Detailed Finite Element Analysis of Darlington NGS Feeder Pipes With Locally Thinned Regions Below Pressure Minimum Thickness

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Abstract

Feeder Pipes in CANDU nuclear stations are experiencing wall thinning due to flow accelerated corrosion (FAC) resulting in locally thinned regions in addition to general thinning. In Darlington NGS these locally thinned regions can be below pressure based minimum thickness (t_{min}), required as per ASME Code Section III NB-3600 Equation (1). A methodology is presented to qualify the locally thinned regions under NB-3200 (NB-3213 & NB-3221) for internal pressure loading only. Detailed finite element models are used for internal pressure analysis using ANSYS v11.0. All other loadings such as deadweight, thermal and seismic loadings are qualified under NB-3600 using a general purpose piping stress analysis software. The piping stress analysis is based on average thickness equal to t_{min} along with maximum values of ASME Code stress indices (Table NB-3681(a)-1). The requirement for the use of this methodology is that the average thickness of each cross-section with the locally thinned region shall be at least t_{min}. The finite element analysis models are thinned to 0.75 t_{min} (in increments of 0.05 t_{min}) all-around the circumference in the straight section region allowing for flexible inspection requirements. Two different thicknesses of 1.10 t_{min} and 1.30 t_{min} are assigned to the bends. Thickness vs the allowable axial extent curves were developed for different types of feeder pipes in service. Feeders differ in pipe size, straight section length, bend angle and orientation. The stress analysis results show that all Darlington NGS outlet feeder pipes are fit for service with locally thinned regions up to 75% of the pressure based minimum thickness. This paper demonstrates the effectiveness of finite element analysis in extending the useful life of degraded piping components.

1. Introduction

Feeder pipes in CANDU nuclear power plants carry heavy water to and from reactor fuel channels to remove heat generated from nuclear fission process. In a Darlington NGS unit there are total of 960 (480 outlet and 480 inlet) feeders. Feeder pipes are made from SA 106 Grade B carbon steel and are designed to Class I piping requirements of the ASME Boiler and Pressure Vessel Code, Section III, Subsection NB and CSA Standards. Darlington NGS outlet feeders are experiencing wall thinning near the Grayloc end fitting due to Flow Accelerated Corrosion (FAC). Thinning is in the general area close to the Grayloc including the bends downstream of the Grayloc. Severe thinning is encountered in straight pipe (STR1) between Grayloc and bend 1 downstream of the Grayloc. In previous Darlington NGS feeder fitness for service analyses, the acceptable thickness for the straight section (STR1) adjacent to the Grayloc is found to be pressure based minimum thickness, i.e.; t_{min} = 2.75 mm for 2" and 3.33 mm for 2.5" feeders. In these analyses, the pressure based minimum thickness is uniformly modeled on the straight section.

However, in recent inspections it was found that a large number of feeders could have a predicted localized thickness below t_{min} near the Grayloc. Thinning adjacent to the Grayloc weld is identified as a life limiting condition for majority of Darlington NGS outlet feeders. If pressure based minimum thickness is set as feeder replacement criterion, there would be approximately 230 feeders requiring replacement or repair. If the DNGS feeders were shown to be acceptable at 75% (limit used in current analysis) of the t_{min}, only 21 feeders need to be replaced. This makes huge economical impact for Ontario Power Generation. This paper presents generic stress analysis for DNGS outlet feeders demonstrating fitnss-for-service with localized below pressure based minimum thickness in the straight pipe between Grayloc and bend 1.
This paper presents solutions to the following two issues;
(a) present a methodology for qualification of feeders with below t_{min} localized thicknesses based on ASME Section III and
(b) provide generic solution for quick disposition of localized thicknesses for large number of feeders found during an outage for unit re-start.
Figure 1 shows schematic of a typical DNGS feeder with below pressure based thickness in the vicinity of the Grayloc weld. Important parameters t (uniform thickness beyond the locally thinned region, mm), t_{local} (local thickness below pressure based, mm) and L_{local} (axial length of the locally thinned region, mm) are defined in **Figure 1**.

2. Assumptions and Limitations

1) Local thinning below pressure based minimum thickness is expected in the vicinity of the Grayloc and not near the bend 1.

2) There is no effect of local thinning in one feeder on the stresses in adjacent feeder(s) under pressure loading. Hence feeder sub models can be used. In this study a typical feeder sub-model consists of Grayloc up to and including the pipe section downstream of bend 2.

3) This analysis only takes in to account gradual and smooth thinning near the Grayloc.

4) Local thinning below pressure based thickness is only considered in the straight pipe between the Grayloc and bend 1. This analysis does not cover local thinning in the bends.

5) In case where inspections on straight pipe show thickness below pressure based thickness, inspection on the bends shall also be done.

6) In addition to the straight pipe, Grayloc could also be subjected to FAC caused local thinning. This is included in the modeling by reducing the Grayloc wall thickness at the junction of the straight pipe. However, its structural integrity in general is assumed to be sound because of its higher thickness. Its assessment is not within the scope of this analysis.

3. Basis of Below t_{min} Analysis

In Class I NB-3600 piping analysis the pressure based minimum required thickness is given by the following equation (NB-3641 Equation 1)

$$t_{min} = \frac{PD_o}{2(S_m + Py)} + A$$

where t_{min} = pressure based thickness (mm)

P = Internal Pressure; 11.30 MPa for DNGS outlet feeders

D_o = Outside diameter of feeder pipe

S_m = Maximum allowable stress intensity; S_m = 119 MPa for A106 Grade B at 318.3 ^oC

A = Additional thickness for corrosion; A = 0 for feeders

y = 0.4

Since the above equation is no longer met due to below pressure based thickness (even locally), the hoop stress shall be evaluated. The only relevant loading in Equation 1 is internal pressure. All other loadings do not produce a significant component in the hoop direction. Hoop stress is checked by analyzing the below pressure based thickness in the detailed feeder finite element model with internal pressure loading.

3.1 Application of NB-3200

For any thickness below t_{min}, 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.

According to NB-3221 and NB-3213.10

1. General Primary Membrane Stress (Pm) should be less than $1.0S_m$ away from locally thinned area.
2. Local Primary Membrane Stress (P_L) should be less than $1.5S_m$ and come down to $1.1S_m$ within $\sqrt{Rt}$ (as per NB-3213.10).
3. Primary Membrane plus Bending (P_m+P_b) shall be less than $1.5S_m$ every where.

