Institute for Energy

# ENIQ TGR DISCUSSION DOCUMENT

# ON THE ROLE OF IN-SERVICE INSPECTION WITHIN THE PHILOSOPHY OF DEFENCE IN DEPTH

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# ENIQ TGR DISCUSSION DOCUMENT ON THE ROLE OF IN-SERVICE INSPECTION WITHIN THE PHILOSOPHY OF DEFENCE IN DEPTH

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The present document "ENIQ TGR Discussion Document on the Role of In-Service Inspection Within the Philosophy of Defence In Depth" (ENIQ Report nr. 29) is a type-2 document.

# FOREWORD

The present work is the outcome of activities undertaken by the ENIQ Task Group Risk (TGR) on Risk-Informed In-service Inspection (RI-ISI).

ENIQ, the European Network for Inspection and Qualification, was set up in 1992 and reflects the importance of the issue of qualification of NDE inspection procedures used in in-service inspection programmes for nuclear power plants. Driven by European Nuclear Utilities and managed by the European Commission Joint Research Centre (JRC) in Petten, the Netherlands, ENIQ was intended to be a network in which the available resources and expertise could be managed at European level. It was also recognised that harmonisation in the field of codes and standards for inspection qualification would represent important advantages for all parties involved, with the ultimate goal of increasing the safety of European nuclear power plants. More information on the ENIQ network and its activities can be found at http://safelife.jrc.nl/eniq/.

ENIQ work is carried out by two sub-groups: the Task Group on Qualification (TGQ) focuses on the qualification of in-service inspection (ISI) systems, while the Task Group on Risk (TGR) focuses on risk-informed in-service inspection (RI-ISI) issues. The TGR has published the European Framework Document for Risk-informed In-service Inspection, and is producing more detailed recommended practices and discussion documents on several specific RI-ISI issues.

This document is intended as a basis for discussion on how to apply defence-in-depth concepts within a Risk-Informed In-Service Inspection (RI-ISI) framework. The report discusses the role of the RI-ISI programme (and connected activities) within the entire reactor safety programme, with a special focus on the defence-in-depth philosophy for reactor safety.

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# 1 INTRODUCTION

In-service inspection (ISI), which consists of non-destructive examination and pressure/leakage testing, is an essential element of the defence-in-depth (DID) concept. ISI helps to confirm that the basic nuclear safety functions are preserved and to reduce the probability of radioactive materials breaching containment. In practice, the main purpose of ISI is to examine the critical components of pressure boundaries (pipes, welds, bends, etc.) in order to confirm that no defects or deficiencies are present or – if they are – to ensure that they are detected as early as possible, before they affect the safe operation of the plant.

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 bring about a continuous improvement in overall plant safety measured by risk, together with reduced doses for the inspection teams.

Risk is defined here in the broad engineering sense as the product of the consequences of a failure and the probability of that failure occurring, as follows:

Risk = Probability of Failure x Consequence of that Failure

In the nuclear industry, quantitative calculations of risks associated with plant operation and maintenance are carried out in probabilistic safety assessments (PSA). Risk is measured in terms of the frequency of occurrence of various events, leading to a consequence of interest (e.g. core damage or release of radioactive material). In the most basic PSAs (level 1) risk measurement is usually expressed as the core damage frequency (CDF). Components that significantly contribute to core damage frequency are thus given priority in a risk-informed inspection programme. If a more detailed PSA study (level 2, for instance) is available, risk measurement can be expressed in terms of large early release frequency (LERF). Similar consideration can thus be given to components whose contribution to LERF is higher but which do not top the list for CDF (usually, a minor group of components).

Developing an RI-ISI programme involves evaluating the first version of a new inspection programme against the defence-in-depth principle. The risk-informed inspection programme generated at the end of the analysis should be evaluated against the DID principle to see if more inspections are needed with a view to creating a more robust inspection programme.

Unfortunately, DID concepts are used incorrectly in many applications, by dint of only looking at the effect on one single barrier. This report discusses how to apply DID concepts by looking at several DID levels. Further, this report looks at the role of the in-service inspection programme (and connected activities) within the entire reactor safety programme, with special focus on the defence-in-depth philosophy for reactor safety. More specifically, the report deals with such issues as:

- the role of ISI within the defence-in-depth concept;
- the tools and the processes used to determine pipe break frequencies;
- a perspective on pipe break frequency's contribution to core damage frequency.

## 2 THE DEFENCE-IN-DEPTH CONCEPT

The concept of defence in depth is fundamental to the safety of nuclear power plants. This section is based on the definitions and strategies described in IAEA's INSAG 10 report [Ref. 1].

