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FOREWORD-BRIEF REVISION HISTORY OF FRAMEWORK DOCUMENT

The first issue of European Framework Document for Risk-Informed In-Service Inspection was issued by the ENIQ Task Group Risk (TGR) and was approved by the ENIQ Steering Committee for publication in 2005. The second issue of the document was updated by NUGENIA Technical Area 8 (TA8) Sub-Area for Inspection Effectiveness (SAE), taking into account more recent experience and developments in the field. The objective is to provide guidelines to utilities both for developing their RI-ISI approaches and for using or adapting already established approaches to the European environment taking into account utility-specific characteristics and national regulatory requirements. This document was formally approved for publication by the NUGENIA TA8 - ENIQ Steering Committee in February 2019.

EXECUTIVE SUMMARY

Risk-informed in-service inspection (RI-ISI) approaches are used to define inspection programmes based on analysis of consequences and probability for leakage in pressure components important to reactor safety. By using plant specific consequence analysis and detailed review of degradation susceptibility and analysis of failure probability, the risk-informed approaches have the capability to identify the items presenting the highest risks of failure, including important locations that might otherwise be overlooked.

This document is intended to provide general guidelines to utilities for developing their RI-ISI approaches or adapting already established approaches, taking into account utility-specific characteristics and national regulatory requirements. This ENIQ document is Issue 2 of the European Framework Document for RI-ISI.

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1. Introduction

In-service inspection (ISI) is an essential element in integrity and safety management. ISI consists of non-destructive testing (NDT) and may also include pressure and leakage testing. The inspections help to confirm that basic safety functions are preserved and that the probability of radioactive materials breaching containment is reduced. Inspections have the purpose to detect any defects, degradation and damages, before leakage can occur and provide a base line for future inspections (Pre-Service Inspection (PSI)).

Risk-informed in-service inspection (RI-ISI) aims at rational plant safety management by taking into account the results of plant-specific risk analyses. The fundamental idea is to identify high-risk locations where the inspection efforts should be concentrated. The objective is to provide an ongoing improvement in the overall plant safety, measured by risk, together with reduced radiation doses for the inspection personnel.

RI-ISI reflects recent developments in Probabilistic Safety Assessment (PSA), the understanding of degradation mechanisms (e.g. root cause evaluations, structural reliability modelling) and the experience gained from more than 17,000 reactor operating years.

The development of a RI-ISI programme requires expertise from a number of different disciplines including inspection, maintenance, design, materials, chemistry, stress analysis, systems, PSA, inspection qualification, operations and safety. It requires a long-term co-ordinated management commitment, in order to maintain a living ISI programme, updated by analysis of inspection results and new knowledge providing feedback to the risk analysis. Before embarking on a risk-informed programme it is essential, therefore, to obtain the backing and commitment of the utility and plant management.

This document is structured as follows. The scope is laid down in Section 2. In Section 3, the most relevant definitions that apply herein are given. The principal elements of RI-ISI are described in Section 4. In particular, the RI-ISI scope is discussed in Sub-section 4.3 and qualitative, quantitative and semi-quantitative methods are discussed in Sub-section 4.4. Sub-section 4.7 deals with the assessment of degradation and probability of failure (POF). The issues concerning consequence of failure (COF) assessment are examined in Sub-section 4.8. Risk characterisation and ranking are discussed in Sub-section 4.9. The definition of the RI-ISI programme is considered in sub-section 4.10. In section 5 organizational responsibilities supporting the RI-ISI application are discussed including a suggested management structure. Finally, Section 6 deals with issues related to the documentation and archiving of the results produced in a RI-ISI application.

2. Scope

This document is intended to provide guidelines about the development of an ISI programme aimed at providing early detection of any degradation that may impact plant safety. This document has been developed specifically for RI-ISI planning in the nuclear industry, but the general principles can be adapted to other industries as well.

The scope of this document is limited to establish principles that an organisation carrying out RI-ISI should follow. The decision on whether a risk-informed approach should or should not be applied to devising an inspection strategy is a matter for agreement between all involved stakeholders.

This document identifies the key principles that any RI-ISI approach needs to meet. This is regardless of the level of quantification in the assessment of failure probabilities and consequences. Challenges for purely qualitative methods, that do not use the PSA in order to define the consequences or any form of structural integrity modelling to determine the POF, are not treated extensively in this document.

Currently, the main application area of RI-ISI is piping systems. Nevertheless, it is recognised that it is possible to apply the principles of RI-ISI to any system, structure, or component (SSC). ENIQ has produced a report on the role of ISI of the reactor pressure vessel (RPV) [1] as a basis for further discussion on this topic. For RPV and internals, differences as compared to a piping system emerge for example in the use of PSA in consequence analysis.

An important part in developing an inspection programme is to ensure the use of appropriate NDT methods. The link between inspection qualifications that complies with the European Qualification Methodology and a RI-ISI programme [2] is identified as an essential step in ensuring the effectiveness of ISI.

This document is intended to be general, and different countries can use the main principles to develop RI-ISI programmes which are consistent throughout Europe but which also meet their different national legal, regulatory and technical requirements.

3. Basic definitions

The definitions that apply to this document are given in the ENIQ Glossary of Terms [3] and the List of Abbreviations. The following concepts are fundamental within this document and are therefore discussed here in more detail.

3.1 Failure

Failure of a structural component is an event involving leakage, rupture or a condition that would disable its ability to perform its intended safety function. For piping, failure usually involves a leak or a rupture, resulting in a reduction or loss of the pressure-retaining capability of the element in question. The plant response to the leakage depends on the severity of the failure, which is generally related to the leak size and location. Hence, if the consequences of the piping failure vary significantly with leak size, it is necessary to define and analyse different degrees of failure states of a single structural component.

3.2 Probability of Failure

POF is the likelihood that a component or weld will fail at a given time, considering the potential degradation mechanisms it could be susceptible to and factors such as disturbance loads, cyclic loads and environment management. Fundamental for the risk assessment is a systematic assessment for the identification of potential degradation mechanisms (hazards identification). The POF over a given time period may be assessed by use of modelling, expert judgments or statistics, depending on the degradation mechanism, service experience and available information.

In this document the term ‘POF’ is used as an abridged version of the full wording ‘POF over a given time into the future’. POF is defined either in terms of failure frequency or POF on demand in the case of components in a stand-by system actuated only on demand.

In PSA models the failure frequency is commonly assumed to be a constant failure rate. However, when dealing with passive components subject to a time dependent degradation mechanism, the POF is not constant with time. For situations where the POF is low throughout the life of the plant, this time dependency may be of small significance. However, when the degradation mechanism is more aggressive, improved treatment is recommended.

3.3 Consequence of Failure

Consequence is measured as the adverse outcome that is conditional on failure. For RI-ISI the consequence is measured as the Conditional Core Damage Probability (CCDP) or Conditional Core Damage Frequency (CCDF). The consequence that arises given failure of a component or system is commonly determined by use of PSA. Most plants have a Level-1 PSA defining CCDP or CCDF. Many PSAs also include containment failure metrics (e.g. Large Early Release Frequency (LERF)) and the consequence assessment for the RI-ISI programme may include these metrics, for example conditional large early release probability (CLERP) or conditional large early release frequency (CLERF).

3.4 Risk

The risk is defined herein in the engineering sense as the product of the probability of a failure and the consequences of that failure occurring, as follows:

Risk = {Probability of Failure} × {Consequence of that Failure}

As probability is dimensionless, it follows that the metric of risk is the same as the metric of COF.

4. Principles of Risk-Informed In-Service Inspection

RI-ISI aims at a rational plant safety management strategy by taking into account the results of plant-specific risk analyses.

Fundamental principles for development of an effective inspection programme are:

1. Ability to define the consequence and probability associated with component and weld failures, so that the ISI programme can focus on safety-significant items for an integrated inspection strategy;
2. Identification of an inspection programme that will improve the safety as far as it is practical, with due consideration of resources and accumulated radiation dose to plant workers.

The advantage of such an approach is the optimisation of the inspection efforts. The term 'optimisation' in this context is seen as a process that:

a) Improves or at least maintains the overall plant safety;

b) Minimises the radiation dose to personnel involved in the inspection activities;

c) Provides improved plant reliability.

4.1 The Process of Risk-Informed Inspection Planning

The key steps in the process of risk-informed inspection planning are summarized in Figure 1.

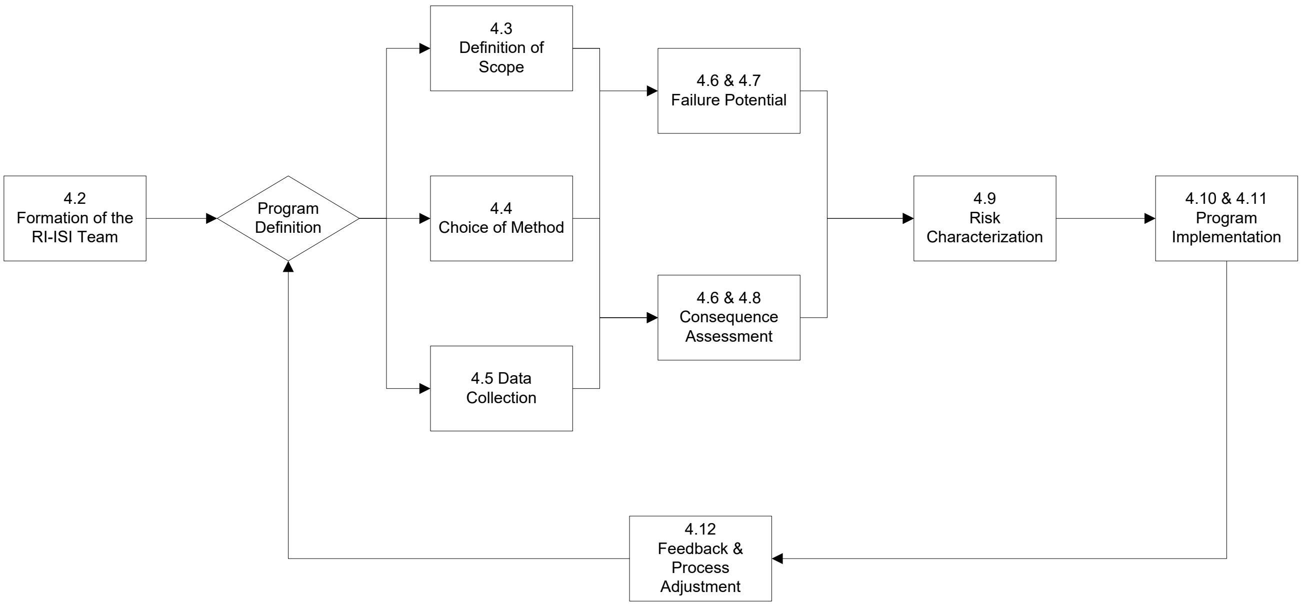

Figure 1: RI-ISI Process Overview.