Figure 2 provides more details about the limits of different stresses.

As a conservative measure, the limit on the Local Primary Membrane Stress (P_L) is also set to $1.0S_m$.

3.2 Axial Stress Under Other Loadings and Fatigue Evaluation

The longitudinal or axial stress intensity limits for design and service conditions (Level A/B and Level C) are provided in NB-3650 as Equation(s) 9, 10, 12 & 13. In general, the minimum local acceptable thickness at a specific location is seldom determined by the axial stress because axial pressure stress (which is half of the hoop pressure stress) plus primary bending stress is generally less than the hoop pressure stress and the allowable axial stress is often higher than the allowable hoop stress (e.g., $1.5S_m$ versus $1.0S_m$ ASME Section III, NB). In addition, axial bending stresses are usually high at only a few locations in the system, and if the local thinning does not occur at high axial stress location, the axial stress intensity limit could be easily met.

In previous 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 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. This approach is inherently conservative since the loads are calculated based on the average thickness (higher thickness gives higher loads), indices are based on minimum thickness (lower thickness gives higher indices) and code equations are evaluated based on average thickness.

Note that the range of applicability of the stress indices given in NB-3681(a)-1 is $D_o/t \leq 100$ for C or K indices and $D_o/t \leq 50$ for B indices. DNGS feeders with below pressure based thickness (up to $0.75t_{min}$) fall in to the above mentioned range. Since the K indices are independent of thickness, the previous fatigue assessments based on the pressure minimum thickness are still valid provided the average thickness is equal to or above t_{min}.

4. Darlington NGS Outlet Feeders

In Darlington NGS there are 22 types of feeder bends. These types are categorized by pipe size, bend angle, bend radius, length of straight pipe(s), etc. Some similar bend types have small differences in geometry, away from the region of interest, e.g.; different length straight pipe between the bend 1 (1st bend downstream of Grayloc) and bend 2 (2nd bend downstream of Grayloc) or different bend radius for the second bend. Since the loading used in this analysis is only internal pressure, it is assumed that there is negligible effect of these changes 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 types as shown in **Table 1** according to pipe size and the length of STR1.

4.1. Bend Thicknesses

Wall thickness of the feeder pipe away from the locally thinned area is an important consideration in the current assessment. The wall thickness of feeder pipes in the generally thinned area 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. Two wall thickness values in the region away from the locally thinned area are selected for this analysis. The selected values are provided in **Table 2**. The values in **Table 2** were selected using the minimum wall thickness measured in the bend 1 and straight pipe between Grayloc and bend 1 during the last two outages and projected to future outages.

4.2. Finite Element Modeling

In all ANSYS finite element models, default mesh options, 3 elements through thickness and 36 elements around the circumference are used. ANSYS element SOLID 186 (20 node quadratic brick) is used to generate the mesh. In the axial direction, higher mesh density is used in the region of interest (STR1 and bend 1) and lower mesh density in the region beyond bend 1. The Grayloc connection is fully constrained in 6 degrees of freedom. On the de-coupled end of the feeder, axial force is applied to balance the axial force generated by the internal pressure.

In order to eliminate sharp corners, a transition is modeled between two sections 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 t within the STR1 or inside the bend 1 (for short length STR1 feeder bend types)
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 3 gives a picture of a typical finite element 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 any where around the circumference for a given axial extent (average thickness at each cross-section shall be equal to or higher than t_{min}). **Figure 4** is a thickness profile for a typical 2.50 inch feeder C13W. Note that the below pressure based thickness is modeled all around the circumference.

Thickness of the thinned region was fixed and the axial extent of thinning was adjusted such that the stresses were just within the limits of ASME NB-3221. The thickness increments used in going from $0.75t_{min}$ to t_{min} are given in **Table 3** (Part 1and Part 2). Several iteration were required to find an axial extent for a given thickness of the localized region which meets the Code allowable.

5. Results

Analysis was performed to determine the acceptable below pressure thickness in the straight pipe between Grayloc and Bend 1. Loading used is internal pressure.

Figure 5 shows the primary stress distribution in the feeder B18W (bend type B) for t_{local} = 2.06 mm and t = 3.50 mm. The axial extent is 9.50 mm and un-limited circumferential extent. **Figure 6** shows the primary membrane plus bending stress distributions for the same feeder geometry. **Figure 7** shows the stress distribution along the feeder axis for feeder B18W (bend type B). Both primary membrane and primary membrane plus bending stress distribution is shown. A vertical dotted line shows the end of STR1. It is evident that the highest stress occurs in STR1. A similar graph (**Figure 8**) is shown for feeder C13W (bend type E) for t_{local} = 2.47 mm and t = 4.30 mm. Since for bend type E feeders STR1 is short (15.33 mm, as compared to 38.55 mm for bend type B); the highest stress is controlled by the bend 1; as seen from **Figure 8**.

Figure 9 shows the allowable minimum thickness (below t_{min}) as a function of axial extent of thinning for un-limited circumferential thinning for analysis model 1 (bend type A). The solid line is for "t" of 3.50 mm (case 1 for 2.0 inch feeders in **Table 2**) and the dotted line is for "t" = 3.0 mm (case 2 for 2.0 inch feeders in **Table 2**). **Figure 10** shows the allowable minimum thickness (below t_{min}) as a function of axial extent of thinning for un-limited circumferential thinning for analysis model 2 (bend type B & F). **Figure 11** shows the allowable minimum thickness (below t_{min}) as a function of axial extent of thinning for un-limited circumferential thinning for analysis model 3 (bend type C). The solid line is for "t" of 4.30 mm (case 1 for 2.5 inch feeders in **Table 2**) and the dotted line is for "t" = 3.6 mm (case 2 for 2.5 inch feeders in **Table 2**).

Figure 12 shows the allowable minimum thickness (below t_{min}) as a function of axial extent of thinning for un-limited circumferential thinning for analysis model 4 (bend type E, H1, J, L1, L2, L3, L4, L5 & L6). **Figure 13** shows the allowable minimum thickness (below t_{min}) as a function of axial extent of thinning for un-limited circumferential thinning for analysis model 5 (bend type D, G1, I, K1, K2, K3, K4 & K5). **Figure 14** shows the allowable minimum thickness (below t_{min}) as a function of axial extent of thinning for un-limited circumferential thinning for analysis model 6 (bend type M).

