A LAST LOOK AT PLGS LIFE-LIMITING FEEDER DEGRADATION

J.P. Slade[1], T.S. Gendron[2]
[1] NB Power Nuclear, Lepreau, New Brunswick, Canada
[2] Atomic Energy of Canada Limited, Chalk River, Ontario, Canada

Abstract

Severe feeder degradation was one of the main drivers for PLGS refurbishment three years prior to its design life. The first part of this paper provides an overview of PLGS feeder degradation, including wall thinning adjacent to the Grayloc hub weld.

PLGS shut down for refurbishment in March 2008 after ~21 FPY service. The entire feeder assembly is being replaced with improved piping that is expected to achieve its 24 FPY post-refurbishment design-life. The second part of this paper provides a summary of these improvements.

The paper concludes with a discussion of plans to manage feeder degradation during post-refurbishment operation with the goal of ensuring the feeders achieve their design intent with minimal maintenance.

1. Introduction

PLGS has experienced some of the most severe feeder degradation within the CANDU industry. It is the only CANDU reactor to replace feeder bends because of cracking. The projected need to replace feeders because of life limiting cracking and wall thinning was one of the main drivers for PLGS refurbishment three years prior to its design life. The first part of this paper provides a high level summary of PLGS feeder degradation and its management for the first ~21 FPY of operation.

PLGS shut down for refurbishment in March 2008. All feeders are being replaced from the fuel channel connections up to the header nozzles. The second part of this paper provides a summary of the design improvements that are expected to prevent feeder life-limiting degradation for PLGS's 24 FPY post-refurbishment design-life. The paper concludes with a discussion of changes to PLGS feeder management strategies and activities for post-refurbishment operation.

2. PLGS Feeder Degradation Operating Experience

This section provides a high-level summary of PLGS feeder degradation and management strategies during pre-refurbishment operation. Wall thinning adjacent to the Grayloc hub weld is described in more detail; more information on the other topics can be obtained from previous publications [1-4]. For COG members, there are numerous Feeder Integrity Joint Project reports that provide a wealth of additional information about work that contributed to this summary.

NBPN replaced tight radius outlet bends from twenty-four feeders during the first ~21 FPY of PLGS operation. Twelve were replaced because of cracking at bends, six because of wall thinning at bends, and six because of false positive inspection indications of cracking. Information about these feeders is summarized in Table 1.

Table 1: PLGS Feeder Replacement History Prior to Refurbishment
Tight Radius Outlet Feeder Bends

Feeder	Bend with* crack	Surface with Crack	Max Crack Size (mm)		Detected /Removed		Crack Detected by	Previous Inspection	
			Long	Deep	Year	FPY		Date	FPY
Feeders Removed with Confirmed Cracks – all 2.5” Diameter Pipe									
S08a	1st	Inside	63	7.0	1997	12.5	Leak	-	-
K16a	1st	Inside	55	7.3	2001	15.4	Leak	-	-
U15c	1st	Inside	30	5.7	2001	15.4	UT	-	-
Q08a	1st	Inside	50	3.6	2001	15.4	UT	-	-
N19a	2nd	Inside Outside	66 40	6.9 4.8	2003	17.4	UT	-	-
C13a	1st	Inside	38	5.8	2003	17.4	UT	May 2001	2.00
P09a	1st	Inside	15	3.7	2003	17.4	UT	May 2002	1.11
N11a	1st	Inside	18	2.8	2004	17.9	UT	Sept 2003	0.58
D14a	2nd	Outside Inside	15 19	2.7 2.5	2005	18.6	UT/ET Burst Test	May 2004	0.73
H12a	2nd	Outside	17	3.2	2006	19.5	UT	Apr 2005	0.87
N16c	1st	Inside	28	3.3	2006	19.5	UT	Apr 2005	0.87
N12c	1st	Inside	~25♠	2.9♠	2007	20.2	UT	Apr 2006	0.73
Feeders Removed due to False Positive NDE Indications – all 2.5" Diameter Pipe									
E08c	2nd	Inside	-	-	2005	18.6	UT	May 2004	0.73
E14c	2nd	Inside	-	-	2005	18.6	UT	May 2004	0.73
K05c	1st	Inside	-	-	2005	18.6	UT	May 2004	0.73
P18c	2nd	Inside	-	-	2005	18.6	UT	May 2004	0.73
L16c	1st	Outside	-	-	2005	18.6	ET	May 2004	0.73
O07c	1st	Outside	-	-	2005	18.6	UT	May 2004	0.73

Feeders Removed due to Wall Thinning – all 2" Diameter Pipe

Feeder	Minimum Wall Thickness		Removed		Measured By	Previous Inspection	
	Bend with* Minimum	Measured in 2005 (mm)	Year	FPY		Date	FPY
C06	2nd	2.96	2005	18.6	METAR	May 2004	0.73
C17	2nd	2.99	2005	18.6	METAR	May 2004	0.73
D05	2nd	2.85	2005	18.6	METAR	May 2004	0.73
D18	2nd	2.85	2005	18.6	METAR	May 2004	0.73
E19	1st	3.17	2005	18.6	METAR	May 2004	0.73
H02	1st	3.02	2005	18.6	METAR	May 2004	0.73

