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ENIQ TGR DISCUSSION DOCUMENT

ON THE ROLE OF IN-SERVICE INSPECTION OF THE REACTOR PRESSURE VESSEL

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Approved by the ENIQ Task Group on Risk

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This document "ENIQ TGR Discussion Document on the Role of In-Service Inspection of the Reactor Pressure Vessel (RPV)" (ENIQ Report No 35) is a Type 2 document.

FOREWORD

This document is the outcome of one of the activities of ENIQ's Task Group on Risk (TGR) concerning risk-informed in-service inspection (RI-ISI).

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ENIQ's work is done 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 RI-ISI-specific issues.

This document is intended to act as a basis for discussion on how to apply RI-ISI concepts to the Reactor Pressure Vessel (RPV).

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1 BACKGROUND

The ENIQ Framework Document on Risk-Informed In-Service Inspection [1] has been produced to serve as a guideline for both developing own risk-informed in-service inspection (ISI) approaches and using or adapting already established approaches to the European environment, taking into account utility-specific characteristics and national regulatory requirements.

The Framework Document focuses on piping but its application to the Reactor Pressure Vessel (RPV) is not excluded. This report discusses the application of an RI-ISI strategy to the RPV.

2 REACTOR PRESSURE VESSEL

In terms of plant safety, the reactor pressure vessel (RPV) is the most critical pressure boundary component in a Pressurised Water Reactor (PWR) or Boiling Water Reactor (BWR).

The RPV guarantees a safety barrier against fission-product release, supports control rods and vessel internals, provides coolant around the reactor core and directs reactor coolant to the steam generator (PWR) or steam to the turbine (BWR).

The RPV is a 1x100% vessel, i.e. it has no redundancy in order to fulfil its safety functions as a pressure-retaining barrier. This is in contrast to the normal design philosophy of multiple trains (e.g. 4x50%) or diversification to fulfil a specified task. This has influenced design, manufacturing and inspection during manufacturing so that the end product is a robust vessel based on conservative assumptions.

3 RI-ISI OF RPV

In-service inspection (ISI) is an essential element of the defence-in-depth concept, consisting of non-destructive examination as well as pressure and leakage testing [2]. ISI helps to guarantee that the basic nuclear safety functions are preserved and that the probability of radioactive materials breaching the containment is reduced.

Risk-informed in-service inspection (RI-ISI) reflects recent developments in Probabilistic Safety Assessment (PSA) technology, the understanding of degradation mechanisms (e.g. structural reliability modelling, root cause evaluations) and the experience gained from nearly 10000 reactor years of operating experience by NPPs.

RI-ISI is aimed 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 inspection efforts should be concentrated. In other words, the principle underlying RI-ISI is that inspections will be performed where they give the largest safety benefit.

This is, at least in principle, applicable to the RPV as well as to piping. The RPV is a vital component of the risk profile in a nuclear reactor. If it is accepted that ISI should be governed by risk, then the RPV should be included in the RI-ISI programme.

It is worth recalling that in this document risk is defined in the 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}

The consequence of failure is usually measured as Conditional Core Damage Probability (CDDP) as defined by a Level-1 PSA, or as an estimation of off-site fission-product release, such as Conditional Large Early Release Probability (CLERP), if a Level-2 PSA is available.

When applying the equation above to a structural element of the RPV (for instance, a weld), it is typically concluded that:

1. The consequence of a structural failure is very high.
2. The probability of such failure is very low, due to the very stringent design and manufacturing requirements.

The RPV is thus a high-consequence/low-failure probability site, discussed in Section 4.9.4.2 of the ENIQ Framework Document on Risk-Informed In-Service Inspection [1]. The overall risk level is not necessarily the highest that can be derived when all the plant components are considered together, and considerations based on risk alone could logically cause the RPV to be excluded from the ISI programme.

Traditionally, ISI programmes (and more generally, the concept of nuclear safety) have been based on considerations of consequence of failure alone. This has led the RPV to feature very prominently as the very top candidate for inclusion in a traditional ISI programme. Even when RI-ISI programmes have been approved, the RPV has been altogether excluded from its scope, and a special, more “traditional” programme carried out in parallel.

