TOWARDS RISK-INFORMED IN-SERVICE INSPECTION FOR CANDU NUCLEAR POWER PLANTS

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Abstract

Risk-informed in-service inspection (RI-ISI) program has been applied in several countries to enhance the traditional periodic inspection program (PIP). While the Canadian Nuclear Safety Commission is becoming increasingly interested in risk-informed decision making and at the same time small-scale pilot studies on RI-ISI have been initiated by Canadian utilities, a RI-ISI methodology appropriate for the CANDU industry that can be accepted by the stakeholders has yet to be developed. The paper discusses the major steps of RI-ISI, compares the RI-ISI methodologies currently used in international nuclear power industry and reviews the Canada's current periodic inspection standard CSA N285.4-05 from a RI-ISI perspective. The aim of the paper is to identify implications of transitioning from the traditional PIP as defined by CSA N285.4 to RI-ISI and to suggest a path forward for applications of RI-ISI at CANDU stations.

1 INTRODUCTION

The objectives of in-service inspection (ISI) are two-fold: One is to verify that no unexpected degradation mechanism is degrading the systems, structures and components of the nuclear power plant; and the other is to verify that known degradation mechanism do not cause damage or deterioration to a significant extent that damage the plant safety [1]. Traditional ISI programs were established mainly based on deterministic rules using engineering judgment and insights for the nuclear power plant systems. In USA, ASME Boiler and Pressure Vessel Code, Section XI (abbreviated as ASME SC XI hereafter) selects for inspection terminal ends, dissimilar metal welds, and welds with higher stress levels and fatigue usage factors [2]. However, experience has shown that the majority of inspection effort was spent at locations where few flaws were found, while degradation mechanisms not anticipated by the Code, such as intergranular stress corrosion cracking (IGSCC), flow accelerated corrosion (FAC), thermal stratification and excessive thermal fatigue, caused damage at locations that were not inspected. In other words, the traditional ISI is not successful in fulfilling the objectives of inspection listed above. This caused

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the introduction of augmented inspection programs dedicated to particular degradation mechanisms such as IGSCC and FAC, which gradually made the inspection paradigm shift from 'inspection for confirmation' to 'inspection for cause' [3,4].

As probabilistic risk assessment (PRA) methods matured in the mid 1990s, a new idea of risk-informed in-service inspection (RI-ISI) appeared that integrated risk insights from PRA with service experience, plant and operating conditions, and other deterministic information to optimize selection of inspection locations. Since then, the risk-informed in-service inspection (RI-ISI) programs have been successfully implemented by a number of US, European, Japanese, and Korean utilities, and have resulted in a significant reduction in periodic inspection scope without a corresponding increase in plant risk [4, 5].

In Canada, the requirements for periodic inspection of nuclear pressure-retaining components are specified in CAN/CSA Standard N285.4 [6]. Compliance with N285.4 is a requirement of the nuclear power reactor operating licenses granted by the CNSC, Canada's nuclear regulator. The Standard provides an implicit risk-related rationale based on likelihood and consequence of failure, but it does not include explicit requirements for risk-informed decisions based on the station PRA. The CNSC is becoming increasingly interested in risk-informed decision making, and the CSA has proposed a standard be developed on RI-ISI as well [7].

The main objective of the paper is to re-examine N285.4 from the RI-ISI perspective, to identify implications of transitioning from the traditional PIP as defined by CSA N285.4 to RI-ISI and to suggest a path forward for applications of RI-ISI at CANDU stations. The paper is organized as follows. Section 2 discusses the fundamental philosophy and major steps of RI-ISI. The RI-ISI methodologies currently used in international nuclear power industry are briefly introduced with their main features compared in Section 3. Section 4 reviews Canada's current periodic inspection standard CSA N285.4-05 from a RI-ISI perspective. The implications for Canadian nuclear power industry of transitioning from the traditional PIP as defined by CSA N285.4 to RI-ISI are identified and a path forward for applications of RI-ISI at CANDU stations is suggested in Section 5. Conclusions are drawn in Section 6.