UT – Ultrasonic Crack Detection Inspection   ET – Eddy Current Inspection   ♠ estimated from NDE

* if unacceptable degradation was detected in a compound bend, both bends were replaced

2.1 Feeder Wall Thinning

Excessive wall thinning at feeder bends near the reactor outlet was first discovered by inspections at PLGS in 1995. Since that time, comprehensive inspections, examinations of removed feeders, and research programs have identified the rates and patterns of wall thinning throughout the feeder system, and the mechanism and key factors driving it. For operation up to reactor refurbishment, the primary strategy to manage feeder wall thinning has been inspection and repair, requiring replacement of bends from six 2" diameter feeders. The subsections below provide an overview of these topics.

Mechanism

The mechanism of wall thinning was identified as Flow Accelerated Corrosion (FAC) based on the thin magnetite film (~1-4µm) and scalloped appearance of feeder inside surfaces (Figure 1), and the constant corrosion rates. FAC is caused by coolant flow and chemistry conditions that remove the magnetite film that normally protects the feeders from corrosion, and promote a high transport rate of corrosion reactants and products to and from the surface, respectively.

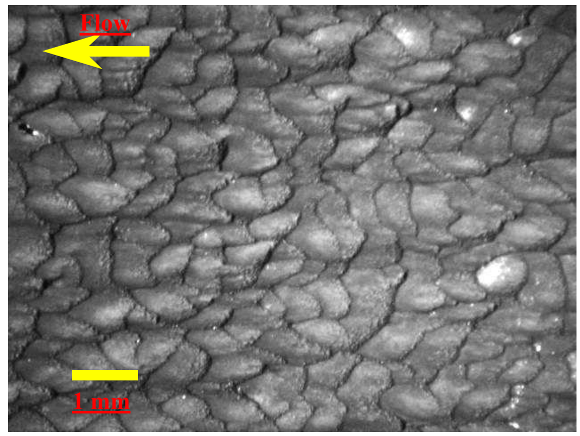


Figure 1: Scallops on Feeder S08a

Key Factors Causing Feeder Wall Thinning

The primary factors causing feeder wall thinning are given in Table 2. All original PLGS feeder material has relatively low chromium content (~0.02wt%) and is susceptible to FAC when key environmental factors are present. These factors are coolant that is both turbulent[1] and is unsaturated in dissolved iron with respect to the formation of magnetite. Turbulence occurs to varying degrees throughout the feeder system, dependant on coolant velocity and geometries that promote local flow disturbances. However, the coolant is only unsaturated in iron in outlet feeders and hot-leg piping where the temperature is high and dissolved iron has already precipitated in the cold-leg of the circuit, in particular in the steam generators and inlet feeders and headers. Based on field experience and research results [5], utilities also aim to operate at the low end of the coolant pH_a specification (10.2-10.4) to minimize FAC rate. PLGS has been doing so since 1996.

Another important factor that affects the lifetime of piping affected by FAC is the initial pipe wall thickness. Locations where the initial thickness is relatively low from fabrication steps such as bending and grinding are more susceptible to life-limiting wall thinning. The "warm bending" procedure [6] used to bend PLGS feeders thickens the bend intrados and thins the extrados, as shown in Figure 2.

[1] More specifically, high mass transfer rates in the coolant boundary layer at the pipe wall

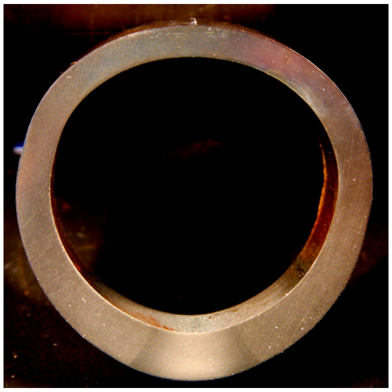


Figure 2: Spare Bend Apex

Table 2: Key Factors Causing Feeder Wall Thinning

	Key Factor	Affects Location
Material	Geometries that create turbulence[1]	Downstream of fuel channel outlets, bends, orifices, reducers
	Areas thinned during fabrication	Bend extradoses, grinding spots at welds
	Steel with low wt% Cr	All feeders (~0.02wt%Cr)
Environment	High coolant velocity / turbulence	High power channel feeders more affected
	Coolant unsaturated in iron (high temperature, low dissolved iron)	Outlet feeders only
	Coolant pH_a	FAC minimized at 10.2-10.4

Rates and Patterns of Wall Thinning

The variation in key factors present in the outlet feeders gives rise to varying wall thinning rates and patterns. Maximum rates of individual feeders estimated by repeat wall thickness measurements made beginning after ~12 FPY range from ~0.03 up to ~0.13mm/FPY for the highest velocity channels. The highest rates are at the intrados upstream of the first two tight radius bends and at the bend extradoses near the bend apex. The pattern from a PLGS removed single bend is shown in Figure 3.

