FEEDER GRAYLOC HUB LOCAL ALLOWABLE THICKNESS -A COMPARISON OF ASME SECTION III AND FFSG APPENDIX E LEVEL 2 EVALUATION

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ABSTRACT

Flow assisted corrosion (FAC) causes high rates of wall loss at outlet feeder pipes. The most affected area for Darlington outlet feeders is close to the Grayloc end fittings. Inspection data since 2007 identifies that thinning near the Grayloc weld is 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 in the near future. Stress analyses must be performed to demonstrate feeder fitness for service (FFS) with reduced wall thickness as per ASME Section III or other accepted Codes and Standards.

The stress analyses using both ASME III (**Reference 1**) and Fitness For Service Guideline for Feeders (FFSG) Appendix E Level 2 (**Reference 2**) methodologies were performed under the Localized Feeder Stress Analysis Project (LFSA). It has demonstrated that almost all DNGS outlet feeders have sufficient structural integrity to be declared FFS until the planned Darlington reactor refurbish dates. This results in significant reduction in feeder replacement associated economical cost and personnel radiation dosage.

This paper presents the generic methodologies and a comparison of the results of ASME III and FFSG Appendix E Level 2. It demonstrates both the advantages and limitation of the FFSG method.

ABBREVIATION

CMTR	Certified Material Test Report	COG	CANDU Owners Group
CUF	Cumulative Usage Factor	DNGS	Darlington Nuclear Generation Station
EoL	End of Life	EFPY	Effective Full Power Year
FAC	Flow Assisted Corrosion	FEA	Finite Element Analysis
FFS	Fitness 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		

1.0 INTRODUCTION

In a 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. At DNGS, it is predicted that thickness near the Grayloc Hub of a large population of feeders will be below PB due to the local wall loss. The cause is most likely due to the initial post-weld grinding during construction and the wall loss worsened by FAC during the service.

The thickness assessment is carried out to show whether the reduced 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 and CSA N289.3 for seismic requirements.

On one hand, ASME Section III type finite element analysis is feeder specific and time consuming. For the DNGS large scale feeder disposition project or called LFSA, a generic method is developed to capture the bounding relation of the local thinning extent and associated allowable thickness for all 22 types of feeder bends. In most cases, the acceptable local thickness of a feeder with associated inspected or predicted thickness profile could be easily determined from the pre-generated graphs. A small number of feeders with more severe thinning may still need feeder specific finite element analysis.

On the other hand, Appendix E of FFSG (**Reference 2**) 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, however is not suitable when a local thickness is below the pressure base value. Level 3 is suitable for localized thinning, which uses more complex finite element 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 more rapid disposition of inspection results.

This paper presents two effective assessment methodologies: a generic local thinning allowable thickness vs. thinning extent correlation using ASME III rules, and FFSG Level 2 closed form calculation, as well as the comparison of respective assessment results.

2.0 ASME SECTION III STRESS ANALYSIS

2.1 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:

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

where P - Internal Design Pressure
D_o - Outside diameter of a feeder pipe
S_m - maximum allowable stress intensity (S_m = 119 MPa for SA106 Gr. B @318.3 ^{o}C)
y = 0.4

The only relevant loading condition in Equation (1) is the internal pressure. A severely thinned pipe which thickness in a large area is below t_{min}^{sp} should be immediately removed or repaired. However, if the wall thinning is only limited to one or several small zones with thickness below t_{min}^{sp}, 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 75% t_{min}^{sp} regardless of the acceptance of the assessment.

For any thickness below t_{min}^{sp}, detailed finite element models including local thinning profiles must be developed to perform stress analysis under internal pressure loading according to NB-3221 and NB-3213.10, which is permitted by NB-3600. 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 $1.1S_m$ for a distance of $\sqrt{(Rt)}$, R is the pipe radius.

2.2 Finite Element Models and Generic Results

There are 22 types of feeder bends in DNGS. These types are primarily categorized by pipe size, bend angle, bend radius, length of straight pipe(s) and etc. Bends of different types may have differences in geometry away from the region of interest, e.g. different length straight pipe between the bend 1 (1st bend downstream of the Grayloc) and bend 2 (2nd 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, effect of these variations on the stresses in the straight pipe between the Grayloc and bend 1 is assumed negligible. The 22 feeder bend types have been divided into 6 feeder bend models as shown in **Table 1** according to the pipe size and the length of straight pipe (STR1) between the Grayloc and bend 1.

In the current assessment, local thinning is assumed in STR1. Local thickness (t_{local}) is expected to be confined within the length of STR1 for most types of feeders. Wall thickness of bend 1, which is immediate adjacent to the locally thinned area, has an important impact on the localized thinning assessment. The wall thickness of generally thinned feeder bends is typically non-uniform. However, in this assessment bend thickness is assumed uniform to reduce the amount of calculations and to simplify the model without reducing conservative. Since it is impractical 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. Compared to thinning rate near the Grayloc region, bend thinning rate is lower and proves to be more accurate with the current inspection tools.

In order to tackle uncertainty in thickness inspection, analysis is performed with unlimited circumferential thinning profile. The typical model sketch is illustrated in **Figure 1**, which shows how various transitions are modeled. The models were prepared with thinning all-around the circumference, i.e. un-limited circumferential extent of thinning. This allows the local thickness to be anywhere around the circumference for a given axial extent but the average thickness at each cross-section shall be equal to or higher than t_{min}^{sp}.

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 STR1 or inside bend 1 (for short length STR1 feeder bend types or long thinning extent);
3. Transition of 5 mm is used to go from t to t_{nom} for the transition beyond bend 2.

Analysis results are shown in **Figure 2, 3 and 4**, which provide generic localized acceptable thickness for various types of bends:

- **Figure 2** is for Bend Types of K, I and D (2"Feeder), which shows that the local thinning limit of $0.75t_{min}^{sp}$ (2.06 mm) is achievable when the axial thinning extent is no more than 5.4 mm.

