Increase Plant Safety and Reduce Cost by Implementing Risk-Informed In-Service Inspection Programs

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Abstract

The idea behind the program is that it is possible to *"inspect less, but inspect better"*.

In other words, the risk-informed In-Service Inspection (ISI) process is used to improve the effectiveness of examination of piping components, i.e. concentrate inspection resources and enhance inspection strategies on high safety significant locations, and reduce inspection requirements on others.

The Westinghouse Owners Group (WOG) risk-informed ISI process has already been applied for full scope (Millstone 3, Surry 1) and limited scope (Beznau, Ringhals 4, Ascó, Turkey Point 3). By examining the high safety significant piping segments for the different fluid piping systems, the total piping core damage frequency is reduced. In addition, more than 80% of the risk associated with potential pressure boundary failures is addressed with the WOG risk-informed ISI process, while typically less that 50% of this same risk is addressed by the current inspection programs.

The risk-informed ISI processes are used

- to improve the effectiveness of inspecting safety-significant piping components,
- to reduce inspection requirements on other piping components,
- to evaluate improvements to plant availability and enhanced safety measures, including reduction of personnel radiation exposure, and
- to reduce overall Operation and Maintenance (O&M) costs while maintaining regulatory compliance.

A description of the process as well as benefits from past projects is presented, since the methodology is applicable for VVER plant design.

1. Background to Risk-Informed Inspection

The purpose of In-Service Inspection (ISI) of pressure retaining components is to identify conditions, such as material flaws, that may be precursors to failure of the pressure boundary. By the timely detection and mitigation of such conditions, failure may be prevented and knowledge gained about the degradation behaviour of plant components.

Traditionally, ISI is required in piping at locations where the analysis of record has shown a high fatigue stress or usage factor, as specified in the ASME Code for example [1], with the ISI technique and extent of inspection being a function of the traditional piping safety classification. Consequently, most of the ISI effort and cost has been concentrated on highly reliable piping, with the focus on areas where cracks could initiate but without consideration for the actual potential for failure.

Since the commissioning of the first generation of Nuclear Power Plants (NPPs), other, more potent piping failure, mechanisms have come to light, such as Flow Assisted Corrosion (FAC) and Stress-Corrosion Cracking (SCC). NPP owners have consequently augmented their traditional ISI programs to take them into account. However, attempts to integrate rules covering these mechanisms into the codes and standards governing ISI have so far proved unsuccessful.

In parallel with these developments, the way in which NPP safety is measured and analysed has also evolved with the application of Probabilistic Risk Assessment (PRA). Today, NPPs typically have their own plant specific PRA model, allowing to quantify the safety significance of individual systems and components, in terms of a global plant risk measure, such as Core Damage Frequency (CDF) or Large Early Release Frequency (LERF). However, as well as being a safety analysis tool, PRA is increasingly being considered for use in the optimisation of the way in which NPPs are operated and maintained. High cost activities such as ISI and In-Service Testing (IST) are obvious candidates for such attention.

Whereas reliability data for active components, such as pumps and valves, are readily available, there exists relatively little data on the failure probability of NPP piping, that may be readily transposed for use with PRA. Indeed, apart from treating pipe failures as initiating events, PRAs typically do not consider the effect of pipe failure. However, recent work in the area of probabilistic fracture mechanics has lead to the development of efficient techniques that allow to estimate the probability of failure of piping based on specific materials and service conditions. By combining this estimated likelihood of failure, with the simulated consequence of failure, determined by the PRA, this risk associated with the failure of a given segment of pipe may be quantified and thus used in the decision process for selecting ISI locations.

It must be recognised that probabilistic techniques have their limitations and may require to be complemented by other engineering insights or expert judgement. For this reason the terminology for this approach to decision making, which was previously known as "risk-based", is now referred to as "risk-informed". The following sections discuss the development of a risk-informed ISI program, using the approach that was developed by the Westinghouse Owners Group (WOG) in conjunction with ASME Research [2], and compare the results of a number of applications. An overview of the complete process is given in Figure 1, below.