The steps or phases may be iterative and may impact previous steps (e.g. the results of a sensitivity study may impact the initial risk ranking):

1. Assurance of long-term commitment of senior management to the risk-informed programme;
2. Formation of the RI-ISI assessment team (Sub-section 4.2);
3. Definition of the scope of the SSC to be considered in the analysis (Sub-section 4.3);

4. Collection and analysis of the information required to carry out the risk assessment (Sub-section 4.5);
5. Grouping of items and definition of the level of the evaluation (Sub-section 4.6);
6. Assessment of the POF for all the components included in the scope of the application (Sub-section 4.7). This step includes the hazard (degradation) identification;
7. Assessment of the consequences of failure for all the components included in the scope of the application (Sub-section 4.8);
8. Ranking of the risks associated with all the components (Sub-section 4.9);
9. Performing sensitivity studies to determine the effect of changes in key assumptions or data (Sub-section 4.9.2);
10. Identification and selection of components to be inspected and criteria (Sub-section 4.10);
11. Inspection intervals, qualification and other measures for risk reduction (Sub-section 4.11);
12. Feedback of the obtained information after completing the inspection, or from input changes in PSA, damage assessments, or other (Sub-section 4.12).

Each step is further discussed in the following sub-sections.

4.2 Formation of the RI-ISI Assessment Team

The formation of an appropriate workforce structure is an essential factor in devising and implementing a RI-ISI programme. Such a workforce will need to contain or have access to a range of different disciplines including inspection, maintenance, design, materials, chemistry, stress analysis, systems, PSA, operations and safety. An example of a possible RI-ISI management structure, together with the roles, responsibilities and interfaces of the different parties involved, is described in Section 5.

4.3 RI-ISI Scope

The first practical step in developing a RI-ISI programme is to define its scope. The scope definition should clearly define the boundary of the programme, e.g. which SSCs and which structural elements (circumferential welds, longitudinal welds, socket welds, attachments, lugs, etc.) are to be included in the programme.

The scope of a RI-ISI programme can be either a full scope programme or, when an alternative programme is already in place (e.g. ASME Section XI, SKIFS 1994:1, CSAN285.4), a partial scope programme. The scope should be clearly defined and documented.

A full scope programme can be defined as including all passive SSCs, including:

1. Those relied upon to perform a safety function during all design-basis plant conditions;
2. Those whose failure could compromise the function of safety-related SSCs or could cause a plant trip or actuation of a safety-related system.

A partial scope programme is restricted to any subset of the systems or functions defining the full scope. The partial scope application can be justified, for instance, if an alternative (such as deterministic, augmented) programme is in place for the other passive components or degradation mechanisms.

A full scope RI-ISI programme is recommended, because it treats all SSCs in a consistent and objective manner for relative comparisons. In addition a greater portion of the plant risk from pressure boundary failures is addressed. Nonetheless, it is recognised that in the application of RI-ISI, a partial scope programme can and has been justified.

A RI-ISI methodology usually allows flexibility in the scope of application. Therefore, conducting the application on a large scale (e.g. a whole plant application), a system specific application (e.g. a single system) or a class of components (e.g. the reactor coolant pressure boundary) should still produce consistent and reliable results.

4.4 Qualitative, Quantitative and Semi-Quantitative Methods for RI-ISI

In principle, three different approaches to the assessment can be used in developing ISI programmes: quantitative, semi-quantitative and qualitative approach.

In the nuclear industry, one tool that is frequently used in assessments of risks associated with plant operation (normal and abnormal) is the PSA. The COF can be quantified using the PSA model, and results are applied for many risk-informed applications including RI-ISI.

Quantitative approaches should be chosen when feasible. However, it is recognised that the current state of knowledge and understanding of some of the degradation mechanisms and the availability of the required plant data can be insufficient to accurately quantify the POF (see Sub-section 4.7). Likewise, many current PSA analyses may not be detailed enough for the level required in RI-ISI application, and thus the consequence analysis must be complemented by some degree of qualitative assessment (see Sub-section 4.8). A frequently applied approach to development of a RI-ISI programme is a semi-quantitative one, based on a plant-specific PSA and with consideration of the current understanding of potential degradation mechanisms.

A benchmark study RISMET [4] has been conducted with the purpose to compare various RI-ISI methodologies applied to the same case. It was concluded that the use of consequence assessment based on a plant specific PSA model improves identification of risk-important locations. Further, successful failure probability assessment is strongly dependent on in-depth knowledge of degradation assessment and structural integrity analysis for piping systems, independent of the level of quantification in the methodology.

4.5 Information Collection and Analysis for a RI-ISI Assessment

The process of risk-informed inspection planning brings together a large amount of information from many different sources, which needs to be collected and analysed. This information can be divided into the following categories:

1. Equipment data;
2. Historical plant operating data;
3. General nuclear industry information;
4. Safety analysis report and technical specifications;
5. PSA specific data.

The information required will depend on the approach adopted, but may include:

<u>Equipment data</u>

a) Design and manufacturing records;
b) As-built information;
c) Design basis conditions;
d) Deterministic design stress and fatigue analysis;
e) Defined boundaries of plant items to be considered for inspection planning.

<u>Historical plant data</u>

a) Operational transient data and condition monitoring data;
b) Plant failures and service experience data;

c) Pre-service and ISI records;

d) Environmental conditions including temperatures, water chemistry and flow rates;

e) In-service degradation assessments (fatigue, stress corrosion cracking (SCC), erosion-corrosion, external effects).

General nuclear industry information

a) National and international databases;

b) National and international publications.

Safety analysis report and technical specifications

a) Test procedures and frequencies;

b) Emergency operating procedures;

c) System failure procedures.

PSA specific data

a) System design and modifications;

b) Frequencies of initiating events (internal and external);

c) Failure modes and effects analysis (FMEA);

d) Failure frequencies (in the consequence assessment);

e) Common cause failures (CCF);

f) Data on human reliability;

g) Success criteria.

The availability and accessibility of this information will vary depending on the particular circumstances.

Data collection is an essential part of the process, as it constitutes the basis for the whole analysis and decision process. Due care and diligence should therefore be practised during this phase. Data collection can be a resource-demanding phase in the RI-ISI process, but the data gathered is of considerable value. The data should be made available for other safety and reliability related activities, as for example periodic safety review.

4.6 Grouping of Elements and Level of Evaluation

The risk assessment in a RI-ISI programme can be carried out either at the element level (e.g. each weld and discontinuity) or for groups of contiguous elements where all relevant conditions are similar. Grouping of elements may be performed with consideration of consequence or degradation.

The advantage of evaluation at element level is that the output can be unique for every element and there is a clear distinction between elements. However, to reach this distinction between the elements, a rather large amount of detailed input data is needed which might be prohibitive from a cost point of view.

The main advantage of grouping elements with the same consequence conditions (often called segmentation) is that it provides time savings. The initial segmentation is normally based on the postulated direct consequences of a failure, but it is important that indirect consequences are also considered for further segmentation. Piping segments are normally defined at major components such as pumps, heat exchangers, check-valves, remote controlled valves or at pipe size changes. The possibility for operator action to mitigate the consequence can also be a reason for a segment boundary.

For the degradation assessment, grouping may also be performed with respect to elements of same material and subjected to same environmental conditions.

4.7 Probability of Failure Assessment

A fundamental and initial step in any risk analysis process is to identify potential hazards, with the objective to make a complete identification of threats. In the case of RI-ISI, we consider hazards due to degradation mechanisms, such as fatigue cracking, SCC, local corrosion, embrittlement and unusual loads. During the identification step it is important to be open to all possible threats and underlying causes. For this reason, one may defer the assessment of the probability of the threat to a subsequent step, after the identification of possible threats. It is recommended that the identification is executed as a systematic review of all degradation mechanisms, performed as an in-depth analysis by experts, to identify active and potential damage mechanisms. Examples of different types of degradation mechanisms are found in ASME II, App A [5], IGALL [6] and similar documents. Some damages can occur due to certain loads such as vibrations, thermal mixing, stratification or steam collapse.

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.

The POF over a given time period may be assessed by use of physical modelling, expert judgments or statistics, depending on the degradation mechanism, failure mechanism and available information for influencing factors.

The POF of a component may be analysed in a quantitative way by use of structural reliability models (SRMs). However, two important facts are recognised concerning SRMs. Firstly, such models only exist for some of the degradation mechanisms that affect nuclear power plants (NPPs). Secondly, for degradation mechanisms that do have a viable prediction model, quantitative values may serve to quantify relative differences in the POF between different locations with differences in influencing variables. Because of the above, failure probabilities for RI-ISI applications are generally estimated on the basis of a combination of quantitative and qualitative assessments. This is referred to as 'semi-quantitative' analysis. The analysis aims at using all available knowledge to derive an auditable ranking of the POF. An assessment of the POF can be obtained by:

1. Use of SRMs, where they exist, to provide estimates of the relative differences in the failure probabilities (see Sub-section 4.7.1);
2. Statistical estimates based on plant-specific data and global databases in order to provide anchoring points for SRM analysis or expert judgments (see Sub-section 4.7.2);
3. Use of expert judgements for identification and ranking of susceptibility, using a combination of knowledge on degradation, operational experience, design and supporting deterministic model results (see Sub-section 4.7.3).

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 herein.

Different leak sizes can result in large differences in consequences. Depending on the leak detection capabilities, this implies that it can be useful to estimate the POF for different defined leak sizes, e.g. the probability for detectable leak after wall penetration and the probability for pipe rupture. Leak detection assessment within the RI-ISI framework is discussed in Sub-section 4.9.4.

4.7.1 Structural Reliability Models

SRMs are essential tools in the evaluation of probabilities of failure for components of NPPs. A SRM is based on analytical modelling of a degradation mechanism and failure mode, together with evaluation using stochastic variables that are described by distributions. Probabilistic Fracture Mechanics (PFM), with probabilistically distributed parameters, is used for degradation mechanisms that cause cracking. The objective of structural reliability analysis is to determine the probability of an event occurring during a specified reference period. There are several degradation mechanisms that are not covered with the available analytical models, but when models exist they provide valuable insights.