- **Figure 3** is for Bend Types of L, J, H or E (2.5"Feeder), which shows that the local thinning limit of $0.75t_{min}^{sp}$ (2.75 mm) is achievable when the axial thinning extent is no more than 8.3 mm.
- **Figure 4** is for Bend Types of M (2"Feeder), which shows that local thinning limit of $0.75t_{min}^{sp}$ (2.06 mm) is achievable when the axial thinning extent is no more than 4.0 mm.
- **Figure 5** is for Bend Types of A (2"Feeder), which shows that local thinning limit of 0.75tminsp (2.06 mm) is achievable when the axial thinning extent is no more than 10.0 mm with a 3.5 mm bend thickness, or a lower thinning extent value of 5.0 mm or less with a 3.0 mm bend thickness.
- **Figure 6** is for Bend Types of B (2"Feeder), which shows that local thinning limit of 0.75tminsp (2.06 mm) is achievable when the axial thinning extent is no more than 10.0 mm with a 3.5 mm bend thickness, or a lower thinning extent value of 5.0 mm or less with a 3.0 mm bend thickness.

To perform an assessment by using a spreadsheet, least-square curve fitting is applied to **Figures 2, 3, 4, 5 and 6** to obtain the correlation between the allowed axial extent of local thinning (L) and local allowed thickness (t_{local}).

Type D, G, I and K: $L = 3.2775t_{local}^3 - 12.908t_{local}^2 + 15.297t_{local}$, $R^2 = 0.9999$

Type E, H, J and L: $L = 3.8991t_{local}^4 - 33.528t_{local}^3 + 96.433t_{local}^2 - 89.679t_{local}$, $R^2 = 0.9969$

Type M: $L = -66.614t_{local}^5 + 626.99t_{local}^4 - 2204.6t_{local}^3 + 3435.3t_{local}^2 - 2000.5t_{local}$, $R^2 = 0.9991$

Type A, B: $L= 75.209t_{local}^4 – 679.63t_{local}^3 + 2315.1t_{local}^2 – 3509.9t_{local} + 2002.3$ $R^2 = 0.9995$

Note: R^2 is the square of the correlation coefficient between input data and their predicted values.

Some instances, as shown in **Section 5** of this paper, a feeder with a local thinning profile cannot meet the generic results, the thickness specific finite element method must be used to check code compliance.

3.0 LEVEL 2 ASSESSMENT METHOD

In this paper, the evaluation procedure is according to Article E-2 of FFSG Appendix E. Level 2 evaluation on internal pressure and bending moment coincident with internal pressure.

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

As shown in **Figure 7,** 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 axial extent of thickness less than t_{eval}. L_m is the maximum value of $L_{m(t)}$ and $L_{m(a)}$. 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 geometry characterization of a thinned 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. Based on axial and circumferential extent, three classes of local thinned region geometry are defined here after. The allowable local wall thickness t_{aloc} is calculated by using formulas or empirical curves defined in each category.

(a) ***Limited Circumferential Extent (LC)***: when the circumferential extent, $L_{m(t)}$, of a 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:

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

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

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

(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:

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

(ii). Satisfy reinforcement requirement:

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

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

$$t_{aloc}/ t_{min}^{sp} = 0.75 \tag{5}$$

(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:

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

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

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

3.2 Level 2 Structural Evaluation of Thinned Region under 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 8**. 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. The local thinning is characterized having a uniform wall thickness t_2 and a circumferential extent 2θ, as denotes, the depth of local thinning, $a = t_1 - t_2$

3.2.1 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

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

3.2.2 Membrane Axial Stress

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

$$\sigma_m^{p^*} \le \frac{\sigma_m^c}{SF_m} \quad (8)$$

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

At present, the evaluation formula in Appendix E for applied bending moment plus internal pressure are only applicable to the straight section of feeder pipe, i.e., not applicable to thinning assessment on the feeder bends.

4.0 DARLINGTON FEEDER INPUT DATA

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

4.1 Feeder Pipe Geometric Data

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

Item	2” NPS	2.5” NPS
Outside diameter	D_o = 60.33 mm	D_o = 73.03 mm
Nominal wall thickness	t_{nom} = 5.54 mm	t_{nom} = 7.01 mm
Pressure based thickness (PB)	t_{min} = 2.76 mm	t_{min} = 3.34 mm
FFSG local thinning limit	0.75* t_{min} = 2.07 mm	0.75* t_{min} = 2.50 mm

4.2 Loading Condition and Material Properties

4.2.1 Design Condition

The design conditions are as per the Darlington design specifications:

Outlet feeder design temperature: 318.33 ºC

Outlet feeder design internal pressure: 11.275 MPa(g)

4.2.2 Material Properties

The feeder pipe is procured according to the SA-106 Grade B material specifications. 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 for both 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

5.0 ASSESSMENT PROCEDURE AND RESULTS

5.1 Application of Thickness Inspection Data

The 6-probe pack, as shown in **Figure 9**, is used by the Inspection Organization to measure wall thickness adjacent to 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 up to a distance of 12.5 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 2**.

5.2 Assessment Procedures

The following evaluation steps are used to assess the acceptable local thickness for each individual feeder:

1) Determine disposition feeders: Using the minimum inspected thickness to calculate the minimum thickness for a future outage or at EoL using a reasonable thinning rate. Feeders below PB will be screened out for disposition.

2) Determine thinning size: Calculate projected thickness at all 6 probes and 14 probes if necessary to determine the thinning sizes, in both axial and circumferential directions.

3) Determine allowable local thinning thickness: The local allowable thickness could be evaluated by generic ASME type results provided in **Section 2**, or FFSG Level 2 in **Section 3,** or feeder and thickness specific FEA for more severely thinned feeders . The results of these analyses demonstrate 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. The length of thinning extents determines how low the local thinning thickness can reach. However, the minimum acceptable thickness is limited to $0.75t_{min}^{sp}$ of FFSG limit regardless of the thinning extent.

