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PLM integrated Risk Informed In-Service Inspection in Nuclear Power Plants

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Abstract – **The paper comprises development of risk informed techniques in the field of Asset Management by integration of PLM. Risk Informed In-Service Inspection is one such technique which deals with the prioritization of piping components for their inspection level and intervals. While planning the inspection program varied parameters like risk, radiation exposure to the employees and cost of inspections have to be considered. In an attempt to achieve an optimized solution, EPRI methodology has been employed which has already established its suitability in optimizing Surveillance and Maintenance activities in Nuclear Power Plants. The paper describes the application of this methodology in optimizing the ISI of Emergency Cooling Water system of the Research Reactor.**

Keywords* – *Asset Management, EPRI methodology, In-Service Inspection, PLM, Risk, Thomas Approach.

I. INTRODUCTION

In a nuclear power plant the main asset of the reactor is the piping system. In order to monitor the smooth working (product lifecycle) of the nuclear plant's (NPP) piping system, they are subjected to in-service inspections (ISI). Inspections are performed by achieving shutdown and only a portion of the piping components is inspected. The purpose of these inspections is to detect the possible degradation of the piping components. The risk of a pipe failure is thus minimized, assuming that corrective actions are taken if potential flaws are detected. As a part of surveillance programme, In-Service Inspection programme is put in place for research reactor and the programme is carried out as per the guidelines provided in ISI Programme and technical specifications (management). [1]

Product lifecycle management (PLM) is the process of managing the entire lifecycle of a product from inception, through engineering design and manufacture, to service and disposal of manufactured products. PLM integrates people, data, processes and business systems and provides a product information backbone for companies and their extended enterprise [2]. Asset management refers to any system that monitors and maintains things of value to an entity or group. It may apply to both tangible assets such as buildings and to intangible assets such as human capital, intellectual property, and goodwill and financial. Asset management is a systematic process of deploying, operating, maintaining, upgrading, and disposing of assets cost-effectively [3]. An integration of AM and PLM processes can reduce operational costs and boost efficiency for manufacturers of all types.

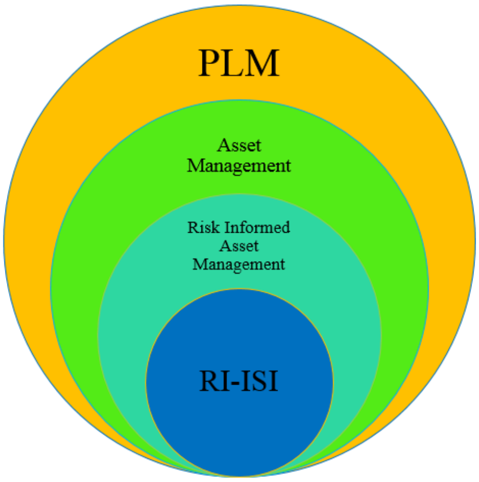

Figure 1: Hierarchy of RI-ISI

Risk informed approach in decision making represents a philosophy whereby risk insights derived from risk assessment, by comparison of the results with the probabilistic safety goals, are considered together with other information obtained from deterministic safety analysis, engineering judgement, operation & maintenance experience, and is employed for formulating the surveillance program. When risk insights are applied to planning in-service inspection, it is termed as 'Risk Informed In-Service Inspection'.

II. LITERATURE REVIEW

RI-ISI is a sub topic of Risk Informed Asset Management. Till now many researchers and scientist have published many papers on this topic of Risk Informed Asset Management. There has been a varied use of Risk Informed Asset Management in the fields of financial, infrastructural, enterprise and public asset management. Paper [4] deals with the public asset management as the risk of sanitary sewer pipe failure has been applied to a mid-sized city in Ontario using a risk matrix system and a weighted scoring summation methodology in ArcGIS. Out of 4656 uninspected pipe assets, 3.5% have a high failure risk whereas 6% showed high to very high Consequence of Failure. The methodology adapted in this paper is general and can serve as a basis for future planning and decision making. Case study [5] worked for a 40-year plan for the operating railway assets. The optimized overhaul cycle in 4-8-12 year interval saved HK$4.9 Million per annum, an average 11% of existing total overhaul maintenance cost. The basic method remains the same for every paper/research by calculating the failure rates and consequences due to these failures. This gives the risk associated with each component of the system under evaluation.

