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Aging Evaluation for the Extension of Qualified Life of Nuclear Power Plant Equipment

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1. Introduction

In recent decades, the aging of nuclear power plants, the upgrading of safety systems and the concern for life extension of licensed plants close to completing 40 years of operation have been considered by regulatory agencies.

The extension of operating licenses for power reactors over 40 years has been a viable option for operators of nuclear power plants to ensure the adequacy of future capacity of power generation, in terms of economic benefits, compared with the construction of new power reactors.

Routine reviews of nuclear power plant operation (including modifications to hardware and procedures, significant events, operating experience, plant management and personnel competence) and special reviews following major events of safety significance are the primary means of safety verifications. Rereviews include an assessment of plant design and operation against current safety standards and practices, and they aim at ensuring a high level of safety throughout the plant's operating lifetime. They are complementary to the routine and special safety reviews and do not replace them (IAEA, 2009).

In 1991, the US Nuclear Regulatory Commission (NRC) issued rules and associated documentation describing how the licensee must demonstrate that the unit can continue operating for 20 years following the expiration of the 40-year license. These rules were established in 10CFR51 (NRC, 2007a), environmental protection requirements, and 10CFR54 (NRC, 2010a), technical requirements.

In 1994, the International Atomic Energy Agency (IAEA) issued recommendations, guidance and associated documentation describing how the licensee must demonstrate that the unit can continue operating through a systematic safety reassessment, named periodic safety review (PSR) (IAEA, 1994, 2003). The safety guide has the purpose of providing recommendations and guidance on the conduct of a PSR each 10 years for an existing nuclear power plant, and it is directed at plant operating organizations and regulators. In addition, some member states have initiated this reassessment to evaluate the cumulative effects of plant aging and plant modifications, operating experience, technical developments and siting aspects.

Considering this scenario, it is important to pursue knowledge and competence to assess the impact of aging and degradation mechanisms in systems and equipment for a nuclear plant, and from this knowledge, to decide on the plant acceptability considering the operational experience. The knowledge of these effects can indicate what action is applicable (renewal or repair), and then assist in corrective actions to be adopted.

The purpose of this chapter is to discuss and present an application of probabilistic models for the rate of occurrence of failures of active repairable systems using stochastic point processes, to decide for the extension of qualified life of equipment. The model application is within the context of the Plant Life Management (PLIM) and the Plant Life Extension (PLEX) or License Renewal of Nuclear Power Plants. The basic literature on PLIM and PLEX is (NRC, 2010b, 2010c, 2005; IAEA, 1994, 2002, 2003, 2004; Young 2009a, 2009b, 2009c).

The emphasis for this subject is the maintenance rule (NRC, 1997, 2000, 2007b; NEI, 1996). This rule is a prerequisite for the license renewal for US plants (Young, 2009c), and it provides an aging management tool for active equipment. Its performance criteria monitoring combined with the license renewal rule, equipment qualification, and life cycle management provides a sound basis for extending operation periods (Saldanha et al., 2001; Saldanha & Frutuoso e Melo, 2009).

The chapter is organized as follows. Section 2 discusses the aging concepts, aging management, equipment qualification, life extension and repairable systems. Section 3 presents an overview of the regulatory aspects related to plant life management and plant life extension. Section 4 discusses the aging evaluation for extension of qualified life of repairable systems through stochastic point process (non-homogeneous Poisson model, NHPP). Section 5 presents a case study of service water pumps of a pressurized nuclear power plant. Section 6 presents conclusions and recommendations. References can be found in Section 8. It is noteworthy that NRC periodically updates paragraphs and appendices of 10 CFR Part 50 and associated Regulatory Guides. The references to these documents are related with the dates of last update described in the address <http://www.nrc.gov/reading-rm/doc-collections/cfr/part050/>.

2. Basic concepts

Operational experience at nuclear power plants has shown that two types of time-dependent changes occur in systems, structures and components/equipments (SSC): physical aging, or aging (that, henceforth, will be used in this text), which results in degradation (gradual deterioration) in physical characteristics; and the obsolescence that is the condition that occurs in structures and components that cease to be useful, despite being in perfect condition, owing to the emergence of other technologically more advanced ones.

Then, aging means the ongoing process by which physical characteristics of a system, structure and components or equipment (equipments and components will be used interchangeably in this text) change with time or usage. This process can proceed through a single aging mechanism or as the contribution of several mechanisms (cumulative effects).

Aging can lead to large scale degradation of physical barriers and redundant components, which can result in common-cause failures. These conditions can reduce the margins of safety equipment to values below the plant design basis or regulatory requirements, and cause damage to safety systems.

The knowledge of the aging and degradation processes and the developing of methods and guidelines for its management is important to the reliable and safe operation of nuclear power plants. The management of aging components can predict or detect the degradation of a component and take the appropriate corrective mitigation actions.

Evaluation of the cumulative effects of both physical aging and obsolescence on the safety of nuclear power plants is a continuous process and is assessed in a periodic safety review or an equivalent systematic safety reassessment program, as a renew of operating licenses, (IAEA, 2009).

The equipment qualification program of a nuclear power plant provides an effective aging management of plant components important to safety. The scope of the equipment qualification program should include equipment that performs safety functions and contributes to safety functions performance. Noteworthy is the demonstration that the equipment will continue performing its safety functions under harsh environmental conditions. These service conditions are those that exist after the postulated initiating event, and they are significantly different from normal operating conditions, which have their functionality demonstrated by performance during normal operation (pre-operational tests and periodic testing).

Qualified life (established by equipment qualification program) is the period of time of normal operation for which an aging degradation would not prevent satisfactory performance of equipment if a postulated initiating event were to occur. The qualified condition of equipment established is expressed in terms of one or more measurable condition indicators for which it has been demonstrated that the equipment will meet its performance requirements, (IAEA, 2009).

Installed life is the period of time from the installation to the removal of equipment. A system, structure or equipment can have components whose qualified life can be lesser than the installed life. These components can be replaced (renewal) or undergo a repair program to maintain their qualification.

According to (IAEA, 2009), it is important to demonstrate that aging issues have been correctly taken into account for the whole planned plant lifetime, by ensuring that: (1) qualification tests take into account potential aging effects, in light of international knowledge and practice; (2) environmental conditions at the site are monitored to detect any changes from assumed values; (3) procedures for modifying qualified lifetimes are provided, especially in the case of changes from assumed values or of increasing failure frequency of some item of equipment; and (4) procedures for adapting aging tests and their duration of validity are provided.

The extension of qualified life should be approached through probabilistic methods. The evaluation based on deterministic methods defines the difference between the current state and condition of the item in the qualification phase, but does not define its probability of continuing performing its function adequately for a period longer than the one defined by its qualified life.

The combination of deterministic and probabilistic methods in the evaluation stage of aging effects is necessary because the extension of qualified life is an item of upgrading to a new life cycle since the system or equipment has operated for a number of years.

During operation, predictive, preventive and corrective maintenance work to maintain equipment in proper performance. Thus, maintenance works in both: functional equipment aspects, and how to check its availability through periodic tests laid down in the technical specifications and operating procedures.

In the operation of a nuclear power plant, the effectiveness of maintenance becomes an essential parameter in assessing system reliability (NRC, 2007a). It can be observed that the pursuit of maintenance effectiveness can not be done without: (1) adequate knowledge of aging mechanisms, (2) to assess the conditions for qualification of equipment, and (3) knowledge of equipment performance and trends in the records of operational experience.

