Application of the Leak Before Break Concept to CANDU Feeder Piping with Service Induced Cracking

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ABSTRACT

It has been claimed that Leak Before Break (LBB) is the failure mode for CANDU feeder piping experiencing service induced intergranular cracking at Point Lepreau Nuclear Generating Station (PLGS) and Gentilly-2 (G-2) operating in Canada. The feeders at PLGS will be replaced in the latter part of 2009 as part of the refurbishment program for plant life extension and G-2 is also scheduled to undergo refurbishment in 2011. No such cracking has been discovered in the feeders at other CANDU stations. However, due to the limited understanding of the cracking mechanism, particularly the root causes, it is currently not possible to preclude the susceptibility to the same cracking mechanism of the feeders at other CANDU stations which have similar manufacturing history and operating conditions to those of PLGS and G-2. Although the root cause is not yet confirmed, it is generally accepted that tensile residual stress plays a critical role in initiating and propagating the service induced cracks. Accordingly, cracking should be considered credible at the feeders possessing sufficient levels of residual tensile stresses. Once service induced cracking becomes an active degradation mechanism and there are uncertainties in the assurance of prevention of through wall cracking during operation based on crack growth rate estimation and detection limits of the in-service inspection technique, then LBB should be demonstrated as one of the elements supporting the fitness for continued service of the entire feeder population. Through the LBB assessment, it should be confirmed that a feeder rupture is an unlikely event even when cracks are not identified during an expanded inspection program scope and those remaining cracks would grow through wall during the next operating interval.

It is the regulatory view in Canada that the procedures for demonstrating LBB to support the continued operation of degraded components should be developed in a different manner from those used for conventional LBB which is used for the elimination of pipe whip restraints. It should incorporate actual characteristics of the degradation mechanisms, such as crack morphology, aspect ratio, material properties and so on. Particularly, demonstrating that there is a procedure to ensure actions are taken in a timely and safe manner would be the most important element. The safety margins adopted in the leak rate assessment and margin to crack stability should be subjected to regulatory review and acceptance.

A detailed regulatory perspective on the application of LBB to CANDU feeder pipes with susceptible service induced cracking is discussed in this paper.

1. INTRODUCTION

In the CANDU industry, the concept of leak before break (LBB) has been credited as a means of supporting the fitness for continued service of degraded CANDU components. [Jin et al. (2007)] The use of LBB in such cases implies that unidentified flaws, or flaws undetectable by available non-destructive examination (NDE) methods which could propagate into a through-wall flaw during the next operating interval would not grow to unstable size due to the early detection of the leakage by the plant leak detection systems and consequentially appropriate actions could be taken before the leaking flaw becomes unstable. In this regard, the LBB concept supporting continued operation of degraded components may have different connotations from the concept of the LBB which is used to justify the elimination of pipe whip restraints to compensate for local dynamic effects from a postulated pipe break. LBB, as a means of eliminating the pipe whip requirement, has screening criteria to exclude from the assessment those piping systems with credible active degradation mechanisms. Therefore, it has been recognized that the criteria for LBB to support continued service of degraded components should be developed in such a way to take into account characteristics of active degradation.

After the discovery of intergranular cracking in carbon steel CANDU feeder pipes at the PLGS in 1997, there has been extensive research carried out by the CANDU industry to support the fitness for continued operation of the feeders susceptible to cracking. These efforts include various engineering evaluations and testing programs to demonstrate that the failure mode of the cracked feeder would be LBB. The LBB argument was required, in addition to the replacement of cracked feeders, expanded inspection scope and adjusted operating interval, to address uncertainties involved with inspection capability and insufficient understanding of cracking mechanism in terms of rates for crack initiation and growth and also to quantify margins in the structural model to rupture of cracked feeders..

2. DESIGN CHARACTERISTICS AND DEGRADATION MECHANISMS

Design Characteristics

Feeders at CANDU stations are small diameter (mostly 2” and 2.5”) carbon steel pipes which constitute the primary pressure boundary and are accordingly classified as Nuclear Safety Class 1 designed to the ASME Section III, Subsection NB. CANDU is a pressurized heavy water reactor utilizing a number of fuel channels that contain fuel bundles. There are 380 fuel channels in the 600MWe class CANDU-6 power plants and 480 fuel channels at 900 MWe plants. Each fuel channel has an inlet and an outlet allowing for the flow of reactor coolant (D_2O) through the fuel bundles to remove heat generated by the fuel. The feeders connect the fuel channel inlets/outlets to the inlet/outlet headers which are all a part of the Primary Heat Transport System (PHTS). The CANDU feeders are made of SA106 Grade B carbon steel. The diameter of the schedule 80 feeder pipes ranges from 1.5 inches to 3.5 inches nominal pipe size (NPS). Depending on the routing, each feeder pipe has several bends, either long-radius or tight-radius. The operating temperature in the feeders ranges from 299^{o}C up to 318^{o}C and the pressure ranges from 10.0 MPa to 11.3 MPa and maximum flow rates from 24 kg/s to 29 kg/s.