III. PROBLEM STATEMENT

In a NPP there are various systems. Among these system there is one system known as the Emergency cooling water system (ECW) or the shutdown cooling system. This system is responsible for the removal of excessive heat from the primary coolant. This system consists of numerous piping segments and equipment. The failure of these piping segment and equipment lead to an initiating event internal flooding. Internal flooding leads to failure or outage of subsequent system. ASME BPVC section XI provides the rules for in-service inspection of nuclear power plants. Traditional in-service inspection serves to detect the possible degradation of any piping segment or equipment involved in a system under consideration. According to ASME BPVC section XI the inspection interval for these inspection is 5 yrs. During these inspection plant has to be shut down and the inspection programme is not started till the nuclear radiations are below a certain prescribed limit. This leads to the following problems:

- Increased man-rem exposure
- Increased inspection costs (LPT, UT, VT, etc.)
- Plant outages and shutdown time
- Chance of complicating the plant operation (scaffolding, leakages, etc.)

IV. DATA COLLECTION AND ASSESSMENT

For risk analysis appropriate and most suitable data is of prime importance as it facilitates the best results. From the literature we found that the data taken for risk analysis is gathered from various sources like historical data, performance manuals, fault tree analysis, event tree analysis, expert judgement, questionnaire, etc.

For RI-ISI we have used PLM software FaultTree+ Version 10.1 for estimation of the failure frequencies of each event involved in the initiating events and mitigating actions. The data required for the fault tree was taken from plant records, generic data, expert opinion, etc. and for event tree the frequency of the initiating event is taken as the rupture frequency of the pipe segments each, while human error probabilities were calculated using THERP. The failure consequences were evaluated adopting Dhruva Level 1+ PSA models. [6] [7] The consequences from their failures were resulting in events such as internal flooding and severity depends on whether a leaky pipe segment can be isolated or not. Accordingly, two Categories are formed.

V. METHODOLOGY

The methodology employed in this paper is the EPRI methodology. The EPRI RI-ISI procedure includes the following four major steps [8]

- Identification of the system and evaluation of boundaries, including the selection of the piping systems to be inspected,
- Failure mode and effect analysis (FMEA), in which the potential failure modes of the chosen piping systems are determined and the consequences of a possible pipe rupture are estimated by using PLM tool Faulttree+
- Division of selected piping systems into separate segments, where a piping segment consists of a continuous pipe run, the components of which have common rupture impacts and degradation/failure modes and
- Risk assessment of each pipe segment.

Based on the risk assessment, pipe segments are divided into categories of high, medium and low risk, using as a risk parameter the conditional core damage probability (CCDP) given in the following risk matrix, which is the possibility that a rupture in a segment results in a core damage (CD), for a limiting pipe break size and the probability of a pipe break, where the probability of a pipe break is assessed on the basis of the determined degradation mechanism(s) for each pipe segment.

Table 1: EPRI Risk Matrix

Potential for pipe rupture	*Consequences of pipe rupture*			
	None	Low	Medium	High
High	Category 7	Category 5	Category 3	Category 1
Medium	Category 7	Category 6	Category 5	Category 2
Low	Category 7	Category 7	Category 6	Category 4

Pipe elements within each segment are candidate locations to be selected for the inspection program. The number of elements to be examined as part of the RI-IS program depends on the risk category for the risk-significant segments. For elements determined to have degradation mechanisms other than those included in the existing plant flow accelerated corrosion (FAC) and Intergranular Stress corrosion cracking(IGSCC) inspection programs, the following number of elements are to be volumetrically examined (beyond pressure/leak testing requirements) as part of the RI-ISI program:

- For risk Category 1, 2, or 3, the minimum number of inspection elements in each category should be 25 percent of the total number of elements in each risk category (rounded up to the next higher whole number).
- For risk Category 4 or 5, the number of inspection elements in each category should be 7.5 percent of the total number of elements in each risk category (rounded up to the next higher whole number).

VI. RI-ISI APPROACH

Inspection and maintenance of nuclear reactor is a normal practice for safe operation and this procedure incurs significant amount of revenue for plant operation. If focused inspection and maintenance schedules can be implemented, the amount of expenditure, utilization of manpower, man-rem consumption and reactor outage time will optimize and at the same time safety of the plant will increase. These objectives can be achieved through a comprehensive RI-ISI programme. The objective of the programme is to develop improved procedures, to identify where the highest likelihood of damage/failure associated with significant leak rate is located in plant and then, to provide quantitative measures of the associated risks.