A system may be defined as a collection of two or more components which must perform one or more functions. Nonrepairable systems are those which, when fail, must be replaced by new ones. Repairable systems are those which, after failure to perform at least one of their required functions, can be restored to perform all of their required functions by any method, other than the replacement of the entire system, and put into operation again under the same conditions before failure. By this definition, it is possible to repair without replacing any component (Asher & Feingold, 1984).

The failure process of a repairable system depends on the failure mechanism of the equipment and the maintenance policy applied. Hence, the choice of the statistical model to analyze the failure data of a repairable system should take into account the maintenance policy applied to the equipment, (Calabria et al., 2000).

The effects of aging increase the probability of equipment failures or even make it unavailable. These effects are traditionally calculated by using reliability models incorporating rates of time-dependent occurrence of failures. Thus, the behavior of components and systems in a plant are represented through changes in failure rates with time (Hassan et al., 1992).

The idea of modeling aging effects by simply considering that time-dependent failure rates can model this effect is not necessarily adequate because failure times may not be independent and identically distributed. This leads to the use of point processes and the concept of rate of occurrence of failures. Then, it is necessary to carefully evaluate the rate of occurrence of failures behavior detected in periodic testing and maintenance performance on the equipment and on the system. These actions can significantly impact aging effects studies (Saldanha et al., 2001; Saldanha & Frutuoso e Melo, 2009).

3. Regulatory aspects of plant life management and plant life extension

There are two regulation concepts for long term operation of nuclear plants. One is based on the periodic safety review, the other on the license renewal. Most European countries use the periodic safety review. The renewal of licenses is the practice adopted in the US. Both approaches have been adapted in some IAEA member states, including approaches that combine those two concepts. More detailed information about the practices and experiences of IAEA member states can be found in (IAEA, 2006, 2010).

Technical requirements and elements of the life management program remain the same for the two concepts (preventive maintenance and aging management programs, time limited aging analysis, equipment maintenance and qualification of response to obsolescence issues).

Considering regulatory aspects, it is important to control aging management practices of the operating organization and to verify the validity of forecasts for aging systems, structures and components important to safety. The environmental impact of long term operation, due to plant life management has to be assessed, although the study details depend on regulatory requirements (IAEA, 2006)

3.1 Periodic safety review

The periodic safety review is governed by the Safety Guide NS-G-2.10 (IAEA, 2003). It is a systematic review of a nuclear power plant safety analysis conducted at regular intervals

(usually 10 years) to deal with aging cumulative effects (both physical aging and obsolescence), modifications, operating experience, changes in international safety standards, to ensure a high level of safety through the operating lifetime of the plant. Thus, it has become an instrument for responding to requests by operating organizations allowed to continue operating plants beyond a deadline licensee or a specified period of safety evaluation. The process of periodic safety review is valid for nuclear power plants throughout its lifetime and guarantee that there remains a basis for valid licenses.

The regulatory system does not limit the number of periodic safety review cycles, even if the new cycle extends beyond the original design lifetime of the plant. The only condition is to demonstrate the plant safe operation for the next periodic safety review cycle, while maintaining safety margins. The periodic safety review is a tool that may be used by regulatory bodies to identify and solve safety issues (IAEA, 2006).

According to (IAEA, 2009), the review objective of aging management in a periodic safety review by operating organization is: (1) to determine whether aging in a nuclear power plant is being effectively managed so that required safety functions are maintained, and (2) whether an effective aging management program is in place for future plant operation (IAEA, 2003).

Therefore, the review of aging management within a periodic safety review therefore aims to establish whether: (1) for each SSC important to safety, all significant aging mechanisms have been identified; (2) there is a thorough understanding of relevant aging mechanisms and their effects; (3) the aging behaviour of SSCs over the period of operation is consistent with predictions; (4) there are adequate margins in respect to aging to ensure safe operation for at least the period until the next periodic safety review is due; (5) there is an effective aging management program (addressing operations, chemistry, maintenance, surveillance and inspection) in place for future plant operation, (IAEA, 2009).

Aging management for nuclear power plants is governed by safety guide NS-G-2.12 (IAEA, 2009). The objective of this safety guide is to provide recommendations for aging managing of SSC important to safety in nuclear plants. It focus on: (1) for the operating organization, providing technical support to establish, implement and make improvements of aging management program; and (2) regulatory organizations, providing technical support to prepare standards and regulatory guides to verify whether aging is being properly and effectively managed. It highlights the basic concepts of aging management and makes recommendations to make the proactive management of physical aging during the life of a nuclear power plant, presents a systematic approach to aging management of nuclear plants in operation, management of obsolescence, and aging management review in support of long-term operation.

IAEA has sponsored various programs and projects related to the aging of nuclear power plants, focusing on the management of aging, long-term operation reliability and economical aspects of life extension of licensed plants. The results of these programs are expressed in a series of technical documents related to methodologies for aging management, guide to operational data collection and maintenance for the management and evaluation mechanisms of aging (IAEA, 1992, 1992b, 1998, 1999, 2002, 2004, 2006, 2008). These documents can support and be references in the implementation of safety guide NS-G-2.12 (IAEA, 2009).

3.2 License renewal

The operating licenses of US plants have been issued with its lifetime of 40 years of operation. This limit was established by the 1954 Atomic Energy Act, which considered the perspectives of energy consumption.

The emphasis of this discussion focuses on the requirements of 10CFR54 (NRC, 2010a). The process of renewing the operating license is based on two principles: (1) the regulatory process, continued during the extended period of operation, is adequate to ensure that the licensing bases of all plants proceed at acceptable safety levels, with the possible exception of adverse effects of aging on certain systems, structures and components, and possibility of a few other issues related to safety during the extension period of operation; and (2) the licensing basis of each plant is maintained during the license renewal.

10CFR54 (NRC, 2010a) requires operators to identify all systems, structures and components: (1) that are related to safety; (2) whose failure may affect functions related to safety; and (3) that are able to demonstrate compliance with NRC fire protection requirements, 10CFR50.48 (NRC, 2007c), environmental qualification 10CFR50.49 (NRC, 2007d), heat shock 10CFR50.61 (NRC, 2007e), reactor transient shutdown reactor provided without scram 10CFR50.62 (NRC, 2007f), and total loss of electrical power into alternating current 10CFR50.63 (NRC, 2007g).

Requirements should be included in the license renewal application in conformance to regulatory guide RG 1.188 (NRC, 2005), which will be assessed according to the standardized review plan, NUREG-1800 (NRC, 2010b). Structures and passive components are included in this item, they perform their functions without moving parts or without changes in the configuration, as follows: reactor, steam generator, piping, supports, seismic structures.

Active equipments are considered adequately monitored by the existing regulatory process where aging effects that may occur are more easily detectable, and therefore, more easily corrected, either by the testing program, or by the maintenance program, or even through the indicators highlighted in this performance (NRC, 2007b; NEI, 1996).

The important activity is the evaluation of the Analysis of Time-Limited Aging (TLAA), which is a set of analyses and calculations that involve systems, architectures and components that fall within the scope of the rule. TLAA should consider aging effects with approaches based on the original 40 years period, and: check the limits of renewal period, review or recalculate these limits by determining whether the sentence is appropriate, and demonstrate that aging effects are covered by the calculations.

License renewals are based on the determination that each plant will continue to maintain an adequate level of safety and, over plant life, this level should be increased by maintaining the licensing basis, with appropriate adjustments to consider new information from operational experience. The licensee may submit the license renewal to NRC 20 years before the end of the term of the current operating license.

