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Extending Risk-Informed In-Service Inspection to General Mechanical Components – Benefits and Challenges

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Executive Summary

This technical report discusses the extension of risk-informed in-service inspection (RI-ISI) approaches beyond pipe welds to cover other general mechanical components of a nuclear power plant (NPP). The term "general mechanical components" as used in this report includes pressure boundary components other than the reactor pressure vessel (e.g. tees, elbows, pipe welds, tanks, heat exchangers), parts or sections of active reactor components with pressure boundary function (e.g. valve body, pump body) and their supports (e.g. spring can, rigid restraint, snubber, anchor). Currently there is a lack of RI-ISI approaches to cover mechanical components other than pipe welds. As a result, there is an imbalance in inspection requirements and practices between pipe welds and other general mechanical components. The authors of this report see adapting existing risk-informed methodologies to general mechanical components as an effective way to develop such extended ISI programmes.

The purpose of this document is to provide a set of principles and to highlight both the challenges and benefits of applying RI-ISI approaches to general mechanical components. The document is intended for ISI personnel of NPPs that already have a RI-ISI programme in place for pipe welds. It also targets NPPs that wish to develop a RI-ISI programme of wider scope, including a wide range of mechanical components, straight from the beginning. The main tasks of a RI-ISI programme are reviewed to assess how these are affected when the scope of the RI-ISI programme is expanded to mechanical components beyond pipe welds.

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1. Introduction

In-service inspection (ISI) needs to be capable for early detection of any degradation and damage development that can pose a threat to mechanical components. Risk-informed (RI) approaches for planning of ISI (RI-ISI) have evolved during the last decades to become a technology to systematically achieve this. The approaches result in carefully adapted inspection programmes with the purpose to limit the probability of failure and its uncertainty. In addition, the programme needs to fulfil national regulatory requirements. The ENIQ Sub-area for Inspection Effectiveness (SAE) is developing and promoting the use of RI-ISI approaches, as they are a valuable tool for improving the overall plant safety (measured by specific risk quantification), together with reducing the radiation exposure for inspection personnel.

IAEA report NP-T-3.1 [1] provides an overview of RI-ISI approaches, status for industry application, and an identification of relevant associated issues. ASME XI [2][3] describes approaches to create and evaluate a RI-ISI programme. For nuclear power plant (NPP) piping systems, an important European background document is the ENIQ Framework document for RI-ISI [4]. A comparative study applying several RI-ISI methods for piping systems is presented in the RISMET benchmark study [5].

The ENIQ RI-ISI framework document [4] provides guidelines that may be used for any pressure boundary components, but the focus of the document is application to pipe welds and associated issues. However, there is a need to extend RI-ISI approaches to cover other types of mechanical components of a NPP as well, such as vessels, tanks, pump bodies, valve bodies, heat exchangers, and supports. These components may be in Class 2, Class 3 or Class 4 systems[1]. It is worth noticing that Class 4 systems in particular, but also some portions of Class 2 and Class 3 systems may not be currently subject to ISI.

The need to extend RI-ISI beyond pipe weld inspections can be well understood, when observing the inconsistency in inspection requirements between pipe welds and other pressure boundary components. Experience has shown that after implementation of RI-ISI for pipe welds, the piping inspection programme is more effective than the previous inspection programme. At the same time, experience has also shown that other components may follow an inspection programme that does not incorporate risk insights, other components may not be required to be inspected, or may be subject to a much more conservative (uninformed) system-level risk-based treatment.

There have been some earlier RI-ISI applications considering other parts and locations beyond welds in piping systems. EPRI report 1013390NP [10] considers stress corrosion cracking (SCC) risk for core spray pipe welds in BWR internals. Probabilistic analyses are used in [11] for risk ranking of reactor pressure vessel (RPV) welds. Some studies related to the integrity and ISI of the RPV are summarised in the ENIQ report no. 35 [12]. Quantitative RI-ISI analysis with respect to SCC in valve components in piping systems are reported in [13]. In [14] some guidance is given for RI classification of different types of mechanical components.

The extension of RI-ISI beyond pipe welds has clear benefits, but also challenges. Potential benefits include e.g. systematic work process for all components, similar evaluation basis with unified risk principles to identify high risks among all types of components, and all together improved ISI focus and

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[1] These Classes refer to the Safety Classification according to various industry standards [6][7], where secondary consequences (e.g. indirect effects) may not be fully considered. In order to address these secondary consequences, plants follow other recognized standards/methodologies (e.g. IAEA NS-G-1.11 [8], NUREG-0800 [9]). However, these other standards/methodologies are typically deterministically based and there has been some experience where application of RI methodologies to "lower classes" of piping systems has been shown to provide additional safety improvements.

improved safety (i.e. plant and personnel safety). Challenges arise from the inclusion of new types of components with different materials, degradation mechanism, geometries and failure consequences.

The aim of this document is to describe the main aspects of applying a RI-ISI approach to "general mechanical components", and to identify how the steps in RI-ISI approaches will be affected when the scope is expanded. The report will review the main steps of a RI-ISI procedure:

- Definition of the scope,
- Collection of data,
- Screening,
- Assessment of consequences,
- Assessment of failure probabilities,
- Risk characterisation and ranking,
- Proposal of new inspection programme,
- Assessment of effectiveness.

In the following sections these steps are briefly described, and both associated benefits and challenges in the application RI-ISI to general mechanical components are highlighted.