Degradation Mechanisms

Operating experience has shown that the feeders are susceptible to two major degradation mechanisms, pipe wall thinning due to flow accelerated corrosion (FAC) and intergranular cracking. [Jin et al. (2007)] Virtually all outlet feeder pipes at all CANDU plants are experiencing pipe wall thinning due to the FAC at a rate much higher than design allowances for corrosion. Intergranular cracking is active or, when not active, believed to be credible in the tight radius bends of outlet feeders at some CANDU plants. Cracks found in the bends were initiated both at the inside and outside surfaces. Two possible causes for the cracking have been proposed by the industry: 1) Stress corrosion cracking (SCC) caused by exposure to the mildly oxidizing hot coolant; and 2) Low temperature creep cracking exacerbated by hydrogen. The latter mechanism has been invoked to explain cracks initiating at the outside surface. Since the creep cracking mechanism in carbon steels has in general not been observed at the operating temperature of outlet feeders, it is proposed by the industry that cracking is facilitated by a flux of atomic hydrogen generated by FAC at the inside surface of affected feeders.

Although the root cause analysis of this cracking remains inconclusive, it is generally accepted that tensile residual stress plays a critical role in initiating and propagating the service induced cracks. Accordingly, cracking should be considered credible at any outlet feeder bend possessing sufficient residual tensile stress to initiate cracking and is subjected to similar operating environmental conditions as bends known to have experienced cracking. Because of station-to-station differences in the fabrication process for feeder bends and differences with regard to the application of post-bending stress-relief treatments, the level of residual stress varies across Canadian CANDU plants.

CANDU Leak Detection Systems

The CANDU industry has claimed that leak detection systems installed at the CANDU plants are more sensitive compared to those at other types of nuclear plants as a result of the costs associated with upgrading of heavy water and the presence of tritium in the primary coolant. Economic considerations lead to the initiation of shutdowns due to unidentified leaks from the primary heat transport system circuit at rates of less than 360 kg/hr and station procedures are typically more conservative using rates of about 100 kg/hr or less Three different methods for leak detection are employed: (i) heat transport system inventory monitored via storage tank level, (ii) vapour recovery systems utilizing drier collection and powerhouse exhaust, and (iii) liquid detection systems using beetles (liquid collection trays) and the D_2O recovery trench level. An additional leak detection method, enhanced tritium detection, has been installed in the feeder cabinet at the plants that have experienced feeder cracking. The operators of the PLGS claim that the improved tritium detection system installed in the feeder cabinet has an absolute detection limit of 0.5 kg/hr.

Meanwhile, it is a challenge to locate small leaks in the CANDU since the design provides for many sources of minor spills, for instance leakage from fuelling machines, Grayloc joint, instrument tubes, gaskets and valves. Operational leak rate (shutdown action) limits are established to make it possible to monitor the leaks for the purpose of identifying the source of the leakage.

3. OPERATING EXPERIENCE

To date, there have been three incidents of feeder piping leaks at Canadian CANDU stations, two from feeder bends at PLGS in 1996 and 2001 and one from a feeder weld at G-2 in 2003. After the incidents at the PLGS resulted in the identification of feeder bend cracking, an expanded inspection program had detected several other part-through wall cracks, ranging from one to three surface cracks during each outage, until the plant entered a refurbishment outage in 2008. All feeders are being replaced during this refurbishment. The feeder leaking at a weld at G-2, which is also scheduled for refurbishment starting in 2011, triggered a comprehensive inspection scope for the welds with repairs at all CANDU stations but there have not been notable indications at feeder welds elsewhere to date.

Those three through-wall cracks described above were found as a result of detection by the plant leak detection systems. The leaks from the actual through-wall cracked feeders were detected and monitored for weeks and the reactor was shutdown at leak rate less than the operational leak rate limit. The leak rate history from a cracked feeder is shown in Fig. 1 as an example. It can be seen from the picture that the trend in leakage rate from feeder cracking allows sufficient time period enough for operating procedures to be taken. Although the trend shown in the picture can not be used for generalizing all possible leaking events, it gives an insight that fast brittle fracture may not be a governing mode of failure.