Essentially, the concept of defence in depth has led to five successive strategy levels. It uses various tools to maintain the effectiveness of physical barriers placed between radioactive materials and the biosphere.

Defence in depth is defined by two principles: accident prevention and accident mitigation. This high-level definition has traditionally been broken down into five levels. Should one level fail, the subsequent level comes into play. The demands on the subsequent levels must be set independently and without taking any credit for earlier-level actions. The objectives of the levels are described below.

**Table 1 Five levels of defence in depth**

| Level | Objective |
|---|---|
| **1** | Prevention of abnormal operation and failures (conservative, robust design, high-quality performance) |
| **2** | Control of abnormal operation and detection of failures (supervision, surveillance) |
| **3** | Control of accident within the design basis (engineered safety features/systems and accident management) |
| **4** | Control of severe plant conditions, prevention of accident progression and mitigation of the consequences of severe accidents |
| **5** | Mitigation of radiological consequences of significant releases of radioactive materials (off-site emergency response) |

In-service inspection and related issues are mainly part of (but not limited to) level 2. This level is preceded by a preventive level (level 1) and followed by a mitigating level (level 3) that comes into play if failure detection fails or is inappropriate.

Plant design (level 1) must be such that ISI can be performed on all-important components. Design, as well as design modifications, should take into account the information obtained from ISI performed in the plant and worldwide. This will make the plant safer and reduce the need for ISI in the first place.

At level 3, the design of engineered safety features (safety systems) is based on the assumed failure of the design level (level 1) and maintenance activities such as supervision, surveillance or inspections (level 2). Experience from ISI worldwide could affect level 3 by demanding a scaled-up or scaled-down safety system design.

Thus there is a feedback loop from ISI to design state and demands on safety systems, which is part of the overall safety aspects with a long-term safety impact. Without ISI the feedback loop would be much slower, and the experience would consist of leaks and breaks instead of early indications of cracks and wall thinning.

The ISI programme should be developed to protect against failure at the design state. Deficiencies in the maintenance programme (including the ISI programme) failing to detect failures should be covered by the of safety system functions (defence-in-depth level 3).

Defence–in-depth levels are discussed in more detail below.

### 2.1 Level 1 Prevention of failures: Design and quality issues

To avoid pipe breaks, the reactor safety programme includes the following actions and design considerations in the defence-in-depth programme:

- Design of pipes and welding procedures with a high quality level. This comprises the choice of material, the choice of welding method and technique and welding qualification, plant design issues in terms of minimising loads, vibrations etc from normal operation and transient conditions.

- A water chemistry programme that reduces the stresses, corrosion attacks or other challenges on the materials in order to avoid deficiencies or failures to propagate.

### 2.2 Level 2 Detection of failures: In-service inspection issues

To detect deficiencies and to gain further knowledge of failure mechanisms the following actions should be taken:

- Establish an ISI programme to examine the piping and welds, based on knowledge of various parameters like pipe materials, welding techniques, water chemistry, environmental impact, potential failure mechanism, failure propagation etc.

- Evaluate operating experiences (OPE) from other plants with similar design and operating conditions, by transferring knowledge from OPE to the ISI programme and design procedures and demands.

- Ensure that the inspection programme covers the way systems function in normal operation in stand-by mode (safety systems).

### 2.3 Level 3 Control of accidents: Consequence mitigation on leakage

A set of actions and strategies are geared to mitigating the effect of leakages and pipe breaks of all kinds as they occur. The actions must be totally independent of the results or effectiveness of the actions taken at level 1 or level 2 described above. The following steps should be taken:

- Detect leakages from the primary coolant piping. Leak detection system and leak rate measurement facilities are installed (temperatures, pressure, humidity, and level/inventory). When the leak rate exceeds a specific set point the reactor protection system is initiated. Such systems are able and qualified to detect leakage flow rates in the range of 10 kg/s or higher.

- Design Emergency core cooling (ECC) systems that fulfil the demands for LOCA events (10CFR50.46 and appendix K [Ref. 2]). The design capability of the ECC systems is set to cope with a guillotine break of the largest pipe connected to the reactor vessel, applying a set of conservative design requirements. The ECC function includes both high and low pressure safety injection and an automatic depressurisation system.

- The availability of ECC support systems, such as power supply, service water, reactor protection circuits and logics, is kept at a high level by the design quality and the test programme set out in the technical specifications.