4 SWEDISH EXPERIENCE OF RI-ISI OF RPV

Sweden has had a regulatory requirement to use a risk-informed system for large parts of the RPV since 1995. The requirements were first presented in SKIFS 1994:1 [3] as a request to perform a qualitative risk assessment and to make a relative risk ranking of parts of the RPV. SKIFS 1994:1 was replaced by SKIFS 2000:2 [4] in 2001. The difference between the old and new regulation consisted in the fact that the relative risk ranking was no longer restricted to a qualitative approach. SKIFS 2000:2 was finally replaced by SKIFS 2005:2 [5] but the requirements for ISI are in principle unchanged.

Table 1 summarises which elements of the RPV were excluded from the RI-ISI programme according to the various SKIFS requirements, and were therefore mandatory for inspection.

Table 1 RPV elements excluded from the RI-ISI programme according to various SKIFS requirements

SKIFS 1994:1	SKIFS 2000:2	SKIFS 2005:2
Shell welds	**Shell welds**	**Shell welds**
Nozzle-to-shell welds	**Nozzle-to-shell welds**	**Nozzle-to-shell welds**
Nozzle-to-safe-end welds	**Nozzle-to-safe-end welds**	**Nozzle-to-safe-end welds**
Inner radius area of nozzles		
Safe ends (component)		
Safe-end-to-pipe welds		
		RPV flange/stud/bolt

4.1 Swedish qualitative approach

The entire fleet of light water reactors in Sweden has used a qualitative risk-informed approach to create a relative ranking of RPV structural components. The risk ranking has been based on a risk matrix of inspection groups where A represents high risk, B medium risk and C low risk (Table 2).

Table 2 Risk matrix for ranking of components according to SKIFS methodology

	Consequence index		
Damage index	1	2	3
I	A	A	B
II	A	B	C
III	B	C	C
Inspection Group A = High Risk Inspection Group B = Medium Risk Inspection Group C = Low Risk			

The “consequence index” is based on how severe a rupture or leakage is, considering:

- core damage
- containment penetration
- external release of radioactive material

The “damage index” is based on the probability of degradation of the mechanical equipment. Stress corrosion cracking is the dominant damage mechanism for parts within the scope of RI-ISI. For mandatory components, radiation embrittlement and mechanical fatigue were postulated as active damage mechanisms.

4.2 Conclusion from a Swedish BWR with internal circulation pumps

Experience from applying RI-ISI according to the qualitative requirements of SKIFS 1994:1 [3] is briefly summarised below. By using the risk matrix it was possible to make a ranking within the different inspection groups A to C. The result was that inspection group C (low risk) dominated. This resulted from the fact that the maximum flow from a leakage below the core was < 45 kg/s. Such flow could be controlled by 2 out of 4 high-pressure injection trains, thus giving a consequence index of 3 (low).

Results from RI-ISI of RPV according to SKIFS 1994:1:

- total number of components (welds) ~2 000
- mandatory components ~104 (shell welds, nozzle-to-shell welds, inner radius of nozzles, nozzle-to-safe-end, safe ends, safe-end-to-pipe)
- inspection group A components ~16 (RPV lid attachments)
- inspection group B components ~30 (instrumentation nozzles)
- inspection group C components ~1 900 (instrumentation nozzles, main circulation pump nozzles, nozzles, housing, attachments to RPV)

4.3 Risk reduction due to in-service inspection

Risk reduction is not explicitly mentioned in SKIFS 1994:1. The requirement is that inspection is to be directed against high-risk areas, inspection groups A and B, and that inspection is to be performed with a qualified system. This leads to the conclusion that inspection is to be performed where the benefit in terms of risk reduction is greatest.

5 RISK STUDIES RELATED TO THE MECHANICAL INTEGRITY OF THE RPV

5.1 The BWR Vessel and Internals Project (USA)

The BWR Vessel and Internals Project (BWRVIP-05) made recommendations [6] for alternative inspection requirements for RPV shell welds. The report was issued in 1995.

To accomplish the objectives of the project a number of aspects were addressed.

