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CANADIAN REGULATORY PERSPECTIVE ON THE APPLICATION OF BREAK EXCLUSION ZONE (BEZ)

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ABSTRACT

The safety and reliability of piping components, particularly those forming part of high-energy lines (HEL) in a nuclear power plant, are paramount. The Canadian Nuclear Safety Commission (CNSC) regulatory framework provides that Structures, Systems and Components (SSCs) important to safety must be designed and located in a manner that minimizes the probability and effects of hazards (e.g., fires and explosions) caused by external or internal events. A postulated HEL break inside the Reactor Building (RB) is a typical internal hazard considered in the design of Nuclear Power Plants (NPP). For the Canadian operating nuclear fleet, this hazard was addressed via the application of postulated pipe break analysis and pipe whip jet impingement analysis (PWJIA) following a systematic approach that assumes the failure at every pipe weld connection. The consequence of a piping break on adjacent safety critical targets supporting safety functions including reactor shutdown, fuel cooling, and the containment boundary has been evaluated by means of PWJIA. Whip restraints and supports are used to restrain and limit the consequences of these postulated pipe breaks. Although whip restraints and supports may increase access limitations for inspection and maintenance activities within containment and the RB, they enhance safety by design. The Break Exclusion Zone (BEZ) concept has been applied in some countries as a method to screen out portions of high-energy piping near the containment boundary from requiring further assessments for protection against dynamic effects of postulated pipe breaks. The BEZ approach aims to optimize the use of pipe whip restraint to increase accessibility for inspection within containment and reduce containment volume. This article will discuss the Canadian perspective regarding the BEZ concept in comparison to other international practices used to assess the effects of HEL breaks.

BACKGROUND

Pipe break, including guillotine and longitudinal breaks, and through-wall cracks, is a typical internal hazard to the safety of nuclear power plants (NPPs), and therefore must be considered in the design of piping systems. The postulated pipe break may result in environmental and dynamic effects, hence piping systems which support safety functions or has impact on systems that support safety functions must be qualified to withstand postulated breaks and their impact. The break of High Energy Lines (HELs) could result in pipe whipping or high energy jet impingement. The consequential damage caused by pipe whipping or jet impingement from high energy pipe break can be severe if the dynamic effects of break were not appropriately addressed in the design phase. In Canada, regulatory document REGDOC-2.5.2 [1], requires that the design of structures, systems, and components (SSCs) includes protection against postulated pipe rupture. Pipe Whip Jet Impingement Analysis (PWJIA), or alternatively Leak Before Break (LBB) assessment, have been used in Canada to evaluate the need for physical restraints against postulated pipe breaks and provide justification for their removal in order to comply with the layered Defence-in-

Depth (DiD) principle as per REGDOC-2.5.2, and international norms and guidelines. The CNSC regulatory framework allows for alternative approaches to those provided for by REGDOC-2.5.2 and REGDOC-1.1.2 [1][2].

As the primary accepted method in Canada, the PWJIA applied plastic hinge analysis at every weld connection to postulate the consequential impact of a break at these weld points. The Break Exclusion Zone (BEZ), or otherwise referred to as Break Preclusion Concept (BPC) in Germany [3], or High Integrity Components (HIC) in the UK [4], is an approach used to justify elimination of dynamic effects resulting from postulated breaks in HEL from the design basis. Hence, it is implicitly intended to justify removal of pipe whip restraints, guards, barriers, and shielding typically used for prevention and mitigation of consequential damage. Designers of NPPs claim that the application of BEZ will increase accessibility within containment and thus enables inspections while reducing the overall size of containment. Although the Canadian regulatory framework does not include explicit references or acceptance of BEZ in HEL, alternative approaches maybe accepted where justified to be of equivalent or superior safety. For example, the CNSC accepted the Leak Before Break (LBB) in some cases to support the elimination of pipe whip restraint for limited scope in large pipes where pipe whip restraints were deemed impractical.