4. Aging evaluation for extension of qualified life

The study of time-dependent failure rate models conducts to (Ascher & Feingold, 1969, 1978, 1984; Ascher, 1992; Ascher & Hansen, 1998). They discuss and establish the terminology and notation used for performing the statistical analysis of repairable systems. They emphasize the distinction between non-repairable and repairable systems related to times to failure. They also criticize the reliability literature which considers repair as a renewal of the system to its original condition (the so-called 'as good as new' concept). They consider that this assumption is unrealistic for probabilistic modeling and leads to major distortions in the statistical analysis.

The non-homogeneous Poisson process (NHPP) and the renewal process (RP), generally homogeneous Poisson process (HPP), are commonly used models for repairable systems.

NHPP assumes that the unit is exactly at the same condition immediately after repair as it was immediately before failure ("as bad as old" concept), assuming that the repair time is negligible, while for the renewal process the repaired unit is always brought to a like new condition (as good as new concept). These two models and their implications are discussed in detail in (Ascher & Feingold, 1984).

NHPP application to the evaluation of the extension of qualified life can be useful due to the possibility, by controlling and monitoring the NHPP parameters, to identify whether the failure process is homogeneous in time. Then, by applying adequate corrective maintenance actions to mitigate aging effects, the repairable system can return to or be maintained under a homogeneous process.

Non-homogeneous Poisson point processes have wide application, like the analysis of failure occurrence trends, (Asher & Feingold, 1984), optimal replacement problems, (Bagai & Jain, 1994), warrant data analysis, (Majeske, 2003) and accident sequence precursor analysis, (Modarres et al., 1996). NHPP applications have been extensively made to the reliability growth model, (Crow, 1974). This model has been applied to the defense and aerospace industries in the US. Krivtsov (2007a) considers some practical extensions in the reliability application of this model.

It is possible to postulate a variety of point process models for the analysis of repairable systems. If one focus attention on the non-homogeneous Poisson process (NHPP), then it will be clearly seen that it is able to model time-dependent rates of failure occurrence. This model is conceptually simple and the relevant statistical methodology (maximum likelihood estimation and linear regression modeling) is well developed and easy to apply.

The importance of NHPP resides in the fact that it does not require the conditions of stationary increments. Thus, there is the possibility that events may be more likely to occur during specific time intervals. The NHPP has memory. Then, it is an adequate tool to analyze events where there may be, for example, aging.

By observing the successive failures of a repairable system, it is generally advisable to consider first the NHPP and, if there are no trends in the occurrence of failures, test the homogeneous model. The adoption a priori of a homogeneous model (iid) can lead to an inadequate reliability assessment.

The NHPP model has been tested and validated in several publications. The basis of this text, including the case study, is discussed in (Saldanha et al., 2001).

In 2007, the Reliability Engineering & System Safety journal issued a special number concerning stochastic processes (Krivtsov, 2007b). It contains papers on applications of NHPP to repairable systems (Asher, 2007; Krivtsov, 2007a; Finkelstein, 2007). In a workshop in the 17th International Conference on Nuclear Engineering, ICONE17, in 2009 in Brussels, the model called Crow-AMSAA (Pandey & Jyrkane, 2009) that uses the power law model for assessing the reliability of repairable systems was presented and discussed.

4.1 Basis for defining the model to extend qualified life of equipment

Safety analysis is the study, examination and description of a nuclear power installation behavior through its life, under normal and transient conditions, and also postulated events in order to determine safety margins provided in normal operation and transient regimes, and the adequacy of items to prevent consequences of accidents that might occur. It is essential for the safety assessment in the licensing process. The safety of the plant must be continuously monitored during operation and have constant review to maintain the level of safety. The safety analysis can be performed in two different ways that are complementary: the deterministic and probabilistic approaches.

In the deterministic safety analysis, the plant behavior, after an initiating event or malfunction, is studied with model calculations that describe the physical processes in reactor systems. The objective of this type of analysis is to verify whether allowed values of key variables of the plant are exceeded.

Probabilistic safety analysis (PSA) focuses on identifying the sequence of events that can lead to reactor meltdown, and on reliability studies of safety systems. The objective of this type of analysis is to indicate potential weaknesses in the design of systems and provide a basis for improving safety. It assumes that component failure rates are constant. When aging is explicitly considered, then changes in component failure rates as a function of aging should be considered.

In the beginning of the installation life, the repairable system has a constant rate of occurrence of failures and it is governed by a homogeneous process. The study of aging impact becomes more coherent by observing its effects. It is more appropriate to study the behavior of equipments and systems failures under the action of time, defining its probability density function and probability distribution function, and comparing with the probability density function and probability distribution function when they were not under the action of time.

Differences between probability distribution functions will be related to the increases in the probability of failure due to aging and can be used to aging control and management to reduce the impact of aging over system failures. They will be incorporated into studies of qualified life extension, and their effects on core damage frequency will be assessed.

The following is a sequence of actions that can be performed to define the model : (1) identify the nature of the system, whether repairable or non-repairable; (2) identify the stochastic point process associated to system failures: (2a) for the repairable system, the impact of aging through occurrences of failures can be assessed and it defines the model of failure intensity (ROCOF), these failures can be critical or degradation; and (2b) for the non-repairable systems, one can evaluate the impact of aging through replacements or renewals carried out.

The equipment qualification requirements are defined to repairable systems for a satisfactory performance in their qualified life, according to the requirements of the licensing basis established in the safety analysis report.

In the reliability study of repairable systems, each time between failures and the time of the last failure shall be considered. It is possible to obtain the expected number of failures for the next cycle of operation.

By monitoring and controlling the parameters of the probability model, during equipment operation, it is possible to check whether the equipment is leaving the basis of its qualification process, and so to check how the effects of time, degradation and operation modes can influence the equipment performance. The evaluation of the probability model parameters can be verified through the improvement (or degradation) of equipment. The knowledge of aging mechanisms allows reducing the values of these parameters and cast the model into a homogeneous process.

Here, the extension of qualified life must be defined by considering the operational experience of the equipment and then to perform equipment maintenance in compliance with the qualification basis. In this case, it means the return of the equipment to the “as good as new” condition. For this purpose, one should use as operation criteria goals values

the parameters of the probabilistic model. If the equipment operates within these limits, the process of occurrence of failures will be very close to some of the homogeneous processes and the influence of aging effects will be reduced.

4.2 Stochastic point process and repairable systems concepts

A stochastic point process $\{N(t)\}$ is a collection of usually interrelated random variables, each labeled by a point t on the time axis and such that $N(t_2) - N(t_1) = N(t_1, t_2]$ expresses a finite nonnegative integer for all $t_2 > t_1 \geq 0$.

A stochastic point process is a mathematical model for physical phenomena characterized by highly localized events randomly distributed in a continuum. Thus, these processes can be designed to model a probabilistic experiment that arises in points, which can be named as "arrivals" on the time axis. Accordingly, failures of a repairable system can be represented as "arrivals" of a stochastic point process (Cox & Lewis, 1996).

The distinction between repairable and non-repairable systems is crucial and it should be emphasized if terminology is not adequately explained (Asher & Feingold, 1984; Ascher, 2007).

The concept of failure and how it must be taken into account quantitatively is not the same as the one for nonrepairable systems analysis. The classical idea of failure rate, traditionally employed is not adequate, as long as only the times to first component failures are considered. In this sense, after fixing a component which fails and is repaired, its particular history is investigated in terms of operational records.

The reliability figure of interest of nonrepairable systems is the survival probability. The times between failures of a nonrepairable system are independent and identically distributed (Asher & Feingold, 1984).

