Overview and Lessons from more than a Decade of Feeder Life Management

A. Usmani[1], Z. Walker[2] and A. Meysner[1]
[1] AMEC NSS, Power and Process Americas, Toronto, Ontario, Canada
(Aman.Usmani@amec.com)
[2] Candu Energy Inc., Mississauga, Ontario, Canada

Abstract

This paper provides an overview of the degradation in CANDU feeders in operating plants observed from mid 1990s onward, the industry's response to the discovery of this degradation, and the methodologies, tools and technology developed to monitor the degradation and assess continued fitness for service to manage the plant life. The lessons gained from more than a decade of industry effort, and how these are being implemented in the refurbished and new CANDU plants, are discussed.

1. Introduction

Feeder pipes form an integral part of the CANadian Deuterium Uranium (CANDU) Heat Transport System (HTS), transporting heavy water coolant to and from the fuel channels and the inlet and outlet headers. By virtue of their sheer number (up to 480 inlet and 480 outlet feeders) and their congested layout at the reactor face and in the feeder cabinet, the feeders are precision engineered, fabricated and installed components. Each feeder is comprised of one or two tight-radius bends and several long radius bends, and may contain a flow orifice for controlling flow, a flow element for measuring flow, and a swaged reducer for accommodating changes in pipe diameter. All of these components are welded together, resulting in several thousands of welds throughout the feeder piping system. The feeders are fabricated from SA-106 Grade B carbon steel (Grade C in CANDU plants beginning with Qinshan Units 4 and 5) with the exception of flow devices which are fabricated from alloy 600 material.

Considering their complexity and the demanding performance requirements, the feeder pipe systems have performed, in general, very well. However, beginning in the mid 1990's, higher than expected rates of wall loss of outlet feeders were first reported at the Point Lepreau Generating Station (PLGS) and eventually confirmed at all CANDU stations. Then, in 1997, a through-wall crack was discovered in the tight-radius bend of the S08 outlet feeder at the PLGS. Bend cracking was eventually found to be a widespread degradation mechanism in the outlet feeder piping system at the PLGS; bend cracking has not been observed at any other CANDU station.

To address the discovery of wall thinning and cracking in the feeder piping system, the Canadian CANDU industry, including the CANDU utilities (New Brunswick Power Nuclear, Hydro Québec, Bruce Power and Ontario Power Generation) and the CANDU designers (Atomic Energy of Canada Limited, and more recently Candu Energy Inc.) jointly funded projects through the CANDU Owners Group (COG) beginning in the 1990's. These projects identified the root cause for the observed degradation, as well as the mechanistic factors driving the degradation, and developed strategies for managing the degradation in operating plants. To support the implementation of these strategies, the industry funded projects to develop Non-Destructive Examination (NDE) tools and procedures to assess the extent of degradation in operating plants, Fitness for Service Guidelines for dispositioning all forms of degradation found, and, in the cases where the feeders failed to meet the acceptance criteria, tools for the repairing and replacing feeder components. This paper provides a summary of these activities and demonstrates how the industry has successfully managed feeder degradation in the current CANDU fleet.

2. Background to Feeder Wall Thinning and Feeder Cracking

By the mid-1990's, it became apparent that relatively large deposits of magnetite were being observed in the cold leg of the steam generators, and carbon steel feeder pipes were suspected as being the source of the iron. Wall thickness inspections performed on the tight radius bends near the reactor face, first at PLGS in 1995 and subsequently at other CANDU stations, revealed higher than expected rates of wall loss. The mechanism responsible for the wall thinning of outlet feeders was confirmed to be Flow Accelerated Corrosion (FAC) following the removal of a section of the S08 outlet feeder from PLGS in 1997 and the appearance of the characteristic scalloped surface and thin oxide (magnetite) film on the inside surface.

With the collection a large number of wall thickness measurements from CANDU outlet feeders over the ensuing years, stations confirmed that [1],[2]

- outlet feeders were experiencing a linear rate of feeder wall loss with time, and
- the rate of wall loss was dependent upon coolant velocity and turbulence, as manifested through bend geometries and hydraulic conditions.

Not only did the development of this understanding reinforce the conclusion that the higher than expected wall loss was attributed to FAC, it also provided the means to confidently predict the future wall thickness of outlet feeders. The understanding of the roll of water chemistry on FAC provided an opportunity to reduce the wall thinning rate through tighter control of coolant alkalinity [3]. Inspections performed on a significant number of inlet feeders across the industry demonstrated the absence of this form of degradation. In recent years, the removal of inlet feeders during refurbishment related activities confirmed that iron oxides were indeed showing net deposition, rather than net removal, at inlet feeder surfaces.

