ACCELERATED LIFE TESTING OF COMPONENTS OF NUCLEAR RESEARCH REACTORS

Vanderley de Vasconcelos, vasconv@cdtn.br
Antônio Carlos Lopes da Costa, aclc@cdtn.br
Wellington Antonio Soares, soaresw@cdtn.br
Raíssa Oliveira Marques, raissaomarques@gmail.com
Centro de Desenvolvimento da Tecnologia Nuclear (CDTN/CNEN-MG), Av. Presidente Antônio Carlos 6.627, Belo Horizonte, 31270-901, Brazil.

Abstract. There are several alternatives to quantify the life data of equipment, system or component, like Mean Time-To-Failure (MTTF). The first alternative involves analyzing times-to-failure data obtained under normal operating conditions. Obtaining such life data may be very difficult or impossible for many reasons. The major limitation of this alternative is the long time of testing, making difficult the decision-making regarding the component specification, supplier selection and acceptance tests. Accelerated Life Testing (ALT) can be performed under stress conditions (higher overload, higher temperature, higher frequency of use, etc.), forcing the items to fail more quickly than they would be under normal use conditions. Piping and valve failures in nuclear reactors can have operational and safety implications, and may even lead to failures in other components of the facilities. Nuclear research reactor owners must demonstrate to regulatory bodies that design, specification, manufacture, maintenance and operation of their components, equipment and systems comply with the required safety standards in order to protect health and minimize danger to life and property. ALT of components can be needed in order to understand the failure mechanisms and to select items on the market, with adequate reliability for use in a nuclear research reactor. This paper proposes a method for planning ALT of components used in such nuclear reactors. A case study analyzing components of a boiling water irradiation circuit to be installed in a nuclear research reactor is carried out. This circuit requires a previous extensive test program for experimental validation of its design criteria, operational limits and processes used during the manufacturing of its components. Piping and valve failures in this circuit can have operational and safety implications, and may even lead to failures in other components of the facility. Failure Mode and Effect Analysis (FMEA) technique was applied in order to select the components of the circuit most important to safety and prioritize them to perform Life Data Analysis (LDA). FMEA analysis, accelerated life data analysis and life-stress relationship modeling can be carried out with support of XFMEA®, ALTA® and WEIBULL® software, developed by Reliasoft® Corporation. Reduction in the time needed to get the MTTF data from the analyzed components, generating rapid, strategic, reliable and low-cost information and a better understanding of stress effects are some expected results to be highlighted. The life data obtained can also be used in design comparisons and to assist risk assessments.

Keywords: Accelerated life testing, nuclear research reactor, valves, piping.

1. INTRODUCTION

Nuclear research reactor owners must demonstrate to regulatory bodies that design, specification, manufacture, maintenance, operation and modification of their components, equipment and systems comply with the required safety standard, in order to protect health and minimize danger to life and property (IAEA, 2005). They have also to demonstrate that improvements to plant safety are being implemented continuously. Moreover, risk management is also used as a tool to mitigate, control or eliminate hazards in order to ensure greater safety, reliability and availability.

The installation of a boiling water circuit for irradiation tests in a nuclear research reactor has many safety requirements. The irradiation circuit (IC) requires a previous extensive test program for experimental validation of its design criteria, operational limits and processes used during the manufacturing of its components. Piping and valve failures in this circuit, for instance, can have many operational and safety implications, and may even lead to failures in other components of the facility. Technical specification, supplier selection and acceptance tests require life data and reliability information that are not always available (Costa, 2009).

There are several alternatives to quantify the life data of equipment, system or component, like Mean Time-To-Failure (MTTF), and then get reliability information. The first alternative involves analyzing times-to-failure data obtained under normal operating conditions. Obtaining such life data may be very difficult or impossible for many reasons. The major limitation of this alternative is sometimes, long time of testing, making difficult the decision-making regarding the component specification, supplier selection and acceptance tests. An alternative is the use of Accelerated Life Testing (ALT) performed under stress conditions (higher overload, higher temperature, higher frequency of use, etc.), forcing the items to fail more quickly than they would be under the normal use conditions (Euthymíou, 2013).