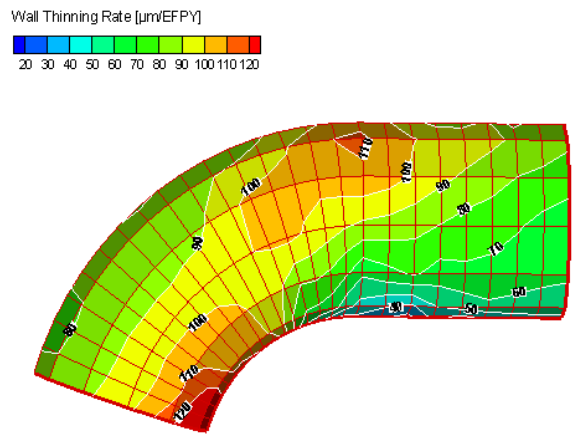
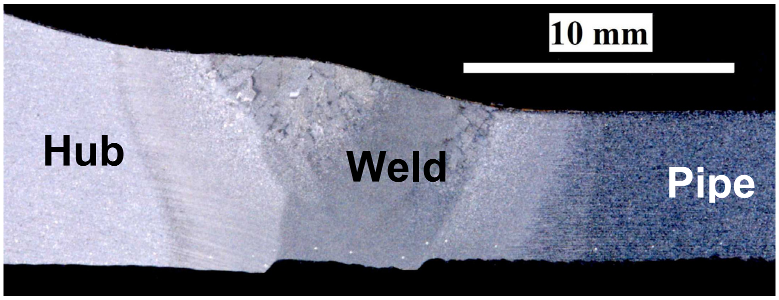


Figure 3: P09a Wall thinning Rate Pattern

Wall thinning has occurred over the whole length of outlet feeders but at lower and variable rates (resulting from geometric factors) downstream of the first bends. For example, in the highest velocity channels, wall thinning rates of bends in the upper feeders are ~15% lower than the first bends. Although no upper feeder locations were life-limited to 2008, ~75-100 90º bends downstream of the field weld were predicted not to achieve the post-refurbishment design life.

At the outlet Grayloc connection, the variation in chromium content between the hub (~0.12wt%), the pipe (~0.02wt%), and the weld between (~0.07%), led to different FAC rates, and the creation of a surface step profile in the axial direction. Figures 4a and b illustrate this in cross-section and plan-view. This profile has been observed on all removed PLGS feeders and is most pronounced at the intrados, where FAC rates are higher. The preferential wall thinning of welds reported by EPRI [7] has never been observed on PLGS feeders. However, thinned areas adjacent to the Grayloc welds with subtle profiles have developed. The dark patch in the center of Figure 5b (beneath the weld) is the most acute thinned area of this type observed at PLGS. This is discussed in more detail in the subsection below.



a) Cross section of S08a after ~13 FPY

b) Plan view, O07a after ~18 FPY

Figure 4: Step profile of the Grayloc hub-feeder weld location

The development of surface scalloping is worth further mentioning because some of the false positive crack indications in 2005 were attributed to scallop patterns. All four feeders that were repaired because of false positive indications of inside surface cracks (Table 1) were examined in the locations of the rejectable indications. In each case, axially aligned scallops, which had created groove-like features, were observed (Figure 5) with some individual scallops as deep as 0.4mm. When these features were mechanically removed, the ultrasonic indications also disappeared. A review of past inspection reports suggests that these axial patterns became more distinctive with time and created ultrasonic indications that only became rejectable after ~18 FPY. Use of a modified COG crack inspection procedure since 2005 has been successful in distinguishing indications between scallop patterns and cracks. There have been no additional false positive indications.

Figure 5: Axially aligned scallop patterns created after ~18FPY in feeder E14c

Thinned Locations Adjacent to the Grayloc Hub Weld

Until 2006, the focus of feeder thickness measurements was the bend extradoses where high rates and low initial thickness are roughly coincident. However, after another utility discovered some significant wall thinning near hub-to-feeder welds, inspections and assessments of PLGS feeders began to target this location also. Examination of PLGS removed feeders found the thinnest location was adjacent to the Grayloc hub weld for eight of eleven 2.5" feeders that were still intact in this area. All thinned spots were subtle depressions; the most distinctive of these is shown in Figure 4b. None of the six 2" removed feeders had minima adjacent to the weld. Because the axial and circumferential position of the thinned areas was variable, it was suspected that a somewhat random factor contributed to the pattern. An investigation identified this factor to be excessive removal of metal near the welds by pre-service grinding.