In **Figure 9 – Figure 14**, any thickness below t_{min} (up to 0.75 t_{min}) to the left and top of the curve(s) is acceptable.

6. Guidelines on Using this Assessment

The following guidelines must be followed when using the results provided in this assessment.

(a) The minimum thickness in a localized region below pressure thickness must be assigned to the whole region below the pressure based thickness.

(b) The average thickness at each cross section, which has a thickness below pressure based must be equal to or higher than the pressure based thickness. The pressure based thickness is given below

Feeder Size [inch]	Pressure Minimum Thickness [mm]
2.0	2.75
2.5	3.3

The average thickness shall be calculated by adding all the measured thickness in that cross-section and divide by the number of thickness data points. In case of missing data, it shall be conservatively filled with pressure based thickness (if the last available data points are above pressure based thickness) or interpolated between the available thickness points (if the last available point(s) are below pressure based thickness).

(c) The average thickness at each cross-section, which has minimum thickness equal to or higher than the pressure based thickness and below the analyzed “t” thickness, must be equal to or higher than the “t” thickness.

The average thickness shall be calculated by adding all the measured thickness in that cross-section and divide by the number of thickness data points. In case of missing data, it shall be conservatively filled with pressure based thickness (if the last available data point(s) are below the “t” thickness) or interpolated between the available thickness points (if the last available point(s) are above “t” thickness).

(d). Linear interpolation can be used for thickness in-between curves.

(e) In finite element modeling for this assessment, a linear transition(s) of 5 mm is used from t_{local} to t thickness. If required, this transition region can be used in the thickness evaluations.

(f) Multiple local thinning spots shall be combined if distance between them is $\leq \sqrt{(R_o t_{min})}$ in circumferential and axial direction

(g) Only smooth and gradual thinning is covered by this assessment. Sudden changes in thickness or blunt flaw is not covered and needs to be analyzed separately.

7. Application of Assessment Results to J24E Predicted Thicknesses

The Darlington J24E feeder was inspected in D721 outage and the inspected thicknesses were predicted to a future outage. The predicted thicknesses were found to be below pressure based thickness in a localized region in the vicinity of the Grayloc.

Hoop Stress Check Due to Internal Pressure

The thickness data is given in **Figure 15** and in **Table 4**. The 6-probe pack which was used for thickness inspections has 6 probes in the axial direction at an equal distance of 2.5 mm apart. The first probe is located at 2.5 mm away from the weld cap and the probe 6 (last probe) is 12.5 mm away along the feeder from probe 1.

From **Figure 15** it can be seen that the circumferential extent of thinning below the pressure based thickness is approximately 17 mm (32^o). From **Figure 13** the allowable axial extent is approximately 9.3 mm for 2.54 mm thickness.

The minimum and average thickness at each probe is given in **Table 4**. Please note that the average thicknesses reported in **Table 4** are the average of the available data points and missing data is not interpolated. The below pressure based thinning occurs only on probe 1. The average thickness of the cross-section at probe 1 is 3.47 which is well above the required thickness of 2.75 mm (t_{min} for 2.0 inch feeder). In the axial direction, the pressure based thickness is violated at probe 1 only, so the maximum extent of axial thinning possible due to inspection uncertainty is approximately 5.0 mm (by assuming the probe 1 is at distance of 2.5 mm away from the weld cap and add it to the 2.5 mm distance between probe 1 and probe 2). This takes to in-between probe 4 and probe 5. The minimum thicknesses on probe 4 and 5 are 3.48 mm and 3.45 mm respectively.

The transition in the finite element model is 5 mm long in the axial direction which runs from 2.54 mm to 3.5 mm. Probe 4 (at 7.5 mm) falls within the allowed axial extent of thinning. Probe 5 (at 10.0 mm) is outside the allowed axial extent by 0.7 mm. At 10.0 mm, the thickness in the finite element model is ~ 2.67 mm, whereas the minimum thickness at 10 mm (probe 5) is 3.45 mm. **Figure 16** shows the projected and analyzed thicknesses schematically.

<u>Axial Stress Check and Fatigue Evaluation</u>

The axial stress check is done for NB-3650 Equation(s) 9, 10, 12 and 13 for Level A/B and Level C. The ASME Code maximum values (**Table 5**) for stress indices are used. The minimum average thickness of 3.47 mm from projected values (given in **Table 4**) was used in the analysis. Stress and fatigue evaluation results are given in **Table 6**.

8. Conclusions

The results of present assessment show that the thickness of DNGS outlet feeders can be up to $0.75t_{min}$ in a localized region near the Grayloc weld area and meet the requirements of ASME B & PV Code NB-3200 for internal pressure loading. The thickness of $0.75t_{min}$ can be any where around the circumference (un-limited circumferential extent) for the given axial extent. All other loadings (deadweight, thermal, seismic and fatigue evaluation) do not need to be re-evaluated provided the average thickness at each cross-section is equal to or higher than the pressure based thickness and stress indices are the ASME Code maximum values.

9. References

[1] Li, M., et al; "Darlington NGS: Generic Relief Wall Thickness Values for All Outlet Feeders for Service Level A, B and C Loads"; OPGl Document No. NK38-CALC-33160-10050 R001; October, 2006

[2] Haq I, "Darlington NGS: Acceptability of Below Pressure Based Thickness due to Local Thinning Near the Grayloc for 22 Feeder Bend Types"; OPGI Document No. NK38-CALC-33160-10068 R001; May 2009

[3] The American Society of Mechanical Engineers; "ASME Boiler & Pressure Vessel Code (1995 Edition including 1997 Addenda), Section III, Division I, Subsection NB"

[4] Li M., et al; "Localized Thinning Assessment – Service Life Extension for Darlington Feeders"; <u>31st Annual Conference of the Canadian Nuclear Society</u>; Montreal, QC, May 24-27, 2010

Nomenclature

CUF	Cumulative Usage Factor
DNGS	Darlington Nuclear Generating Station
FAC	Flow Accelerated Corrosion
STR1	Straight pipe between Grayloc and Bend 1
t	Thickness in the generally thin region beyond local thinning
t_{min}	Pressure based minimum thickness
t_{local}	Localized below pressure based minimum thickness

Table 1 Analysis Models and Equivalent Feeder Types

Analysis Model	Sample Feeder	Equivalent Feeder Types
1	A15W	A
2	B18W	B, F
3	B14W	C
4	C19W	D, G1, I, K1, K2, K3, K4, K5
5	C13W	E, H1, J, L1, L2, L3, L4, L5, L6
6	M01E	M