2 BASICS OF RISK-INFORMED IN-SERVICE INSPECTION

The basic idea behind RI-ISI is to integrate risk insights from PRA with service experience, plant and operating conditions and other deterministic information into the decision making of in-service inspection. The main role of risk insights in the process is to guide the ranking of inspection elements and thereby support decisions on locations to be inspected. Evaluation of the risk requires identification of anticipated degradation mechanisms and how likely these are to lead to various failure modes. The anticipated degradation mechanisms may be used to guide inspection methods whilst the kinetics of the anticipated degradation mechanisms may be used to guide the frequency of inspections [8, 9].

The basic objective of RI-ISI is to make ISI programs more effective and efficient from both safety and economic points of view. Instead of passively checking for existence of a degradation mechanism in the traditional periodic inspection programs, the RI-ISI program takes a proactive step by performing an inspection "for cause" that is targeted at the anticipated degradation mechanisms. Furthermore, the NDT inspections in a RI-ISI program are focused on areas with highest potential for reduction of plant risk, while the inspections in areas where the potential for the reduction of plant risk is low are reduced or eliminated. In doing so, the inspection scope can either be reduced or at least maintained unchanged, and the radiological risk for the public at large and the inspection personnel can be reduced.

Reduction in inspection scope from application of RI-ISI is achieved mainly by a reclassification of piping to lower safety significance levels requiring fewer inspections. For example, under ASME SC XI, 25% of Class 1 piping welds must be inspected and 7.5% of Class 2. Under ASME Code Case N-578-1, one of the several ASME code cases for RI-ISI, 25% of welds in piping assigned a "high risk" category must be inspected and 10% in the "medium risk". However, if much of the Class 1 piping can be assigned medium risk or lower, then the total number of inspection sites can be significantly reduced, at some plants by up to 80% relative to the original ASME requirements [10, 11], while still achieving risk reduction. Therefore, RI-ISI is essentially the process by which the reallocation of piping classification on the basis of risk significance is justified by using plant risk as the overall prioritization indicator [12].

There are five basic steps in any RI-ISI methodology, although some approaches use predetermined assumptions in place of analysis:

1) Definition of scope of program and application
2) Failure potential/probability evaluation
3) Failure consequence evaluation
4) Risk ranking and site selection (expert panel review)
5) Change-in-risk evaluation, also called delta risk analysis

These are shown schematically in Figure 1. Note that the RI-ISI is a living program for which the overall program performance should be monitored and the examination results, plant design changes and plant PRA updates should also be reviewed [13].

Other important aspects of RI-ISI include, program scope, level of evaluation (i.e., segmentation), structural reliability models, analysis of operating experience data, use of expert judgment, levels and scope of PRA, treatment of passive component failures in PRA, risk outliers, leak detection, selection of inspection elements, delta risk analysis, etc. For details of the discussions, see for example [9, 12, 14, 15].