4) Determine feeder FFS: The local allowable thickness is compared to the disposition thickness to determine if a feeder is fit for service. Since these two methods are independent, an individual feeder is deemed to be FFS by the acceptance of **one or both** of ASME and FFSG assessments.

The flowcharts for ASME III and FFSG Appendix Level 2 assessment are shown in **Figures 10 and 11** respectively.

5.3 Assessment Examples and Results

More than 70 feeders/profiles have been assessed to the projected thickness at various planned outages or at reactor refurbishment (EoL). A typical locally thinned feeder K24W of Unit 2 is taken as an example to demonstrate both ASME and FFSG types of assessment.

5.3.1 ASME III Assessment

1. Determining Projected Thickness at Future Outages or EoL

Using the most updated inspection data and a reasonable thinning rate, the minimum thickness at the Grayloc weld for K24W will be 2.68 mm at EoL, which is below the accepted PB of 3.33 mm. Therefore, a disposition of localized thinning has to be preformed for FFS. The inspected and projected thickness profiles are shown in **Figure 12**.

2. Determining Local Thinning Size in the Vicinity of the Grayloc

Feeder K24W is a K bend type feeder. The variation of axial extent of thinning for allowable local thickness is shown in **Figure 2** for ASME III analysis or using the FFSG formula provided in **Section 2.2**. The allowable axial extent for the predicted minimum thickness of 2.68 mm is 10.3 mm length, which is less than the straight pipe length of 10.4 mm for K type bend. The circumferential extent ($< t_{min}^{sp}$) is approximately 4.0 mm or 8.0 degree as shown in **Table 3**.

The minimum inspected thickness at last outage is 3.27 mm and is located at probe no. 1. Circumferentially, the minimum thickness location corresponds to the intrados region of the first bend. The average thickness at every probe is significantly higher than the PB value. Therefore, the thinning is considered to be localized only in the intrados region.

The projected thickness of all other probes, as shown in **Table 3**, is calculated by assuming the same thinning rate for all six probes when probe no. 1 reaches the disposition thickness (EoL thickness). The inspected thickness from the six individual probes and the projected thickness at probe no. 1 are shown in **Figure 12** in which PB thickness (t_{min}^{sp}) and FFSG Level 2 evaluation thickness T_{eval} ($1.10t_{min}^{sp}$) are also plotted to show circumferential thinning extent.

3. Determining the Acceptance of Projected Thickness and FFS

The modeled uniform thickness, minimum and average projected thicknesses (at EoL) are shown in **Figure 12**. The minimum and average thicknesses are higher than the modeled thickness. In addition, the minimum and average are higher than the transition thickness used in the FEA model (**Reference 3**).The predicted bend thickness is also higher than what is assumed in the FEA model. Therefore, the EoL thickness is acceptable with the current generic assessment results for K24W. The assessment is summarized in **Table 4**. K24W is FFS to EoL and as such, it inherently FFS for next two future planned outages, which occur earlier.

5.3.2 FFSG Level 2 Assessment

In Level 2 approach, assessments using internal pressure loading and internal pressure plus moment loading are performed. The local allowable thickness is the <u>maximum</u> required thicknesses from the two loading evaluations. In Level 2 assessment, the local thinning size is determined by $T_{eval} = 1.10t_{min}^{sp}$ rather than the pressure based thickness t_{min}^{sp}. The evaluation wall thickness T_{eval} is used in the geometry characterization procedures for Level 2 evaluation of a local thinned region for internal pressure loading, including proximity rules for adjacent local thinned regions.

Since the current FFSG Level 2 local thinning assessment method is only applicable to the straight pipe, the local thinning length of an assessed feeder must be evaluated to ensure it is shorter than the straight pipe length. The local thinning length is determined by either 6-probe or 14-probe. 14-probe is an ultrasonic tool to inspect bend thickness. The 6-probe inspection is limited to 12.5 mm from the Grayloc weld, thus 14-probe results have to be assessed to find the total thinning length for feeders which are longer than 12.5 mm of the straight pipe length. The following criteria were used to justify if a feeder is applicable to FFSG 2 assessment:

Criterion 1: If local thinning length (by 6-probe) < straight pipe length, FFSG 2 assessment is applicable

Criterion 2: For feeders having straight pipe longer than 12.5 mm, if local thinning length (by 6-probe) > 12.5 mm and thickness the first 25 mm from the 14 probe is greater than T_{eval}, FFSG 2 assessment is applicable

- L type: assuming thinning length = 15.3 mm (STR1 length);
- A and B types: using conservative length of 25 mm. (A type: STR1 = 45.5mm; B type: STR1 = 38.5 mm)

Criterion 3: Since M-type feeders have a straight pipe length of only 3.1 mm, it is generally true that current FFSG 2 is not applicable to M-type feeders.

All feeders were evaluated using tables similar to **Table 3** for K24W, where axial thinning extent could be estimated by comparing the projected minimum thickness at each probe with T_{eval}. The results of 60 assessed feeders are shown in **Table 5**. With the exception of 12 M-type feeders, there are only 3 feeders, D1 H02W, D1 Y11E and D3 G22E, having local thinning length exceeding the straight pipe length thus not suitable for current FFSG 2 assessment.

