appropriate model is selected in each case for the component type, failure mechanism and type of maintenance activity.

As shown in reference [19], ${\lambda_{m-1}}^+$ can be formulated under the PAR and PAS models assuming that preventive maintenance activities are performed regularly at a constant maintenance interval given by M and linear ageing, respectively, as follows:

$${\lambda_{m-1}}^+ = \alpha \cdot (1 - \varepsilon_S) t_{m-1} + \lambda_0 \qquad \text{PAR Model} \tag{2}$$

$${\lambda_{m-1}}^+ = \alpha \cdot \left[t_{m-1} - \sum_{k=0}^{m-2} (1 - \varepsilon_S)^k \varepsilon_S t_{m-1-k} \right] + \lambda_0 \qquad \text{PAR Model} \tag{3}$$

where λ_0 is the baseline standby failure rate, and ε_S is the maintenance effectiveness for standby failures that ranges between [0, 1].

Let us consider that the regularly equipment undertakes surveillance tests at a constant test interval given by T. Now, adopting the usual case in which test interval T is shorter than preventive maintenance interval M, it is possible to obtain an average age-dependent failure rate over the interval between two consecutive surveillance tests, *n-1* and *n*, which are performed at times t_{n-1} and t_n, respectively, where t_n represents the time at which the last test *n* was performed and is equal to the product $T \cdot n$. The average age-dependent failure rate between two consecutive surveillance tests can be obtained from $\lambda_m(t)$ as follows:

$$\lambda_n = \frac{1}{t_n - t_{n-1}} \int_{t_{n-1}}^{t_n} \lambda_m(t)\, dt \tag{4}$$

By s

$$\lambda_n = \lambda_{m-1}^{+} + \frac{\alpha}{2}(t_{n-1} - t_{m-1}) + \frac{\alpha}{2}(t_n - t_{m-1}) = \lambda_{m-1}^{+} + \alpha\,(t_{n-1} - t_{m-1}) + \frac{\alpha}{2}\,T \qquad (5)$$

Eqn. (5) shows that λ_n is a step function that is not necessarily a monotonously increasing function with the number of test intervals *n*. The maximum of this function for a given time period, named herein time of reference (TR), can then be obtained to assess the maximum increase in the ageing failure rate of the component between surveillance tests for a given time horizon following a given maintenance strategy. This maximum value can be expressed as follows:

$$\lambda = max\{\lambda_n for\ t \leq TR\} = f(\lambda_0, \alpha, IMM, \varepsilon_S, M, T, TR)\ n = 1,2,\ldots,N \qquad (6)$$

where $N=\lfloor TR/T \rfloor$ represents the maximum number of tests performed in *TR* and $\lfloor x \rfloor$ the floor function that gives the largest integer less than or equal to x. In addition, the total number of preventive maintenance tasks performed in this *TR* is given by the function $\lfloor TR/M \rfloor$.

Eqn. (6) provides a single result for λ, which corresponds to a particular test interval represented by θ_λ. Eqn. (6) shows that this result depends on the ageing rate, represented by α, the maintenance plan, represented by ε_S, M and the *IMM (PAS or PAR)*, the test interval *T* and the time of reference *TR*.

Surveillance tests are performed regularly to detect hidden failures so that the component can be restored to its operational state (normally BAO state) by corrective maintenance after the test has detected a failure. However, the test is normally not one hundred per cent efficient in detecting failures, so that test efficiency, represented by η, must be considered, which can be formulated as the percentage of the failure rate that is detected during the test. It represents the coverage of the test, which normally ranges in the interval [0, 1] [23]. Ref. [18] and [23] give values of η for the test efficiency of several component types.

Thus, the average age-dependent failure rate given by Eqn. (6) can be split into two fractions: one associated with detected failures, λ^D, and the other associated with undetected failures, λ^U, such that:

$$\lambda = \eta_S \cdot \lambda + (1 - \eta_S) \cdot \lambda = \lambda^D + \lambda^U \qquad (7)$$

where η_S is the surveillance test efficiency to detect failures in stand-by.

On the other hand, many critical components require an additional surveillance test during NPP refuelling, the refuelling interval (RI) normally being equal to 18 months. This type of test is usually highly efficient because the component's entire capacity is tested, i.e. the component operates very close to real conditions in an emergency. The test efficiency, represented by η_R, is thus very close to one in detecting hidden failures. To address such a second or refuelling test, the undetected age-dependent failure rate λ^U, given by Eqn. (7), must be split again into two new contributions: those detected and undetected after the refuelling test, to yield:

$$\lambda^U = \eta_R \lambda^U + (1 - \eta_R)\lambda^U = \lambda^{UD} + \lambda^{UU} \qquad (8)$$

whe [illegible] ter the refuelling test, while, λ^{UU} represents the age-dependent failure rate contribution associated with failures that remain undetected even after the refuelling test.

3.1.1 Demand failure probability model

The age-dependent probability of failure on demand, depending on the number of demands on the component, which is often associated with performing surveillance tests in the interval between m-1 and m- maintenance can be formulated as in reference [26], as follows:

$$\rho_m(t) = \rho_{m-1}^{+} + \rho_0 p_1 \left\lfloor \frac{t - t_{m-1}}{T} \right\rfloor \qquad (9)$$

where $\rho_{m-1}^{+}$is the demand failure probability for the time immediately after performing the *m-1* preventive maintenance activity , ρ_0 is the baseline demand failure probability, p_1 is the degradation factor, which is the same for all types of demands, and *T* represents the test interval.