- The next activity barrier, the containment, is designed, during the course of an accident, to keep almost all activity within rigorous design limits. Also, severe LOCA events beyond design specifications do not exceed the set limits on radiological releases to the environment (NRC Regulatory Guides 1.3, Ref. 3, and 1.183, Ref. 4). The control room ventilation system is designed to protect operators from critical doses.

### 2.4 Subsequent levels

Under the DID philosophy, it is assumed that measures considered at the first three levels will limit potential hazards for members of the public. Nevertheless, additional efforts are made to further reduce the risk, in a number of ways. The most important objective in terms of mitigating the consequences of an accident is to protect the containment (level 4).

Should even this barrier fail, off-site emergency plans are in place to limit the consequences of severe accidents involving any release of radioactive material to the environment (level 5).

### 2.5 Summary

The aim of this chapter has been to illustrate how the ISI programme fits into the defence-in-depth concept as an important element of the entire philosophy. It can be stated that:

- The ISI programme should be seen as part of an independent line of defence within that concept (level 2). Feedback from ISI experience will affect the other levels.

- Subsequent levels (3-5) are designed to be independent of the effectiveness of level 2.

- Changes in the ISI programme and performance will not have any major impact on the design of other lines of defence. The changes will be based on new knowledge from worldwide and plant experience and ISI.

- Changes in “ISI performance” may, after several years, result in changes in worldwide pipe break frequencies. This will affect design rules and safety philosophy, especially at DID level 3, after several years of consistent change. The ongoing work to redefine LOCA demands is based on this knowledge and will affect the design of many safety systems.

- Overall plant safety and risk depends on the effects of all defence levels. In this context, the ISI programme mostly affects plant safety and risk in cases where there are weaknesses or limitations in the other lines of defence. PSA is an effective means of identifying such areas, as PSA evaluates all systems and their interaction without any reference to deterministic demands or system classification.

# 3 OPTIMISATION OF ISI PROGRAMME

To optimise an ISI programme based on reactor safety aspects, it is important to realise that DID has practical drawbacks at all five levels.

1. The design and materials are not perfect.

2. ISI activities (or other preventive maintenance activities) will possibly miss some flaws.

3. The design and performance of the safety system may fail to deal with some kinds of events.

4. The containment will not withstand every kind of load.

5. The pre-planned mitigation actions, as the emergency operating procedures, will not be perfect.

Optimising an ISI programme will therefore depend on the weaknesses at the different defence–in-depth levels, mainly at levels 1 and 3. If those weaknesses are reduced or eliminated by some other means (such as plant modifications), the content of an optimised ISI programme will be affected. Optimisation of an ISI programme will also have to address the quality of the inspections (e.g. inspection reliability).

PSA studies can be used to pinpoint the weaknesses at the various defence-in-depth levels, and are thus a good way of optimising the ISI programme. The weaknesses are presented in risk terms, and the influence on CDF and/or LERF is an indication of the effectiveness of an ISI programme.

# 4 PSA IMPACT ON IN-SERVICE INSPECTION

A probabilistic safety assessment (PSA) is made for most power plants. PSA determines the risk of core damage (level 1) and radioactive releases to the environment (level 2). A qualified PSA study should be used as the basis for evaluating the consequences of a pipe break. Its scope should include the availability of the following (parts of defence level 3):

- Leak detection systems
- Signals indicating failure detection or exceeded plant parameters
- Reactor protection system
- Emergency core cooling systems
- Power supply systems
- Service water system

The frequency of event occurrence is in part a result of weaknesses at defence level 1. The PSA covers all kind of events, transient and accidents, including pipe leakage or pipe breaks. The total risk of core damage and releases to the environment is evaluated against common goals and acceptance criteria. If the criteria are not met for the most risk-dominant accident sequences, utilities will have to consider countermeasures. Measures designed to reduce the overall risk might consist of changes in the design, changes in routines, procedures, methods or frequencies of supervision or periodic tests.

The level of detail at which pipe break frequencies in PSA studies are modelled varies from user to user. The modelling in most PSAs is based on pipe break frequencies from databases that do not distinguish between different pipe design or pipe environments. Such knowledge is needed to support the development of an RI-ISI programme. The failure rate in PSA studies is the same for all pipes in large groups.

If the risk of core damage and severe accident consequences is, after appropriate improvements at the plant, considered acceptable, further efforts in a specific area will have only a minor safety impact. This includes the consequences of large pipe breaks, where in most licensed plants further efforts to reduce the risks are considered ineffective. In this context, changes in the effectiveness of an ISI programme should be accepted as long as the overall risk stays constant (within the uncertainty boundaries) or is reduced.

