FEEDER GRAYLOC HUB LOCAL ALLOWABLE THICKNESS - AN APPLICATION OF FFSG APPENDIX E LEVEL 2 EVALUATION

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ABSTRACT

Flow assisted corrosion (FAC) caused the highest rates of wall loss at outlet feeder pipes in the regions close to the Grayloc end fittings. In the past, almost all stress analyses on reduced thickness, above or below pressure based value, were conducted based on ASME III Code compliance.

However, above assessments were feeders specific in nature and time consuming. For a large scale planned outage, more than several hundreds outlet feeder baseline and repeat inspections may be conducted. There is a reasonable risk that a number of feeders may be found with a wall thickness at or below the pressure based thickness. It is possible that unanticipated results from the inspection could extend the outage duration due to the need to perform unplanned stress analyses to demonstrate the fitness for service of the feeder pipes.

To be effective to prevent outage delay it is necessary to conduct a generic feeder structural integrity assessment prior to the start of the outage. FFSG Appendix E (**Reference 1**) provides acceptance criteria and evaluation procedure for assessing local thinning near the Grayloc region for thickness below pressure based value. The structural evaluation procedure in Appendix E is not feeder specific in such a preventive assessment could provide predetermined acceptable thickness limits to be compared with inspection data. The acceptable thickness limits shall result in significant reduction of feeder disposition time.

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.

The thickness assessment is carried out to show whether or not the analyzed wall thickness values with excessive local thinning at the Grayloc would meet the Code requirements. The majority of feeder structural integrity assessments were based on ASME Section III, NB class 1 piping code (**Reference 2**) and CSA N289.3 for seismic requirements.

The procedures in ASME SEC III are developed for design analysis for new components, rather than for the in-service assessment for degraded feeder piping systems. The analysis rules and methods used in new component design by nature are overly conservative for in-service evaluation of feeder thinning. Feeders are inspected in accordance with the CSA Standards CAN/CSA-N285.4. When a detected wall thinning or a flaw does not satisfy the criteria of acceptance by examination in N285.4, the CSA code allows a fitness-for-service assessment to determine the acceptability for continue operation. FFSG provides the unique set of assessment rules with the consideration of feeder fabrication, design, configuration and degrade mechanisms. The assessment will be used to justify continued operation of feeders in degraded condition.

Appendix E of FFSG was developed to evaluate thinned region in feeder piping. It follows the 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 base value. Level 3 is 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. This paper is to provide a proactive measure to develop a set of acceptable local thickness for piping section next to the feeder Grayloc hub, thus inspection results can be compared and be dispositioned. It would reduce the potential risk of outage delay due to adverse feeder thickness.

2.0 LEVEL 2 ASSESSMENT METHOD

The evaluation procedure is as per Article E-2 of FFSG Appendix E and shown in **Figure 1**. Level 2 evaluation on internal pressure and bending moment coincident with internal pressure were carried out in this paper.

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

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

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

where P – Internal Design Pressure, D_o – Outside diameter of feeder (R_o=D_o/2), S_m – maximum allowable stress, Y = 0.4

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, as limited by the line-in-granite rule in FFSG.

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 2**. The separation distance for multiple local regions is $2.5(R_{eval}t_{eval})^{0.5}$, where $R_{eval} = R_o - t_{eval}/2$. Once multiple thinning regions are detected, the proximity rules should be checked against the separation distance, then the combination of thinning regions or single separate region can be evaluated accordingly. The acceptable thickness obtained in this paper is suitable for both combined and single thinning region.

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 $R_{min}t_{min})^{0.5}$.

For a straight pipe, the ratio of t_{aloc}/ t_{min}^{sp} can be calculated using following formula:

$$t_{aloc}/ t_{min}^{sp} = 0.75 \qquad \text{for } L_{m(a)}/(R_{min}\, t_{min}^{sp})^{0.5} < 2.75$$

$$t_{aloc}/ t_{min}^{sp} = 0.046*(x - 2.75) + 0.75 \qquad \text{for } 2.75 \le x = L_{m(a)}/(R_{min}\, t_{min}^{sp})^{0.5} < 6.0 \qquad (2)$$

$$t_{aloc}/ t_{min}^{sp} = 0.9 \qquad \text{for } L_{m(a)}/(R_{min}\, t_{min}^{sp})^{0.5} > 6.0$$

(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 $2.65(R_{min}t_{min})^{0.5}$.

For a straight pipe or bend, the ratio of t_{aloc}/ t_{min}^{sp} is the maximum value of following three requirements:

(i). Protection against pressure blowout:

$$\frac{t_{aloc}}{t_{min}^{sp}} = 0.353 L_m \left(\frac{1}{R_{min} t_{min}^{sp}}\right)^{1/2} \qquad (3)$$

(ii). Satisfy reinforcement requirement:

$$\frac{t_{aloc}}{t_{min}^{sp}} = 1 - 1.5 \frac{(R_{min} t_{min}^{sp})^{1/2}}{L}\left(\frac{t}{t_{min}^{sp}} - 1\right) \qquad (4)$$

(iii). Line-in-Granite of FFSG for local thinning:

$$t_{aloc}/ t_{min}^{sp} = 0.75 \qquad (5)$$

(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 $(R_{min}t_{min})^{0.5}$.

For a straight pipe, the ratio of t_{aloc}/t_{min}^{sp} can be calculated using following formula:

$t_{aloc}/t_{min}^{sp} = 0.75$ for $x = L_{m(a)}/(R_{min}t_{min})^{0.5} < 0.725$

$t_{aloc}/t_{min}^{sp} = -0.0287x^4 + 0.2243x^3 - 0.6768x^2 + 0.9688x + 0.3251$ for $0.725 < x = L_{m(a)}/(R_{min}t_{min})^{0.5} < 2.5$ (6)

$t_{aloc}/t_{min}^{sp} = 0.9$ for $L_{m(a)}/(R_{min}t_{min})^{0.5} > 2.5$

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. The geometry characterization of the circumferential cross-section of the straight pipe section of feeder pipe is illustrated in **Figure 3**. In this figure, the pipe original or nominal wall thickness t_{nom} is assumed to have been uniformly thinned on the inside surface by FAC to a wall thickness t_1 (or t in equations below). The local thinning is characterized as having a uniform wall thickness t_2 and a circumferential extent 2θ. The depth of local thinning is $a = t_1 - t_2$

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:

$$\sigma_b^p \le \frac{1}{SF_b}(\sigma_b^c - \sigma_b^s) - \sigma_m^{p^*}(1 - \frac{1}{SF_m}) \quad (7)$$

where SF_b - structural factor on primary bending moment

SF_m - structural factor on internal pressure or primary axial force

(i). *The nominal bending axial stress* σ_b^c at net-section collapse

$$\sigma_b^c = \frac{M_{nsc}R_0}{I} \quad (8)$$

Bending moment corresponding to a state of net-section collapse of a straight section (M_{nsc}) is calculated as following:

(a). Short thinning region: for thinned region not penetrating the compressive region of the cross section such that $\theta + \beta \le \pi$, the bending moment at net-section is given by

$$M_{nsc} = M_o\left\{\sin\beta - \frac{1}{2}[1-(1+\alpha\frac{a}{D})^2(1-\frac{a}{t})]\sin\theta\right\} \quad (9)$$

where $\beta = \frac{\pi}{2}\left\{1 - \frac{\theta}{\pi}\frac{a}{t}\left[1-\alpha\frac{t}{D}(1-\frac{a}{t})\right] - (\frac{P^*}{P_o} + \frac{F_p}{F_o})\right\}$,

F_p − Primary axial force, $\alpha = 1$

(b). Long thinning region: for thinned region penetrating the compressive region of the cross section such that that $\theta + \beta > \pi$, the bending moment at net-section is given by

$$M_{nsc} = M_o \left\{ (1+\alpha\frac{a}{D})^2 (1-\frac{a}{t}) \sin\beta - \frac{1}{2}[1-(1+\alpha\frac{a}{D})^2(1-\frac{a}{t})]\sin\theta \right\} \tag{10}$$

where $$\beta = \frac{\frac{\pi}{2}\left\{1-(2-\frac{\theta}{\pi})\frac{a}{t}\left[1-\alpha\frac{t}{D}(1-\frac{a}{t})\right]-(\frac{P^*}{P_o}+\frac{F_p}{F_o})\right\}}{1-\frac{a}{t}[1-\alpha\frac{t}{D}(1-\frac{a}{t})]}$$

and $P_o = 4\sigma_f \dfrac{\frac{t}{D}}{(1-\frac{t}{D})^2})$, $\quad F_o = \pi D t \sigma_f$, $\quad M_o = D^2 t \sigma_f$, $\quad \lambda = 2\alpha(1+\alpha)\dfrac{\frac{t}{D}}{(1-\frac{t}{D})^2}$

$$P^* = P\left\{1+\lambda\frac{\theta}{\pi}\frac{a}{t}[1-\frac{t}{D}(1-\frac{a}{t})]\right\}$$

mean diameter : $D = D_o - t$, flow stress : $\sigma_f = \dfrac{\sigma_y + \sigma_u}{2}$, inside area : $A_i = \dfrac{\pi}{4}(D-t)^2$