The continued operation of the feeders at PLGS and G-2 after the discovery of the intergranular cracking was allowed with the following measures taken by the licensees:

- replacements of all cracked feeders
- expanded inspection scope
- adjusted operating interval
- LBB evaluation, as a defense-in-depth

4. REGULATORY PERSPECTIVE

It has been the regulator's expectation that all Nuclear Class 1 pressure boundary components should be designed and operated with its pressure boundary integrity to be maintained under all circumstances. Licensing conditions for the Canadian CANDU's require pressure boundary components to be operated in compliance with the limitations specified in design documents and applicable codes and standards. The Class 1 pressure boundary components of CANDU's are designed to ASME Section III, subsection NB, which requires that the pressure boundary integrity be maintained under all operating conditions, i.e., normal, abnormal, upset and faulted conditions. However, even with the high quality of design and manufacturing of the components in accordance with ASME Section III, it has been recognized from operating experience that in-service inspections are required to monitor for service induced degradation. For this reason, CSA-N285.4, which references ASME Section XI, has been developed to provide requirements for in-service inspection and procedure for the assessment of detected flaws. If there is possibility that the flaw is service induced and therefore is believed to be growing, then the flaw growth rate should be assessed and taken into account in fitness for service assessments with sufficient supporting evidence. Section XI permits the assessment of flaws in Class 1 piping with end-of-evaluation period depth not exceeding 75% through wall. Therefore, it should be construed that any leakage through Class 1 piping during operation is not considered under applicable codes and standards. The basic philosophy of licensing is to detect flaws by in-service inspection so that the leakage of coolant does not occur.

However, even though the pressure boundary components are designed and operated in accordance with the requirements given by appropriate codes and standards, there are issues remaining as a result of uncertainties involved with the NDE detection limits and probability of detection. If the flaw is service induced, then the degree of uncertainty increases if there is insufficient mechanistic understanding of the mode of the degradation. These uncertainties should be taken into account in the fitness for service assessment with the provision of adequate safety margins. Although the consideration of the consequence of leakage deviates from the pressure boundary design concept as mentioned above, it has been recognized that the management of a degradation mechanism could be based on the consequences of a leak, if there is concrete evidence demonstrating that final failure mode would be LBB and that necessary operating procedures are in place to support LBB (e.g., redundancy and diversity in leak detection and response to detected leak). In this case, the concept of LBB shall be applicable for a specified operating period, not as a principal long term method for managing service induced degradation. The acceptance of the LBB argument is based on:

- Single feeder failure was already considered in the safety analysis for Canadian CANDU plants as a design basis accident.

- LBB argument is only permitted to address the uncertainties involved with the limitations of the in-service inspection and uncertainties associated with crack initiation and crack growth rate. The LBB argument would not be approved for disposition of a detected service induced crack.
- Consequential leakage should be evaluated for most limiting upset and faulted condition to demonstrate assurance that there is no significant incremental risk of an inadequate margin between estimated total accumulated dose and applicable site dose limits. The consequential leakage for a 40 mm long through axial crack in the extrados of a 2.5" tight-radius bend thinned to 4.0mm wall thickness would be less than 1500 kg/hr. This consequential leakage is claimed to be significantly less than the initial discharge rate for the smallest break that would require emergency core injection.
- In-service inspection program should be enhanced to be commensurate with the risk associated with the consequences of the failure of the degraded components.
- Operating experience at PLGS and G-2 indicates that the detection of leakage from a through-wall crack would be possible by the plant leak detection systems before a feeder rupture occurs with sufficient margins.

Recently it was noted that, during the course of dealing with the issue of pressurized water stress corrosion cracking (PWSCC) discovered in LBB applied piping at some PWR plants, the US-NRC approved Advanced FEA evaluation that used more realistic assumptions for the LBB evaluation to demonstrate that the potential PWSCC would progress through wall and exhibit detectable leakage prior to causing a possible rupture event, through a reduction of excessive conservatism and uncertainties from previous analysis. [Sullivan (2008)]

Although the criteria for LBB may differ case to case, the fundamental elements of demonstrating LBB should not differ. These elements include (i) leak detection capability, (ii) sufficient margin on crack stability and (iii) procedures to ensure a timely response to detected leakage. It is the regulator's view in Canada that the requirement for LBB to support the continued operation of degraded components should be developed differently from those for conventional LBB which is used for the elimination of pipe whip restraints. It should incorporate actual characteristics of the degradation mechanisms, such as crack morphology, aspect ratio, material properties and so on. Particularly, demonstrating that there is a procedure to ensure actions are taken in a timely and safe manner would be the most important element. The safety margins adopted in the leak rate assessment and margin to crack stability should be subjected to regulatory review and acceptance.