As with the age-dependent standby failure-rate, it is possible to consider the effect of maintenance activities on the failure on demand of the component by adopting similar imperfect maintenance models to those considered in the previous section. Again, the selection of the most appropriate model in each case depends on the component type, failure mechanism and sort of maintenance activity. As in reference [26], ρ_{m-1}^{+} can be formulated under the PAR model and PAS model assuming that preventive maintenance activities are performed regularly at a constant maintenance interval given by *M* and linear ageing, respectively, as follows:

$$\rho_{m-1}^{+} = \rho_0 + \rho_0 p_1 (1 - \varepsilon_D) \left\lfloor \frac{t_{m-1}}{T} \right\rfloor \qquad \text{PAR Model} \qquad (10)$$

$$\rho_{m-1}^{+} = \rho_0 + \rho_0 p_1 \left\{ (1 - \varepsilon_D) \sum_{k=0}^{m-2} (1 - \varepsilon_D)^k \left\lfloor \frac{t_{m-k-1} - t_{m-k-2}}{T} \right\rfloor \right\} \qquad \text{PAS Model} \qquad (11)$$

where ε_D is the maintenance effectiveness for demand failures that ranges between [0, 1] and t_{m-1} represents the time at which the last maintenance *m-1* was performed.

Now, again assuming the usual case in which test interval *T* is shorter than preventive maintenance interval *M*, it is possible to obtain an average age-dependent probability of failure on demand over the interval between two consecutive surveillance tests, *n-1* and *n*, which are performed at times t_{n-1} and t_n respectively. This average age-dependent probability of failure on demand can be obtained from $\rho_m(t)$ as follows:

$$\rho_n = \frac{1}{t_n - t_{n-1}} \int_{t_{n-1}}^{t_n} \rho_m(t) dt \qquad (12)$$

Since Eqn. (9) is constant between two consecutive tests, *n-1* and *n*, it is simple to demonstrate using Eqns. (9) and (12) that it yields [26]:

$$\rho_n = \rho_m(t = t_n) \qquad (13)$$

Eqn he number of test intervals *n*. The maximum of this function for a given time period, TR, can then be obtained to assess the maximum increase in the ageing probability of failure on demand of the component between surveillance tests for a given time horizon, following a given maintenance strategy. This maximum value can be expressed as follows:

$$\rho = max\{\rho_n for\ t \leq TR\} = g(\rho_0, p_1, IMM, \varepsilon_D, M, T, TR)\ n = 1,2, \ldots, N \qquad (14)$$

Eqn. (14) provides a single result for ρ, which is that of a test interval represented by θ_ρ. Eqn. (14) shows that this result depends on the test degradation factor, represented by p_1, the maintenance plan, represented by ε_D, M and the IMM(PAS or PAR), the test interval *T* and the time of reference *TR*.

3.2 *Unavailability model*

The age-dependent unavailability of a single piece of safety-related equipment, normally on stand-by, can be divided into the following two categories [23]:

$$u = u_R + u_{MT} \qquad (15)$$

where u_R is the equipment unavailability due to hidden failures between tests, i.e. the unreliability effect, and u_{MT} is the equipment unavailability contribution due to maintenance and testing downtimes, known as the *downtime effect*.

The following assumptions were made in developing both contributions in the following subsections:

- Test efficiency in detecting failures on demand is considered equal to one because these types of failures are always discovered, for example, in actuating the motor-operated valve.
- Maximum values of λ_n and ρ_n are reached in the same testing interval, thus the following condition normally applies $\theta_\lambda = \theta_\rho = \theta$,
- The surveillance tests and preventive maintenance intervals, *T* and *M* respectively, are kept constant over the time horizon.
- In addition, it is assumed that *T* is a multiple of *M*. This condition can be expressed as follows: $\exists a \in \mathbb{N}: M \quad = a * T$

3.2.1. Unreliability contributions, u_R

Unavailability due to the unreliability effect can be expressed as the sum of three different contributions based on Ref. [23]:

$$u_R = u_R^D + u_R^{UD} + u_R^{UU} \qquad (16)$$

whe nd caused failures (ρ), which are detected by surveillance testing, u_S^{UD} is the unreliability contribution due to hidden failures that are not detected by surveillance testing but are then detected by a second functional test, and u_S^{UU} is the unreliability contribution due to hidden failures that remain undetected after both surveillance and functional tests. These contributions can be defined as follow:

$$u_R^D = \rho + \frac{1}{2}\lambda^D T \tag{17}$$

$$u_R^{UD} = \frac{1}{2}\lambda^{UD} RI \tag{18}$$

$$u_R^{UU} = \frac{1}{2}\lambda^{UU} TR \tag{19}$$

Substituting Eqns. (17), (18) and (19) for Eqn. (16), the unreliability contribution is obtained:

$$u_R = \rho + \frac{1}{2}\lambda^D T + \frac{1}{2}\lambda^{UD} RI + \frac{1}{2}\lambda^{UU} TR \tag{20}$$

3.2.2. Downtime contributions, u_{MT}

As defined in Ref. [23], the downtime effect can be split into the following downtime contributions:

$$u_{MT} = u_T + u_M + u_C \tag{21}$$

where, u_T represents the unavailability contribution due to testing, u_M is the unavailability contribution due to preventive maintenance and u_C is the unavailability contribution due to corrective maintenance. These contributions can be formulated as follow:

$$u_T = \frac{\tau}{T} \tag{22}$$

$$u_M = \frac{\sigma}{M} \tag{23}$$

$$u_C = (\frac{1}{T} \cdot \rho \ + \lambda^D) \cdot \mu \tag{24}$$

where the following notation is used:

τ = downtime for surveillance testing,

σ= downtime for preventive maintenance,

μ = downtime for repairs.

Thus, substituting Eqns. (22), (23) and (24) in Eqn. (21), the unavailability due to downtimes is obtained:

$$u_{MT} = \frac{\tau}{T} + \frac{\sigma}{M} + \left(\lambda^D + \frac{1}{T}\rho\right)\mu \tag{25}$$

The risk metrics established in RG 1.174 and RG 1.177 are adopted to evaluate the risk impact. These metrics are referred to as the *single downtime risk* and the *yearly risk contribution*, which can be quantified by adopting the approach proposed in Refs. [29, 30]. Risk metrics may be quantified in terms of the Core Damage Frequency (CDF), for example using the age-dependent level 1 PRA model introduced in Ref. [23].