(ii). *The nominal primary and secondary bending axial stress σ_b^p and σ_b^s* in the straight pipe section due to applied primary and secondary bending moment M_p and M_s are given by

$$\sigma_b^p = \frac{M_p R_0}{I}, \qquad \sigma_b^s = \frac{M_s R_0}{I} \tag{11}$$

$$I = \frac{\pi}{4}(R_o^4 - R_i^4)$$

(iii). *The effective applied nominal primary membrane axial stress $\sigma_m^{p^*}$* due to pressure, axial force is calculated by

$$\sigma_m^{p^*} = \frac{P^* A_i + F_p}{\pi D t} \tag{12}$$

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

$$\sigma_m^{p^*} \le \frac{\sigma_m^c}{SF_m} \tag{13}$$

where *the nominal membrane axial stress σ_m^c* at net-section collapse with zero coincident bending stress is calculated by

$$\sigma_m^c = \sigma_f \left\{ 1 - \frac{\theta}{\pi}\frac{a}{t}\left[1 - \alpha \frac{t}{D}(1 - \frac{a}{t}) \right] - \frac{2}{\pi}\Phi \right\} \quad (14)$$

$$\text{where } \Phi = \sin^{-1}\left\{ \frac{1}{2}[1 - (1 + \alpha \frac{a}{D})^2 (1 - \frac{a}{t})] \sin\theta \right\}$$

3.0 DARLINGTON FEEDER INPUT DATA

This section is to establish the various input parameters required to perform the structural integrity assessments of a postulated local thinning region below pressure based value in the vicinity of the Grayloc weld of Darlington outlet feeder pipes.

3.1 Feeder Pipe Geometric Data

There are only two bend sizes of outlet feeder pipe at DNGS: 2” NPS and 2.5” NPS.

2” NPS feeders:

D_o = 60.325 mm	outside diameter
t_{nom} = 5.537 mm	nominal wall thickness
t_{min} = 2.757 mm	pressure based thickness
0.75* t_{min} = 2.07 mm	FFSG line-in-granite value

2.5” NPS feeders:

D_o = 73.025 mm	outside diameter
t_{nom} = 7.010 mm	nominal wall thickness
t_{min} = 3.338 mm	pressure based thickness
0.75* t_{min} = 2.50 mm	FFSG line-in-granite value

There are 22 types of feeder bends for all 480 Darlington outlet feeders. Bend type is categorized by feeder’s size, bend radius, angle, straight pipe length, and etc. It is noted that the maximum and minimum length of the straight pipe is 45.5 and 3.1 mm respectively.

3.2 Application of Inspection Thickness Data

The 6-probe pack is used by the Inspection Organization to measure wall thickness adjacent the Grayloc weld. The 6-pack is a 6-transducer array and can be manually moved by the operator in the circumferential direction while keeping the 6-pack abutting the weld cap. An encoder allows the collected data to be synchronized with circumferential position. It can measure the thickness of the pipe material in a zone bounded by the edge of the weld cap to a distance 15 mm from the edge of the weld cap. The inspection is to cover the full circumference of the pipe where access and contact conditions permit. The numbering and offset in axial and circumferential offsets are listed in **Table 1**. From the table, the closest measured thickness next to the Grayloc weld is 2.5 mm. Past experience indicates that local thinning rarely extends beyond 15 mm away from the weld cap.

3.3 Loading Condition and Material Properties

3.3.1 Design Condition

The design conditions are as per Darlington design specification:

Outlet feeder design temperature: 318.33 ºC

Outlet feeder design internal pressure: 11.275 MPa(g)

3.3.2 Operating Condition

The maximum transient pressures under ASME III Level A, B, and C conditions are following (there is no Level D loading in feeders):

Outlet feeder maximum Level A pressure: 11.26 MPa(g)

Outlet feeder maximum Level B pressure: 12.09 MPa(g)

Outlet feeder maximum Level C pressure: 13.60 MPa(g)

The enveloped primary and secondary loads are summarized from the previous OPG feeder Darlington stress analysis and are given in **Table 2**.

3.3.3 Material Properties

The feeder pipe is procured to the SA-106 Grade B material specification. The material properties used in the local thinning assessment are code specified values at the design temperature of 318.33 ºC. It should be noted that the Darlington feeder CMTRs report much higher values both for yield tensile and ultimate tensile strength. Thus the use of code value is conservative.

σ_m = 119.18 MPa Class 1 allowable stress intensity

σ_y = 178.23 MPa Specified yield tensile strength

σ_u = 413.7 MPa Specified ultimate tensile strength

4.0 ASSESSMENT RESULTS

Using closed-form equations in given in **Section 2.1 and 2.2** or article E.5 of Appendix E. The *Operational Assessments* are performed for the end-of-evaluation-period outlet feeder thickness to demonstrate that the feeders are fit for continue service. The allowable thickness obtained in this assessment should be compared to the predicted thickness or the inspection thickness minus the thinning rate times the EFPY value of the next planned outage when the feeder is going to be replaced.

The evaluation thickness t_{eval} equal to 3.03 mm for LC and UC and 3.12 mm for LAC mm for 2 inch feeder, the respective values for 2.5 inch feeder are 3.67 mm and 3.77 mm. Once the inspected or predicted thickness is found to be below t_{min}, the allowable local thickness assessment has to be initiated. However, the size of local thinning is determined by the evaluation thickness of t_{eval}, rather than t_{min}.

4.1 Allowable Thickness Assessment by Internal Pressure Loading

The applicability of the evaluation is dependent on the axial and circumferential extents of the local thinning regions of the two different sizes feeders: 2" and 2.5". The detailed calculations are carried out in **Table 3** and are shown in **Figure 4** for 2" feeder. The results are summarized in **Table 4** and **Table 5** for 2" and 2.5" feeders respectively.

A thinning extent could fall into two classification regions when $L_m/(R_{min}t_{min})^{0.5} < 2.65$, i.e. LC or LAC, UC or LAC, depending on the value of $L_{m(t)}/(R_{min}t_{min})^{0.5}$, the minimum value of t_{aloc} from two classification calculations is taken as the final acceptable value.

As shown in two tables, if the axial thinning extent is less than 6 mm regardless of circumferential extent, or the circumferential extent is less than 15º and the axial extent is less than 15 mm, the allowable thickness is 0.75 t_{min} or the "line-in-granite" of FFSG for local thinning.

If the axial extent exceeds 20 mm and circumferential extent exceeds 20º, the allowable thickness is approximately 0.90 t_{min} and becomes independent of thinning extent.

4.2 Allowable Thickness Assessment under Moment Loading with Coincident Internal Pressure Loading

In this assessment, the uniform thickness t_1 (or t used in equations in **Section 2.0** is the t_{eval} or higher, while local thinning thickness t_2 ($t_2 = t_1 - a$) is the minimum allowable thickness of 0.75 t_{min} or higher values obtained in **Section 4.1** from the internal pressure evaluation. Since it is unlikely that surrounding wall thickness is uniformly thinned to t_{eval} around the local region (t_2), thus the calculation is very conservative.

As shown in **Table 6**, the local thickness is taken as of 0.75 t_{min} or 2.07 mm, the surrounding thickness is assumed as t_{eval} or 1.13t_{min} of 3.11 mm. For the circumferential extent up to 2θ = 20º, both membrane plus bending axial, and membrane axial stresses meet the Appendix E criteria. When the circumferential extent exceeds 20º, the membrane plus bending axial stress fails to meet the requirements. In order to meet the requirements, either t_1 or t_2 has to be increased, as shown in **Table 7 and 8**.

5.0 APPLICATION EXAMPLE

An example is illustrated in this section to show the application of the assessment methodology as well as the direct use of the result tables obtained in the **Section 4.1** and **4.2**.

Darlington feeder J24E of Unit 2 was identified to have a predicted below pressure based thickness local thinning area before the scheduled outage. A detailed NB-3200 stress analysis was performed and demonstrated that the ASME III code compliance is met for the local thinning (**Reference 3**). The same thinning parameters are used here for the demonstration of Level 2 evaluation of FFSG Appendix E.

5.1 Predicted Thickness

The predicted minimum and average thicknesses are shown in **Table 9**.