Grinding was performed on the hub-to-pipe weld caps to aid the radiographic inspection of the weld region and also at the weld root to remove any protrusion or mismatch of the internal pipe surfaces exceeding 1/32". Pre-service radiographs and metallographic examination results have provided evidence of the degree of material removed from individual feeders. The radiograph in Figure 6 indicates the location of initial minimum wall thickness, adjacent to the weld.

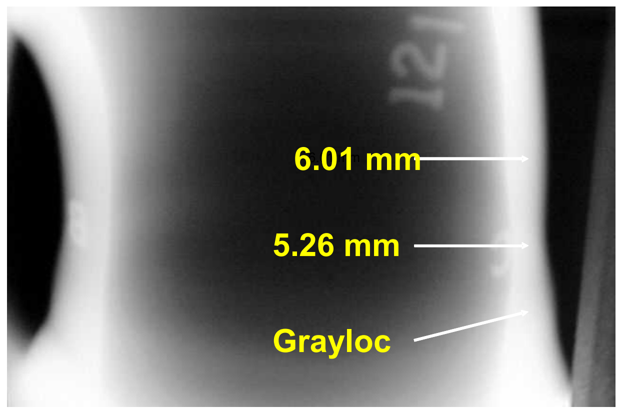


Figure 6: PLGS Feeder-Hub Weld Pre-Service Radiograph

This location was inspected using a COG Grayloc-Area Inspection Tool. Figure 7 shows the wall thickness pattern for two PLGS feeders over a two-year period. Feeder S14a had the least margin to the minimum allowable thickness but was not life-limiting by 2008.

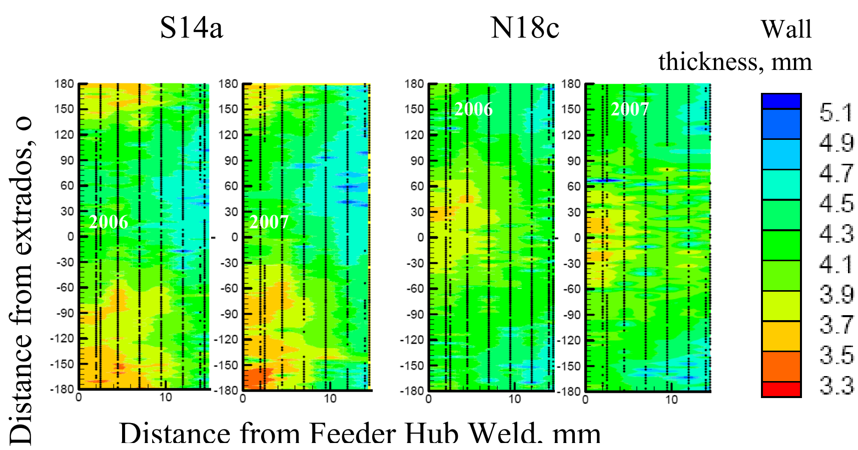


Figure 7: Wall thinning Patterns Adjacent to the Grayloc Hub

Feeder Wall thinning Management

Inspection and repair has been the primary strategy to manage feeder wall thinning. The history of outlet feeder wall thickness measurements at PLGS is shown in Table 3. By 1998, a 100% baseline measurement of outlet bends was complete. Also, 7 inlet bends and 12 inlets adjacent to the hub were inspected in 1995/96 and 2006, respectively.

Deterministic methods were successfully used for operational assessments of bend wall thinning. The industry standard correlation between wall thinning rates and time averaged flow conditions [8] was used to identify the most limiting PLGS feeders. Wall thickness of these feeders was periodically measured to demonstrate acceptable margins and to determine when replacement was required.

Table 3: History of wall thickness inspection of PLGS outlet feeders

Year	Feeder bends		Next to Hub		Total
	2 inch	2.5 inch	2 inch	2.5 inch	
1995	4	14	0	0	18
1996	26	40	0	0	66
1997	25	157	0	0	182
1998	15	134	0	0	149
1999	11	14	0	0	25
2000	13	1	0	0	14
2002	20	5	0	0	25
2003	21	4	0	0	25
2004	21	8	0	0	29
2005	11	31	0	0	42
2006	10	14	13	67	116
2007	10	34	7	18	69
Total	**187**	**456**	**20**	**85**	**760**

An empirical probabilistic Monte Carlo model was developed to predict the minimum thickness next to the Grayloc hub because wall thinning at this location was not well characterized. The model used initial thickness data from fabrication radiographs, FAC rates based on the bend model, and considered the circumferential dependence of the FAC rate. The model was benchmarked against measurements from PLGS removed feeders.

The Monte Carlo model was used to identify feeders most likely to thin below the minimum allowable thickness. It was also used to determine the minimum inspection scope required to ensure a probability <5% that one or more non-inspected feeders would fall below the minimum allowable thickness. This approach allowed the use of a risk-based inspection scope that maintained a low risk while keeping radiation exposure ALARA.

