CHEMICAL ENGINEERING TRANSACTIONS
VOL. 33, 2013
Guest Editors: Enrico Zio, Piero Baraldi

ISBN 978-88-95608-24-2; ISSN 1974-9791

A publication of
AIDIC
The Italian Association
of Chemical Engineering
Online at: www.aidic.it/cet

DOI: 10.3303/CET1333148

Reliability Attributes and the Maintenance Rule for Nuclear Power Plant Safety Systems

Pedro Luiz C. Saldanha*[,a], Newton J. Ferro[b], Paulo Fernando Frutuoso e Melo[c], F. F. Marques[b]

[a] CNEN/CGRC, RJ and UBM/Cicuta, B. Mansa, R. General Severiano 90, S.426, Rio de Janeiro, RJ- Brazil, 22290-901.
[b] CMatFN/Marinha do Brasil, Pç. B.de Ladário s/n- Rio de Janeiro, RJ – Brazil,20091-000.
[c] Graduate Nuclear Engineering Program, COPPE, Federal University of Rio de Janeiro, Av Horacio Macedo 2030, S. G-206, Rio de Janeiro,RJ- Brazil, 21941-914.
plsaldanha@gmail.com

The Maintenance Rule (MR) is a requirement established by the U. S. Nuclear Regulatory Commission (NRC) to check the effectiveness of maintenance carried out in nuclear plants. MR was consolidated in the U.S. in 1996. MR classifies Structures, System or Components (SSC) into two categories: Category (a)(2), the SSCs that reach the intended performance demonstrate that preventive maintenance is being appropriately performed, and category (a)(1), which stands for the SSCs that do not fulfill category (a)(1), and must have established goals, so that the discrepancies can be revised and then return to Category (a)(2).
The purpose of this paper is to present a model that can be implemented in a personal computer, which allows the reliability analysis of nuclear power plant safety systems to be performed, starting from a state transition diagram, typically employed in Markovian reliability analyses. The classical Markovian model will not apply if at least one of the transition rates in the state transition diagram is time-dependent, due to equipment aging. To overcome this difficulty, the model is recast into a Markovian model by means of supplementary variables. The algorithm developed for this purpose also estimates the necessary parameters for the reliability analysis, starting from crude failure information available from the plant and using goodness of fit statistical tests for the most commonly employed probability distributions.

1. Introduction

The Maintenance Rule (MR) is a requirement established by the U. S. Nuclear Regulatory Commission (NRC) to check the effectiveness of maintenance carried out in nuclear plants. MR classifies Structures, System or Components (SSC) into two categories, (NEI, 2000): Category (a)(2), SSCs that reach the intended performance demonstrate that preventive maintenance is being appropriately performed, and Category (a)(1), which stands for the SSCs that do not fulfill Category (a)(1), and must have established goals, so that the discrepancies can be revised and then return to Category (a)(2). SSCs are monitored to verify whether their performance meets the established criteria or whether they undergo a Maintenance Preventable Functional Failure (MPFF).
A periodic evaluation of the reliability and unavailability balance is scheduled, according to the MR, at each refueling cycle or every two years. The MR simplified flowchart may be found in (NRC, 2013).
NRC requirements establish that all SSCs can be evaluated to verify the pertinence of their inclusion in a MR scope. Otherwise, it remains under the existing maintenance program, outside the MR scope. An Expert Panel determines the relationship between the selected SSC and plant safety within the MR scope (high or low significance).
Okoh and Hougen (2013) present an analysis of eight major maintenance-related accidents. The main objective was to discuss how maintenance has influenced some serious accidents in the chemical, oil, and gas industries. The accident causes are related to maintenance management and barrier-based factors (lack of maintainnability and deficiecies in: fault diagnosis, planning, scheduling, execution and checking).

Although the Maintenance Rule is focused in the nuclear industry, it can be adapted for monitoring and verification of the effectiveness of maintenance for other industries and contribute to the reduction of accidents caused by the aspects analyzed

The purpose of this paper is to present a model that can be implemented in a personal computer, which allows the reliability analysis of nuclear power plant safety systems, starting from a state transition diagram, typically employed in Markovian reliability analyses.