This paper proposes a methodology of planning ALT for components used in nuclear research reactors. A case study analyzing components of the irradiation circuit to be installed in a nuclear research reactor is carried out. Failure

Mode and Effect Analysis (FMEA) technique is used in order to support the selection the components most important to safety and prioritize them to perform Life Data Analysis (LDA). It is proposed the use of XFMEA®, ALTA® and WEIBULL® software, developed by Reliasoft® Corporation, in order to support FMEA application, accelerated life data analysis and life-stress relationship modeling.

2. LIFE DATA ANALYSIS (LDA)

Life Data Analysis (LDA) refers to the study and modeling of observed component lives. Lifetime can be defined as the time the component operated successfully, or the time the component operated before it failed. These lifetimes can be measured in terms of hours, kilometers, cycles-to-failure or any other metric with which the life or exposure of a component can be measured. All such data of component lifetimes can be referred to, generally, as component life data.

When performing LDA, it is necessary to make predictions about the life of all components in a population by fitting a statistical distribution to life data from a representative sample. The parameterized distribution for the data set can be used to estimate important life characteristics of the component such as reliability or probability of failure at a specific time, the mean life and the failure rate. Therefore, LDA requires gathering life data for the component, selecting a lifetime distribution that will fit the data and model the life of the component, estimating the parameters that will fit the distribution to the data, and generating results that estimate the component life characteristics, such as the reliability or mean life.

2.1 Lifetime Distributions

The probability density function (pdf) is a mathematical function that describes the statistical distribution, and can be represented on a plot where the x-axis represents time, t, and y-axis the life data, f(t). Some distributions, such as the Weibull and lognormal, tend to better represent life data. The Weibull model can be applied in a variety of forms (including 1-parameter, 2-parameter, 3-parameter or mixed Weibull). Other commonly used life distributions include the exponential, lognormal (Figure 2) and normal distributions. The analyst should choose the life distribution that is most appropriate to model each particular data set based on experience and goodness-of-fit tests (RELIASOFT, 2015a).

2.2 Parameter Estimation

In order to fit a statistical model to a life data set, the analyst estimates the parameters of the life distribution that most closely fit the data. The parameters control the scale, shape and location of the pdf function. For example, in a 3-parameter Weibull distribution (Figure 1), the scale parameter (or characteristic life), η, defines where lies the bulk of the distribution. The shape parameter (or slope), β, defines the shape of the distribution and the location parameter (or failure free life), γ, defines the location of the distribution in time. In Lognormal distribution (Figure 2), μ' is the mean of the natural logarithms of the times-to-failure, and σ_T is the standard deviation of the lognormal distribution.

Several methods to estimate the parameters that will fit a lifetime distribution to a particular data set are available. Some parameter estimation methods include probability plotting, Rank Regression on x (RRX), Rank Regression on y (RRY) and Maximum Likelihood Estimation (MLE). The most appropriate analysis method will depend on data set and life distribution selected.
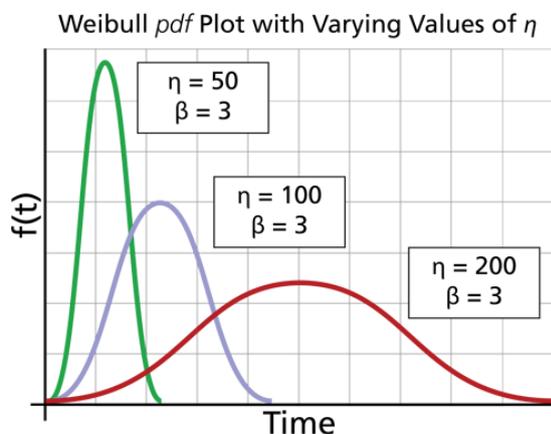