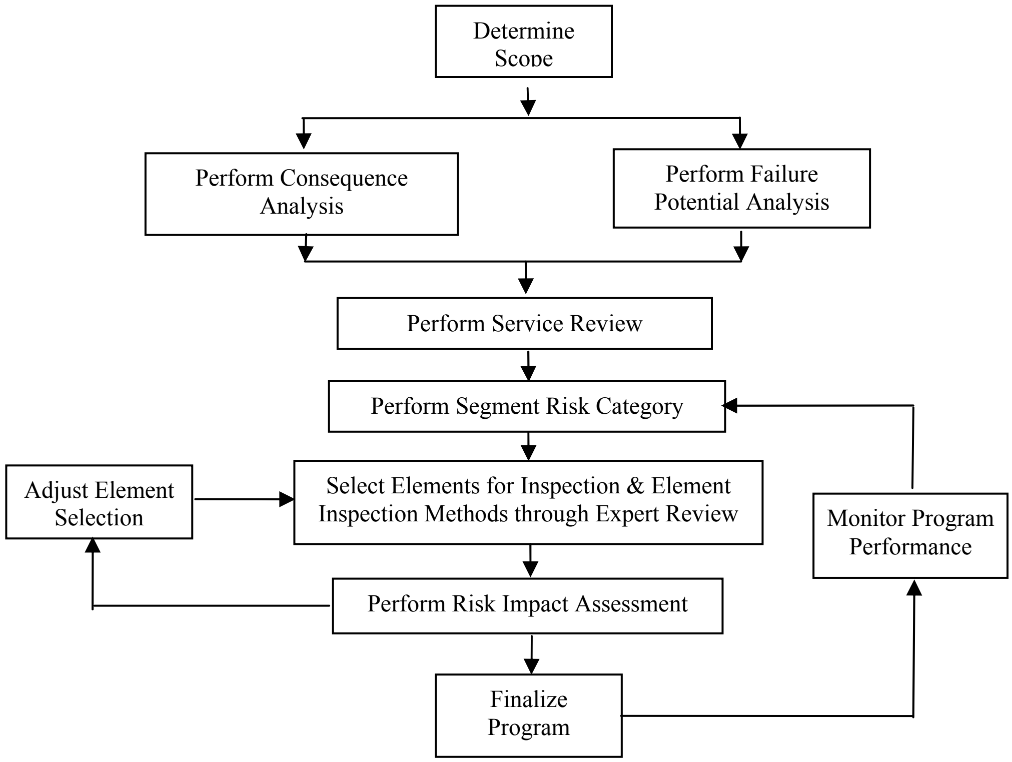

Figure 1: Steps in RI-ISI Implementation

3 EXISTING RI-ISI METHODOLOGIES AND RECENT DEVELOPMENT

There are two methodologies that have been widely applied in USA and they are referred to as the EPRI and PWROG methodology, respectively, named after their developers. Both methodologies have been approved by the USNRC as alternatives for the deterministic ASME SC XI inspection procedure. Three ASME Code Cases have been developed based on the EPRI methodology: N-560-2, N-578-1 and N-716. The scope of N-560-2 is limited to Class 1 Category B-J piping welds while the other two allow a much broader inspection scope. Code Case N-716 represents a streamlined version of the EPRI methodology that predetermines the high safety significance (HSS) locations. For PWROG methodology, ASME Code Case N-577-1 can be followed. All these Cases were subsequently combined for incorporation as Nonmandatory Appendix R, "Risk-Informed Inspection Requirements for Piping", ASME SC XI in the 2004 edition and thereafter. Detailed implementation guides for the two methodologies can be found in the EPRI topical report TR-112657 Rev. B-A [16] and the Westinghouse topical report WCAP-14572 Rev 1-NP-A [17].

The PWROG methodology makes extensive use of analytical models and quantitative analyses. Probabilistic fracture mechanics (PFM) model is used to calculate the piping failure probability. Risk importance measures (risk reduction worth and risk achievement worth derived from PRA models) are used to rank the risk significance of the piping segments. For selection of inspection locations, a random sampling plan based on the so-called Perdue method is used [17]. To address the uncertainty associated with the quantitative models involved in the methodology, an expert panel is required and it is the panel that finalizes the selection of the locations to be inspected. Comparing to the PWROG methodology, the EPRI approach tends to be more qualitative. The failure potential categorization is mainly based on criteria derived from pipe failure data and service experience. More recent developments in EPRI methodology include the four-state Markov model to quantify the change of the piping failure probability due to revised inspection programs. Detailed comparison of the two methodologies and ASME SC XI as well as N285.4-05 is summarized in Table 1.