In the case of repairable systems, the reliability is interpreted as the probability of not failing for a given period of time. The analysis must be performed without assuring that the times between failures are independent and identically distributed. It is important to emphasize that there may be a system with repairable components which is different from a repairable system in the sense that the first may have nonrepairable components (Asher & Feingold, 1984).

The first concept to discuss is the rate of occurrence of failures. For a repairable system, let $N(t)$ be the number of failures in the interval $(0, T]$ and t_1, t_2, \dots , be the system failure times and T_i ($i = 1, 2, 3, \dots$) the elapsed time between the $(i-1)th$ and the ith failure.

The behaviour of T_i is of great importance in reliability analyses, for it allows the determination of trends in the times between failures, increasing (sad system), decreasing (happy system) or constant (Asher & Feingold, 1984).

The rate of occurrence of failures $v(t)$ is defined as (Asher & Feingold, 1984; Crowder et al., 1991)

$$v(t) = \frac{d}{dt} E\{N(0, t]\} \quad (1)$$

It is important to distinguish the concept of rate of occurrence of failures from that of failure rate, a concept traditionally employed in reliability engineering (Asher & Feingold, 1984).

A natural estimator of $v(t)$ is given by (Crowder et al., 1991) and discussed by (Lai & Xie, 2006):

$$\hat{\nu}(t) = \frac{\{N(t, t + \Delta t)\}}{\Delta t} \quad (2)$$

for an adequate Δt . The choice of this interval is arbitrary but like the choice of interval widths for histograms, the idea is to highlight the main features of the given data.

The expected number of failures in the interval $(t_2 - t_1)$ is given by

$$E[N(t_2) - N(t_1)] = \int_{t_1}^{t_2} \nu(t) dt, \quad (3)$$

and the reliability function is

$$R(t_2 - t_1) = \exp\left\{-\int_{t_1}^{t_2} \nu(t) dt\right\}. \quad (4)$$

4.3 Model for rate of occurrence of failures (ROCOF) by Poisson processes

A stochastic point process $\{N(t), t \geq 0\}$ is said to be a homogeneous Poisson process (HPP) if it satisfies the following conditions (Asher & Feingold, 1984): (1) $N(0)=0$; (2) it has independent and stationary increments; and (3) the number of events in each time interval follows a Poisson distribution with mean $m(t) = \mu t$, $0 < \mu < \infty$, so that:

$$P\{N(t, t + s) = k\} = (\mu t)^k (k!)^{-1} \exp(-\mu t) \quad (5)$$

for all $t, t \geq 0$ and $k = 0, 1, \dots$.

One possible generalization of a HPP is a nonhomogeneous Poisson process (NHPP), which has a time-dependent rate of occurrence of failures, $M'(t) = dE[N(t)]/dt = \nu(t)$, $t \geq 0$, and the events, that are not independent and identically distributed, follow a Poisson distribution

with mean $m(t) = \int_0^t \nu(s) ds$, so that:

$$P\{N(t, t + s) = k\} = \left(\int_t^{t+s} \nu(x) dx \right) (k!)^{-1} \cdot \exp\left[-\int_t^{t+s} \nu(x) dx\right], \quad (6)$$

By choosing a suitable parametric form for $\nu(t)$, a flexible model for failures of repairable systems can be obtained. In the literature, two NHPP failure models are widely used: the log-linear and the power law (Crowder et al., 1991). It is necessary to decide which of these models is preferable in each case.

The NHPP with a log-linear rate of occurrence of failures is discussed by (Cox & Lewis, 1966) and is given by:

$$\nu_1(t) = e^{\beta_0 + \beta_1 t}. \quad (7)$$

The ROCOF decreases (happy system) if $\beta_1 < 0$. If $\beta_1 > 0$, the ROCOF increases (sad system). If $\beta_1 \cong 0$, the ROCOF has a linear trend over short periods of time.

The second model is based on the Weibull distribution and is referred to as the power law, (Crow, 1974; Ascher and Feingold, 1984). It is given by

$$v_2(t) = \gamma \cdot \delta \cdot t^{\delta-1}, \quad \gamma > 0, \quad \delta > 0, \quad \text{and } t \geq 0. \quad (8)$$

If $\delta > 1$, the ROCOF increases. The ROCOF decreases when $0 < \delta < 1$. For $\delta = 2$, one has a linearly increasing ROCOF.

If failures of repairable systems were observed for the time period $(0, t_0]$ and the logged times of occurrence were t_1, t_2, \dots, t_n , then the likelihood function could be obtained by analysing the probability of observing no failures in $(0, t_1)$, one failure in $(t_1, t_1 + \Delta t_1)$, no failures in $(t_1 + \Delta t_1, t_2)$ and so on, until the last interval of no failures in $(t_n + \Delta t_n, t_0)$, for small $\Delta t_1, \dots, \Delta t_n$ and taking the limit as the Δt_n go to zero. The likelihood function obtained from Eq. (3) is given by

$$L = \prod_{i=1}^n v_1(t) \exp[N(0, t_0)]. \quad (9)$$

Another possibility to observe failures of repairable systems is to record them until the occurrence of the n th failure. In this case, the likelihood function of Eq (9) or the loglikelihood is still valid but t_0 must be replaced by t_n , the time of occurrence of the n th failure.

To fit a NHPP with a rate of occurrence of failures given by Eq (7) to a set of failure data of a repairable system, using statistical likelihood-based methods it is necessary to obtain the loglikelihood function of Eq (9). It is given by

$$l_1 = n\beta_0 + \beta_1 \sum_{i=1}^n t_i - \left[\frac{\exp(\beta_0) \exp\{(\beta_1 t_0) - 1\}}{\beta_1} \right] \quad (10)$$

From maximum likelihood equations $\partial l_1 / \partial \beta_1 = 0$, the maximum likelihood estimator of β_1 can be obtained by solving the transcendental equation:

$$l_1 = \sum_{i=1}^n t_i + \frac{n}{\beta_1} + \frac{nt_0}{1 - \exp\{-\beta_1 t\}} = 0 \quad (11)$$

After obtaining $\hat{\beta}_1$, one has

$$\hat{\beta}_0 = \ln \left\{ \frac{n \hat{\beta}_1}{\exp\{\hat{\beta}_1 t_0\} - 1} \right\} \quad (12)$$

A natural test of hypothesis, when considering the reliability of a repairable system, is to check whether the rate of occurrence of failures is constant. For the log-linear model, it is $\beta_1 = 0$. A commonly employed hypothesis test is the Laplace test, (Crowder et al., 1991), which is based on the statistic

$$U = \left[\frac{\sum_{i=1}^n t_i - \frac{1}{2} n t_0}{t_0 \sqrt{n/12}} \right] \quad (13)$$

which under the null hypothesis approaches a standard normal distribution. If $H_1: \beta_1 \neq 0$, one rejects H_0 if $|U|$ is large. On the other hand, if $H_1: \beta_1 > 0$, one rejects H_0 if U is large, and if $H_1: \beta_1 < 0$, one rejects H_0 if $-U$ is large.