Table 2 Wall Thickness Used in Feeder Section Away from the Locally Thinned Region

Feeder Size (Inch)	Case	Thickness in STR1 (Note 1) [mm]	Thickness in Bend 1, Bend 2 and Straight Pipe in-Between [mm]	Thickness Beyond Bend 2 [mm]
2.0	Case 1	3.5 (~1.3t_{min})	3.5 (~1.3t_{min})	5.537
	Case 2	3.0 (~1.1t_{min})	3.5 (~1.3t_{min})	5.537
2.5	Case 1	4.3 (~1.3t_{min})	4.3 (~1.3t_{min})	7.01
	Case 2	3.6 (~1.1t_{min})	4.3 (~1.3t_{min})	7.01

Note 1: This thickness is assigned to the axial section of straight pipe left after the locally thinned region and a transition (5 mm) from locally thinned region to this thickness. For feeder bend types where the total length of the straight pipe is ~10.3 mm, usually there is no section left for these thicknesses.

Table 3 Thicknesses Used in the Current Assessment

Part - 1

Local Thickness t_{local} (% of t_{min})	Profile No.	Analysis Model	Thickness Away From Locally Thinned Region
0.75	P1	1, 2, 3, 4, 5, 6	t = 3.5 mm for 2.0 inch and t=4.3 mm for 2.5 inch feeder size
0.775	P2	4, 6	
0.80	P3	1, 2, 3, 4, 5, 6	
0.825	P4	4, 6	
0.85	P5	1, 2, 3, 4, 5, 6	
0.90	P6	1, 2, 3, 4, 5, 6	
0.95	P7	1, 2, 3, 4, 5, 6	
1.00	P8	1, 2, 3, 5	

Part - 2

Local Thickness t_{local} (% of t_{min})	Profile No.	Analysis Model	Thickness Away From Locally Thinned Region, t [mm]
0.75	PS1	1, 2, 3	t = 3.0 mm for 2.0 inch and t=3.6 mm for 2.5 inch feeder size
0.775	PS2	-	
0.80	PS3	1, 2, 3	
0.825	PS4	-	
0.85	PS5	1, 2, 3	
0.90	PS6	1, 2, 3	
0.95	PS7	1, 2, 3	
1.00	PS8	1, 2, 3	

Table 4 Thickness Data from 6-probe Pack for Darlington NGS J24E

Probe No.	Probe 1	Probe 2	Probe 3	Probe 4	Probe 5	Probe 6
Axial Location on STR1 [mm]	2.5	5.0	7.5	10.0	12.5	15.0
Minimum Thickness [mm]	2.54	2.80	2.86	3.48	3.45	3.63
Average Thickness [mm]	3.47	3.58	3.70	3.82	3.88	4.00

Table 5 ASME Code Stress Indices Maximum Values for 1:3 Transition

Stress Index for 1:3 Transition	B1	C1	K1	B2	C2	K2	C3	C3’	K3
Value Used (ASME Code Maximum Value)	0.50	1.80	1.26*	1.00	2.10	1.80	2.00	0.60	1.70

* 5% increase in K1 stress index to account for surface roughness

Table 6 ASME Code NB-3650 Analysis Results for Average Thickness of 3.47 mm

NB-3650 Equation	Design Equation 9	Level A/B Equation 9	Level A/B Equation 10	Level C Equation 9	Level C Equation 10	Level C Equation 13	Fatigue CUF
Stress / Allowable	0.37	0.32	0.98	0.66	1.29	0.69	0.35

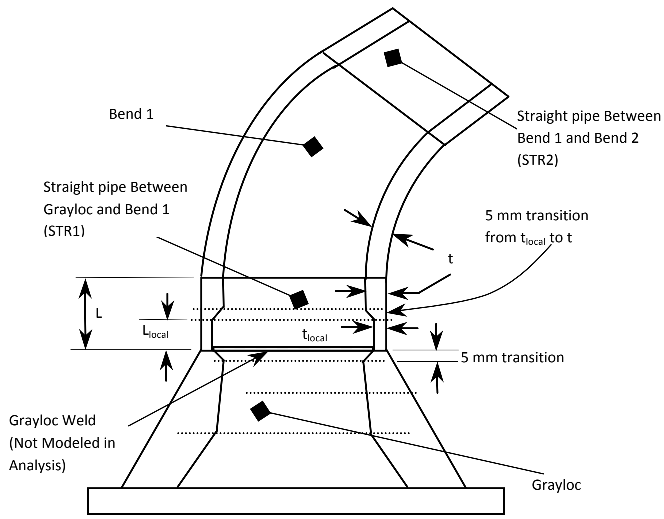

Figure 1 Schematic of a Typical DNGS feeder With Below Pressure Based Thickness in the Vicinity of Grayloc Weld

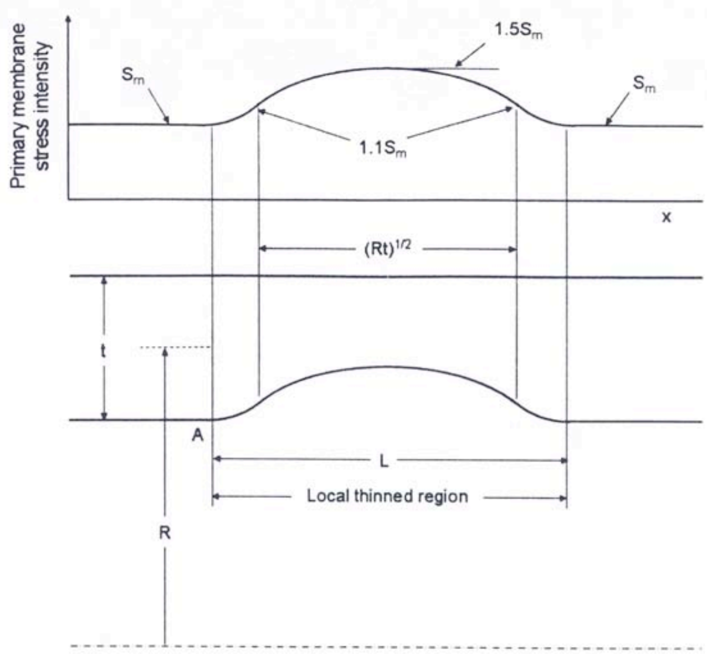

Figure 2 Schematic Illustration of Local Stress Region with Distribution of Primary Membrane Stress Intensity