2. Definition of the Scope

RI methodologies may be applied to all types of components in all safety classes, including non-safety class systems. However, extending RI-ISI to cover every general mechanical component in a NPP requires large efforts, and thus the actual work scope should be defined cautiously. To fulfil its purpose, the scope must be sufficient but also realistic to perform, and one may consider a gradual approach by extending the scope with a few systems at a time or a few types of components at a time.

Generally, the scope should include auxiliary systems, even though they are not in continuous or even intermittent use, as they provide important safety functions and regular tests involve application of pressure. However, active parts of pressure boundary components (such as internal parts of pumps and valves), can be excluded from the RI-ISI scope, as these parts do not constitute the pressure boundary.

While all pressure boundary systems and components are suitable for inclusion in the RI-ISI scope, some components are unique enough that they may need additional or separate efforts. The RPV and its internal components, steam generators and pressurisers may require to be considered apart, due to their special characteristics with respect to consequences, degradation, and regulatory requirements. For instance, regarding the RPV, the failure consequences are significantly higher than in case of piping components, there are more failure modes, and degradation mechanisms of piping are not applicable to RPV. As an illustration, ENIQ has published a separate discussion document on the role of ISI for RPV [12], including RI-ISI aspects.

The scope for a more general application of RI-ISI may include mechanical components as:

- All passive pressure boundary systems and components (e.g. pipes, vessels, tanks)
- Active safety or functional equipment with a pressure boundary function, such as heat exchanger shell, valve body, pump body, bursting disc, etc. Functional parts in active components are suggested to be excluded, for example pump impellors.
- Supports and snubbers for pressure boundary systems.

3. Collection of Data

The type of data that is necessary to accomplish the analysis for general mechanical components corresponds largely to the data needs of RI-ISI evaluations of pipe welds. The information can be divided into the following categories:

1. General equipment data,
2. Historical plant operating data,
3. Safety analysis report and technical specifications,
4. PSA specific data,
5. General nuclear industry information, e.g. degradation databases.

More details on typical data that is used can be found in [4], Chapter 4.5.

Many lower safety class (Class 3 & 4[2]) systems/subsystems may have been manufactured and installed to lesser documentation requirements, and therefore as-built isometrics with weld locations, physical dimensions/lengths and orientation may not be available. This can be a concern for the failure consequence analysis, for example flooding assessment, but it may also be important from a failure potential perspective (e.g. retrieving plant specific operating experiences). As most of these systems have most likely not been subject to a periodic ISI programme, identifying areas for inspections and preparing areas for inspection may create special challenges.

On the other hand, as many Class 3 and Class 4 systems are either lower energy systems (e.g. raw water cooling, heating, ventilation, air conditioning, HVAC), or systems that are typically found at other industrial facilities (e.g. fossil-fuelled power plants) there may be other data sources available (e.g. insurance) that are typically not representative of Class 1 and 2 systems.

Collecting all necessary information needed to support development of a RI-ISI programme for systems that are not normally part of an existing inspection can be very resource intensive. However, the resource needs can be reduced by a screening process, where an initial analysis is made at a less detailed level, and resources are focused on higher risk areas. Some examples of reduced data collection needs are given below. Screening approaches are further discussed in Section 4.

As previous RI-ISI applications have shown, low risk systems/subsystem do not require inspection. Therefore, there is a subset of information that is not needed for these systems/subsystems (e.g. weld locations, scaffolding requirements). Additionally, for systems/subsystems with failure consequences of low significance, inspections are not required unless the system is susceptible to an aggressive type of degradation, e.g. flow accelerated corrosion. Therefore, for these systems/subsystems a failure potential evaluation would not be needed and the required documentation to conduct the failure potential evaluation would not need to be developed.

With respect to the consequence evaluation, the initial evaluation could be conducted with available limited documentation, such as simplified schematic, and training manual sketches. Further, the plant walkdown that is conducted to assess spatial interactions (e.g. flooding impacts) could also be used to verify assumptions taken from the limited documentation available. As for the failure potential evaluation, some systems may be agreed to be highly reliable based upon plant and industry operating experience. For example, system operating characteristics (material, temperature, pressure, flow, fluid) are relatively mild and the system is located in a benign operational environment (e.g. located indoors, processing/flowing fluid is nonaggressive fluid, radiation, temperature, humidity). For these

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[2] See the footnote in the introduction on Safety Classification. If the classification is not based on ANSI standard, but on more thorough analysis of consequences, this can be used to better define the scope of the new programme.

systems a tabletop exercise by plant knowledgeable personnel could be used instead of a formal failure potential evaluation. It is valuable to use available degradation databases to support this work.

COLLECTION OF NECESSARY DATA

Benefits: Collected data will serve other purposes. Data collection improves the knowledge of the plant.

Challenges: Availability of documentation, especially for low safety class components.

4. Screening

The purpose of a screening process is to identify at an early phase those systems or components that can be excluded from further analyses, and thus considerably decrease the resource needs. The deeper analysis is then focused on those components that are significant from a safety point of view.

For an efficient process, the screening criteria should be simple and conservative. In case of extending an existing RI-ISI programme (piping systems) to general mechanical components, earlier screening process and criteria can be used as a basis, but should be reviewed and adapted to be applicable for other types of general mechanical components than piping and pipe welds. If a new screening process is developed, suitable metrics need to be determined for the purpose.