The classical Markovian model will not apply if at least one of the transition rates in the state transition diagram is time-dependent, due to equipment aging. To overcome this difficulty, the model is recast into a Markovian model by means of supplementary variables.

The algorithm developed for this purpose estimates the necessary parameters for the reliability analysis, starting from crude failure information available from the plant and using goodness of fit statistical tests for the most commonly employed probability distributions, and provides conditions to evaluate the requirements of the system under varying conditions of availability of components and verify the impact of these components to continue in operation under the categories established in MR, and can also define a performance index for the system.

2. The algorithm to complement the approach for Maintenance Rule, restriction of the Markovian model and supplementary variables.

This work establishes a new approach to complement the MR, with the intermediate parameters insertion to be used as a tool to support the previously established inspection frequency or to inspect at any time if necessary. Such approach will also provide the possibility of using more realistic policies by means of the plant failure data. Thus, the algorithm is intended to consolidate and process the failure data, so that it can be used in the areas responsible for the respective analyses and inserted in the MR context.

The complementary approach inserts the reliability parameters to be compared with the established performance criteria. As long as the parameters and criteria are compatible, that is, both approve or disapprove the monitored SSC, the regular periodic SSC reevaluation each 24 months or at the end of the refueling cycle are kept, as established in the MR procedure. When the parameters and criteria are incompatible, the MR procedure feedback begins, with the check of the algorithm that calculated the reliability parameters, being this algorithm revised whenever any discrepancy is identified. On the other hand, the performance parameter must be revised and corrected, if necessary. Figure 1 presents the new approach simplified flowchart.

The proposed model allows, starting from failure data records, to perform a dynamic process analysis by means of a state transition diagram that allows for representing the system failure and success states and analyzing it through the Markovian reliability approach, using supplementary variables, (Cox and Miller, 1965), to take into account possible time-dependent transition rates. Pareto's method is suggested in order to choose the failure processes to be analyzed.

After the statistical treatment and the identification of the necessary parameters from the sample, a transition state diagram is used, where transitions with time dependent rates (for failures data, repair and others) will appear. In this case, when the SSC presents aging characteristics, boundary conditions are typically established, to organize a data base and make the modeling feasible.

These conditions have to do with repair and/or replacement policies used in nuclear plants. The applicable technical specifications will be followed, when necessary. The information presented in the transition diagram is then cast into a coupled differential equations hybrid system whose solution will be through finite differences, using the data already mentioned. The hybrid character is due to the existence of both ordinary and partial differential equations. From the solution of these equations, the reliability figures of interest are calculated as, for example, the system unavailability.

It is intended that this model, after its validation, allows to be used not only for aging processes but, also during plant useful life, because both plants and components that are in their useful life have failure times that follow exponential distributions. The proposed methodology is summarized in Figure 2.

From the Cumulative Distribution Function [F(t)] of the Weibull distributions, it is possible to find the coefficients of correlation and determination, used for the least square method that indicates the distributions candidates for better representing the failure data obtained. (Ebeling, 2005) presents the necessary basis to obtain the Weibull distribution parameters. The details of the parameters calculations of Case Study can be seen in (Ferro et al, 2012).

The basic Markov model has the advantage of being simple to be formulated and it is largely employed for practical cases, but it has the disadvantage of not considering aging processes, being necessary the use of a model that eliminates this restriction. This gap can be filled by the method of supplementary variables, based on the insertion of additional variables to cast the so called Non-Markovian model into a Markovian one, (Cox and Miller, 1965).