Table 1: Comparison of Technical Aspects of RI-ISI Approaches

Methodology	**EPRI**	**PWROG**	**ASME SC XI**	**CSA N285.4**
Scope of Program	Both full and partial scopes are allowed; N-716 requires full scope	Both full and partial scopes are allowed, but full scope preferred	Full scope with exemptions	Full scope with exemptions
Piping Segmentation	Risk based	Consequence based	System based	Geometry based
Consequence Evaluation and categorization	PRA, CCDP- and CLERP-based; N-716 predetermined	PRA, RRW-based, assisted by RAW and expert panel	Safety system based	Safety system and failure size based
Evaluation of Piping Failure Frequency	Qualitative, degradation mechanism based	Quantitative	Stress intensity and fatigue usage	Stress intensity and fatigue usage
Assessment of Degradation Mechanisms	Industry experience, operation database	Industry experience, Expert panel	Design based and posterior assessment	Mainly for supplementary programs
Uncertainty Analysis	Not applicable	Monte Carlo simulation	Not applicable	Not applicable
Risk Ranking and Categorization	7 risk categories divided into 3 risk groups from a 3 x 4 risk matrix	A 2x2 risk matrix, five regions	Safety Class 1, 2, and 3	Failure size, stress intensity and fatigue usage, A, B, C1 and C2
Selection of Inspection Samples	25% for high risk group, 10% for medium risk group and 0% for low risk group	100% for Region 1(A), Statistical Perdue method for Region 1(B) and Region 2	25% for Class 1, 10% for Class 2, 0% for Class 3	One weld for each pipe run; significant reduction allowed for identical welds
Change in Risk Evaluation	Four methods: qualitative, bounding estimate with and without	Quantitative via SRRA, credit for inspection in the estimation of	Not applicable	Not applicable

	credit for increase of POD, and Markov model	piping failure frequency		
Use of Expert Panel	No	Yes	No	No

European countries have been very active in the development and applications of RI-ISI. In Sweden, a qualitative risk-informed procedure, known as SKIFS methodology, for selecting pressure-retaining components for inspections has been in place since 1988. Swedish nuclear regulatory body SKI later integrated some elements of the SKIFS approach into the PWROG methodology and developed a Swedish version of the PWROG methodology. In France, according to the RIBA project report [12], a method called OMF-Structures is developed by EDF that takes a balanced account of safety, availability and maintenance costs. Unlike the other RI-ISI methodologies, the OMF-Structure methodology is designed for the entire reactor system and it is a reliability-centred maintenance strategy in which ISI is included as one of maintenance activities that needs to be optimized. Other RI-ISI methodologies also include DNV approach that uses their in-house software NURBIT ("Nuclear Risk Based Inspection Tool"), STUK procedure [12], and more recently the VTT methodology that integrates the PFM and Markov modeling to obtain more accurate risk estimation [18]. However, their applications have been rather limited so far.

In 2004 the European Commission, Nuclear Regulators' Working Group (NRWG) published a report on the regulatory experience of RI-ISI of NPP components and common views, in which the key technical aspects of RI-ISI were analyzed from the regulatory point of view and a series of recommendations of good practice or common positions reached by the regulators were presented [19]. Slightly later after this report, the European Network for Inspection and Qualification (ENIQ), a consortium supported by European nuclear utilities and managed by European Commission Joint Research Centre of Petten, the Netherlands, released the "European Framework Document for Risk-informed In-service Inspection" which is designed to provide guidelines to utilities both for developing their RI-ISI approaches and for using or adapting already established approaches to the European regulatory environment [9,12]. The overall position of the European practice is to use a semi-quantitative methodology that makes most use of the analytical models, whenever they are able to be verified and validated, and complement them with expert judgment and qualitative analysis. Several international collaborative projects (e.g., MERIT and RISMET) are currently being undertaken to advance the development of the PFM-based structural reliability method [20, 21]. Some other projects (e.g. OPDE), however, aims at developing statistical analysis of the field failure data to estimate the piping failure frequency. The NUREG-1829 report on estimating LOCA frequencies through the elicitation process was published in April 2008, after intensive peer reviews [22].