2.2 Feeder Cracking

Since 1997 and after ~ 13 FPY operation, PLGS experienced life-limiting cracking in twelve feeder bends (Table 1). Because this cracking is unique in the industry, has a relatively high growth rate, and has the potential for safety-related consequences if not managed properly, it has created significant challenges for NBPN. Despite those challenges, knowledge of the key factors driving cracking and a relatively linear failure rate has allowed NBPN to manage cracking economically, primarily using inspection and repair. The subsections below provide a summary of PLGS cracking up to the Refurbishment Outage.

Failure rates and Locations

Since 1997, feeder bends have been replaced because of cracking at a rate of about 1 to 2 per year. A linear fit of the data for all repaired feeders in Figure 8 shows a failure rate of 1.3 per hot year. All twelve life limiting cracks were in 2.5" diameter outlet tight radius first or second bends with an external angle of >45˚. Eleven of the twelve bends had significant cracks that had initiated on the inside surface between ~30 to 75° from the intrados. Beginning in 2003, significant cracking on the outside surface of three bend extradoses was also discovered; two of those bends also had deep inside surface cracks (Table 1). Figure 9 illustrates the three locations of cracking on the second bend of feeder N19a. Examinations of removed bends have revealed that a high percentage of tight radius bend extradoses contain very shallow (50-200µm deep) outside surface incipient cracks, that are assumed to have developed during operation. All of the observed cracking is in the location of high residual tensile stresses from the bending process [6]. In-situ ultrasonic inspection and destructive examination of removed Grayloc hub-to-feeder welds did not reveal cracking on any PLGS feeder welds. No cracks were detected in 100% inlet bends inspected.

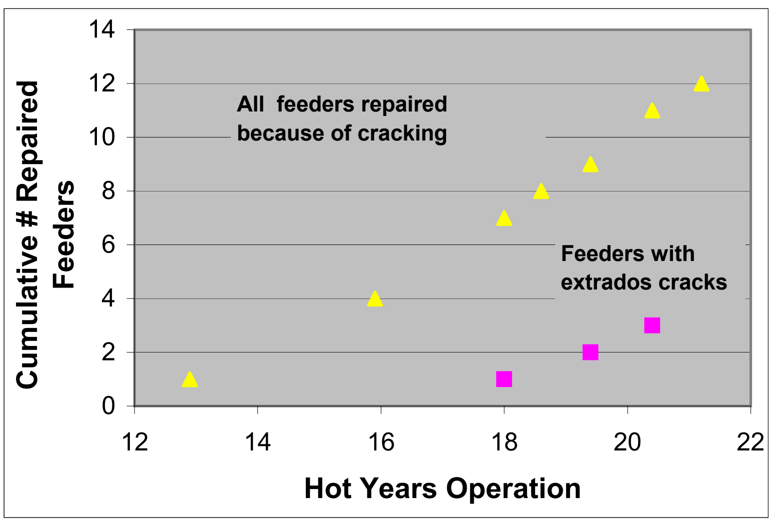


Figure 8: Rate of Feeder Repair due to Cracking

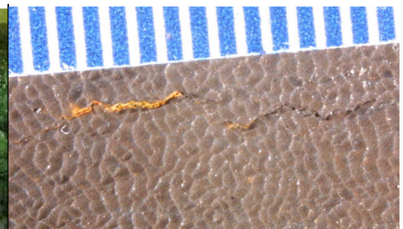
Figure 9: Feeder N19 2nd Bend. Outside surface cracks at the extrados (0°) and inside surface cracks at 115° and 247°

Crack Characteristics

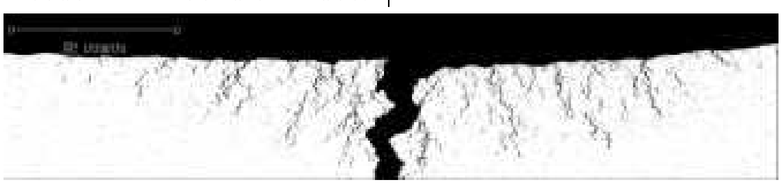
All cracks are axial in orientation and entirely intergranular. No physical feature or surface contaminant has been observed to identify a specific mechanism of failure. Outside surface cracks tend to be straighter and have fewer secondary cracks near the main crack. Cracks initiate in multiple locations and with time, some of those that are axially aligned, coalesce to form larger cracks. Figure 10 illustrates some of these features. Additional details about the physical features and development of cracks are provided in references 1 and 4. The maximum crack dimensions from each repaired feeder are listed in Table 1.