The first indication of cracking in CANDU feeders came following the discovery of a through-wall crack in the S08 outlet feeder bend at PLGS in 1997. Following the discovery of an additional outlet feeder bend with a through-wall crack, and two outlet feeder bends with partial through-wall cracks, in 2001, the widespread nature of bend cracking at PLGS became apparent [1]. In the years that followed, partial through wall cracks were detected, through in-service inspections, in an additional eight outlet feeders. By the time that PLGS was shut down for refurbishment, a total of 12 outlet feeder bends had been removed due to the presence of a mixture of inside and outside surface initiated cracks.

In 2003 at the Gentilly-2 Nuclear Generating Station, a crack was found in the G09 feeder field weld, which had been repaired during construction. Post-removal examination of the cracked weld revealed similarities with the bend cracks observed at the PLGS, namely that all cracks initiated in locations of [1];

- high-residual tensile stress [4] (the PLGS feeder bends had not been stress relieved during fabrication) and

- in material that had been subjected to cold work.

The fact that the cracking had exclusively occurred in outlet feeders indicated that the higher temperatures synonymous with outlet conditions were also likely a prerequisite for cracking susceptibility. Evidence obtained through post-removal examination of cracked feeder bends, as well as through laboratory testing of feeder pipe material, indicated that the bend cracking was most likely caused by either or both stress corrosion cracking, in the case of the inside surface initiated cracks and low temperature creep cracking, possibly enhanced by the presence of atomic hydrogen in the steel, which is formed during the FAC of the inside surface.

In spite of extensive inspections of non-stress relieved tight-radius bends and of feeder welds in other CANDU plants, no evidence of additional cracking has been observed. Although this suggests that the PLGS feeder pipes were predisposed to cracking, no material or operating condition unique to PLGS has yet been identified.

3. Industry Response

Upon the discovery of feeder wall thinning in the 1990's, the Feeder Wall Thinning Project was initiated and funded through the COG. Much of this work was focused on improving the understanding of the extent of feeder wall thinning in the stations and developing the first Fitness for Service Guidelines to deal with the observed wall loss degradation. A similar joint project was initiated following the discovery of the first crack in the S08 outlet feeder bend at PLGS, with an emphasis on identifying the mechanism(s) responsible. Following the discovery of three cracked feeder bends at PLGS in 2001, and the realization that the extent of wall loss in some CANDU plants was likely to limit the operating life of some of the outlet feeders, the Feeder Integrity Joint Project (FIJP) was initiated with a mandate to address all forms of feeder degradation.

The FIJP was comprised of multi-disciplinary technical specialists organized and directed by the Feeder Integrity Steering Committee. The technical specialists were aligned under teams addressing;

- chemistry related aspects of feeder degradation,

- non-destructive examination technology,
- integration of industry data and understanding,
- repair and replacement technology, and
- fitness for service.

Strategies were developed to manage feeder degradation, together with the tools necessary to implement these strategies. These tools were comprised of

- assessment methodologies, including Fitness for Service Guidelines (FFSG),
- NDE inspection tools for performing in-service inspections, and
- tools required for the repair and replacement of feeder components.

4. Assessment Methodologies

With the discovery of feeder wall thinning and subsequent feeder cracking, the CANDU industry performed a significant amount of stress analyses using a range of methodologies including linear, elastic-plastic, limit and collapse analyses. Probabilistic assessments of the degradation and extent of condition were also performed. Effort was spent to validate these methods and demonstrate the availability of ample margins. The highlights of these methodologies are provided below.

4.1 Stress Analysis

The stress analysis of degraded feeders was initially based on the ASME Section III NB3600 requirements of the design and construction code. Various modeling approaches were employed and included;

- single feeder models, as well as more complex multi-feeder models, using uniformly thinned pipe bends to simulate thinned pipe bend profiles with bounding amounts of ovality,
- the stress indices used in the analysis included both code prescribed values for pipe bends and elbows as well as more realistic, finite element calculated values,
- elastic-plastic fracture mechanics methods,
- seismic analysis using both linear modal superposition floor response spectrum and direct integration time history approach.