As the screening aims at excluding systems and components from the final ISI scope, the existing ISI codes and standards, if they exist, need to be well known and taken into account to avoid any violations of existing requirements. The requirements are country specific and to some extent even plant-specific. Many national regulators require plants to follow some national or international ISI code or standard. These codes and standards often define periodic ISI requirements, which are quite prescriptive in terms of number, frequency and type of applied inspection method and technique. One challenge is that these codes typically only apply to a subset of plant systems (e.g. some safety-related systems) and therefore may not be pertinent to many of the general mechanical components addressed by this technical report.

Additionally, there may be augmented ISI programmes required in response to a plant design issue or in response to some type of identified active degradation. These augmented inspections may not be subjected to regulatory audits, third party audits, or periodic re-baselining, but if conducted and maintained in a robust manner, one may screen out that degradation mechanism.

The screening consists of an initial simplified assessment of the consequence and the probability of failure. Figure 1 shows the idea of a screening process. This example from the European standard EN 16991 [15] used in non-nuclear industries, gives an illustration of a coarse (2x2) matrix for the screening analysis, prior to a more detailed risk assessment.

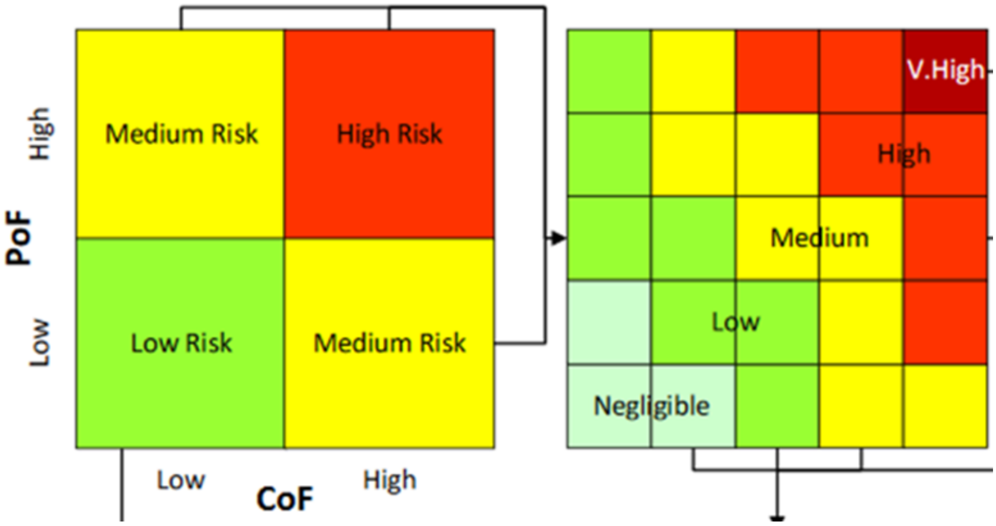


Figure 1: Example of a coarse screening matrix (on left) [15]
(PoF = probability of failure; CoF = consequence of failure)

In a RI approach as applied to NPPs, conditional core damage probability (CCDP) or conditional large early release probability (CLERP) are the typical measures for the consequence. Some suitably low screening limits for those should be defined. For whole plant purposes other metrics, such as plant reliability and occupational safety, such as radiation doses or risks of water jets or hot steam to the personnel in case of a leak or break, may also need to be considered.

In developing a screening process, other plant activities that could impact pressure boundary reliability should also be understood. For example, many plants have developed single point vulnerability (SPV) studies (high consequence). These studies identify those components, that if they fail, result in a plant trip or reduction of power. When a component is identified as SPV, these studies will usually identify activities (e.g. inspection, monitoring, etc.) to assure components reliability.

When it comes to screening based on failure potential, criteria exist, based on technical data, to conservatively identify components with extremely low potential for degradation and damage mechanisms. Susceptibility to significant degradation mechanisms can be evaluated based on a few parameters. As an example, if the carbon content of a piping component of austenitic stainless is less than the limit value given by U.S. NRC [16] it is considered resistant to intergranular stress corrosion cracking (IGSCC). Severity of loading is another important issue. When the cyclic temperature loading for piping components of austenitic stainless and ferritic steel is less than the limiting values given in the NESC-Thermal Fatigue Project Report [17] they are considered not susceptible to high cycle thermal fatigue.

For screening of NPP components due to ageing and degradation, some procedures have been developed, for example the IAEA procedure [18] and the EPRI procedure [19]. A screening process is described in the Canadian standard CSA N285.7 [14] which provides requirements for the periodic inspection of balance of plant systems and components.

DEFINITION OF SCOPE AND SCREENING

Benefits: Screening is an efficient work step to focus the efforts on the most important components from a safety and availability perspective.

Challenges: Definition of component adapted screening metrics and criteria.

5. Assessment of Consequences

While the screening phase may have excluded entire systems, or portions of systems, with negligible risk from further analyses, a more detailed assessment needs to be carried out for the remaining scope. Again, for NPPs the evaluation is based on CCDP and CLERP estimates.

The consequence analysis approaches used in piping RI-ISI processes are in most cases readily transferable to other pressure boundary components. For example, failure of a valve body, flange, or pump body may have similar impact on the plant as failure of the pipe attached to the valve, flange or pump.

In piping RI-ISI analyses, the pipe segments are typically defined between some discontinuities, such as valves. When the consequence class changes at such segment boundary component, it is recommended to assign the higher consequence class to such component.

There are cases where the consequence assessment cannot be derived from piping system RI-ISI experiences. For example in the case of tanks and heat exchangers, the consequence assessment is different and more challenging. Tanks typically provide inventory for an entire system or multiple systems. Therefore, postulated failure of the tank can cause loss of the entire system (as opposed to loss of one train of a system) or multiple systems if the tank provides inventory to multiple systems.