Fracture surface of feeder H12a after burst testing showing outside surface cracks have started to coalesce

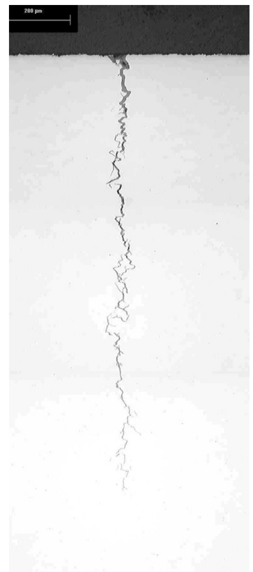
Magnetic particle image of feeder D14a bend extrados.

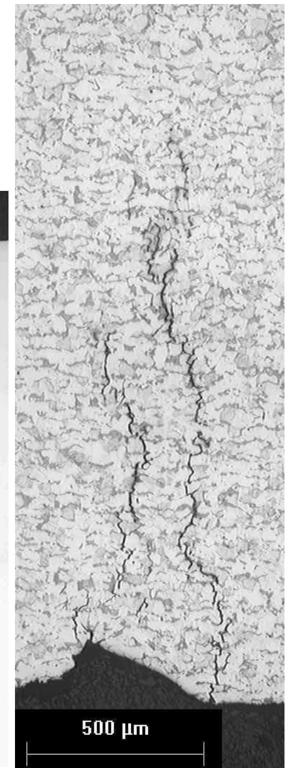


Visual image of inside surface cracks



Optical micrograph of feeder S08a showing secondary cracking near the mouth of the main inside surface crack





a) Outside crack b) Inside crack

Optical micrographs of intergranular cracks in feeder N19a second bend, same scale

Figure 10: Images of PLGS Feeder Cracks

Mechanism and Key Factors Driving Cracking

Numerous studies and comprehensive failure investigations have identified the key factors driving cracking, shown in Table 4. Although it has not been possible to conclusively determine the cracking mechanism, two likely and possibly inter-related candidates are Stress Corrosion Cracking (SCC) caused by exposure to mildly oxidizing hot coolant and Low Temperature Creep Cracking (LTCC), possibly exacerbated by atomic hydrogen flux from FAC. SCC due to air ingress or insufficient dissolved hydrogen to suppress the radiolytic generation of oxidizing species is a credible cause of cracking initiated at the inside surface. LTCC (decohesion of grain boundaries from localization of creep strain ahead of a crack tip or another stress-concentrating feature) could explain cracks initiated at both inside and outside surfaces.

Table 4: Factors Driving Feeder Cracking

Category	Primary Factors	Possible Secondary Factors
Stress	Residual Tensile Stress	Cyclic Operating Stress
Material	Cold Work	Ovality, Impurities
Environment	Temperature	FAC-hydrogen, coolant oxidizing species & impurities

Crack Growth Rates

Crack growth rate has been estimated from OPEX (Figure 11) to be ~2mm/year in the through-wall direction. This is an average growth rate once cracks reach a detectable size. Figure 11 plots the maximum crack depth in an individual feeder versus the operating time since the last inspection when no crack was detected. Other assessments from laboratory examinations of artefacts have concluded similar rates with variation suggested with crack age (size) and slightly slower rates for cracks initiated on the outside surface.

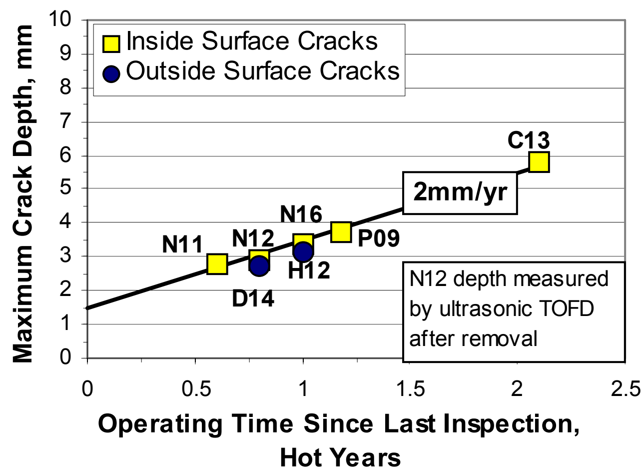


Figure 11: Average Crack Growth Rate

Management

After two leaks from through-wall cracks in 1997 and 2001, NBPN realized that a different strategy was required to prevent additional leaking feeder cracks. The primary management strategy since then has been inspection and repair. This strategy was successful at detecting and repairing cracked bends before leaks developed. Table 4 illustrates the comprehensive inspection program since 1997. With on-going experience and better understanding of the key factors and the likelihood and consequences of cracking at different locations, the inspection scope evolved to become 100% inspection of all tight radius outlet first and second bends on an annual basis. This scope was supported by comprehensive probabilistic safety evaluations [3, 4] and assessments of partial-through wall crack stability from feeder burst testing [9].

3. Feeder Design Improvements Made During the Refurbishment Outage

The benefits of experience and understanding have contributed to numerous improvements to the replacement feeders being installed during the Refurbishment Outage. Neither FAC nor cracking are expected to be life-limiting during PLGS extended design life of 24 FPY. A summary of some of the key improvements is listed in Table 5. Improvements considered to have the greatest benefit are shown in bold.

