EVALUATION OF PIPING RELIABILITY AND FAILURE DATA FOR USE IN RISK-BASED INSPECTIONS OF NUCLEAR POWER PLANTS

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ABSTRACT

During operation of industrial facilities, components and systems can deteriorate over time, thus increasing the possibility of accidents. Risk-Based Inspection (RBI) involves inspection planning based on information about risks, through assessing of probability and consequence of failures. In-service inspections are used in nuclear power plants, in order to ensure reliable and safe operation. Traditional deterministic inspection approaches investigate generic degradation mechanisms on all systems. However, operating experience indicates that degradation occurs where there are favorable conditions for developing a specific mechanism. Inspections should be prioritized at these places. Risk-Informed In-service Inspections (RI-ISI) are types of RBI that use Probabilistic Safety Assessment results, increasing reliability and plant safety, and reducing radiation exposure. These assessments use both available generic reliability and failure data, as well as plant specific information. This paper proposes a method for evaluating piping reliability and failure data important for RI-ISI programs, as well as the techniques involved.

Keywords: Nuclear Power Plants, In-Service Inspection, Piping, Failures

INTRODUCTION

Risk of accidents in industrial facilities generally increases as the lifetime of equipment important to safety increases. Equipment degradation monitoring through inspections is one way to prevent that a certain level of risk is not exceeded. Risk-Based Inspection (RBI) involves planning of inspection based on equipment risk analysis. Risk analysis identifies both the possible degradation mechanisms and threats to equipment integrity, assessing probability and consequence of its failure. In case of Nuclear Power Plants (NPP), In-service Inspection (ISI) is one of the defense-in-depth levels to ensure reliable and safe operation.Traditional inspection programs are carried out by adopting a deterministic approach, while probabilistic approaches focus inspections on places and equipment of major risks. ISI traditional approaches investigate generic degradation mechanisms in all plant systems. However, operating experience indicates that degradation occurs where there are favorable conditions for developing a specific mechanism, that is, in places with greatest failure probability, where inspections should be prioritized.

In the context of NPP, Risk-Informed In-Service Inspections (RI-ISI) are RBI that generally uses results from Probabilistic Safety Assessment (PSA) and operational experience of nuclear sector to define the importance of systems and components contributing to the risk. This allows increasing reliability and plant availability, as well as reduces worker exposure to radiation doses to as low as reasonably achievable (ALARA) levels.

In the scope of a RI-ISI program, piping systems are one of the most important items to safety, and their failure mechanisms and rupture consequences are major contributors for NPP risks. Risk assessments use both available generic reliability and failure data available for PSA (WASH-1400, EPRI and NRC reports, OECD piping failure database, etc.), and plant specific information, taking into account PSA developed or under development, and facility operational experience.

This paper proposes a method and techniques for estimating piping reliability and failure probability, incorporating ISI effects. It starts with a survey on available reliability and failure data of piping systems to be used in RI-ISI programs of NPP, particularly applicable to places with potential of Loss of Coolant Accidents (LOCA). It is recommended the use of analysis tools and techniques, as Failure Mode and Effects Analysis (FMEA), Markov models, Fault Tree Analysis, Bayesian estimation and Monte Carlo method. It is also proposed the use of XFMEA, RENO, WEIBULL^{++} and BLOCKSIM software package, developed by Reliasoft® Corporation(1), in order to support the analyses.

AVAILABLE DATA FOR USE IN RI-ISI PROGRAMS

RI-ISI programs involve, among others, the following tasks(2):

- estimating the probability of leak and rupture for piping segments;
- identifying the structural elements for which ISI can be modified based on factors such as risk insights, defense-in-depth, and reduction of unnecessary radiation exposure to personnel;
- determining the risk impact of changes on ISI programs;
- determining the consequences of piping rupture, measured in terms of the conditional probability of core damage given a piping rupture (CCDP), and the conditional probability of large early release given a piping rupture (CLERP).