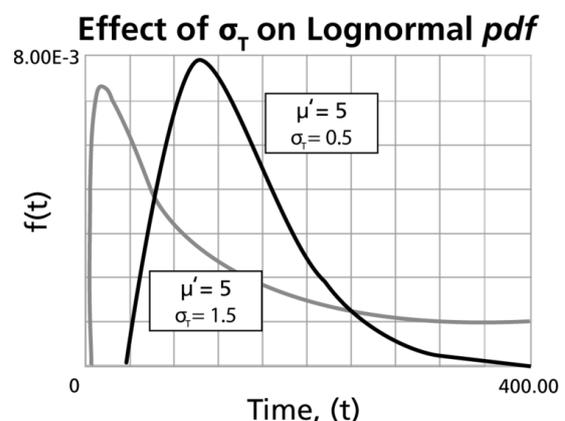Figure 1. Weibull distribution (RELIASOFT, 2015a)

Figure 2. Lognormal distribution (RELIASOFT, 2015a)

2.3 Life Characteristics of Components

After estimating the parameters to fit a life distribution to a particular data set, many calculated results from the analysis can be obtained, including (Calixto, 2013):

- **Reliability at a given time**: probability that an item will operate successfully at a particular point in time.
- **Probability of failure at a given time** (unreliability): probability that an item will fail at a particular point in time;
- **Mean life**: average time that the item in the population is expected to operate before failure. This metric is often referred to as "Mean Time-to-Failure" (MTTF) or "Mean Time Before Failure" (MTBF);
- **Failure rate**: number of failures per unit of time that can be expected to occur for the item;
- **Warranty time**: estimated time when the reliability will be equal to a specified goal;
- **B(X) life**: estimated time when the probability of failure will reach a specified point (X %);
- **Contour Plot**: graphical representation of the possible solutions to the likelihood ratio equation. It is employed to make comparisons between two different data sets.

3. ACCELERATED LIFE TESTING (ALT)

Traditional LDA involves analyzing times-to-failure data obtained under normal operating conditions in order to quantify the life characteristics of a component. Often, obtaining such life data may be very difficult or impossible. The difficulties are related to the long life times of some components, the minor time between design and release, and components that are used continuously under normal conditions. Given these difficulties and the need to observe failures to better understanding failure modes and life characteristics, methods to accelerate component failures were developed. ALT methods involve the acceleration of failures with the purpose of quantifying the life characteristics of the component at normal use conditions. ALT can be classified into qualitative and quantitative accelerated life testing.

3.1 Qualitative Accelerated Testing

In qualitative accelerated testing, the engineer is mostly interested in identifying failures and failure modes without attempting to make any predictions as to the component life under normal use conditions. Qualitative tests are often performed on small samples, under constant or time-varying stresses (e.g., stress cycling, cold to hot, etc.). If the specimen survives, it passes the test. Otherwise, appropriate actions will be taken to improve the component design in order to eliminate the cause(s) of failure. Qualitative tests are mainly used to reveal probable failure modes. However, if not designed properly, they may cause the component failure due to modes that would never have been encountered in real life. A good qualitative test is one that quickly reveals those failure modes that will occur during the life of the component under normal use conditions. In general, qualitative tests are not designed to yield life data that can be used in subsequent quantitative accelerated life data analysis. In general, qualitative tests do not quantify the life (or reliability) characteristics of the component under normal use conditions; however, they provide valuable information as types and levels of stresses one may wish to employ during a subsequent quantitative test.

3.2 Quantitative Accelerated Life Testing (QALT)

In Quantitative Accelerated Life Testing (QALT), the interest is to predict the component life (life characteristics such as reliability, failure probability, MTTF and B(X) life) at normal use conditions, from data obtained in accelerated life testing. This information can be used, for instance, to support probabilistic risk assessments, comparisons of design alternatives and component specifications. In accelerated life data analysis, it is necessary to determine the use level pdf from accelerated life test data. To accomplish this task, a method that allows extrapolating the use level characteristics from data collected at accelerated conditions must be developed. There are infinite ways to relate stress level to use stress level data. The functions could be as simple as linear or exponential relationships, as illustrated on Figure 3.

