LOCALIZED THINNING ASSESSMENT - SERVICE LIFE EXTENTION FOR DARLINGTON FEEDERS

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ABSTRACT

Flow assisted corrosion (FAC) causes the highest rates of wall loss at outlet feeder pipes in the regions close to the Grayloc end fittings. Stress analyses have to be performed to demonstrate feeder fitness for service (FFS) with reduced wall thickness as per ASME Section III or other accepted Codes and Standards. Based on inspection data since 2007 it was identified that thinning near the Grayloc weld was randomly distributed throughout outlet feeders at the Darlington Nuclear Generation Station (DNGS). The extent of thinning is predicted to reduce the remaining wall below the pressure based (PB) thickness limit for a large portion of the feeder population. With ccurrent projection, more than 230 feeders in all 4 DNGS Units will require replacement/repair by the End of Life (EoL).

The results of generic stress analysis performed under the Localized Feeder Stress Analysis Project (LFSA) demonstrated that all DNGS outlet feeders have sufficient structural integrity to be declared FFS when subjected to localized wall loss adjacent to the Grayloc weld below the current approved PB thickness values 2.75mm and 3.33 mm for 2.0’’ and 2.5’’ feeders respectively. In most cases, it is possible to demonstrate that a thickness equivalent to 75% of the current allowable limit is acceptable: 2.07mm and 2.50mm for 2.0’’ and 2.5’’ feeders respectively (**Reference 1** and **2**).

This paper presents methodologies employed in LFSA and its generic results. Conservative operational margin is discussed and used in feeder disposition. A disposition procedure is demonstrated on a sample application.

ABBREVIATION

FAC - Flow Assisted Corrosion;
COG - CANDU Owners Group
CUF - Cumulative Usage Factor
DNGS - Darlington Nuclear Generation Station
EFPY - Effective Full Power Year
EoL - End of Life
FFS - Fit For Service
FFSG - Fitness-For-Service Guideline for Feeders
LFSA - Localized Feeder Stress Analysis
PB - Pressure Based Thickness
STR 1 - Straight pipe between the Grayloc and bend 1
VBO - Vacuum Building Outage

1.0 INTRODUCTION

In CANDU nuclear power plant, feeder pipes carry heavy water to and from the reactor fuel channels to remove heat produced by the fission of uranium fuel. The feeder pipes connect the inlet and outlet headers to the reactor core. The number of feeder pipes is in the range of 760 to 960 for various types of CANDU designs. The feeders are made of SA106 Grade B carbon steel. Feeder piping is designed to Class 1 piping requirements of the ASME Boiler and Pressure Vessel Code, Section III, Subsection NB and CSA Standards. In general, bends closest to the fuel channel connections represent the most critically stressed sections of feeder pipes. Severe wall loss due to FAC has been found in CANDU stations, the wall thickness reduction could be as high as the half of nominal wall values.

Thinning adjacent to the Grayloc weld of feeders was identified in 2007 to represent a life limiting condition for the majority of DNGS outlet feeders. Typical local thinning is illustrated **Figure 1**. The local thickness and bend thickness are measured by 6-probe and 14-probe respectively. A sample of inspection with localized thinning is shown in **Figure 2**. In order to have an effective life cycle management plan, accelerated inspection program at DNGS will complete a 100% baseline inspection by spring 2010.

The current acceptable thickness for the straight pipe section adjacent to the Grayloc is assessed at the pressure based thickness as per NB-3641 (**Reference 3**) , i.e. t_{min} = 2.75 mm for 2", 3.33 mm for 2.5" feeders respectively. The thickness allowable limits would have great impact on current feeder or reactor service life. **Table 1** demonstrates the impact of reducing the allowable wall thickness for outlet feeder pipes. As shown in the table, shall pressure based thickness be set as feeder replacement criterion, there would be approximately 230 feeders need to be replaced or repaired, which would have significant economical impact on the utility. The minimum acceptable local wall thinning limit in current FFSG (**Reference 4**) is 75% of pressure based thickness. If DNGS feeders were acceptable for this limit, only approximately 21 feeders need to be replaced and the problem becomes manageable. The majority of to be replaced feeders would have 6 additional EFPY in service life if this limit were implemented.

2.0 LOCAL THINNING STRESS ASSESSMENT METHODS

Feeder bend thinning has been effectively managed through thickness inspection, stress analysis and small number of feeder replacement. In stress analysis, the thickness assessment is carried out to show whether or not the analyzed wall thickness values with local thinning at the Grayloc would meet the Code requirements. The generic local thinning thickness assessment carried out in LFSA were based on two independent methods: ASME Section III, NB class 1 and Appendix E of Fitness-For-Service Guideline for Feeders (FFSG).

2.1 ASME Section III Stress Analysis

2.1.1 Piping Analysis for Thickness below Pressure Based Value

The design pressure based thickness for straight pipe (t_{min}^{sp}) of NB-3641 is limited by hoop stress under internal pressure:

$$t_{min}^{sp} = \frac{PD_o}{2(S_m + Py)}, \tag{1}$$

where P – Internal Design Pressure (DNGS outlet feeders P = 11.3 MPa)

D_o - Outside diameter of feeder pipe

S_m – maximum allowable stress intensity (S_m = 119 MPa for SA106 Gr. B @318.3 ^oC)

y = 0.4

The only relevant loading condition in Equation (1) is the internal pressure. Severely thinned pipe for a large area below t_{min}^{sp} should be immediately removed or repaired. However, if the wall thinning is only limited to one or several small zones having thickness below t_{min}, further evaluations using alternative methodology should be conducted rather than costly repair or removal. The line-in-granite rule in FFSG states that the minimum value of acceptable thickness for local thinning shall be greater than or equal to 0.75 t_{min}^{sp} regardless the acceptance of the assessment.

For any thickness below t_{min}^{sp}, detailed finite element models including local thinning profile have to be developed to perform stress analysis under internal pressure loading as per NB-3221 and NB-3213.10, which is permitted by NB-3600. The relevant rules of NB-3200 are schematically illustrated in **Figure 4**. It is noted in NB-3200, the local membrane stress limit is 1.5S_m for the localized area ($\sqrt{(Rt)}$ versus S_m used in NB-3641. Article NB-3213.10 also allows local membrane stress up to 1.1 S_m for a distance of $\sqrt{(Rt)}$. However in this assessment, local membrane stress limit is conservatively set to 1.0S_m instead of 1.1S_m.The comparison of relevant rules in NB-3600 and NB-3200 are listed in **Table 2**.

2.1.2 Finite Element Models

There are 22 types of feeder bends in DNGS. These types are categorized by pipe size, bend angle, bend radius, length of straight pipe(s) and etc. Bend types may have differences in geometry, away from the region of interest, e.g.; different length straight pipe between the bend 1 (1^{st} bend downstream of the Grayloc) and bend 2 (2^{nd} bend downstream of the Grayloc) or different bend radius for the second bend but having identical configuration near the Grayloc.

Since the loading used in this analysis is only internal pressure, it is assumed that there is negligible effect of these variations on the stresses in the straight pipe between the Grayloc and bend 1. The 22 feeder bend types have been divided into 6 feeder bend models as shown in **Table 3** according to the pipe size and the length of straight pipe (STR1) between the Grayloc and bend 1.

In the current assessment, the local thinning is assumed in STR1. Local thinning below pressure based thickness (t_{local}) is not expected to be confined within the length of STR1 for most types of feeders. On the other hand, wall thickness of bend 1, which is immediate away from the locally thinned area, has important impact in the localized thinning assessment. The wall thickness of generally thinned feeder bends is typically non-uniform. However in this assessment the wall thickness surrounding the locally thinned region is assumed to be uniform. It is impossible to cover all the combinations of the different wall thickness values in the surrounding material to the locally thinned region, only a few bend thicknesses (t) were used which represent bend thickness in future outages.

In order to eliminate sharp corners, a transition is modeled between two sections, STR1 and bend 1, having different thicknesses. The following transitions are used;

1. Transition of 5 mm is placed inside the Grayloc for the Grayloc and STR1 junction.
2. Transition of 5 mm is used for going from t_{local} to bend t within the STR1 or inside the bend 1 (for short length STR1 feeder bend types or long thinning extent)
3. Beyond bend 2, a 5 mm transition is used to go from t to t_{nom}, this transition is placed inside the feeder section beyond bend 2.

Figure 5 provides a picture of a typical model, showing how various transitions are modeled. The models were prepared with thinning all-around the circumference, i.e. un-limited circumferential extent of thinning. This type of thinning will not occur in reality, but the analysis is performed with un-limited circumferential thinning to cover for uncertainty in thickness inspections. This allows the local thickness to be anywhere around the circumference for a given axial extent (average thickness at each cross-section shall be equal to or higher than t_{min}^{sp}). **Figure 6** is a thickness profile for a typical 2.0 inch feeder C19W. Note that the below pressure based thickness is modeled all around the circumference.