4 A NEW LOOK AT CSA N285.4 FROM THE RI-ISI PERSPECTIVE

The current edition of N285.4 was released in 2005 and it supersedes the previous editions published in 1994, 1983, and 1978, although the earliest edition can be traced back to the preliminary standard in 1975, which sets the tone of the standard [6]. The Canadian utilities are undergoing the transition period of updating their PIP programs from the 1994 edition to the 2005 edition.

The general idea of N285.4 is to provide assurance that the likelihood of a failure that could endanger the radiological health and safety of persons has not increased significantly since the plant was placed into operation, by ensuring that an unacceptable degradation in component quality is not occurring and that the probability of failure remains acceptably low for the remaining life of the plant.

The logic behind the Standard is summarized in Annex A of N285.4. Basically, the inspection areas and the degree of inspection are determined by considering the failure size (magnitude and type of failures) and the safety margin. For pressure-retaining piping systems, the failure size is expressed as the ratio of the maximum energy release rate from the failure being considered to the maximum energy release rate from the postulated most severe failure events. The safety margin, or the failure potential, depends on the duty factor, characterized by stress ratio and fatigue usage factor from the design report. Depending on the combination of the failure size, stress ratio, and fatigue usage factor, the inspection elements are grouped into four categories: A, B, C1 and C2, each having different inspection requirements in terms of location, number and method of inspections. Category C2 does not need periodic inspections.

While the failure potential is assessed for each weld or joint, the evaluation of the failure size is taken at the pipe run level. A pipe run in N285.4 is defined as "a length of piping that extends to, but not beyond, a large component (e.g., vessel, pump) or a piping intersection. The pipe run can extend beyond an intersection where the run pipe has an extruded outlet or a weld-on fitting for the branch connection". Although the definition does not explicitly specify the change of diameter as a delimiter of the pipe run, the common engineering practice is to keep the pipe diameter uniform along the pipe run so that each run would not have more than one failure size. Note, however, the joints in the same pipe run may have different Inspection Categories because of the different duty factors.

The selection of inspection locations consists of two steps. In the first step, called preliminary selection, only one joint in each pipe run is selected for inspection. The selected joint should have the highest Inspection Category, and among the joints of the highest Inspection Category the selected joint shall have the highest fatigue usage factor, or highest stress ratio if the fatigue usage factor is not calculated. In effect, the initially selected joint has the highest duty factor, because, as mention earlier, the failure sizes for the joints in the pipe run are the same. If the highest Inspection Category is C2, or C1 but no welds are composed of dissimilar metals, no joint is selected for inspection for the pipe run.

In the second step, the initially selected inspection locations are subject to a number of additions and deletions. Additional inspections are required for corrosive and/or erosive environment. Material thickness is measured at both locations of highest corrosion rate or highest stress intensity and of highest erosion rate. Besides, the area that includes the most significant indication (i.e., relevant evidence or signal of deterioration as revealed by a NDT) in each pipe run, regardless of its Inspection Category and stress ratio or fatigue usage factor, shall be volumetrically examined. Reduction of the number of inspection location can be made in two ways. First, for a multi-unit power generation station, N285.4 assumes that experience obtained from the lead unit can be applied to reduce inspection on later units. Second, for identical components under similar working conditions, N285.4 provides an equation to compute the reduced number F of components to be inspected: $F = 1 + \alpha \log_{10}(n)$, where n is the number of identical components *that have been pre-selected for inspection in the first step*; and $\alpha = 2.22$ for Category A components and 1.11 for Category B. Figure 2 shows the required number as a function of n for $n \leq 100$. For Category B, $F = 2$ when $n \leq 15$ and 3 otherwise. For Category A, $F = 2$ until $n = 4$ and then $F = 3$ until $n = 12$. That is, a significant reduction is obtained, especially when the number of identical components is large.