Table 4: Numbers and percentages of bends and welds inspected for cracking

Date	Outlet Feeders				Inlet Feeders			Total # of Sites
	Tight Radius		Long Radius Bends	Repaired Welds	Tight Radius		Repaired Welds	
	1st Bend	2nd Bend			1st Bend	2nd Bend		
1997	110 (29%)	0	0	0	48 (13%)	0	0	158
1998	14 (4%)	0	0	0	10 (3%)	0	0	24
2001	379 (100%)	41 (33%)	0	0	100 (26%)	0	0	520
2002	238 (63%)	42 (34%)	0	0	30 (8%)	0	0	310
2003	380 (100%)	178 (100%)	0	0	190 (50%)	25 (13%)	0	773
2004 (May)	347 (91%)	122 (69%)	12	21	106 (28%)	44 (23%)	23	675
2004 (Oct)	48 (13%)	6 (3%)	0	0	0	0	0	54
2005	380 (100%)	178 (100%)	9	8	58 (15%)	34 (21%)	5	672
2006	380 (100%)	178 (100%)	0	0	10 (3%)	4 (2%)	0	572
2007	380 (100%)	178 (100%)	0	0	10 (3%)	4 (2%)	0	572
Total	**2656**	**923**	**18**	**29**	**562**	**111**	**28**	**4330**

Table 5: Summary of Improvements to PLGS Replacement Feeders

	Improvement	Expected Benefit
Material	**Piping and weld wire shall be alloyed with >0.3wt%Cr**	Reduce the FAC rate by >50%
	Pipe made with aluminium-killed steel	Reduce free nitrogen believed to lower the likelihood of creep cracking
	Steel-making processes that produce cleaner steel (low S, P, inclusion content)	Improved and consistent fracture toughness
Fabrication and Installation	**2” piping increased thickness by 0.050”**	Increases FAC margins
	Pipe cold-bending procedure with a compressive boost	Reduce ovality and variability in material properties and wall thickness
	Piping manufactured to the requirements of SA106 Grade C instead of Grade B	Take advantage of higher allowable stresses
	All bends (and swages) shall be stress relieved	Significant decrease in residual tensile stresses, considered a primary factor driving cracking
	No localized through-thickness weld repairs permitted	Prevent high residual stresses that can increase the likelihood of cracking
	Automatic process for all welding	Low rate and extent of weld repairs
	Improved control on grinding of welds	Maintain FAC margins
	Heat straightening not permitted for feeder alignment	Prevent formation of unacceptable microstructures

The use of carbon steel with >0.3wt%Cr is expected to reduce the feeder wall thinning rate by at least 50% compared to the original PLGS feeders. This is based on experimental loop tests and wall thinning measurements of some PLGS replaced feeder bends [10]. Figure 12 compares measured minimum wall thickness data from bend S08a which was replaced with original PLGS steel in 1997 and three feeder bends replaced with >0.3%Cr steel in 2001. The estimated reduction in FAC rate from this data for steel with higher Cr is ~65% [10].

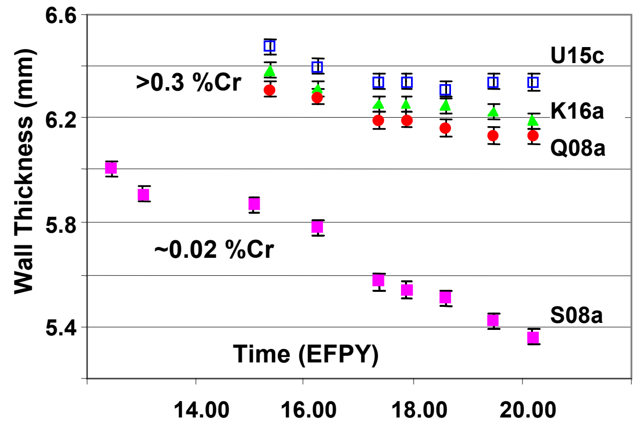


Figure 12: Wall thinning of replaced bends [10].

4. Feeder Management Strategy after Refurbishment

The inspection and repair strategy used to manage PLGS feeder wall thinning and cracking was successful in allowing safe, reliable operation until 2008. However, feeder management during this period also had two significant drawbacks. It consumed a significant portion (~5%) of the PLGS operations and maintenance budget and it contributed to about 30% of outage dose. For post-refurbishment operation, “prevention with improved materials” will be the primary feeder management strategy. By replacing the entire feeder assembly with the improved materials described in the preceding section, NBPN believes there will be no life-limiting feeder degradation during post-refurbishment operation. FAC will continue to be active but the higher chromium content will prevent life-limiting rates. Cracking will be prevented, primarily by stress relieving bends. The justification for this will be captured in a COG technical basis document for consistency among utilities with similar feeder material.