A level 1 PRA of a PWR NPP in full-power operations is adopted here, considering internal events are available, which have been adapted by integrating the age-dependent RAM-model introduced in the previous section, since it can obtain the CDF of the NPP as a function of parameters representing equipment ageing, testing and maintenance frequency and their associated effectiveness and other IMM-related parameters. These models can help to predict the equipment RAM performance and NPP CDF in any time horizon, as they can simulate the impact of ageing, testing and maintenance planning, and can thus be used for testing and maintenance frequency planning and control.

The first risk metric proposed by RG 1.174 is the change in yearly CDF contribution, which requires assessing the CDF before and after the change to yield the increase in the age-dependent CDF as follows:

$$\Delta R = \Delta CDF(\theta) = CDF_a(\theta) - CDF_b(0) \tag{26}$$

where $CDF_b(0)$ is the initial CDF before (b) the change and $CDF_a(\theta)$ is the age-dependent CDF after (a) the change and projected to a given time horizon, TR.

Eqn. (26) accounts simultaneously for the CDF impact of a testing and maintenance frequency change and equipment ageing between an initial or departing situation (t=0) and a given chronological time *t*. This equation can therefore project the CDF impact of a given testing and maintenance policy accounting for the effect of NPP ageing and obsolescence in a given time horizon *TR*. As in Ref. [29, 30], Eqn. (26) can be simplified for the case of a single piece of equipment considering the relationship between the age-dependent risk model [23] and the age-dependent RAM model in the previous section. It is therefore quite simple to approximately calculate the yearly CDF contribution of the unavailability of a single component for a given testing and maintenance plan and accounting for equipment ageing at chronological *t*, as follows:

$$\Delta R_i = \Delta CDF_i(\theta) = \Delta u_i(\theta) \cdot B_i \tag{27}$$

$$\Delta u_i(\theta) = u_i(\theta) - u_i(0) \tag{28}$$

where $u_i(\theta)$ and $u_i(0)$ are the unavailability of the equipment after and before the change, respectively, which can be obtained by Eqns. (15) to (25) and B_i represents the Birnbaum importance measure of equipment *i*, which can be derived from a standard PRA.

The second risk metric proposed by RG 1.177 is the single downtime risk, which requires assessing the incremental core damage probability (ICCDP) when a level 1 PRA is used, given by the following equation:

$$r_i = ICCDP_i(\theta) = d \cdot B_i \tag{29}$$

whe he downtime which is often limited by technical specifications through the allowed outage time.

5 DECISION-MAKING CRITERIA

This section describes the multiple criteria to be considered in the RAM and risk-informed decision-making on changes to testing and maintenance programs as required by the current NPP regulations, i.e. technical specification changes (RG. 1.74 and RG 1.177) [3, 4] and maintenance rule (10 CFR 50.65), which are formulated in terms of the RAM and risk models and the data introduced in Sections3 and 4.

5.1 *Criteria related to changes to Technical Specifications*

The current technical specifications lay down test intervals, *T*, which are given individually or for a group of relevant safety components according to their risk significance. By imposing a fixed *T*, the current technical specifications also indirectly impose a constraint on the component unavailability contribution associated with hidden failures between consecutive tests, i.e. $u_{RT,i}$ given by the sum of the contributions of Eqn. (16) and Eqn. (22), which is commensurate with its risk impact.

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 considered in this paper.

Principle 4 establishes that when changes increase core damage frequency (CDF), these increases should be small. The overall impact of the changes is normally assessed and compared to the quantitative risk acceptance guidelines in RG 1.174. For each individual change, the total change in CDF shall be less than an acceptance criterion as follows:

$$\Delta CDF(\theta) \leq \ 10^{-06} \text{ year}^{-1} \qquad (30)$$

As regards Technical Specification changes, RG 1.177 limits the single-risk contribution of a component *i* downtime to less than an acceptance criterion as follows:

$$ICCDP \leq \ 5\,.\,10^{-07} \qquad (31)$$

Principle 5 in RG 1.174 states that the impact of the proposed change should be monitored by performance measurement strategies, which are required to prove that the change does not degrade the equipment's performance, for example, as regards its reliability and availability. In certain cases, the existing performance monitoring required by the maintenance rule is adequate for equipment whose SF is controlled under the surveillance requirements in the technical specifications. The output of performance monitoring can be periodically reassessed and appropriate adjustments made to the Surveillance Frequencies (and maintenance frequencies) as required.

5.2 *Criteria related to changes to Maintenance Rule*

The objective of the Maintenance Rule (MR) [5-6] is to require monitoring the overall continuing effectiveness of licensee maintenance programs to guarantee safety and prevent the failure of Structures, Systems and Components (SSCs) to perform their safety-related functions. The following describes the requirements for monitoring the effectiveness of maintenance, which are applicable during all conditions of plant operation.

The Maintenance Rule, in 10 CFR 50.65(a)(3) [5], requires the assessment of preventive maintenance activities to ensure that the objective of preventing SSC failures through maintenance is appropriately balanced against the objective of minimizing SSC unavailability due to downtime contributions, including preventive and corrective maintenance, replacements, testing, monitoring and inspection, as recommended in the MR guidelines [6]. This means that, broadly speaking, downtimes for testing can be included in the monitoring process. Both criteria were thus considered in the MR framework, control and/or monitoring unavailability due to maintenance and surveillance testing. This objective is thus refocused on minimizing the unavailability due to downtime formulated in Eqn. (21).

The MR in 10 CFR 50.65(a)(1) [5] also sets unavailability goals in order to guarantee that the SSCs can fulfil their intended functions. These goals should be commensurate with safety and taking into account industry-wide operating experience. This constraint can be formulated as follows:

$$u_{MT} < u_{MT}^{goal} \tag{32}$$

where u_{MT}^{goal}, represents the limit of unavailability due to the downtime effect, which is not set by the regulator, but is usually based on operational NPP experience, and normally takes values in the range [0.01, 0.05], depending on the risk significance of the monitored component.