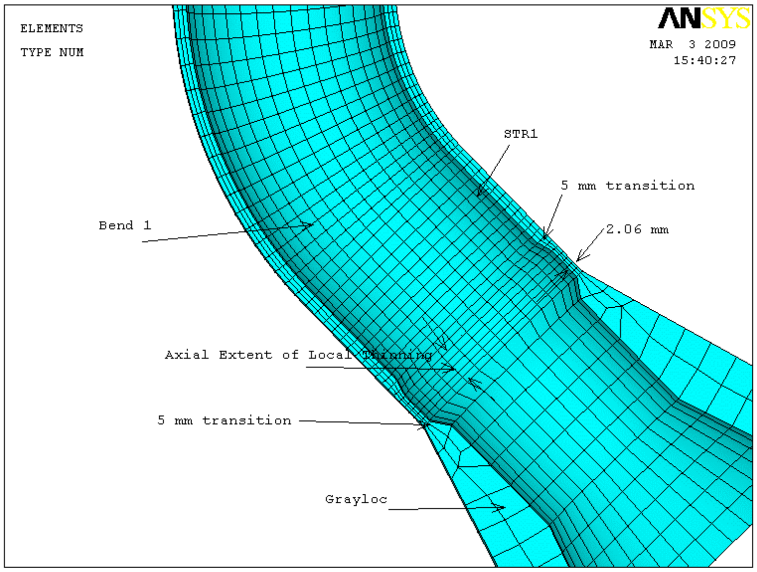

Figure 3 Computational Finite Element Model for Below Pressure Based Thickness in the Grayloc Weld Region for DNGS Feeder A15W (bend type A)

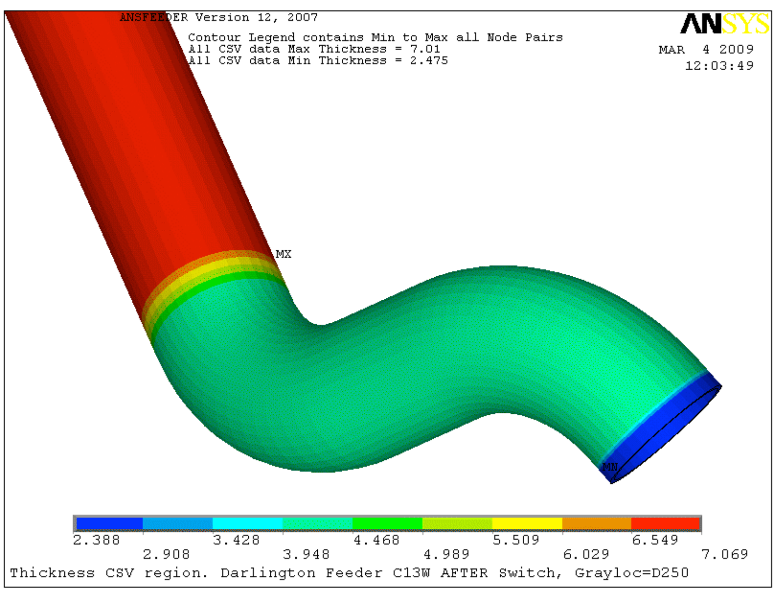

Figure 4 Thickness Profile With Below Pressure Based Thickness in the Grayloc Weld Region for DNGS Feeder C13W (Bend Type E NPS 2.5 Inch) Thickness in mm.

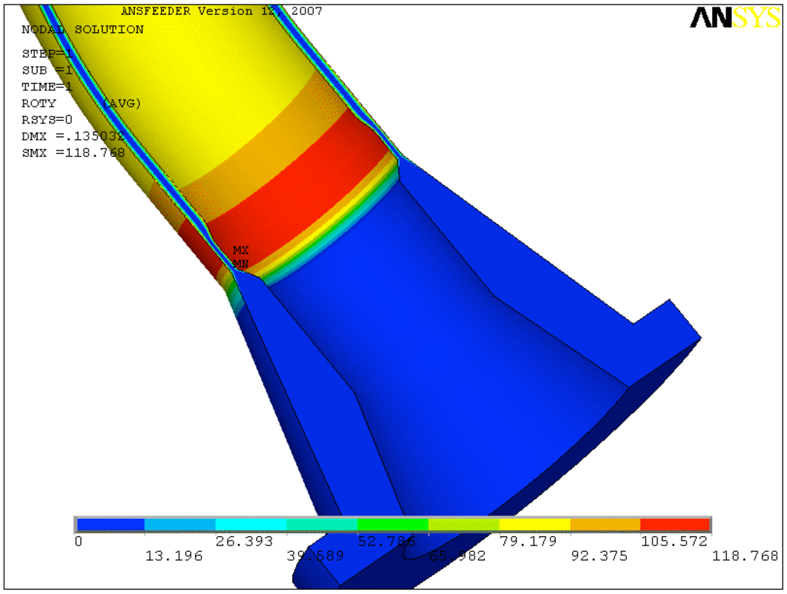

Figure 5 DNGS Feeder B18W (Bend Type B) Primary Membrane Stress [MPa] Distribution for t_{local} = 2.06 mm and t = 3.50 mm.

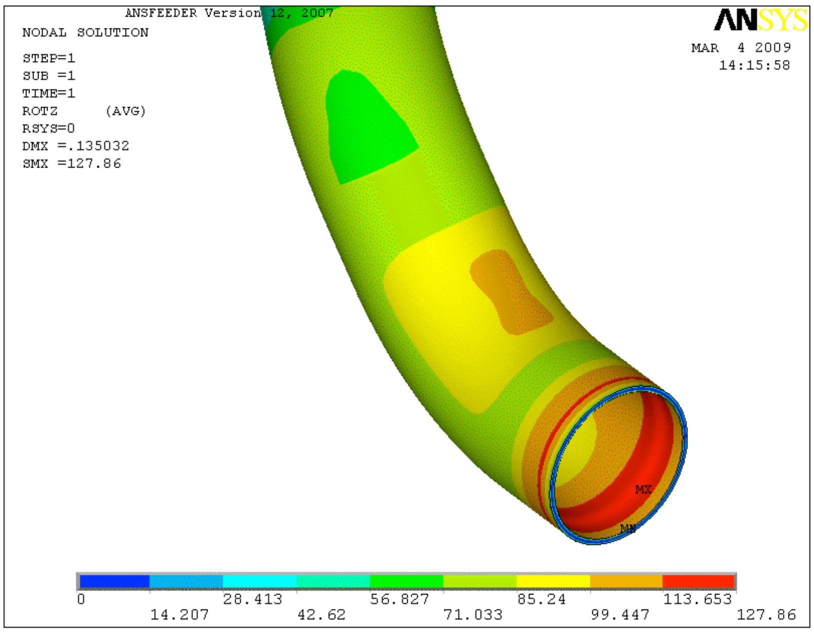

Figure 6 DNGS Feeder B18W (Bend Type B) Primary Membrane Plus Bending Stress [MPa] Distribution for t_{local} = 2.06 mm and t = 3.50 mm