The industry directed effort at standardizing the analysis methodologies, eventually producing a document describing the various methodologies used in each submission to the CNSC by the member utilities. Along with a check list, this stress analysis summary report facilitated regulatory reviews of the fitness for service submissions. In some cases elastic plastic, limit and collapse load methodologies of ASME Code NB 3200 were also used to demonstrate the fitness for service of thinned feeders. A representation and a successful submission to revise the number of cycles and the permissible value of damping in seismic analysis of feeders was made to the CSA N289 technical committee, with the revised values appearing in the latest revision of the CSA N289.3-10 Standard.

In parallel with the conventional ASME code approach to demonstrate the fitness for service of degraded feeders, the Fitness for Service Guidelines (FFSG) for feeders subjected to various degradation mechanisms were also developed. The development of the technical basis and the FFSG is described in a subsequent subsection.

4.2 Technical basis document and FFSG

Over the period of a decade, more than two hundred technical reports on various relevant topics were prepared by FIJP investigators. The results from these technical reports ware integrated in two Technical Basis Documents and provided the foundation for the FFSG. The development of FFSG was a major accomplishment of the FIJP.

The FFSG document for CANDU feeders is similar in approach to ASME Section XI for the operating light water reactors. The FFSG address all three forms of degradation; namely wall thinning, cracking/planar flaws and blunt flaws. The guidelines provide reasonable assurance, using industry acceptable consistent methodologies, that feeder structural integrity is maintained and that any consequential leakage from feeder flaws would be acceptable in that the leak could be detected in a timely manner and the reactor safely shutdown, if required.

The FFSG Revision 2 was accepted by the CNSC on a trial basis for 2 years in 2010. The updated Revision 3 of the FFSG will be submitted to CNSC for approval this year.

4.3 Feeder Bend Testing

One of the major accomplishments of the FIJP was to perform feeder bend tests simulating thinning and cracking, under internal pressure and moments loading. At the outset, the margins to failure of feeders subjected to active degradation were not known. It was recognized early on that full size components tests would be required to take full advantage of these unidentified margins. These tests were performed using removed ex-service, archived and new fabricated feeder bends. The feeder bend test program results demonstrated that even the most significantly degraded feeders have adequate margins to failure.

4.4 Probabilistic Methods and Software tools

Due to some of the limitations associated with inspecting the complex feeder piping system in a radiation environment, the amount of inspection data available often leads to overly conservative outcomes when using deterministic analysis methods. As a consequence, probabilistic methods were developed to provide the required degree of confidence when estimating wall thinning rates, optimizing inspection sample size and in assessing the possible extent of degradation in the non-inspected feeder population.

The first statistical/ probabilistic approaches were applied to feeder thinning at Pickering A NGS and to feeder cracking at PLGS [5]. Eventually, these probabilistic approaches were incorporated into the following qualified software tools;

- Feeder Inspection Regression Statistical Tool (FIRST) for feeder thinning and
- Probabilistic Feeder Analysis Tool (Pro-FAST) for feeder cracking.

Probabilistic methods have also been applied to estimate the rupture frequency of elbows with blunt flaws [6].

4.5 Dissimilar Metal Welds

Following the OPEX from pressurized water reactors indicating the susceptibility of dissimilar metal welds involving nickel-based materials, work was performed, under the COG R&D program, to investigate the potential susceptibility of dissimilar metal welds between the carbon steel feeder pipes and alloy 600 flow devices located in some of the outlet feeders at the Darlington and Bruce Nuclear Generating Stations. CSA N285.4 standard governing the in-service inspections of the feeder piping system requires that locations susceptible to in-service cracking be inspected. Unfortunately, these feeder dissimilar metal welds are very difficult to access and any attempts to inspect them will be dose intensive.

To manage the issue of dissimilar metal welds and their in-service inspection requirement, probabilistic and deterministic leak-before-break assessments were initiated under the FIJP. These assessments are intended to be used to demonstrate an acceptably low probability of rupture and to demonstrate that the margins on crack size, load, and detectable leak rate are sufficient to conclude that leakage from through-wall circumferential cracks would be detected and the unit shutdown prior to the feeder rupturing. This work was recently transferred to the COG R&D program where activities required to resolve outstanding issues are underway

5. Inspection Tools

Monitoring the degradation being experienced in the outlet feeders of CANDU plants was complicated by several factors unique to CANDU feeders. The complex feeder geometry and the close proximity of feeders to other feeders, components and support structures, resulted in significantly challenging clearance issues for traditional NDE tooling. The relatively thin wall of feeder pipes meant that wall thickness inspection tooling had to detect relatively small changes in wall thickness with high spatial resolution. In terms of volumetric inspection for feeder cracks, the tooling had to have the sensitivity to detect relatively small (shallow) cracks while maintaining a low rate of false positive calls. The relatively high radiation fields associated with the reactor face meant that the inspection tooling had to operate efficiently so as to limit the inspectors' exposure to dose. These restrictions necessitated the development of feeder specific inspection tooling and procedures.