The results of assessing internal pressure loading and internal pressure plus bending moment are demonstrated in **Table 6 and 7** respectively for D2 K24W, as outlined in **Section 3.1 and 3.2**. The bending moments at the Grayloc were calculated by a piping program. The local thinning in the Grayloc region, where the average thickness maintains above the PB value, should have a negligible impact on bending moments. The average thickness at the probe where the disposition thickness located is conservatively used as the adjacent thickness t_1 in the **Table 7** calculation. It is noticed that in most cases the local allowable thickness t_2 could reach $0.75t_{min}^{sp}$ or 2.06 mm for all 2" feeders and 2.50 mm for 2.5" feeders under the internal pressure plus bending moment assessment. The formula below is used to determine the local allowable thickness:

The local allowable thickness t_{aloc} = Max [minimum required thickness under pressure, minimum thickness (t_2) under pressure plus moment loading] [9]

It is observed that from all calculations performed to date that the limiting thickness equals to the required thickness under internal pressure loading. This is consistent with the ASME III evaluation, i.e., the limiting loading at the Grayloc is internal pressure loading rather than mechanical bending moments. The FFSG 2 required thicknesses are then compared to the thicknesses at the disposition date for each feeder. If the disposition thickness is higher than the required thickness, it would be acceptable and the feeder is FFS to the particular disposition thickness or date. The FFSG Level 2 evaluation for 60 assessed feeders is summarized in **Table 8**. For the purpose of the comparison, the ASME III assessment results of the same disposition thickness for each feeder is also listed in the same table.

5.3.3 ASME III and FFSG Level 2 Assessment Comparison

Among 60 feeders dispositioned by both methods, it is found that:

- 3 feeders (one M-type) have projected thickness lower than 75%PB, i.e., below FFSG local thinning limit, thus disposition could not be made by either FFSG or ASME method.
- 12 M-type feeders are not suitable for current FFSG 2 assessment. Those feeders were assessed by ASME methods (5 by FEA) and deemed acceptable.
- 3 feeders (D1 H02W, D1 Y11E, D3 G22E) have axial thinning extent beyond the straight pipe region, thus they could not be assessed by FFSG 2. Two of them were analyzed by feeder specific FEA and one by generic ASME III method and all are found acceptable.
- Only 2 feeders (D2N19W, D4 S17E) could not meet FFSG criteria but were accepted by ASME III FEA analysis.
- Among 57 feeders accepted by ASME III, the majority of feeders (36) were acceptable by the simple generic assessment approach, 21 feeders still needed thickness specific FEA analysis.

Therefore, with the exception of M-type feeders, FFSG results are consistent with those of ASME III. The un-acceptance of two feeders by FFSG is primarily due to conservative estimation of axial thinning extent of 15.3 mm. Since FFSG Level 2 uses t_{eval} instead of t_{min}^{sp} to determine the thinning size, it tends to produce more conservative results than detailed FEA analysis. The latter could incorporate a refined thinning profile in the circumferential direction. The current FEA still uses the uniform axial thinning extent up to 6-probe range. The assessment method applicable to bends under internal pressure plus moment loading is under development within the COG program. Once it is completed, FFSG level 2 could be used to all thinning scenarios, including thinning extended to bends, and M type bend feeders.

6.0 CONCLUSIONS

Both the generic assessment using ASME III rules and FFSG Level 2 evaluation provide effective and conservative tools for the disposition of feeders shown to be life limited by FAC induced localized thinning. In many cases, FEA may be still required for feeder with severe thinning. The conclusions of from FFSG Level 2 assessment correlate well with the ASME III methodology – either from generic approach developed in this paper or feeder specific FEM.

FEA is feeder specific in nature and time consuming. For a large scale planned outage, more than hundreds outlet feeder baseline and repeat inspections may be conducted. There is a reasonable probability that a number of feeders may be found with localized thinning. The 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. The two assessment methods presented in this paper could provide effective tools to prevent outage delay. It is recommended to apply the generic approach and/or FFSG Level 2 method to carry out assessment on localized thinning to check code compliance for continuing safe operation. Feeder and thickness specific FEA could be applied only if the previous two methods do not meet requirements.

To broaden the application of FFSG Level 2 to all type feeders, the work to extend the method to feeder bends is in progress.

7.0 ACKNOWLEDGEMENT

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8.0 REFERENCES

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Table 1 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 2 Transducer Numbering and Location for the 6-Pack

Transducer No.	Axial Offset (mm)	Circumferential offset (mm)	Incidence Degree
1	0	3.0	normal
2	2.5	0.0	normal
3	5	-3.0	normal
4	7.5	0.0	normal
5	10	-3.0	normal
6	12.5	3.0	normal

Table 3 Inspected and Predicted Thickness for Unit 2 K24W

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)	3.63	3.98	4.15	4.18	4.24	4.21	RC-EX-LC
2nd scan Min Thk. (mm)	3.27	3.55	3.73	3.88	3.97	4.00	RC-IN-LC (back scan)
Average Thickness (mm)	4.09	4.25	4.25	4.27	4.29	4.32	4.24
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.					
K24W							
Disposition Year	EFPY	Insp. & Projected Minimum Thickness	Thinning rate	Disposition thickness	Disposition Thk./Min Inspection Thk.		
Last outate	16.14	3.27	0.089	**2.68**	0.82		
1st next outage	19.14	2.96					
2nd next outage	22.14	2.69					
EOL	22.29	2.68					
Below are the predicted thicknesses at EOL							
Probe No.	1	2	3	4	5	6	Note
Probe Location	0	2.5	5	7.5	10	12.5	Note
Projected Thk.	2.68	2.96	3.14	3.29	3.38	3.41	extent t < T_{min}
Average Thk.	3.50	3.66	3.66	3.68	3.70	3.73	3.65
t_{min}^{sp}	T_{eval} $=1.10t_{min}^{sp}$	Thickness Profile	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}
2.75	3.03	1st next outage	N/A	N/A	N/A	N/A	n/a
		2nd next outage	1.3	4.0	3.75	21.7	41.2
		EOL	1.3	4.0	3.75	21.7	41.2

Table 4 Acceptance for Feeder K24W - Unit 2 (ASME Assessment)