In the case of heat exchangers, a postulated failure of the heat exchanger shell most likely has the same impact on the plant as a postulated failure of the connected piping. However, postulated failure of a tube, multiple tubes or the tube sheet, can have different impact on the plant and need to be considered with respect to CLERP, CCDP and plant availability.

If plant availability and occupational safety issues are taken into account, their consequence assessment calls for different methods than those used for reactor safety considerations. It is possible, for instance, that a small leak of negligible plant safety importance can have high consequences for occupational health. When to decide which segment or portion of the system should be included for occupational safety, additional criteria for selection are needed, such as pressure, media, temperature, availability, visiting frequency etc. The inclusion of such components/locations is justified only if an active degradation mechanism can be identified.

ASSESSMENT OF CONSEQUENCES

Benefits: Improves understanding of the consequences and safety significance of various failures.

Challenges /Development needs: Evaluation of the consequence of tanks and heat exchangers. Assessing other than reactor safety consequences.

6. Assessment of Failure Probabilities

For the components included in the analysis after the initial screening, their failure potential needs to be assessed. In the case of RI-ISI, we consider failure potential due to degradation mechanisms, such as fatigue cracking, SCC, local corrosion, flow assisted corrosion (FAC), embrittlement and unusual loads. Some degradation mechanisms can occur due to certain loads such as vibrations, thermal mixing, stratification or steam collapse. It is recommended that the identification of failure potential is executed as a systematic review of all degradation mechanisms, to identify active or potential damage mechanisms.

The evaluation requires consideration of a range of influential parameters, such as, design and fabrication information, loadings, environmental conditions, and inspection results. This analysis should be supported with a review of operating experience at the plant, the same or similar plants as well as insights from general world-wide generic data. (See also Chapter 3 on data collection.)

The probability of failure (POF) over a given time period may be assessed by use of expert judgment, structural reliability analysis, and/or operating experience statistics, depending on the degradation mechanism, available physical models, and information on influencing factors. Assessment of the POF can be obtained by:

1. Use of expert judgement for identification and ranking of susceptibility to degradation, using a combination of knowledge on damage mechanisms, operational experience, design and supporting deterministic model results.
2. Use of structural reliability models (SRMs), where they exist, to provide estimates of the relative differences in the failure probabilities.
3. Statistical estimates based on plant-specific data and global databases in order to provide anchoring points for SRM analysis or expert judgments.

It should be recognised that there is not a single, optimal method for assessing POF. As such, each above mentioned approach, or combination of them, needs to address the issues identified. Successful failure probability assessment is strongly dependent on in-depth knowledge of degradation assessment and structural integrity analysis. Challenges when conducting this assessment for general mechanical components are:

- Identification of significant degradation mechanisms,
- All necessary technical input data for POF computation may not be available,
- Applicable SRMs can be difficult to find and in some cases may not exist at all,
- Statistical degradation data in the databases can be very scarce.

As the quantification of failure probabilities for all components within the scope after screening is very challenging, a qualitative assessment and ranking may be a feasible solution. The qualitative ranking would then be based on some simple rules based on possible degradation mechanisms and influencing factors. If the applied RI-ISI methodology requires a quantification of POF, rough estimates could be developed by anchoring the qualitatively ranked failure potential to some calculated reference values of components for which quantification by e.g. SRM is possible.

ASSESSMENT OF FAILURE PROBABILITIES

Benefits: Improves understanding of the reliability of various components.

Challenges: Lack of reliability data or SRM tools to estimate the failure probabilities.

7. Risk Characterisation and Ranking

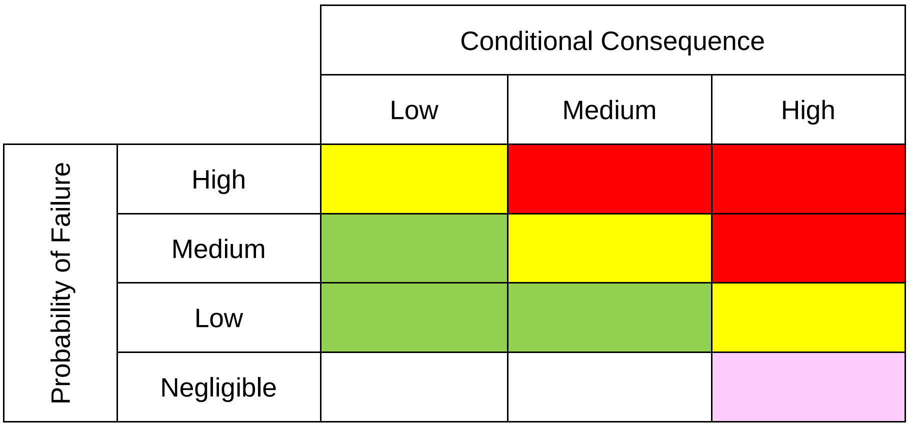
Risk characterisation and ranking are done in principle in the same way as when the RI-ISI scope is limited to pipe welds. The approach to do this varies between the existing RI-ISI procedures, some of them being described and discussed in the RISMET benchmark report [5]. In case of an extension of an existing RI-ISI programme, it is most convenient to use the same approach as already used for the more limited scope, when appropriate.

For any RI-ISI approach, the basic principle of risk ranking is valid for the extended scope: the purpose is to combine the results of the consequence and failure probability assessment to obtain a ranking of components in terms of risk. However, the challenges faced in the earlier phases – failure probability and consequence assessments – are transferred to the risk ranking phase as well. Due to the wider scope that contains a lot of different components, there is an increased heterogeneity in failure probability assessments. There can be a mix of different kind of results from the performed analysis, i.e. quantitative, semi-quantitative and qualitative result data.