6 OPTIMIZATION APPROACHES

This section describes three approaches for testing and maintenance optimization problems (OPs) based on the criteria introduced in the previous section. Each approach represents a different implementation alternative of the RMTS philosophy. The first approach, OP_1, is based on the current situation in Spanish NPPs with static surveillance requirements, which are kept fixed, and dynamic maintenance, which can be optimized. The second, OP_2, searches for a single/permanent and optimal risk-informed change of a surveillance requirement once the dynamic maintenance has been optimized following alternative OP_1. OP_3 represents an alternative that aims to harmoniously optimize SR and maintenance activities, based on the concept of flexible surveillance requirements and dynamic maintenance, which can be adjusted according to the ageing and obsolescence scenario faced in long-term NPP operations.

Firs [illegible] he criteria established in the Maintenance Rule (see CFR 50.65(a)(3) [5]), as follows:

$$
\begin{aligned}
&Min \quad u_{MT}(M) \\
&s.t.: \quad \Delta CDF(M) < 10^{-06}\text{year}^{-1} \qquad (33) \\
&\qquad u_{MT} \leq 0.05 \\
&\qquad M1 \leq M \leq M2 \\
&\qquad M = aT\,;\ \ a \in \mathbb{N} \\
&\qquad T = T_{TS} \\
&d.\,v.: \quad M
\end{aligned}
$$

In Eqn. (33) the preventive maintenance interval, *M*, is the only decision variable that can range between *M1* and *M2*. The test interval, *T*, is kept at the value laid down in the current NPP Technical Specifications. *T* thus acts as a constraint on this optimization problem. Other constraints are imposed on the unavailability contributions due to downtimes for testing and maintenance, u_{MT}, and the increase in the CDF, ΔCDF. The final constraint is that *M* must be a multiple value of *T*.

Secondly, OP_2 can be formulated to try to minimize u_{RT}, considering that maintenance interval M is kept at the value found after solving OP_1 (providing an optimal value of M=M_{op1}), as follows:

$$
\begin{aligned}
&Min \quad u_{RT}(T) \\
&s.t.: \quad \Delta CDF(T) < 1.0E-06 \qquad (34) \\
&\qquad u_{MT} \leq 0.05 \\
&\qquad T1 \leq T \leq T2 \\
&\qquad M = aT\,;\ \ a \in N \\
&\qquad M = M_{op1} \\
&d.\,v.: \quad T
\end{aligned}
$$

In Eqn. (34) the test interval, *T*, is the only decision variable that can range between *T1* and *T2*. Preventive Maintenance interval *M* acts as a constraint to this optimization problem, as described above. Other constraints are imposed on the unavailability contributions due to downtimes for testing and maintenance, u_{MT}, and the increase in the CDF, ΔCDF. The final constraint is that M must be a multiple value of T.

The third alternative is a hybridization of the previous approaches and aims to introduce improvements in testing and maintenance policies that minimize the total unavailability of the component. OP_3 thus aims to minimize total unavailability, *u*, i.e. the sum of the unavailability due to unreliability, u_R, and downtime unavailability contributions due to maintenance and testing activities, u_{MT}. It can be formulated as follows:

$$Min \quad u(T,M)$$

$s.t$:

$$u_{MT} \leq 0.05$$

$$T1 \leq T \leq T2$$

$$M1 \leq M \leq M2$$

$$M = aT\ ;\ \ a \in N$$

d. v.: $\{T, M\}$

In Eqn. (35) both test interval *T* and maintenance interval *M* act as decision variables, ranging between *T1* and *T2*, and *M1* and *M2*, respectively. Other constraints remain the same as in OP_1 and OP_2.

As shown in this section, total unavailability depends on the T and M policies applied. Adopting Strategy 3 allows the NPP operator to set the best plan for the flexible adaptation of testing and maintenance and reduces the unavailability of the systems and components to the minimum. In contrast, the first strategy, in which the testing interval remains fixed, limits the plant management and the space of possible solutions that minimize total unavailability. The second strategy is an intermediate situation that can find optimum values in a better search space than the first, but places solutions in discontinuous regions in which the change in the testing interval is conditioned by an optimal maintenance interval, which remains fixed. The third strategy therefore seems in theory the best strategy to ensure the adequate management of plant equipment and reduce risks. The case study described below is intended to demonstrate these assumptions.

7 CASE STUDY

The case study can be placed in the context of a Periodic Safety Review (PSR) in which re-examining the NPP safety assessment is required to apply for a renewed licence for plant operations. The PSR should include a study of the RAM and the risk impact of equipment ageing for the extra NPP operating time, represented by parameters α and p_1 in the previous models, which may include long-term operations when the NPP is close to the end of its design life. The extra time, which may coincide partially or totally with the license renewal period, e.g. 10 years, may be adopted as the *TR*. Technical obsolescence may be considered to degrade maintenance effectiveness ε_S *and* ε_D in this time horizon, which should be compensated by the appropriate optimization of *M* and *T* intervals when possible. Otherwise, other measures for technical obsolescence management should be explored.

7.1 *Safety-related equipment, RAM, risk models and data*

A motor-operated valve (MOV) in the Auxiliary Feed Water System (AFWS) was considered since it is one of the most important safety components of a PWR NPP. The age-dependent RAM models described in Section 3 were integrated into an available Level 1 PRA of the PWR NPP, which is adopted as an age-dependent risk model to evaluate the risk impact described in Section 4, following the approach proposed in

Ref. act according to the testing and maintenance intervals, and the effect of ageing and obsolescence for the time horizon considered, in this case TR equal to10 years (87600h).

Table 1shows the values of the parameters associated with the RAM model of the MOV considered, as well as the test and maintenance intervals initially considered in the PRA, based on the current Technical Specifications for the PWR NPP. These RAM model parameters were estimated from historical data in a previous study (Ref. [28]).