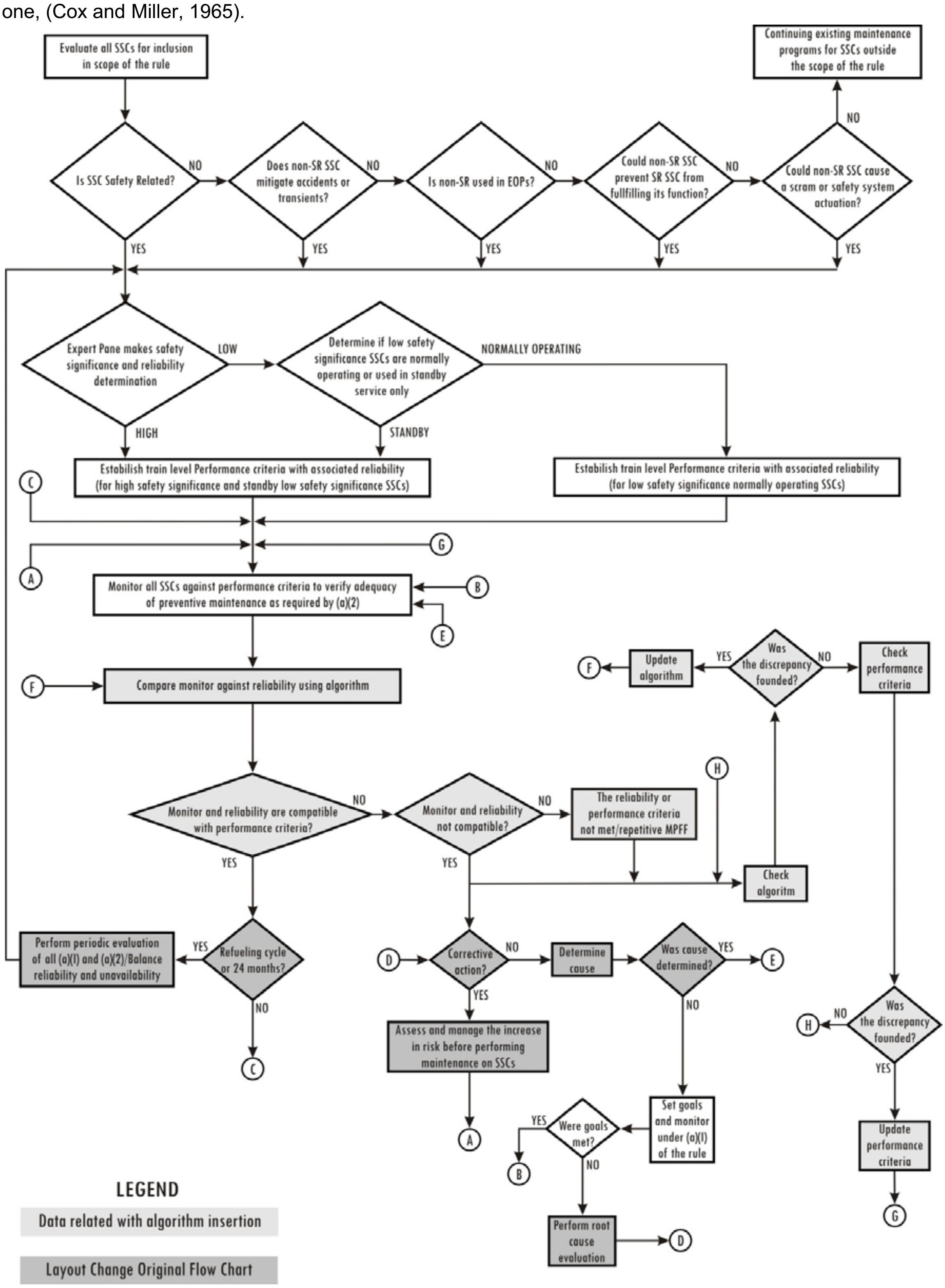

Figure 1: New Approach Simplified Maintenance Rule Flow Chart, (Ferro et al, 2012)

It should be noted that another advantage of using the Markov model jointly with supplementary variables is that there is no need to run simulations by Monte Carlo method, which has the characteristic of being computationally very time consuming.

The greatest difficulty in using the Markov model with supplementary variables is to identify the required solution sequence to be used for the coupling of the hybrid equations (ordinary and partial differential equations). Further details can be found in (Ferro et al, 2012). This reference also present an algorithm for the reliability analysis of safety systems of nuclear power plants in the context of the plant qualified life extension, where aging mechanisms are present.