It is recommended to rank all similar type of components together, to assess their relative risk level. For example:

- Rank all pump bodies in the risk matrix together,
- Rank all valve bodies in the risk matrix together,
- Rank all tanks on the risk matrix together,

A commonly applied way to illustrate the risk ranking is to use a risk matrix approach. Figure 2 shows a general qualitative risk matrix, but also quantitative values can be set for the categories. While in risk matrix approaches the consequence dimension is often determined quantitatively, for the failure potential a quantitative categorisation is difficult. This is due to uncertainties in and limited scope of the available failure potential assessment approaches.



		Conditional Consequence		
		Low	Medium	High
Probability of Failure	High	🟨	🟥	🟥
	Medium	🟩	🟨	🟥
	Low	🟩	🟩	🟨
	Negligible			🟪

Figure 2: General risk matrix format

There is no category for negligible consequences, since these components or segments have already been excluded in the screening phase. For the POF, such category is kept, with the idea of addressing unknown degradation or failure mechanism that could challenge the integrity of the component and have high consequences (bottom right corner of the risk matrix in Figure 1). This would provide an element of conceptual defence-in-depth (DiD).

Possible risk outliers and risk dominance are discussed in the RI-ISI Framework Document. The same principles are valid for RI-ISI approaches extended to general mechanical components.

RISK CHARACTERISATION AND RANKING

Benefits: Understand the risk-importance of components within the scope.

Challenges: Choice of risk-criteria, limits for failure probability and consequence categories, and treatment of risk outliers.

8. Proposal of New Inspection Programme

The inspection programme offered by this report may be applied to systems/components that are currently not subject to inspection. As such, the following guidelines are recommended for the development of the RI-ISI programme.

- The criteria applied to define minimum inspection populations need to be simple and straightforward so that it can be consistently applied regardless of plant/system design. This type of approach benefits not only the plant operator, but also the regulator.
- The sampling population criteria need to be sensitive to the type of degradation mechanism present. For some mechanisms, the inspection population needs to be based on performance trending and degradation rate predictions. This is especially true for degradation mechanisms such as FAC.
- The examination distribution should be weighted toward segments in the higher risk categories.

- The element selection process and examination methods should be designed to ensure that the overall success rate or probability of detection (POD) is improved. This implies that the failure and rupture frequencies under the new programme are reduced.

Appendix 1 provides examples of risk classification for valves and supports at or near segment boundaries.

With respect to selecting the individual locations (e.g. welds) for inspection, insights from previous RI-ISI can also be used. The considerations identified in the revised EPRI RI-ISI Procedure (TR-112657) [20] are provided in Appendix C.

Finally, as the term implies, ISIs are inspections that are carried out on components that are currently in-service (i.e. in operation). For nuclear grade piping systems many of these locations were also inspected prior to entering service (i.e. pre-service inspection (PSI)). These PSI exams provide a baseline for future ISI exams and when an indication is found during the ISI, the PSI exam can help to determine if the indication is service induced or possibly a pre-existing fabrication inclusion.

For the type of systems and component addressed in this report, there are few components (if any) that are subject to PSI prior to entering service. Therefore, it is recommended that the first ISI is also used as the PSI for the component. This is similar to what has been done for RI-ISI programmes that identify locations for inspection that were not previously inspected (PSI or ISI). PSI is further described in Chapter 10.

It is recommended to complement ISI with other preventive measures with the purpose to reduce the risk, for example, by monitoring of temperatures, corrosive environment and stresses/strains, local leak detection, and also involve research and laboratory work to quantify the potential degradation mechanisms.

PROPOSAL FOR NEW ISI PROGRAMME

Benefits: An ISI programme based on latest knowledge, with improved balance between different components and structures.

Challenges: Requirements for new qualified inspection methods on new components and materials, definition of sample size for components of small population.

9. Effectiveness Assessment

Typically, RI-ISI programmes are developed as an alternative to existing deterministic ISI programmes. As such, a RI-ISI programme is compared to the old deterministic ISI programme to assess the change in risk (delta risk) and the benefits of each programme. Providing that the RI-ISI programme manages to better capture the risk-important locations, it is deemed a better (more effective) inspection programme.

The comparison or optimisation process is particularly applicable to situations where there are a number of options available to address an issue of safety with limited resources and there are a number of different factors and goals (i.e., it is a multi-attribute or multi-task problem) that need to be considered in order to select the optimum, balanced solution. It is particularly powerful when there is no obvious optimum answer and there are several potential options, each of which may not provide a complete solution to a safety and cost-benefit issue.

Delta risk assessment is performed to verify that the new RI-ISI programme fulfils the demand stipulated in regulations or used methodology. Usually the new programme should have a risk reduction or at least be risk neutral compared to the previous programme. A small risk increase could be allowed for specific systems, as long as the overall result is at least risk neutral.

For many of the systems/components addressed in this report, there is normally no existing formal ISI programme. Therefore, assessing the change in risk (delta risk) accomplished by improvements caused by this new ISI programme will be very difficult to quantify, with any degree of certainty. However, as this new programme is imposing additional inspection activities, as compared to the current practice, it is highly certain that the plant will experience a risk reduction (safety improvement) as compared to current practices.