NBPN plans to discontinue using a Feeder Piping Management Plan after refurbishment and will include all feeder inspection activities in the periodic inspection plan (PIP). Table 6 compares the planned inspection scope with CSA N285.4-05 minimum requirements. The planned scope exceeds CSA requirements mainly for insurance against any unforeseen degradation. An extensive wall thickness baseline is included because a known initial thickness eliminates significant uncertainty when assessing wall thinning rate, if required later on. A limited inspection for feeder cracks is included even though stress relieved bends are very unlikely to crack. This inspection is considered to be an added measure to ensure high stakeholder confidence in reliable post-refurbishment operation, in view of the unique PLGS cracking OPEX in the past ten years. A partial baseline crack inspection is also included because some manufacturing features were observed in the replacement feeders (Figure 13), which caused rejectable crack indications using the COG in-service crack inspection procedure. These features were assessed to be benign and baseline results will prevent them from causing false positive indications in future crack inspections.

Table 6: PLGS Post-Refurbishment Feeder Inspection Plans

Scope	CSA Minimum Requirement	PLGS Plan
Wall thickness Inspection for Wall thinning		
Baseline	20 inlet and 20 outlet	100% outlet, 25% inlet 1st and 2nd bends 100% outlet, 25% inlet adjacent to Grayloc hub
PIP	10 inlet and 10 outlet at 6 year intervals	~50 1st and 2nd bends, ~50 adjacent to the Grayloc hub at 6 year intervals. Focus on outlets
Visual Inspection for Loss of Configuration		
Baseline	Baseline of all areas	100% general visual, seismic restraints, cantilevers spacers, spring cans
PIP	One quadrant general plus 10 feeders detailed at 10 year intervals	25% of above at 10 year intervals
Ultrasonic Volumetric Inspection for Cracks		
Baseline	No code requirement	25% tight radius, high angle outlet bends
PIP	Develop an inspection program if cracking is assessed to be credible	~50 outlet tight radius, high angle bends at 6 year intervals, starting after ≤12 years.

NBPN will continue to use other secondary management activities, listed in Table 7, for validation and defense-in-depth.

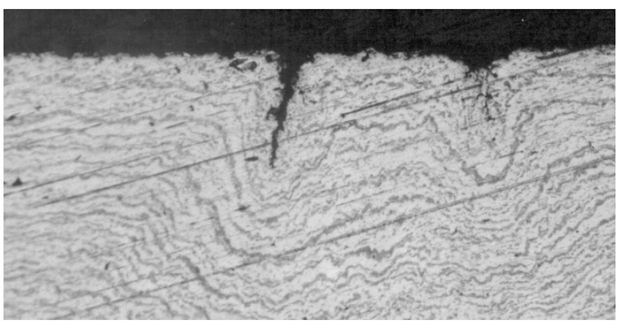


Figure 13: Benign manufacturing features in PLGS replacement feeder piping (maximum depth 200μm)

Table 7: Post-Refurbishment Secondary Feeder Management Activities

Mechanism	Management Activities
Active Degradation	
FAC	Inspection - wall thickness
	Chemistry control - pH_a
Plausible or Postulated Degradation[2]	
Intergranular Cracking	Inspection - volumetric
	Leak Detection & Response
	Chemistry control - oxidants
Fretting	Inspection - visual
	Configuration Management
Fatigue Cracking	Inspection - volumetric
	Configuration Management
	Leak Detection & Response

[2] PLGS equipment program plans list some forms of degradation considered very unlikely of occurring as *plausible* or *postulated,* to define ageing management activities for reasons in addition to reducing risk (e.g. to meet license requirements, increase stakeholder confidence, and other reasons specific to PLGS). In this table, intergranular and fatigue cracking are considered very unlikely.

5. Concluding Remarks

The experience of managing PLGS feeder degradation in the past ten years has been challenging and costly but it has also brought benefits. In response to the severity of feeder degradation, NBPN aggressively developed and adopted some effective management activities that may not have been considered at that time, or considered at all. The concept of risk-reduction to evaluate management activities, the use of pre-planned responses to inspection results, and the use of probabilistic safety evaluations to quantify the nuclear safety risk of degradation are a few examples. These activities to manage feeder degradation led to safe, reliable operation until 2008. They are now being successfully applied to manage degradation issues in other areas of the plant [11].

On the other hand, NBPN has no wish to repeat the feeder degradation experience and is taking extra precautions to prevent life-limiting degradation during post-refurbishment operation. The primary defence is to replace the feeder assembly with components that are not susceptible to intergranular cracking and are more resistant to FAC. NBPN believes this approach will be successful so this paper should be our 'last look' at PLGS life-limiting feeder degradation[3].

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[3] Others may wish to look further at seven PLGS outlet feeder sections that have been removed and set aside for use by COG. These are feeders N12a, removed in 2007 with partial through wall cracking plus six others removed during the Refurbishment Outage.

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