For a NHPP with rate of occurrence of failures given by Eq (8), the loglikelihood function of Eq (3) is given by

$$l_2 = \sum_{i=1}^n [\ln \gamma + \ln \delta + (\delta - 1) \ln t_i] - \gamma t_0^\delta \quad (14)$$

From maximum likelihood equations $\partial l_2 / \partial \gamma = 0$ and $\partial l_2 / \partial \delta = 0$, one obtains:

$$\hat{\gamma} = \frac{n}{t_0^\delta} \quad (15)$$

and

$$\hat{\delta} = \frac{n}{n \ln t_0 - \sum_{i=1}^n \ln t_i} \quad (16)$$

In order to test whether the rate of occurrence of failures is constant, that is $\delta=1$, the following statistic is employed (Crowder et al., 1991)

$$V = 2 \sum_{i=1}^n \ln \left(\frac{t_0}{t_i} \right) \quad (17)$$

which under the null hypothesis follows a $\chi^2(2n)$ distribution. Large values of V indicate reliability growth ($0 < \delta < 1$), whereas small ones indicate deterioration ($\delta > 1$).

A question that naturally arises in this context is which model to choose for $v(t)$. It was suggested (Crowder et al., 1991) to make this choice using the models based on loglikelihood methods and after comparing with the models obtained by linear regression (graphical methods): (1) a first step is to plot the failure number i against the t_i . The lack of linearity is an indication that the rate of occurrence of failures is not constant; (2) the second step is to obtain the expression for $v_1(t)$ and $v_2(t)$ by loglikelihood methods; and (3) the last step is to choose $v(t)$ using linear regression (graphical method).

The graphical method is based on the expected number of failures until time t , $E[N(t)]$. Using Eqs. (7) and (8) in Eq (3), one has:

- $v_1(t)$,

$E[N(t)] = \frac{e^{\beta_0}}{\beta_1} \{e^{(\beta_1 t)} - 1\}$; and

(18)

- $v_2(t)$,

$E[N(t)] = \gamma t^\delta$.

(19)

Considering that the observation period $(0, t_0]$ is divided into k arbitrary intervals of the form $(0, a_1]$, $(a_1, a_2]$, $(a_{k-1}, t_0]$, an estimate of $v\left[\frac{1}{2}(a_{j-1} + a_j)\right]$, is given by (Crowder et al., 1991):

$$v\left[\frac{1}{2}(a_{j-1} + a_j)\right] = \frac{N(a_j) - N(a_{j-1})}{a_j - a_{j-1}}$$

(20)

for $j = 1, 2, \dots, k$, where $a_0 = 0$ and $a_k = t_0$.

Making $b_j = \frac{1}{2}(a_{j-1} + a_j)$, a plot of $v(b_j)$ x b_j furnishes an indication of the shape of the rate of occurrence of failures, $v(t)$. The choice of k and a_j is left to the user. However, it is advisable to test different subdivisions of the observation interval in order to verify that the shape of the plot does not depend on the chosen subdivision.

If $v_1(t)$ is appropriate for $v(t)$, then the plot of $\ln v(b_j)$ x b_j will show a straight line with slope β_1 and intercept β_0 . On the other hand, if $v_2(t)$ is appropriate for $v(t)$, the plot of $\ln v(b_j)$ x $\ln b_j$ will also show a straight line, but with slope $(\delta - 1)$ and intercept $(\ln \gamma + \ln \delta)$. If there is a competition between the models evaluated, the choice will be the model that has the highest value for the maximum likelihood function.

For NHPP models, the extension of qualified life must be defined by the return of the equipment to the “as good as new” condition using the operation criteria goals presented in Table 1. As the equipment operates within these limits, the process will be very close to the homogeneous processes.

ROCOF model	homogeneity	linear trend
$v_1(t) = e^{\beta_0 + \beta_1 t}$ (log-linear)	$\beta_1 < 0$	$\beta_1 \cong 0$
$v_2(t) = \gamma \cdot \delta \cdot t^{\delta-1}$ (power law) $\gamma > 0, \delta > 0$, and $t \geq 0$	$0 < \delta < 1$	$\delta = 2$

Table 1. Operating criteria for NHPP parameters for reducing aging effects

5. An application of the NHPP model

The following analysis is related to the service water pumps (SWP) of a typical PWR nuclear power plant. Considered was the degradation or critical failures for which corrective actions in parts, subsystems, and systems inside limits of SWP, for which maintenance corrective actions were necessary (IAEA, 1988).

Failures of SWPs were revealed in operation by daily inspection (lub-oil level of pump systems components pump, discharge pressure, leaks, vibrations, etc) or malfunction indications by sensors or alarms.

The failure times employed in the analysis were generated as follows. A time period of 1725 calendar days has been considered, which is equivalent to approximately three burnup fuel cycles and reload periods. The corresponding operational time for the SWPs was 20,300 hours, (NRC, 1988).

The first step is to check whether the rate of occurrence of failures is constant. A plot of the accumulated number of failures versus the accumulated failures times (operation times) is displayed in Figure 1, which is based in data from the first and second columns of Table 2. No linearity is seen for the plotted points so that the rate of occurrence of failures is clearly time dependent.

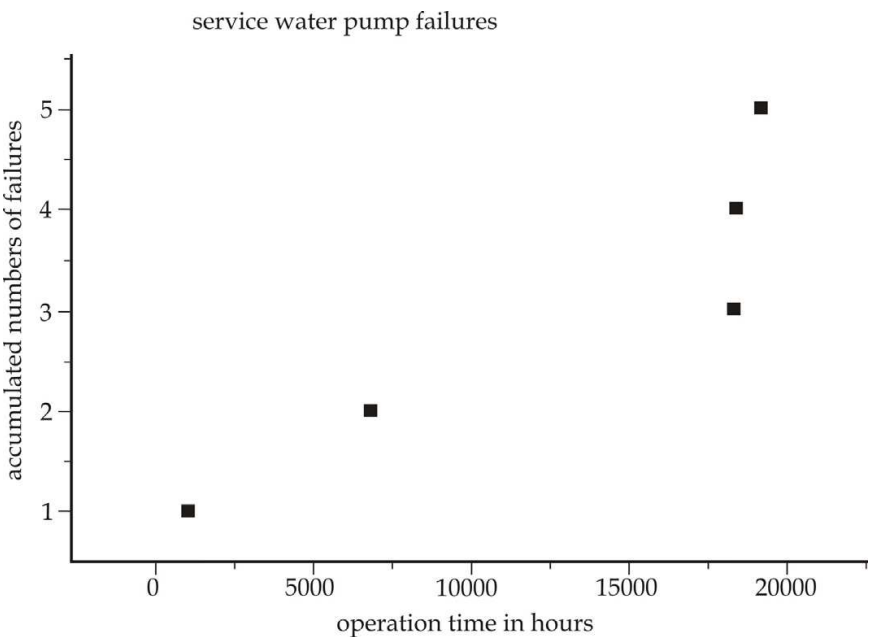


Fig. 1. Accumulated number of failures x accumulated operation time of SWP.

i	t_i	TEF	$\ln t_n/t_i$
1	1080		2,875
2	6840	5760	1,029
3	18300	11460	0,045
4	18360	60	0,042
5	19140	780	0
	$\Sigma= 63720$		$\Sigma= 3,991$

i = failure number; t_i = time to failure, in hours; and TEF= time between failures, in hours.

Table 2. Data for loglikelihood-based methods for the rate of occurrence of failure models

The second step in the analysis, it to check which model is applicable for $\nu(t)$, Eq (7) or Eq (8). The data is also presented in Table 2.