Thickness of the thinned region was fixed in calculation and the axial extent of thinning was adjusted such that the stresses were just within the limits of ASME NB-3221. The thickness increases from 75% t_{min}^{sp} to 100%t_{min}^{sp}. Several iterations may be required to find an axial extent for a given thickness of the localized region which meets the Code allowable.

2.1.3 Results

A typical result is shown in **Figure 7**: the allowable minimum thickness (below t_{min}^{sp}) as a function of axial extent of thinning for un-limited circumferential thinning for model 4 in **Table 3** for bend types E, H1, J, L1, L2, L3, L4, L5 & L6. Local thickness in the region to the left and top of the limiting curve is acceptable.

2.1.4 Axial Stress under Other Loadings

Longitudinal or axial stress intensity limits for design and anticipated service conditions (Level A, B, C and D) are provided in NB-3650. In general, the minimum local acceptable thickness at the Grayloc weld is not determined by axial stress due to following causes:

- Axial primary bend stress due to pressure is ½ of hoop stress
- Axial stress allowable for primary loading is $1.5S_m$ versus $1.0S_m$ for hoop stress
- Axial bending stress is high at only a few locations, such as tee, elbow or other fittings. If the local thinning doesn't occur at fitting or higher axial stress locations, the axial stress intensity limit could be easily met.

In previous OPG feeder assessments, the axial stress intensity for design, Level A/B and Level C and fatigue evaluation are shown to meet the ASME Code NB-3650 stress intensity limits for pressure based thickness. In case of below pressure based thickness, the axial stress intensity does not need to be re-evaluated provided that the average thickness of the cross-section(s) is equal to or higher than the pressure based thickness and the stress indices are the ASME Code maximum values.

The above statement is in-line with the "Average-Minimum-Average" approach used in OPG feeder analyses (**Reference 5**). This approach is inherently conservative since the loads are calculated based on the average thickness (higher thickness giving higher loads), indices are based on minimum thickness (lower thickness giving higher indices) and code equations are evaluated based on average thickness.

2.2 FFSG Level 2 Assessment Method

Appendix E of FFSG was developed to evaluate thinned region in feeder piping. It follows the similar methodologies of ASME Section XI. The evaluation procedures maintain the design intent margins of Section III. There are three levels of evaluation for internal pressure loading and pressure coincidence with bending moment respectively. Level 1 refers to ASME III NB-3640 and NB-3650 assessments. But it is not suitable when a local thickness is below the pressure based value. Level 3 is a finite element based approach, including elastic, limited load and plastic-collapse analyses.

Level 2 evaluation consists of a set of closed form rules which were developed with the first principle and verified by extensive finite element modeling. It provides an easy-to-use and conservative tool for the fast disposition of adverse inspection results. The assessment on DNGS feeders develops a set of acceptable local thickness next to the feeder Grayloc hub (**Reference 2**).

The evaluation procedure is as per Article E-2 of FFSG Appendix E. Level 2 evaluation on internal pressure and bending moment coincident with internal pressure were carried out in this assessment.

2.2.1 Level 2 Structural Evaluation for Thinned Region for Internal Pressure Loading

In Appendix E, a local thinning region is defined when a local wall thickness is less than the evaluation *of* wall thickness, t_{eval}, which is defined as 1.10 t_{min}^{sp} or 1.13 t_{min}^{sp}. $L_{m(t)}$ is the circumferential extent of thickness less than t_{eval}. $L_{m(a)}$ is the circumferential extent of thickness less than t_{eval}. L_m is the maximum value of $L_{m(t)}$ and $L_{m(a)}$, as shown in **Figure 8**.

The geometry characterization of thinning region is defined as $(R_{min}t_{min})^{0.5}$, where R_{min} (= R_o - $t_{min}/2$) is the mean radius of the piping item. There are three classifications of local thinned region geometry based on axial and circumferential extent. The allowable local wall thickness t_{aloc} is calculated using formulas or empirical curves defined in each category.

(a) Limited Circumferential Extent (LC): when the circumferential extent, $L_{m(t),}$ of the local thinned region predicted to be less than t_{eval} does not exceed $R_{min}t_{min})^{0.5}$.

(b) Limited Axial and Circumferential Extent (LAC): when the maximum extent, $L_{m(t),}$ of local wall thickness predicted to be less than t_{eval} is less than or equal to $2.65(R_{min}t_{min})^{0.5}$.

(c) Unlimited Circumferential Extent (UC): when the circumferential extent, $L_{m(t)}$, of the local thinned region predicted to be less than t_{eval} exceeds to $(R_{min}t_{min})^{0.5}$.

2.2.2 Level 2 Structural Evaluation for Thinned Region for Applied Bending Moment and Coincident Internal Pressure Loading

The structure integrity is evaluated for membrane plus bending axial stress and membrane axial stress respectively.

2.2.2.1 Membrane plus Bending Axial Stress

For each ASME III Level A, B C, and D loading under evaluation, the following criterion shall be satisfied:

$$\sigma_b^p \le \frac{1}{SF_b}(\sigma_b^c - \sigma_b^s) - \sigma_m^{p^*}\left(1 - \frac{1}{SF_m}\right) \qquad (2)$$

where SF_b - structural factor on primary bending moment

SF_m - structural factor on internal pressure or primary axial force

σ_b^c - nominal bending axial stress at net-section collapse

σ_b^p and σ_b^s - nominal primary and secondary bending axial stress

σ_m^{p*} - effective applied nominal primary membrane axial stress e

2.2.2.2 Membrane Axial Stress

For each ASME III Level A, B C, and D loading under evaluation, the following criterion shall be satisfied

$$\sigma_m^{p^*} \le \frac{\sigma_m^c}{SF_m} \qquad (3)$$

where σ_m^c - nominal membrane axial stress at net-section collapse with zero coincident bending stress

2.2.2.3 Generic Local Allowable Thickness

It is necessary to summarize the minimal acceptable thicknesses obtained in **Section 2.2.1** and **2.2.2** under two loading assessments. The highest allowable local thickness value from two evaluations under the same input conditions should be the minimum acceptable thickness through the evaluation of Appendix E.

One of implicit assumptions in **Section 2.2.2** is the infinite axial extent of local thinning. On the other hand, the axial extent is limited by the internal pressure evaluation of **Section 2.2.1**, where the surrounding wall thickness has no direct effects on the acceptable thickness value, except in LAC calculation. In this report, t_{eval} is conservatively used in LAC calculation as per Article E-5.4.2 (b). Any higher surrounding wall thickness t should reduce the t_{aloc} value. The indirect effect of surrounding wall thickness value in pressure loading evaluation is the length of thinning extent, circumferentially and axially, whereat it influences the allowable thickness. In the meanwhile, the surrounding thickness has significant impacts on moment loading assessment.

Non-uniform inspection thickness data has to be properly interpreted to implement the evaluation. It is reasonable to assume the average cross-section thickness as the surrounding thickness for a single local thinning region assessment, while t_{eval} is used to identify the size of local thinning region. Typical allowable thickness value calculated from enveloped DNGS feeder loads were shown in **Table 4** and **5** for 2” and 2.5” respectively.

2.2.2.4 Fatigue Evaluation

Similar to arguments made in **Section 2.1.4**, the crack initiation evaluation was carried out by fatigue cumulative usage factor (CUF) calculation in previous DNGS feeder assessments. When the straight pipe next to the Grayloc was evaluated at the pressure based thickness, the maximum ASME code defined stress indices were used at the Grayloc weld transition. Since the pressure loading and bending moment coincident with pressure have been evaluated by the alternative methods in here, the values of B and C indices at the Grayloc are no longer relevant. Equation (9), (10), (12) and (13) in NB-3650 are not used in this alternative approach to evaluate the longitudinal or axial stress intensity limit for the Grayloc to pipe transition.

The peak stress related K index is independent of minimum thickness. The applicable thickness range for stress indices in Table NB-3681(a)-1 is $D_o/t \leq 100$ for C, K indices, and 50 for B indices. For feeder piping item even with $0.75t_{min}$ local thinning, the diameter versus thickness ratio is approximately 30 and is well below the limits.

From past inspection data, it is confident that the average thickness in the area where the local thinning occurs is still higher than the pressure based value. Thus the previous fatigue assessments based on pressure minimum thickness are still valid in spite of local thinning. In addition, there is a large margin at the Grayloc for the fatigue evaluation. The highest CUF value in general is at the 1st bend location.

3.0 FEEDER SERVICE LIFE MARGIN MANAGEMENT

During the 2009 DNGS Vacuum Building Outage (VBO), feeder wall inspection was performed on more than 600 feeders. Feeder replacement schedule were updated after the VBO and identified that current deposition limit (pressure based thickness) will results in a large number of feeders requiring replacement/repair due to localized thinning near the Grayloc weld. The generic aspects of localized thinning assessments, as discussed in previous two sections, can be utilized to significantly reduce the replacement feeders. This would also reduce radiological exposure and minimize risks associated with replacement/repair while maintaining the code safety margins.