It is essential to verify and validate the SRMs used in the evaluation of probabilities of failure. To this end, a number of steps can be defined [7]:

1. The analytical assumptions should be well grounded and based on theory that is accepted as representative of the situations considered by the given SRM.
2. The scope, the analytical assumptions and the limitations of the modelling capability should be well defined.
3. The basic programming and modelling should be shown to have suitable quality assurance (QA) documentation.
4. The model should be capable of reproducing the data on which its analytical assumptions are based. Examples should be provided that can demonstrate its general agreement with available experimental data.
5. The model should be benchmarked against other SRM models within the same field or scope and any differences should be adequately explained.
6. Attempts should be made to show how the model compares with the world or field data, accepting the inherent limitation of this data.

The verification and validation of SRMs is described in more detail in ENIQ Recommended Practise 9 (RP9) [8].

The results from SRMs can provide a relative risk ranking valuable for the purpose of developing a RI-ISI programme. It is important to recognize that the absolute values developed by SRMs need to be used with caution if used for other applications.

An important advantage of most SRMs is the possibility to quantify the influence of inspections, both in terms of differences in inspection capability and inspection interval. This is a key factor in RI-ISI since it is desirable to select the most appropriate inspection interval and inspection capability for every risk significant location. The probability of detection (POD) function for different NDT systems may be used to describe the reliability and efficiency of the inspections. These issues are discussed in more detail in sections 4.11.1 and 4.11.2. Note that when probability assessments are based on statistical experience data or expert judgment, it is not possible to quantify the effect from using different inspection intervals or detection capability.

Further recommendations and discussion on requirements for SRMs and associated software in applications for RI-ISI are found in reports produced within the NURBIM project [7].

4.7.2 Use of Operating Experience Data and Statistics

Operating experience data provides useful qualitative and quantitative information on the degradation of structural components. For example, different types of SCC have been discovered from field failures, and general event information has been transferred to other plants for their hazard identification work. Operating experience data covers not only leak and rupture data, but also other information on the presence of non-critical levels of degradation, such as small defects and wall thinning. The degradation information can be of considerable value in the development of SRMs and in the assessment of structural failure probabilities.

Operating experience data should be considered in the evaluation of degradation hazards. Data can be divided according to, for example, degradation mechanisms, materials and major environmental characteristics. The data should be broken down as finely as possible without becoming too sparse, which can be a challenge for safety-significant systems where the number of leakage events is low.

When parameters are assessed by use of structural component failure data and degradation databases, the following shortcomings have to be taken into consideration:

1. Passive components usually have an increasing failure rate (due to ageing effect), and thus the exponential distribution does not correctly model future failure occurrence.
2. The data quality may be insufficient for obtaining reliable estimates due to:
   a) Missing information related to the component population and conditions;
   b) Uncertainties related to failure mechanisms and root causes;
3. Data is often very scarce, and at application it has to be considered that data is grouped for many different conditions and ISI programmes.

Due to the shortcomings related to the quality and quantity of data, statistical estimates of failure probabilities for passive components are often subject to large uncertainties. For RI-ISI applications, POF estimates obtainable from world-wide or generic data may not be sufficient. However, the generic data is extremely valuable in establishing initial preliminary probabilities. These values can then act as an anchor for either SRM estimates or expert judgement, where plant-specific information is applied to identify the differences in POF throughout the plant.

4.7.3 Use of Expert Judgement

As discussed, quantitative assessments are not feasible and possible for all degradation mechanisms and in all situations. Analytical models do not exist for all degradation mechanisms, and statistical data is often scarce. An alternative and complement is to use expert judgement for qualitative assessments. Expert judgments may be used to rank and classify POF. Sometimes qualitative assessment can also be applied as a first step to prioritize components for further detailed analysis.

Useful risk insights can be gained also with qualitative assessments. A qualitative evaluation should be performed by experts and using a structured approach. Qualitative approach uses qualitative terms, such as very low, low, medium, high and very high, which represents classes that commonly differ in a non-linear logarithmic scale. The classes should provide sufficient differentiation to assess and compare different components and positions. Another consideration for quantitative assessment is that conservative assessment limits need to be applied for a robust method, since the assessments are less detailed.

It is very important to assess all influencing parameters, and any sequences of events, to facilitate adequate assessment and classification of the failure probability. Sometimes deterministic results exist that can give partial support for the classification.

Well-structured expert judgement can be a powerful tool for expanding the range of application of a RI-ISI. Elicitations can be used to support and integrate individual expert judgements to provide POF estimates. Details on expert elicitation are described in ENIQ RP11 [9]. It is recommended to ensure that the use of expert judgement is conducted within a structured expert elicitation process, with the principal phases:

1. Selection and training of experts;
2. Elicitation of judgements;
3. Modelling and combination of judgements;
4. Sensitivity analyses;
5. Discussion and feedback from experts;
6. Documentation.

It is recognised that experts, who are experienced within other areas, are often not very familiar with estimating probabilities and using non-linear scales. Training in giving probabilistic estimates is important. Aggregation of opinion from multiple experts (three or more) tends to improve accuracy compared to the opinion of a single expert. Further, the quality of judgments can be substantially improved by decomposing the problem into more elementary problems.

The person leading a structured expert elicitation process should have proper knowledge in decision analysis, probabilistic modelling and statistics. This person is called the normative expert. His or her responsibility is to facilitate the process by giving training, conducting the elicitation and aggregating the expert opinions. A detailed discussion on the expert assessment approach within the nuclear industry can be found for example in [10] and [11]. An adaptation of expert judgement to the estimation of pipe rupture frequencies is provided in [12].

Using an expert judgement for all locations, including those for which an SRM and possible statistical data exists, can be a format to combine qualitative information and quantitative POF estimates. The SRM and statistical data then act as, both an anchor for the rankings and as a form of cross correlation with the expert ranking. An example of such an approach is described in [7].

4.8 Consequence of Failure

The consequence, given a leakage or rupture of a component, is usually assessed using the measure CCDP. The consequence assessment part of a RI-ISI analysis is commonly performed using PSA model results.

The failure of a passive component in a NPP can basically lead to one of the following classes of events of interest:

1. Initiating event: A pressure boundary failure occurs in an operating system resulting in an initiating event.
2. Loss of mitigating ability (stand-by): A pressure boundary failure occurs in a standby system and does not result in an initiating event, but degrades the mitigating capabilities of a system or train. After the failure is discovered (if discovered), the plant enters the Allowed Outage Time defined in the Technical Specification.
3. Loss of mitigating ability (demand): A pressure boundary failure occurs in a standby system when the system/train operation is required by an independent demand.
4. Combination: A pressure boundary failure causes an initiating event with an additional loss of mitigating ability (in addition to the expected mitigating degradation due to the initiator).

Furthermore, a pressure boundary failure that also affects the containment performance can be identified as a separate class.

The consequence analysis part of the RI-ISI process aims at evaluating the impacts of any of the above-mentioned events on plant risk. The consequence evaluation consists of the following primary steps:

a) A qualitative FMEA that determines the plant impacts of postulated failures of postulated sizes (e.g. small leakage, medium leakage, complete rupture). This step can consume a large share of resources;

b) Qualification of the PSA for RI-ISI application;

c) Quantitative analysis with PSA.

PSA techniques have been developed since the 1970s [13] and PSA studies exist today for most types of NPPs and individual power stations. Although the level of details and quality of these studies vary, the PSA methodology has become a well-known and frequently used tool in the analysis of nuclear safety.

The following items are considered critical for a robust interface between PSA and RI-ISI is to be developed:

- Levels and scope of PSA to be used in RI-ISI (Sub-section 4.8.1);
- PSA quality, limitations and uncertainty (Sub-section 4.8.2);
- Passive component failure treatment (Sub-section 4.8.3).

4.8.1 Levels and Scope of PSA to be used in RI-ISI

PSAs are performed at different levels, dealing with different types of consequences:

Level 1: Assessment of plant failures with respect to core damage and the estimation of core damage frequency (CDF);

Level 2: Estimation of off-site fission product release: Consequences are usually expressed in terms of the combination of small or large and early or late containment failures, related to estimation of release frequency (e.g. LERF);

Level 3: Assessment of off-site consequences leading to estimates of the effects of fission product release on human health. Consequences are usually expressed in terms of fatalities, public radiation doses and environmental pollution.

All modern NPPs have plant-specific PSA studies, usually at Level 1 or Levels 1 and 2. The Western European Nuclear Regulators' Association (WENRA) state in their document on safety reference levels for operating NPPs [14] that PSAs shall be developed for both Levels 1 and 2. It is natural to utilize these as the basis for the consequence evaluation. Current RI-ISI applications mainly rely on CDF and LERF as the consequence metrics of interest.

It is recognised that the use of Level 2 consequence metrics (e.g. large early release) could be important for RI-ISI application for reactors whose complete primary pressure boundary is not fully covered by the containment structure (for instance, RBMK and CANDU reactors). In any case it should be borne in mind that Level 2 studies are based on assumptions that can be very difficult to verify in practice, and thus are in general subject to higher uncertainties than estimates of core damage.

In view of the above, it is concluded that the Level 1 PSA forms the recommended (as well as the minimum) basis for analyses for most plant designs. Insights from Level 2 metrics can be considered in handling priorities for elements with lower POF but higher consequences.

The scope of the most comprehensive PSA Level 1 studies includes evaluation of the risk at power operation, start-up, shut down and cold shutdown. Among the initiating events that are usually considered are typical transients, loss-of-coolant accidents (LOCAs), support system failures, internal fire, flooding, seismic and other external events.

The basic requirement on the scope of a PSA is that all relevant operating plant modes and initiating events must be addressed in the evaluation. It is however, not necessary that all modes and events are included in the calculations. A qualitative treatment of omitted modes and events is sufficient when they have little influence on the result. This will differ from plant to plant.

With respect to external hazards, it is important to understand the purpose of the PSA application. The purpose of a RI-ISI application is to develop a periodic inspection programme that maintains or improves plant safety. Therefore, consideration of other hazards outside the baseline PSA (e.g. external hazards) are not needed for the consequence assessments, if they would not significantly impact the relevant decision-making process (e.g. selection of inspection location) [15].