Feeder	Size	Bend Type	6-Probe Min	t_{min}^{sp}	$0.75t_{min}^{sp}$	Thinning rate	Disposition Year	Projected Minimum Thickness	Projected thickness < Pressure thickness?	Allowed axial extent for Disp. Thk.	Projected axial thinning length @ Disposition	Meet transition thickness	Analyzed Bend Thk.	Projected Bend Min. Thk.	Bend thickness requirement	Result
K24W	2"	K4	3.27	2.75	2.06	0.089	1st next outage	2.96	Thk. >= PB, FFS	10.30	< 5.0	not required	3.50	3.84	not required	**Acceptable**
							2nd next outage	2.69	Require Assessment	10.30	< 5.0	OK	3.50	3.65	OK	**Acceptable**
							EOL	2.68	Require Assessment	10.30	< 5.0	OK	3.50	3.64	OK	**Acceptable**

Table 5 Applicability of FFSG 2 Assessment on 60 Disposition Feeders

NO	Unit	Feeder	Size	T_{eval} (mm) = $1.10t_{min}^{sp}$	Feeder type	STR1 Length (mm) (G column)	Local Thinning Length (predicted t < T_{eval}) (H column)*	$T_{min}^{14\_probe}$ (projected thickness using 14-probe Min within the 1st 25 mm coverage)	$T_{min}^{14\_probe}/T_{eval}$ (within the beginning of 25 mm probe coverage)	Applicable to FFSG II notes	Length used in the Level II Assessment or N/A to FFSG
1	1	W06W	2"	3.03	I	10.4	7.5	3.42	1.13	OK - 6 probe	7.50
2	1	N01W	2"	3.03	M	3.1	12.5	2.97	0.98	M type - N/A	N/A
3	1	U11E	2.5"	3.66	L5	15.3	12.5	4.04	1.10	OK - 6 probe	12.50
4	1	K10W	2.5"	3.66	L5	15.3	12.5	4.22	1.15	OK - 6 probe	12.50
5	1	S10W	2.5"	3.66	L4	15.3	12.5	4.48	1.22	OK - 6 probe	12.50
6	1	M01E	2"	3.03	M	3.1	11.25	3.02	1.00	M type - N/A	N/A
7	1	F11E	2.5"	3.66	L1	15.3	12.5	4.53	1.24	OK - 6 probe	12.50
8	1	N24E	2"	3.03	M	3.1	12.5	3.32	1.10	M type - N/A	N/A
9	1	H02W	2"	3.03	I	10.4	11.25	3.42	1.13	thinning length > STR1 - N/A	N/A
10	1	L09W	2.5"	3.66	L6	15.3	12.5	4.05	1.11	OK - 6 probe	12.50
11	1	G22E	2"	3.03	K2	10.4	8.75	3.12	1.03	OK - 6 probe	8.75
12	1	G08E	2.5"	3.66	L2	15.3	8.75	4.85	1.33	OK - 6 probe	8.75
13	1	Y11E	2"	3.03	I	10.4	12.5	4.21	1.39	thinning length > STR1 - N/A	N/A
14	1	O15E	2.5"	3.66	L5	15.3	12.5	4.37	1.19	OK - 6 probe	12.50
15	1	R07W	2.5"	3.66	L1	15.3	12.5	4.69	1.28	OK - 6 probe	12.50
16	1	L07W	2.5"	3.66	L6	15.3	12.5	4.07	1.11	OK - 6 probe	12.50
17	1	J15W	2.5"	3.66	L4	15.3	3.75	4.14	1.13	OK - 6 probe	3.75
18	1	V15W	2.5"	3.66	L4	15.3	12.5	4.50	1.23	OK - 6 probe	12.50
19	1	R14E	2.5"	3.66	L5	15.3	12.5	4.23	1.16	OK - 6 probe	12.50
20	1	C06E	2"	3.03	D	10.4	8.75	4.37	1.44	OK - 6 probe	8.75
21	1	O01E	2"	3.03	M	3.1	12.5	4.01	1.32	M type - N/A	N/A
22	1	N04E	2.5"	3.66	H1	15.3	11.25	4.26	1.16	OK - 6 probe	11.25
23	1	O03E	2.5"	3.66	E	15.3	11.25	n/a	n/a	OK - 6 probe	11.25
24	1	E10E	2.5"	3.66	J	15.3	8.75	4.47	1.22	OK - 6 probe	8.75
25	1	E09W	2.5"	3.66	J	15.3	2.5	4.32	1.18	OK - 6 probe	2.50
26	1	D10W	2.5"	3.66	H1	15.3	11.25	4.80	1.31	OK - 6 probe	11.25
27	2	N19W	2.5"	3.66	L1	15.3	12.5	5.06	1.38	OK - 6 probe	12.50
28	2	F17E	2.5"	3.66	L1	15.3	12.5	4.68	1.28	OK - 6 probe	12.50
29	2	H15E	2.5"	3.66	L3	15.3	6.25	n/a	n/a	OK - 6 probe	6.25
30	2	J24E	2"	3.03	K3	10.4	8.75	n/a	n/a	OK - 6 probe	8.75
31	2	N05W	2.5"	3.66	J	15.3	5.00	n/a	n/a	OK - 6 probe	5.00
32	2	J23W	2"	3.03	K1	10.4	10.3	n/a	n/a	OK - 6 probe	10.30
33	2	K24W	2"	3.03	K4	10.4	3.75	n/a	n/a	OK - 6 probe	3.75
34	2	K14W	2.5"	3.66	L5	15.3	8.75	n/a	n/a	OK - 6 probe	8.75
35	2	G19W	2.5"	3.66	L2	15.3	3.75	n/a	n/a	OK - 6 probe	3.75
36	2	K04W	2.5"	3.66	L5	15.3	6.25	n/a	n/a	OK - 6 probe	6.25
37	2	H18W	2.5"	3.66	L3	15.3	6.25	n/a	n/a	OK - 6 probe	6.25
38	2	C18E	2"	3.03	D	10.4	8.75	n/a	n/a	OK - 6 probe	8.75
39	3	O24W	2"	3.03	M	3.1	12.5	3.20	1.06	M type - N/A	N/A
40	3	T13W	2.5"	3.66	L6	15.3	12.5	5.20	1.42	OK - 6 probe	12.50
41	3	G09W	2.5"	3.66	L2	15.3	12.5	4.40	1.20	OK - 6 probe	12.50
42	3	G22E	2"	3.03	K2	10.4	12.5	3.25	1.07	thinning length > STR1 - N/A	N/A
43	3	J02E	2"	3.03	K1	10.4	8.75	3.38	1.12	OK - 6 probe	8.75
44	3	P18E	2.5"	3.66	L2	15.3	8.75	4.46	1.22	OK - 6 probe	8.75
45	3	R02E	2"	3.03	M	3.1	11.25	2.92	0.96	M type - N/A	N/A
46	3	A14E	2"	3.03	A	45.5	12.5	3.71	1.22	OK - 6 probe	12.50
47	3	R13W	2.5"	3.66	L6	15.3	12.5	4.33	1.18	OK - 6 probe	12.50
48	3	W19E	2"	3.03	I	10.4	8.75	3.75	1.24	OK - 6 probe	8.75
49	3	H05E	2.5"	3.66	L3	15.3	11.25	4.85	1.33	OK - 6 probe	11.25
50	3	M01E	2"	3.03	M	3.1	12.5	3.52	1.16	M type - N/A	N/A
51	3	W06W	2"	3.03	I	10.4	10	3.79	1.25	OK - 6 probe	10.00
52	4	O01E	2"	3.03	M	3.1	12.5	2.97	0.98	M type - N/A	N/A
53	4	S17E	2.5"	3.66	L2	15.3	12.5	4.92	1.34	OK - 6 probe	12.50
54	4	P01W	2"	3.03	M	3.1	12.5	3.25	1.07	M type - N/A	N/A
55	4	N01W	2"	3.03	M	3.1	12.5	3.51	1.16	M type - N/A	N/A
56	4	S10W	2.5"	3.66	L4	15.3	12.5	4.73	1.29	OK - 6 probe	12.50
57	4	B09E	2"	3.03	B	38.5	12.5	3.92	1.29	OK - 6 probe	12.50
58	4	M01E	2"	3.03	M	3.1	12.5	4.00	1.32	M type - N/A	N/A
59	4	P24E	2"	3.03	M	3.1	3.75	3.50	1.16	M type - N/A	N/A
60	4	C19W	2"	3.03	D	10.4	6.25	3.70	1.22	OK - 6 probe	6.25