The first step in performing an accelerated life data analysis is to choose an appropriate life distribution. Although it is rarely appropriate, the exponential distribution was very used in the past because of its simplicity. The Weibull and lognormal distributions, although require more calculations, are more appropriate for most uses.

After selecting the appropriate life distribution to available data, the second step is to select a model that describes a stress-life relationship. Among the common life-stress relationships can be found: Arrhenius Relationship; Eyring Relationship; Inverse Power Law Relationship; Temperature-Humidity Relationship; Temperature Non-Thermal Relationship; Multivariable Relationships: General Log-Linear and Proportional Hazards; and Time-Varying Stress Models (RELIASOFT, 2015b).

Once selected life distribution and life-stress relationship models to fit the accelerated test data, the next step is to perform parameter estimation. Available methods for estimating the parameters of a model include the graphical, the least squares and the MLE methods. After estimating the parameters of life distribution and life-stress relationship, the reliability information about the component can be obtained. If life characteristics of component under use stress

condition are available, the estimation can be validated. The use of specialized computer programs, as ALTA® and WEIBULL®, makes easier to get the stress-life relationships and derive the reliability information.
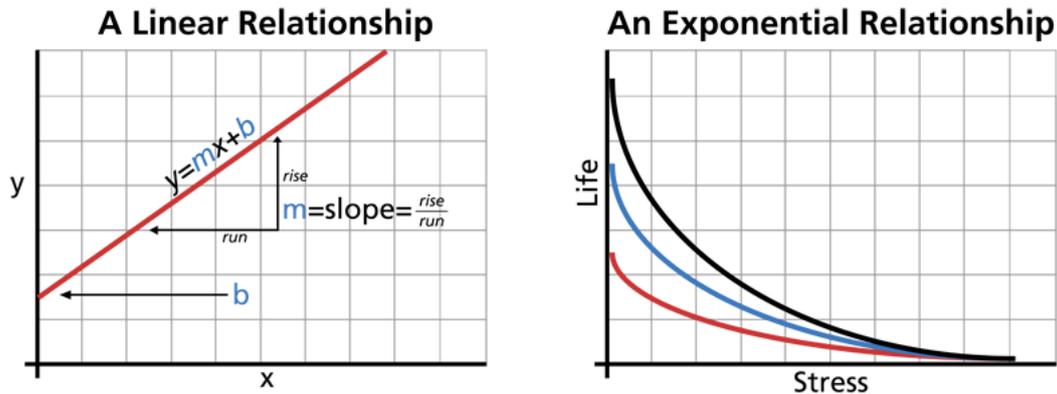

Figure 3. Stress-Life relationships (RELIASOFT, 2015b)

4. FAILURE MODE AND EFFECTS ANALYSIS (FMEA)

In order to select the components most important to safety and prioritize them to perform Life Data Analysis, the Failure Mode and Effect Analysis (FMEA) technique was applied. FMEA is a method designed to identify and understand potential failure modes and their causes, and the effects of failure on a product or process. It is then possible to assess the risk associated with the identified failure modes, effects and causes, and prioritize corrective actions.

A Design FMEA (DFMEA) focuses on product design, typically at the subsystem or component level. The focus is on deficiencies related to design, with emphasis on improving it and ensuring that product operation is safe and reliable during its useful life. The scope of the DFMEA includes the subsystem or component itself, as well as the interfaces among adjacent components. Design FMEA usually assumes that the product will be manufactured according to specifications. Table 1 is an example of a Generic FMEA Worksheet. Meaning of the columns are presented after this table.

Table 1. Example of a Generic FMEA Worksheet.

Item / Function	Potential Failure Mode(s)	Potential Effect(s) of Failure	S	Potential Cause(s)/ Mechanism(s) of Failure	O	Current Design Controls	D	RPN	Recommended Action(s)
I	II	III	IV	V	VI	VII	VIII	IX	X

Column I: An "item" is the focus of the FMEA project. For a DFMEA, this is the subsystem or component under analysis. A "function" is what the item or process is intended to do, usually to meet a given standard of performance or requirement. For DFMEA, this is the primary purpose or design intent of the item (basic function). It is necessary to include the standard of performance, in order to identify more easily the correct failure mode. There can be many additional functions for each item (secondary functions), regarding, for instance, interface, safety, reliability or waste management.