If changes in the ISI programme result in lower radiation doses, lower costs and/or constant or reduced risk, such a programme becomes attractive to utilities for reasons other than reactor safety.

Risk reduction can be achieved by an optimised ISI programme, as it reduces the risk of pipe break frequency. Reduced core damage frequency and environmental hazards from pipe breaks will also be achieved by a broad set of alternative actions (plant modifications, operator training and procedures, plant supervision, etc). Such actions will in many cases result in greater risk reduction than an extended ISI programme. If a specific pipe area *(*for instance, a group of welds*)* dominates the risk (risk outliers) the total risk can be reduced by a more effective ISI programme but the preferred method is by modifications in the plant (new pipe design, new safety system design, etc.).

When new failure mechanisms are discovered somewhere in the world and supported by measurements at a plant, the inspection programmes are revised immediately and the total risk of the new failure mechanism is evaluated. In the case of IGSCC and bimetallic welds, the new knowledge has resulted in a re-design of systems. In the case of thermal fatigue in mixing points, it has resulted in new mixers being installed in piping. With those changes, a total new risk profile becomes valid for the plant, and the ISI programme should be revised again.

An extended ISI programme will be effective for such cases if the pipe failure rate is somewhat high and no modifications are planned to reduce the failure rates. The ISI programme will then reduce the pipe break frequency (strengthening DID level 2).

Demands on the design and preoperational controls – defence level 1 – for components within the RCPB are extremely high. Experience has shown this to result in low failure rates. The good experience of defence level 1 affects the demands on the other defence levels, and the PSA will result in minor demands on defence level 2, as the deterministic design has put strong demands on defence levels 3 and 4.

In systems with lower demands on defence level 1 (safety class 3 or less), experience has indicated that an extended ISI programme is more effective in reducing the risk as pipe break frequencies are higher and the deterministic demands on the following defence levels are lower.

The knowledge set out in the two paragraphs above is based on observations from several PSA studies where large LOCAs do not dominate the CDF, not even in the group of failures from leakages and pipe breaks.

# 5 OPERATING EXPERIENCE IN THE FIELD OF ISI

The established ISI methodologies are developed from operating experience and from research programmes on failure mechanisms in different materials and in different welding methods or techniques.

For materials or conditions with known failure mechanisms or problems, an extended ISI programme is easy to justify. For welds in large pipes, the risk of degradation and cracks is considered extremely low, based on available worldwide experience. So, from the point of view of reactor safety alone, it is not fully justified to do frequent inspections of welding in those piping systems. The reactor safety at the plant is guaranteed by other defence-in-depth elements which aim to protect the environment and are considered appropriate on the strength of the deterministic and the probabilistic assessments performed.

However, for such piping systems it is still important to extend our knowledge base on failure mechanisms and degradations, derived from operating experience programmes. Such programmes should, as a first priority, acquire worldwide experience, especially from twin plants or similar plant. The existing networks for sharing operating experiences (WANO, NEA) can be complemented by separate co-operational programmes with plants that might be subject to the same (or similar) conditions. They can also be complemented by experience from research programmes. This should provide a basis for improving an operator's own ISI programme. In the past, this has proved to be an effective way of gaining new insights in previously unknown failure mechanisms.

# 6 CONCLUSIONS

The above overview of the defence-in-depth strategy is aimed at putting the in-service inspection programme into the perspective of the entire nuclear safety concept. It also gives insights on how the defence-in-depth concept should be applied in developing ISI programmes. The ISI programme is part of the total defence in depth for the plant, with the aim of avoiding pipe breaks or leakages from the reactor coolant pressure boundary (RCPB) and, ultimately, avoiding radiological impact on the environment and the public. In more specific terms, we could say that:

- The in-service inspection programme is one of five subsequent levels of preventing or mitigating strategies, and is not the last barrier.
- The reactor coolant pressure boundary is one of four physical barriers for the confinement of radioactive material, and is not the last.
- Weaknesses in the in-service programme are covered by the next barrier.

Each physical barrier against radioactivity release, as well as each specific level in the defence-in-depth programme, is more or less independent of the others. Optimising an ISI programme should focus on the weaknesses in other defence-in-depth levels. The PSA is a suitable way of doing this.

## 6.1 Reactor safety concerns

A specific goal (criterion) must be defined for each level of defence. For the ISI programme (part of level 2), this will in most cases be related to and harmonised with frequencies of pipe breaks (weakness at level 1) and weaknesses at level 3 (function of safety systems) considered in the Final Safety Analysis Report (FSAR) and PSA analyses.