Notes: The purpose of this column is to determine, based on values in columns G (Straight Pipe Length) and H (Local Thinning Length), whether or not FFSG II can be used as an assessment method for an individual feeder. he current FFSG Level II local thinning assessment method is limited to the straight pipe, thus the local thinning length of the assessed feeder must be less than the straight pipe length, i.e. H < G.

Criterion 1: If G < H , the output is "thinning length > STR1", indicating that FFSG II assessment is not applicable to this feeder.

Criterion 2: If G > H , the FFSG II is applicable, and the output is "OK- 6 probe" since the H value comes directly from 6 - probe data.

Criterion 3: If H > 12.5 mm (6 probe coverage) but the 14 probe value (I column) is less than T_{eval}, it indicates that the bend thickness is above T_{eval}, and thinning is limited to straight pipe, the output is "OK - 14 probe". For L type, assume thinning length = 15.3 mm (STR1 length); for A and B types, use conservative length of 25 mm.

Criterion 4: Since M-type feeders have a straight pipe length of only 3.1 mm, it is generally true that FFSG II is not applicable to M-type feeders, "M type-N/A" is the output.

* In order to compare, value in H column greater than 12.5 mm is input as 12.5.

Table 6 Internal Pressure Loading Assessment for K24W – Unit 2 (2"Feeder)

Inputs	Darlington 2.0 inch Feeders		
Design pressure	P_D	11.3 MPa	
Nominal outside diameter	D_o	60.3 mm	
Design stress intensity	S_m @318 ºC	119.1 MPa	
Outside Radius	$R_o = D_o/2$	30.150 mm	
Geometry Characterization			
Pressure based thickness for SP	$t_{min}^{SP} = P_D D_o/[2(S_m + yP_D$	2.756 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)	3.11	
Mean Evaluated Radius	$R_{eval} = R_o - t_{eval}/2$ (LC,UC	28.63	=> Radius at the at surrounding region
	$R_{eval} = R_o - t_{eval}/2$ (LAC)	28.59	
Minimum Length for surrounding material t > t_{eval}	$2.5(R_{eval}*t_{eval})^{1/2}$ (LC,UC	23.29	=> 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)	23.59	
Mean Inside Radius	$R_{min} = R_o - t_{min}/2$	28.77	=> Mean radius at local thinning region
Characterized size	$(R_{min}*t_{min})^{1/2}$	8.90	=> 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 $t < t_{eval}$	8.90	$t_{aloc}/t_{min} = 0.75$ 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 $t < t_{eval}$	23.60	$t_{aloc}/t_{min} \ge 0.353L_m[1/(t_{min}^{sp}R_{min}^{sp})]^{0.5}$ $t_{aloc}/t_{min} \ge 1 - 1.5(R_{min}t_{min})^{0.5}(t_{eval}/t_{min} - 1)/L_m$ $t_{aloc}/t_{min} = 0.75$ 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 $t < t_{eval}$	8.90	$t_{aloc}/t_{min} = 0.75$ 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 $L_{m(a)}$	3.75 mm	**Length is Calculated from 6-probe Inspection**
$L_{m(a)}/(R_{min}t_{min})^{1/2}$	0.42	