Even with generic thickness allowables, feeder assessment has to be performed on each individual feeder on geometric features, such as axial and circumferential lengths of local thinning area. There are two major uncertainties or risk in FFS of local thinning:

- Size of the localized thin area geometry: The size of the localized thinning will be defined by the inspection results. The local allowable thickness is highly dependent on the size of thinning area.
- Feeder Thinning Rates: While it is confident that feeder thinning rate calculations are conservative in nature it is prudent to state the possibility that in some instances they could potentially underestimate actual thinning rates. This risk is present for all types of thinning and has been managed with a 0.5 EFPY standard margin used in thickness prediction.

To account for possible issues related to inspection uncertainty, it is prudent for the utility to cap the required thickness. The required thickness for acceptance will be the thickness which can be demonstrated acceptable by the ASME III/FFSG analyses **plus** the thickness required to one outage interval or 3 EFPY of operation at the risk-informed thinning rate of the individual feeder.

Risk Informed Rates (typically 90-140 μmm/EFPY) is based on the average value of a number of thinning rate calculations (rate from initial thickness, repeat rate, revised rate from initial, QV rate, and bend repeat). Provided there is lack of repeat inspections for the same feeder, it is a suitable rate to predict feeder thickness near the Grayloc and is used in long term feeder replacement planning. In the mean while, removed feeders should be investigated with both destructive and/or non-destructive examinations to provide feedback on the effectiveness of the inspection program and descriptive features of localized thinning.

In the mean time, the repeat inspection rate (typically 60 - 90 μmm/EFPY) is a more accurate rate using 3-point data. Many of feeders at DNGS have 2-point repeat rate, which is prone to larger error. There are only handful feeders with 3-point repeat inspection data for now. This assessment could extend feeder service life with current thinning rate, but more inspections can be performed in the future to validate expected lower thinning rate.

4.0 ASSESSMENT PROCEDURE AND INPLEMENTATION EXAMPLE

The assessment is carried out to assess the disposition thickness, defined in **Section 4.1** below, for each individual feeder. The acceptable disposition thickness and associated thinning extents are then compared to the projected thickness at a specific outage to determine whether or not the individual feeder is fit for service to the specific outage before repair or replacement. If the projected thickness is higher than the disposition thickness and the corresponding thinning extents are less than the evaluated value, the projected thickness would be "acceptable" to the specific outage.

4.1 Assessment Procedures

Following assessment steps are used to assess acceptable thickness for an individual feeder.

1) Feeders below the pressure based thickness will be screened out for disposition using risk informed thinning rate.

2) Local thinning limit in the vicinity of the Grayloc can be calculated by methods described in **Section 2.1** and **2.2** for all types of Darlington feeders. It is concluded from both analyses that all feeders are acceptable for local thinning as low as $0.75t_{min}^{sp}$ for the specified thinning extents in the vicinity of the Grayloc.

3) To account for possible issues related to inspection uncertainty, the disposition thickness for acceptance will be the minimum thickness acceptable by the ASME III analysis or FFSG Appendix E plus the thickness required to achieve 3 EFPY of operation at the risk-informed thinning rate of the individual feeder:

Disposition Thickness = Local thinning limit ($0.75t_{min}^{sp}$, 2.07 mm for 2", 2.50 mm for 2.5") + 3EFPY x Thinning Rate

4) Using the disposition thickness as the minimum local thickness, localized thinning size of target feeders will be determined by the thickness profile projection based on the most updated inspection results.

5) The disposition thickness from Step 3 and thinning size from Step 4 will be assessed with the results of **Section 2.1** for the same bend type of feeder for ASME III assessment, or calculated with formulas developed in **Section 2.2** for FFSG Appendix E Level 2 assessment. The assessment will determine whether the specified localized thinning is acceptable as per ASME III or FFSG.

6) Compare the disposition thickness to the projected future outage thickness to determine whether the individual feeder is fit for service to the planned outage (note: additional 0.5 EFPY conservative margin is built in projected thickness calculation).

ASME III and FFSG assessments only differ in Step 5 in acceptance criterion. The other assessment steps are essentially the same. The assessment procedure is demonstrated in details below for feeder F17E in Unit 2.

4.2 Assessment of Feeder F17E

4.2.1 Step 1 - Screen Out Target Feeders Below Pressure Based Thickness

Using the most updated inspection data (D921 -2009 planned outage) and risk-informed thinning rate, it is projected that the minimum thickness at the Grayloc weld for F17E is 3.31 and below PB of 3.33 mm at D1321 (2013 planned outage), as shown in **Table 6**. Therefore, disposition of localized thinning has to be preformed for fitness for service.

4.2.2 Step 2 **-** Local Thinning Limit In the Vicinity of the Grayloc

Feeder F17E is a L1 bend type feeder. The variation of axial extent of thinning for allowed local thickness is shown in **Figure 7** of ASME III analysis. The all-around circumferential thinning or uniform thinning is assumed in the analysis model. It shows that local thinning limit of $0.75t_{min}^{sp}$ (2.50 mm) is achievable when the axial thinning extent is less than 6.8 mm.

Table 5 of FFSG method shows that 75% pressure based thickness is achievable depending on the axial and circumferential extent and adjacent thickness. Note that this table was obtained using conservative enveloped loads from all feeders.

4.2.3 Step 3 - Disposition Thickness

The risk informed thinning rate of 0.148 mm/EFPY for F17E is obtained from inspection data and is given in **Table 7**. The disposition thickness is 2.94 mm based on this rate and local thinning limit of 2.5 mm for 2.5" feeder.

4.2.4 Step 4 **-** Projection of Future Thickness Profile Using Current Inspection Data

6-probe inspections were conducted on these feeders in the latest D921 outage. The thickness profile, i.e. the local thinning extent, has to be obtained by projecting the minimum thickness from the current inspection data to the disposition value. The disposition thickness combined with thinning extent will be evaluated for ASME III assessment and FFSG Level 2 assessment.

The minimum inspected thickness (D921) is 3.95 mm and located at probe no. 1, as shown in **Table 8**. Circumferentially, the minimum thickness location is corresponding to the intrados region of the 1st bend. The average thickness at every probe is significantly thicker than the pressure based value. Thus the thinning is localized only at the intrados location (the bend orientation is used in this evaluation for convenience).

The projected thickness for other probes, shown in **Table 9**, is calculated by assuming the same thinning rate as probe no.1 when probe no. 1 reaches the disposition thickness 2.94 mm. The inspected thicknesses from 6 individual probes and projected probe no. 1 thickness are shown in **Figure 9**. The pressure based thickness t_{min}^{sp} and FFSG Level 2 evaluation thickness of t_{eval} ($1.10t_{min}^{sp}$) are also given to indicate the circumferential thinning extent. The circumferential and axial thinning extents are also provided in **Table 9**.

4.2.5 Step 5 - Acceptance of Disposition Thickness and Profile

This step is to assess the disposition thickness combined with its thinning extent against the allowable axial thinning extent for a specific local thickness using ASME III or FFSG Appendix E Level 2 assessment rules.

4.2.5.1 ASME III Assessment of F17E

1. For the given disposition thickness of 2.94 mm of F17E, the corresponding allowed axial extent is approximately 9.5 mm (given in **Figure 7**) while the projected axial length of disposition thickness is less than 5.0 mm (distance between 2 probes).

2. When the Grayloc weld minimum thickness reaches the disposition value, the projected bend minimum thickness 4.64 mm (shown in **Table 10)** is higher than the uniform value of 4.3 mm used in analysis model of **Figure 7**. It is conservative that there is more material in the proximity for reinforcement.

3. In the analysis model, the entire circumference from the Grayloc to the allowed axial length is assumed as a specified thickness t_{local}. There is a 5.0 mm transition from t_{local} to bend uniform thickness (4.3 mm for **Figure 7**). It is necessary to verify the projected thickness is above the assumed thickness within the transition region.

The modeled thickness, minimum and average projected thicknesses for F17E are shown in **Figure 10**. The inspected thickness, especially averaged thickness is well above the modeled thickness.

4. There are no multiple local thinning regions below pressure thickness as shown in **Figure 9**.

In conclusion, the local thinning is acceptable for F17E for the specified disposition thickness, as shown in **Table 10**.

4.2.5.2 FFSG Appendix E Level 2 Local Thinning Assessment of F17E

The assessment using FFSG Level 2 method only differentiates from ASME III method described above in terms of acceptance criteria, the rest assessment steps are essentially the same.

In Level 2 assessment, both internal pressure loading and internal plus moment loading are performed. The local thinning required thickness is the minimum required thicknesses from two loading assessments. In this assessment, the local thinning size is determined by evaluation thickness $t_{eval} = 1.10t_{min}^{sp}$ (3.66 mm) rather than pressure based thickness t_{min}^{sp}.