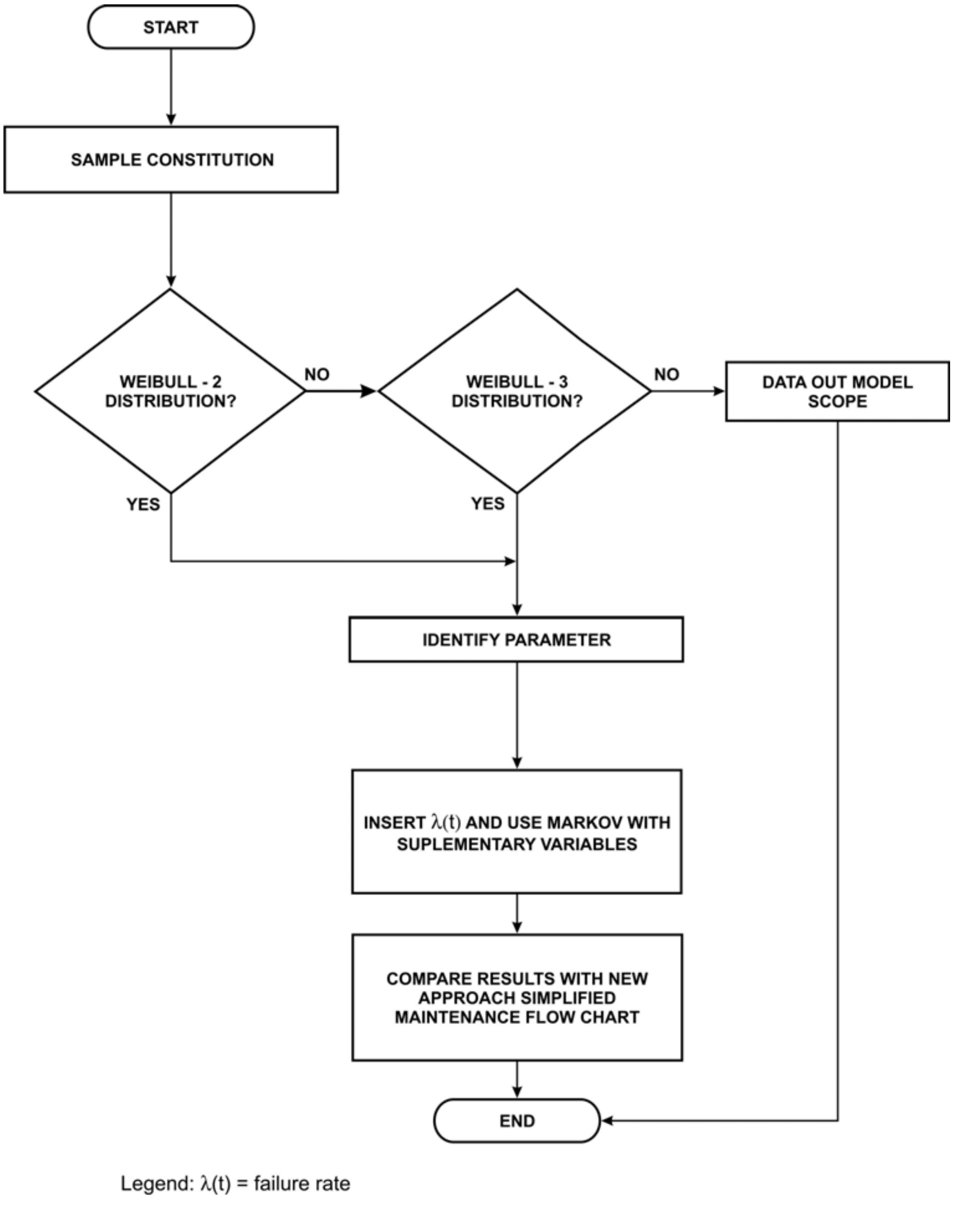

Figure 2: Simplified Methodology, (Ferro et al, 2012).

3. Development of case study

In order to analyze the adequacy of the proposed methodology, a case study was developed concerning the Auxiliary Feed Water System (AFWS) of a typical Westinghouse PWR Nuclear Power Plant.