Column II: A "failure mode" is the manner in which an item potentially fails to meet the intended function and associated requirements. Failure modes may include the failure to perform the function within defined limits, inadequate or poor performance of the function or, intermittent performance of the function. There may be many failure modes for each function.

Column III: An "effect" is the potential consequence of the failure on the system or end user. There can be more than one effect for each failure mode.

Column IV: "Severity" (S) is a ranking number associated with the most serious effect for a given failure mode, based on the criteria from a severity scale. It is a relative ranking within the scope of the specific FMEA and is determined without regarding the likelihood of occurrence or detection. It can range, for instance, from 1 ("No noticeable effect") to 10 ("Potential failure mode affects safe operation or regulatory requirements, without warning"). First column of Table 2 shows an example of a Severity Scale for DFMEA (Carlson, 2014).

Column V: A "cause" is the specific reason for the failure. For DFMEA, the cause is the design deficiency that results in the failure mode. "Failure mechanisms" are the physical, chemical, thermodynamic or other processes that result in failure. Failure mechanisms are categorized as either overstress or wear-out mechanisms. At the component level, causes can be further defined and developed by understanding their failure mechanisms. Causes are the

circumstances that induce or activate a failure mechanism. Wherever possible, causes should be defined at the failure mechanism level for high-risks.

Column VI: "Occurrence" (O) is a ranking number associated with the likelihood that the failure mode and its associated cause will be present in the item being analyzed. It can range, for instance, from 1 ("Failure is eliminated through preventive control") to 10 ("New technology/new design with no history"). Second column of Table 2 shows an example of an Occurrence Scale for DFMEA (Carlson, 2014).

Column VII: "Current Controls" are the methods or actions currently planned or already in place to reduce or eliminate risks. Controls can prevent or detect the cause during product development. There can be many controls for each cause. "Prevention-type design controls" describe how a cause, failure mode or effect in the product design is prevented, based on current or planned actions. They are intended to reduce the likelihood that the problem will occur, and are used as input to the occurrence ranking. "Detection-type design controls" describe how a failure mode or cause in the product design is detected, based on current or planned actions, before the product design is released to production, and are used as input to the detection ranking. Detection controls are intended to increase the likelihood that the problem will be detected before it reaches the end user.

Column VIII: "Detection" (D) is a ranking number that considers the likelihood of detection of the failure mode/cause, according to defined criteria. It can range, for instance, from 1 ("Failure cause or failure mode cannot occur because it is fully prevented") to 10 ("No current design control or cannot be detected"). Third column of Table 2 shows an example of a Detection Scale for Design FMEA (Carlson, 2014).

Column IX: "Risk Priority Number" (RPN) is a numerical ranking of the risk of each potential failure mode/cause, made up of the arithmetic product of the three elements: severity of the effect (S), likelihood of occurrence of the cause (O) and likelihood of detection of the cause (D). When RPN is used, high severity must be considered regardless of RPN value.

Column X: "Recommended actions" are the tasks recommended as result of FMEA study. These actions can be performed to reduce or eliminate the risk associated with a potential cause of failure. Recommended actions should consider the existing controls, the relative importance (prioritization) and the cost and effectiveness of the corrective actions. There can be many recommended actions for each cause. It can be recommended both detection-type and prevention-type controls.

Table 2. Example of Severity, Occurrence and Detection Scale for Design FMEA (Carlson, 2014)