Several tools were developed to facilitate the wall thickness inspection of the following feeder locations;

- Feeder bends- A scanning tool [7], comprised of 14 conventional ultrasonic probes mounted in a flexible bracelet covering a significant fraction of the pipe's circumference, was developed. The tool can be translated over long lengths of feeder pipe, either manually or using a mechanized crawler, including over bends. Data are collected simultaneously from all 14 probes with high axial spatial resolution.

- Feeder pipe adjacent to welds - To provide wall thickness inspection data in regions immediately adjacent to welds, such as the hub-to-pip weld, which the 14 probe tool cannot access, specialized tools containing 6 to 8 conventional ultrasonic probes, were developed.

- Feeder pipe under welds: To provide measurements of wall thickness directly under weld caps, a tool based on phased-array ultrasonic techniques, was developed.

Furthermore, to efficiently process the very large quantities of ultrasonic time of flight data generated with these specialized inspection techniques, the Feeder Automated Analysis and Trending Software (FAATS), data analysis software package was also developed.

Specialized tools and procedures were also developed for detecting cracks through volumetric inspections of the following feeder locations;

- Feeder bends: A manual shear wave technique and a highly evolved procedure optimized for axial crack detection has been widely used in the industry for over a decade [8]. In recent years, the delivery and application of this shear wave technique has been automated, significantly reducing the time required for an inspector to spend at the reactor face, thereby reducing the associated dose.

- Feeder welds: An phased-array ultrasonic technique and procedure were developed to detect for the possible presence of circumferential cracks,. The delivery and application of this inspection methodology was also automated to reduce inspector dose.

To ensure the reliability of these NDE inspection methodologies, and to comply with regulatory requirements, these inspection technologies are being qualified to the requirements of the CANDU Inspection Qualification Bureau.

6. Feeder Repair and Replacement

Upon recognizing the significance and potential impact of feeder wall thinning and feeder cracking, and the likely need to replace a significant number of feeders, effort was directed at developing tooling that could be used to either repair feeders in-situ or to assist with the removal of the feeder and the replacement with a new spool piece. Due to the limited access associated with the feeders, especially at the reactor face, the tools, as well as the procedures, had to be highly customized.

To date, all feeder sections failing to meet acceptance criteria have been cut out and replaced using specialized tooling using procedures developed by the service providers performing the replacements. The FIJP also funded work to develop technology that could provide isolation to an outlet feeder nozzle, a location that would be impossible to isolate using standard freeze plugging technology.

7. Lessons Learned

Upon discovering the presence of active feeder degradation mechanisms, the industry undertook a concerted effort to understand the mechanisms and causes of degradation and to implement measures to monitor and manage degradation, including tools and methodology development. Through more than a decade of industry experience, lessons have been gained and are discussed below.

7.1 Operating Experience (OPEX)

Ongoing attention to operating experience from CANDU and LWR plants and ongoing findings from R&D is extremely important. Some examples of relevance to feeder degradation are noted below.

- The catastrophic failure of a high pressure condensate line in Surry Nuclear Power Plant in 1986- gave the first indication of the FAC in carbon steel pipe; this was nearly a decade prior to the first detection of FAC in CANDU feeders. The effectiveness of small additions of chromium to carbon steel was fully established and was implemented immediately in new CANDU reactors subsequent to the discovery of feeder wall thinning. As well a recommendation to operate the reactors coolant circuit at the lower end of the permissible range of pHa was also implemented.
- The role of residual stresses in crack initiation and propagation has long been known. Although stress relieving heat treatments of cold worked feeder material had been

adopted at many CANDU plants prior to the discovery of the first crack at PLGS, it is now a mandatory requirement for refurbished and new plants.

- Dissimilar metal welds, involving nickel-based materials, have been of concern to the pressurized water reactors for many years and this OPEX was the trigger for assessing the condition of dissimilar metal welds in some outlet feeders at a small number of CANDU plants.

7.2 Joint Projects

Given the relatively smaller size of the CANDU industry, the role and effectiveness of pooling of resources to cooperatively handle issues such as those in feeders in operating plants is highly recommended.