Solving Eq (10) for $v_1(t)$, one obtains $\hat{\beta}_1 = 0.000112$ and from this result, $\hat{\beta}_0 = -9.51$ from Eq (12). These values are tested through Eq (13), $U= 1.98$. This value is considered large by

(Crowder et al., 1991) and the estimated parameters are considered adequate for the model (rejection of the $\beta_1=0$ hypothesis). Then, for this case, Eq (7) is given by:

$$v_1(t) = \exp \{-9.51 + 0.000112 \ t\} \ (h^{-1})$$

(21)

Solving Eqs. (15) and (16) for $v_2(t)$, one obtains $\hat{\delta}=1.253$ and $\hat{\gamma}=0.00000216$. These values are tested by Eq (17), $V=7.982$. This value is considered small (Crowder et al., 1991) and the estimated parameters are considered adequate for the model (rejection of the $\delta=1$ hypothesis). Then, for this case, Eq. (8) is given by:

$$v_2(t) = 2.71 \times 10^{-5} \ t^{0.253} \ (h^{-1}) .$$

(22)

The third step in the analysis is the application of linear regression to the failure data in order to choose which model is applicable for $v(t)$, Eq (7) or Eq (8). The observation period $[0.19140]$ has been divided into three distinct intervals, and the shape of $v(t)$ has been checked through the plot $v(b_j) \times b_j$. Linear regression has been performed for each interval considering the plots of $\ln(v(b_j)) \times b_j$, for $v_1(t)$ and of $\ln(v(b_j)) \times \ln(b_j)$, for $v_2(t)$.

Table 3 presents the results obtained by linear regression methods for each interval and by the loglikelihood method. It may be inferred that the $v_1(t)$ model adequately fits the rate of occurrence of failures $v(t)$, considering the results of interval splitting #2 and the loglikelihood method.

Table 4 presents the performed interval splitting #2 for the data where n_i represents the number of failures in the interval. Figures 2 and 3 show the shape of $v(t)$ through the plot $v(b_j) \times b_j$ and the scattering diagram for the data in Table 4, respectively.

Parameter	β_1	β_0	δ	γ
Interval splitting # 1	0.00015	-9.82	2.111	0.0005E-5
Interval splitting # 2	0.00012	-9.33	1.862	0.0007E-5
Interval splitting # 3	0.00008	-9.18	1.584	0.0760E-5
Loglikelihood method	0.000112	-9.51	1.253	2.16E-5

Table 3. Estimated parameters for choosing $v(t)$

interval (hr)	n_i	b_j	$\ln b_j$	$v(b_j)$	$\ln v(b_j)$
0-6000	1	3000	8.006	0.000017	- 8.699
6000-11000	1	8500	9.048	0.000020	- 8.517
11000-18400	2	14700	9.596	0.000270	- 8.216
18400-19140	1	18770	9.840	0.001350	- 6.607

Table 4. Division 2 for the model of Eq (7)

One can see that $v_1(t)$ is appropriate to model $v(t)$, because the fit of the line $\ln v(b_j) \times \ln b_j$ values in Table 3, obtained a slope $\hat{\beta}_1=0.00012$, and an intercept

$\hat{\beta}_0 = -9.33$, values that are close to those obtained through the maximum likelihood method.

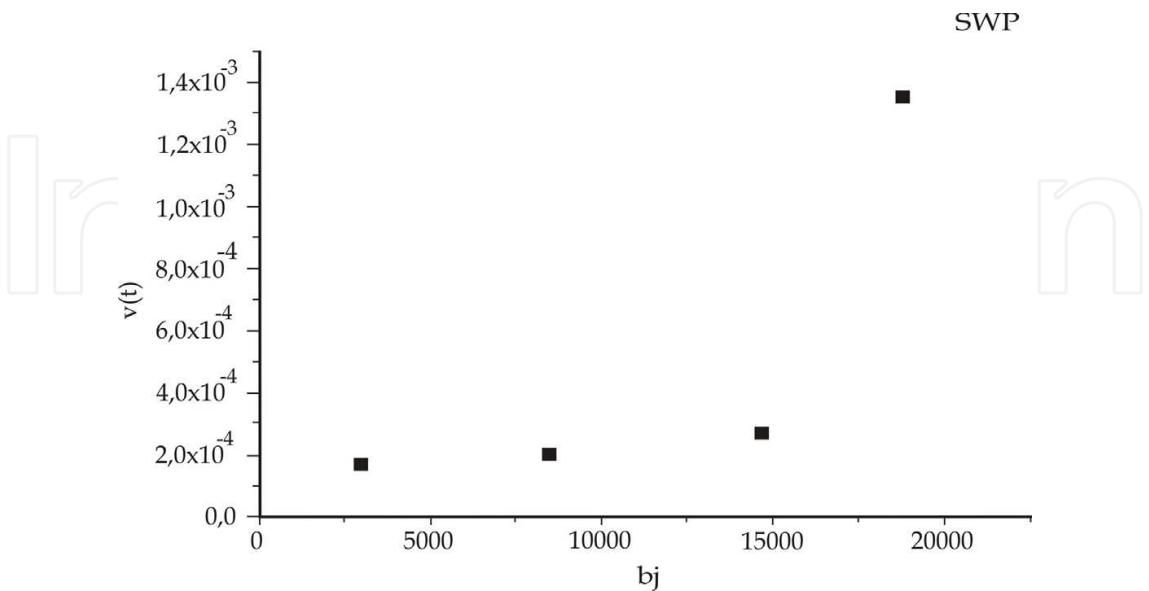


Fig. 2. Analysis of the model of Eq. (7)

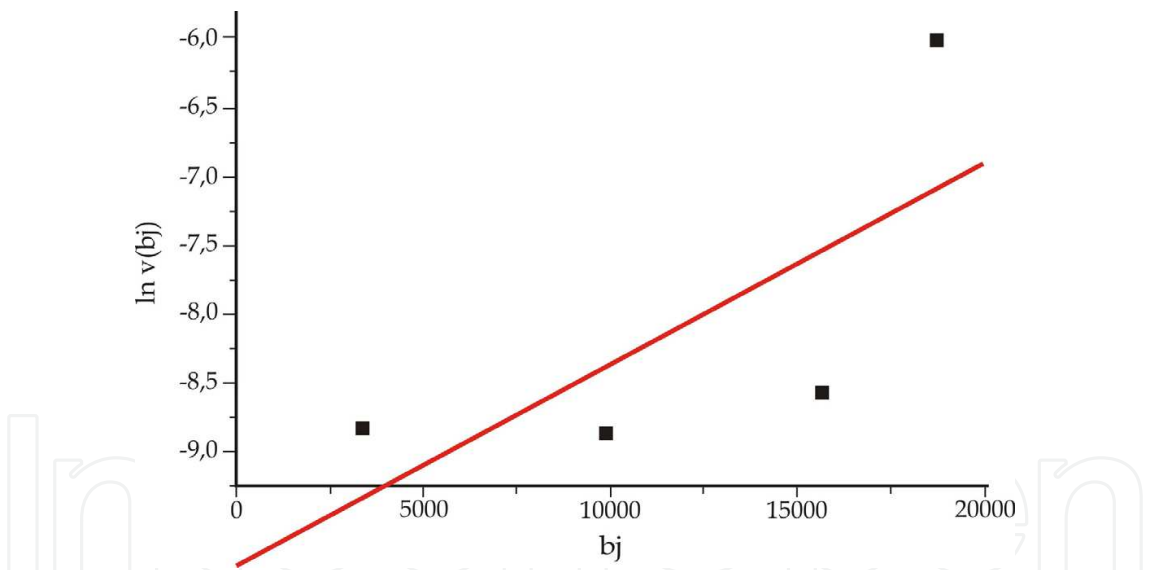


Fig. 3. Scatter diagram (data in Table 3), $\hat{\beta}_1 = 0.00012$ (slope) and $\hat{\beta}_0 = -9.329$ (intercept).