D2J24E is a 2” feeder, t_{min} = 2.757 mm

t_{eval} = 3.03 or 3.12 mm (3.12 mm is used to be conservative to estimate the thinning size)

As shown in **Table 9**, the axial length where the thickness below t_{eval} 3.12 mm (not t_{min}) is between the Grayloc weld to Probe 3 or 8.75 mm (2.5+2.5+2.5+2.5/2, i.e. 3 ½ probe distance).

The circumferential thickness distribution is shown in **Figure 5**. The circumferential length of local thinning, where the thickness is less than 3.12 mm, is 40 mm long. The thickness at the extrados region is below t_{eval} of 3.12 mm but higher than t_{min} of 2.757 mm, thus it is not defined as a local thinning region and therefore no assessment is required. In the distance of $2.5(R_{eval}t_{eval})^{0.5}$ of 23.6 mm range, there is no another region where the thickness is below 3.12 mm. Thus this local thinning can be characterized as a single local thinning region.

In summary: the size of local thinning region:

- axial thinning extent $L_{m(a)}$ = 8.75 mm.
- circumferential extent $L_{m(t)}$ = 38.2 mm

  (40 mm is the circumferential length measured from the outside diameter, it has to be converted to the circumferential length calculated from the mean radius, $40*R_{min}/R_o$ = 40*28.78/30.163 = 38.2 mm)
- target allowable thickness t_{aloc} = 2.54 mm
- surrounding thickness t_{avg} = 3.47 mm (conservatively assumed as the average thickness at probe 1)

5.2 Allowable Local Thickness for J24E

5.2.1 Assessment by Calculation

Assessment on internal pressure loading is performed in **Table 10** using the local thinning size identified above. The minimum allowable thickness is 2.23 mm. Assessment on bending moment coincident with internal pressure loading is performed in **Table 11.** The minimum allowable thickness is 2.09 mm. Thus the minimum allowable local thickness is the maximum value of two values, i.e. 2.23 mm. It is below the target thickness of 2.54 mm.

In summary, the predicted thickness meets FFSG Appendix E local thinning requirements and the reactor can operate up to the end of evaluation period.

5.2.2 Assessment by Result Tables

Applying the thinning size and surrounding thickness to the generic allowable thickness for 2 inch feeder in **Table 4**, the minimum acceptable thickness is approximately 2.29 mm, which is below the target thickness of 2.54 mm. Thus the local thinning is compliant to FFSG Appendix E requirements.

6.0 CONCLUSIONS

Level 2 evaluation provides an easy-to-use and conservative tool for the fast disposition of adverse inspection results. The allowable thicknesses developed in this paper can be used for the disposition of inspected or predicted below pressure base thickness in the vicinity of the Grayloc. It would reduce the potential risk of outage delay due to adverse feeder thickness.

7.0 ACKNOWLEDGEMENT

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8.0 REFERENCES

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[3] Li, M. “Darlington NGS: Feeder D2J24E Acceptable Thickness Due to Local Thinning Near the Grayloc Level A, B, C and D Loads”, OPGI Document No. NK38-CALC-33160-10060 R001; May, 2008.

Table 1 Transducer Numbering and Location for the 6-Pack

Transducer #	Axial Offset (mm)	Circumferential offset (mm)	Incidence Degree	Distance relative the Weld Edge (mm)
1	0	3.0	normal	2.5
2	2.5	0.0	normal	5
3	5	-3.0	normal	7.5
4	7.5	0.0	normal	10
5	10	-3.0	normal	12.5
6	12.5	3.0	normal	15

Table 2 Enveloped Primary and Secondary Loads for All Darlington Outlet Feeders

2 inch feeders

Level A, B Loads	F_{res} (N)	M_{res} (N-m)
DWT (Deadweight)	921	223
THM (Thermal)		
Fixed short feeders	1223	1147
Free short feeders	1630	1630
Long feeders (assume free)	1451	730
Level C (Seismic) Loads		
Seismic Anchor Movement (EAM)	497	187
Seismic Inertia (EEM)	1324	831

2.5 inch feeders

Level A, B Loads	F_{res} (N)	M_{res} (N-m)
DWT (Deadweight)	1124	398
THM (Thermal)		
Fixed short feeders	2003	1692
Free short feeders	2655	2785
Long feeders (assume free)	2402	1653
Level C (Seismic) Loads		
Seismic Anchor Movement (EAM)	688	261
Seismic Inertia (EEM)	2580	1580

Note: Forces and Moments are obtained at the Grayloc sealed face.

Table 3 Allowable Thickness under Internal Pressure Loading for 2.0 inch Feeders

Inputs	**Darlington 2 inch Feeders**		
Design pressure	P_D	11.3	MPa
Nominal outside diameter	D_o	60.325	mm
Design stress intensity	S_m @318 ºC	119.1	MPa
Outside Radius	$R_o = D_o/2$	30.163	mm
Geometry Characterization			
Pressure based thickness for SP	$t_{min}^{SP} = P_D D_o/[2(S_m + yP_D)]$	2.757	mm
Evaluation Wall at Grayloc	$t_{eval} = 1.10\, t_{min}^{SP}$ (LC, UC)	3.03	=> The inspected or predicted thicknesses are required to compared to t_{eval} instead of t_{min}
	$t_{eval} = 1.13\, t_{min}^{SP}$ (LAC)	3.12	
Mean Evaluated Radius	$R_{eval} = R_o - t_{eval}/2$ (LC,UC)	28.65	=> Radius at the at surrounding region
	$R_{eval} = R_o - t_{eval}/2$ (LAC)	28.60	
Minimum Length for surrounding material $t > t_{eval}$	$2.5(R_{eval} * t_{eval})^{1/2}$ (LC,UC)	23.30	=> 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)	23.60	
Mean Inside Radius	$R_{min} = R_o - t_{min}/2$	28.78	=> Mean radius at local thinning region
Characterized size	$(R_{min} * t_{min})^{1/2}$	8.91	=> 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 $t < t_{eval}$	8.91	$t_{aloc}/t_{min} = 0.75$ 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 $t < t_{eval}$	23.61	$t_{aloc}/t_{min} \ge 0.353 L_m[1/(t_{min}^{sp} R_{min}^{sp})]^{0.5}$ $t_{aloc}/t_{min} \ge 1 - 1.5(R_{min} t_{min})^{0.5}(t_{eval}/t_{min} - 1)/L_m$ — t_{aloc} equals to the maximum three values $t_{aloc}/t_{min} = 0.75$
(c) Unlimited Circumferential Extent (UC):	Circumferential extent, $L_{m(t)} > (R_{min} t_{min})^{1/2}$ where $t < t_{eval}$	8.91	$t_{aloc}/t_{min} = 0.75$ 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 $L_{m(a)}/R_{min}t_{min})^{0.5} > 2.5$
1			

Maximum Axial Extent $L_{m(a)}$	6.0 mm
$L_{m(a)}/(R_{min} t_{min})^{1/2}$	0.67

circumferential thinning angle (deg)	arch length (mm) $L_{m(t)}$	$L_m = (L_{m(a)}^2 + L_{m(t)}^2)^{1/2}$	$L_m / 2.65(R_{min}^{sp} t_{min}^{sp})^{1/2}$	$L_{m(t)}/(R_{min} t_{min})^{1/2}$	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
5	2.51	6.50	0.276	0.3	LC or LAC	0.750	0.258	0.733	0.750	0.750	n/a	0.750	LC
10	5.02	7.83	0.331	0.6	LC or LAC	0.750	0.310	0.778	0.750	0.778	n/a	0.750	LC
15	7.54	9.63	0.408	0.8	LC or LAC	0.750	0.382	0.820	0.750	0.820	n/a	0.750	LC
20	10.05	11.70	0.496	1.1	UC or LAC	n/a	0.464	0.852	0.750	0.852	0.750	0.750	UC
25	12.56	13.92	0.590	1.4	UC or LAC	n/a	0.552	0.875	0.750	0.875	0.750	0.750	UC
30	15.07	16.22	0.687	1.7	UC or LAC	n/a	0.643	0.893	0.750	0.893	0.750	0.750	UC
35	17.58	18.58	0.787	2.0	UC or LAC	n/a	0.736	0.906	0.750	0.906	0.750	0.750	UC
40	20.09	20.97	0.888	2.3	UC or LAC	n/a	0.831	0.917	0.750	0.917	0.750	0.750	UC
45	22.61	23.39	0.991	2.5	UC or LAC	n/a	0.927	0.926	0.750	0.927	0.750	0.750	UC
55	27.63	28.27	1.198	3.1	UC	n/a	n/a	n/a	n/a	n/a	0.750	0.750	UC
60	30.14	30.73	1.302	3.4	UC	n/a	n/a	n/a	n/a	n/a	0.750	0.750	UC
90	45.21	45.61	1.932	5.1	UC	n/a	n/a	n/a	n/a	n/a	0.750	0.750	UC
180	90.43	90.63	3.839	10.2	UC	n/a	n/a	n/a	n/a	n/a	0.750	0.750	UC
270	135.64	135.77	5.751	15.2	UC	n/a	n/a	n/a	n/a	n/a	0.750	0.750	UC
360	180.85	180.95	7.665	20.3	UC	n/a	n/a	n/a	n/a	n/a	0.750	0.750	UC