Instead of a formal quantitative “change in risk” assessment, an effectiveness assessment can be developed based on Table 1 below (note: the attributes are generally taken from Appendix C). The table identifies various factors for consideration and indicates whether the condition suggest the inclusion in the ISI programme or not. As an example: it would be better to choose for inspection a site with poor service history, than one with good service history; or a site with high stress concentration is a better candidate than one with low stresses.

The final step for the decision-making is to present the list of acceptable options together with a preferred option, which is considered optimal in relation to addressing the issue and the safety requirements. It may be that only one option is acceptable but in cases where there may be multiple acceptable options, the advantages and disadvantages of the other acceptable options should be explained to the decision makers and other stakeholders, as appropriate, with the reasons for choosing the preferred option.

Table 1: Factors to be considered when selecting inspection sites

Factors to be Considered	**Favours inclusion in ISI programme**	**Disfavours inclusion in ISI programme**	**Addressed by New Programme?**
Plant Service History	Poor	Good	Yes, data collected for each system
Assessment of Consequence of Failure	High	Low	Yes
Assessment of Degradation Potential	High	Low	Yes
Severity of Damage Mechanisms	High	Low	Yes, part of element selection process used
Element Configuration / Accessibility	Good	Poor	Yes, part of element selection process used
Radiation Exposure	Low	High	Yes, part of element selection process used
Stress Concentration	High	Low	Yes, part of element selection process used
Physical Access	Readily	Difficult	Yes, part of element selection process used
Occupational Safety	Benign	Challenging	Yes, part of element selection process used
Plant level considerations	Benign	Challenging	Yes, part of element selection process used

EFFECTIVENESS ASSESSMENT

Benefits: It is highly certain that the plant will experience a risk reduction compared to current practices, when new components are included in ISI. Plant may even experience cost reduction, due to focus on higher risk locations, while the total number of inspections is optimised.

Challenges: Uncertainties and lack of data; for many of the systems/components addressed, a formal in-service inspection programme does not exist.

10. Aspects related to NPP Lifecycle

10.1. Pre-Service Inspection (PSI)

To date, most of the work for developing and implementing RI-ISI programmes has been, as the name implies, covered by ISI examinations. However, the technology is equally applicable and valuable to pre-service inspection (PSI). For new build PSI examinations are performed in accordance with the requirements defined for the ISI examination at least once prior to initial plant service. For the operating fleet, PSI examinations are performed in accordance with the requirements defined for the ISI examination prior to a return to service following a repair/replacement activity. These PSI examinations form the baseline for subsequent ISI examinations. As such, having the PSI examination conducted to the requirements of the future RI-ISI examinations is much more valuable than having the PSI conducted according to deterministic PSI requirements. For example, it will be much more valuable and informative to conduct the PSI on the appropriate examination volume (e.g. wall thickness versus outside diameter surface) and to use the appropriate examination technique (e.g. ultrasonic versus dye penetrant).

10.2. RI-ISI and Long-term Operation

It is clear that ISI plays a major role in long-term operation (LTO) and even more if the concept of RI-ISI is used. RI-ISI methodologies provide a (more) proactive and systematic approach as a base for the evaluation of degradation and adaption of ISI in the LTO phase. It is valuable to extend RI-ISI to include more components as a plant approach LTO, since more components accumulate damage and enter a phase of increasing ageing.

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Appendix A: An approach for Extending Existing RI-ISI to Include Valves

In this Appendix, a simplified method is suggested for expanding an existing RI-ISI programme for pipes to include valves.

Figure A-1 shows a simple method to expand a RI-ISI programme to include valves. Methods other than those presented may be used.

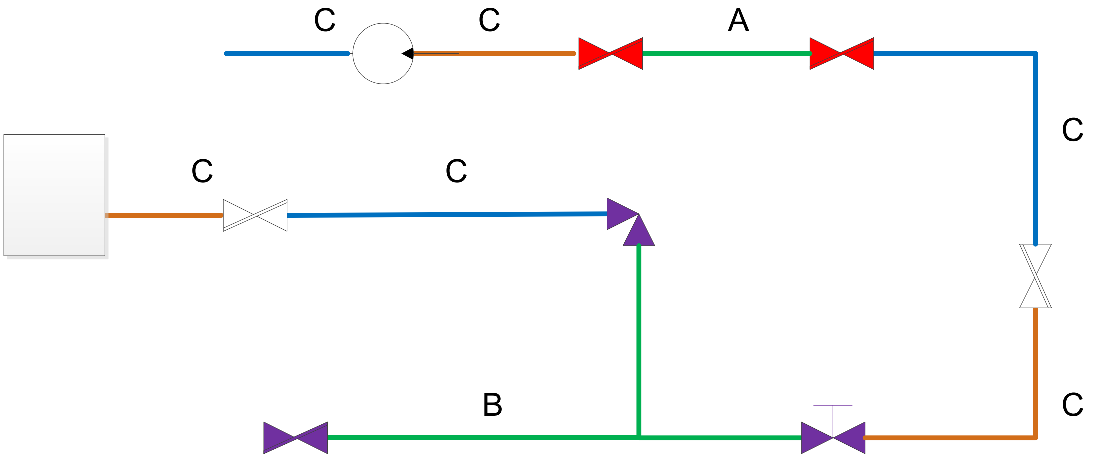

Figure A-1: Using risk ranking for piping to expand RI-ISI programme to include valves

Green segments are high-risk (A labelled) and medium-risk (B labelled) segments respectively. The remainder (C labelled) are low-risk segments. Valves that are included in an A segment or connected to an A segment should be ranked as a high-risk and thus be included in the RI-ISI programme for valves. Valves that are included in a B segment or connected to a B segment should be ranked as medium-risk and thus be included in the RI-ISI programme for valves. Valves that are included in a C segment or connected to a C segment should be ranked as a low-risk and thus be included in an owner-defined ISI programme for valves.