The following provides a summary on why some hazards in general not need to be included in a PSA used to develop COFs for a RI-ISI programme for piping. However, one or more of these hazards may be included at the option of the RI-ISI programme developer.

Internal Fire Hazard: The potential contribution of piping failure to internal fire risk is insignificant because the failure probability of piping is insignificant compared to the failure probability of other SSCs such as pumps, valves, and power supplies. Fire events are also not likely to present significantly different challenges to the piping in the scope of RI-ISI. The design basis events remain unchanged and safety margins are maintained. Meeting defence-in-depth (DiD) and safety margin principles provides additional assurance that this conclusion will remain valid. ISI is a part of DiD, and the RI-ISI process will maintain the basic intent of ISI (that is identifying and repairing flaws) and provide reasonable assurance of an ongoing substantive assessment of piping condition.

Seismic Event: Well-engineered systems and structures (for example, piping systems) are seismically rugged. Individual plant examination of external events (IPEEE) and other industry and NRC studies (see e.g. [16], [17]), have shown that piping systems in general have seismic fragility capacities greater than the screening values typically used in seismic assessments, and they are generally not considered likely to fail during a seismic event. ISI is not considered in establishing fragilities of such components.

High Wind, External Flood, and Other External Hazards: As described previously, the purpose of developing an RI-ISI programme for piping is to define an alternative ISI strategy for piping systems. External hazards (for example, high wind or external flood) need not be considered in the development of an ISI programme for piping. The reasons include the structural ruggedness of the piping systems to loads during this type of events, location (because relevant systems are typically inside well-engineered structure), and the consequence assessment for internal events already includes the consideration of spatial impacts. The industry experience with plants implementing RI-ISI programmes has not identified changes based on insight from the evaluation of these external hazards. The approaches to maintain DiD and safety margins summarized previously provide additional confidence in this conclusion.

In summary, reasons for not including some hazard groups in the PSA results used for risk-informed decisions according to [18] are:

- The magnitude of the potential consequence is not significant.
- Including the hazard group would not affect the decision; that is, would not alter the results of the comparison with acceptance guidelines.
- Traditional engineering arguments including preserved balance in defence and preserved margin to design basis events are applied.

However, to be adequate for developing COFs for a RI-ISI programme, the scope and quality of the PSA should reach established requirements for plant specific PSA, which is discussed in the next section.

4.8.2 PSA Quality, Limitations and Uncertainty

It is important to develop results in the RI-ISI programme that are robust. Therefore, the PSA should be qualified for this purpose.

An overriding requirement is that the PSA should realistically reflect the actual design, construction, modifications, operational practices and operational experiences of the plant. The plant's different functions should be modelled with the same accuracy and level of detail. The evaluation of system demands should be done with the same level of realism and conservatism for all functions, and the input data used for PSA analyses should be verified to ensure that it reflects the state of the art.

It is recommended that the PSA study is qualified for use in RI-ISI application by fulfilling demands specified by ASME [19] or EPRI [15]. The qualification could also be performed by peer review of the PSA for RI-ISI application. The qualification of the PSA should be documented ([15], [19]-[23]).

Passive components generally have low failure probabilities in comparison with active components, and the former only contribute to a small proportion of the total plant risk evaluated in the PSA. Moreover, because of low probabilities of failure, data available regarding failure of passive components is usually limited. This has led to very limited treatment of such failures within the PSA. Due consideration must be given to this fact and how the passive components should be treated in the consequence analysis. ISI is a very important preventive action to ensure the situation of very low POF for the passive components. The next Sub-section (4.8.3) discusses this issue in more detail.

If the PSA does not fully meet the quality requirements for RI-ISI application, specific attention should be paid before its use in the consequence evaluation. The PSA may still provide useful information for the analysis, but in this situation, it should be supported by complementary analyses that may be of qualitative or quantitative nature.

Each PSA is also subject to unavoidable uncertainties, such as parameter uncertainties, model uncertainties and completeness uncertainties. Parameter uncertainties related to statistical data are usually quantified and a PSA may provide uncertainty boundaries as a part of its output. Model and completeness uncertainties are normally not included in the PSA, but they have to be evaluated in the process of PSA qualification.

Quantified PSA uncertainties, such as parameter uncertainties, could be transferred to the RI-ISI procedure, but it is recognised that there are no straightforward algorithms for this. The RI-ISI evaluation should specify the effects of the parameter uncertainties in connection to sensitivity analyses (Sub-section 4.9.2).

4.8.3 Passive Component Failure Treatment in PSA

The PSA model can be used to estimate the COF at different locations for use in RI-ISI analysis. The consequence is estimated as the CCDP, that is, the CDP given failure assumed at a location. Pipe breaks are modelled directly as initiating events such as LOCAs, main steam or feed-water line breaks or flooding. PSA may spatially subdivide the pipework into zones and then consider various types of LOCAs occurring within the zone as initiating events, but the studies do not normally model initiating events at segment or element level. Furthermore, the components are normally modelled in the PSA with two states: full function or total failure. In the case of piping, these states are ‘no leakage’ and ‘complete pipe break’. Thus, a ‘partly failed’ component (such as a crack or a small leak) that is handled by a manual action, is not modelled in a basic PSA. All events leading to an automatic initiation of safety systems are included in the PSA.

As the modelling of structural components in the base PSA may be coarse and incomplete (with respect to RI-ISI needs) for many systems, additional analysis may be required to determine the consequences at the degree of detail needed in RI-ISI. A complementary FMEA should be conducted in order to define both the direct and indirect impact of failure on plant operation. Indirect effects include failure consequences affecting other SSCs or piping segments, such as:

1. Pipe whip;
2. Jet impingement;
3. Decompression waves;
4. Flooding;
5. High environmental temperatures, etc.;
6. Loss of inventory.

It is recognised that indirect effects of passive component boundary failures may have a significant influence on the consequence and it is therefore required that such effects are explicitly taken into account. Spatial consequences (or area events) are determined based on the location of the failure and relative position of important equipment and it is recommended that the analyses are confirmed by a walk-down.

The FMEA should include the evaluation of consequences for several leak sizes (normally 2 or 3 sizes are sufficient), and the analysis should address the possibility to isolate the leak or break. Both automatic and manual isolation should be considered. Considerations of leak detection are discussed in Sub-section 4.9.4.

The extent to which the findings of the FMEA can be incorporated in the PSA model for the quantitative consequence evaluation depends on the PSA and plant-specific issues. Issues not explicitly included in the PSA model should be judged qualitatively and be taken into account in the final review and adjustment of the consequence ranking.

The base PSA does not usually include models of passive component failures that could result in the loss of mitigating ability (e.g. safety system pipe break). A way to address these situations is to identify basic events or groups of events already modelled in the PSA, whose failure captures the effects of a piping segment failure. This method is sometimes called the ‘surrogate component approach’.

The use of the plant-specific PSA for consequence assessment in RI-ISI analysis can be summarised as follows:

a) The PSA model and success criteria are used to define safety functions and backup trains.

b) PSA results for all initiators are applied directly for relevant consequence impacts.

c) PSA system and/or train unavailability are used to determine the reliability of mitigative equipment given a pressure boundary failure.

d) Internal flood analysis results are used in the analysis of spatial effects.

e) Shutdown PSA, if available, is used in the evaluation of other modes of operation.

f) Level 2 PSA results can be used to identify event sequences that provide the dominant contribution to containment performance (e.g. LERF) with respect to pipework failures, as applicable.

4.9 Risk Characterisation and Ranking

This sub-section provides guidance on how the risk characterisation and ranking may be developed to support the establishment of an ISI programme. As already stated, risk is defined in engineering terms as the product of the measure of the consequence resulting from a failure and the probability of that failure occurring within a given period of time. Combining the information from the POF assessments and the consequence analyses forms the basis for the risk ranking. The risk ranking may be carried out at both element/component level and segment/group level.

4.9.1 Graphical Representation of Risk

Each segment or element can be ranked from highest to lowest according to its risk level. For evaluation of the risk it is useful to represent it in a graphical way by developing risk plots, risk matrices or Pareto risk diagrams.

In risk plots, each component is represented as a point on a log-log plot. The COF can be represented on the x-axis (the abscissa of the point). The POF can be represented on the y-axis (the ordinate of the point). Figure 2 shows an example of a risk plot, with illustrative scales for the POF per year, and for the consequence measured as the conditional CDP.

A risk plot provides a picture of how the risk is distributed over the range of consequences. When using log-log axes, locations of constant risk are identified by straight lines. Parallel lines of constant risk can be drawn at fixed distances apart, identifying risk bands (for example decades), see Figure 2. This visualises the risk situation and helps with ranking, among all considered components and hazards, and for the assessed time instant.

In a qualitative approach, POF and COF are not numerically evaluated in absolute terms, but are classified using either a qualitative scale such as high, medium, low, or broad categories such as from 10^{-3} to 10^{-4} etc. In this case, a risk matrix can be used to represent different risk situations as shown in Table 1 (the values are purely illustrative and should in no way be taken as a requirement). Each component may be entered in its classified position in the matrix.

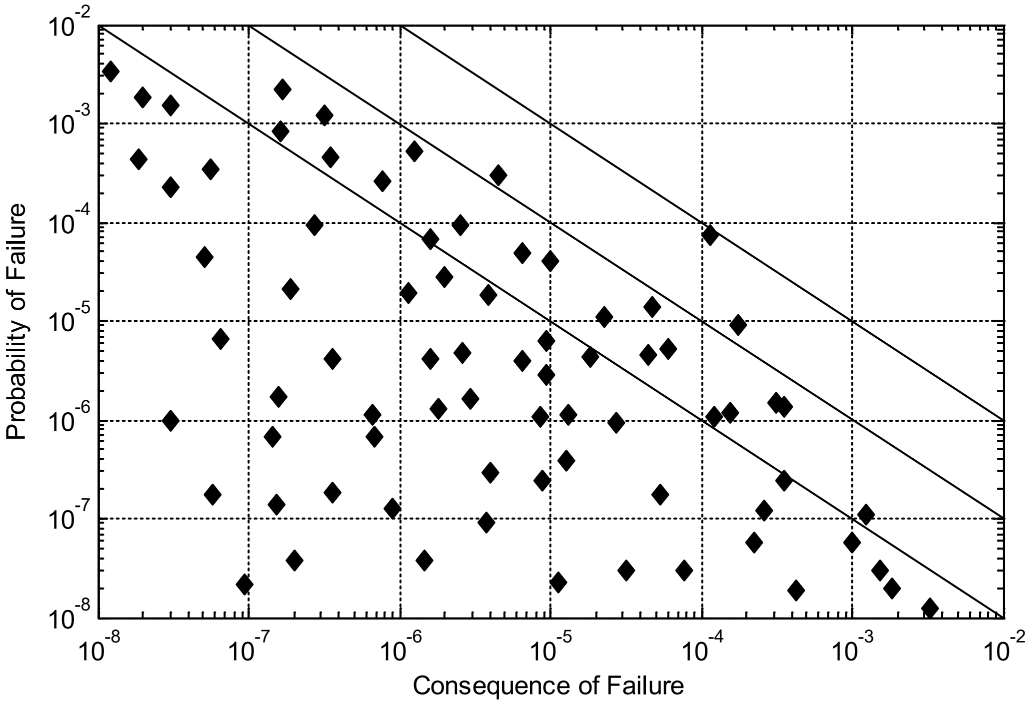

Figure 2: Illustration of a risk plot

Table 1: Risk Matrix (the values in this table are purely illustrative).