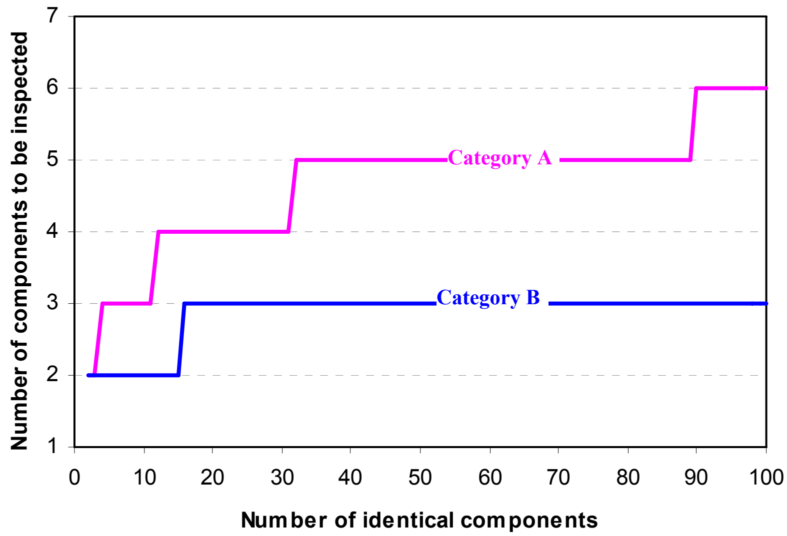

Figure 2: Inspection sample for identical components/welds

Compared to the ASME SC XI approach, the CSA approach to ISI in N285.4 is closer to the philosophy of RI-ISI in that the latter has finer treatment on the failure consequence evaluation. ASME SC XI simply adopts the safety classification, a design concept, for separating the different inspection requirements. In N285.4, the failure size of the pipe run plays a very important role. In fact, many pipe runs do not require an inspection at all owing to its small pipe diameter and thus small failure size, although they may belong to Class 1 or Class 2 components. This partly explains why N285.4 requires a much fewer number of locations for inspection than the ASME counterpart does. The other part of the reason is the unique reducing sampling strategy used in N285.4, as explained in the preceding paragraph. A pilot study for CANDU inspection indicates inspection of only a few percent of the total welds in Class 1 piping is required as per N285.4-2005, which is significantly less than the ASME SC XI requirement of 25% and also a smaller number than the 10% of the EPRI RI-ISI methodology [23].

Comparing to the RI-ISI methodologies (either EPRI or PWROG), however, N285.4 considers in the failure analysis only the "consequence" term of PRA, but does not account for the system configuration, the propagation of the hazard through the system or the impact on the core damage or large early release of radioactivity. In this sense the N285.4 can be viewed as being in the preliminary stage of the RI-ISI. Besides, the failure potential is evaluated qualitatively based solely on the design information, except for the additional inspection requirements which use the inspection results to determine the new inspection locations for the next time. Moreover, the N285.4 still lacks a systematic approach to identifying the potential degradation mechanisms through ISI, although the additional inspection requirements in the Standard that are used to monitor the most significant indications and corrosion/erosion environment have shown the path towards this direction. Furthermore, in the existing RI-ISI methodologies, risk rank is performed at the pipe segment level, whereas in N285.4 the Inspection Category, which is equivalent to risk ranking in RI-ISI, is assigned to each inspection element. From the piping reliability perspective, one joint usually dominates the failure probability of the whole pipe run. Even when it does not, the multiple joints usually have the same degradation mechanisms and failure modes. Therefore, ranking the Inspection Category for the pipe runs, instead of the welds, may be a better practice, and this is also how the PWROG methodology addresses this issue [17].