- A description of previous and current ASME Code and Regulatory ISI requirements:
  - inspect 100% (>90%) of longitudinal seam welds;
  - inspect 100% (>90%) of circumferential seam welds.
- The need for alternative inspection criteria.
- A historical review of the fabrication of reactor pressure vessels, including such topics as welding, repairs and pre-service inspection.
- A general discussion of in-service inspection methods, techniques, limitations and other factors affecting vessel weld inspections.
- Results of a survey conducted on BWR vessel shell weld inspections.
- A discussion of operational loadings and transients.
- A qualitative review of the BWR attributes demonstrating the inherent safety of BWR reactor pressure vessels.
- A discussion of potential degradation mechanisms and their anticipated impact on pressure vessel integrity.
- A discussion of the current inspection criteria and scope.
- A “Monte Carlo” probabilistic analysis which evaluates the effect that reactor shell weld in-service inspection has on establishing vessel integrity.
- Recommendations for new criteria for inspections, scope expansions and re-inspections.
- A cost-benefit evaluation of existing inspection criteria v. the recommended new criteria.

The project proposed the following inspection requirements based on the only damage mechanism considered to have an effect on vessel failure probability (postulated SCC in low-alloy steel in irradiated axial weldment):

- inspect 50% of longitudinal seam welds;
- inspect 0% of circumferential seam welds.

The US Nuclear Regulatory Commission made an extensive review and issued a final safety evaluation report [7]. The review covered several aspects concerning the likelihood and sizes of defects, degradation mechanisms, transients and in-service inspection. In conclusion, the USNRC accepted the following revised inspection requirements:

- inspect 100% of longitudinal seam welds;
- inspect 2-3% of circumferential seam welds (intersections axial — circumferential).

The result of the review was based on the following conclusions:

- There is a difference of three orders of magnitude in failure frequencies between longitudinal ($4.4 \cdot 10^{4}$/year) and circumferential welds ($8.2 \cdot 10^{7}$/year).
- In-service inspection of longitudinal welds is expected to reduce failure probability only by a factor of 2–3, but it can provide important information regarding unanticipated degradation.

- The circumferential weld failure frequencies are below the acceptable core damage frequency (CDF) and large early release frequency (LERF) according to Regulatory Guide 1.174 [8]. In-service inspection is estimated to reduce the probability of failure by a factor of approximately 10, which is considered negligible because of the failure probability being already low without inspection.

5.2 ASME (USA)

ASME published in 1998 an update of risk-based inspection guidelines [9]. Based on probabilistic fracture mechanics calculation, the report concluded that there is a difference in probability of failure by several magnitudes between different weld locations. Postulated damage mechanisms were radiation embrittlement and mechanical fatigue.

The belt region, which is susceptible to radiation embrittlement, is dominant. Mechanical fatigue was assessed to be a damage mechanism of less concern. In-service inspection was estimated to reduce the probability of failure by one to two orders of magnitude.

5.3 RIP-RT (Sweden)

The Swedish utilities are managing a project called RIP-RT [10] with the aim of seeking acceptance by the regulator of a risk-informed selection of RPV parts whose inspection is today mandatory. Up to date (2007), three BWRs have been analysed.

The performed analysis has comprised the following steps:

- fabrication of the vessel
- in-service inspection survey
- assessment of degradation mechanisms
- assessment of consequences of failure
- evaluation of failure probabilities by use of Probabilistic Fracture Mechanics
- risk evaluation
- risk reduction by inspection of the RPV
- other risk-reducing measures for the RPV butt welds
- unknown damage mechanisms or conditions
- conclusion and recommendations

The only known degradation mechanism is embrittlement in the core region, whilst mechanical fatigue and stress corrosion are considered non-relevant. Probability of failure is calculated to be ~1E-3 for longitudinal and circumferential welds in the core region, and <1E-6 for the remaining welds. In-service inspection is expected to reduce the probability of failure by a factor of between 2 and 16.

5.4 Conclusion

The three studies mentioned above came to similar conclusions.

- The only known damage mechanism of interest is embrittlement due to neutron flux in the core region. This is not a new conclusion and programmes exist for surveillance testing of RPV shell material.
- The probability of failure for the different shell welds of a BWR/PWR varies by several orders of magnitude. Welds in the core region have a relatively high probability of failure, compared to other locations where there is no identified damage mechanism.
- ISI has the potential to reduce the probability of failure approximately by a factor of between 2 and 10.

6 RI-ISI AS PART OF THE DEFENCE IN DEPTH FOR THE RPV

The RPV is part of the third barrier (Reactor Coolant Pressure Boundary) and the single most important pressure-retaining part in a light water reactor. As stated above, the RPV has no redundancy in order to fulfil its safety functions as a pressure-retaining barrier.