			Conditional Consequence				
			Very Low	Low	Medium	High	Very High
			$<10^{-6}$	10^{-6}-10^{-5}	10^{-5}-10^{-4}	10^{-4}-10^{-3}	$>10^{-3}$
Probability of Failure	Very High	$>10^{-4}$					
	High	10^{-5}-10^{-4}					
	Medium	10^{-6}-10^{-5}					
	Low	10^{-7}-10^{-6}					
	Very Low	$<10^{-7}$					

An additional way to graphically represent the risk distribution in a system is by means of Pareto diagram. A Pareto risk diagram shows the risk from individual components ranked in a descending order in the form of histograms. See examples of Pareto diagrams (linear and logarithmic) in Figure 3. The Pareto plot is for example illustrative when evaluating the Risk Reduction Worth (RRW), commonly used in PSA technology, as discussed in [7].

The Pareto diagram gives a ready impression of the risk distribution and the risk level of the components being inspected. However, the risk plot and risk matrix are probably better graphical representations with regards to inspection planning. These are more informative since they also show if the risk is governed by the POF or by its consequence. It may be noted that ISI is a preventive action for early detection of any degradation. Inspections can reduce the POF, but to reduce the consequence other actions are needed. Further, ‘High consequence–low probability’ locations require different considerations than ‘high probability–low consequence’ locations even if they have an equal risk. In general, larger uncertainties are associated with more rare situations. This issue is further discussed in Sub-sections 4.9.3.3 and 4.9.3.4.

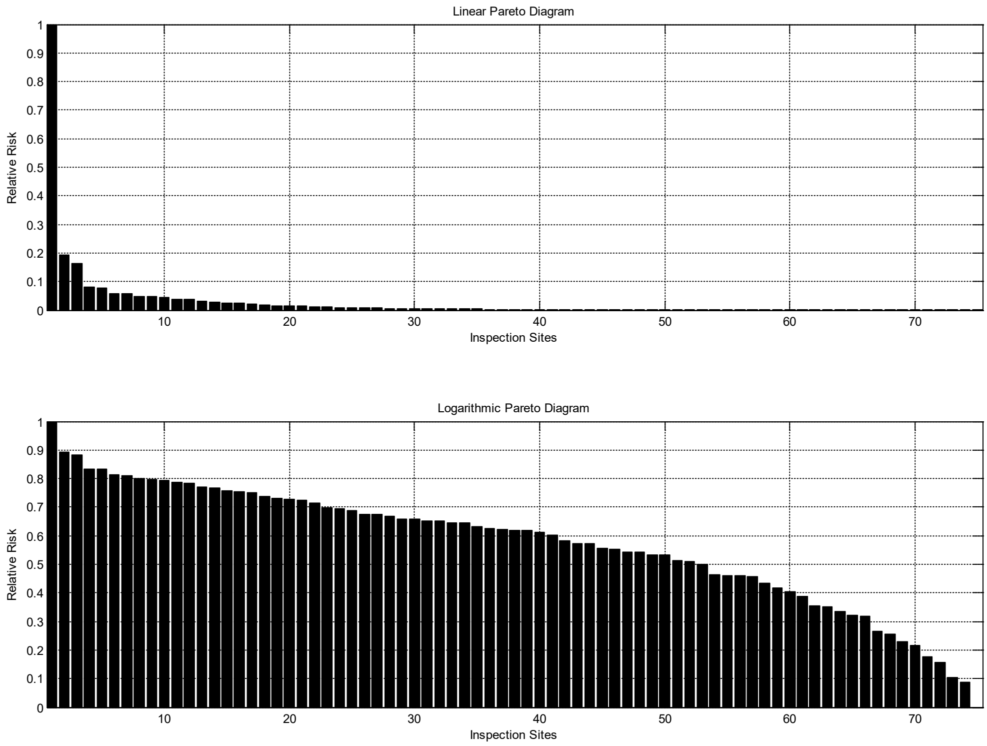

Figure 3: Illustration of Pareto diagram for all inspection locations, using linear and logarithmic scales.

4.9.2 Sensitivity Analysis

Sensitivity studies should be performed to determine if changes in key data or assumptions could have any significant impact on the rankings. These sensitivity studies should address the potential changes in component ranking by varying the estimates of pressure boundary failures and estimates of the COF. Also, crediting the effect of leak detection on the results should be investigated. These results should then be integrated in the decision-making process.

The sensitivity studies can identify potential high risk components that exhibit significant shift in risk level for changes in operational modes, PSA assumptions, data and other model uncertainties.

4.9.3 Identification of Safety Significant Locations

The development of a risk plot or ranking does not in itself identify all locations that could be said to be safety-significant and additional considerations are needed. What follows is only advisory but provides a possible structure regarding this process.

The first step in the process of determining risk-significant locations is the identification of risk outliers. Risk outliers are locations that have a much higher risk than the overall mean risk level for all locations. Outliers should be treated as recommended in Sub-section 4.9.3.1.

The next step consists of identifying components and locations that should be included in the inspection programme based on the applied risk criteria. The decision criteria may be based on relative risk or on absolute risk levels. Generally, more inspections are performed for high risk components than for those associated with lower risk. For identification based on relative risk, a risk level can be defined relative to the highest risk (excluding any outliers) in order to capture significant locations. Locations falling above this risk level are considered as potentially safety-significant. No specific relative risk level is given here since different factors may need to be considered for different utilities and different regulatory bodies.

Among such factors are for example the risk distribution of the plant, the definition of risk outliers, the nature of risk associated with each location, the ambition the utility has with its RI-ISI programme and national regulatory requirements. Further, the total change in risk on a system level is often evaluated and risk neutrality may be required, and this may result in correction of the risk level separating potentially safety-significant locations.

When identifying locations to include in the inspection programme, it must be borne in mind that ISI leads to radiation exposure to the inspection personnel. Each combination of ISI programme is associated with a certain radiation exposure. In principle, it is possible to develop ISI programmes with the same risk reduction but with different total radiation exposure. When faced with such choice, the RI-ISI programme that gives as little radiation exposure as possible should be chosen, according to the As-Low-As-Reasonably-Practical (ALARP) principle.

If the RI-ISI analysis is done at segment level, the evaluation of safety significance is done first at segment level. In this case, the POF and probability of consequence are evaluated for a representative worst element within the segment. The risk associated with such elements also approximates the risk of the other elements within the segment.

Locations characterized by High Consequence and Low Probability generally need special consideration due to uncertainties, as discussed further in 4.9.3.3.

Having identified the potentially safety-significant locations for a RI-ISI programme, it is recommended that an expert panel is used to review the proposed selection of locations. This panel should review the information, analysis and insights that have been used to identify the safety-significant locations.

It is also important to investigate alternative, or complementing, possibilities for mitigation against the risk, based on the nature of the damage mechanism and risk associated with each location. It may be possible to identify ways other than inspection to address the risk level. This may be especially true for High Consequence – Low POF locations.

4.9.3.1 Risk Outliers

A risk outlier is a location with an associated risk level much higher than the overall risk level for most of the locations. Risk outliers, the few locations dominating the overall risk, should be treated carefully to avoid giving a skewed view of the risk distribution.

The occurrence of risk outliers should be seen as locations requiring special treatment and the locations have to be separated from the rest of the locations when using relative risk criteria. Inspection alone may not be considered sufficient to address the risk from these high risk locations, and consideration should be given to other complementary methods such as redesign, continuous monitoring, new or improved operator actions (e.g. detection/isolation of the break), improved leak rate detection, load reduction or component replacement or re-location. Reducing risk outliers can result in a more uniform risk distribution and help assure redundancy and DiD.

4.9.3.2 Flat Risk Distribution

There are situations where the method of identifying a specific risk band to determine which locations are safety-significant is not applicable. One such situation would occur when using a criterion based on relative risk and the risk distribution across the plant is very flat. In this case the Pareto diagram, see Sub-section 4.9.1, would show a flat distribution across all the locations. The risk plot would show that most of the locations having the highest risk fall in the same narrow risk band. Relative risk may then no longer result in a clear differentiation between locations for inspection. One possible option could be to weight the selected locations for inspection with focus towards higher consequence, with possibly some random inspections.

4.9.3.3 High Consequence – Low Probability of Failure Locations

It is recognised that locations characterised by high consequence and low POF can be of concern for reasons of uncertainties, even if the risk at the location is moderate in absolute or relative terms. Such locations would fall in the lower right hand corner of a risk plot, see Figure 4. The plot is purely illustrative and the way the regions are represented should in no way be taken as a requirement. Note that these locations are not identified by the Pareto plot or the RRW measure.

Hazards in this area of the risk matrix naturally involve large uncertainties in both the estimated consequence and the estimated POF. For these reasons, it is suggested to apply a suitable lower risk level for identification of safety-significant locations, see Figure 4. It is recognised that confidence can be a challenge when the component's POF is well below the level for which there is practical experience. Inspection of locations in this area of the risk plot provides additional confidence in the estimated POF. Inspection is also valuable to address unexpected (or unknown) degradation mechanisms that could challenge the integrity of the component. This provides an element of conceptual DiD. For items in this area of the risk matrix it is recommended to complement ISI with other preventive measures with the purpose to reduce the risk, for example monitoring of temperatures, corrosive environment and strains, local leak detection and also research and laboratory work to quantify potential degradation mechanisms.