Inspection data, piping reliability and LOCA frequencies can be taken from plant specific information or generic database. Plant specific data are drawn directly from sources available at the plant (maintenance records, work orders, etc.). This is normally considered the best data source for a plant under analysis. However, data with the required quality and quantity are rarely available. Generic data, updated with plant specific operating experience, is usually applied when limited plant specific data are available. For this case, Bayesian estimation is the approach usually employed. Table 1 shows a set of selected piping database for supporting RI-ISI studies.

Table 1. Selected piping database for supporting RI-ISI studies.

Description	Source
WASH 1400: Reactor Safety Study (NUREG 75/014)	USNRC(3)
Pipe Break Frequency Estimation for Nuclear Power Plants (NUREG/CR-4407)	USNRC(4)
Pipe failures in U.S. commercial Nuclear Power Plants (EPRI-TR-100380)	EPRI(5)
Conditional frequency of piping ruptures after leaking, determined by the frequency of severe water hammer events (EPRI-NP-6766)	EPRI(6)
Piping system failure rates, leak frequencies and rupture frequencies for use in risk informed in-service inspection applications (EPRI-TR-111880)	EPRI(7)
Industry-Average Performance for Components and Initiating Events at U.S. Commercial Nuclear Power Plants (NUREG/CR-6928)	USNRC(8)
Estimation of loss of coolant accident frequencies, partly based on fracture mechanics has been used to form a basis for the priors for the conditional pipe rupture probabilities (NUREG-1829)	USNRC(9)
OECD-NEA Piping Failure Data Exchange Project (OECD-NEA OPDE)	OECD(10)

WASH 1400 was the first known probabilistic safety study performed in 1975, and used data derived from different sources, including reports, handbooks, industrial operating experience and nuclear power plant experience(3). It included piping reliability study and remained as a primary source of data in subsequent PSA studies(11).

In 1987, an extensive study aimed at replacing WASH-1400 (NUREG/CR-4407) was carried out. Nuclear piping failure data were reviewed and frequencies were estimated taking into account these data and the number of operating years of U.S. reactors. The frequencies of failure were relatively large because the small number of operating reactor-years. This study provided frequencies as function of plant type, pipe size, leak rate, as well as system and operational modes(4).

Until 1992, most existing databases including pipe failure rates were based on judgment from industry experts. Then, EPRI has developed a methodology and database that used actual experience of nuclear industry to support failure rate calculations on a plant specific basis (EPRI-TR-100380). In addition to update pipe failure rates, this study provided quantitative information on plant aging effects on pipe failures, break-before-leaks probabilities, and plant outage times due to pipe failures(5).

Another report, prepared by SWEC (Stone and Webster Engineering Corporation) in 1992 for EPRI (“Water hammer prevention, mitigation, and accommodation: plant water hammer experience” – EPRI-NP-6766), is still used in RI-ISI studies. Among the useful data can be highlighted the conditional frequency of piping ruptures after leaking, estimated by the frequency of severe water hammer events(6). Piping system failure rates, leak frequencies and rupture frequencies for use in RI-ISI applications are available in EPRI-TR-111880(7).

NUREG/CR-6928(8) characterizes current industry-average performance for components and initiating events at U.S. commercial nuclear power plants. Four types of events are covered: component unreliability, component unavailability resulting from test or maintenance outages, especial event probabilities covering operational issues, and initiating event (including LOCA) frequencies.

A 2008 USNRC report “Estimating Loss-of-Coolant Accident (LOCA) Frequencies through the Elicitation Process” (NUREG-1829) shows estimations of LOCA frequencies, partly based on fracture mechanics. It has been used to form a basis for the conditional piping rupture probabilities estimations. The elicitation required each member of an expert panel to qualitatively and quantitatively assess important LOCA contributing factors and quantify their uncertainties(9).

The last piping database included in Table 1 is the Piping Failure Data Exchange Project (OECD-NEA OPDE), a multilateral co-operation in the collection and analysis of data relating to degradation and failure of piping in NPP(10). The main goals of this OPDE Project are:

- collect and analyze piping failure event data to promote a better understanding of causes, impact on operations and safety, and prevention;
- generate qualitative insights into the root causes of piping failure events;
- establish a mechanism for efficient feedback of experience gained in connection with piping failure phenomena, including the development of defense against their occurrence;
- collect information on piping reliability and factors influencing piping failure frequencies.