Figure 4 exhibits the shape of $v(t)$ for the observed period $(0, 19140]$, using Eq. (21). An increasing trend in the failure occurrence and actions on degradation factors in pump performance can be observed. Thus, it is possible to obtain the expected numbers of failures in other burnup fuel cycles from Eq. (22). Considering that the SWPs will operate under the same model than that for the past three cycles, the evaluated time period will be $(19140, 25500]$. Using the parameters β_1 and β_2 in Eq (18), 6 failures have been obtained. Table 5 present these values. Figure 5 presents the expected cumulative number of failures in hours of operation until the C4 cycle.

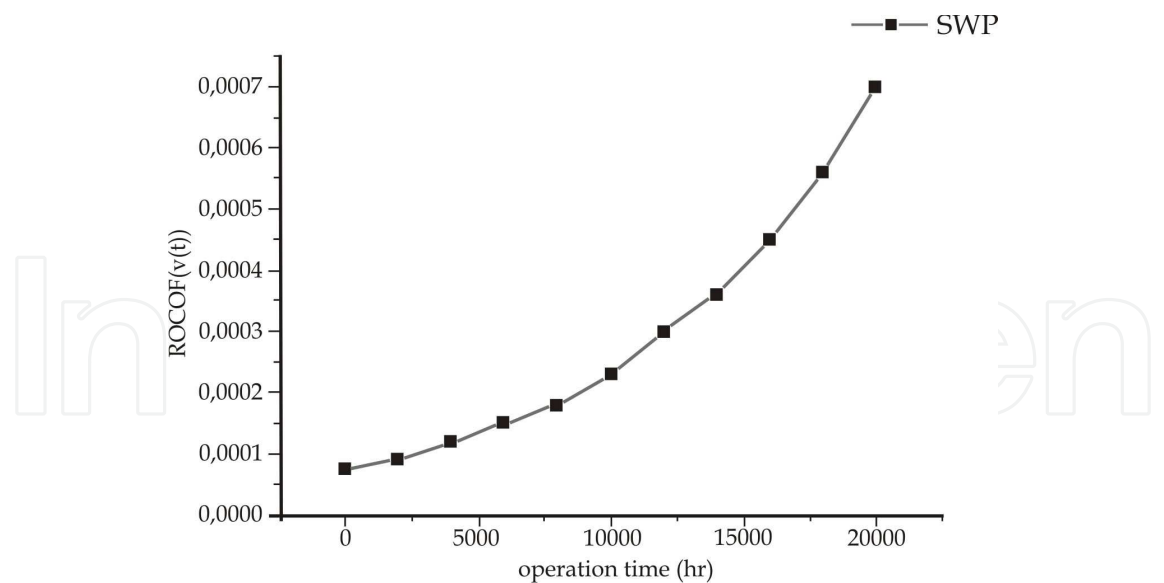


Fig. 4. Rate of occurrence of failures $v(t)$ in the operation period $(0, 19140]$, in hours

interval	E[N]
19140 - 21140	1
21140 - 2314	2
23140 - 25500	3

Table 5. Expected numbers (E[N]) of failure for period $(19140, 25500]$ until the C4 cycle

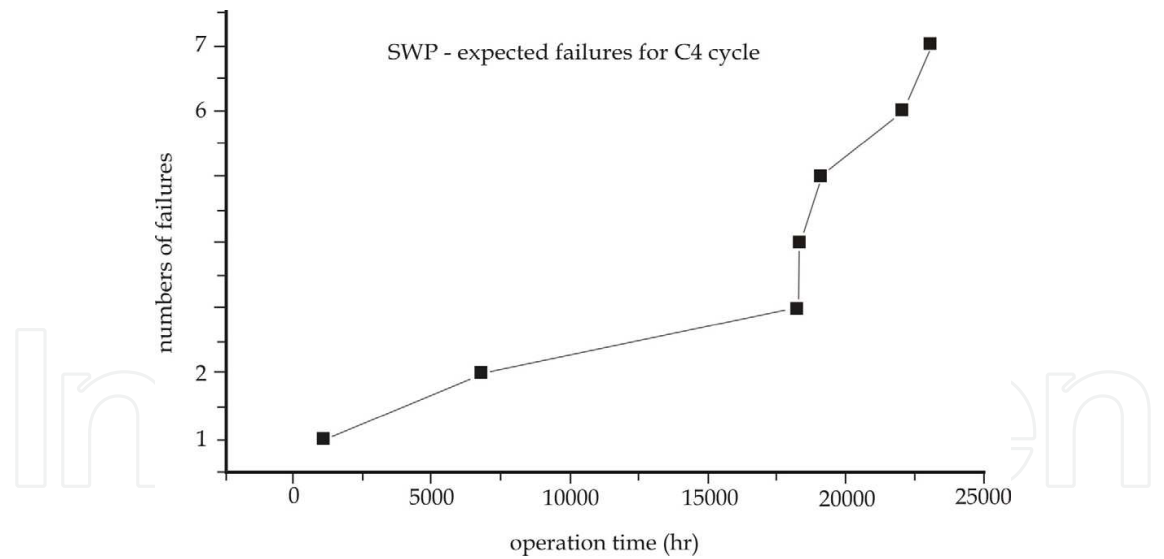


Fig. 5. Expected cumulative number of failures in hours of operation until the C4 cycle

Supposing that in order to decrease the expected number of failures for the period $(19140, 25500]$ adequate aging management actions have been taken, like periodic testing and maintenance, then it would be possible to reduce the number of failures to 2 in the period, occurring, in time points, 22104 h and 23112 h, respectively.

The impact of failure reduction may be quantified by the application of the NHPP model considering the period $(0, 25500]$. Using the same procedure discussed before, one obtains the following expression for $v(t)$:

$$v_{c\,4}(t)=\exp\{-9.4+(9.9E-5)t\}h^{-1}\tag{23}$$

Figure 6 shows the comparison between the rates of occurrence of failures considering the expected trend by Eq (21), Table 5, and considering management of aging and maintenance actions in the period (19140, 25500]. It can be observed that the corrective actions reduce the increasing trends in failures, ($\hat{\beta}_1=0.00012>\hat{\beta}_{1C4}=0.00009$).