4.2.5.2.1 Internal Pressure Assessment

The assessment is performed in **Table 11**. The axial thinning extent is assumed on entire straight pipe section (15.3 mm). The circumferential thinning extent is approximately 130^o observed from **Figure 9** and given in **Table 8**. In this range the required local thickness for pressure loading is $0.862t_{min}^{sp}$ or 2.88 mm.

4.2.5.2.2. Internal Pressure plus Moment Loading Assessment

To obtain **Table 4 and 5**, enveloped loadings were used for internal pressure plus bending moment assessment. It was intended to be an expeditious disposition during VBO or providing a general guidance for an unexpected inspection finding. However, when a disposition is used for the feeder life cycle management plan, more realistic loadings specific to the individual feeder should be used. The calculation of local allowable thickness under individual feeder loading and adjacent thickness reinforcement is presented in **Table 12** for F17E. The average thickness at the probe where the disposition thickness located is used as the adjacent thickness t_1 in calculations. It is found that the local allowed thickness t_2 could reach $0.75t_{min}^{sp}$ or 2.50 mm under this loading as shown in the table.

Therefore, the limiting thickness of FFSG assessment is the required thickness under internal pressure loading, i.e. 2.88 mm. It is less than the disposition thickness of 2.94 mm. Thus the disposition thicknesses are acceptable. The summary of FFSG Level 2 evaluation is summarized in **Table 13**.

4.2.6 Step 6 **-** Compare Disposition Thickness and Projected Future Outage Thickness

The final step of assessment is to compare the disposition thickness to the projected future outage thickness to determine whether the individual feeder is fit for service to a future planned outage. As shown in **Table 10** and **13**, the projected Grayloc minimum thickness at D1321 is higher than the disposition thickness, in the meanwhile the corresponding thinning extent should be smaller than the values used in the assessment. In conclusion, feeder F17E is fit for service at least until D1321 from two independent assessments.

F17E is one of a few lead feeders which may be unable to extend service life till the reactor refurbishment especially with 3EFPY administrative operation margin is used. However, thinning rate could be greatly improved with at least 3-point inspection data, which can be obtained during the extended service period. It is expected that most of feeders could extend their service life to station EoL.

5.0 CONCLUSIONS

The generic minimum acceptable local thicknesses in the vicinity of the Grayloc for all Darlington outlet feeders are obtained. The evaluation was performed according to ASME or FFSG Appendix E Level 2 Evaluation Procedure for local thinning at the straight pipe section next to the Grayloc. Shall the inspected or predicted wall thickness next the Grayloc be higher than these values with defined thinning extent both circumferentially and axially, the subject feeder would be fit for continued service. Even with administrative margin of 3EFPY, feeder service life would be extended. With improved thinning rate from repeat inspections, the service life would be extended beyond reactor EoL.

6.0 ACKNOWLEDGEMENT

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Table 1 Number of Potential Replacement Feeders at DNGS due to local Thinning

Administrative Limit (PB%)	Approximately number of Replacement	Average Life Extension (EFPY)
100 (current)	230	-
90	95	2
85	58	3
75	21	6
Note: Assumes all Unit operation to 2020.		

Table 2 Comparison of NB-3600 and NB-3200 Rules on Internal Pressure Loading

NB-3600 Class 1 Piping	NB-3200 Rules
$t_{min}^{sp} = PD_o/[2*(S_m + Py)]$	NB-3221.1: General membrane stress $P_m \le S_m$
	NB-3221.2: Local membrane stress $P_L \le 1.5\ S_m$
	NB-3221.3: Local membrane plus bending stress $P_L + P_b \le 1.5\ S_m$
	NB-3213.10: Local membrane stress $P_L \le 1.0\ S_m$ beyond $\sqrt{(Rt)}$

Table 3 Analysis Models and Equivalent Feeder Types

Analysis Model	Sample Feeder	Equivalent Feeder Types	STR1 Length (mm)
1	A15W	A	45.5
2	B18W	B, F	38.5
3	B14W	C	43.5
4	C19W	D, G1, I, K1, K2, K3, K4, K5	10.4
5	C13W	E, H1, J, L1, L2, L3, L4, L5, L6	15.3
6	M01E	M	3.1

Table 4 Allowable Thickness for 2" Feeder with Average Cross-Section Higher than 3.31 mm ($t = 1.20t_{min}^{sp}$)

2" feeder			Maximum Axial Extent $L_{m(a)}$ (mm)											
No.	Circumferential Thinning		6		8		10		15		20		30	
	angle (degree)	OD length (mm)	t_{aloc} / t_{min}	t_{aloc}	t_{aloc} / t_{min}	t_{aloc}	t_{aloc} / t_{min}	t_{aloc}	t_{aloc} / t_{min}	t_{aloc}	t_{aloc} / t_{min}	t_{aloc}	t_{aloc} / t_{min}	t_{aloc}
1	10	5.0	0.75	2.07	0.75	2.07	0.75	2.07	0.75	2.07	0.75	2.07	0.78	2.15
2	15	7.5	0.75	2.07	0.75	2.07	0.75	2.07	0.75	2.07	0.75	2.07	0.78	2.15
3	20	10.0	0.75	2.07	0.79	2.19	0.83	2.29	0.88	2.42	0.90	2.48	0.90	2.48
4	25	12.6	0.75	2.07	0.79	2.19	0.83	2.29	0.88	2.42	0.90	2.48	0.90	2.48
5	30	15.1	0.75	2.07	0.79	2.19	0.83	2.29	0.88	2.42	0.90	2.48	0.90	2.48
6	35	17.6	0.75	2.07	0.79	2.19	0.83	2.29	0.88	2.42	0.90	2.48	0.90	2.48
7	40	20.1	0.75	2.07	0.79	2.19	0.83	2.29	0.88	2.42	0.90	2.48	0.90	2.48
8	45	22.6	0.75	2.07	0.79	2.19	0.83	2.29	0.88	2.42	0.90	2.48	0.90	2.48
9	55	27.6	0.75	2.07	0.79	2.19	0.83	2.29	0.88	2.42	0.90	2.48	0.90	2.48
10	60	30.1	0.75	2.07	0.79	2.19	0.83	2.29	0.88	2.42	0.90	2.48	0.90	2.48
11	75	37.7	0.85	2.34	0.85	2.34	0.85	2.34	0.88	2.42	0.90	2.48	0.90	2.48
12	90	45.2	0.90	2.48	0.90	2.48	0.90	2.48	0.90	2.48	0.90	2.48	0.90	2.48

Note: Adjacent Thickness Higher Than $1.20t_{min}$

Table 5 Allowable Thickness for 2.5" Feeder with Average Cross-Section Higher than 4.01 mm ($t = 1.20t_{min}^{sp}$)

2.5" feeder			Maximum Axial Extent $L_{m(a)}$ (mm)											
No.	Circumferential Thinning Extent $L_{m(t)}$		6		8		10		15		20		30	
	angle (degree)	OD length (mm)	t_{aloc} / t_{min}	t_{aloc}	t_{aloc} / t_{min}	t_{aloc}	t_{aloc} / t_{min}	t_{aloc}	t_{aloc} / t_{min}	t_{aloc}	t_{aloc} / t_{min}	t_{aloc}	t_{aloc} / t_{min}	t_{aloc}
1	10	6.1	0.75	2.50	0.75	2.50	0.75	2.50	0.75	2.50	0.75	2.50	0.75	2.51
2	15	9.1	0.75	2.50	0.75	2.50	0.75	2.50	0.75	2.50	0.75	2.50	0.75	2.51
3	20	12.2	0.75	2.50	0.75	2.50	0.80	2.67	0.86	2.87	0.89	2.95	0.90	3.00
4	25	15.2	0.75	2.50	0.75	2.50	0.80	2.67	0.86	2.87	0.89	2.95	0.90	3.00
5	30	18.2	0.75	2.50	0.75	2.50	0.80	2.67	0.86	2.87	0.89	2.95	0.90	3.00
6	35	21.3	0.75	2.50	0.75	2.50	0.80	2.67	0.86	2.87	0.89	2.95	0.90	3.00
7	40	24.3	0.75	2.50	0.75	2.50	0.80	2.67	0.86	2.87	0.89	2.95	0.90	3.00
8	45	27.4	0.75	2.50	0.75	2.50	0.80	2.67	0.86	2.87	0.89	2.95	0.90	3.00
9	55	33.4	0.75	2.50	0.75	2.50	0.80	2.67	0.86	2.87	0.89	2.95	0.90	3.00
10	60	36.5	0.75	2.50	0.75	2.50	0.80	2.67	0.86	2.87	0.89	2.95	0.90	3.00
11	75	45.6	0.77	2.57	0.77	2.57	0.80	2.67	0.86	2.87	0.89	2.95	0.90	3.00
12	90	54.7	0.84	2.80	0.84	2.80	0.84	2.80	0.86	2.87	0.89	2.95	0.90	3.00