Very low POF implies that there is no experience of damages and failure over the lifetime of the component. The setting of inspection qualification goals is therefore not a straightforward matter. The approach may vary, depending upon circumstances and regulatory requirements, but generally it is sensible to postulate the least unlikely mechanism.

4.9.3.4 High Probability of Failure – Low Consequence Locations

Despite their low consequence (low CCDP), components falling in the upper left corner of the risk plot in Figure 4 are risk-significant due to their high POF. However, in these cases inspections may also be justified in order to maintain plant availability or to improve workers' safety. Since the POF is high, inspection may be even more important for these reasons than for nuclear safety. In order to evaluate this, additional consequence assessments are needed for these locations, with respect to other consequence measures such as workers' safety and availability (production losses), in addition to CCDP. Inspection related costs can be compared to the financial benefit obtained from improved plant reliability due to risk reduction from ISI. This may result in more items included from this region of the risk plot, see illustration in Figure 4.

For these locations, specification of a defect type and size for ISI and qualification can be made to a clearly identifiable damage mechanism.

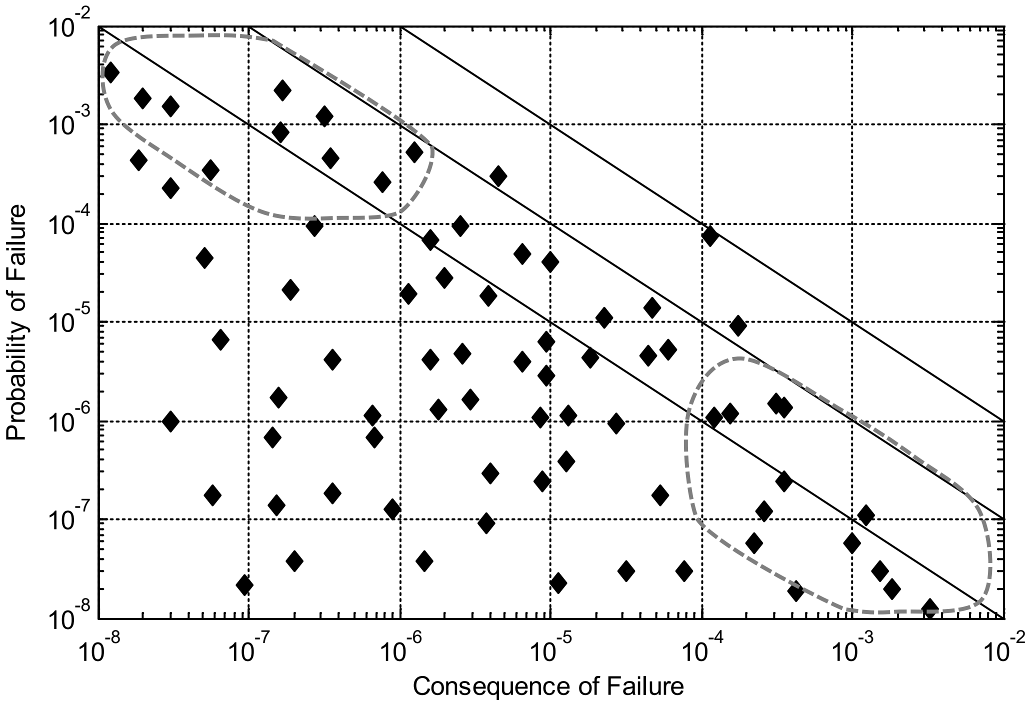

Figure 4: Risk plot illustrating two regions that can require separate considerations; the region of high consequence - low probability objects, and the region of high probability - low consequence objects.

4.9.4 Leak Detection

Degradation mechanisms can result in leakages of different sizes, and in many cases leakages gradually increase with time. Smaller leakages are easier to manage, and consequence analysis by PSA models shows that different leak sizes correspond to large differences in CCDP. Thus, early detection of leakage is valuable. The consequence level may be estimated for two or three leak sizes scenarios. In the risk assessment, the probabilities of failure resulting in small leakage or large leakage are then combined with the different consequence levels.

Extensive experience accumulated over years of operation has shown that failure in very few cases occur catastrophically (guillotine break), but rather in the form of a smaller leak for most degradation mechanisms. This is because if a crack grows to a through-wall configuration, then it is likely that the leakage is detected by the plant leak monitoring systems, operator walk-downs or ISI, before the crack grows to a size that would result in total rupture and large leakage. On the other hand, for the degradation mechanism flow-accelerated corrosion (FAC), no small leakages are expected.

In some plants leak detection functions are part of the reactor protection system, as they automatically initiate the plant safety function if the leak rate exceeds a specified value. Furthermore, operating procedures give the operators guidance on how to act when leakage increases above certain rates.

For cases when leak-before-break is likely for the specific degradation mechanism and loads, the probability of large leak (or rupture) is affected by the capability to detect small leakage, before developing to a large leak. The leak detection capability will influence the scenario at leakage and consequently will influence the estimated POF and the resulting consequences.

RI-ISI analyses can include the effects of leak-detection, both for scenarios resulting in actuation of automatic safety functions and of manual actions. The reliability of leak detection and related actions could be quantified in the consequence evaluation and the leak size in the POF evaluation, and then combined in a proper way. Alternatively the leak detection may be included as a model within the SRM applied for evaluation of the failure probability. The RI-ISI documentation should describe how the effect of leak detection is modelled.

Within the RI-ISI framework, some studies [7] [24] have shown that neglecting leak rate detection in the assessment of POF may cause a distorted view of the risk situation and result in unjustified focus on low-risk components for inspection selection. Since the rupture and large leak probabilities will approach the small leak probabilities, it will be more difficult to identify the highest risk locations.

When crediting leak detection, care should be taken to ensure that realistic data is used, and not conservative or non-conservative assumptions. Leak rate detection credited when evaluating the POF has to be commensurate with the leak detection capabilities and operating procedures for the plant. Adequate models of crack opening areas, leak flow rates and leak flow rate detection should be used. The reliability of the leak detection capability should be assessed and documented, and its impact on the results should be documented as well.

Experience has shown that crediting leak detection may result in RI-ISI programmes with much less inspection required for piping located inside containment. This increases the requirement on qualifying and maintaining a high leak detection capability. Leak detection with the purpose to early reveal degradation can contribute to large risk reductions, especially when also accounting the large difference in COF for small versus large leakage. Sensitive leak detection systems may be installed locally at certain components, for example based on moisture and temperature measurements.

In areas without leak detection systems, leaks may be detected by walk-around or by means of other alarms. In the analysis of failure probabilities, the probability of leak detection may be estimated also for elements or segments at such locations. It is however recognised that a reliable and consistent assessment of leak detection from walk-arounds is a difficult task that carries large uncertainties.

When estimating the POF, it is recommended to perform sensitivity analysis to investigate the effect of both crediting and not crediting leak detection, and for different detection capabilities.

4.10 Selection of items for the RI-ISI Programme

The first step to define a RI-ISI programme consists of identifying the possible existence of risk outliers, as described in section 4.9.3.1. The next step is to identify the items and positions that are significant to the risk level. The risk criteria may be based on absolute risk levels or on relative risk. It was recognised in section 4.4 that it is challenging to demonstrate that the assessed levels of risk are true in absolute terms. For this reason, it can be beneficial to use an approach based on relative risk ranking, as described in section 4.9.3.

After having identified items and positions with significant risk contribution, additional considerations may be necessary, especially for positions that have moderate risk levels. Other considerations beyond safety-risk include radiation dose, alternative locations with better accessibility, and the inspection costs. The scope of the RI-ISI programme may also need to be complemented with locations requiring inspection in order to meet other legal requirements, for instance in relation to the safety protection of workers.

For the planning of ISI and complementing actions, the equipment may be evaluated according to characteristics of the risk. Locations that have a low POF but high consequence should be considered as discussed in Sub-section 4.9.3.3. This area of the risk plot involves higher uncertainties and a lower risk criterion may be applied for identification, since inspections are important for the continuous assurance that the assumptions of the analysis remain valid. Locations with low consequence but high POF may need additional assessment of other than nuclear safety-related consequences, as discussed in Sub-section 4.9.3.4.

When moving to a RI-ISI programme it is sometimes required that at least risk neutrality should be achieved. After having established an initial selection of locations, the risk associated with the selected elements should be compared with the risk associated with the current ISI programme. The total risk level should be equal or lower than the level by the current ISI programme. This may imply iterative adjustment of the risk criteria applied for separating risk-significant locations.

The risk reduction achieved by ISI and other measures is not only dependent on the initial risk level, but also on the rate of degradation, the tolerance to defects, and the capability and frequency of inspections. The issue of risk reduction is discussed in more detail in the next section.

4.11 Risk Reduction through ISI

Risk reduction through implementation of RI-ISI is achieved through several means. Examples include increasing the number of inspections at identified high risk locations, tailoring the inspection techniques to the degradation mechanism predicted (i.e. inspection for cause), altering the inspection interval in relation to potential rate of degradation and tolerance to damage, identifying the appropriate examination volume and improvements to the reliability of the NDT method.

To gain confidence that the proposed new ISI programme is at least as effective as the current ISI programme in reducing risk, it is recommended that the two programmes are compared, considering the inputs to the POF estimates, the inspection intervals, and inspection capability. References [24]-[27] provide additional information on the assessment of the change in risk. This process is also called a delta risk assessment.

In addition to risk neutrality, sometimes acceptable risk reduction is also evaluated using the ALARP principle. This involves weighing the risk cost against the cost needed to prevent and control it, in order to judge whether it would be disproportionately expensive to implement measures for further risk reduction, compared to the benefits of risk reduction that would be achieved.

The sensitivity of the risk change to the inputs should also be investigated. This could include sensitivity to assumed degradation rates, loads and damage tolerance, inspection intervals, and inspection capability. These analyses could be used the other way around, to identify the level of inspection interval and capability required for achieving sufficient risk reduction

As discussed previously, performance of ISI will not change the COF. Consequently, the assessment of risk reduction from ISI is linked to the estimated POF with its influencing parameters for degradation, defect tolerance and inspection efficiency. For an active degradation mechanism ISI can confirm the rate of degradation, which may have been assessed based on a general corrosion rate. A potential degradation mechanism may initiate after long operational time due to susceptibility to variations in the operating environment, or may evolve very nonlinearly by time. ISI will decrease the uncertainty about the status of the equipment and therefore the assessed POF could decrease after an inspection.