Table 1. RAM data for a Motor-Operated Valve

Description	**Parameter**	**Value**
Baseline standby failure rate	$\lambda_0(h^{-1})$	5.86E-06
Maintenance effectiveness for standby failures	$\varepsilon_S(-)$	0.995
Linear ageing factor	$\alpha(h^{-2})$	3.424E-10
Surveillance test efficiency to detect failures in stand-by	$\eta_D(-)$	0.6
Functional test efficiency to detect failures in stand-by	$\eta_R(-)$	1
IMM	-	PAR
Baseline demand failure probability	$\rho_0(-)$	6.42E-03
Degradation factor for failures on demand	$p_1(-)$	5.415E-3
Maintenance effectiveness for failures on demand	$\varepsilon_D(-)$	0.886
Surveillance test efficiency to detect failures on demand	$\eta_D(-)$	1
Imperfect Maintenance Model	-	PAS
Downtime for surveillance testing	$\tau(h)$	1
Downtime for preventive maintenance	$\sigma(h)$	1
Downtime for corrective maintenance	$\mu(h)$	24
Surveillance test Interval fixed in the available PRA	$T_{PRA}(h)$	2190
Maintenance interval fixed in the available PRA	$M_{PRA}(h)$	13140

7.2 *Optimization results*

This section gives the results obtained for each of the three Optimization Problems (OPs) described in Section 6. The above-described RAM, risk models and data were adopted under several maintenance and surveillance test intervals in a ten-year horizon. In the three approaches the unavailability due to downtime effects, u_{MT}, the sum of the unreliability contributions and testing, u_{RT}, the total unavailability, u, and the increase in the CDF, ΔCDF, were calculated. The optimization problems were solved using a heuristic search algorithm [31]. Table 2 summarizes the results obtained for each optimization problem and show that all the values of downtime unavailability, u_{MT}, are below the limit set in 10 CFR 50.65(a)(1), in this case equal to 0.05. The cons[illegible] in all three cases.

Table 2. Results of each optimization problem

Case	Test Interval [hours]	Maintenance Interval [hours]	u_{MT}	u_{RT}	u	Increase in the CDF (ΔCDF) [$year^{-1}$]
PRA Case. Initial values	2190	13140	5.47E-04	2.93E-02	2.94E-02	6.05E-07
OP1	2190	21840	5.23E-04	3.85E-02	3.85E-02	8.441E-07
OP2	624	21840	1.67E-03	3.53E-02	3.53E-02	7.60E-07
OP3	720	5040	1.60E-03	1.99E-02	2.01E-02	3.60E-07

Figure 3 plots the relevant results from OP_1. In this figure, u_{MT} is drawn as a function of M for a fixed test interval laid down in the current Technical Specifications of the PWR NPP, T_{TS} equal to 2190h. The maintenance interval was allowed to take values from 24h to 21888h. The objective function OP_1 focused on minimizing the value of u_{MT}. The value of M_{op1} that minimizes the value of u_{MT}(M) is equal to 21840 hours (red dot in Figure 3), which yields u_{MT} = 5.23E-04.

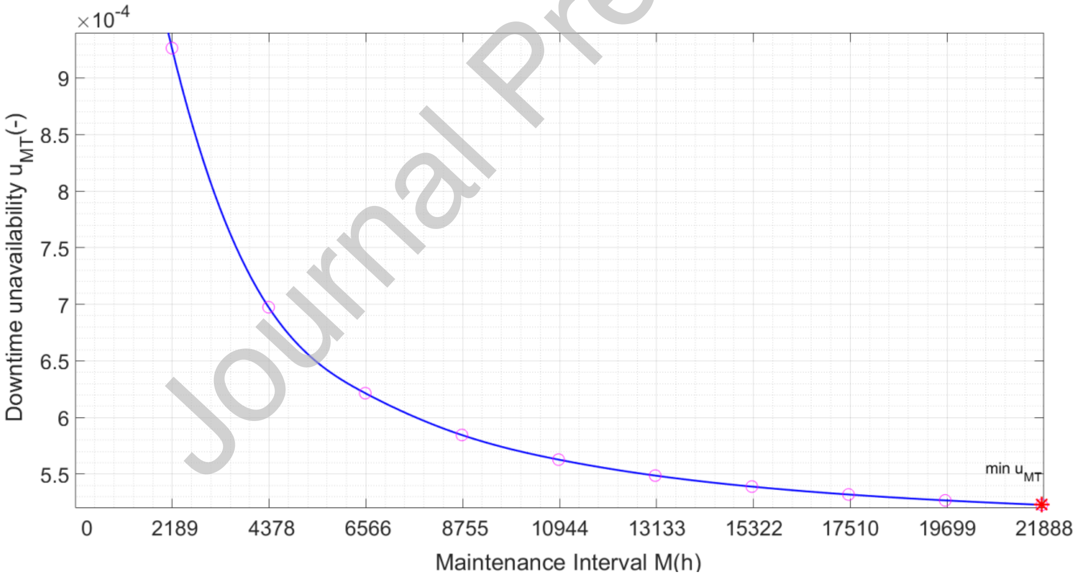

Figure 3. Unavailability due to downtime effect versus M (T_{PRA}=2190 h)

Figure 4 plots relevant results from OP_2. In this figure u_{RT} is drawn as a function of T for a fixed maintenance of M_{op1} found in the previous optimization problem. The test interval was allowed to take different *T* values between 24 h and 13128 h. The objective function OP_2 focused on minimizing the value of u_{RT}. The value of T_{op2} that minimizes the value of u_{RT}(T) is thus equal to 624 hours (red dot in Figure 4), which yields u_{RT} = 3.53E-02.