The sample size in each group is determined by the plant owner, so that it fulfils the regulation. Usually different inspection sampling sizes are required for different risk regions. The EPRI methodology proposes an inspection sample size of 25% for high-risk regions and 10% for medium-risk regions. If a quantitative methodology is used, including a SRM code, it is possible to define decision rules on the inspection sample size of the owner defined ISI programme. A proposal for such a rule could be 10% inspection sample size for locations with at least 2” NPS and a failure probability greater than 10^{-5}. Similarly, if quantitative tools are available (consequence and failure potential), 1% of a risk metric (e.g. CDF) could conceivably be used to select the sample size (e.g. the number of valves to be inspected).

Appendix B: Methods for Consequence / Risk Ranking of Supports

As support structures are designed to be redundant, unless there is a link between support, failure mechanism, and consequence, it is expected that in most cases failure of a support should have no impact on pipework or component and therefore on component failure. Thus, it is reasonable to assume that supports would be an order of magnitude less important than the supported pipework or component.

It is possible that a method could be developed that focuses on areas where the redundancy of supporting structures is most likely to be compromised, although it is expected that this would require considerable analysis and resources. Additionally, as it is anticipated that inspection of supports would typically involve visual examinations or at most some surface examinations (e.g. for welded attachments), the cost of an inspection programme for supports would not be huge. As such, several simplified and conservative options are available:

B-1: EPRI report no. 3002015999

According to EPRI report no. 3002015999 [B-1] the following options may be used for categorising supports:

a) Supports (component support, hanger or snubber) may remain un-categorised until a need has been identified (e.g. a significant repair/replacement or modification is required).

b) A component support, hanger, or snubber shall have the same categorisation as the highest ranked pipe segment within the piping analytical model in which the support is included. (ASME Code Cases N660 & N752)

c) A combination of restraints or supports such that the light safety significance (LSS) piping and associated structures, systems and components (SSCs) attached to the high safety significance (HSS) piping is included in scope up to a boundary point that encompasses at least two (2) supports in each of three (3) orthogonal directions. [B-2][B-3].

B-2: CSA N285.7 method

According to the Canadian standard [B-4], the risk category of supports and attachment welds shall be determined separately as follows:

(a) risk category of pipe supports and attachment welds shall be the highest of:

(i) risk category of pipe support / attachment weld,

(ii) risk category of supported pipe segment;

(b) risk category of component supports and attachment welds shall be the highest of:

(i) risk category of component support / attachment welds,

(ii) risk category of supported component segment.

B-3: An alternative approach for extending existing RI-ISI to include supports

Figure B-1 shows a simple method to expand the RI-ISI programme to include supports.

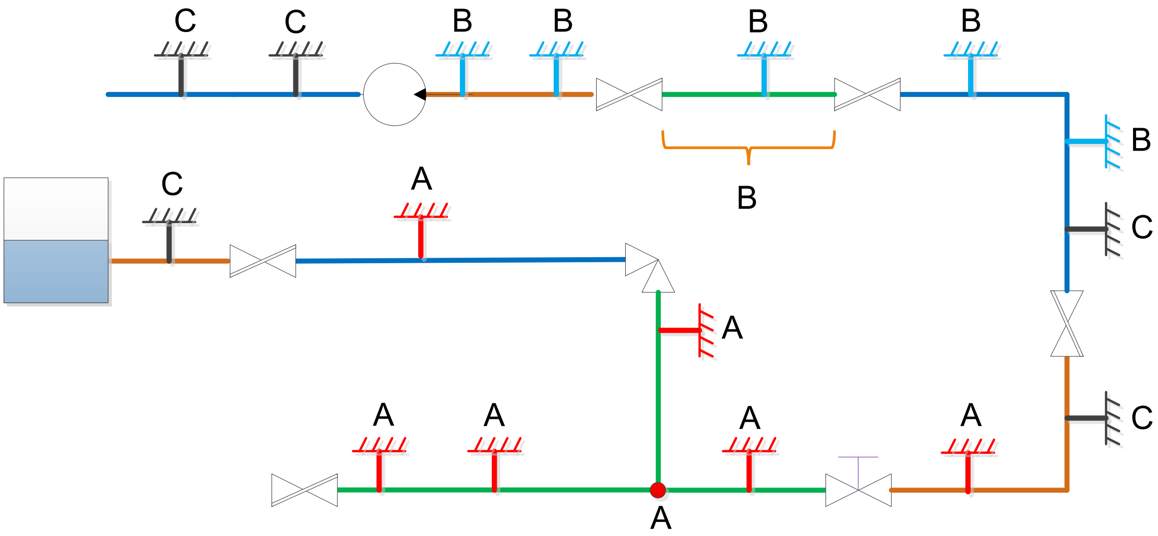

Figure B-1: Using risk ranking for piping to expand RI-ISI programme to include supports

Green segments a either high-risk segment or high-risk locations on a segment (A labelled) or medium-ranked segments (B labelled). The remaining segments are low-risk segments (C labelled).

For a high-risk piping location, like A in Figure B-1, supports in all directions should be classified as high-risk. If the segments are very large and include a large number of supports, only the two supports closest to the high-risk location are classified as high-risk. The remaining supports should be classified as low-risk.