The effect from ISI is dependent on the detection capability of the applied inspection system, the coverage, and the selected time interval between inspections. The degree of risk reduction achieved by the ISI will furthermore depend on the dynamics of the potential degradation and the tolerance to defects under possible upset loads for the actual item.

4.11.1 Inspection Interval and Inspection Method

Inspection intervals are determined with the purpose to ensure that degradation is detected at an early stage before it results in leakage or failure. After locations for inspection have been identified and selected based on risk, the inspection interval and the NDT system to apply should be determined for each location or group of items.

Inspection techniques need to be selected carefully to ensure effective detection of the predicted types of (active or potential) degradation. The inspection technique has to be suitable for the targeted degradation mechanism with respect to type of defect, characteristics of the defect, and coverage of local regions that have been identified to potentially be degraded.

ISI intervals may be based on general prescriptive rules, which are based on historical operating experience and judgments for different equipment and operating conditions. These types of rules have to be conservative since they need to cover the full range of situations. Improved adaptation of intervals may be established by further analysis.

An established approach to determine inspection intervals is based on deterministic damage tolerance analysis, see e.g. ASME XI [28], R6 [29], BS7910 [30] and SSM 2018:18 [31]. The advantage of this approach is that the method will consider information available for degradation growth, the actual damage tolerance of the component, and will consider the detection capability (qualification defect size) of the inspection system used. In this case established deterministic safety margins will influence the interval. The damage tolerance analysis will consider the plant specific conditions for geometry, loads, residual stresses, environment and materials, for the actual item or group, together with the capability for applied NDT systems.

Inspection intervals can also be evaluated by use of probabilistic principles and validated SRM approaches including data and models for POD. In this case the established risk criteria will influence the interval. Development is ongoing in this area and attention to uncertainties in models and criteria is important. For the decision on ISI intervals, results from probabilistic analyses may be combined with results from deterministic analyses. For example, the probabilistic results may support adjustment factors for the deterministic intervals.

It is recommended to assess and quantify the change in risk by the proposed new ISI programme, considering the influence from different inspection intervals and NDT capability.

4.11.2 Inspection Qualification

ENIQ has established a methodology for inspection qualification [2] and it is recommended that this approach is adopted.

An essential input to the ENIQ qualification process is the identification of appropriate inspection qualification requirements defining the defects of concern for which the capability of detection and sizing is to be demonstrated. The ENIQ qualification process, if followed to a successful outcome, provides high confidence that the inspection system can achieve the inspection qualification requirements for defect detection and sizing. An important point to note is that the process does not provide a quantitative measure of inspection efficiency, but the output statement from the process is expressed in linguistic terms such as ‘highly reliable’ or ‘highly efficient’. However, subsequently developed documents [32], [33] have described methodology to extract POD data from qualification efforts.

If a validated SRM can be used, the target qualification defect size may be determined so that the proposed inspection programme aims at reducing the POF of the inspected items by a certain degree (see [34]). Simplified but realistic quantitative estimates of POD curves could facilitate this. Consideration could also be given to assess the efficiency in striving for smaller qualification size with the aim to reduce risk even further but without incurring high costs. The effect on risk reduction can be evaluated for a considered group of components (typical geometries and operating conditions) to determine if a smaller detection target will have a significant effect.

4.11.3 Complementing and Alternative Measures for Risk Reduction

In order to efficiently reduce the risk from degradation in a system, it is important to apply measures that complement ISI. Some measures are needed to monitor changes in the operating parameters and ensure that important assumptions behind the decisions for the ISI programme are valid. Other measures may be needed to cover cases when ISI by NDT is ineffective or impossible. The risk reduction achieved by complementing and alternative measures to ISI is dependent on the nature of the degradation and damage mechanism, the uncertainties in rate of degradation, loads and other main influencing parameters.

Examples of measures that complement ISI or may be possible alternatives include:

- Regular sampling and/or monitoring of operational environment. This is an essential basis for the degradation assessments when developing the RI-ISI;
- Water chemistry monitoring, action levels on water chemistry data with respect to different degradation mechanisms, filtering to remove impurities, water treatment;
- Local leak monitoring (by moisture, temperature, etc.);
- Local load and temperature monitoring, for estimation of fatigue damage (e.g. vibration, or leak at standby valve), or effect from occasional loads (e.g. steam collapse);
- Experimental work to quantify and confirm degradation rates;
- Experimental and numerical work to confirm and quantify residual stress fields, which can have profound effect on SCC;
- Review and functional testing of safeguards that limit loads and temperature, as safety relief valves and snubbers. Limited pressure is an essential assumption when developing the RI-ISI;
- Material sampling or replica tests to confirm or follow damage or micro structural changes;
- R&D to identify degradation mechanisms;
- Operator instructions and training to prevent or reduce the severity of upset events;
- Surface coatings and linings, improved paint systems and isolation systems, surface treatment for residual stress improvement;
- Review of design and material selection at repairs, modifications, and new-build;
- PSI to establish a fingerprint for future NDT;
- New or revised operating procedures to increase the likelihood of isolating a postulated break;
- Plant modifications to reduce the consequence of a pipe break (e.g. flow restricting orifice or pipe whip restraints).

4.12 Regular Updating for a Living RI-ISI Programme

The risk assessment provides the risk distribution at a given point in time. It is recommended that the risk assessment is updated regularly so that it reflects as accurately as possible, the distribution of risk for the evaluated systems at the time of the ISI. To ensure that this is the case, consideration of all currently available plant knowledge has to be carried out on a regular basis. An effective risk-informed inspection strategy also requires the development of a feedback procedure for updating the risk ranking based on inspection results, new knowledge or after any plant changes affecting the probabilities of failure or consequences of failure.

The RI-ISI programme should be re-evaluated as new information affecting the programme becomes available, such as system or component design change, plant operating condition changes, plant PSA changes, industry-wide failure notifications, etc.

The information gathered after inspections have been completed is also very relevant as it increases the knowledge of the plant condition, even if no acting damage mechanism is found. This information may influence the assessment of the POF as more data is known (i.e. less uncertainty), concerning the presence or absence of a degradation mechanism.

This living process with recurrent updating is one of the strengths of the risk-informed approach, as it leads to a process that is responsive to operating experiences and emerging problems.

If evidence of damage is found by inspection it is assumed that actions are taken to reduce the risk. These actions include component replacement, repair, or fitness-for-purpose assessments. Fitness-for-purpose assessment may justify continued operation coupled with prescriptive follow-up inspections (or monitoring) of the affected locations. An assessment should also be carried out to determine the root cause for the damage and whether the defect is due to particular conditions at the detected location or if the conditions can occur more widespread in the plant. In the latter case, additional examinations should be carried out to determine the possible extent of the condition.

Validation of the assessment methodology is important and the question must be posed as to whether the occurrence of the degradation was in line with the prediction when the risk was assessed prior to inspection. If the answer to this question is negative, then the models and assessments that were used to evaluate the POF need to be reassessed.

Even if no evidence of defects is found after the performance of a certain number of inspections, it is still very important to consider the meaning of these results. One critical issue is the capability of the applied inspection technique (see Sub-section 4.11.2 for a discussion on inspection qualification). Another issue could be conservative assumptions and data used in the evaluation of failure probability (e.g. for DiD purposes). However, it is emphasised that for components with low failure probability, it is expected and useful that the inspections essentially results in no findings, since this confirms the condition of no active degradation mechanism.

Plant changes and updates to the PSA models may affect the estimated COF. For update of the COF, some guidance regarding living PSA can be found in [35], [36]. For an example of guidance on living programme concerning RI-ISI see [37].

4.13 RI-ISI for Long Term Operation

Plants entering Long Term Operation (LTO), beyond the initial plant design life, should re-evaluate their RI-ISI programme to incorporate any new considerations that may be relevant due to the extended operation. Examples include additional fatigue cycles, environmental effects on fatigue life, thermal aging and embrittlement.

Re-assessments should be performed for mechanisms such as SCC and FAC to consider actual conditions and any new knowledge, e.g. loads due to power uprates, new knowledge about loads or residual stresses, new information on susceptibility and degradation rates, or improved NDT capabilities. Existing work processes for the continuous management of ageing and degradation will proceed during LTO, but increasing severities can be expected at long operational times. Thus, there is an increasing need for efficient processes for developing well adapted ISI programmes, and RI-ISI can be very useful.

Generally, application of risk principles may help achieving balanced efforts in a LTO work process by ensuring allocation of resources in proportion to safety-importance. ISI and other preventive actions are increasingly important and should be balanced in relation to equipment risk level and uncertainties, in order to focus on items, degradation mechanisms and hazards that can have real effect on safety and reliability.

5. Organisation and Responsibilities

5.1 Introduction

The overall responsibility for the RI-IS programme lies with the plant operator (licensee).

In this section the roles, responsibilities and interfaces of the different parties involved in the creation of a RI-ISI programme are described.

It is recognised that utilities in different countries have different structures that vary in detail. Hence, what follows is a suggested management structure and interfaces that can be used as a guide for a typical organisation in order to implement a RI-ISI programme.

5.2 Outline of Management Structure

The main parties and personnel involved are as follows:

1. RI-ISI Responsible Person;
2. RI-ISI Advisory Panel;
3. RI-ISI Team;
4. RI-ISI Review Panel;
5. Inspection Qualification Team.

An example of a reporting chain of the responsible parties/personnel is shown in Figure 5.