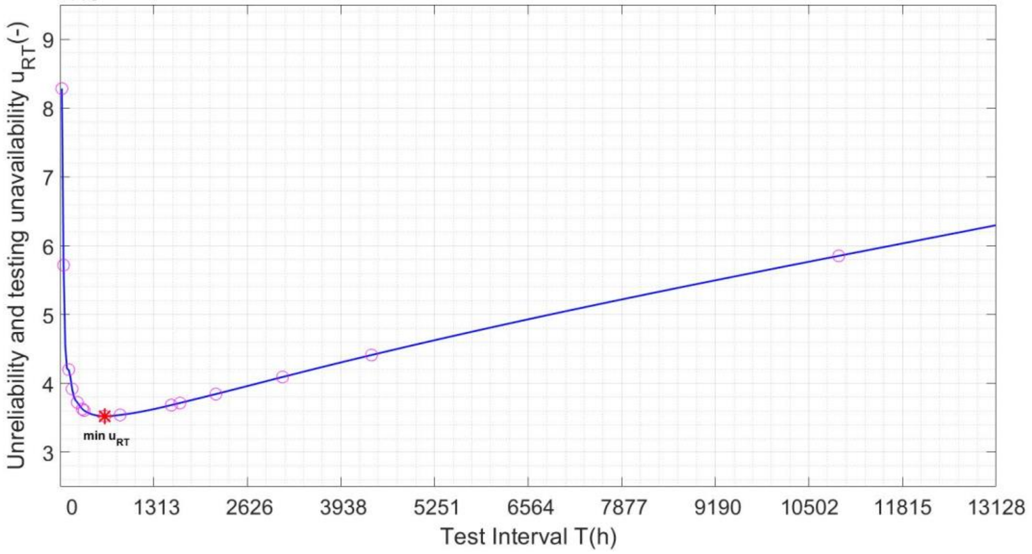

Figure 4. Unavailability due to unreliability and the downtime due to testing versus T evaluated in M_{1OP}

Figure 5 plots results of OP_3, in which the values of *u* for different combinations of *T* and *M*, are represented in the 3D plot. For these combinations, a grid is drawn that represents *u* as a function of T and M. The test interval was allowed to vary from 24h to 13128 h, while the maintenance interval was allowed to range between 24 h and 21888 h. The objective function OP_3 focused on minimizing the value of *u*. The couple {T, M} for which this unavailability reaches the minimum, i.e. *u*=2.01E-02, is that of {T_{op3}, M_{op3}}, being {720, 5040} in hours. This couple is represented in Figure 5 by a red dot.

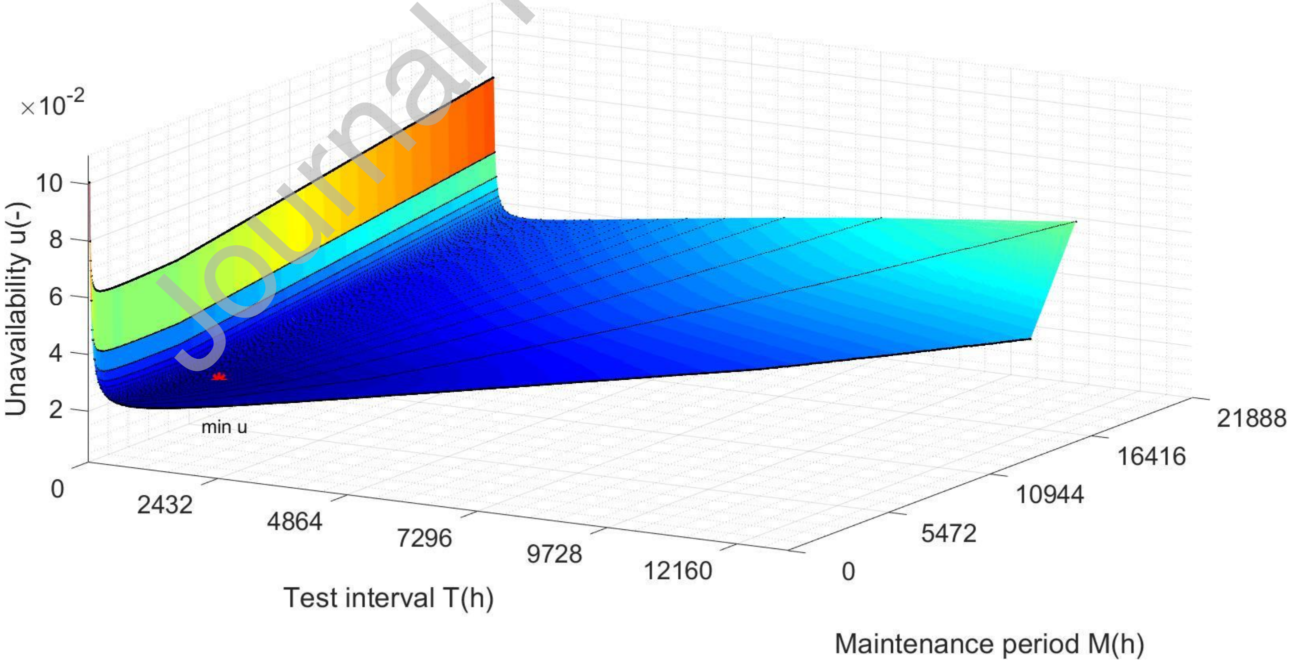

Figure 5. Total unavailability versus T and M

Figure 6 plots the 3D evolution of the *ΔCDF* for this OP_3 as a function of the value of the couples {*T,M*}, in which two different types of behaviour can be seen. The first consists of the grid in which the black dots repr he combinations of T and M in which the constraint for ΔCDF is not accomplished, ΔCDF >1.0E-06 / year.