Note: Adjacent Thickness Higher Than $1.20t_{min}$

Table 6 Feeder F17EThickness Projection

Feeder	size	14 PROBE MIN (D921)	EFPY of 14 PROBE MIN	Bend Thinning rate (QV)	Projected bend minimum thickness				6 PROBE MIN (D921)	EFPY of 6 PROBE MIN	Risk Informed Rate	Projected Grayloc minimum thickness				EFPY when Grayloc reaches $0.75t_{min}$ [3]	Bend t_{min} at the time of disposition thickness [4]	Required Bend uniform thickness [5]
					at D1021 (16.2 EFPY)	at D1321 (19.2 EFPY)	at D1621 (22.2 EFPY)	at D1921 (25.2 EFPY)				at D1021 (16.2 EFPY)	at D1321 (19.2 EFPY) [2]	at D1621 (22.2 EFPY)	at D1921 (25.2 EFPY)			
F17E	2.5	5.57	9.9	0.093	4.99	4.71	4.43	4.16	3.94	14.9	0.148	3.75	3.31	2.86	2.42	22.96	4.64	3.67

Notes: 1. The most updated inspection D921 data is used.
2. Pressure thickness is 3.33 mm for 2.5" feeders. The minimum thickness of three feeders will be below this value at D1321.
3. This is the EFPY value when the minimum thickness at Grayloc reaches $0.75t_{min}^{sp}$ based on current inspected thickness and thinning rate.
4. Projected bend minimum thickness corresponding to the disposition thickness or at the time of EFPY(Grayloc reaches $0.75t_{min}^{sp}$) - 3EFPY.
5. Bend required minimum uniform thickness is 3.67 mm.

Table 7 Disposition Thickness for F17E

Feeder	Size	Bend Type	6-Probe Min (D921)	t_{min}^{sp}	$0.75t_{min}^{sp}$	Thinning rate	Disposition Thickness	Projected Grayloc Min at D1021	Projected Grayloc Min at D1321	Projected Bend Min at D1321
F17E	2.5"	L1	3.94	3.33	2.50	0.148	**2.94**	3.75	**3.31**	4.71

Table 8 Inspected Minimum and Average Thickness for F17E at D921

Probe No. (location)	1 (0 mm)	2 (2.5 mm)	3 (5.0 mm)	4 (7.5 mm)	5 (10 mm)	6 (12.5 mm)	Note
1st scan Min Thk. (mm)	4.05	3.98	4.05	4.59	4.68	4.91	RC-EX-LC
2nd scan Min Thk. (mm)	**3.95**	4.27	4.27	4.36	4.56	4.65	LC-IN-RC
Average Thickness (mm)	5.03	5.12	5.05	5.16	5.20	5.29	5.14
6-probe scan convention:	RC-EX-LC: Scan starts from Right Cheek, passes EXtrados and ends at Left Cheek.						
	LC-IN-RC: Scan starts from Left Cheek, passes INtrados and ends at Right Cheek.						

Table 9 Projected Thickness, Thinning Size at the Time of Disposition Thickness for F17E

Disposition thickness	Disposition Thk./Min Inspection Thk. (2.94/3.95)
2.94	0.74

Note: Projected thickness at other probe locations = 0.74 x current inspected thickness.

Probe No. (location)	1 (0 mm)	2 (2.5 mm)	3 (5.0 mm)	4 (7.5 mm)	5 (10 mm)	6 (12.5 mm)	Note
Projected Thk.	**2.94**	3.18	3.18	3.24	3.40	3.46	axial extent t < t_{min}^{sp}
Average Thk.	3.75	3.81	3.76	3.84	3.88	3.94	3.83

t_{min}^{sp}	$T_{eval} = 1.10t_{min}^{sp}$	Axial length of each Probe	Axial length of below t_{min}^{sp}	Circumferential below t_{min}^{sp}	Axial length of below T_{eval}	Circumferential length below T_{eval}	Circumferential angle below T_{eval}
3.33	3.66	2.5	8.8	42.8	12.5	83.0	130.2

Table 10 Acceptance of Feeder F17E (ASME III Assessment)

Feeder	Size	Bend Type	6-Probe Min	t_{min}^{sp}	$0.75t_{min}^{sp}$	Thinning rate	Disposition Thickness	Projected Grayloc Min at D1321	Allowed axial extent for Disp. Thk.	Projected axial thinning length @2.94 mm	Analyzed Bend Thk.	Projected Bend Min. Thk.	Result
F17E	2.5"	L1	3.94	3.33	2.50	0.148	**2.94**	3.31	9.5	< 5.0	4.30	4.64	**Acceptable**

Table 11 Internal Pressure Loading Assessment

Title : LEVEL 2 STRUCTURAL EVALUATION OF THINNED REGION FOR INTERNAL PRESSURE LOADING
File: G:\Feeder\2009_WORK\Darlington\EVAL\Level 2 DNG Pressure & Moment - Three Feeders.xls
Author: Ming Li
Date: October, 2009
Sheets Pressure
Notes: 1. Based on Appendix E of FFSG Rev. 1 (COG-JP-4107-V06-R01), issued on January 19, 2009
2. The consistent units used in this file are: mm, MPa
3. The local thinning is assumed within the straight pipe next to the Grayloc, all calculations are based on straight pipe assumptions
4. Only single local thinned region is considered in this calculation

Inputs	**Darlington 2.5 inch Feeders**		
Design pressure	P_D	11.3	MPa
Nominal outside diameter	D_o	73.025	mm
Design stress intensity	S_m @318 ºC	119.1	MPa
Outside Radius	$R_o = D_o/2$	36.513	mm

Geometry Characterization			
Pressure based thickness for SP	$t_{min}^{SP} = P_D D_o/[2(S_m + yP_D)]$	3.338	mm
Evaluation Wall at Grayloc	$t_{eval} = 1.10\ t_{min}^{SP}$ (LC, UC)	3.67	=> The inspected or predicted thicknesses are required to compared to t_{eval} instead of t_{min}
	$t_{eval} = 1.13\ t_{min}^{SP}$ (LAC)	3.77	
Mean Evaluated Radius	$R_{eval} = R_o - t_{eval}/2$ (LC,UC)	34.68	=> Radius at the at surrounding region
	$R_{eval} = R_o - t_{eval}/2$ (LAC)	34.63	
Minimum Length for surrounding material $t > t_{eval}$	$2.5(R_{eval}*t_{eval})^{1/2}$ (LC,UC)	28.21	=> The wall thickness in the material surrounding the local thinned region shall be greater than or equal to t_{eval} from this minimum distance.
	$2.5(R_{eval}*t_{eval})^{1/2}$ (LAC)	28.57	
Mean Inside Radius	$R_{min} = R_o - t_{min}/2$	34.84	=> Mean radius at local thinning region
Characterized size	$(R_{min}*t_{min})^{1/2}$	10.78	=> Thinning region characteristic dimension

Classification of Local Thinning Region

Classification	Extent of Thinning Less Than t_{eval}	L_m	Formulas to calculate allowable thickness
(a) Limited Circumferential Extent (LC):	Circumferential extent, $L_{m(t)} \le (R_{min}t_{min})^{1/2}$ where $t < t_{eval}$	10.78	$t_{aloc}/t_{min} = 0.75$ for $L_{m(a)}/(R_{min}t_{min})^{0.5} < 2.75$ $t_{aloc}/t_{min} = 0.046*(x - 2.75) + 0.75$ for $x = L_{m(a)}/(R_{min}t_{min})^{0.5} > 2.75$
(b) Limited Axial and Circumferential Extent (LAC):	Maximum extent, $L_m \le 2.65\ (R_{min}t_{min})^{1/2}$ where $t < t_{eval}$	28.58	$t_{aloc}/t_{min} \ge 0.353 L_m[1/(t_{min}^{sp}R_{min}^{sp})]^{0.5}$ $t_{aloc}/t_{min} \ge 1 - 1.5(R_{min}t_{min})^{0.5}(t_{eval}/t_{min} - 1)/L_m$ $t_{aloc}/t_{min} = 0.75$ t_{aloc} equals to the maximum three values
(c) Unlimited Circumferential Extent (UC):	Circumferential extent, $L_{m(t)} > (R_{min}t_{min})^{1/2}$ where $t < t_{eval}$	10.78	$t_{aloc}/t_{min} = 0.75$ for $L_{m(a)}/(R_{min}t_{min})^{0.5} < 0.725$ $t_{aloc}/t_{min} = -0.0287x^4 + 0.2243x^3 - 0.6768x^2 + 0.9688x + 0.3251$ for $0.725 < x = L_{m(a)}/(R_{min}t_{min})^{0.5} < 2.5$ $t_{aloc}/t_{min} = 0.9$ for $L_{m(a)}/(R_{min}t_{min})^{0.5} > 2.5$