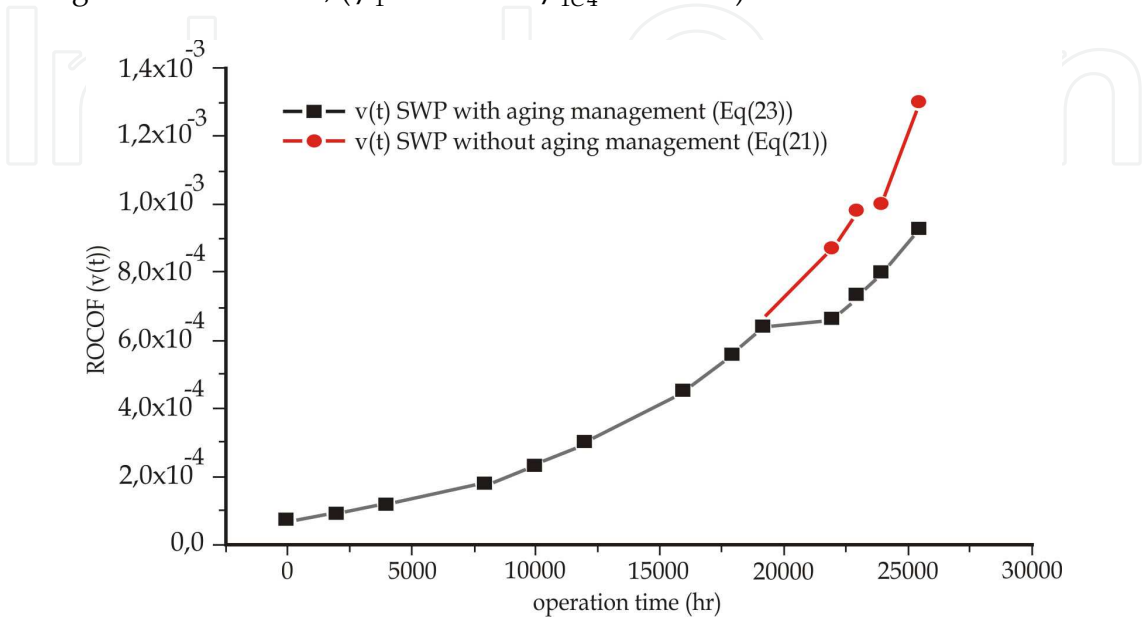


Fig. 6. Comparison of $v(t)$ by Eq (21) (trends) and Eq. (23) (released) in period (19140, 25500], in operation hours

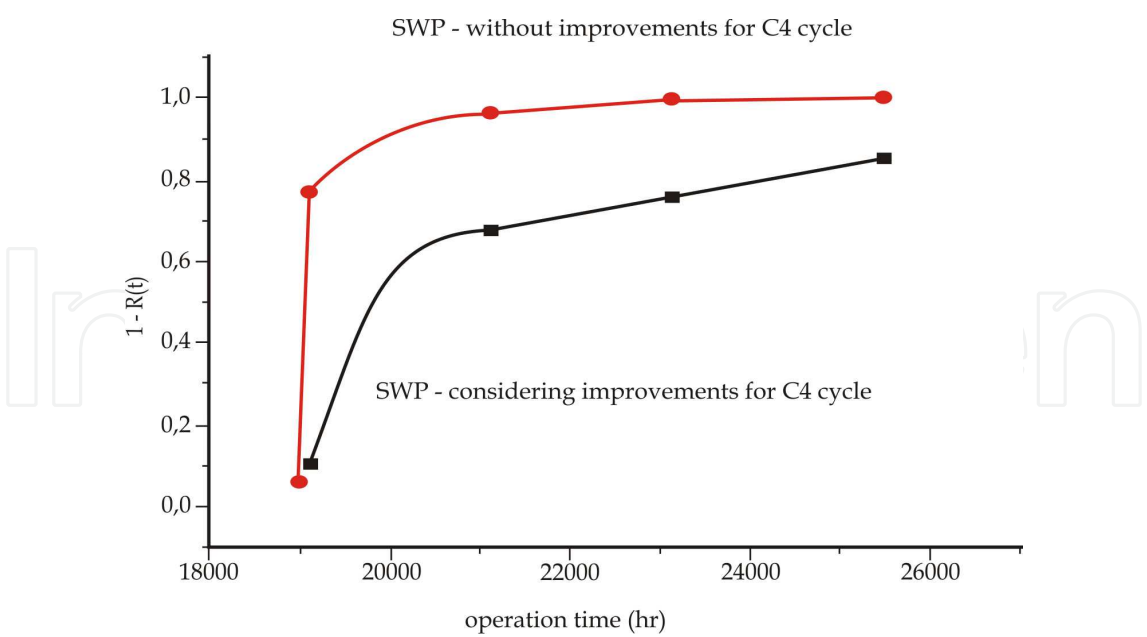


Fig. 7. Comparison of the curves of SWP failure probability with improvements and without improvements to the C4 cycle

Figure 7 shows the comparison of the SWP curves failure probability with improvements and without improvements to the C4 cycle. It can be verified that a repairable system with a

time-dependent rate of occurrence of failures can be influenced by management of aging and maintenance policies.

6. Conclusion

The equipment qualification program of a nuclear power plant provides an effective aging management of plant components important to safety. The knowledge of the aging and degradation processes and the development of methods and guidelines for its management is important to the reliable and safe operation of nuclear power plants. The management of aging components can predict or detect the degradation of a component and take the appropriate corrective mitigation actions.

The extension of qualified life is a reality. It must bear combination of deterministic and probabilistic methods in the evaluation stage of aging effects. While the evaluation based on deterministic methods defines the difference between the current state and condition of the item in the qualification phase, probability methods define whether it can continue performing its function adequately for a longer period than is defined by its qualified life.

It is possible to postulate a variety of point process models for the analysis of repairable systems for the extension of qualified life. If one focuses attention on the non-homogeneous Poisson process (NHPP), then it will be clearly seen that it is able to model time-dependent rates of occurrence of failures.

This model is conceptually simple and the relevant statistical methodology (maximum likelihood estimation and linear regression modeling) is well developed and easy to apply. By considering it, one eliminates the unrealistic assumption for the probabilistic modeling of the ROCOF that considers a renewal as a repair ('as good as new' versus 'as bad as old' hypothesis). Different models for the rate of occurrence of failures are possible and we discussed the two most common, namely, the log-linear and the power law.

The application discussed is quite simple but this is not a methodology shortcoming. Our concern was to show how to perform the analysis by taking into account a general procedure for hypothesis testing.

At first, one of those models should be adequate for the analyzed data but the hypothesis testing could reveal that none is appropriate. Sound statistical inference should always be employed for the obtained results in terms of the expected number of failures because the reliability for a given time period could be misevaluated.

The pattern of successive failures of repairable systems will define the model to be used. If failures exhibit increasing trends, one applies the NHPP (time-dependent ROCOF); otherwise, one should apply the HPP (constant ROCOF). The NHPP model adequately includes the variations in the rate of occurrence of failures behavior due to periodic testing and maintenance activities performed in repairable systems. Then, it may be used to survey aging mechanisms during the operational life of repairable systems and to the assessment of maintenance effectiveness.

The case study demonstrates that it is not difficult to perform failure data analysis, to evaluate trends and verify the impact of these trends in the reliability analysis of repairable systems. Considering the requirements of the Maintenance Rule (NRC, 2007a), in the aging management for active equipments, the study of the SWPs shows that the MPLP complies with the licensing basis.

In what concerns applications of other point processes models, (Saldanha & Frutuoso e Melo, 2009) discuss the application of the Modulated Power Law Process (MPLP) to

represent the ROCOF of repairable systems for evaluating the extension of qualified life as a generalization of the NHPP model that turns to be more realistic to represent the impact of maintenance actions.

In the area of maintenance policies, applications of Generalized Renewal Process (GRP) are very recent in the field of reliability engineering. (Kahle, 2007) discusses the optimal maintenance policies for the models of standard GRP repair. (Garcia et al, 2008) address the scheduling of preventive maintenance using genetic algorithms for systems modeled by this class of point processes. (Damaso et al, 2009) consider again the GRP for the modeling of multi-objective optimization of testing policies of aging systems.

7. Acknowledgment

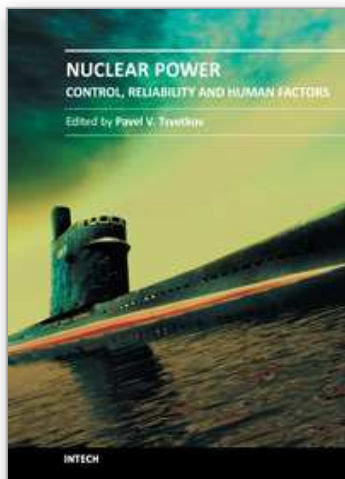
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