From a defence-in-depth perspective [2] this has influenced design, manufacturing and inspection during manufacturing so that the end product is a robust vessel based on conservative assumptions (defence in depth level 1).

Further, ISI is an important activity at level 2 of defence in depth. At this level, ISI has two main objectives: (1) to be used in those areas where it can detect active degradation in order to reduce the probability of failure; and (2) to be performed as a way of confirming assumptions made regarding the absence of active damage mechanisms.

6.1 Consequence of an RPV rupture or leakage

A leakage or rupture in the RPV potentially threatens the ability to keep the core cooled. The loss of inventory needs to be replaced by high- and low-pressure coolant make-up systems. The consequence of a rupture of or leakage from the RPV is similar to the corresponding loss of coolant (LOCA) through piping, except for the very unlikely situation where the size of the rupture exceeds the size of the largest piping attached to the RPV.

6.2 Probability of failure

Due to the high quality of design, there are few known damage mechanisms affecting the RPV. The following points can be made to summarise the situation:

- Embrittlement in the core region. This is an important factor to consider, but the phenomenon is typically kept under strict surveillance by means of mechanical testing programmes.
- Integrity analyses (fracture mechanics) of shell welds and nozzle-to-shell welds are often based on mechanical fatigue, the reason being that mechanical fatigue is considered to constitute the most likely (albeit low-probability) damage mechanism.
- Except for postulated mechanical fatigue no other damage mechanism is identified.

This experience is supported by fracture mechanics analyses performed by different organisations. These results conclude that the probability of failure may differ by several orders of magnitude depending on location on the RPV.

Performed studies [6, 11] conclude that transients at low temperature during shutdown, for instance low-temperature overpressure (LTOP), are the dominant failure mode for BWR. The same situation [7] applies for PWR given a pressurised thermal shock (PTS) transient.

6.3 Risk reduction due to in-service inspection (ISI)

Qualified in-service inspection has the capability to reduce the probability of failure with a factor of between 2 and 10 [7, 9, 10, 11, 12]. If ISI is to be performed with the aim of reducing risk, it would be expected that inspection effort would be focused on risk-significant sites where probability of failure is considered to be high. However, defence-in-depth considerations may also lead to inspection of high-consequence/low-probability components such as the RPV, see Section 6.4, below.

6.4 High-consequence/low-probability components

The European Framework Document for Risk-Informed In-Service Inspection [1] acknowledges the special situation of inspection sites with a high consequence and a low probability of failure.

> "These sites are considered not to be safety-significant due to the very small associated probability of failure. However, it is recognised that a problem of confidence can arise if the component's probability of failure is well below the area for which there is any practical experience. Any inspection in this area is intended to provide additional confidence in the assessed probability of failure. In this way the inspection can be considered to cover an unknown or unexpected degradation mechanism that could challenge the integrity of the component and thus provides an element of conceptual defence in depth." [1].

This situation is particularly true for the RPV and must be considered in the chosen inspection strategy.

6.5 Conclusion regarding RI-ISI applicability for the RPV

Based on the discussion above, the following conclusions may be drawn:

- The RPV is part of the third barrier (Reactor Coolant Pressure Boundary) and the single most important pressure-retaining part in a light water reactor. As part of the second defence in depth ISI should be used where it gives as large a benefit as possible to reduce the risk for rupture or leakage.
- RI-ISI as outlined in the ENIQ Framework Document [1] is applicable for planning and performing in-service inspection of the RPV.
- Experience based on known damage mechanisms, on the probability of failure and on the capability of ISI to reduce the probability of failure, clearly indicates that ISI should be aimed at relatively high-risk locations.
- Special consideration should be given to the issue regarding high-consequence/low-probability components. Such consideration is of particular importance in the case of the RPV.

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ACRONYMS

BWR	Boiling Water Reactor
ISI	In-Service Inspection
LERF	Large Early Release Frequency
LOCA	Loss of Coolant Accident
PSA	Probabilistic Safety Assessment
PWR	Pressurised Water Reactor
RI-ISI	Risk-Informed In-Service Inspection
RPV	Reactor Pressure Vessel

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