Maximum Axial Extent $L_{m(a)}$	15.3 mm	**Conservatively assume the thinning is on entire Straight Section (15.3 mm)**
$L_{m(a)}/(R_{min}t_{min})^{1/2}$	1.42	

circumferential thinning angle (deg)	arch length (mm) $L_{m(t)}$	$L_m = (L_{m(a)}^2 + L_{m(t)}^2)^{1/2}$	$L_m/(R_{min}^{sp}t_{min}^{sp})^{1/2}$ / 2.65	$L_{m(t)}/(R_{min}t_{min})^{1/2}$	Geometry Classification	LC	LAC (a)	LAC (b)	LAC (c)	LAC Max (a,b,c)	UC	t_{aloc}/t_{min}^{sp} Min(LC,LAC,UC)	Results by Thinning Classification
10	6.08	16.46	0.576	0.6	LC or LAC	0.750	0.539	0.872	0.750	0.872	n/a	0.750	LC
15	9.12	17.81	0.623	0.8	LC or LAC	0.750	0.583	0.882	0.750	0.882	n/a	0.750	LC
20	12.16	19.55	0.684	1.1	UC or LAC	n/a	0.640	0.892	0.750	0.892	0.862	0.862	UC
25	15.20	21.57	0.755	1.4	UC or LAC	n/a	0.706	0.903	0.750	0.903	0.862	0.862	UC
30	18.24	23.81	0.833	1.7	UC or LAC	n/a	0.779	0.912	0.750	0.912	0.862	0.862	UC
35	21.28	26.21	0.917	2.0	UC or LAC	n/a	0.858	0.920	0.750	0.920	0.862	0.862	UC
40	24.33	28.74	1.006	2.3	UC	n/a	n/a	n/a	n/a	n/a	0.862	0.862	UC
90	54.73	56.83	1.989	5.1	UC	n/a	n/a	n/a	n/a	n/a	0.862	0.862	UC
180	109.46	110.53	3.868	10.2	UC	n/a	n/a	n/a	n/a	n/a	0.862	0.862	UC
270	164.20	164.91	5.771	15.2	UC	n/a	n/a	n/a	n/a	n/a	0.862	0.862	UC
360	218.93	219.46	7.680	20.3	UC	n/a	n/a	n/a	n/a	n/a	0.862	0.862	UC

Table 12 Internal Pressure Plus Moment Loading Assessment for F17E

Title :	LEVEL 2 STRUCTURAL EVALUATION OF THINNED REGION FOR APPLIED BENDING MOMENT WITH COINCIDENT INTERNAL PRESSURE LOADING
File:	G:\Feeder\2009_WORK\Darlington\EVAL\Level 2 DNG Pressure & Moment - Three Feeders.xls
Author:	Ming Li
Date:	October, 2009
Sheet:	F17E

Inputs	**Darlington 2.5 inch Feeders**			
Design pressure	P_D		11.3	MPa
Nominal outside diameter	D_o		73.025	mm
Nominal thickness	t_{nom}		7.01	mm
Design stress intensity	σ_m		119.1	MPa
Yield strength	σ_y		178.23	MPa
Ultimate tensile strength	σ_u		413.7	MPa
Flow stress	σ_f	$= (\sigma_y + \sigma_u)/2$	295.97	MPa
Since the local thinning is within the short section of straight pipe, all calculations are based on a straight pipe assumption.				
Nominal outside radius	R_o	$R_o = D_o/2$	36.5125	mm
Nominal inside radius	R_i	$R_i = R_o - t_{nom}$	29.5025	mm
Pressure based thickness for SP	$t_{min}^{SP} = P_D D_o/[2(\sigma_m+Py)]$		3.338	mm
Evaluation Wall at Grayloc	$t_{eval} = 1.10\ t_{min}^{SP}$ (LC, UC)		3.67	mm
	$t_{eval} = 1.13\ t_{min}^{SP}$ (LAC)		3.77	mm
Mean Diameter at t_{min}	$D = D_o - t_{min}$		69.7	at local thinning region
Characterized size	$(R_{min} * t_{min})^{1/2}$		10.8	mm
Mean Evaluated Radius	$R_{eval} = R_o - t_{eval}/2$ (LC,UC)		34.68	at surrounding region
	$R_{eval} = R_o - t_{eval}/2$ (LAC)		34.63	
Location of thinning	α		1	inside surface thinning

F17E Loads (2.5 inch)	Resultant Load		Primary Load		Secondary Load	
	F_{res} (kN)	M_{res} (kN-m)	F_p	M_p	F_s	M_s
DWT (Deadweight)	0.322	0.074	0.322	0.074	-	-
THM (Thermal)	1.238	1.430	-	-	1.238	1.43
EAM (Seismic Anchor Mvt)	0.115	0.06	-	-	0.115	0.06
EEM (Seismic Inertia)	1.086	0.822	1.086	0.822	-	-

Load Case	primary loads			secondary loads		structural factors			effective load components (not used)		
	P	F_p	M_p	F_s	M_s	SF_m	SF_b	SF_e	P_{eff}	F_{eff}	M_{eff}
Level A/B	**12.1 MPa**	**0.322 kN**	**0.074 kN·m**	**1.2 kN**	**1.430 kN·m**	2.7	2.3	1.0	32.59 MPa	2.11 MPa	1.60 MPa
Level C	**13.6 MPa**	**1.408 kN**	**0.896 kN·m**	**0.1 kN**	**0.060 kN·m**	1.8	1.6	1.0	24.48 MPa	2.65 MPa	1.49 MPa

Case	No.	Characterization of Feeder Local Thinning											Net-section Characterized Collapse Parameters					
		t_2/t_{min}	t_2	t_1/t_{min}	adjacent t_1	depth a	2θ	PDA	mean D	t_1/D	a/t_1	a/D	P_o	F_o	M_o	λ	P*	θ/π
Level A/B	1	0.75	2.50	1.12	3.75	1.25	130°	50.38%	69.28	0.05	0.332	0.018	71.59	241.44	5.32	0.24	12.41	0.361
Level C	1	0.75	2.50	1.12	3.75	1.25	130°	50.38%	69.28	0.05	0.332	0.018	71.59	241.44	5.32	0.24	13.98	0.361

Case (Continue)	No.	Net-Section Collapse Bending Moment					Membrane Plus Bending Axial Stresses, and Membrane Axial Stress								Structural Evaluation			
		β/π	check a/t, θ/π	flaw type	β/π	M_{nsc}/M_o	A_i	I	σ_m^{p*}	σ_b^{p}	σ_b^{s}	Φ	σ_m^{c}	σ_b^{c}	Mem + Bending		Mem Axial	
Level A/B	1	0.355	ok	short	0.355	0.758	3372.5	4.91E+05	51.69	5.50	106.38	0.14	235.37	300.33	0.69	pass	0.59	pass
Level C	1	0.342	ok	short	0.342	0.739	3372.5	4.91E+05	59.52	66.65	4.46	0.14	235.37	292.78	0.60	pass	0.46	pass

Table 13 Allowable Local Thickness Using FFSG Level 2 Assessment

Feeder	Size	Bend Type	6-Probe Min	t_{min} sp	$0.75t_{min}$ sp	Thinning rate	Disposition Thickness	Projected Grayloc Min at D1321	$T_{eval} = 1.10t_{min}^{sp}$	Axial thinning length	Circum. thinning length	Circum. thinning angle	The minimum allowable thickness (P, and P+M)	Result
F17E	2.5"	L1	3.94	3.33	2.50	0.148	**2.94**	**3.31**	3.66	12.5	83.0	130.2	**2.88**	**acceptable**