RI-ISI Process

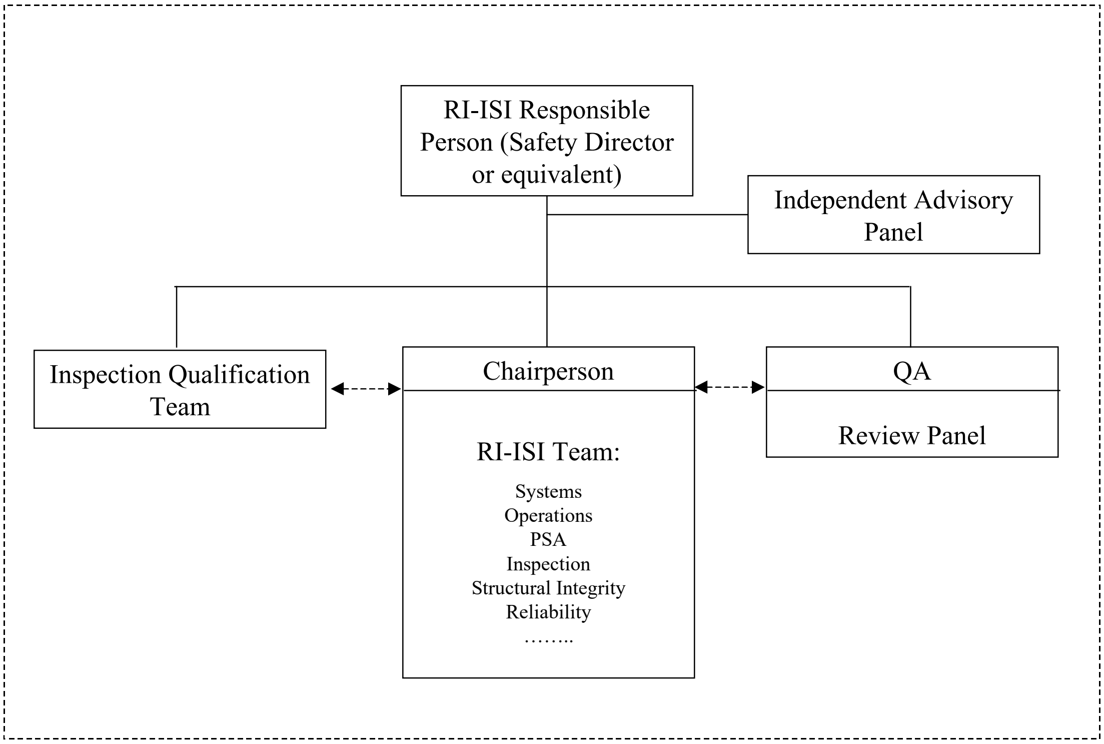

Figure 5: Reporting Chain Identifying the Main Responsibilities in a RI-ISI Process.

5.3 Definition of Responsibilities

5.3.1 The RI-ISI Responsible Person

The RI-ISI Responsible Person is responsible for setting the boundary and scope of the RI-ISI programme. The person is ultimately responsible for the acceptance of the final RI-ISI programme, and for these reasons the Responsible Person should be a senior employee of the utility. Another way to address the setting for boundary and scope is that a proposal developed by the RI-ISI team is presented for an Expert Panel who will approve the final scope.

The Responsible Person will ensure that sufficient resources are made available for the full RI-ISI process, all the way to the final Inspection Qualification and data archiving of the proposed inspections. The Responsible Person will form the RI-ISI team and appoint its chairperson. It will then be the RI-ISI team responsibility to recommend a RI-ISI programme to the Responsible Person. In order to assist the Responsible Person in accepting the proposed RI-ISI programme, he or she may wish to form a RI-ISI Advisory Panel, appointing senior advisors.

5.3.2 The RI-ISI Independent Advisory Panel

The responsibility of the Advisory Panel is to counsel the Responsible Person with regard to any areas of the proposed RI-ISI programme that in its opinion are questionable, be it from the analytical modelling used, possible omissions, external considerations, etc.

The Advisory Panel should not have the power to change the risk rankings or, more specifically, change how the probabilities or consequences of failure and hence the risk are derived. It may recommend changes, verification of the work carried out, etc.

The panel should raise any questions or concerns associated with ISI that may not be directly described in terms of the parameters used to measure the failure or consequence aspects in the risk-informed methodology adopted. This may include any political or public concerns that cannot be uniquely described in terms of the consequence.

The RI-ISI Advisory Panel should be independent from commercial or operational considerations. Representatives from the regulator could attend meetings of the panel as observers.

5.3.3 The RI-ISI Team

The RI-ISI team will need to be a multi-disciplinary team, with expertise including inspection, design, materials, chemistry, stress analysis, systems, PSA, operations, maintenance, quality and safety.

The RI-ISI team has the responsibility of developing the RI-ISI programme and following it through to its implementation. It is responsible for co-ordinating the required effort within the utility, to produce the necessary documentation, compile the RI-ISI dossier and ensure that the relevant QA procedures are followed and records kept.

It is the responsibility of this team, via the authority of the RI-ISI Responsible Person, to demand that the relevant departments within the utility provide the necessary support to generate a RI-ISI programme. This support will be required to produce a ranking of the probabilities of failure and the consequences for all the probable inspection locations within the defined ISI boundary. The team will be responsible for setting up expert elicitation exercises when required and ensuring an adequate interchange between the various experts required for a RI-ISI programme.

The RI-ISI Team will present for review its POF and COF rankings to the RI-ISI Review Panel. It also has ultimate responsibility for the finalisation of the rankings of POF and COF, and for integrating such rankings in order to construct a risk plot for all the locations within the scope of the exercise.

The RI-ISI team will establish risk acceptance criteria, and ensure acceptance from the Regulatory Body.

The RI-ISI team will outline an inspection programme based on estimated risk levels, risk acceptance criteria and taking into due account:

1. Risk outliers;
2. High consequence-low probability locations;
3. Uncertainties associated with the models, etc.;
4. DiD considerations.

In doing so, the team will also interface with the Inspection Qualification team to assess that the proposed inspection locations are both practical in the sense of carrying out the inspection and that there is a realistic chance of providing an inspection qualified according to the European methodology for qualification of NDT.

The RI-ISI team will present the RI-ISI programme for approval to the Responsible Person.

5.3.4 The RI-ISI Review Panel

The purpose of the Review Panel is to provide an essential independent element in the QA process.

The Review Panel should contain experts in the relevant areas that are independent from those belonging to the RI-ISI team. Such experts could be from either inside or outside the utility. Their independence must be ensured in the sense that they should not have been at any stage involved in the generation of the basic POF and COF data to be assessed.

The critical task of the Review Panel is to review the work carried out by the utility (RI-ISI team) in deriving the estimates of POF and COF.

As a part of the RI-ISI process, the RI-ISI team should provide the Review Panel with draft POF and COF rankings, plus details regarding the assumptions made and the calculations carried out. The members of the Review Panel should be in dialogue with the RI-ISI Team to agree a final risk ranking. The RI-ISI team will ultimately be responsible for the finalisation of the estimated probabilities of failure and consequences of failure.

The Review Panel should use all the pertinent probabilistic and deterministic data provided by the RI-ISI team plus any world data available, together with their own expertise and experience.

5.3.5 The Inspection Qualification Team

The Inspection Qualification team has the responsibility of advising the RI-ISI team with regard to the feasibility of achieving the specified NDT capability for a proposed ISI programme. It should be clearly understood that the Inspection Qualification team cannot, at this time, guarantee that any subsequent inspection qualification against the specified requirements will be successful.

5.3.6 The Regulatory Body

The Regulatory Body is assigned the task of monitoring and evaluating safety and of ensuring that the licensee fulfils the conditions of its location licenses.

In the context of a safety-driven RI-ISI programme, the Regulatory Body either defines or reviews the basic safety requirements that must be met.

The Regulatory Body also undertakes audits, periodic reviews and monitors the licensee's compliance with the safety requirements. To these ends the Regulatory Body may wish to observe the development of any safety-driven RI-ISI programme. For instance, the Regulatory Body may wish to participate with the status of observer in the RI-ISI Advisory Body meetings.

While the relationship between each plant operator and its regulator may be country specific, the experience with several European RI-ISI applications has shown that having early engagement with the regulatory body is very beneficial.

6. Documentation and Archiving

6.1 RI-ISI Programme Dossier

The RI-ISI team will prepare the RI-ISI dossier which should contain all information related to the whole process of risk-informed inspection planning and should comprise at least the following:

1. Nomination of the personnel involved in the process;
2. Scope of the RI-ISI programme;
3. Input data:
    a) All data used in calculations (design specifications, historical plant data, etc.);
    b) Assumptions made;
    c) Models used;
    d) PSA data;
    e) Risk criteria used;
4. Output data:
    a) Records of meetings of panels, etc.;
    b) List of locations to be inspected;
    c) Requirements for inspection qualification (including qualification level);
    d) Subsequent analysis;
    e) Further action required;
    f) Risk change for locations inspected.

If parts of this information cannot be included, precise references should be made in the RI-ISI dossier.

6.2 Obsolescence of Storage Medium

Problems associated with the future obsolescence of the medium used for storing the RI-ISI dossier information should be properly addressed.

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List of abbreviations

ALARP	As-Low-As-Reasonably-Practicable
ASME	American Society of Mechanical Engineers
CANDU	Canadian Deuterium Uranium
CCDF	Conditional Core Damage Frequency
CCDP	Conditional Core Damage Probability
CCF	Common Cause Failures
CDF	Core Damage Frequency
CLERF	Conditional Large Early Release Frequency
CLERP	Conditional Large Early Release Probability
COF	Consequence of Failure
DiD	Defence-in-Depth
ENIQ	European Network for Inspection and Qualification
EPRI	Electric Power Research Institute
FAC	Flow-Accelerated Corrosion
FMEA	Failure Modes and Effects Analysis
IAEA	International Atomic Energy Agency
ISI	In-Service Inspection
LERF	Large Early Release Frequency
LOCA	Loss-of-Coolant Accident
LTO	Long Tem Operation
NDT	Non-Destructive Testing
NPP	Nuclear Power Plant
PSI	Pre-Service Inspection
POD	Probability of Detection
POF	Probability of Failure
PSA	Probabilistic Safety Assessment
QA	Quality Assurance
RBMK	Reactor Bolshoy Moshchnosty Kanalny (Russian designed high-power channel reactor)
RI-ISI	Risk-Informed In-Service Inspection
RPV	Reactor Pressure Vessel
RRW	Risk Reduction Worth
SCC	Stress Corrosion Cracking
SSC	Systems, Structures, and Components
SRM	Structural Reliability Model
WENRA	Western European Nuclear Regulators' Association

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ABOUT NUGENIA AND ENIQ

NUGENIA is an international non-profit association under Belgian law established in 2011. Dedicated to the research and development of nuclear fission technologies, with a focus on Generation II & III nuclear plants, it provides scientific and technical basis to the community by initiating and supporting international R&D projects and programmes. The Association gathers member organisations from industry, research, safety organisations and academia.

The activities of NUGENIA cover plant safety & risk assessment, severe accidents, reactor operation, integrity assessment and ageing of systems, structures & components, development of fuel, waste & spent fuel management & reactor decommissioning, innovative light water reactor design & technologies, harmonisation and in-service inspection & their qualification.

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 for nuclear power plants. Since its establishment in 1992 ENIQ has issued over 50 documents. Among them are the "European Methodology for 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 became Technical Area 8 of NUGENIA in 2012.

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