Table 4 Summary of Allowable Thickness under Internal Pressure Loading for 2" Feeder

<table>
<tr><td>2" feeder</td><td colspan="5">Maximum Axial Extent $L_{m(a)}$ (mm)</td><td rowspan="2">Adjacent Wall Thickness</td></tr>
<tr><td>Circumferential Thinning Extent $L_{m(t)}$</td><td>6</td><td>8</td><td>10</td><td>15</td><td>20</td></tr>
<tr><td>angle (degree)</td><td colspan="5">t_{aloc} (mm)</td><td>t_{avg} (≥ t_{eval})</td></tr>
<tr><td>5 - 15</td><td colspan="4">2.07</td><td>2.15</td><td rowspan="2">≥ 3.12</td></tr>
<tr><td>20</td><td rowspan="3">2.07</td><td rowspan="3">2.19</td><td rowspan="4">2.29</td><td rowspan="5">2.42</td><td rowspan="5">2.48</td></tr>
<tr><td>45</td><td rowspan="4">≥ 3.5</td></tr>
<tr><td>60</td></tr>
<tr><td>75</td><td colspan="2">2.20</td></tr>
<tr><td>90</td><td colspan="3">2.37</td></tr>
</table>

Table 5 Summary of Allowable Thickness under Internal Pressure Loading for 2.5" Feeder

<table>
<tr><td>2.5" feeder</td><td colspan="5">Maximum Axial Extent $L_{m(a)}$ (mm)</td><td rowspan="2">Surrounding Average Wall Thickness</td></tr>
<tr><td>Circumferential Thinning Extent $L_{m(t)}$</td><td>6</td><td>8</td><td>10</td><td>15</td><td>20</td></tr>
<tr><td>angle (degree)</td><td colspan="5">t_{aloc} (mm)</td><td>t_{avg} (≥ t_{eval})</td></tr>
<tr><td>15</td><td colspan="5">2.50</td><td rowspan="2">≥ 3.77</td></tr>
<tr><td>20</td><td rowspan="3">2.50</td><td rowspan="3">2.50</td><td rowspan="4">2.67</td><td rowspan="5">2.87</td><td rowspan="5">2.95</td></tr>
<tr><td>45</td><td rowspan="4">≥ 4.31</td></tr>
<tr><td>60</td></tr>
<tr><td>75</td><td colspan="2">2.67</td></tr>
<tr><td>90</td><td colspan="3">2.84</td></tr>
</table>

Table 6 Allowable Thickness under Bending Moment and Pressure for 2” Feeder

Inputs	Darlington 2 inch Feeders			
Design pressure	P_D		11.3	MPa
Nominal outside diameter	D_o		60.3	mm
Nominal thickness	t_{nom}		5.54	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		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	$R_o = D_o/2$	30.15	mm
Nominal inside radius	R_I	$R_I = R_o - t_{nom}$	24.61	mm
Pressure based thickness for SP	$t_{min}^{SP} = P_D D_o/[2(\sigma_m+Py)]$		**2.756**	mm
Evaluation Wall at Grayloc	$t_{eval} = 1.10\ t_{min}^{SP}$ (LC, UC)		**3.03**	mm
	$t_{eval} = 1.13\ t_{min}^{SP}$ (LAC)		**3.11**	mm
Mean Diameter at t_{min}	$D = D_o - t_{min}$		57.5	at local thinning region
Characterized size	$(R_{min}{*}t_{min})^{1/2}$		**8.9**	mm
Mean Evaluated Radius	$R_{eval} = R_o - t_{eval}/2$ (LC,UC)		28.63	at surrounding region
	$R_{eval} = R_o - t_{eval}/2$ (LAC)		28.59	
Location of thinning	α		1	inside surface thinning

Enveloped Loads (2 inch)	Resultant Load		Primary Load		Secondary Load	
	F_{res} (kN)	M_{res} (kN-m)	F_p	M_p	F_s	M_s
DWT (Deadweight)	0.921	0.223	0.921	0.223	-	-
THM (Thermal)	1.63	1.63	-	-	1.63	1.63
EAM (Seismic Anchor Mvt)	0.497	0.187	-	-	0.497	0.187
EEM (Seismic Inertia)	1.324	0.831	1.324	0.831	-	-

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**	**0.921 kN**	**0.223 kN·m**	**1.6 kN**	**1.630 kN·m**	2.7	2.3	1.0	32.59 MPa	4.12 MPa	2.14 MPa
Level C	**12.1 MPa**	**1.324 kN**	**0.831 kN·m**	**0.5 kN**	**0.187 kN·m**	1.8	1.6	1.0	21.73 MPa	2.88 MPa	1.52 MPa

Case	No.	Characterization of Feeder Local Thinning											Net-section Characterized Collapse Parameters					
		t_2 ($0.75t_{min}$)	t_1 / t_{min}	adjacent t_1	R_i	depth a	2θ	PDA	mean D	t_1/D	a/t_1	a/D	P_o	F_o	M_o	λ	P*	θ/π
	1	2.07	1.13	3.11	27.04	1.05	10°	41.82%	57.19	0.05	0.336	0.018	72.1 MPa	165.59 kN·m	3.01 MPa	0.24	12.10	0.028
	2	2.07	1.13	3.11	27.04	1.05	20°	42.35%	57.19	0.05	0.336	0.018	72.1 MPa	165.59 kN·m	3.01 MPa	0.24	12.12	0.056
	3	2.07	1.13	3.11	27.04	1.05	45°	43.67%	57.19	0.05	0.336	0.018	72.1 MPa	165.59 kN·m	3.01 MPa	0.24	12.19	0.125
	4	2.07	1.13	3.11	27.04	1.05	60°	44.47%	57.19	0.05	0.336	0.018	72.1 MPa	165.59 kN·m	3.01 MPa	0.24	12.23	0.167
	5	2.07	1.13	3.11	27.04	1.05	75°	45.26%	57.19	0.05	0.336	0.018	72.1 MPa	165.59 kN·m	3.01 MPa	0.24	12.27	0.208
Level A/B	6	2.07	1.13	3.11	27.04	1.05	90°	46.05%	57.19	0.05	0.336	0.018	72.1 MPa	165.59 kN·m	3.01 MPa	0.24	12.31	0.250
	7	2.07	1.13	3.11	27.04	1.05	135°	48.43%	57.19	0.05	0.336	0.018	72.1 MPa	165.59 kN·m	3.01 MPa	0.24	12.43	0.375
	8	2.07	1.13	3.11	27.04	1.05	180°	50.81%	57.19	0.05	0.336	0.018	72.1 MPa	165.59 kN·m	3.01 MPa	0.24	12.55	0.500
	9	2.07	1.13	3.11	27.04	1.05	235°	53.72%	57.19	0.05	0.336	0.018	72.1 MPa	165.59 kN·m	3.01 MPa	0.24	12.69	0.653
	10	2.07	1.13	3.11	27.04	1.05	270°	55.57%	57.19	0.05	0.336	0.018	72.1 MPa	165.59 kN·m	3.01 MPa	0.24	12.78	0.750
	11	2.07	1.13	3.11	27.04	1.05	360°	60.32%	57.19	0.05	0.336	0.018	72.1 MPa	165.59 kN·m	3.01 MPa	0.24	13.02	1.000
	1	2.07	1.13	3.11	27.04	1.05	10°	41.82%	57.19	0.05	0.336	0.018	72.1 MPa	165.59 kN·m	3.01 MPa	0.24	12.10	0.028
	2	2.07	1.13	3.11	27.04	1.05	20°	42.35%	57.19	0.05	0.336	0.018	72.1 MPa	165.59 kN·m	3.01 MPa	0.24	12.12	0.056
	3	2.07	1.13	3.11	27.04	1.05	45°	43.67%	57.19	0.05	0.336	0.018	72.1 MPa	165.59 kN·m	3.01 MPa	0.24	12.19	0.125
	4	2.07	1.13	3.11	27.04	1.05	60°	44.47%	57.19	0.05	0.336	0.018	72.1 MPa	165.59 kN·m	3.01 MPa	0.24	12.23	0.167
	5	2.07	1.13	3.11	27.04	1.05	75°	45.26%	57.19	0.05	0.336	0.018	72.1 MPa	165.59 kN·m	3.01 MPa	0.24	12.27	0.208
	6	2.07	1.13	3.11	27.04	1.05	90°	46.05%	57.19	0.05	0.336	0.018	72.1 MPa	165.59 kN·m	3.01 MPa	0.24	12.31	0.250
Level C	7	2.07	1.13	3.11	27.04	1.05	135°	48.43%	57.19	0.05	0.336	0.018	72.1 MPa	165.59 kN·m	3.01 MPa	0.24	12.43	0.375
	8	2.07	1.13	3.11	27.04	1.05	180°	50.81%	57.19	0.05	0.336	0.018	72.1 MPa	165.59 kN·m	3.01 MPa	0.24	12.55	0.500
	9	2.07	1.13	3.11	27.04	1.05	235°	53.72%	57.19	0.05	0.336	0.018	72.1 MPa	165.59 kN·m	3.01 MPa	0.24	12.69	0.653
	10	2.07	1.13	3.11	27.04	1.05	270°	55.57%	57.19	0.05	0.336	0.018	72.1 MPa	165.59 kN·m	3.01 MPa	0.24	12.78	0.750
	11	2.07	1.13	3.11	27.04	1.05	360°	60.32%	57.19	0.05	0.336	0.018	72.1 MPa	165.59 kN·m	3.01 MPa	0.24	13.02	1.000