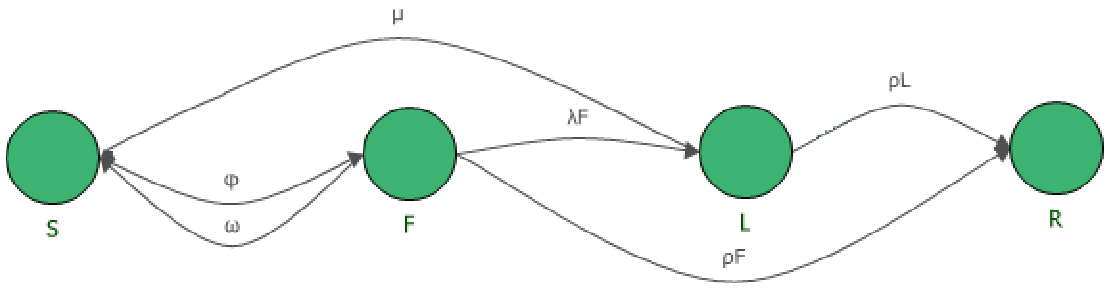
A list of potential OPDE database applications includes, among others, Identification of new degradation mechanisms, evaluation of effectiveness of ISI programs (flaws not detected by prior inspections), effectiveness of mitigation measures, leak rate versus flaw size correlations and piping damage frequency estimation. This continuously updated database is then fundamental for support risk informed applications, such as RI-ISI and PSA.

A critical issue in the estimation of failure rates is the treatment of uncertainties, which can exceed an order of magnitude deviation from failure rate point estimates. Sources of uncertainty include failure data reporting issues, scarcity of data, poorly characterized component populations, and uncertainties about the physical characteristics of the failure mechanisms and root causes. A quantification of these uncertainties using a Monte Carlo method(11) can be carried out with support of RENO Reliasoft® software(1) and used in RI-ISI applications.

MARKOV MODELS FOR PIPING RELIABILITY ASSESSMENT

As part of an EPRI sponsored research project to develop technology for risk informed in-service inspection evaluations, new methods and databases were developed to predict piping system reliability. The methods include a Markov modeling technique for predicting the influence of alternative inspection strategies on piping system reliability estimation, and Bayes uncertainty analysis methods for quantifying uncertainties in piping system reliability parameters(12).

Fig. 1 shows a simplified four state Markov model that has the capability to model piping locations that do not involve severe loading conditions but are susceptible to damage mechanisms, such as IGSCC (Inter-granular Stress Corrosion Cracking) and erosion–corrosion. For these locations, a leak or rupture can only occur from the state of an existing flaw, eliminating some of the transitions permitted by general models that includes all the known piping failure mechanisms(12). This kind of simplified model can be applied in RI-ISI evaluations due to its ability to model ruptures at different rates from a flaw or leak state. It has also the capability for modelling repairs after detecting the presence of a flaw or a leak. S, F, L and R in Fig. 1 are the piping element states of “Success”, “Detectable flaw”, “Detectable leak” and “Rupture”, respectively. The strategies for estimating each one of the state transition rates are shown in Table 2.



Piping Element States	**State Transition Rates**
S – Success, no detectable damage	Φ – Flaw occurrence rate
F – Detectable flaw	λ_F – Leak failure rate
L – Detectable leak	ρ_F– Rupture failure rate given flaw
R - Rupture	ρ_L– Rupture failure rate given leak
	ω – Repair rate via ISI exams
	μ – Repair rate via leak detection

Figure 1. Four state Markov model for crack propagation mechanism (adapted from Fleming(12) and drawn with support of BLOCKSIM software(1)).

Table 2. Strategies for estimating Markov model parameters mechanism (adapted from Fleming(12)).