INTERNATIONAL PRACTICES

Internationally, the application of BEZ has been handled by different approaches, however the common aspect in most approaches was the necessity to demonstrate enhanced reliability of piping components within the scope of BEZ. For example, in the United States (US), General Design Criteria (GDC-4) states that for important to safety, “structures, systems, and components shall be appropriately protected against dynamic effects, including the effects of missiles, pipe whipping, etc” [5]. However, the BEZ concept was accepted in Light Water Reactors in the US since the early 1970s. The US Nuclear Regulatory Commission (USNRC) has established a Branch Technical Position, BTP 3-4, to provide the criteria for the applicability and scope of BEZ in HELs [6]. The US approach to BEZ relies on augmented design margins to enhance stress tolerance of the piping design. The US approach requires that piping considered in the scope of BEZ should amongst other criteria, include no active degradation mechanisms, and meet a minimum length criterion. Additionally, the US methodology for BEZ employs the concept of “enhanced requirements” through augmented design margins, fabrication processes, and in-service inspection to provide assurance that the probability of a piping rupture is “extremely low” under conditions consistent with the design basis for the piping.

The Electric Power Research Institute (EPRI) developed a report on risk-informed HEL break evaluation requirements as an alternative to the deterministic analysis requirements [7]. The proposed approach aims to assign a commensurate level of scrutiny to HEL breaks based on the risk significance of each postulated failure. The risk is determined based on the chance of failure and the consequence of failure of these components or systems. The intent of application this approach is primarily for the existing US fleet to address issues with HEL breaks arising from operation, upgrade, or relicensing requirements, but it has not yet been adopted by USNRC at this point.

The UK Office of Nuclear Regulation (ONR) does not accept Break Exclusions / Preclusion concept as a design basis, except for limited situations [4], [8]. Therefore, NPP proponents would be typically required to demonstrate the implementation of enhanced measures such that the risk or consequence of failure are “As Low As Reasonably Practicable (ALARP)” or “So Far As Is Reasonably Practicable (SFAIRP),” in addition to the ASME requirements [9][10], which are regarded as minimum design requirements.

The guide jointly produced by the French Institute for Radiological Protection and Nuclear Safety (IRSN), the French Nuclear Safety Authority, ASN, permits the Break Preclusion Approach on a case-by-case basis, requiring sufficient justification to support the absence of a physical means of limiting the consequences of breaks and demonstrating overall benefits to the plant safety gained by the application of this approach [11]. LBB may be acceptable as supporting justification only if backed by high sensitivity detection combined with ability to locate leakage sources.

The German Nuclear Safety Standards Commission, KTA, perspective on BEZ stems from the Basis Safety Concept introduced in 1979 [3]. The KTA expects applicants to follow an integrated safety approach to demonstrate piping reliability and as precursor to considering the application of BEZ. This integrated approach includes, amongst other less important factors, quality through manufacturing, independent testing, worst case principle of failure investigation, continuous monitoring and surveillance, and validation using codes and fracture mechanics. Hence, the KTA approach prescribes more enhanced requirements to consider the acceptability of BEZ.

Various approaches may be followed to assess the acceptability of BEZ in different jurisdictions. However, the congruity in these approaches is that the BEZ is regarded internationally as an exception from typical design practice and one which requires a set of enhanced measures to support the proposed approach and the scope/extent of application to demonstrate the reliability of the HEL design.

CANADIAN PERSPECTIVE ON APPLICATION OF BEZ

The Canadian regulatory framework permits the use of alternative approaches; however, they must demonstrate equivalent or superior level of safety. In accordance with Canadian regulatory document REGDOC-1.1.2, clause 2.2, any proposed alternative, including the use of codes and standards other than those referenced in that and other REGDOCs, should appropriately address the complexities and hazards of those alternatives. This includes appropriate analysis of consequential effects and addressing the layered DiD approach in line with regulatory requirements. To address layered DiD, licence applications are to demonstrate several key elements in the proposed integrated BEZ approach which are further elaborated in the following section.