The AFWS consists of two trains, each with 100% capacity of supplying the design flow (to supply the steam generators, when safety related). One of these trains is composed by two motor-driven horizontal centrifugal pumps (AF-1A and AF-1B), while the other one is composed by a turbine-driven pump (AF-2).

With the plant in the normal operation mode, the system remains in a standby condition, automatically operating when demanded by the Reactor Protection System, RPS. Technical Specifications establish, among other requirements, that the reactor shall not be made critical unless the turbine-driven pump and at least one of the motor-driven pumps, with valves and associated pipelines, are operational. Surveillance tests establish that the motor and the turbine pumps must be tested at least monthly, and a flow test must be performed for the steam generators at least once each 18 months or during each refueling cycle, whichever comes first. If any of the requirements cannot be satisfied within 48 hours, with the plant in the operation or critical condition, then the plant must be placed in a cold shutdown condition, (Ferro et al, 2012)

With the failure times given in Table 3 and using linear regression models (Ebeling, 2005) and (Ferro et al, 2012), the failure rates of Table 4 may be found. It can be observed that AF-1A and AF-2 pumps are under aging mechanism effects, since $\beta>1$. In this case these pumps would be classified as MR category (a)(1), and would be monitored. The performance criteria to be achieved is a reduction of the parameter value to satisfy $\beta<1$ (according to the decision of the Expert Panel). AF-1B pump was included in MR category (a)(2). Observing these features, it is important to verify the impact of these components in (a)(1) category system reliability and make the decision for the continued operation of the plant.

Using the simplified nomenclature of *A*, *B* and *T* for pumps *AF*-1*A*, *AF*-1*B* and *AF*-2, respectively, the transition diagram of Figure 3 is obtained wich shows the relevant system states. In this diagram a bar over a letter means component failure.

Table 3 – AFWS Failures Data, Running Time until Pump Failures (h)

AF-1A	144	264	348	924	1584					
AF-1B	12	24	60	84	300	456	480	624	1020	
AF-2	12	72	108	132	144	228	276	423	468	600

Table 4 – AFWS Weibull Failures Rate

AF – 1A	AF – 1B	AF – 2
Shape Parameter (*β*): 1.037	Shape Parameter (*β*): 0.6899	Shape Parameter (*β*): 1.074
Scale Parameter (*Θ*): 729.31 h	Scale Parameter (*Θ*): 334.82 h	Scale Parameter (*Θ*):302.28 h

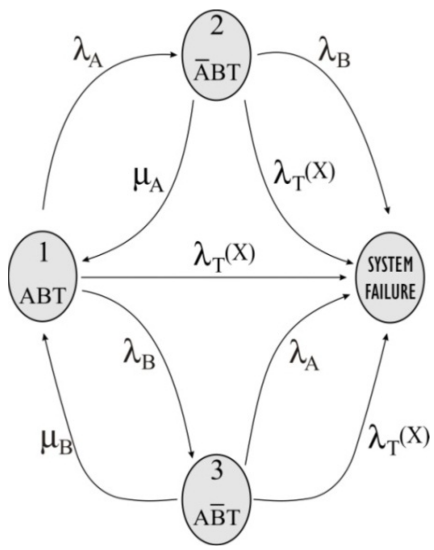

Figure 3: State Diagram for the Auxiliary Feeding Water System, (Ferro et al, 2012).

As established in (Ferro et al, 2012) the turbine-driven pump and at least one motor-driven pump, with valves and associated pipelines, must be operational being the plant placed in a cold shutdown condition within 48 hours otherwise. This means that these three system states must be rigorously monitored.