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	
	1	0.404	ok	short	0.404	0.941	2296.3	2.29E+05	51.29	29.31	214.24	0.01	290.74	372.89	0.96	pass	0.48	pass
	2	0.399	ok	short	0.399	0.923	2296.3	2.29E+05	51.40	29.31	214.24	0.03	285.53	365.77	0.98	pass	0.49	pass
	3	0.388	ok	short	0.388	0.879	2296.3	2.29E+05	51.67	29.31	214.24	0.06	272.73	348.07	1.02	**FAIL**	0.51	pass
	4	0.380	ok	short	0.380	0.852	2296.3	2.29E+05	51.84	29.31	214.24	0.08	265.28	337.71	1.05	**FAIL**	0.53	pass
	5	0.373	ok	short	0.373	0.827	2296.3	2.29E+05	52.00	29.31	214.24	0.10	258.07	327.70	1.08	**FAIL**	0.54	pass
Level A/B	6	0.366	ok	short	0.366	0.803	2296.3	2.29E+05	52.16	29.31	214.24	0.11	251.17	318.15	1.11	**FAIL**	0.56	pass
	7	0.345	ok	short	0.345	0.740	2296.3	2.29E+05	52.65	29.31	214.24	0.14	232.76	293.28	1.19	**FAIL**	0.61	pass
	8	0.324	ok	short	0.324	0.696	2296.3	2.29E+05	53.14	29.31	214.24	0.16	218.51	275.57	1.26	**FAIL**	0.66	pass
	9	0.299	ok	short	0.299	0.668	2296.3	2.29E+05	53.74	29.31	214.24	0.14	207.21	264.64	1.31	**FAIL**	0.70	pass
	10	0.282	ok	long	0.297	0.664	2296.3	2.29E+05	54.12	29.31	214.24	0.11	203.21	263.00	1.31	**FAIL**	0.72	pass
	11	0.240	ok	long	0.355	0.618	2296.3	2.29E+05	55.10	29.31	214.24	0.00	200.03	244.87	1.40	**FAIL**	0.74	pass
	1	0.406	ok	short	0.406	0.943	2296.3	2.29E+05	52.01	109.23	24.58	0.01	290.74	373.70	0.95	pass	0.48	pass
	2	0.401	ok	short	0.401	0.925	2296.3	2.29E+05	52.12	109.23	24.58	0.03	285.53	366.62	0.96	pass	0.49	pass
	3	0.390	ok	short	0.390	0.881	2296.3	2.29E+05	52.39	109.23	24.58	0.06	272.73	349.01	1.01	**FAIL**	0.52	pass
	4	0.383	ok	short	0.383	0.855	2296.3	2.29E+05	52.56	109.23	24.58	0.08	265.28	338.71	1.03	**FAIL**	0.53	pass
	5	0.376	ok	short	0.376	0.830	2296.3	2.29E+05	52.72	109.23	24.58	0.10	258.07	328.75	1.06	**FAIL**	0.55	pass
Level C	6	0.369	ok	short	0.369	0.806	2296.3	2.29E+05	52.88	109.23	24.58	0.11	251.17	319.26	1.09	**FAIL**	0.57	pass
	7	0.348	ok	short	0.348	0.743	2296.3	2.29E+05	53.37	109.23	24.58	0.14	232.76	294.56	1.17	**FAIL**	0.62	pass
	8	0.326	ok	short	0.326	0.699	2296.3	2.29E+05	53.86	109.23	24.58	0.16	218.51	277.00	1.24	**FAIL**	0.67	pass
	9	0.301	ok	short	0.301	0.672	2296.3	2.29E+05	54.46	109.23	24.58	0.14	207.21	266.26	1.28	**FAIL**	0.71	pass
	10	0.284	ok	long	0.301	0.668	2296.3	2.29E+05	54.84	109.23	24.58	0.11	203.21	264.65	1.29	**FAIL**	0.73	pass
	11	0.242	ok	long	0.358	0.621	2296.3	2.29E+05	55.82	109.23	24.58	0.00	200.03	246.08	1.38	**FAIL**	0.75	pass

Table 7 Revised Allowable Local Thickness under Bending Moment and Pressure for 2” Feeder

Case	No.	Characterization of Feeder Local Thinning											Net-section Characterized Collapse Parameters					
		t_2 ($0.75t_{min}$)	t_1 / t_{min}	adjacent t_1	R_i	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	3	2.07	1.27	3.50	26.65	1.43	45°	37.70%	56.80	0.06	0.409	0.025	82.8 MPa	184.85 kN·m	3.34 MPa	0.28	12.24	0.125
	4	2.07	1.27	3.50	26.65	1.43	60°	38.78%	56.80	0.06	0.409	0.025	82.8 MPa	184.85 kN·m	3.34 MPa	0.28	12.29	0.167
	5	2.20	1.27	3.50	26.65	1.30	75°	39.32%	56.80	0.06	0.370	0.023	82.8 MPa	184.85 kN·m	3.34 MPa	0.28	12.32	0.208
	6	2.37	1.27	3.50	26.65	1.13	90°	39.54%	56.80	0.06	0.323	0.020	82.8 MPa	184.85 kN·m	3.34 MPa	0.28	12.33	0.250
	7	2.67	1.27	3.50	26.65	0.83	135°	40.00%	56.80	0.06	0.236	0.015	82.8 MPa	184.85 kN·m	3.34 MPa	0.28	12.36	0.375
	8	2.76	1.27	3.50	26.65	0.74	180°	41.10%	56.80	0.06	0.213	0.013	82.8 MPa	184.85 kN·m	3.34 MPa	0.28	12.41	0.500
	9	2.76	1.27	3.50	26.65	0.74	235°	43.12%	56.80	0.06	0.213	0.013	82.8 MPa	184.85 kN·m	3.34 MPa	0.28	12.52	0.653
	10	2.76	1.27	3.50	26.65	0.74	270°	44.41%	56.80	0.06	0.213	0.013	82.8 MPa	184.85 kN·m	3.34 MPa	0.28	12.58	0.750
	11	2.76	1.27	3.50	26.65	0.74	360°	47.72%	56.80	0.06	0.213	0.013	82.8 MPa	184.85 kN·m	3.34 MPa	0.28	12.75	1.000
Level C	3	2.07	1.27	3.50	26.65	1.43	45°	37.70%	56.80	0.06	0.409	0.025	82.8 MPa	184.85 kN·m	3.34 MPa	0.28	12.24	0.125
	4	2.07	1.27	3.50	26.65	1.43	60°	38.78%	56.80	0.06	0.409	0.025	82.8 MPa	184.85 kN·m	3.34 MPa	0.28	12.29	0.167
	5	2.20	1.27	3.50	26.65	1.30	75°	39.32%	56.80	0.06	0.370	0.023	82.8 MPa	184.85 kN·m	3.34 MPa	0.28	12.32	0.208
	6	2.37	1.27	3.50	26.65	1.13	90°	39.54%	56.80	0.06	0.323	0.020	82.8 MPa	184.85 kN·m	3.34 MPa	0.28	12.33	0.250
	7	2.67	1.27	3.50	26.65	0.83	135°	40.00%	56.80	0.06	0.236	0.015	82.8 MPa	184.85 kN·m	3.34 MPa	0.28	12.36	0.375
	8	2.76	1.27	3.50	26.65	0.74	180°	41.10%	56.80	0.06	0.213	0.013	82.8 MPa	184.85 kN·m	3.34 MPa	0.28	12.41	0.500
	9	2.76	1.27	3.50	26.65	0.74	235°	43.12%	56.80	0.06	0.213	0.013	82.8 MPa	184.85 kN·m	3.34 MPa	0.28	12.52	0.653
	10	2.76	1.27	3.50	26.65	0.74	270°	44.41%	56.80	0.06	0.213	0.013	82.8 MPa	184.85 kN·m	3.34 MPa	0.28	12.58	0.750
	11	2.76	1.27	3.50	26.65	0.74	360°	47.72%	56.80	0.06	0.213	0.013	82.8 MPa	184.85 kN·m	3.34 MPa	0.28	12.75	1.000