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	5.02	6.27	0.266	0.6	LC or LAC	0.750	0.248	0.723	0.750	0.750	n/a	0.750	LC
15	7.53	8.41	0.357	0.8	LC or LAC	0.750	0.334	0.794	0.750	0.794	n/a	0.750	LC
20	10.04	10.72	0.454	1.1	UC or LAC	n/a	0.425	0.838	0.750	0.838	0.750	0.750	UC
25	12.55	13.10	0.555	1.4	UC or LAC	n/a	0.519	0.867	0.750	0.867	0.750	0.750	UC
30	15.06	15.52	0.658	1.7	UC or LAC	n/a	0.615	0.888	0.750	0.888	0.750	0.750	UC
35	17.58	17.97	0.762	2.0	UC or LAC	n/a	0.712	0.903	0.750	0.903	0.750	0.750	UC
45	22.60	22.91	0.971	2.5	UC or LAC	n/a	0.908	0.924	0.750	0.924	0.750	0.750	UC
90	45.19	45.35	1.922	5.1	UC	n/a	n/a	n/a	n/a	n/a	0.750	0.750	UC
180	90.39	90.47	3.834	10.2	UC	n/a	n/a	n/a	n/a	n/a	0.750	0.750	UC
270	135.58	135.64	5.748	15.2	UC	n/a	n/a	n/a	n/a	n/a	0.750	0.750	UC
360	180.78	180.82	7.663	20.3	UC	n/a	n/a	n/a	n/a	n/a	0.750	0.750	UC
									Acceptable Thicknes for pressure =			**2.07**	mm

Name	Size	Circum. angle below T_{eval}	The minimum allowable thickness (P, and P+M)
K24W	2"	41.2 deg	2.07

Table 7 Internal Pressure Plus Moment Loading Assessment for K24W – Unit 2 (2"Feeder)

Title : LEVEL 2 STRUCTURAL EVALUATION OF THINNED REGION FOR APPLIED BENDING MOMENT WITH COINCIDENT INTERNAL PRESSURE LOADING
File: K:\Reactor Components & Structures\Feeder Thinning\Darlington Thinning Assessments\D123- 2010\Unit 2\FFSG Assessments\Level 2 DNG Pressure & Moment - EOL Feeders -20 IN D2.xlsx
Author: Ming Li/Louise Marentette/Ian Wilcox
Date: January, 2011
Sheet: K24W

Inputs	Darlington 2.0 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 = $(\sigma_y + \sigma_u)/2$	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 $R_o = D_o/2$	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

K24W

Loads	Resultant Load F_{res} (kN)	Resultant Load M_{res} (kN-m)	Primary Load F_p	Primary Load M_p	Secondary Load F_s	Secondary Load M_s
DWT (Deadweight)	0.381	0.147	0.381	0.147	-	-
THM (Thermal)	0.347	0.599	-	-	0.347	0.599
EAM (Seismic Anchor Mvt)	0.033	0.032	-	-	0.033	0.032
EEM (Seismic Inertia)	0.457	0.423	0.457	0.423	-	-

Load Case	primary loads P	primary loads F_p	primary loads M_p	secondary loads F_s	secondary loads M_s	structural factors SF_m	structural factors SF_b	structural factors SF_e	effective load components (not used) P_{eff}	F_{eff}	M_{eff}
Level A/B	**12.1 MPa**	**0.381 kN**	**0.147 kN·m**	**0.3 kN**	**0.599 kN·m**	2.7	2.3	1.0	32.59 MPa	1.38 MPa	0.94 MPa
Level C	**13.6 MPa**	**0.838 kN**	**0.570 kN·m**	**0.0 kN**	**0.032 kN·m**	1.8	1.6	1.0	24.48 MPa	1.54 MPa	0.94 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	2.07	1.27	3.50	1.44	41.2	37.37%	56.80	0.06	0.410	0.025	82.95	185.03	3.35	0.28	12.22	0.114
Level C	1	0.75	2.07	1.27	3.50	1.44	41.2	37.37%	56.80	0.06	0.410	0.025	82.95	185.03	3.35	0.28	13.77	0.114

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	0.403	ok	short	0.403	0.887	2230.6	2.53E+05	44.22	17.51	71.37	0.07	269.97	353.44	0.55	pass	0.44	pass
Level C	1	0.392	ok	short	0.392	0.876	2230.6	2.53E+05	50.48	67.92	3.81	0.07	269.97	349.24	0.49	pass	0.34	pass