Using the following equations (whose details may be found in (Pinho, 2000):

$$\partial p_1/_{\partial x} + \partial p_1/_{\partial t} = -[\lambda_A(x) + \lambda_B(x) + \lambda_T(x)]p_1(x,t) \quad (1)$$

$$\partial p_2/_{\partial x} + \partial p_2/_{\partial t} = -[\lambda_B(x) + \lambda_T(x)]p_2(x,t) \quad (2)$$

$$\partial p_3/_{\partial x} + \partial p_3/_{\partial t} = -[\lambda_A(x) + \lambda_T(x)]p_3(x,t) \quad (3)$$

$$dp_4/_{dt} = \int_0^\infty \lambda_T(x)p_1(x,t)dx + \int_0^\infty [\lambda_B(x) + \lambda_T(x)]p_2(x,t)dx + \int_0^\infty [\lambda_A(x) + \lambda_T(x)]p_3(x,t)dx \quad (4)$$

with the following initial and boundary conditions

$$p_1(0,t) = \mu_A \int_0^\infty p_2(x,t)dx + \mu_B \int_0^\infty p_3(x,t)dx \quad (5)$$

$$p_2(0,t) = \int_0^\infty \lambda_A(x)p_1(x,t)dx \quad (6)$$

$$p_1(0) = 1;\ p_2(0) = 0;\ p_3(0) = 0 \text{ and } p_4(0) = 0 \quad (7)$$

$$P_i(t) = \int_0^x p_i(x',t)\,dx' \ \ , i = 1,2,3. \quad (8)$$

the system reliability figure of interest may be found. Equations (1)-(3) with the initial and boundary conditions defined by Eq. (5)-(7) are solved by means of Lax's finite difference method,(Ferro et al, 2012), and the solution is stable for Courant number $\Delta t/\Delta x < 1$ (Ferro et al, 2012). After obtaining the densities $p_i(x,t)$ of Eqs. (1)-(3), Sympson's one-third repeated integration rule was used to obtain the probabilities $P_i(t)$ [Eq. (8)]. Solving these equations, considering a time period of 48 h, one finds that the system reliability is equal to 92.01 %, so that it can be decided for plant continued operation.

4. Conclusions

The use of the algorithm allows the monitoring of equipment performance and system performance through the results of periodic testing or maintenance performed. Thus, the reevaluation of parameters and criteria of SSC, in accordance with MR procedures, can be carried out in periods of less than 24 months. The need for modeling aging mechanisms means that methods like supplementary variables could be used, as discussed in (Cox and Miller, 1965). As shown here, the Maintenance Rule extension for considering aging effects is quite simple and a personal computer can easily handle all calculations.

A natural extension of the work performed here is the more detailed consideration of safety systems. For this purpose, the need of plant-specific failure data is a demand. In this context, the stochastic model here proposed assumes that failure and repair times are independent and, in most cases, identically distributed. When this is not the case, other stochastic approaches should be considered. One that is being currently used for this purpose concerns stochastic point processes, (Saldanha et al., 2012).

References

Cox, D. R., Miller, H. D, 1965, The Theory of Stochastic Processes, Chapman and Hall, London, UK.

Ebeling, C. E., 2005, An Introduction to Reliability and Maintainability Engineering, Tata McGraw-Hill Publishing Company Limited, New Delhi, India.

Ferro, N. J., Saldanha, P. L. C., Frutuoso e Melo, P. F., Marques, F. F., 2012, Incorporation of reliability attributes into maintenance rule for the qualified life extention of nuclear power plant safety systems. In: PSAM 11 and ESREL 2012 Conference (CD paper nº17 Mo3-3), Helsinqui, Finland, 25-29 June 2012.

NEI, 2000, Industry Guideline for the Monitoring the Effectiveness of Maintenance at Nuclear Power Plants, NUMARC 93-01, 3rd Revision, Nuclear Energy Institute, Washington, USA.

NRC, 2013, (www.nrc.gov) accessed 21.01.2013.

Okoh P. and Haugen S., 2013, The influence of maintenance on some selected major accidents, Chemichal Engineering Transactions, 31, 493-498 DOI: 10.3303/CET1331083.

Pinho, M. O., 2000, On the Application of System of First Order Partial and Ordinary Differential Equations to the Reliability Analysis of Safety Systems under Aging (in Portuguese), D.Sc. thesis, COPPE/UFRJ, Rio de Janeiro, Brazil.

Saldanha, P. L. C., Frutuoso e Melo, P. F., 2012, Analysis of the qualified life extension of nuclear safety systems through modulated Poisson point processes, Progress in Nuclear Energy, 60, 117-128.