RISK BASED INSPECTION OF PIPING: APPROACHES AND APPLICATIONS

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Abstract. Risk-Based Inspection (RBI) is a methodology that involves assessment of both failure probability and consequence associated with equipment or systems. A RBI program classifies equipment by their risks and prioritizes inspection efforts based on this classification. In traditional deterministic approach, inspection frequencies and modes are constant. The use of RBI methodology reduces inspection frequencies, resulting in lower risk levels and keeping safety in acceptable levels. Thus, it reduces inspection of lower risk items, focusing on high-risk items, which, in general, leads to reduction in costs. Another advantage is to reduce worker exposure to hazards during inspections in dangerous activities, like thermal or nuclear radiation expositions. RBI has its origins in the petroleum industry, but other industrial facilities employ this methodology, as nuclear power plants. It is a proactive inspection methodology, which uses available risk information to manage risks. The ultimate goal of RBI is to develop a cost-effective inspection and maintenance program that provides assurance of acceptable mechanical integrity and reliability. In RBI, risk assessment is used to improve the effectiveness of inspection and maintenance programs, increases the reliability of systems and equipment, optimize costs and improve safety and availability. In many industry sectors, such as the petrochemical area, damage to piping is responsible for many accidents, particularly involving pressurized equipment. In the nuclear sector, the majority of the available RBI references are directed to nuclear reactor piping systems, inside the approach called Risk-Informed In-Service Inspections. This paper studies several approaches and applications of RBI to nuclear power plant piping, including the use of softwares developed by Reliasoft® Corporation.

***Keywords**: RBI, maintenance, piping.*

1. INTRODUCTION

Nuclear power plant owners must demonstrate to regulatory bodies that continuous improvements to plant safety are being implemented. Risk management is used as a tool to mitigate, control or eliminate hazards in order to ensure greater safety, reliability and availability.

Risk Based Inspection (RBI) is a methodology that uses risk analysis to optimize equipment inspection plans. Through the evaluation of both probability of failure and their consequences, the items can be ranked taking into account the associated risks and thus prioritize inspection efforts according to this classification.

In traditional deterministic approach, the inspection frequencies are constant. Focusing on high-risk equipment, the RBI approach arises, then, as a possibility to reduce the inspection frequencies of low-risk equipment. Thus, using RBI it is possible to increase safety in systems, and at the same time, to reduce both the exposure of workers to radiation and inspection and maintenance expenditures.

RBI has its origins in the petroleum industry, involving equipment under high pressure, like vessels, piping and boilers. However, this technique also applies to other facilities that use similar equipment, such as nuclear power plants. In petrochemical sector, RBI is commonly used to assess the risks associated to piping damage, which are the main accident causes. Similarly, in the nuclear industry, most available studies and applications of RBI are related to pipe systems in reactors.

Risk-Informed In-Service Inspection (RI-ISI) is the methodology used in the inspection of pipes in the nuclear area. The increasing use of RI-ISI is a consequence of both recent developments in Probabilistic Safety Assessment (PSA), and the experience gained with nearly 10,000 operating reactor-years of nuclear power plants around world (ENIQ, 2012).

In-service inspection (ISI) is a planned activity involving examination, testing and non-destructive evaluation to verify and assure the structural and functional integrity of systems, structures and components of a nuclear reactor (CNEN, 1996). From ISI, material degradation information is obtained and the evolution of its effects are measured and controlled. By usage and ageing, equipment degradation occurs and can be measured in terms of corrosion, thickness reduction of parts or even presence of cracking. Such degradation is dependent on environmental and working conditions of the equipment and can vary from one facility to another. It means that a same equipment in distinct facilities could require different inspection time intervals. Improvements to take into account such uncertainties have resulted in risk-based methodologies (Soares *et al.*, 2015).

By identifying the degradation mechanisms, equipment risk is estimated through the assessment of the probability of failure and its consequences. With RBI, an inspection plan is defined, prioritizing high-risk locations and detecting potential degradation before the operation of the system is compromised. The RBI is then followed by maintenance policies that enable the reduction of risk, ensuring adequate safety levels.

This work presents several available methods to quantify risk information (frequency and consequences) applied to inspection and maintenance management. A case study of RBI application to nuclear power plant systems, using software developed by ReliaSoft® Corporation, is also carried out.