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	3	0.395	ok	short	0.395	0.873	2231.2	2.53E+05	45.19	26.59	194.38	0.07	267.68	347.97	0.93	pass	0.46	pass
	4	0.386	ok	short	0.386	0.842	2231.2	2.53E+05	45.39	26.59	194.38	0.09	258.61	335.48	0.96	pass	0.47	pass
	5	0.382	ok	short	0.382	0.828	2231.2	2.53E+05	45.49	26.59	194.38	0.10	254.44	329.96	0.98	pass	0.48	pass
	6	0.380	ok	short	0.380	0.825	2231.2	2.53E+05	45.53	26.59	194.38	0.10	253.35	328.90	0.98	pass	0.49	pass
	7	0.376	ok	short	0.376	0.827	2231.2	2.53E+05	45.61	26.59	194.38	0.10	252.34	329.47	0.98	pass	0.49	pass
	8	0.368	ok	short	0.368	0.819	2231.2	2.53E+05	45.81	26.59	194.38	0.10	247.93	326.34	0.99	pass	0.50	pass
	9	0.352	ok	long	0.353	0.808	2231.2	2.53E+05	46.19	26.59	194.38	0.09	240.83	322.09	1.00	FAIL	0.52	pass
	10	0.341	ok	long	0.364	0.804	2231.2	2.53E+05	46.42	26.59	194.38	0.07	238.27	320.36	1.01	FAIL	0.53	pass
	11	0.315	ok	long	0.395	0.764	2231.2	2.53E+05	47.04	26.59	194.38	0.00	236.10	304.68	1.06	FAIL	0.54	pass
Level C	3	0.397	ok	short	0.397	0.875	2231.2	2.53E+05	45.83	99.10	22.30	0.07	267.68	348.76	0.92	pass	0.46	pass
	4	0.388	ok	short	0.388	0.844	2231.2	2.53E+05	46.03	99.10	22.30	0.09	258.61	336.34	0.95	pass	0.48	pass
	5	0.384	ok	short	0.384	0.830	2231.2	2.53E+05	46.13	99.10	22.30	0.10	254.44	330.85	0.96	pass	0.49	pass
	6	0.382	ok	short	0.382	0.828	2231.2	2.53E+05	46.17	99.10	22.30	0.10	253.35	329.81	0.97	pass	0.49	pass
	7	0.378	ok	short	0.378	0.829	2231.2	2.53E+05	46.26	99.10	22.30	0.10	252.34	330.40	0.96	pass	0.49	pass
	8	0.370	ok	short	0.370	0.821	2231.2	2.53E+05	46.46	99.10	22.30	0.10	247.93	327.34	0.97	pass	0.51	pass
	9	0.354	ok	long	0.355	0.811	2231.2	2.53E+05	46.83	99.10	22.30	0.09	240.83	323.20	0.99	pass	0.53	pass
	10	0.343	ok	long	0.367	0.806	2231.2	2.53E+05	47.07	99.10	22.30	0.07	238.27	321.38	0.99	pass	0.53	pass
	11	0.317	ok	long	0.397	0.766	2231.2	2.53E+05	47.68	99.10	22.30	0.00	236.10	305.48	1.04	FAIL	0.55	pass

Table .8 Allowable Local Thickness under Bending Moment and Pressure for 2" Feeder with Revised Surrounding Thickness

Case	No.	Characterization of Feeder Local Thinning											Net-section Characterized Collapse Parameters					
		t_2 ($0.75t_{min}$)	t_1 / t_{min}	adjacent t_1	R_i	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	3	2.07	1.27	3.50	26.65	1.43	45°	37.70%	56.80	0.06	0.409	0.025	82.8 MPa	184.85 kN·m	3.34 MPa	0.28	12.24	0.125
	4	2.07	1.27	3.50	26.65	1.43	60°	38.78%	56.80	0.06	0.409	0.025	82.8 MPa	184.85 kN·m	3.34 MPa	0.28	12.29	0.167
	5	2.20	1.27	3.50	26.65	1.30	75°	39.32%	56.80	0.06	0.370	0.023	82.8 MPa	184.85 kN·m	3.34 MPa	0.28	12.32	0.208
	6	2.37	1.27	3.50	26.65	1.13	90°	39.54%	56.80	0.06	0.323	0.020	82.8 MPa	184.85 kN·m	3.34 MPa	0.28	12.33	0.250
	7	2.67	1.27	3.50	26.65	0.83	135°	40.00%	56.80	0.06	0.236	0.015	82.8 MPa	184.85 kN·m	3.34 MPa	0.28	12.36	0.375
	8	2.76	1.27	3.50	26.65	0.74	180°	41.10%	56.80	0.06	0.213	0.013	82.8 MPa	184.85 kN·m	3.34 MPa	0.28	12.41	0.500
	9	2.76	1.27	3.50	26.65	0.74	235°	43.12%	56.80	0.06	0.213	0.013	82.8 MPa	184.85 kN·m	3.34 MPa	0.28	12.52	0.653
	10	2.76	1.27	3.50	26.65	0.74	270°	44.41%	56.80	0.06	0.213	0.013	82.8 MPa	184.85 kN·m	3.34 MPa	0.28	12.58	0.750
	11	2.76	1.27	3.50	26.65	0.74	360°	47.72%	56.80	0.06	0.213	0.013	82.8 MPa	184.85 kN·m	3.34 MPa	0.28	12.75	1.000
Level C	3	2.07	1.27	3.50	26.65	1.43	45°	37.70%	56.80	0.06	0.409	0.025	82.8 MPa	184.85 kN·m	3.34 MPa	0.28	12.24	0.125
	4	2.07	1.27	3.50	26.65	1.43	60°	38.78%	56.80	0.06	0.409	0.025	82.8 MPa	184.85 kN·m	3.34 MPa	0.28	12.29	0.167
	5	2.20	1.27	3.50	26.65	1.30	75°	39.32%	56.80	0.06	0.370	0.023	82.8 MPa	184.85 kN·m	3.34 MPa	0.28	12.32	0.208
	6	2.37	1.27	3.50	26.65	1.13	90°	39.54%	56.80	0.06	0.323	0.020	82.8 MPa	184.85 kN·m	3.34 MPa	0.28	12.33	0.250
	7	2.67	1.27	3.50	26.65	0.83	135°	40.00%	56.80	0.06	0.236	0.015	82.8 MPa	184.85 kN·m	3.34 MPa	0.28	12.36	0.375
	8	2.76	1.27	3.50	26.65	0.74	180°	41.10%	56.80	0.06	0.213	0.013	82.8 MPa	184.85 kN·m	3.34 MPa	0.28	12.41	0.500
	9	2.76	1.27	3.50	26.65	0.74	235°	43.12%	56.80	0.06	0.213	0.013	82.8 MPa	184.85 kN·m	3.34 MPa	0.28	12.52	0.653
	10	2.76	1.27	3.50	26.65	0.74	270°	44.41%	56.80	0.06	0.213	0.013	82.8 MPa	184.85 kN·m	3.34 MPa	0.28	12.58	0.750
	11	2.76	1.27	3.50	26.65	0.74	360°	47.72%	56.80	0.06	0.213	0.013	82.8 MPa	184.85 kN·m	3.34 MPa	0.28	12.75	1.000