The success of the COG FIJP to effectively manage the feeder life in the operating CANDU plants is a good example of this recommendation.

7.3 Communication with Stake Holders including the Regulator

Information sharing, on-going communication amongst the various stake holders and the regulatory organization(s) is extremely valuable in avoiding surprises and delays.

The FIJP developed FFSG, together with the technical basis documents, and acceptance by the CNSC is a good example of the cooperation amongst all the stake holders. Likewise, incorporation of the seismic number of cycles and damping into the CSA N289.3 Standard, to reflect industry practice and current knowledge in the assessment of the degraded feeders, is another good example of such collaboration.

7.4 Testing

Notwithstanding advances and sophistications in computerized analytical methods, experimental testing is very valuable in validating the analytical techniques and in providing reliable determination of margins to failure.

7.5 Probabilistic Methods

The probabilistic methods are valuable in accounting for uncertainties, extending the results to un-inspected population, optimizing the inspection scope and providing associated confidence levels as one of the inputs to the decision makers.

7.6 Independent Reviews

To provide a high degree of confidence, it is advisable to engage knowledgeable and reputable independent reviewers to provide their input and endorsement.

8. Improvements in the Refurbished and New Designs

Considerable insights into the mechanisms of feeder wall thinning and feeder cracking were gained through the work performed in the FIJP, as well as through initiatives undertaken by AECL and the CANDU utilities. This work included the identification of key factors that influence the extent to which these degradation mechanisms are active in outlet feeders of CANDU plants. Understanding how these factors affect feeder degradation provides an opportunity to implement new requirements during the refurbishment and design of current and new reactors respectively to ensure that the design life of feeders is not limited by these mechanisms in the future.

The key improvements introduced to mitigate the impact of feeder wall thinning include;

- A minimum chromium content of 0.30 wt% - Since the FAC of carbon steel is characterized by the rapid dissolution of the magnetite corrosion film, the addition of even small amounts of chromium can significantly reduce the solubility of this corrosion film, and thereby reduce the feeder wall thinning rate [9].

- Increased wall thickness of 2-inch feeders in CANDU 6 and other reactors where considered appropriate- The corrosion allowance of 2-inch outlet feeders was typically ~2/3 of that of 2½-inch outlet feeders. As result, 2-inch outlet feeders were typically life-limiting in CANDU 6 plants. By increasing the wall thickness of the 2-inch pipe, the operating life of these feeders is significantly increased.

- Tighter controls on the reduction of wall thickness - During feeder fabrication, the wall thickness of a feeder can be reduced during the bending process or as a result of localized grinding to facilitate fit up to other components such as hubs. Requirements have been introduced to more tightly control these activities, to ensure that any reduction in wall thickness is within acceptable limits and is properly documented.

- Material specified to SA-106 Grade C rather than Grade B - Although the tensile properties of many heats of the feeder pipe ordered for original CANDU plants met the higher strength requirements of SA-106 Grade C material, the higher strength could not be credited since the material was specified to Grade B requirements. Feeder pipe is now specified to the Grade C requirements, allowing the higher strength properties to be credited and providing additional margin in the feeder design.

Additional improvements have been introduced to eliminate the susceptibility to feeder cracking in the future.

- Stress relieving of all bends and swages - Since the cracking observed to date has all occurred in locations of high residual tensile stress, applying stress relieving operations to all bends will essentially remove the driving force for crack initiation and propagation. The stress relieving operations also reduce the impact of changes in the microstructure of the steel introduced during the cold forming and welding operations, resulting in a material less susceptible to cracking.

- Killing the steel with aluminum - One of the mechanisms believed to be responsible for feeder bend cracking is low temperature creep cracking. Since this mechanism is prevalent in material with high free nitrogen content, killing the steel with aluminum during the steel making process essentially eliminates free nitrogen from the steel and the susceptibility to this form of in-service degradation.

- Elimination of localized weld repairs - Since localized repaired welds, in which material is locally removed and back filled with weld metal, are known to be more susceptible to in-service degradation, the elimination of such repairs in new feeders significantly reduces the likelihood of weld cracking.

9. Summary and Conclusions

The life management of CANDU feeders over more than a decade has provided a good understanding of the degradation mechanisms, means to monitor, assess and establish the fitness for service, as well as the improvements required to mitigate these forms of degradation in the refurbished and new feeder designs. The lessons gained also highlight the significance of ongoing attention to OPEX, the value of industry cooperation, the effectiveness of information sharing and involvement of all stake holders in tackling generic industry issues.

10. References

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