2. RISK BASED INSPECTION

RBI has its origin in the oil industry, involving pressurized equipment such as pressure vessels, pipes, tanks and relief valves. Risk assessment is applied to assure acceptable levels of mechanical integrity and reliability of equipment through well-planned inspection and maintenance policies. API RP 580 and API RP 581 are RBI practices recommended by the American Petroleum Institute (API). API-580 provides guidance on the development of an inspection program based on the risk of equipment of petrochemical and chemical process plants (API, 2002). While API-580 introduces the principles and general guidelines for the RBI, API 581 provides quantitative computation methods for establishing the inspection plans (API, 2008).

3. RISK-INFORMED IN-SERVICE INSPECTION

Risk-Informed In-service Inspection (RI-ISI) is the tool used in the nuclear area for planning in-service inspections of passive components, i.e. pressure-retaining components, especially pipes. It identifies high-risk locations where inspection efforts will be concentrated. Therefore, RI-ISI is the way that RBI is currently applied in nuclear power plants and is the term that has been used in the nuclear area publications.

3.1 Regulatory Requirements

The first document that regulated the in-service inspection at nuclear power plants was developed by American Society of Mechanical Engineers (ASME), the ASME Boiler and Pressure Vessel Code, Section XI: Rules for In Service Inspection of Nuclear Power Plant Components. This section provided inspection rules based on a sampling method, which takes into account the materials, systems and potential stress levels. These criteria were not sufficient to develop appropriate inspection plans and so nuclear power plants dedicated human and financial resources to inspect low-risk components and systems (IAEA, 2010).

As an alternative to deterministic inspection procedure of Section XI of ASME code, RI-ISI approaches have been developed. The most used are the EPRI (Electric Power Research Institute) and the PWROG (Pressurized Water Reactor Owners Group) methods. US Nuclear Regulatory Commission (USNRC) and the International Atomic Energy Agency (IAEA) approved these methods and published reports, and regulatory guides that present research results from accident investigations and technical information on the application of tools for risk-informed inspections.

3.2 RI-ISI Approach

The implementation of RI-ISI can be divided into nine steps (ENIQ, 2012), as described in the following.

3.2.1 Decision on type and level of analysis

The first step is to define the type and level of risk analysis. Regarding the type, the analysis can be classified as qualitative or quantitative. In the qualitative approach, the probabilities of failure (PoF) and consequence of failures (CoF) are characterized by terms such as high, medium and low. In the quantitative analysis, numerical estimates for PoF and CoF are used. Regarding the level, the risk assessment can be performed for each element individually or for groups of contiguous elements for which all the relevant conditions are the same.

3.2.2 Definition of RI-ISI program scope

It is the step in which the limits of application RBI program are established, that is, what systems should be ~~are~~ included. A scope will be "complete" when it covers the whole plant, or "partial", whether only a few systems or equipment is evaluated.

3.2.3 Collection of the required input data

The implementation of RI-ISI requires a variety of data and information, such as equipment technical specifications, plant operation data, general information of the nuclear industry, Safety Analysis Report and Probabilistic Safety Analysis (PSA) results (IAEA, 2010).

3.2.4 Analysis of failure consequence

Analysis of failure consequences includes the assessment of failure impact on the plant. Failure Mode and Effect Analysis (FMEA) can be applied as a qualitative approach, while PSA results can be used as a quantitative analysis. Piping failure consequences are typically measured in terms of the Conditional Core Damage Probability (CCDP) or Conditional Large Early Release Probability (CLERP). These estimations are obtained from PSA's level 1 and 2, respectively.

3.2.5 Analysis of failure probability

The first step to analyze the probability of failure of an equipment is the identification of potential degradation mechanisms. This step requires data of design and manufacturing, loads, environmental conditions and results of inspections (IAEA, 2010). Data from similar plant should also support this analysis.

3.2.6 Risk ranking

Risk can be defined as a product of the probability of failure (PoF) and the effect of this failure on a system (CoF - Consequence of Failure). Mathematically, the risk (R) can be shown as a function of time (t) as shown in Eq. (1):

$$\mathrm{R(t)} = \mathrm{PoF(t)} \times \mathrm{CoF(t)} \tag{1}$$

The distribution of risks of equipment can be shown in a risk matrix, when qualitative analysis is used, or in a risk graph, when quantitative results are available. Examples of such two risk ranking alternatives are depicted in Figs. 1 and 2.