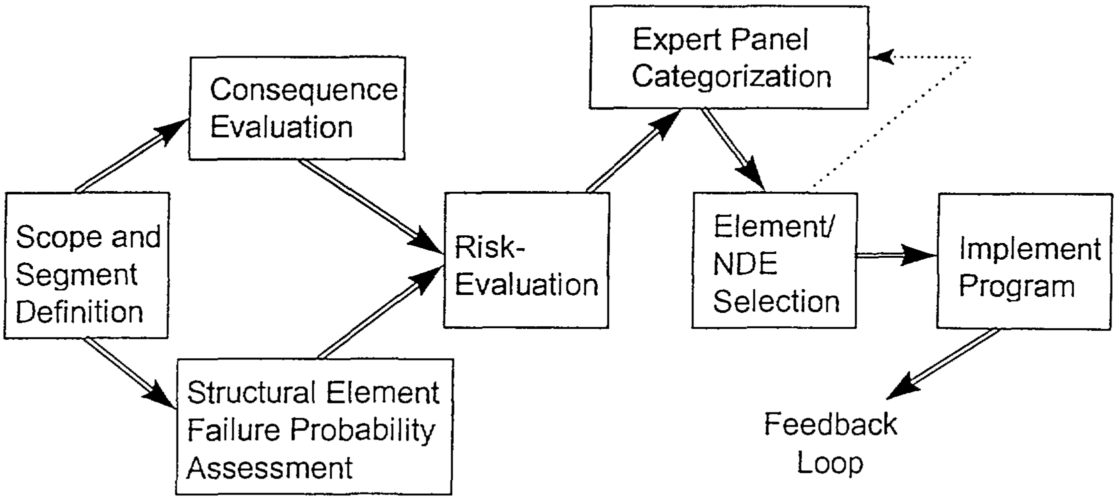

Figure 1: Westinghouse risk-informed In-Service Inspection (ISI) process includes an expert judgement.

Using the notion of risk to establish a ranking scheme for ISI locations, has been the practice in certain countries for some years. In Sweden, for example, the current state guidelines [3] provide a method for determining risk-significance by combining a "damage index" (which gives an indication of the risk of failure of a given pipe segment) with a "consequence index" (which gives an indication of the risk to safety, should that segment fail). The major drawbacks of such a method are that it is highly subjective, meaning it cannot be easily compared with other measures that affect plant safety, and it is essentially qualitative in nature, which means that it is difficult to determine the effect of changes in conditions or inspections.

In the US, initiatives have now been taken by the ASME [4][5] and the NRC [6][7] to provide a framework within which risk-informed programs may be developed and implemented.

2. Determining the Conditional Consequences of Failure

The systems considered in the risk-informed ISI program are, as a minimum, those that are included, as event initiators or mitigating systems, in the plant PRA model. Depending on the scope and extent of the PRA, other systems may have to be addressed on a more qualitative or traditional basis. For example, if shutdown modes are not included in the PRA then the residual heat removal system would fall into this category.

Each system is divided up into piping segments, such that a leak or break anywhere in the segment would have the same direct consequence on the plant, in terms of

- initiating event,
- loss of train, or
- loss of system.

The effect of operator action is also considered. For example a remotely operated normally open valve will be taken as a segment separator.
Segments may also be sub-divided at locations where it is suspected that there may be a change in failure probability, for example at changes of pipe size or material.

Once the direct consequences of failure are determined, the indirect consequences of failure of each segment must also be established in order to have a complete evaluation of the impact of a pipe break or leak on the plant. Such information may be available in the plant documentation related to High Energy Line Break (HELB) protection. Otherwise it may be necessary to perform a plant walk-down to identify the position and nature of potential targets. The mechanical and electrical effects of following consequences of pipe failure must be considered:

- jet impingement,
- water spray,
- flooding,
- temperature, and
- pipe-whip .

The direct and indirect consequences of failure of each segment are associated to the PRA model, and surrogate components are identified to represent piping, which is not explicitly modelled (the surrogate components modelling operator recovery action must be defined carefully).

The segment failure probability is set to unity and conditional consequence of failure (CDF or LERF) is calculated for each segment. This will be combined with the probability of failure of the segment, in order to determine the risk associated to the segment.

3. Determining the Probability of Piping Failure

The probability of piping failure is quantified by a computer code known as SRRA [8], that was developed from previous work in probabilistic fracture mechanics.
The code uses the following engineering input data, that is usually gathered from design records and plant experience:

- material and pipe properties,
- operating conditions,
- service loading,
- design limiting loading,
- inspection accuracy,
- system disabling leak rate,
- potential for FAC or SCC.

A median value, a standard deviation and a distribution function are defined for each parameter.