Symbol	**Strategy for estimation**
Φ	Data from nondestructive evaluation inspections results can be used to estimate this parameter directly or it can be estimated as a multiple of the rate of leaks based on ISI experience
λ_F	Service data for selected failure mechanisms
ρ_F	Service data for ruptures for selected failure mechanisms
ρ_L	Estimates of physical degradation rates and times to failure converted to equivalent failure rates; or estimates of water hammer challenges to the system in a degraded state
ω	Model of Eq. (A) and estimates of P_I ; P_{FD}; T_{FI}; T_R
μ	Model of Eq. (B) and estimates of P_{LD}; T_{LD}; T_R

The repair rate via ISI exams, ω, is given by Eq. (A):

$$\omega = \frac{P_I \,.\, P_{FD}}{(T_{FI} + T_R)}, \qquad (A)$$

where P_I is the probability that a piping element with a flaw will be inspected per inspection interval, P_{FD} is the probability that a flaw will be detected given this segment is inspected (often referred to as the “Probability of Detection” or PoD), T_{FI} is mean time between inspections for flaws (inspection interval), and T_R is mean time to repair once detected (it is assumed that any significant detected flaw will be repaired).

The repair rate via leak detection, μ, is given by Eq. (B):

$$\mu = \frac{P_{LD}}{(T_{LI} + T_{LD})}, \qquad (B)$$

where P_{LD} is the probability that the leak in the segment will be detected per inspection, and T_{LI} is the time between inspections for leaks.

FAULT TREE ANALYSIS FOR PIPING FAILURE ASSESSMENT

Fault Tree Analysis can be used as an alternative to Markov models to estimate the piping failure probability incorporating effect of ISI. Sometimes the use of Markov model is relatively complex, and fault tree get similar results, slightly conservative, but in an easier way(13,14).

By dividing piping states into four types, successive state, detectable flaw state, detectable leakage state and failure state, a fault tree model that is analog to Fig. 1, considering “Piping failure” as top event, can be expressed as shown in Fig. 2. The descriptions of the primary events of the fault tree are listed in Table 3.

The parameters expressing primary events rate in fault tree depends on both historical generic component data and plant specific data, which can be combined through Bayes' method. Among the necessary data for estimating primary event parameters can be highlighted: effectiveness rate to inspect flaw, piping flaw probability, piping rupture probability, effectiveness rate of leakage detection, and leakage occurrence rate.