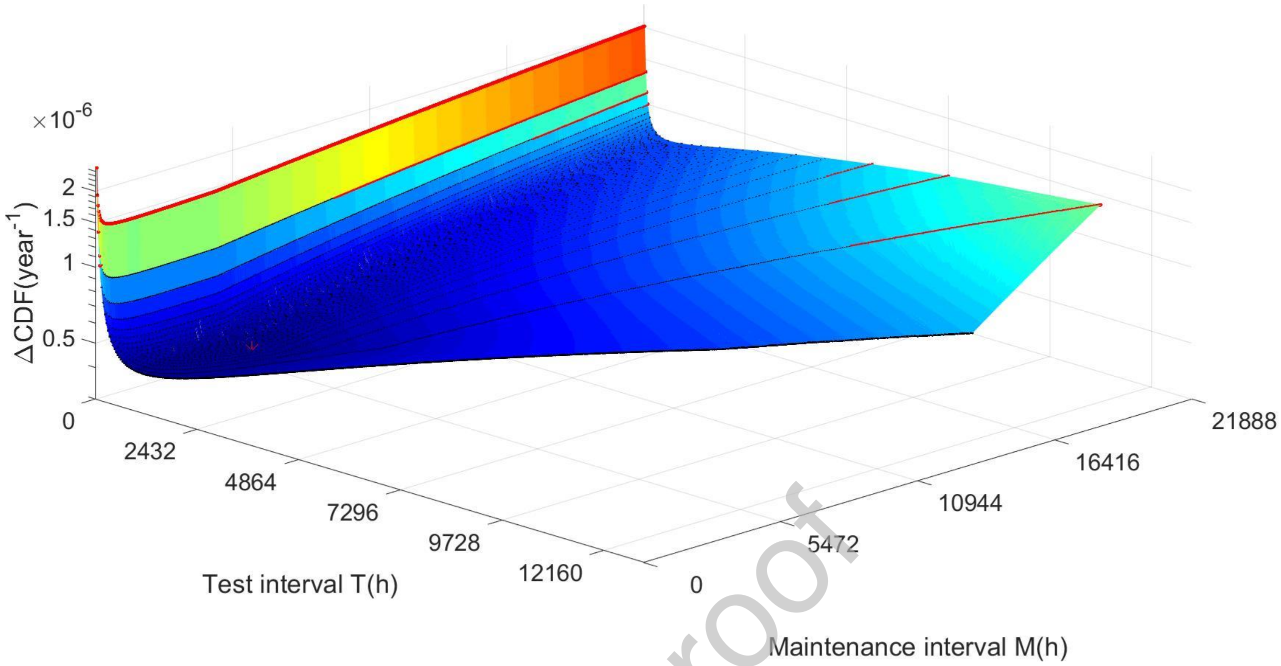

Figure 6. ΔCDF versus T and M

Finally, OP_2 yields better results than OP_1, i.e. optimizing T after having optimized M is advisable, as it is a better compromise between u_{MT} and u_{RT} and allows lower equipment unavailability, u, and therefore has a smaller impact on the ΔCDF. However, OP_3 provides the best results and suggests that the simultaneous optimization of T and M is the best alternative to find the lowest equipment unavailability and therefore the smallest impact on the ΔCDF, which verifies all the decision criteria imposed by the regulator. However, this approach departs from the principle that both test and maintenance planning should be made more flexible, which depends on the regulatory context.

7.3 *Sensitivity analysis of technical obsolescence*

This section gives the results of a sensitivity analysis carried out to study the effect of technical obsolescence on the results obtained, adopting the OP_3 approach.

As technical obsolescence affects both equipment reliability and maintainability, it influences not only equipment ageing, which conditions equipment inherent reliability, but also equipment downtime for maintenance, according to the obsolescence management strategy adopted. It may either increase the ageing rate and reduce maintenance effectiveness, which in turn increases equipment ageing and reduces its reliability, or it may increase maintenance downtime, mainly because of the provisioning logistics of spare parts.

The aim of a technical obsolescence management program (OMP) is to keep these adverse effects under control. One of the main issues of technical obsolescence management is to decide the appropriate strategy for eac a compensatory measure to the component, for example by adapting the maintenance and testing plan. In its simplest form, this may include changing only the testing and maintenance intervals. This section explores how changing testing and maintenance intervals following the OP$_3$ approach can help to compensate the effect of technical obsolescence.

Briefly, it is assumed that obsolescence degrades only maintenance effectiveness $\{\varepsilon_S, \varepsilon_D\}$ and, other than re-adjusting testing and maintenance intervals, no other compensatory measure is adopted. In the sensitivity study proposed here, OP$_3$ is considered and maintenance effectiveness $\{\varepsilon_S, \varepsilon_D\}$ ranges between the initial values (see Table 3) and 0.1. The optimal maintenance and test intervals, total unavailability and the increased CDF for each case are shown in Table 3. The results are shown in Figure 7, in which the couples {T, M} are plotted.

Table 3. Results of sensitivity for ε_S and ε_D on the optimal {T, M} that minimizes *u* and *ΔCDF*

ε_S (-)	**ε_D (-)**	**T [hours]**	**M [hours]**	**u**	**ΔCDF [year^{-1}]**
0.995	0.886	720	5040	2.01E-02	3.60E-07
0.1	0.1	336	2352	8.08E-02	1.95E-06
0.1	0.3	336	3360	8.05E-02	1.95E-06
0.1	0.7	336	3360	8.03E-02	1.94E-06
0.1	0.5	336	3360	8.03E-02	1.94E-06
0.3	0.1	336	2352	6.79E-02	1.62E-06
0.3	0.3	336	2352	6.77E-02	1.61E-06
0.3	0.5	432	4320	6.76E-02	1.61E-06
0.3	0.7	432	4320	6.75E-02	1.61E-06
0.5	0.5	504	2016	5.41E-02	1.25E-06
0.5	0.1	504	2016	5.43E-02	1.26E-06
0.5	0.3	504	2016	5.41E-02	1.25E-06
0.5	0.7	504	2016	5.40E-02	1.25E-06
0.7	0.1	552	1104	4.01E-02	8.85E-07
0.7	0.3	432	1296	4.00E-02	8.82E-07
0.7	0.5	432	1296	3.99E-02	8.81E-07
0.7	0.7	432	1296	3.99E-02	8.81E-07
0.9	0.1	672	1344	2.48E-02	4.84E-07
0.9	0.3	672	1344	2.48E-02	4.82E-07
0.9	0.5	672	1344	2.47E-02	4.82E-07
0.9	0.7	672	1344	2.47E-02	4.81E-07
0.9	0.9	672	1344	2.47E-02	4.81E-07

Figure 7 gives the optimal results of each couple $\{\varepsilon_S, \varepsilon_D\}$ with the associated *u* value, i.e. $(u; \{\varepsilon_S, \varepsilon_D\}$. The results shown in red represent the optimal solutions found by the OP$_3$ alternative, which does not satisfy the regulatory constraints imposed on the *ΔCDF*. This happens when maintenance effectiveness $\{\varepsilon_S, \varepsilon_D\}$ gradually falls be compensated by optimal tuning of the testing and maintenance intervals. As shown in Figure 7, if maintenance effectiveness ε_S goes below 0.7 there is no constraint on ΔCDF. Compensatory measures other than simply re-adjusting the testing and maintenance intervals should be explored within an OMP in such situations.