This paper presents the current CNSC position on the application of a BEZ in new builds. This position is based on the CNSC's regulatory framework including REGDOC-1.1.2 and REGDOC-2.5.2, applicable codes and standards, and international best practices. The application of BEZ to all HEL piping inside containment is not explicitly referenced in the CNSC's regulatory framework, therefore the regulatory position reflects risk-informed considerations.

MULTI-DISCIPLINARY INTEGRATED BEZ APPROACH

The main elements of the integrated BEZ approach are intended to address the Canadian requirements in REGDOC-2.5.2, with the primary goal being to address DiD expectations. The following elements are the result of a multi-discipline staff assessment of the BEZ as an alternative approach to existing Canadian HEL safety and reliability practices.

1. Demonstration of extremely low failure probability using deterministic methods:

The BEZ concept is founded on the assumption of extremely low probability of HEL break based on enhanced HEL design margins and conditions to reduce stress concentrations to demonstrate the reliable operation of piping. In Canada, the assumption of low probability of HEL break is expected to be deterministically demonstrated. Internationally this has been accomplished with one of two methods, Defect

Tolerance Approach (DTA) and/or Leak Before Break (LBB), with the two methods being fundamentally different. LBB postulates a through-wall crack size and assesses crack propagation and stability allowing through-wall leakage within the life of the component and mandates that the plant be able to accurately detect a localized leak providing ample time to intervene to mitigate consequential failure. The DTA postulates a crack size which may propagate without penetrating the pipe wall. Typically, the DTA assumes a crack size double the size of the detection tool being used, with stability demonstrated using fracture mechanics.

Depending on whether LBB or DTA is selected, this will determine which additional steps should be followed to provide a comprehensive approach that would demonstrate extremely low failure probability. For example, if the LBB approach is followed, leak detection capability should be able to demonstrate timely detection of leakage rate and location. On the other hand, if DTA is selected, enhanced material and inspection requirements become paramount to demonstrate reliability of the BEZ approach. Nevertheless, for both methods, the following may need to be considered and/or identified:

- High stress locations
- Plausible degradation mechanisms
- Locations with potential common cause failure mechanisms?
- Locations with severe consequence of failure

Probabilistic safety assessment (PSA) alone is insufficient to demonstrate the extremely low probability of pipe break with high confidence, for the following reasons:

- Uncertainty such as limitations in data and modelling assumptions.
- Difficulty in quantify the rare event such as pipe break.
- The PSA may underestimate risk due to the estimation of initiation event frequencies (e.g., pipe rupture frequencies) through statistical data or an expert elicitation procedure

2. Demonstration of prevention, detection, and mitigation

REGDOC-2.5.2, section 6.1.1 states, “To ensure the overall safety concept of defence in depth is maintained, the design shall provide multiple physical barriers to the uncontrolled release of radioactive materials to the environment”. Therefore, the BEZ approach shall demonstrate measures for prevention by design are addressed, such as material and design considerations to reduce probability of break. Additionally, crack stability analysis using LBB or DTA would be necessary to demonstrate piping resistance to crack propagation and abrupt failure. The application should demonstrate detectability of breaks as well as mitigation measures to prevent consequential damage. This may include restraints and shields for components whose failure may impact safety critical targets (SCT), whose failure may directly result in impairment of fundamental safety functions during a HEL break scenario. It may also include measures such as managing and configuring the layout of affected zones and relocating SCTs to minimize the impact from postulated HEL breaks.

3. Protection against fracture

The BEZ application approach needs to include measures for protection against fracture by crack initiation and propagation under harsh thermal and pressure transient conditions. For example, Appendix G of ASME Boiler and Pressure Vessel Code (BPVC), protection against fracture assessment or other alternatives, may be used to confirm the reliability of piping design. The BEZ approach shall provide information to demonstrate the protection against fracture crack initiation and propagation under harsh thermal and pressure transient conditions. This is particularly important for areas expected to experience steep thermal gradients during normal and upset conditions, such as those experiencing thermal stratification, or thermal mixing.