Severity	Occurrence	Detection	Rank
Potential failure mode affects safe operation or regulatory requirements, without warning	New technology/new design with no history	No current design control or cannot be detected	10
Potential failure mode affects safe operation or regulatory requirements, with warning	Failure inevitable with new design, new application, or change in operating conditions	Design controls have a week detection capability	9
Loss of primary function	Failure likely with new design, new application, or change in operating conditions	Product verification after design freeze and prior to launch with pass/fail testing	8
Degradation of primary function	Failure uncertain with new design, new application, or change in operating conditions	Product verification after design freeze and prior to launch with test-to-failure	7
Loss of secondary function	Frequent failures associated with similar designs or in design testing	Product verification after design freeze and prior to launch with degradation testing	6
Degradation of secondary function	Occasional failures associated with similar design or in design testing	Product validation prior to design freeze using pass/fail testing	5
Item operable, but with annoyance noticed by <75% of customers	Isolated failures associated with similar design or in design testing	Product validation prior to design freeze using test-to-fail	4
Item operable, but with annoyance noticed by <50% of customers	Only isolated failures associated with almost identical design or in design testing	Product validation prior to design freeze using degradation testing	3
Item operable, but with annoyance noticed by <25% of customers	No observed failures associated with almost identical design or in design testing	Design controls have strong detection capability prior to design freeze	2
No noticeable effect	Failure is eliminated through preventive control	Failure cause or failure mode cannot occur because it is fully prevented	1

5. PROPOSED METHOD FOR ALT PLANNING

Figure 4 shows an overview of the ALT planning method developed for components used in nuclear research reactors. The scope of analysis is carried out with aid of tools to facilitate the selection components most important to safety. It is suggested the use of system block diagram, identifying the components of interest and the interfaces among them. The components target prioritization of the action plan involving ALT is carried out with the aid of a Design FMEA. The FMEA analysis starts with the definition of primary and secondary functions, and ends with the recommended actions, including and prioritizing ALT experiments using RPN estimates. These steps can be carried out with support of specialized software as XFMEA$^@$. After completion of ALT experiments, the life data analysis can be supported by Weibull$^@$ and ALTA$^@$ software.
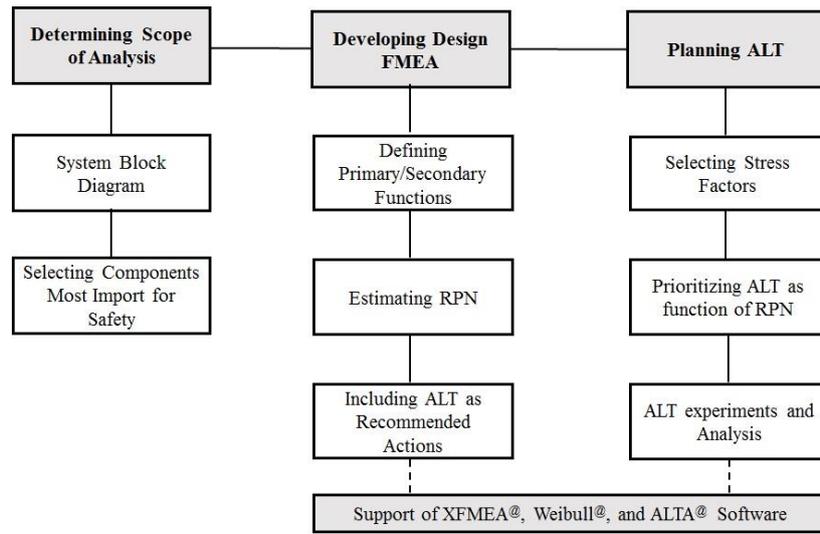

Figure 4. ALT planning developed method.

6. CASE STUDY ON "ALT" APPLIED TO A RESEARCH REACTOR DESIGN

Regulatory bodies and nuclear facilities owners are always interested on continuous improvement of nuclear facility safety and reliability of their components, equipment and systems. The developed method proposes a planning of Accelerated Life Testing of components used in nuclear research reactors. These tests can be necessary to understand the failure mechanisms, support technical specifications and select manufacturers of components with the adequate reliability. Reliability information about components is useful to predict the performance degradation under normal operation, in order to support the design and development of maintenance plans, and increase safety and availability of the systems (Calixto, 2013).