Using a Monte-Carlo technique, with importance sampling, random selections are made for the input parameters. Having determined the most predominant degradation mechanism, either

- low-cycle fatigue,
- FAC,
- SCC, or
- high-cycle fatigue,

the growth of a postulated material defect is simulated over the plant lifetime via a standard mechanistic model. At discreet intervals during the defect growth, the stability of the undamaged section is verified by comparing the design limiting stress to the material flow-stress. If the flow-stress is exceeded, a pipe break is registered and a new trial is initiated. If the flow-stress is not exceeded, the program checks whether the defect has penetrated the pipe wall. If this is the case, the leak rate is calculated and compared to the system disabling leak rate in order to determine whether the leak is classified as large or small.

By running a sufficiently large number of trials, probabilities of failure may be established for full break, large leak and small leak, for each segment. The effect of ISI may also be simulated by entering the ISI interval and the probability of non-detection for the inspection method being used. This gives a reduced probability of failure, which is used in order to determine the change in risk associated with changing ISI programs.

4. Determination of New Inspection Locations

The CDF (or LERF) associated with the failure of each segment is calculated by combining the conditional CDF, with the segment failed, with the probability of failure of the segment, assuming no ISI. Compound calculations are required when the segment may initiate different events, depending on whether the leak is large or small. If mitigating systems are impacted then test intervals and mission times of equipment must also be taken into consideration.

Having calculated the CDF for each segment, the total piping core damage frequency is calculated by summing all the segment CDFs. The Risk-Reduction Worth (RRW) for the segment is calculated as

$$RRW = \frac{total\_piping\_CDF}{conditional\_segment\_CDF\_with\_100\%\_reliability}.$$

A segment with an RRW greater than 1.005 is considered to be of High Safety Significance (HSS), while those with a RRW between 1.001 and 1.005 are usually put to an expert panel, which makes the final risk ranking between HSS and Low Safety Significance (LSS).

To establish the new inspection plan, the segments in the HSS category are sub-divided into two groups: one gathering all those segments where active mechanisms are present, such as FAC, SCC, vibration, thermal stratification, striping, etc., and the other gathering together those segments which only experience benign mechanisms (e.g. low-cycle fatigue), whose failure probability is dominated by design limiting stresses. For the first group all susceptible locations are required to be inspected, while for the second group a sampling process is defined, specifying a minimum number of inspection locations in order to meet a specified level of reliability.

For the LSS segments which experience active degradation mechanisms, it is recommended that the NPP owner continues with ongoing inspection programs associated with the mechanism of concern, while LSS segments with benign mechanisms need only receive standard system pressure tests and visual examinations.

The above described categorisation of HSS and LSS segments is illustrated in the structural element selection matrix, shown in Figure 2 below.

	Low-safety-significant segment	High-safety-significant segment
High-failure-importance segment	Owner-defined program 3	(a) Susceptible locations (100%) --- (b) Inspection location selection process 1
Low-failure-importance Segment	Only system pressure test and visual exams 4	Inspection location selection process 2

Figure 2: The structural element selection matrix defines the best suitable inspection program, depending on the segment failure-importance and safety-significance.

5. Establishing the Change in Risk

Once the new ISI program has been established, it may be compared with the current ISI program through the piping failure probabilities calculated by the SRRA code, taking the effect of ISI into consideration. In a similar fashion to that described above, the total piping CDF is calculated, considering ISI, for both the current program and the new one.

In the case of Surry 1 (Figure 3), one RI-ISI program addresses approximately 86% of the piping CDF risk, while the current ASME Section XI program addresses about 53%. Both programs are given credit for existing augmented inspection programs, such as flow accelerated corrosion programs. The percent of piping LERF risk addressed is even more dramatic: approximately 94% for the RI-ISI program versus 20% only in the current Section XI program. This positive result remains unchanged even when one considers the impact of potential operator actions to recover from piping failure events.