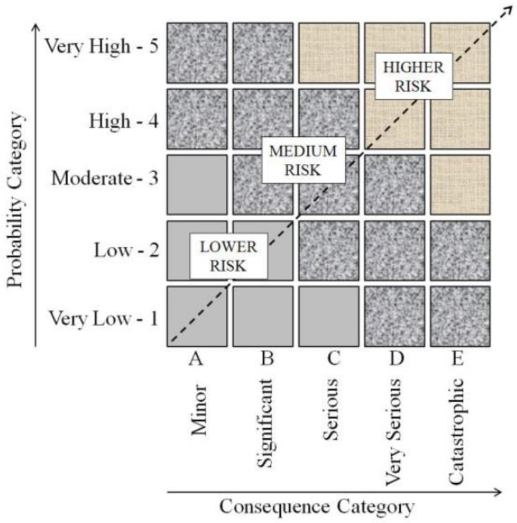

Figure 1. Risk matrix (Soares *et al.*, 2015).

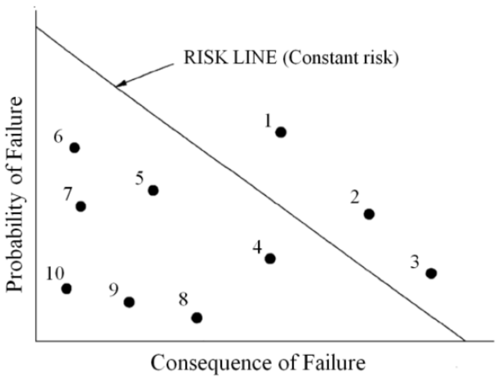

Figure 2. Risk graph (API, 2002).

3.2.7 Definition of the ISI program

The objective of the RI-ISI is to maintain the facility safety and reduce inspection and maintenance costs, prioritizing high-risk systems. To reach this purpose, an in-service inspection program is planned in which the systems, inspection modes and frequencies are defined as function of design information and status of plant equipment. In addition to the risk, other criteria should be met for the definition of ISI plan, as radiation doses that inspectors receive, ease of access, inspection costs and safety.

3.2.8 Impact of changes in inspection program on risk

The RI-ISI program should be compared with the previous inspection plan, so one can evaluate if its implementation resulted in facility safety improvement. The RI-ISI plan is effective when a reduction in the overall risk is reached. It is also acceptable to maintain a same risk level, since a reduction in the inspection frequency can reduce costs and worker exposure to radiation.

3.2.9 Long term management of a RI-ISI program

Risk management is a living process of continuing improvement of facility safety and availability. Risk assessments are time functions to ensure the effectiveness of RI-ISI. They must be updated whenever occurs plant modifications that can affect the component failure probabilities.

3.3 Approaches for implementing RI-ISI

There are several approaches for implementing RI-ISI, but, in general, all of them follow the steps described in item 3.2. Among the most used are the EPRI and PWROG methods. The main difference between these two methods is the type of analysis used: qualitative or quantitative (Sousa, 2004). While the ranking of risks in the EPRI method is qualitative, in PWROG the analysis of failure probabilities and consequences are carried out with quantitative models. RI-ISI EPRI approach uses the FMEA to identify potential degradation mechanisms and effects of piping ruptures. On the other hand, RI-ISI PWROG approach uses data obtained from PSA to classify quantitatively the failure consequences.

3.4 Reliability assessment of reactor piping failures

In order to identify failure mechanisms and consequences of ruptures of nuclear power plant piping, both generic failure data and specific information of the plant under consideration can be used, taking into account PSA results and operational experience. To ensure the effectiveness of RI-ISI approach, it is necessary to assess the quality and reliability of available piping failure data, and defining the scope of PSA in order to provide adequate RI-ISI program data.

4. PSA OF NUCLEAR POWER PLANTS

The PSA is used to analyze probabilistically the plant risks. Starting from an initiating event it examines the event sequences that may occur, leading to an accident (Hirata, 2009). The risk is then be assessed based on accident frequencies and their effects on facility, workers, environment and public. For nuclear power plant assessment, the PSA can be classified into three levels, differing by type of assessed consequences. Level 1 PSA evaluates the failures that lead to reactor core damage. The consequences are expressed in terms of Core Damage Frequency (CDF). Level 2 PSA estimates the release of radioactive material to the environment, expressed in terms of Large Early Release Frequency (LERF). Level 3 PSA assesses the offsite consequences of the release of fission products, which can be expressed as number of deaths, radiation doses to the public and environmental pollution (ENIQ, 2012). RI-ISI mainly uses information obtained is from level 1 PSA.