5 CANADIAN PATH TOWARD RI-ISI

Given that the current N285.4 approach already requires few inspection locations relative to its ASME counterpart, it appears unlikely that a further reduction in ISI scope can be achieved by implementing an existing risk-informed approach. However, there are still opportunities to use RI-ISI in CANDU industry to optimize inspection programs to maximize risk reduction supported by a change-in-risk evaluation. In order to do so, the following areas are considered important to develop a CANDU appropriate RI-ISI methodology:

- An industry-wide review of the effectiveness and efficiency of the current PIP as per N285.4 should be conducted. Both the operational failure events and significant indications of unexpected degradation found during operations should be included. The role of leak detection in finding unexpected degradation should be carefully evaluated.
- The inspection scope of N285.4 is limited to the systems, structures and components within the containment, with the secondary side excluded (although covered by other utility programs). The benefit of including the secondary side piping into the scope of the RI-ISI methodology should be explored.
- Consistent criteria to determine when a potential for a certain damage mechanism exists. This requires an industry-wide database of the degradation data from both experiments and field inspections.
- It is difficult to carry out reliable probabilistic analyses for some damage mechanisms. This is the case for stress corrosion, FAC and vibration fatigue. More efforts should be devoted to further develop probabilistic models that better correlate to service experience data.
- The use of expert panel in both failure potential evaluation and consequence analysis should be explored.
- There is a need for more detailed guidelines for modeling the failure of passive components such as pressure retaining piping in plant-specific PRAs to support the application of risk-informed inspection programs.
- More and better information is needed with respect to the effectiveness of inspection for various NDE methods. Risk-informed inspection should not be directed only to the most

risk significant locations, but also to the locations of which the risk can be most efficiently reduced [24]. Accessibility is an important factor that needs to be considered when selecting the inspection locations.

- Inspection programs include not only the inspection locations (where to inspect), but also the time and method of inspections (when and how to inspect). Most of the existing RI-ISI methodologies are focused on the first question but ignore the latter two. The role of determining inspection intervals using probabilistic methods should be explored.
- It is important that the scope of RI-ISI is periodically updated to include possible new areas that may be risk significant as a result of plant modifications or changes in the plant operation. This is also valid for plant life extension.
- A remaining issue from the industry perspective is how to incorporate supplementary, plant owner defined programs into RI-ISI, e.g., inspections of flow accelerated corrosion typically done at plants. In principle, the same approaches can be used in a full scope application to piping as applied to welds. US experience in integrating their augmented inspection programs may be helpful.
- An approach that integrates the RI-ISI program review and the probabilistic safety review (PSR) should also be developed.

The successful development of a CANDU approach to RI-ISI requires an agreement on how RI-ISI methods can be incorporated into the Canadian regulatory framework and a commitment from the utilities to apply the resources necessary for development and implementation of an effective RI-ISI program.

6 CONCLUSIONS

This paper has reviewed the issues surrounding the introduction of RI-ISI to the CANDU industry. The motivation for introducing RI-ISI is to attempt to focus inspection resources on systems and locations where the risk to the plant (expressed as a function of both failure potential and failure consequences) is greatest. Operational experience suggests that this has not been the case with existing Periodic Inspection Programs.

Many reported applications of RI-ISI have resulted in significant reduction in inspection scope, radiation dose and cost relative to ASME Section XI requirements. It is considered unlikely that application of RI-ISI where inspection programs are defined by CSA N285.4 will result in a major reduction in the number of inspection sites. This is because the CSA has already anticipated some of the considerations that are included in RI-ISI and requires far fewer than the 25%/7.5% weld inspections that would be the case under ASME for Class 1/2 piping.

Nevertheless, benefits of an inspection program optimized in terms of risk and occupational dose reduction may still be available for a given number of inspection sites. This option is available for any scope of application, i.e., to a limited range of piping or to a plant-wide assessment. Overall, applications of RI-ISI in Canada are more likely to provide an opportunity for optimization of the current program effectiveness rather than scope reductions. A number of important issues that needs to be addressed to develop a CANDU appropriate RI-ISI methodology have been identified. The successful development of the CANDU approach to RI-ISI needs an agreement on how RI-ISI methods can be accepted in the Canadian regulatory framework and a commitment from the utilities to apply the resources necessary for development and implementation of a RI-ISI program.

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