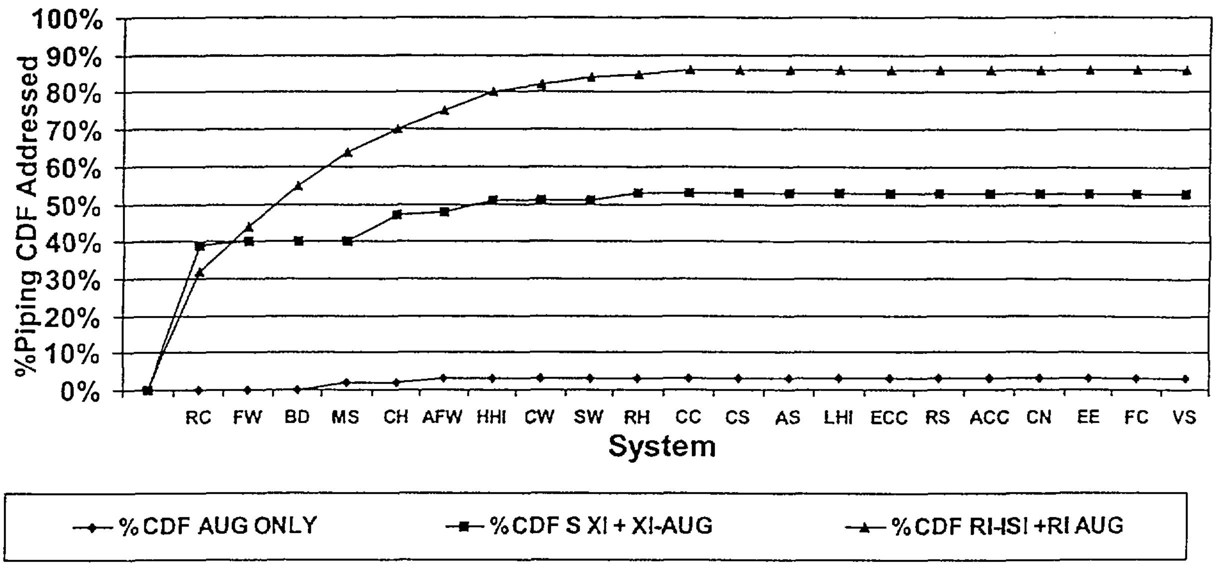

Figure 3: The percentage of CDF addressed by the RI-ISI application at Surry 1 [2] is largely higher than the one addressed by traditional inspection plans.

6. Program Monitoring

Risk-informed ISI programs are living programs: they should be monitored continuously to account for changing conditions in the plant. Such monitoring encompasses many facets of feedback or corrective action, including periodic updates based on inputs and changes resulting from plant design features, plant procedures, equipment performance, examination results and individual plant and industry failure information. This feedback and updating is greatly facilitated by the systematic and quantifiable basis of this risk-informed approach, which uses efficient and easy-to-use computational methods.

7. Results

So far, two US plants have carried out full-scope applications of the approach described above for establishing risk-informed ISI programs. One of them has already received NRC approval for implementation. In Europe, several utilities have carried out limited scope pilot projects, concentrating mainly on the Reactor Coolant System (RCS), to assess the effectiveness of the approach [9].

All the studies performed show a clear reduction in the number of examination locations (Table 1). This redistribution of the ISI effort reduces operating costs and radiation exposure to personnel.

For example, for the Surry 1 application, the total savings are around 150 000 $ per year. They are subdivided as follows:

- 90 000 $ in examination costs,
- 10 000 $ per REM, with a reduction of 9 REM per outage.

In general, the savings are between 150 000 and 300 000 $ per year.

The studies also show a significant safety increase. For example, the pilot program performed for the Swedish PWR shows a reduction in piping CDF (with operator actions and no leak detection) from 8.0 to 2.2 10^{-7}/year.

Plant	Current Exams	Risk-Informed Exams
Surry 1 (full-scope) [2]	385	136
Millstone 3 (full-scope) [2]	753	107
Swedish PWR (RCS) [9]	44	34
Swiss PWR (RCS) [9]	69	34

Table 1. Both full-scope and limited RI-ISI applications lead to a potential reduction in the number of examination locations.

8. Conclusion

All the studied applications have shown that the risk-informed approach leads to an overall improvement in the level of plant safety, while at the same time redistributing the ISI effort and thus reducing operating costs and radiation exposure to personnel.

Cost-benefit studies, performed independently for both full-scope applications, show that risk-informed ISI programs can be implemented at a cost that can be returned in one to two years following implementation, depending on the size and age of the unit. Given that aging effects are directly evaluated in the process using a structural reliability/risk assessment tool, significant additional benefits could come from the use of this technology for defining aging management programs and the associated inspection of piping systems as part of plant life extension programs.

In other words, the RI-ISI program is a useful tool to "inspect less, but inspect better".

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