5. CASE STUDY

Low Pressure Injection System of a nuclear reactor (USNRC, 2016) was the case study selected to apply the RBI approach. This system has the function of removing water from a storage tank and injecting it into the reactor vessel when a depressurization occurs in primary system. A simplified diagram for this system is shown in Fig. 3.

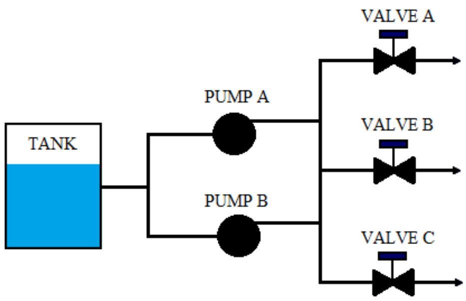

Figure 3. Simplified scheme for the Low Pressure Injection System (USNRC, 2016).

In order to assess the failure risks of this system, Event Trees should be developed, modeling the sequences of accidents that can occur from an initiating event, evaluating which of them could damage the reactor core (PSA level 1). In Fig. 4 is shown an Event Tree, built using the Reliasoft® RENO software, starting from a Small LOCA (Loss Of Coolant Accident) as an initiating event, and proceeds to the logical propagation of actuation of control and mitigation systems. The success of a control or mitigation system in each branch of the event tree is marked as T (True) and its failure is marked as F (Failure). To obtain the failure probabilities of these systems, fault trees such as shown in Fig. 5 are constructed. This tree, built using the Reliasoft® BlockSim software, shows the logical combination of events leading to failure of the mentioned Low Pressure Injection System. Thus, Core Damage Frequency (CDF) can be assessed based on occurrence frequencies of the initiating events and on failure probabilities of the protection and mitigation systems.

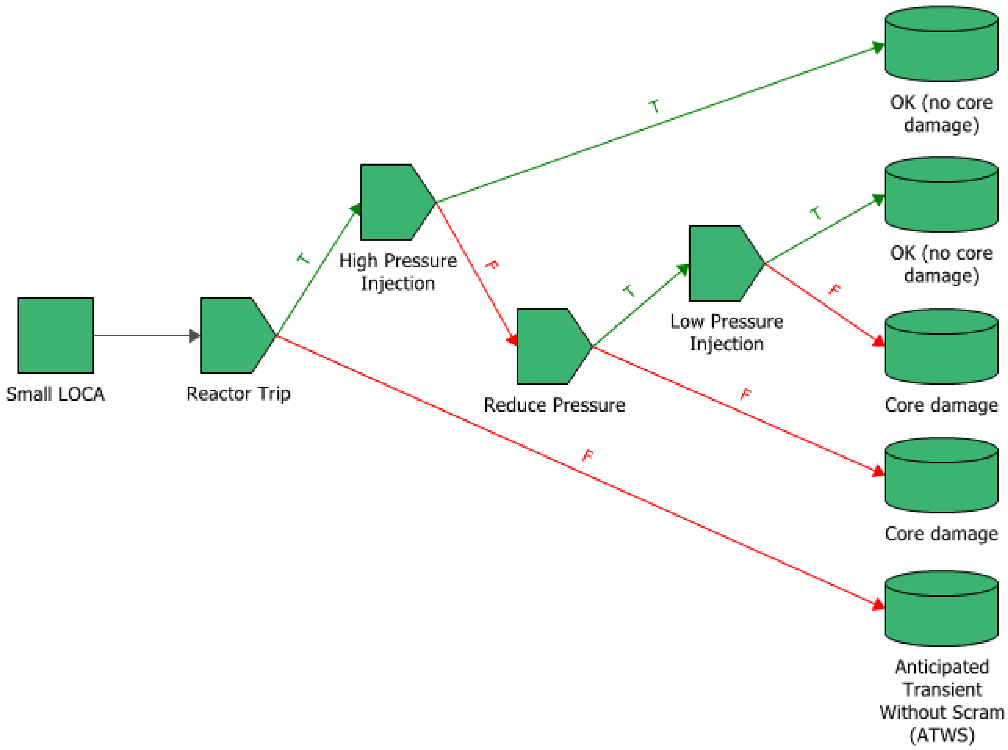

Figure 4. Event Tree for the small LOCA (developed using RENO software, based on USNRC (2016)).