4. Minimum practical length of HEL piping

REGDOC-2.5.2, section 7.7 states that, "Unless otherwise justified, all pressure boundary SSCs shall be designed to withstand static and dynamic loads anticipated in operational states, and DBAs". The BEZ approach is regarded as an exception to design rules rather than a norm and, therefore, the BEZ application shall justify the length of HEL piping within the BEZ and its boundaries, particularly in systems important to safety or that have an impact on safety functions. Historically, the nuclear industry, including in Canada, has accepted the exclusion of dynamic effect analysis for a very limited length of HEL within the vicinity of containment penetrations. In these areas, implementation of inspections and whip restraints was demonstrated to be practically impossible. A broad BEZ application over the entire HEL piping without sufficient technical justification and safety merit may challenge regulatory acceptance of the proposed approach, or at the very least require that such justification and safety benefit be demonstrated.

5. Consequence of failure analysis

A proponent's proposed BEZ application is required to demonstrate a systematic approach to the analysis of consequence of failure and impact on SCTs. In Canada, REGDOC-2.5.2, section 7.4.1 provides that "SSCs important to safety shall be designed and located in a manner that minimizes the probability and effects of hazards (e.g., fires and explosions) caused by external or internal events". The representative scenarios that shall be analysed for consequence of failure should be identified in a systematic way. Additionally, dynamic effects at the piping plastic hinge shall be performed to determine any potential impact on the structural integrity of SCTs such as containment, control and shutdown systems, the reactor building, and others that are required to operate under postulated accident conditions including beyond design basis accidents (BDBA). The application should also highlight proposed plant layout to minimize the impact of a postulated HEL break.

In the systematic approach to the identification of bounding and significant failure case scenarios, the following scenarios should be considered:

- Multiple bounding / representative cases would be expected due to the complexity of HEL failures.
- Dynamic effects at the piping plastic hinge, including cascading effects, to demonstrate that there would be no impact on nearby systems important to safety, e.g. HEL piping, RPV, Outboard Containment Isolation Valve (OCIV), containment, and reactor building, amongst others
- The structural integrity of the SSCs important to safety, including containment, against the resulting impact loads due to the bounding HEL pipe whip and/or missile effects during DBA and DEC conditions.
- Weld break between the flange-bolted connection and piping.
- Potential break at piping discontinuities, including pipe bends.
- Mitigation measures to prevent dynamic effects on piping within the BEZ, such as guard pipes. If the design decision was made to install protective hardware, a demonstration of the protective hardware's inspectability should be included.

6. Accounting for all degradation mechanisms (aging management)

It is well recognized that most piping failures at NPPs have occurred as a results of active degradation mechanisms and that these need to be considered as part of an aging management plan. Based on international practices, the BEZ approach should only be considered for piping systems with demonstrably no known active or plausible degradation mechanisms. Therefore, comprehensive identification of all plausible degradation mechanisms, their mitigation and prevention methods as part of aging management (e.g., Failure Mode Effect Analysis (FMEA)), and their consideration through design, fabrication, monitoring, or otherwise to reduce aging effects, should be part of the proposed BEZ approach. Since vibration is a common degradation mechanism, the following considerations should be addressed as part of a Comprehensive Vibration Assessment Program (CVAP)[12] for BEZ piping:

- Detection and monitoring of vibration on HELs
- Method used in the evaluation of structural integrity against vibration, including crack initiation criteria for vibration-induced cracks.
- Mitigation and preventive actions against the HEL failure due to vibration, including inspection program.

Operating experience (OPEX) and lessons learned such as those documented in the International Generic Again Lessons Learned (IGALL) [13] and in line with the expectations in REGDOC-2.6.3 [14] should be considered in a CVAP.