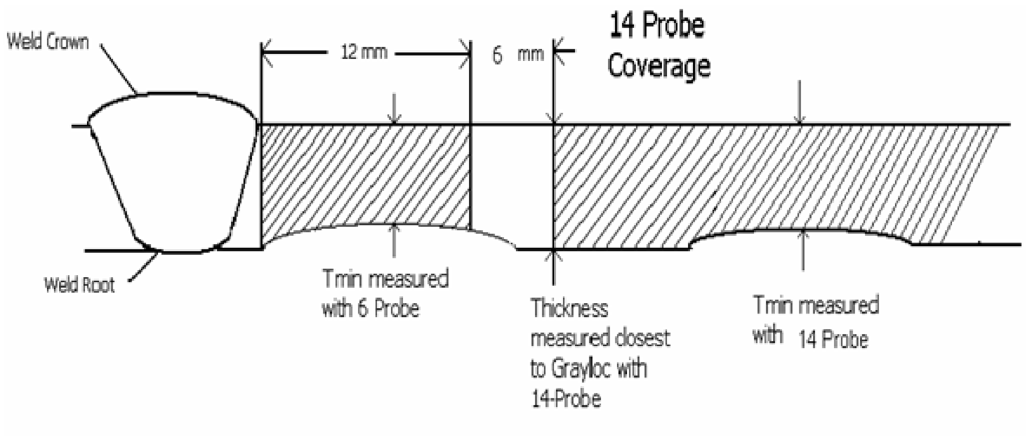

Figure 1 Illustration of Local Thinning at the Grayloc

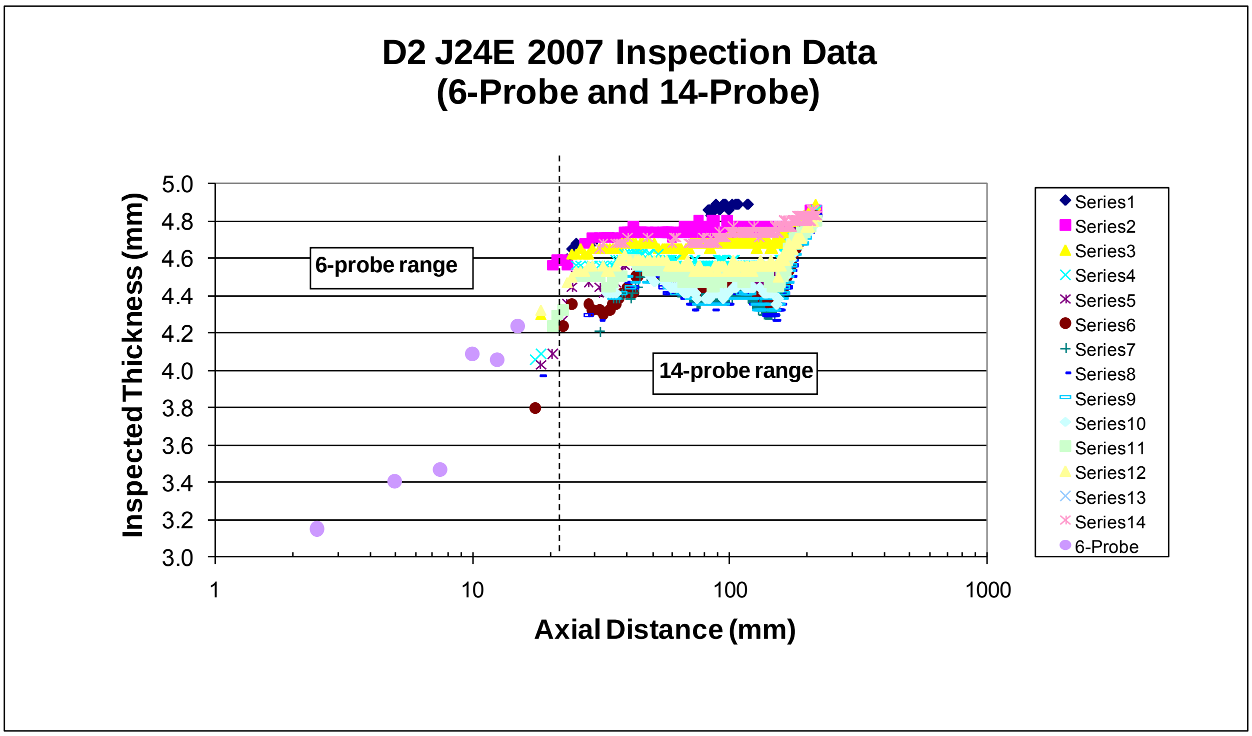

Figure 2 6-Probe and 14-Probe Inspection Data for a Darlington Feeder

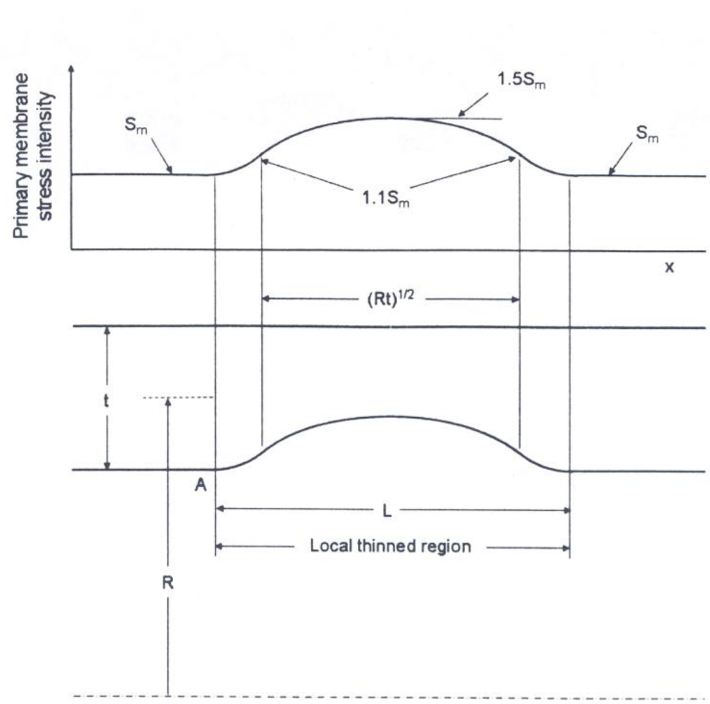

Figure 3 Schematic Illustration of Local Stress Region with Distribution of Primary Membrane Stress Intensity Balancing Force

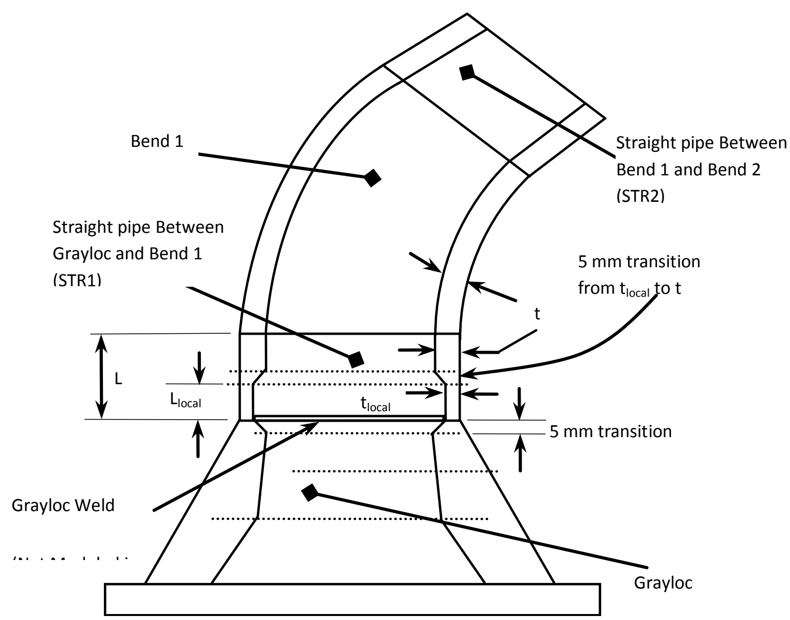

Figure 4 Schematic of a Typical DNGS feeder With Below Pressure Based Thickness in the Vicinity of Grayloc Weld

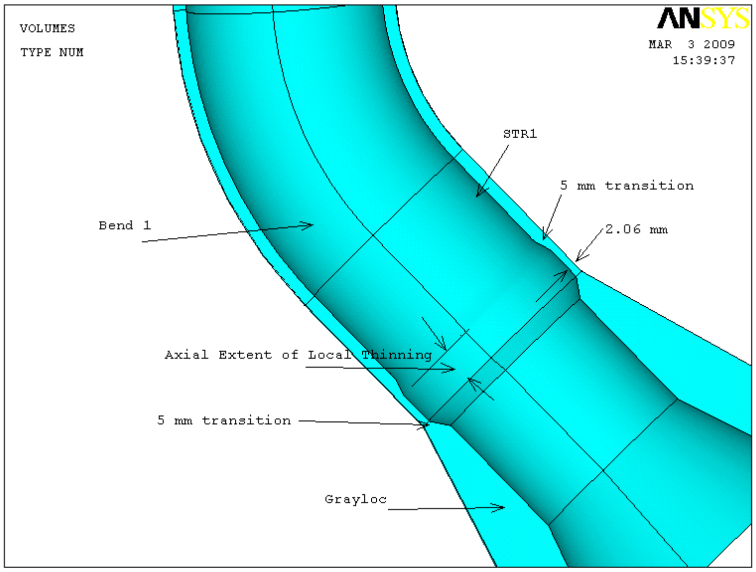

Figure 5 Below Pressure Based Thickness in the Grayloc Weld Region for DNGS Feeder A15W (bend type A)