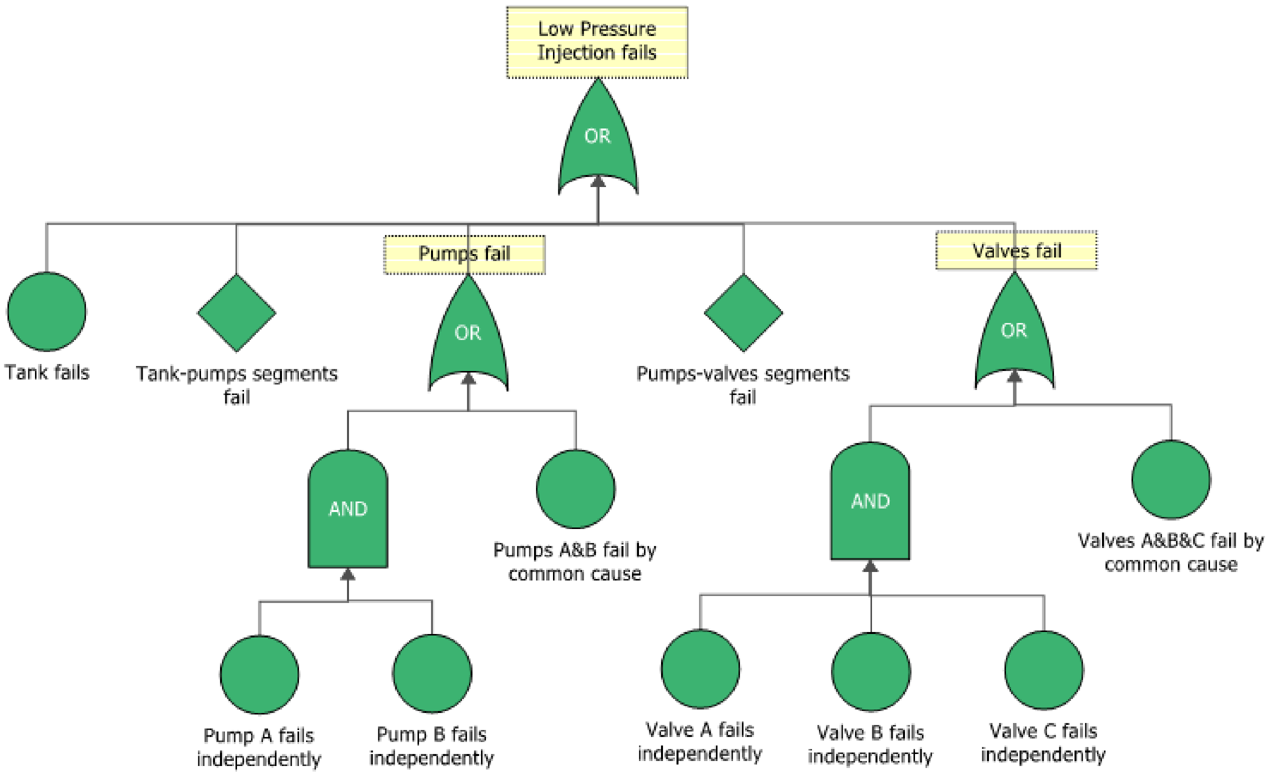

Figure 5. Fault Tree for the Low Pressure Injections System (developed using BlockSim software, based on USNRC (2016)).

The risks evaluated in a RI-ISI plan are determined based on the rupture of the pipe segments, causing the failure of mitigation systems modeled in the PSA. Thus, failure consequences, measured in terms of the Conditional Core Damage Probability given a pipe rupture (CCDP), can be obtained from CDF and Initiating Event Frequency (IEF) data as shown in Eq. (2):

$$\text{CCDP} = \frac{\text{CDF}}{\text{IEF}} \qquad (2)$$

CCDP information is then used to evaluate the failure consequences. Table 1 shows the EPRI (Electric Power Research Institute) criteria adopted for defining the consequence categories (EPRI, 1999).