7. Enhanced material quality

Material selection and quality assurance is essential to ensure reliability of piping components, particularly in the absence of dynamic effect analysis and engineered restraints. REGDOC-2.5.2, section 7.5, provides, “The engineering design rules for all SSCs should be determined based on their importance to safety, as determined using the criteria in section 7.1. The design rules should include, as applicable; reliability and availability, Material selection…”. Enhanced material considerations can be divided into the following two main aspects:

Material fabrication: A primary factor in guaranteeing the reliability of a material is the variance limitations of test results. This is achieved through the implementation of material homogeneity, rigorous control of the test process, and statistical evaluations of test results by performing multiple tests. In particular, the fracture toughness of the selected materials will be influenced by the allowable limits of impurities, and the maximum and minimum range of chemical compositions. An integrated approach would include the consideration of a detailed material selection report to support material selection decisions.

Material testing: International best practice utilizes a confidence interval in fracture toughness test results of up to 95% to ensure reliable pipe material toughness is attained. Since ASME BPVC requirements were not established in consideration of the application of a BEZ, the code only requires three test samples and does not specify a confidence interval to limit the variance of toughness test results. Furthermore, ASME requirements are regarded as minimal requirements in the design of Pressure Retaining Systems and Components. A higher confidence interval typically means that more tests need to be completed in order to demonstrate the high reliability of materials selected for the HEL piping in the proposed BEZ, from fabrication to material testing.

8. Enhanced inspection practices

REGDOC-2.5.2 section 7.14, provides that, “In order to maintain the NPP within the boundaries of the design, the design shall be such that the SSCs important to safety can be calibrated, tested, maintained and repaired (or replaced), inspected, and monitored over the lifetime of the plant”. ASME BPVC code does not specify requirements for fabrication or vendor inspection. However, such inspections would be the first step to identify any defects before accepting materials to be installed at an NPP and would reduce having to consider mitigation measures when defects are identified during preservice inspections. Furthermore, to increase overall confidence in the inspection results, the BEZ application should provide a documented approach to ensure consistency in inspection techniques for vendor, preservice, and in-service inspections. These layered inspections are particularly important to demonstrate the reliability of Dissimilar Metal Welds (DMWs) [15]. The following elements may be considered and addressed in order to demonstrate enhanced inspection approach:

- The technical specifications of non-destructive examination (NDE) tools, including their detection limits, coverage area, and sensitivities.
- Qualification and performance of NDE tools and personnel.
- Information on which inspection tools will be used for fabrication (or vendor) / preservice / in-service inspections.
- Which tools are used for inspection, and whether ultrasonic testing will be used as a primary inspection tool.
- If DMW indications in DMW are identified, whether confirmative inspection using two different NDE methods will be used to confirm indications.
- Whether volumetric inspection at bends during fabrication (pre- and post-bending operations) and in-service inspections will be conducted. Should examinations or inspections for cracks not be performed, technical justification should be provided.

The implementation of an integrated enhanced inspection approach would enable the consideration of all the contributing factors impacting material quality to ensure that the proposed BEZ approach will result in reliable piping design for HELs and reduce the risk to the plant, the public, and the environment.

SUMMARY

This article provides a regulatory overview of the BEZ approach from a Canadian perspective including comparison with international best practices. The BEZ approach is an exception to current design standards that is not explicitly considered in the Canadian (CNSC) regulatory framework. Therefore, any proposed BEZ approach must demonstrate that it would result in an equivalent or superior level of safety and demonstrate compliance with the layered DiD approach. To support any BEZ application, it is necessary to provide an integrated approach to the design of HELs addressing the elements discussed above. Although there are different means to address the required low failure probability for HEL in a BEZ, the implementation of a probabilistic approach alone does not align with the Canadian practices. The proposed BEZ approach should also address:

- The prevention of dynamic effects
- The detection of postulated break
- Mitigation measures to minimize consequential damage

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