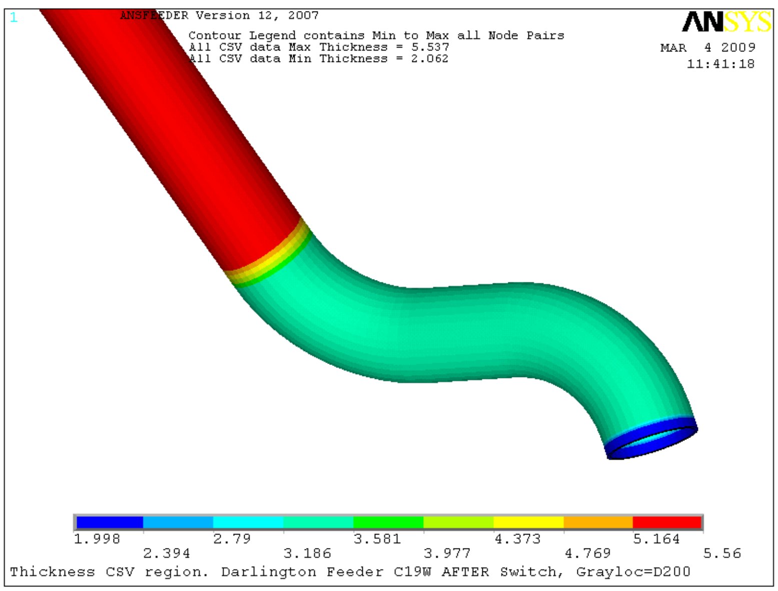

Figure 6 Thickness Profile With Below Pressure Based Thickness in the Grayloc Weld Region for DNGS Feeder C19W (Bend Type D NPS 2.0 Inch)

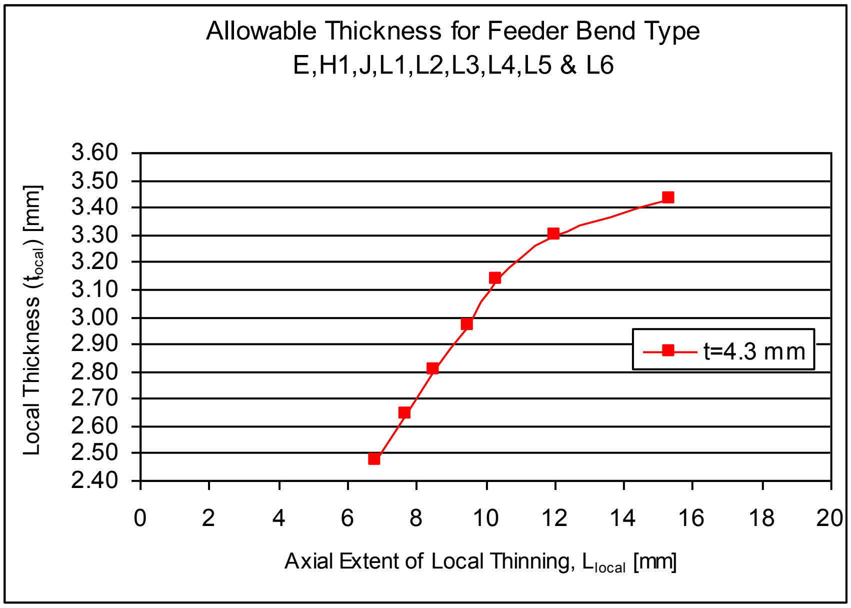

Figure 7 Variation of Axial Extent of Thinning Allowed for Localized Thickness Below Pressure Based Thickness for Feeder Bend Type E, H1, J, L1, L2, L3, L4, L5 & L6 with t = 4.3 mm.

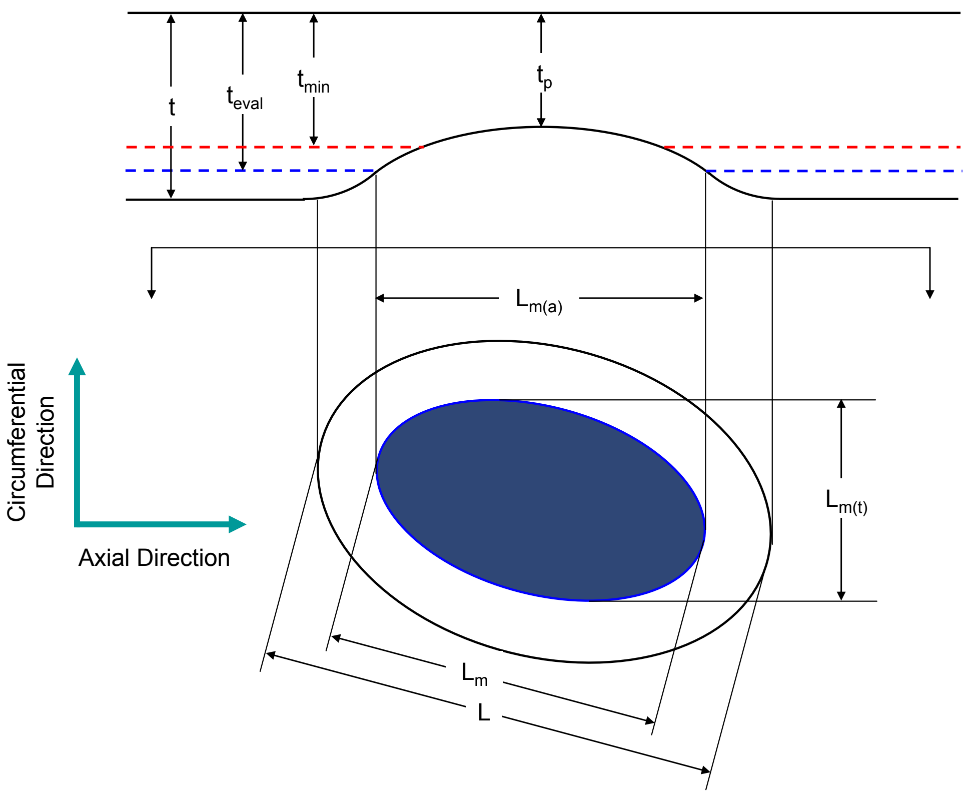

Figure 8 Illustration of Local Thinned Region

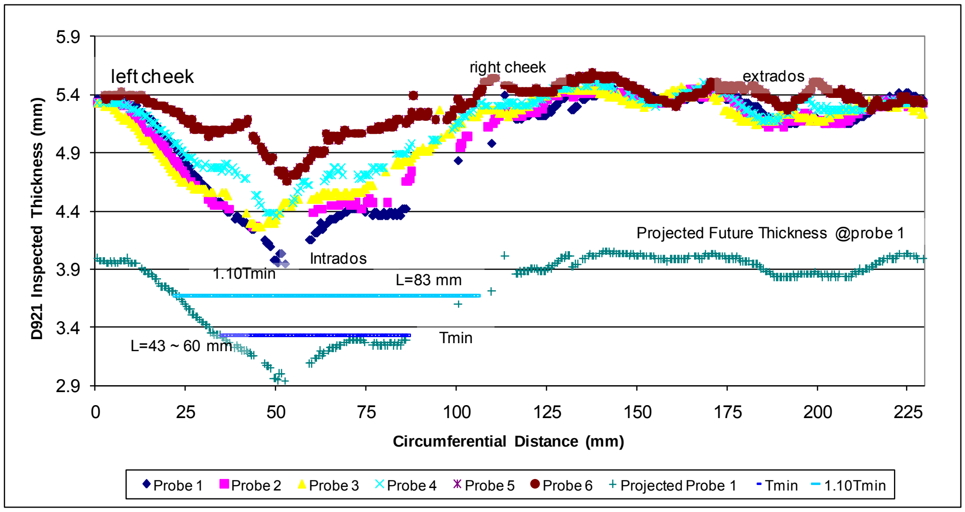

Figure 9 Inspected and Projected Thickness Profiles for Feeder F17E

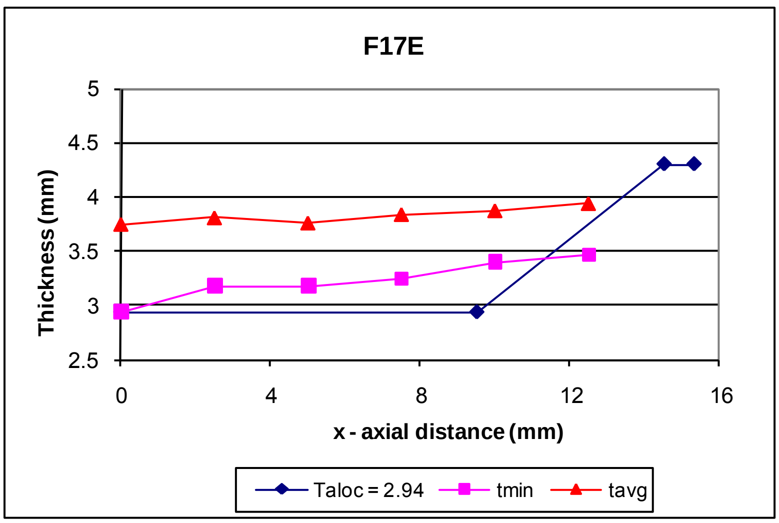

Figure 10 Modeled Thickness, Projected Minimum and Average Thicknesses for F17E