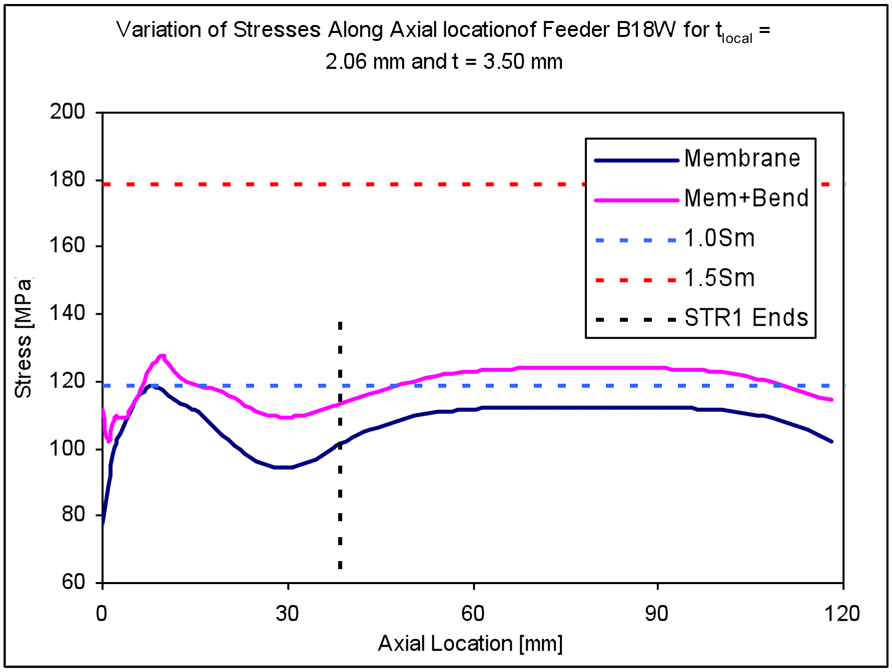

Figure 7 DNGS Feeder B18W (Bend Type B) Pm and Pm+Pb Distribution Along the Feeder Axis for t_{local} = 2.06 mm and t = 3.50 mm

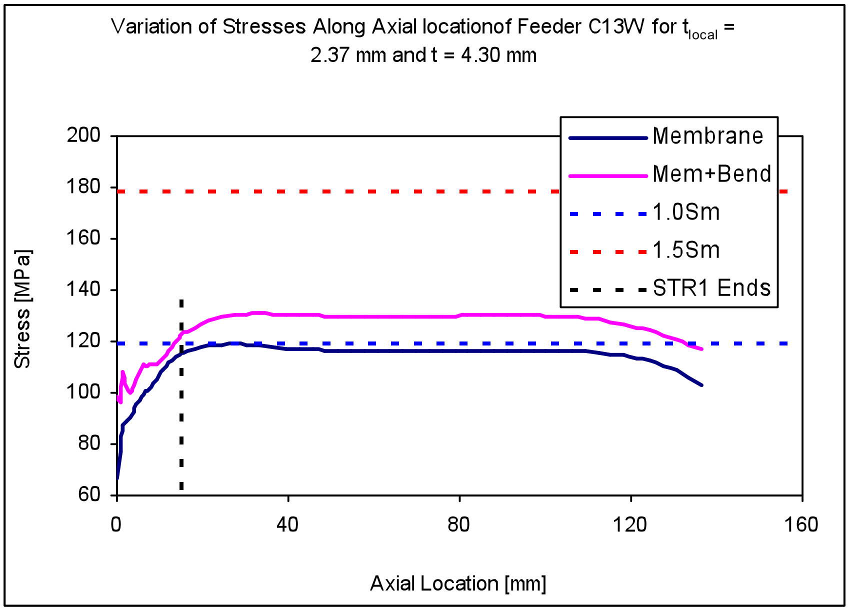

Figure 8 DNGS Feeder C13W (Bend Type E) Pm and Pm+Pb Distribution Along the Feeder Axis for t_{local} = 2.47 mm and t = 4.30 mm

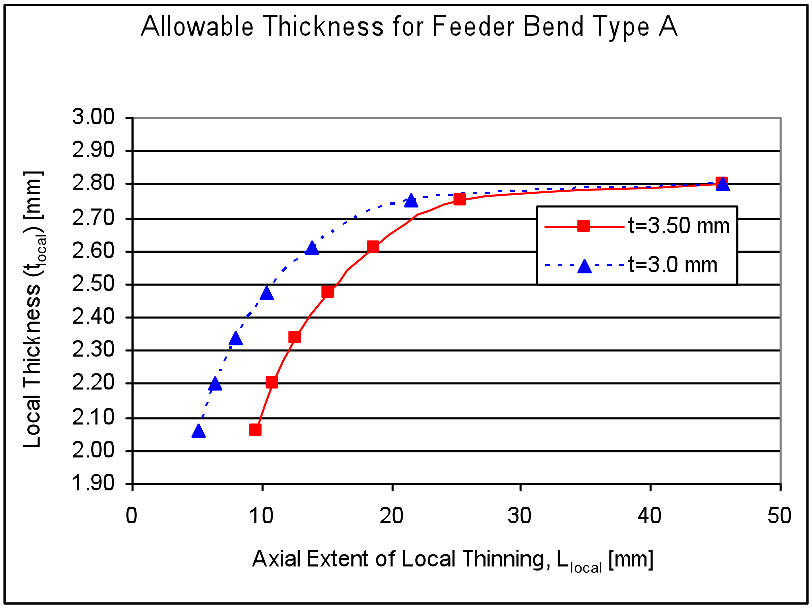

Figure 9 Variation of Axial Extent of Thinning Allowed for Localized Thickness Below Pressure Based Thickness for Feeder Bend Type A with t = 3.5 and 3.0 mm