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	3	0.395	ok	short	0.395	0.873	2231.2	2.53E+05	45.19	26.59	194.38	0.07	267.68	347.97	0.93	pass	0.46	pass
	4	0.386	ok	short	0.386	0.842	2231.2	2.53E+05	45.39	26.59	194.38	0.09	258.61	335.48	0.96	pass	0.47	pass
	5	0.382	ok	short	0.382	0.828	2231.2	2.53E+05	45.49	26.59	194.38	0.10	254.44	329.96	0.98	pass	0.48	pass
	6	0.380	ok	short	0.380	0.825	2231.2	2.53E+05	45.53	26.59	194.38	0.10	253.35	328.90	0.98	pass	0.49	pass
	7	0.376	ok	short	0.376	0.827	2231.2	2.53E+05	45.61	26.59	194.38	0.10	252.34	329.47	0.98	pass	0.49	pass
	8	0.368	ok	short	0.368	0.819	2231.2	2.53E+05	45.81	26.59	194.38	0.10	247.93	326.34	0.99	pass	0.50	pass
	9	0.352	ok	long	0.353	0.808	2231.2	2.53E+05	46.19	26.59	194.38	0.09	240.83	322.09	1.00	FAIL	0.52	pass
	10	0.341	ok	long	0.364	0.804	2231.2	2.53E+05	46.42	26.59	194.38	0.07	238.27	320.36	1.01	FAIL	0.53	pass
	11	0.315	ok	long	0.395	0.764	2231.2	2.53E+05	47.04	26.59	194.38	0.00	236.10	304.68	1.06	FAIL	0.54	pass
Level C	3	0.397	ok	short	0.397	0.875	2231.2	2.53E+05	45.83	99.10	22.30	0.07	267.68	348.76	0.92	pass	0.46	pass
	4	0.388	ok	short	0.388	0.844	2231.2	2.53E+05	46.03	99.10	22.30	0.09	258.61	336.34	0.95	pass	0.48	pass
	5	0.384	ok	short	0.384	0.830	2231.2	2.53E+05	46.13	99.10	22.30	0.10	254.44	330.85	0.96	pass	0.49	pass
	6	0.382	ok	short	0.382	0.828	2231.2	2.53E+05	46.17	99.10	22.30	0.10	253.35	329.81	0.97	pass	0.49	pass
	7	0.378	ok	short	0.378	0.829	2231.2	2.53E+05	46.26	99.10	22.30	0.10	252.34	330.40	0.96	pass	0.49	pass
	8	0.370	ok	short	0.370	0.821	2231.2	2.53E+05	46.46	99.10	22.30	0.10	247.93	327.34	0.97	pass	0.51	pass
	9	0.354	ok	long	0.355	0.811	2231.2	2.53E+05	46.83	99.10	22.30	0.09	240.83	323.20	0.99	pass	0.53	pass
	10	0.343	ok	long	0.367	0.806	2231.2	2.53E+05	47.07	99.10	22.30	0.07	238.27	321.38	0.99	pass	0.53	pass
	11	0.317	ok	long	0.397	0.766	2231.2	2.53E+05	47.68	99.10	22.30	0.00	236.10	305.48	1.04	FAIL	0.55	pass

Table 9 J24E Minimum and Average Wall Thickness of at 6 Probe Locations (mm)

Probe #	Probe 1	Probe 2	Probe 3	Probe 4	Probe 5	Probe 6
min thickness	2.54	2.80	2.86	3.48	3.45	3.63
avg thickness	3.47	3.58	3.70	3.82	3.88	4.00

Table 10 J24E Allowable Local Minimum Thickness under Pressure Loading

Maximum Axial Extent $L_{m(a)}$	8.75 mm													
$L_{m(a)}/(R_{min}t_{min}^{sp})^{1/2}$	0.98													
circumferential thinning angle (deg)	arch length (mm) $L_{m(t)}$	$L_m = (L_{m(a)}^2+L_{m(t)}^2)^{1/2}$	$L_m/2.65(R_{min}^{sp}t_{min}^{sp})^{1/2}$	$L_{m(t)}/(R_{min}t_{min}^{sp})^{1/2}$	Geometry Classification	LC	LAC (a)	LAC (b)	LAC (c)	LAC Max (a,b,c)	UC	t_{aloc}/t_{min}^{sp} Min(LC,LAC,UC)	t_{aloc}	
76	38.2	39.17	1.661	4.3	UC	n/a	n/a	n/a	n/a	n/a	0.810	0.810	**2.23**	

Table 11 Allowable Local Minimum Thickness under Bending Moment Coincident with Pressure Loading for J24E

Case	No.	Characterization of Feeder Local Thinning											Net-section Characterized Collapse Parameters					
		t_2 ($0.75t_{min}$)	t_1 / t_{min}	adjacent t_1	R_i	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	2.09	1.26	3.47	26.68	1.38	76°	40.20%	56.83	0.06	0.397	0.024	82.1 MPa	183.48 kN·m	3.32 MPa	0.28	12.34	0.211
Level C	1	2.09	1.26	3.47	26.68	1.38	76°	40.20%	56.83	0.06	0.397	0.024	82.1 MPa	183.48 kN·m	3.32 MPa	0.28	12.34	0.211

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	0.378	ok	short	0.378	0.814	2235.8	2.51E+05	45.99	26.77	195.65	0.11	250.74	324.21	1.00	pass	0.50	pass
Level C	1	0.380	ok	short	0.380	0.816	2235.8	2.51E+05	46.64	99.74	22.45	0.11	250.74	325.14	0.98	pass	0.50	pass