Table 1. Criteria for consequence categories (Adapted from (EPRI, 1999)).

Consequence Category	**CCDP Range**
LOW	$\text{CCDP} \leq 10^{-6}$
MEDIUM	$10^{-6} < \text{CCDP} \leq 10^{-4}$
HIGH	$\text{CCDP} > 10^{-4}$

The degradation mechanisms are used to define the failure probability category. Table 2 shows the EPRI criteria adopted for the definition of failure probability categories.

Table 2. Criteria for probability categories (Adapted from (EPRI, 1999)).

Probability Category	**Degradation Mechanism**
LOW	None
MEDIUM	Thermal Fatigue Stress Corrosion Cracking Localized Corrosion Erosion-Cavitation
HIGH	Flow Accelerated Corrosion

The risks can be displayed in a matrix format as illustrated in Fig.6, where risk increases as we move to right and to the upper part of such matrix.

		Consequence Category			
		NONE	LOW	MEDIUM	HIGH
Probability Category	HIGH	Low	Medium	High	High
	MEDIUM	Low	Low	Medium	High
	LOW	Low	Low	Low	Medium

Figure 6. Risk matrix (Adapted from (EPRI, 1999)).

After evaluating the risks of each pipe segment, inspections can be planned, giving priority to high-risk locations. The EPRI selection criteria for inspection percentage of welds as function of risk ranking is shown in Tab. 3.

Table 3. EPRI Criteria for piping segment selection.

Risk Ranking	**Percentage selection of welds**
LOW	0%
MEDIUM	10%
HIGH	25%

In order to illustrate how EPRI criteria are applied to risk ranking, pipe welding data on Low Pressure Injection System of Forsmark Unit 3 were used (O'REGAN, 2010). CCDP information, degradation mechanisms, and consequence and failure probability categories of welding, as well as associated risks, are shown in Tab. 4.

Table 4. Risk ranking for the Low Pressure Injection System.

Number of welds	CCDP	Degradation Mechanism	Consequence Category	Probability Category	Risk Ranking
8	1.4 $x10^{-3}$	Stress Corrosion Cracking	High	Medium	High
2	1.4 $x10^{-3}$	Thermal Fatigue	High	Medium	High
35	1.4 $x10^{-3}$	None	High	Low	Medium
4	1.1 $x10^{-4}$	None	High	Low	Medium
2	1.0 $x10^{-5}$	Thermal Fatigue	Medium	Medium	Medium
10	1.0 $x10^{-6}$	Thermal Fatigue	Low	Medium	Low
4	1.0 $x10^{-5}$	None	Medium	Low	Low
120	1.8 $x10^{-5}$	None	Medium	Low	Low
118	1.4 $x10^{-5}$	None	Medium	Low	Low
54	2.3 $x10^{-5}$	None	Medium	Low	Low
181	2.2 $x10^{-5}$	None	Medium	Low	Low

The welding categorization according to risk matrix of Fig. 6, as function on their consequence and failure probability categories, is shown in Fig. 7. The number of welds selected for inspection, in each risk ranking, is shown in Tab. 5.

		Consequence Category			
		NONE	LOW	MEDIUM	HIGH
Probability Category	HIGH	-	-	-	-
	MEDIUM	-	10	2	10
	LOW	-	-	477	39

Figure 7. Risk matrix for the Low Pressure Injection System.

Table 5. Weld selection for the Low Pressure Injection System.

Risk Ranking	Number of welds	Number of selected welds
LOW	487	0
MEDIUM	41	5
HIGH	10	3

After defining the number and locations of welds to be inspected, methods and frequencies of inspections should be determined. These decisions depend on the degradation mechanisms, the severity of the effects caused by failures, the history of inspections and repairs, ease of access, radiation exposure levels, in addition to the costs involved. The inspection plan should be rather developed with the help of a multidisciplinary team that should take into account all this information. The analysis of these criteria is beyond the scope of this work.

After implementing the new inspection program, maintenance should be carried out to ensure adequate levels of system functionality, performance and safety. It is also necessary to compare the proposed RI-ISI program with the previous inspection plan, so that their impacts on risk can be evaluated.