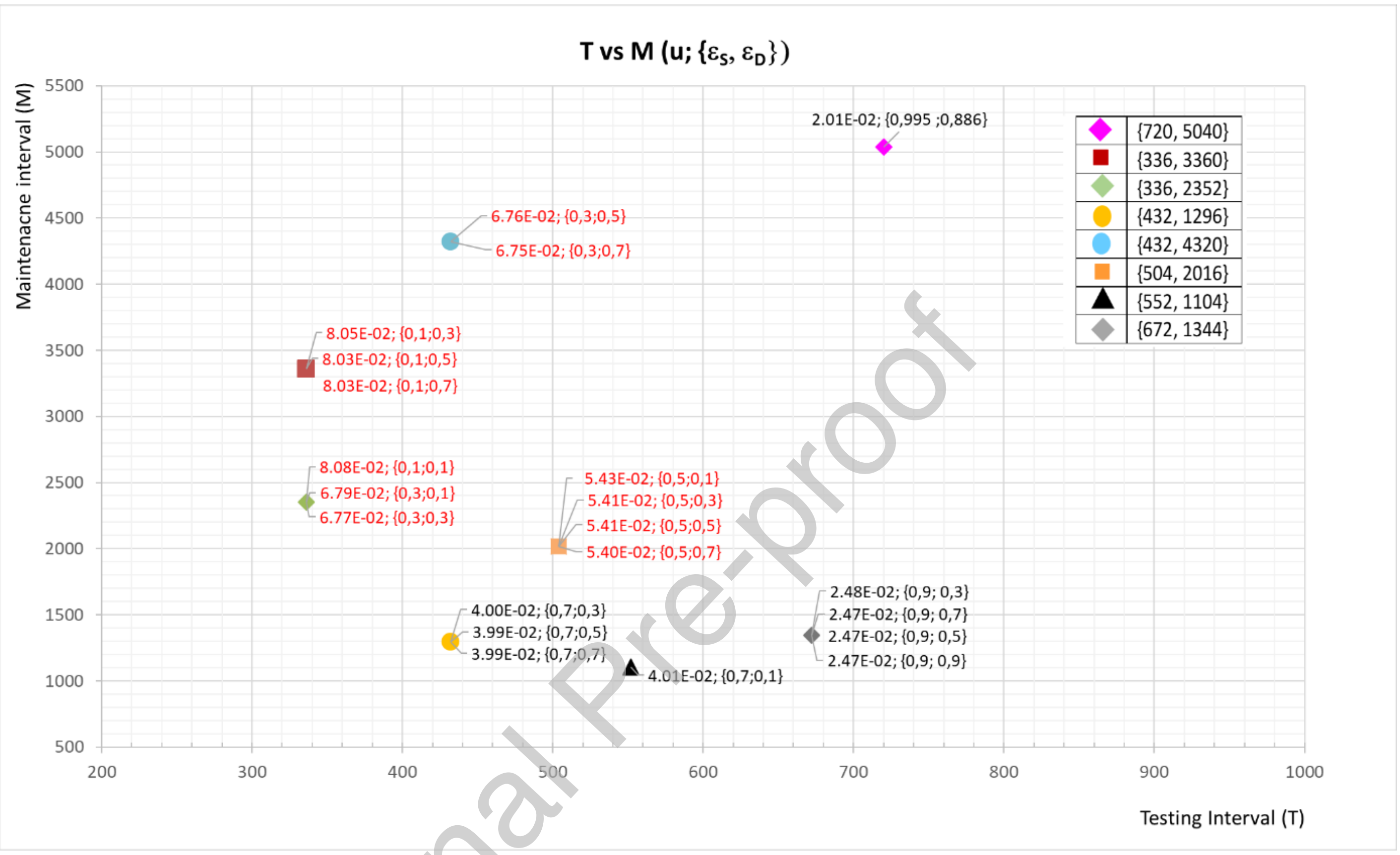

Figure 7. Optimal T versus M for different values ofε_S and ε_D.

8 CONDLUDING REMARKS

This paper compares different optimization alternatives with the aim of harmonizing surveillance requirements and maintenance in an RMTS framework in which RAM and risk-informed regulatory decision criteria must be satisfied.

Three optimization problems were formulated using age-dependent RAM and risk models that consider a detailed physical model of equipment performance. The RAM models proposed explicitly account for the effect of equipment ageing and the positive and negative effects of surveillance tests and maintenance activities. These models were used to evaluate the RAM and risk impact of changing test and maintenance intervals in the context of equipment ageing and technical obsolescence.

A ca [illegible] on, e.g. in a Periodic Safety Review that requires an NPP safety assessment to renew the plant’s operating licence close to the end of its design life or for long term operation. The case study focuses on a motor-operated valve in the Auxiliary Feed Water System, one of the most important safety components in a PWR NPP. The RAM and risk model parameters were taken from a previous study that approached the problem of estimating model parameters using historical failure, testing and maintenance data.

The approaches proposed in this paper may be used by NPP operators and regulatory bodies in the context of the self-assessment of safety factors, particularly for long term operations, such as ageing and obsolescence, the role of maintenance plans and surveillance requirements (in ETF) and their impact on plant risk. For example, with the aim of enabling utilities to relocate surveillance frequencies to licensee control by using an approved risk-informed approach, initiative RITS-5b [7] could take advantage of the OP$_3$ alternative.

A sensitivity analysis was also carried out to study the effect of technical obsolescence on the results obtained by OP$_3$. The results show that although the optimal result of the couple {T,M} depend on technical obsolescence, this approach can help to compensate for the effect of technical obsolescence to some extent. Measures other than simply re-adjusting surveillance testing and maintenance intervals should thus be explored when technical obsolescence has a strong impact on maintenance effectiveness, and may require, for example, the implementation of an obsolescence management program.

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