As mentioned earlier, it has been operating practice at CANDU plants to monitor the leaks to identify the source of leakage. The operational leak rate (shutdown action) limits are set out for this purpose. Industry has claimed that the leaks would be detected at rate much less than the operation leak rate limit. However, assessment of the adequacy of the operational leak limit should be subjected to regulatory review. It would be reasonable to set out the limit based on the structural integrity of the postulated leaking crack compared with the critical crack size.

Assessment of structural integrity of the component with possible deep surface cracks and/or through wall cracks with undetectable leakage should be conducted to demonstrate a sufficient margin to the structural failure.

Meanwhile, there have been continued efforts in the international nuclear industries and regulatory bodies to use a probabilistic approach to strengthen the assessment that there is a sufficiently low probability for a pipe rupture resulting from active degradation mechanism and that there is sufficient margin between the initial detectable leaks and break. [Brickstad. (2008)] Probabilistic evaluations used to demonstrate the extremely low probability of rupture of degraded CANDU components may be reviewed by the regulator on a case by case basis. Validation of a probabilistic fracture mechanics code would be one of the subjects of the review.

5. CONCLUSIONS

Although the consideration of the consequences of leakage deviates from the basis for design and operation of the pressure boundary components, it has been recognized that the management of a degradation mechanism could be based on the consequences of a leak, if there is concrete evidence demonstrating that final failure mode would be LBB and that necessary operating procedures are in place to support LBB.

The procedure for demonstrating LBB for supporting the continued operation of degraded components should be developed differently from those for conventional LBB which is used to support the elimination of the requirements for pipe whip restraints. It should incorporate actual characteristics of the degradation mechanisms, such as crack morphology, aspect ratio, material properties and so on. Safety margins on the leak rate and crack size will be subjected to regulatory review.

Assessment of the adequacy of the operational leak limit should demonstrate sufficient margin on the structural integrity of the postulated leaking crack compared with the critical crack size.

Remarks: This paper should be considered for research purposes and not as constituting an official regulatory position, which must be in the form of formal letter from the CNSC.

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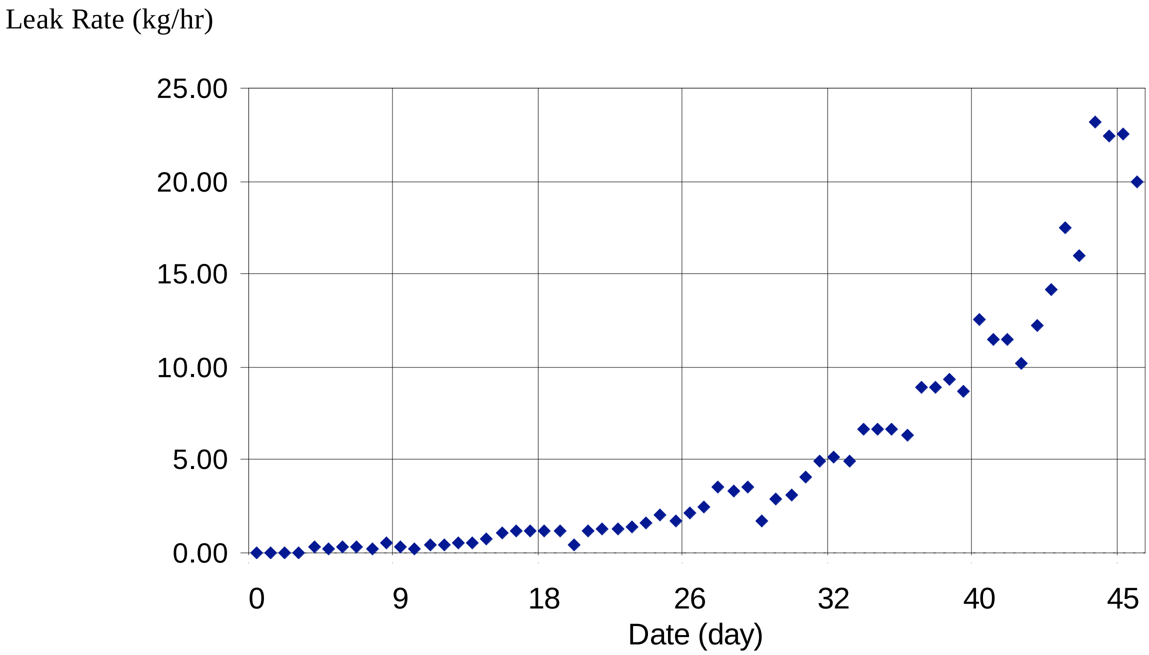

Figure 1 Example of leak rate history of feeder pipe leaking at a CANDU station