A case study analyzing components of a boiling water irradiation circuit to be installed in nuclear research reactors is carried out. This circuit requires a previous extensive test program for experimental validation of its design criteria, operational limits and processes used during the manufacturing of its components (Costa et al., 2009). Piping and valve failures in this circuit can have operational and safety implications, and may even lead to failures in other components of the facility. The selection of the components and items most important to safety and their prioritization to perform Life Data Analysis and Accelerated Life Testing were carried out with the aid of DFMEA.

6.1 Boiling Water Irradiation Circuit

Figure 5 presents a simplified block diagram developed for a boiling water irradiation circuit designed to qualify nuclear fuel rod in nuclear research reactors. An irradiation capsule, operating systems, and instrumentation constitute the irradiation circuit. The irradiation capsule is a safety barrier in case of loss of integrity of the fuel rod during the irradiation tests. This capsule should be designed to work with a high safety level, avoiding accidents that could damage the nuclear fuel rod in test. The operating systems are connected to the inside of the irradiation capsule through pipes. The operating systems are responsible to reproduce inside the irradiation capsule the pressure and temperature similar to operation conditions of a nuclear power reactor. Instrumentation measures, controls, records and monitors safety conditions of the capsule (Costa et al., 2009).

Pipe fracture valves (PFV) are installed in pipe inlet and pipe outlet of the pressurizer, ensuring a minimum pressure inside the capsule and preventing the occurrence of nuclear fuel rod damage, in case of rupture of the flexible metallic piping that connects the pressurizer to irradiation capsule (Loss of Coolant Accident - LOCA). Figure 6 shows the main components of these valves (body, sphere, seat and piston).
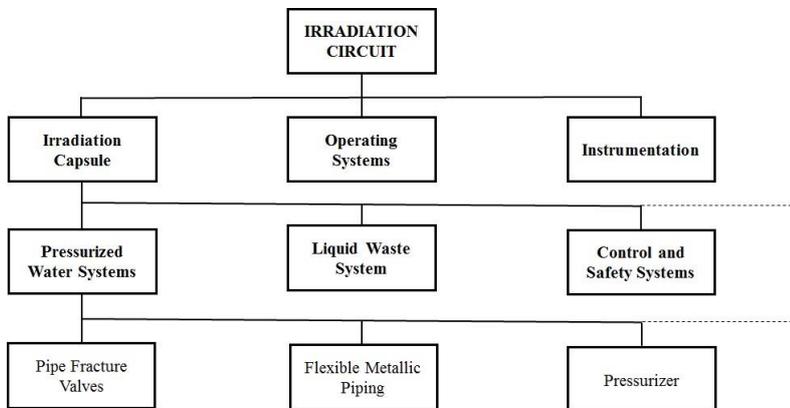

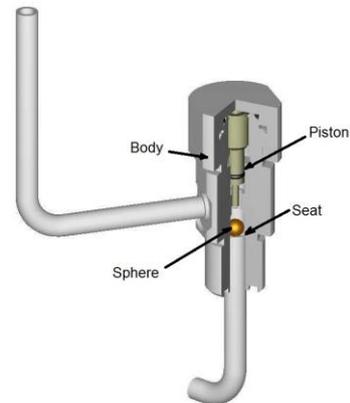Figure 5. Simplified block diagram of irradiation circuit

Figure 6. Pipe fracture valve (Costa et al., 2009)

6.2 Design FMEA of Pipe Fracture Valve (PFV)

Based on the block diagram in Fig.5, the pipe fracture valve (PFV) was the component selected to carry out the Accelerated Life Testing because its importance to safety of irradiation circuit. Table 3 shows a generic DFMEA for a pipe fracture valve.

Table 3. Simplified Generic FMEA Worksheet for pipe fracture valve.