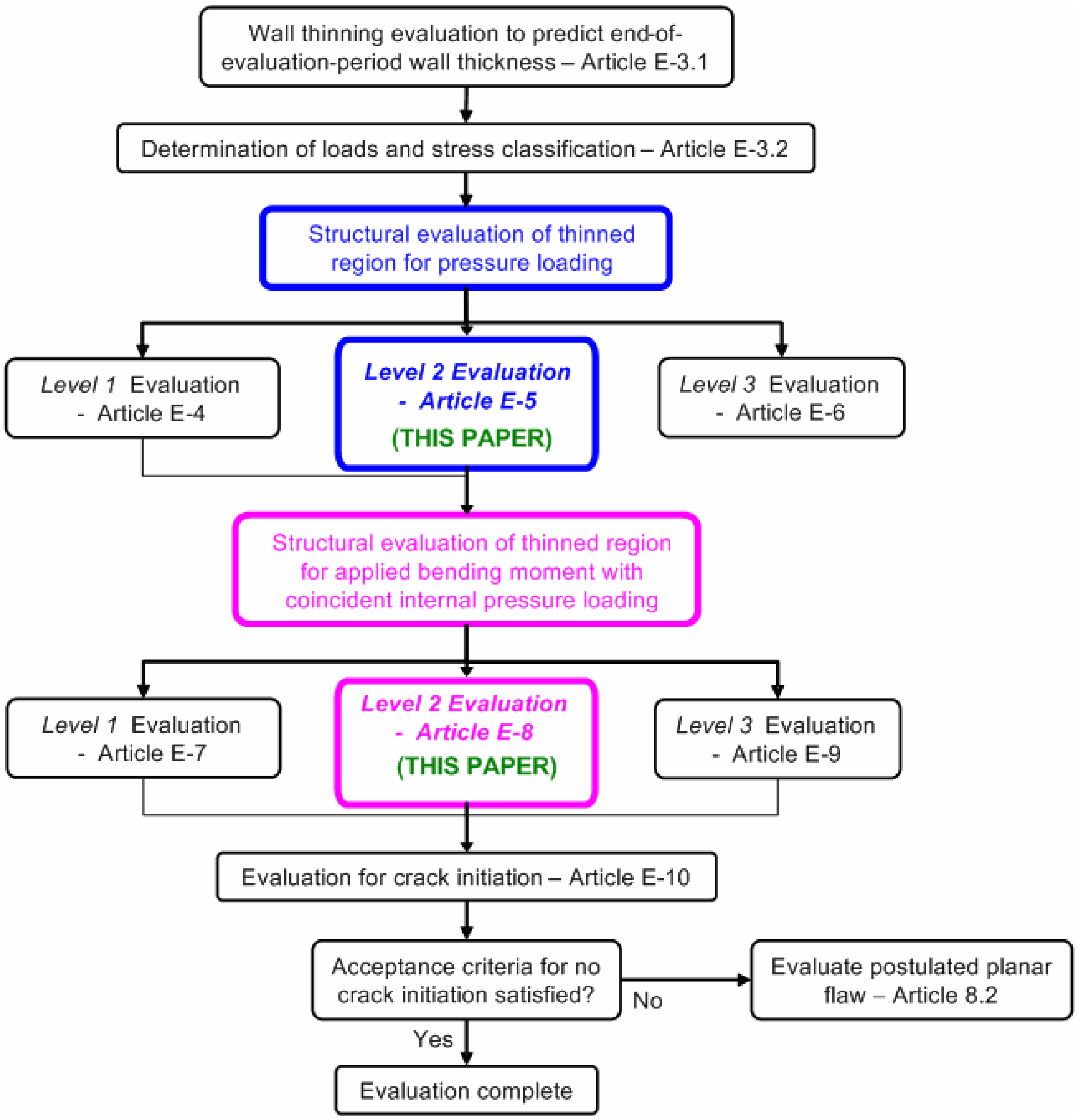

Figure 1 Assessment Procedure of FFSG Appendix E

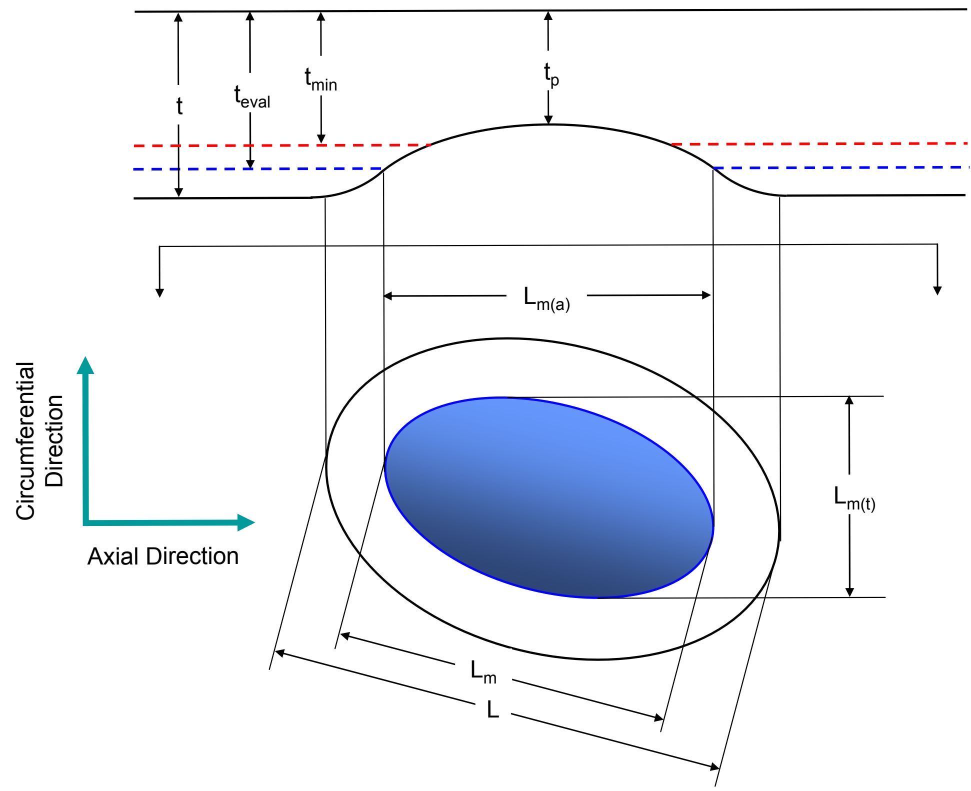

Figure 2 Illustration of Local Thinned Region

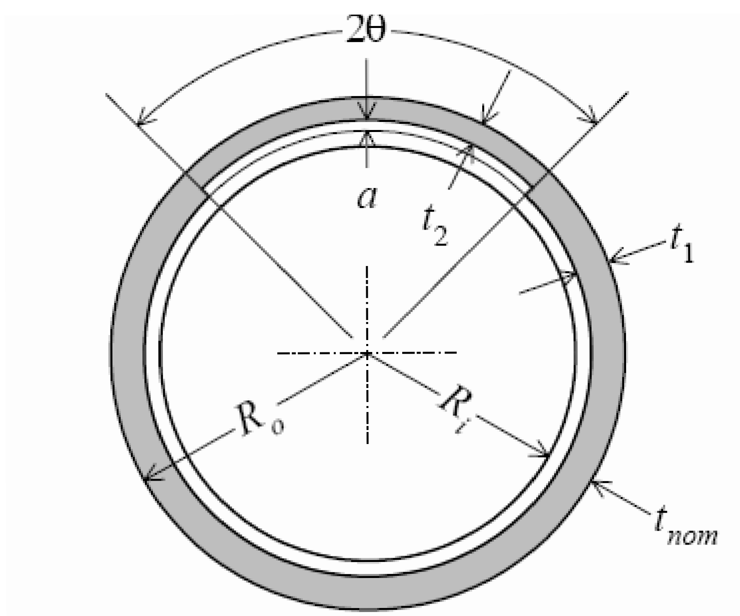

Figure 3 Characterized Feeder Cross-Section

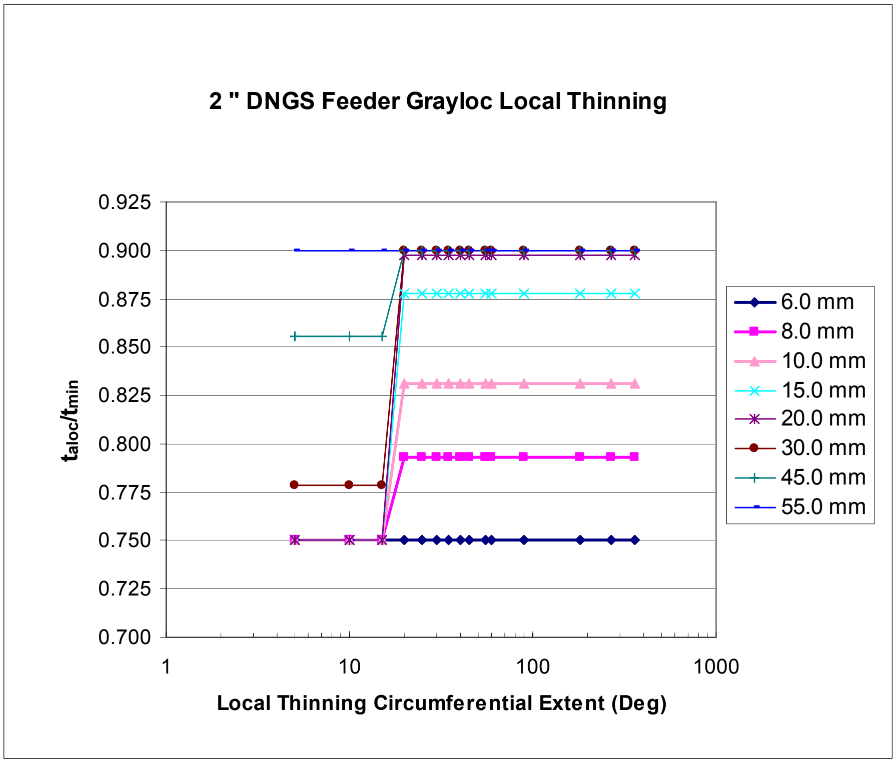

Figure 4 Ratio of Allowable Local Thickness versus Pressure Based Minimum Thickness for a Straight Pipe Section of a 2 Inch Feeder Pipe

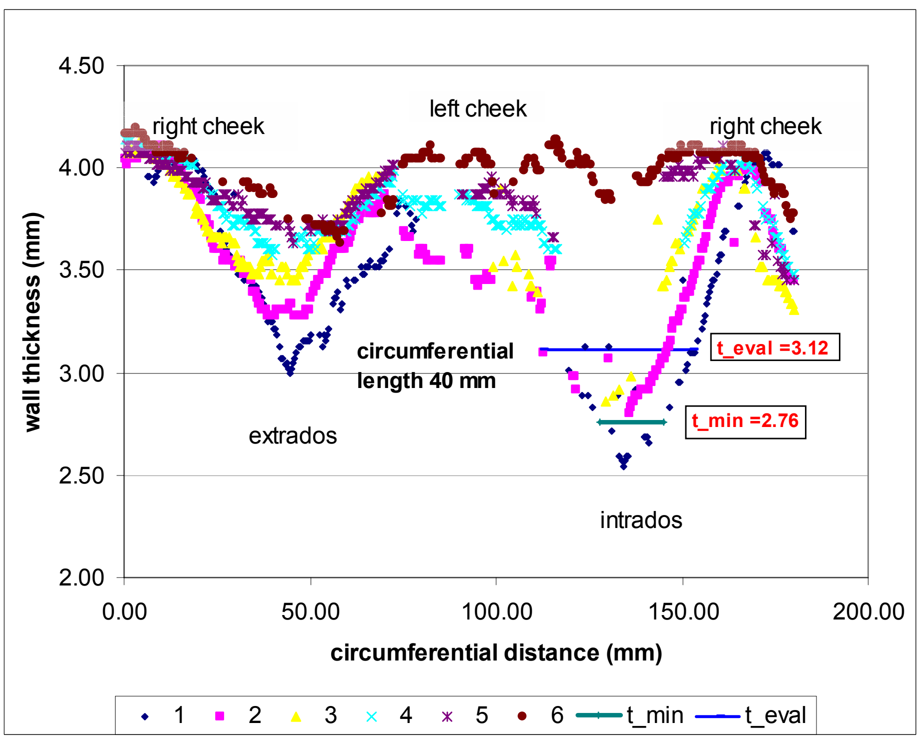

Figure 5 Predicted Thickness Profile for D2J24E near the Grayloc at D1021