For a successful RI-ISI program, the conventional approach has been slightly modified by incorporating the leak rate and zone of piping (Isolatable and non-isolatable);

i. Identify the systems to be included in RI-ISI program.
ii. Identify the applicable degradation mechanisms and estimate the component failure probabilities for leak and rupture cases for each component.
iii. Estimate the consequence of failure and associated risk by using Faulttree+ PLM software.
iv. Apply these estimates in Electric Power Research Institute (EPRI) matrix for risk categorization and find risk index from the matrix.
v. Estimate the leak rate from the pipe segment selected
vi. Identify the zone of the piping
vii. Conduct a Risk impact based on EPRI risk index, leak rate and piping zone.

Identify the systems to be included in RI-ISI program

The identification of the systems to be included in the RI-ISI is related with the safety significance of the system. The systems where degradation will eventually lead to core damage or significant activity release will form the part of RI-ISI.

Applicable degradation mechanisms and piping failure probabilities estimation

Estimation of piping failure probability is a crucial task since this form the basis for further analyses. The literature suggests three methods for piping failure probability estimation: (i) Structural Reliability Analysis (ii) Service Data Analysis and (iii) Expert Opinion. The degree to which one relies on one method or another depends on the availability of data from service experience, experts or structural reliability or risk models. For the scope of this project, Service data analysis is given focus and models based on that approach is employed.

H.M. Thomas has suggested an approach by which the base failure probability is multiplied with factors derived from service experience. Since these factors were derived way back in 1981, B.O.Lydell [9] has modified these factors in 2000, with the reactor experience till then. A correlation model has been proposed between piping design and operational parameters and frequency of leakage.

$\lambda_{F\text{-}TOT} = \lambda_{BASE}\ Q_E\ FB$……(1)

Where,

$\lambda_{F\text{-}TOT}$ = Plant specific total leakage frequency = λ_C

λ_{BASE} = Base line generic frequency (in the range of 1E-9 to 1E-7/ year)

F = plant age factor, B = design learning curve

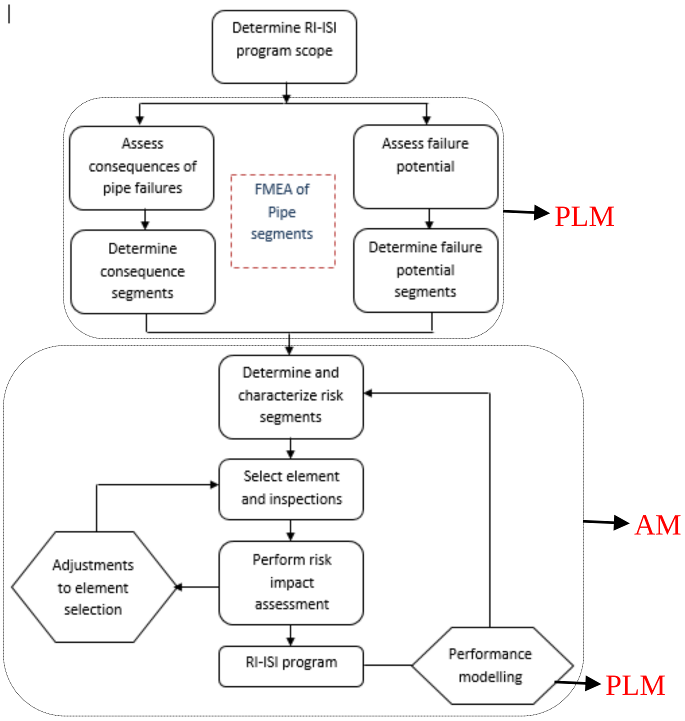

Figure 1: Overview of EPRI RI-ISI methodology

Q_E = Multiplier representing the change in reliability by piping size and shape differences = $Q_P + (AQ_W)$

$Q_P = {}^{L}/_{Dt^2}$, $Q_W = N1.75\ {}^{D}/_{t}$ and A = Weld Penalty factor (suggested value 50)

L = Length of pipe

D = Pipe Diameter

t = Pipe wall thickness

N = Number of circumferential welds in the system

For calculating Age factor F, cumulative number of failures in first ten years is taken as unity and then number of failures per year as a fraction of unity against age is plotted. F factor is then plotted as a function of pipe size and degradation mechanism. As far as design learning curve factor B is concerned, Thomas remarks that unless one is estimating the leak or rupture frequency for a new design there is no need to consider the B factor. It may be assumed to 1.

Finally, Thomas defined relationship between frequency of catastrophic rupture (**λ_C**) and frequency of leakage (**λ_L**).

*$\lambda_C = \lambda_L \times P(C|L) = \lambda_{F\text{-}TOT}$……(2)

Where,

P (C|L) = conditional probability of rupture given leakage

This (P (C|L)) has been derived for all degradation mechanisms from SKI-PIPE database.