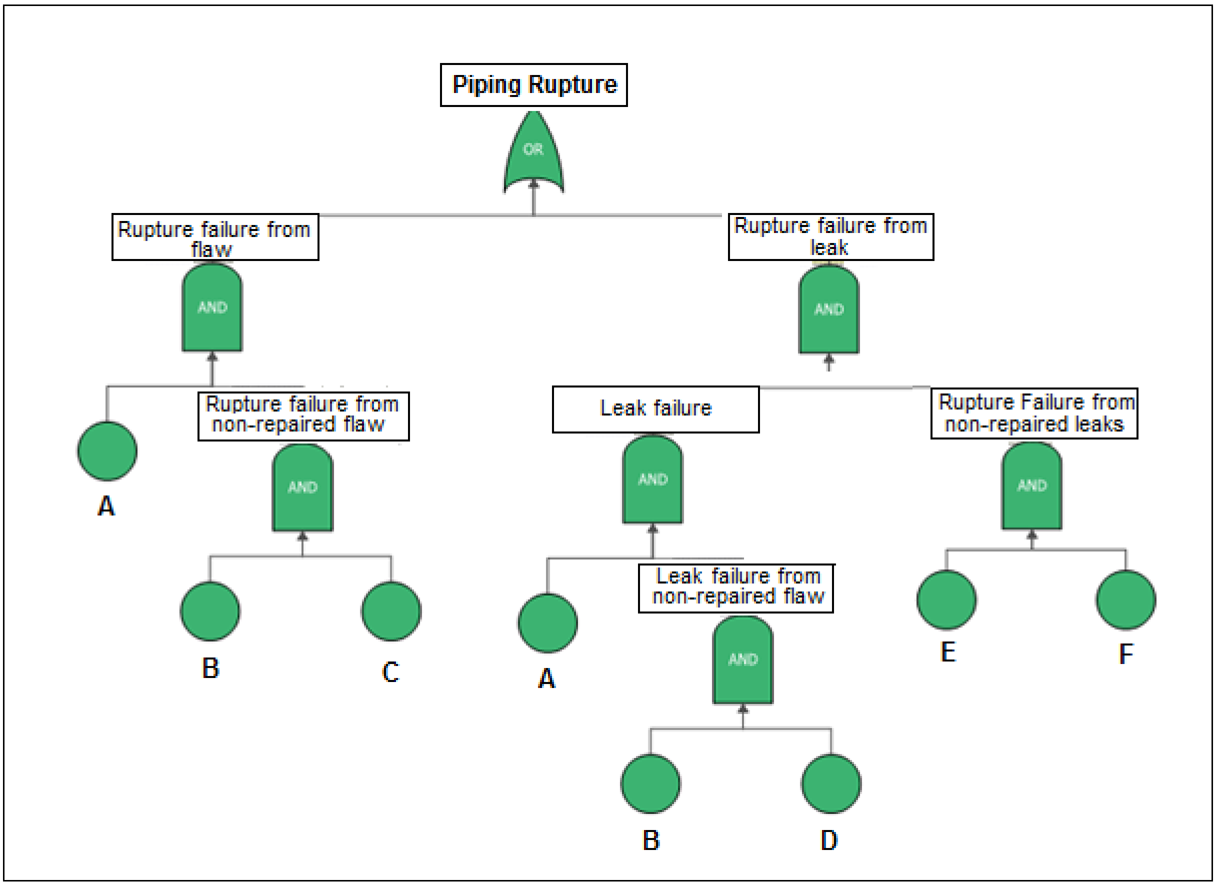


Figure 2. Fault tree model for piping failure (adapted from Guangpei et al.[(14)] and drawn with support of BLOCKSIM software[(1)]).

Table 3. Description of the primary events of fault tree of Figure 2 (adapted from [(14)]).

Symbol	Description
A	Flaw occurrence
B	Non-effective repair via ISI exams
C	Rupture failure given flaw
D	Leak failure given flaw
E	Non-effective repair via leak detection
F	Rupture failure given leak

DATA SPECIALIZATION

Historical data may reflect the effect of previous piping inspection programs, if changes in these programs are proposed; such changes may make the failure rate estimates not work. Bayes' method uses historical data as the prior distribution, and inspected data as the conditional distribution to update the posterior distribution, which is influenced by inspection programs(15).

The fundamental tool for the specialization (or "updating") of probabilities, when new evidence becomes available, is then Bayes' theorem. Considering failure rate (λ) as the parameter under analysis, a mathematical formulation of this theorem could be expressed according to Eq. (C)(16):

$$f(\lambda|E) = \frac{f(\lambda)L(E|\lambda)}{\int_0^\infty f(\lambda)L(E|\lambda)d\lambda}\,, \tag{C}$$

where $f(\lambda|E)$ is the probability density function of λ given evidence *E* (posterior distribution), $f(\lambda)$ is the probability density prior to having evidence *E,* and $L(E|\lambda)$ is the likelihood function (probability of the evidence *E* given λ).

The evaluation of the integral in Eq. (C) cannot, in general, be done analytically, and can be carried out with support of specialized software (e. g., WEIBULL^{++} Reliasoft® software(1)), for specific shapes of the likelihood function.

PROPOSED METHOD FOR ESTIMATING PIPING FAILURE PROBABILITY

Fig. 3 shows an overview of the method proposed for estimating piping failure probability incorporating the ISI effect. The analysis starts with the selection of piping systems of interest and the corresponding plant system and component data. This selection is carried out with support of FMEA technique, prioritizing the piping systems with greater Risk Priority Numbers (RPN). As can be seen in Table 1, there are several available generic database for piping systems, which can be used for estimating frequency of piping ruptures of nuclear power plants. The Bayes' approach makes it possible to estimate piping failure rates (posterior distribution) using the generic data (prior distribution) updated with plant specific data.