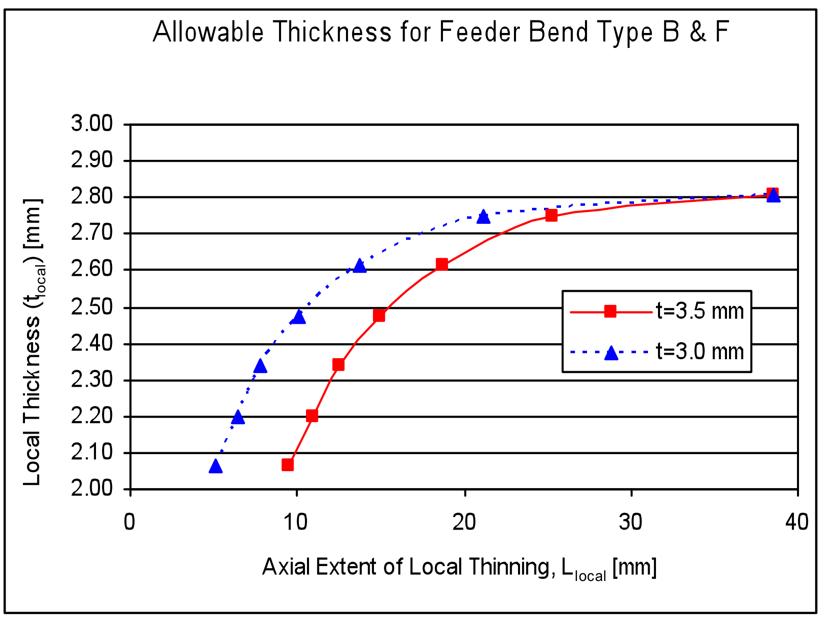

Figure 10 Variation of Axial Extent of Thinning Allowed for Localized Thickness Below Pressure Based Thickness for Feeder Bend Type B with t = 3.5 and 3.0 mm.

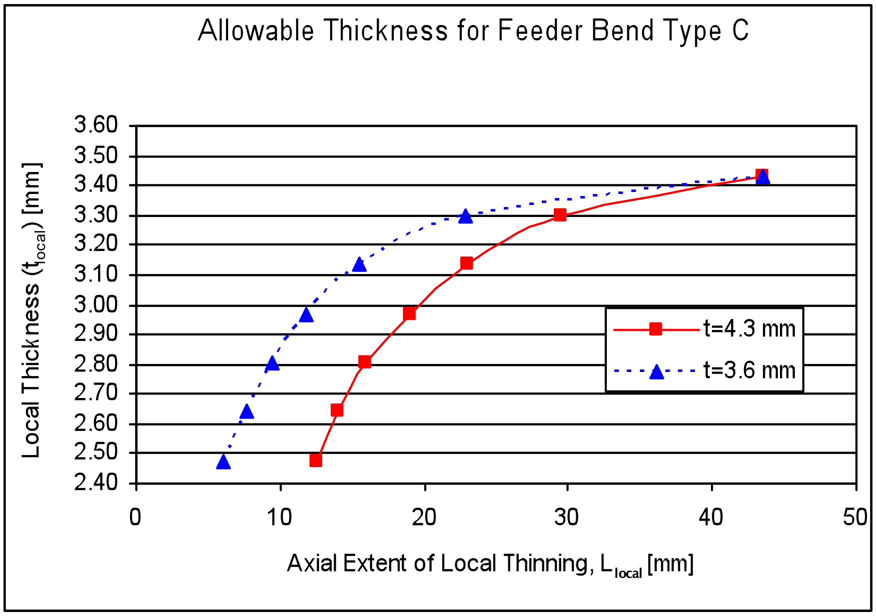

Figure 11 Variation of Axial Extent of Thinning Allowed for Localized Thickness Below Pressure Based Thickness for Feeder Bend Type C with t =4.3 and 3.6 mm.

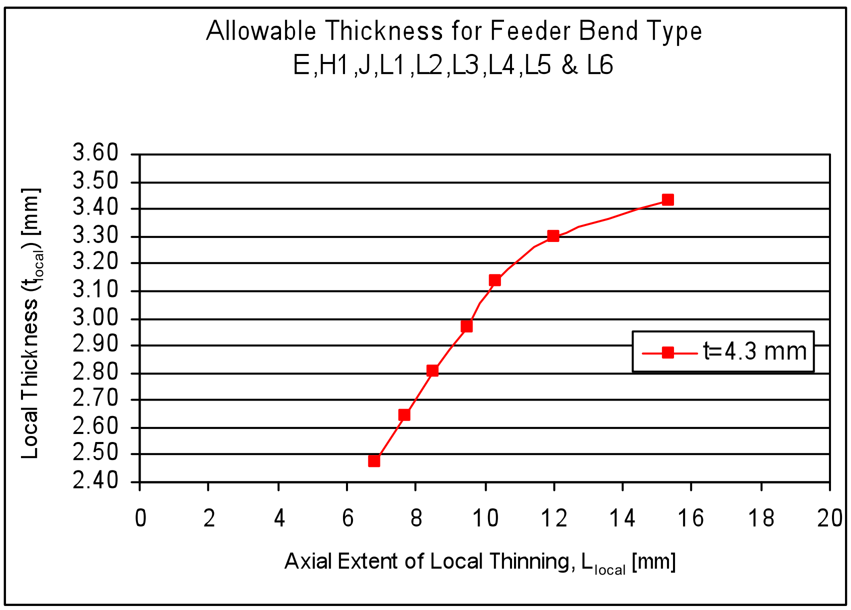

Figure 12 Variation of Axial Extent of Thinning Allowed for Localized Thickness Below Pressure Based Thickness for Feeder Bend Type E, H1, J, L1, L2, L3, L4, L5 & L6 with t = 4.3 mm.