Swedish Nuclear Power Inspectorate (SKI) have collected piping experience of 2,067 Reactor years, which comprises of data on piping failures from different degradation mechanism. This data is utilized for point value estimation (prior values) of failure frequency for each mechanism.

Using Bayes' theorem, the prior values can be updated with plant experience, to obtain the uncertainty distributions. They have taken a prior value that is represented by a lognormal distribution with a mean of $5x10^{-3}$ per year and a 95 percentile value of $1x10^{-2}$ per year for pipe ruptures for all mechanisms. Wherever there is no experience data available, upper bound is estimated assuming 1 rupture for each failure mechanism.

Estimate the consequence of failure

The consequence of a rupture of the pipe will depend on the conditional core damage probability, extent of leak and operator action to isolate the ruptured pipe segment; these are described in the following paragraph.

CCDP estimation due to pipe rupture as Initiating Event:

The event occurs when a pressure boundary failure occurs in an operating system. This failure will lead/could lead to *internal flooding* if corrective action by the plant personnel are not initiated. The importance of every initiating event, caused by a pipe failure, needs to be assessed in order to assign it to its appropriate consequence category. Conditional core damage probability (CCDP) can be directly obtained from the PSA results, by dividing the CDF due to the specific IE (f_{IE}) by the frequency of that IE (λ_{IE}).

$\mathbf{CCDP} = \mathbf{f_{IE}} / \boldsymbol{\lambda_{IE}}$……(3)

Table 2: Consequence Range per category

Consequence category	Corresponding CCDP range
High	CCDP>1E-4
Medium	1E-6<CCDP≤1E-4
Low	CCDP≤1E-6

Risk categorization through Electric Power Research Institute (EPRI) matrix

EPRI methodology blends PSA and deterministic insights using Risk matrix. Risk matrix can be defined as a decision matrix that is used to categorize the pipe segments into high, medium, and low importance, based on degradation mechanism and consequence of its failure. By examining the service data, a basis has been established for ranking pipe segment rupture potential as High, Medium, or Low simply by understanding the type of degradation mechanism present. Consequence can be quantified through the estimation of (CCDP).

VII. RESULTS

For each piping component, in the loop considered in this pilot study, CCDP needs to be evaluated. In Dhruva, total 27 piping segments are taken for preparation of present RI-ISI framework document. The changes in the pipe risk category based on RI-ISI are presented in the table 3.

Table 3: CCDP values

Category	**CCDP**
Internal flooding due Severance failure of ECW line	$5.04 * 10^{-6}$
Internal flooding due Non Severance failure of ECW line	$5.2 * 10^{-6}$

Table 4: Example of Risk Impact assessment

Pipe segt.	Rupt freq	ccdp	Risk category	Existing ISI grading	RI-ISI grading
Pipe 1	0.00011	5.2E-06	5	H	M
Pipe 2	0.00011	5.2E-06	5	H	M
Pipe 3	3.52E-05	5.2E-06	6	H	L
Pipe 4	3.28E-05	5.04E-06	5	H	M

Table 5: Comparison of existing and proposed RI-ISI based pipe segment Inspection

Piping	Existing	RI-ISI	Remark
High	27	0	16 pipe segments got changed from high to low category. 11 pipe segments got changed from high to medium category
Medium	Nil	11	There were no piping segments in medium and low category.
Low	Nil	16	

VIII. CONCLUSION

The traditional ISI programme identifies the required inspections based on deterministic criteria including stress analysis, structural discontinuities, and/or random selection processes. RI-ISI uses plant specific data, operating experience and risk insights to target the pipe segments that present the greatest risk, including both the likelihood and consequences of failure. Due to its systematic, risk-informed nature, the RI-ISI process generally identifies few risk-significant welds for inspection from the set of regularly inspected weld through ISI. This translates to fewer inspections to be performed and reflects in lower system outages time and reduced personnel exposures. Also the integration of PLM tools brings in the ease and accuracy of important characteristics of the system components. Thus forming a template to analyse the system under consideration and getting more precise results for future analysis.

From the first ISI campaign it is evident that the number of weld defects and their location not so significant. Additionally well maintained system chemistry ensures minimum possible degradation of the plant piping. The observed steady state vibration values are within limits. These stresses being in limit do not degrade the system piping and hence calculated pipe failure values falls in conservative domain.

The piping risk categorization based on CCDP, leak rate and piping zone has helped in reducing the number of in-service inspections that will help in dose management, reduction in shutdown time and requirement of lesser manpower.

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