The FSARs and PSAs state that pipe break frequency is in the range $10^{-6}$ (small) to $10^{-3}$ (large) per year. The FSAR and the PSA evaluations are based on these frequencies. A first level of criteria for ISI optimisation should be to ensure that pipe breaks do not exceed these frequencies. Different criteria could be developed for different size of piping.
However, an evaluation which focuses only on failure frequencies will not reveal the strengths and weaknesses at defence levels 3 to 5, and will therefore not produce an optimised ISI programme. An ISI programme with these merits might recommend ISI activities to be focused on piping where the effects of the ISI programme are in fact negligible in terms of changes in the CDF or LERF.

By evaluating the changes in core damage frequencies (level 1 PSA), the effects of DID level 3 will be part of the optimisation. By performing a level 2 PSA, the effects of DID level 4 and, in part, level 5 will be evaluated and become part of the optimisation.

By evaluating the effects of an ISI programme by reference to changes in CDF (level 1 PSA) it will be possible to identify those welds that have the greatest impact on core damage frequencies. Focusing ISI activities on welds with maximum impact on the CDF will increase the safety of the plant.

Trying to achieve a “zero” goal for pipe-break frequency (<< $10^{-10}$) is certainly inefficient in both nuclear safety and economic terms. With DID strategies, leakages and pipe breaks of all sizes can be handled. The PSA evaluations will spell out which initiating events (cracks, etc) have the weakest defence-in-depth chain and where the ISI programme will have maximum effect.

### 6.2 Non-reactor safety concerns

To achieve enhanced reactor safety (i.e. reduce the CDF or LERF), the impact on both failure frequency and failure consequence need to be significant. If one of the factors is more or less insignificant, countermeasures will not impact on reactor safety.

This means that if pipe break frequency is high on components with no impact on the reactor safety, ISI can be justified by reasons other than risk reduction, such as:

- increased availability;
- avoidance of bad publicity;
- lower repair and clean-up costs;
- occupational safety.

On the other hand, if the pipe break frequency is extremely low, extending the ISI programme will not produce any further risk reduction, but can be justified by other means (goodwill, etc.) and will not produce any drawbacks.

### 6.3 General conclusions

Based on the above considerations, the goals of defence-in-depth for the ISI programme should be to:

- ensure the validity of pipe break frequencies in the FSAR studies;

- focus on the risk-dominant piping and welds, by making extensive use of PSA studies;

- optimise the ISI programme, on economic terms and in terms of doses to workers, for welds with high failure probabilities and low core damage frequencies;

- establish an operating experience programme to find new failure mechanisms in piping with extremely low failure frequencies.

## 7 REFERENCES

Ref. 1 IAEA series: INSAG 10 - Defence in depth in Nuclear safety - 26 September 1996.

Ref. 2 US NRC Code of Federal Regulations Section 50.46.

Ref. 3 US NRC Regulatory Guide 1.3 - Assumptions Used for Evaluating the Potential Radiological Consequences of a Loss of Coolant Accident for Boiling Water Reactors. Rev. 2, 1974.

Ref. 4 US NRC Regulatory Guide 1.183 - Alternative Radiological Source Terms for Evaluating Design Basis Accidents at Nuclear Power Reactors, 2000.

## ACRONYMS

| | |
|---|---|
| ALARP: | As Low as Reasonably Practicable |
| CDF: | Core Damage Frequency |
| DID: | Defence in Depth |
| ECC: | Emergency Core Cooling |
| FSAR: | Final Safety Analysis Report (also known as SAR) |
| IAEA: | International Atomic Energy Agency |
| IGSCC: | Intergranular Stress Corrosion Cracking |
| ISI: | In-Service Inspection |
| LERF: | Large Early Release Frequency |
| LOCA: | Loss of Coolant Accident |
| NEA: | Nuclear Energy Agency |
| NRC: | Nuclear Regulatory Commission |
| OPE: | Operating Experience |
| PSA: | Probabilistic Safety Assessment |
| RCPB: | Reactor Coolant Pressure Boundary |
| RI-ISI: | Risk Informed In-Service Inspection |
| WANO: | World Association for Nuclear Operators |

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## Abstract

The present work is the outcome of the activities of the ENIQ Task Group Risk (TGR) on Risk Informed In-service Inspection (RI-ISI). This document is intended to provide as a basis for discussion on how to apply defence in depth concepts within a Risk-Informed In-Service Inspection (RI-ISI) framework. The report discusses the role of the RI-ISI programme (and connected activities) within the entire reactor safety programme, with a special focus on the defence in depth philosophy for reactor safety.

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