- If the whole segment is classified as high-risk, all supports of that segment and the first two supports of the connecting segments should be classified as high-risk.
- If a high-risk segment does not include any supports, the first two supports of the connecting segments should be classified as high-risk, except if they are restraints or fix points at the end of the segments.
- If a segment ends at a T-joint the two closest supports in each direction should be classified as high-risk.
- For a medium-risk segment all supports on the actual segment including the two closest ones on each side of the segment are classified as medium-risk.
- If a medium-risk segment does not include any supports the first three supports of the connecting segments should be classified as medium-risk, except if they are restraints or fix points is at the end of the segment.
- If a segment ends at a T-joint the three closest supports in each direction should be classified as medium-risk.

Supports of a low-risk segment should be ranked as low-risk and included in an owner defined RI-ISI programme for supports.

The inspection sample size of each group is determined by the plant owner so that it fulfils the regulation. Usually different sample sizes are required for different risk regions. The EPRI methodology proposes a sample size of 25% for high-risk regions and 10% for medium-risk regions. If a quantitative methodology is used, including a SRM-code, it is possible to define decision rules for the inspection sample size in the owner defined ISI programme. A proposal for such a rule could be 10% sample size for locations with at least 2” NPS and a failure probability greater than 10^{-5}.

Appendix B References

[B-1] Electric Power Research Institute (EPRI). *Enhanced Risk-Informed Categorization Methodology for Pressure Boundary Components*, EPRI report no. 3002015999. EPRI: Palo Alto, CA, 2019.

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Appendix C: Considerations for Selecting Individual Locations (e.g. Welds) for Inspection, according to TR-112657REVB-A

The EPRI Revised Risk-Informed Inservice Inspection Procedure (TR-112657) [C-1] identifies the following considerations for selecting individual locations or components for inspection:

Plant Specific Service History

The results of the plant specific service history review are a key input in the element selection process. Prior identification of piping cracks or flaws potentially signifies the presence of an active damage mechanism.

Predicted Severity of Postulated Damage Mechanisms

Engineering judgment should be applied to assess the relative severity (e.g., delta temperature or Richardson Number for thermal fatigue) of postulated damage mechanisms. An example of this type of consideration is provided below.

The piping element (pipe-to-valve weld) located nearest to the heat source will be subject to the highest temperature (conduction heating). As such, this location will generally be selected for examination since it is considered more susceptible than locations further away from the heat source, even though a pipe-to-valve weld is inherently more difficult to examine and obtains full coverage compared to most other configurations (e.g., pipe-to-elbow weld).

Configuration / Accessibility of Element to Enable Effective Examination

Whenever possible elements should be selected such that a complete examination of the required volume can be accomplished. Elements that are physically obstructed (e.g., support pipe clamp) should be avoided as well as element configurations that are inherently more difficult to examine, unless other considerations take precedence (see example above).

Radiation Exposure

In general, elements should be selected consistent with ALARA[3] principle.

Stress Concentration

Element selection could be focused on terminal ends and structural discontinuity locations of high stress and/or high fatigue usage in the absence of any identified damage mechanisms and other factors. In these cases, a greater degree of flexibility exists in choosing inspection locations.

Physical Access to Element

Consideration may be given to selection of elements that are readily accessible (e.g., examination can be performed from floor or grating without scaffolding) without the need for additional plant support.

Other considerations to include are:

Occupational Safety

As discussed above, physical access and accessibility are important attributes in the element selection process. These also have an impact on occupational safety (e.g. inspecting a location that does not require scaffolding involves less risk than inspecting a location that requires scaffolding). Other

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[3] As low as reasonably achievable

occupational safety issues should also be key components of the element selection process. These would include, but are not be limited to heat, humidity, noise, lighting, nearby equipment, etc.

Plant level considerations

This includes whether the inspection can be performed during plant operation or only while the plant is shutdown, and whether in addition the inspection increases the likelihood of interruption of plant operation, e.g. is the inspection carried out near sensitive equipment important to plant generation risk (e.g. down power, runback, plant trip).

Appendix C References

[C-1] Electric Power Research Institute (EPRI), *Revised Risk-Informed Inservice Inspection Evaluation Procedure*, EPRI report no. TR-112657REVB-A. EPRI: Palo Alto, CA: 2000.

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European Network for
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NUGENIA Technical Area 8

ABOUT ENIQ AND NUGENIA

The **European Network for Inspection and Qualification (ENIQ)** is a utility driven network working mainly in the areas of qualification of non-destructive testing (NDT) systems and risk-informed in-service inspection (RI-ISI) for nuclear power plants (NPPs). Since its establishment in 1992 ENIQ has issued over 60 documents. Among them are the “European Methodology for the Qualification of Non-Destructive Testing” and the “European Framework Document for Risk-Informed In-Service Inspection”. ENIQ is recognised as one of the main contributors to today’s global qualification guidelines for in-service inspection.

ENIQ is the technical area 8 of NUGENIA, one of the three pillars of the Sustainable Nuclear Energy Technology Platform (SNETP) that was established in September 2007 as a R&D&I platform **to support technological development for enhancing safe and competitive nuclear fission in a climate-neutral and sustainable energy mix.** Since May 2019, SNETP has been operating as an international non-profit association (INPA) under the Belgian law pursuing a networking and scientific goals. It is recognised as a European Technology and Innovation Platform (ETIP) by the European Commission.

The international membership base of the platform includes industrial actors, research and development organisations, academia, technical and safety organisations, SMEs as well as non-governmental bodies.

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