The estimates of the failure probability incorporating effect of ISI can be made with support of several techniques, as Markov models and Fault Tree Analysis. Markov models are appropriate whenever the stochastic behavior of the components of a system depends on the state of other components, or on the state of the system.The advantage of the Markov model over the Fault Tree Analysis is that the reliability can be estimated as a function of time. Contrary to the Markov model approach, the fault tree approach approximates the average failure frequency over the mission time and is referred to as a time independent approach.

The use of specialized software package, as XFMEA, WEIBULL^{++}, BLOCKSIM and RENO, may ease the implementation of the proposed method.

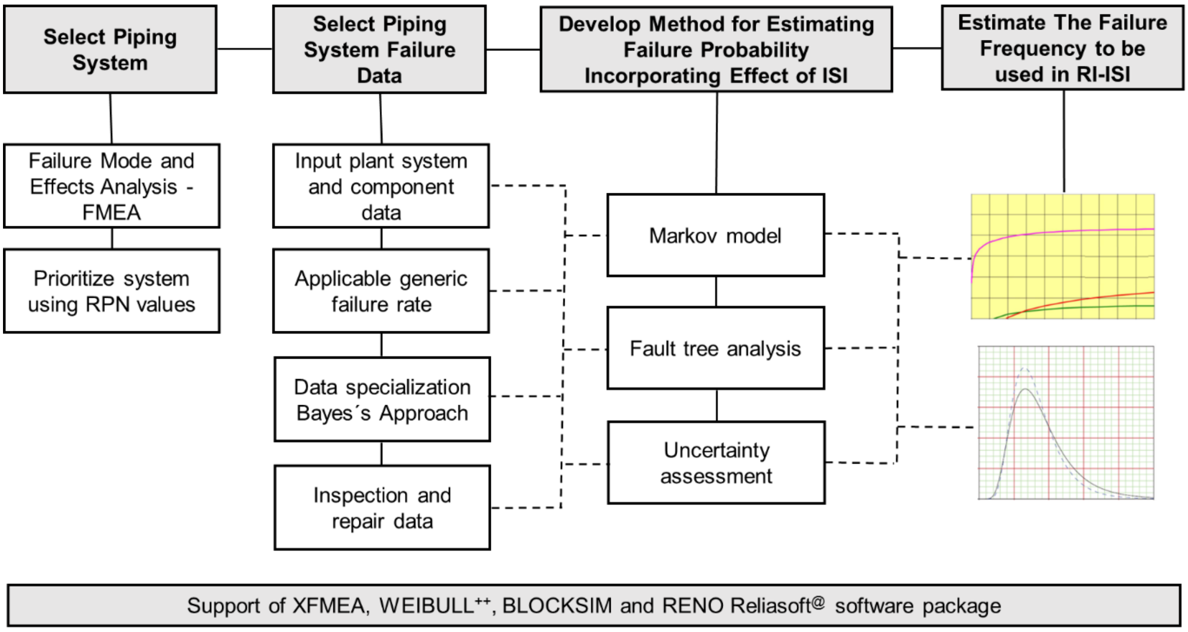


Figure 3. Method proposed for estimating piping failure probability.

FINAL REMARKS

Technical models and their mathematical and computational means of implementation were proposed, in order to predict piping reliability and failure probability of nuclear power plants, including the selection of failure rate database available to be used in RI-ISI programs.

The proposed approach includes the use of FMEA technique for prioritizing the piping systems to be analyzed. The use of Bayes' approach is suggested in order to update the available generic data of piping failure rates taking into account plant specific data. Taking the effect of ISI into account in piping failure probability can be made with support of as Markov models or Fault Tree Analysis, whether time dependent behavior of estimations are necessary or not. Uncertainty assessment in the estimation of failure rates is a critical issue, since its value can exceed an order of magnitude deviation from failure rate point estimates. The Monte Carlo method can be used to quantify these uncertainties.

This proposed method can be implemented with support of XFMEA, WEIBULL^{++}, BLOCKSIM and RENO software package developed by Reliasoft® Corporation(1).

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