6. CONCLUSION

Risk Based Inspection (RBI) is a methodology that uses risk information to optimize inspection planning, reduces costs and efforts, as well as ensures system reliability and safety of the facility, workers, environment and public. The basic idea is to identify high-risk locations where inspection should be prioritized.

Risk-Informed In-Service Inspection (RI-ISI) is an RBI approach developed for the nuclear area. Most studies and RI-ISI applications are focused on nuclear power plants piping, in which inspections are conducted in order to obtain information from damage to materials that enable risk assessment and control its effects.

Effective risk assessments require databases with plant information of process and similar facilities, and the presence of a multidisciplinary team to integrate different skills and knowledge that will enable the identification of all potential failures, assessment of its effects, as well as prioritization and definition of measures to eliminate, mitigate or control them. RI-ISI must also rely on tools and software that allow the development of a PSA and quantify the failure probabilities and consequences. Standards and technical reports should also be used to evaluate the degradation mechanisms and failure probabilities. Thus, risks and priority inspections are then defined.

In addition to the risk, other criteria must be considered in the preparation of an inspection plan, as inspection and maintenance histories, exposure to radiation, associated costs and ease of access to the inspection location. Despite RI-ISI methodologies are available in the literature, the quality of its application will depend on the amount of available data and on the ability of specialists to treat them.

This work presents a method for defining inspection plans at nuclear facilities and its application in a case study available in the literature, illustrating how EPRI criteria could be used to categorize piping segments using welding data on Low Pressure Injection System from Forsmark Unit 3. This categorization allows defining where inspections efforts should be concentrated. The Reliasoft® RENO and BlockSim software were used, respectively, to implement the event trees and fault trees from this case study. Advantages of use of proposed RI-ISI program compared with the previous inspection plan based on constant inspection frequencies are prioritizing welding inspections on high-risk piping segments, and the possibility of reducing inspection frequencies on low-risk piping segments. Thus, RBI use increase safety in systems, and at the same time reduces both the exposure of workers to radiation and both inspection and maintenance expenditures.

7. ACKNOWLEDGEMENTS

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8. REFERENCES

API – American Petroleum Institute, 2002. Risk-Based Inspection. API RP 580, first edition.

API – American Petroleum Institute, 2008. Risk-Based Inspection Technology. API RP 581, second edition.

CNEN – Comissão Nacional de Energia Nuclear, 1996. Inspeção em Serviço em Usinas Nucleoelétricas. CNEN NE 1.25.

ENIQ – European Network for Inspection and Qualification, 2012. Risk-Informed In-Service Inspection: An Overview for the Non-Specialist. ENIQ Report No 46, EUR 25199 EN.

EPRI – Electric Power Research Institute, 1999. Revised Risk-Informed Inservice Inspection Evaluation Procedure. TR-112657 Rev. B-A.

Hirata, D. M., 2009. Estimativa da Frequência de Danos ao Núcleo devido à Perda de Refrigerante Primário e Bloqueio de Canal de Refrigeração do Reator de Pesquisas IEA-R1 do IPEN-CNEN/SP – APS Nível 1. Master's thesis, Instituto de Pesquisas Energéticas e Nucleares, São Paulo, Brazil.

IAEA – International Atomic Energy Agency, 2010. Risk-informed In-service Inspection of Piping Systems of Nuclear Power Plants: Process, Status, Issues and Development. IAEA Nuclear Energy Series No. NP-T-3.1.

O'Regan, P. *et al.*, 2010. Using the EPRI Risk-Informed ISI Methodology on Piping Systems in Forsmark 3. Report number: 2010:42.

Soares, W. A. *et al.*, 2015. Risk-Based Inspection in the Context of Nuclear Power Plants. In: International Nuclear Atlantic Conference, INAC 2015, São Paulo, Brazil.

Sousa, A. L. B, 2004. Uma Avaliação Crítica da Aplicação da Inspeção Baseada em Risco em Instalações Químicas e Nucleares. Master's thesis, Universidade Federal do Rio de Janeiro, Rio de Janeiro, Brazil.

USNRC – United States Nuclear Regulatory Commission, 2016. Tutorial on Probabilistic Risk Assessment (PRA). Available at http://www.nrc.gov/about-nrc/regulatory/risk-informed/rpp/pra-tutorial.pdf. Accessed August 1st 2016.

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