Item / Function	Potential Failure Mode(s)	Potential Effect(s) of Failure	S	Potential Cause(s)/ Mechanism(s) of Failure	O	Current Design Controls	D	RPN	Recommended Action(s)
I	II	III	IV	V	VI	VII	VIII	IX	X
Pipe Fracture Valve (PFV)									
Primary Function: Isolate the Irradiation Capsule in case of rupture of primary piping	PFV does not close	Depressurization of Irradiation Capsule leading to a LOCA	10	Fracture or deformation of valve seat or sphere	10	Acceptance test of 100% of valves (radiation-free and in-pile tests)	5	500	ALT planning of valves using pressure, temperature and irradiation dose as stress factors
				Corrosion in valve seat or sphere	5	Materials qualifying and visual control	4	200	ALT planning of valves using temperature and water quality as stress factors
				Debris in water	2	Irradiation Capsule cleaning and water quality control	2	40	ALT planning of valves using debris concentration as stress factors
Secondary Function: Remove liquid waste from Irradiation Capsule	Piston locking	Does not clean liquid waste	6	Corrosion, overtighthten	1	Pre-service and periodic testing	1	**6**	No additional actions
	O-ring seal failure	Valve leak	7	Radiation embrittlement, overtighthten	2	Irradiation Capsule monitoring	1	**14**	ALT planning of o-ring material using irradiation dose as stress factor

The primary function of PFV is to isolate the irradiation capsule in case of rupture of flexible piping in the pressurizing system (primary piping). When the mass flow rate outside the capsule reaches the maximum limit, the valve closes, maintaining the pressure inside the irradiation capsule over its minimum safety value (50% of normal operation). If PFV does not close, depressurization inside irradiation capsule leads to formation of steam and would prevent the radial heat transmission generated in the nuclear fuel rod to reach the cooling water. This results in a LOCA, and in fuel rod damage, if the control and safety systems do not work properly. According to Table 3, a ranking number of 10 can be assigned to severity (S).

The potential causes/mechanisms of failure mode "PFV does not close" are "Fracture or deformation of valve seat or sphere", "Corrosion in valve seat or sphere" and "Debris in water". For each cause/mechanism there is already foreseen current design controls, as acceptance test of 100% of valves (radiation-free and in-pile tests) (column VII of Table 3). However, according to the ranking numbers assigned to Occurrence (O) and Detection (D), different values of RPN are obtained, which implies in different priorities to recommended actions, including planning of Accelerated Life Testing. Therefore, ALT planning of PFV using pressure, temperature, irradiation dose, water quality and debris concentration as stress factors should be prioritized, in order to detect potential causes/mechanisms of failures, reducing risks related to primary function o PFV.

Regarding the secondary function of PFV "Remove liquid waste from Irradiation Capsule", the potential failure modes imply in operational problems detected by pre-service and periodic testing, as well as by Irradiation Capsule monitoring. Despite a lesser priority than ALT of PFV, ALT of o-ring material using irradiation dose as stress factor can be useful to detect potential failure modes and select o-ring materials during PFV design phase.

7. FINAL REMARKS

A planning method for Accelerated Life Testing (ALT) of components used in nuclear research reactors is proposed. It includes the use of Design Failure Mode and Effect Analysis (DFMEA) technique as support to select the components of the irradiation circuit most important to safety, and prioritize them to perform Life Data Analysis (LDA) using Risk Priority Numbers (RPN) estimates. The use of available commercial software for reliability analysis is also analyzed. FMEA analysis, accelerated life data analysis and life-stress relationship modeling can be carried out with support of XFMEA®, ALTA® and WEIBULL® software, developed by Reliasoft® Corporation. Reduction in the time needed to get the Mean Time to Failure (MTTF) data from the analyzed components, generating rapid, strategic, reliable and low-cost information and a better understanding of stress effects are some results to be reached with the use of the developed method. The life data can also be used to design comparisons and to assist probabilistic risk assessments of nuclear research reactors.

A case study analyzing components of a boiling water irradiation circuit to be installed in a nuclear research reactor was also carried out. Using a DFMEA, ALT planning of a Pipe Fracture Valve (PFV) and o-ring materials was analyzed and prioritized. The stress factors were identified so that ALT can be properly carried out, potential causes/mechanisms of failures can be identified, and reliability data can be obtained, in support to design of the irradiation circuit.

Future works including ALT experiments of pipe fracture valves using the stress factors shown in this paper will be carried out, and the results will be analyzed using ALTA® and WEIBULL® software.

8. ACKNOWLEDGEMENTS

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