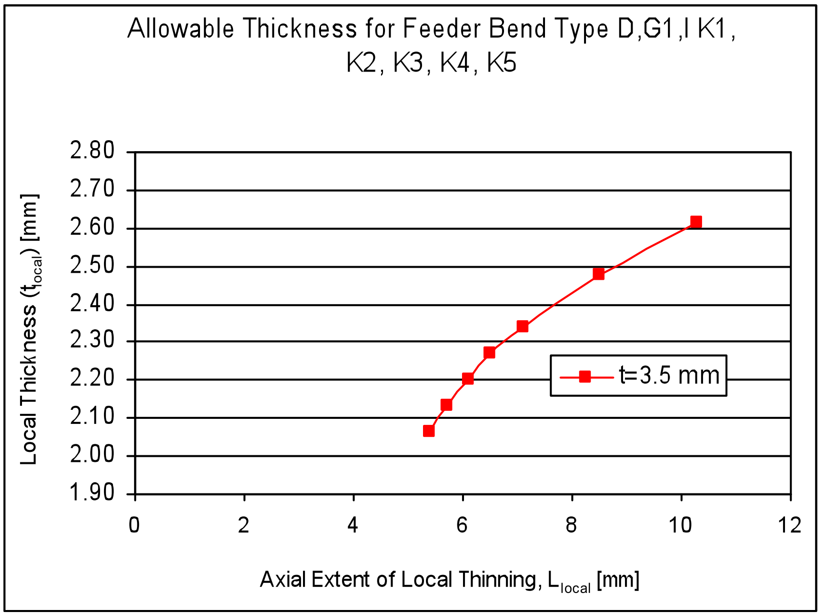

Figure 13 Variation of Axial Extent of Thinning Allowed for Localized Thickness Below Pressure Based Thickness for Feeder Bend Type D, G1, I, K1, K2, K3, K4 & K5 with t = 3.5 mm.

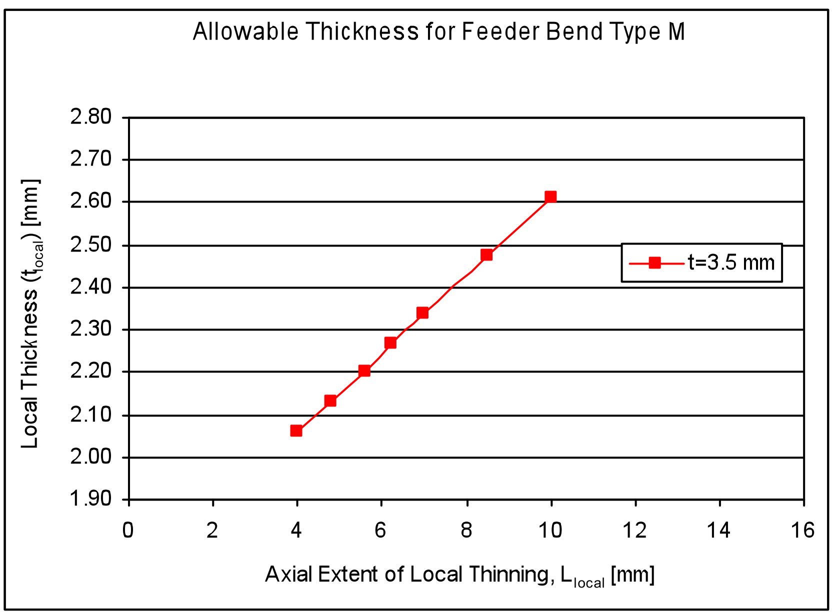

Figure 14 Variation of Axial Extent of Thinning Allowed for Localized Thickness Below Pressure Based Thickness for Feeder Bend Type M with t = 3.5 mm.

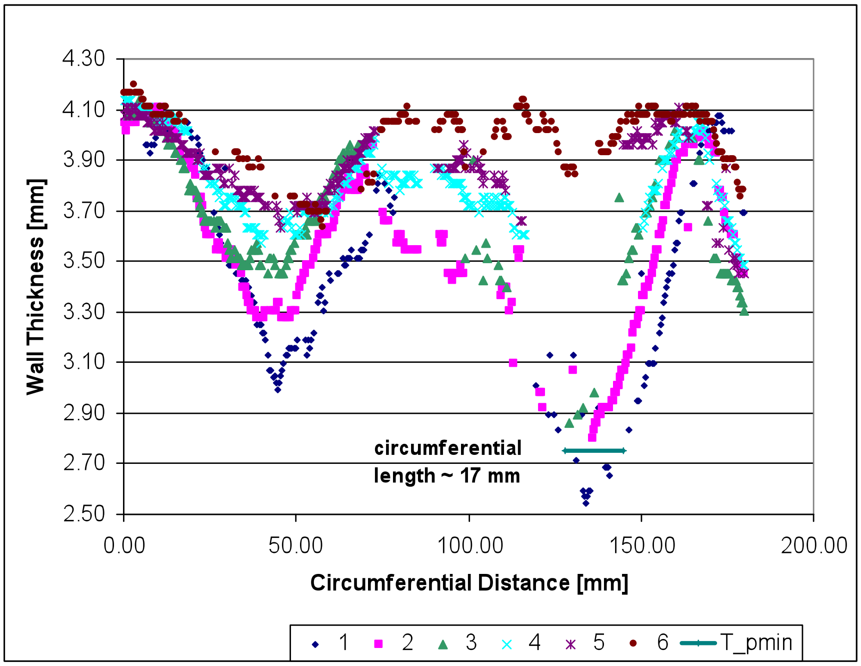

Figure 15 DNGS Feeder J24E Projected Thicknesses from 6-Probe Inspections

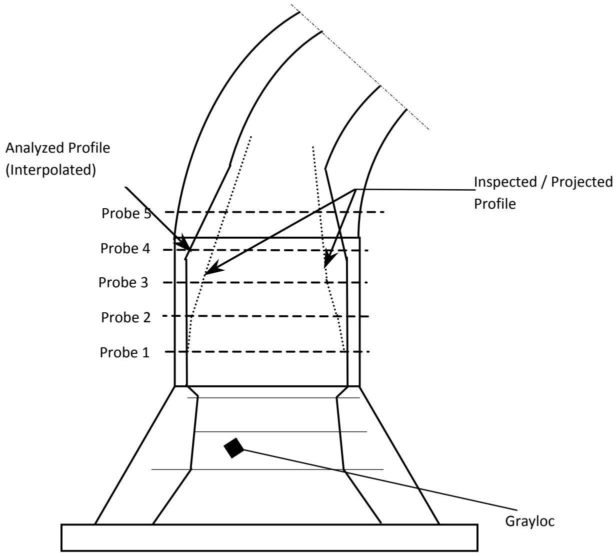

Figure 16 Application of Current Results to Darlington J24E D1021 Projected Thickness Data