Table 8 Summary of FFSG Level 2 and ASME III Assessments of 60 Feeders

Unit	No.	Feeder	Size	Bend Type	Projected Grayloc Min t_{min}	FFSG Level II Assessment			ASME III Assessment
						FFSG required thickness t_{aloc}	Tthickness Ratio t_{aloc}/t_{min}	FFSG II Assessment	
1	1	W06W	2"	I	2.57	2.15	0.84	acceptable	acceptable
	2	N01W	2"	M	2.37	Not Applicable			acceptable by FEA
	3	U11E	2.5"	L5	2.97	2.88	0.97	acceptable	acceptable by FEA
	4	K10W	2.5"	L5	3.22	2.88	0.89	acceptable	acceptable by FEA
	5	S10W	2.5"	L4	2.91	2.88	0.99	acceptable	acceptable
	6	M01E	2"	M	2.54	Not Applicable			acceptable by FEA
	7	F11E	2.5"	L1	3.08	2.88	0.93	acceptable	acceptable by FEA
	8	N24E	2"	M	2.58	Not Applicable			acceptable
	9	H02W	2"	I	2.58	Not Applicable			acceptable
	10	L09W	2.5"	L6	3.13	2.88	0.92	acceptable	acceptable by FEA
	11	G22E	2"	K2	2.63	2.23	0.85	acceptable	acceptable by FEA
	12	G08E	2.5"	L2	3.18	2.58	0.81	acceptable	acceptable
	13	Y11E	2"	I	2.65	Not Applicable			acceptable by FEA
	14	O15E	2.5"	L5	3.20	2.88	0.90	acceptable	acceptable by FEA
	15	R07W	2.5"	L1	3.20	2.88	0.90	acceptable	acceptable by FEA
	16	L07W	2.5"	L6	3.22	2.88	0.89	acceptable	acceptable by FEA
	17	J15W	2.5"	L4	3.23	2.50	0.78	acceptable	acceptable
	18	V15W	2.5"	L4	3.23	2.88	0.89	acceptable	acceptable
	19	R14E	2.5"	L5	3.25	2.88	0.88	acceptable	acceptable
	20	C06E	2"	D	2.70	2.23	0.83	acceptable	acceptable
	21	O01E	2"	M	2.70	Not Applicable			acceptable by FEA
	22	N04E	2.5"	H1	3.27	2.74	0.84	acceptable	acceptable
	23	O03E	2.5"	E	3.28	2.74	0.83	acceptable	acceptable
	24	E10E	2.5"	J	3.29	2.58	0.78	acceptable	acceptable
	25	E09W	2.5"	J	3.30	2.50	0.76	acceptable	acceptable
	26	D10W	2.5"	H1	3.32	2.74	0.82	acceptable	acceptable
2	1	N19W	2.5"	L1	2.86	2.87	1.00	not acceptable	acceptable by FEA
	2	F17E	2.5"	L1	2.89	2.87	0.99	acceptable	acceptable by FEA
	3	H15E	2.5"	L3	2.90	2.50	0.86	acceptable	acceptable
	4	J24E	2"	K3	2.39	2.23	0.94	acceptable	acceptable by FEA
	5	N05W	2.5"	J	3.26	2.50	0.77	acceptable	acceptable
	6	J23W	2"	K1	2.48	2.30	0.93	acceptable	acceptable
	7	K24W	2"	K4	2.68	2.07	0.77	acceptable	acceptable
	8	K14W	2.5"	L5	3.28	2.79	0.85	acceptable	acceptable
	9	G19W	2.5"	L2	3.24	2.50	0.77	acceptable	acceptable
	10	K04W	2.5"	L5	3.13	2.50	0.80	acceptable	acceptable
	11	H18W	2.5"	L3	3.20	2.50	0.78	acceptable	acceptable
	12	C18E	2"	D	2.65	2.23	0.84	acceptable	acceptable
3	1	O24W	2"	M	2.47	Not Applicable			acceptable by FEA
	2	T13W	2.5"	L6	2.94	2.88	0.98	acceptable	acceptable
	3	G09W	2.5"	L2	2.99	2.88	0.96	acceptable	acceptable by FEA
	4	G22E	2"	K2	2.47	Not Applicable			acceptable by FEA
	5	J02E	2"	K1	2.54	2.23	0.88	acceptable	acceptable
	6	P18E	2.5"	L2	3.10	2.70	0.87	acceptable	acceptable
	7	R02E	2"	M	2.72	Not Applicable			acceptable
	8	A14E	2"	A	2.66	2.48	0.93	acceptable	acceptable
	9	R13W	2.5"	L6	3.24	2.88	0.89	acceptable	acceptable
	10	W19E	2"	I	2.72	2.23	0.82	acceptable	acceptable
	11	H05E	2.5"	L3	3.30	2.74	0.83	acceptable	acceptable
	12	M01E	2"	M	2.74	Not Applicable			acceptable
	13	W06W	2"	I	2.75	2.29	0.83	acceptable	acceptable
4	1	O01E	2"	M	2.36	Not Applicable			acceptable by FEA
	2	S17E	2.5"	L2	2.68	2.88	1.07	not acceptable	acceptable by FEA
	3	P01W	2"	M	2.06	Not Applicable			below 75%FFSG limit
	4	N01W	2"	M	2.14	Not Applicable			below 75%FFSG limit
	5	S10W	2.5"	L4	2.91	2.88	0.99	acceptable	acceptable by FEA
	6	B09E	2"	B	2.41	2.48	1.03	not acceptable	below 75%FFSG limit
	7	M01E	2"	M	2.56	Not Applicable			acceptable
	8	P24E	2"	M	2.63	Not Applicable			acceptable
	9	C19W	2"	D	2.68	2.07	0.77	acceptable	acceptable

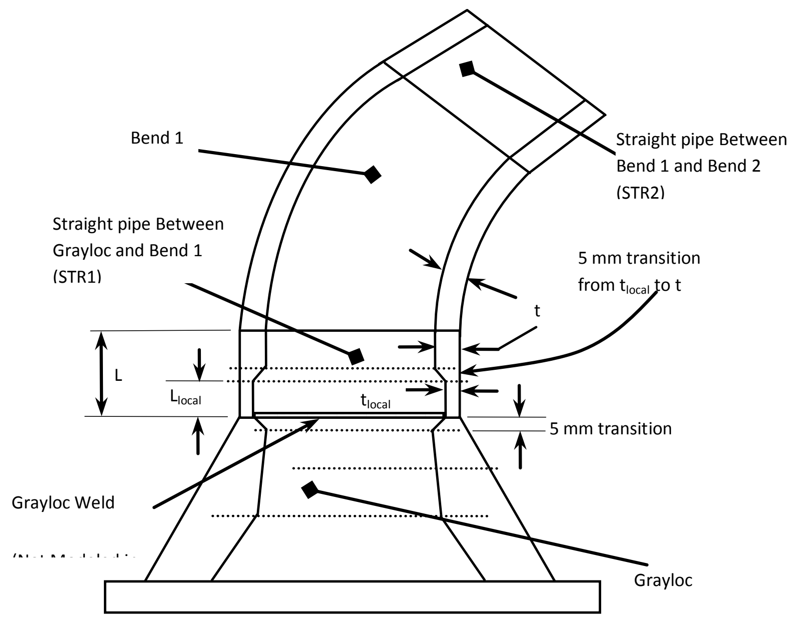

Figure 1 Schematic of a Typical DNGS feeder With Below Pressure Based Thickness in the Vicinity of Grayloc Weld

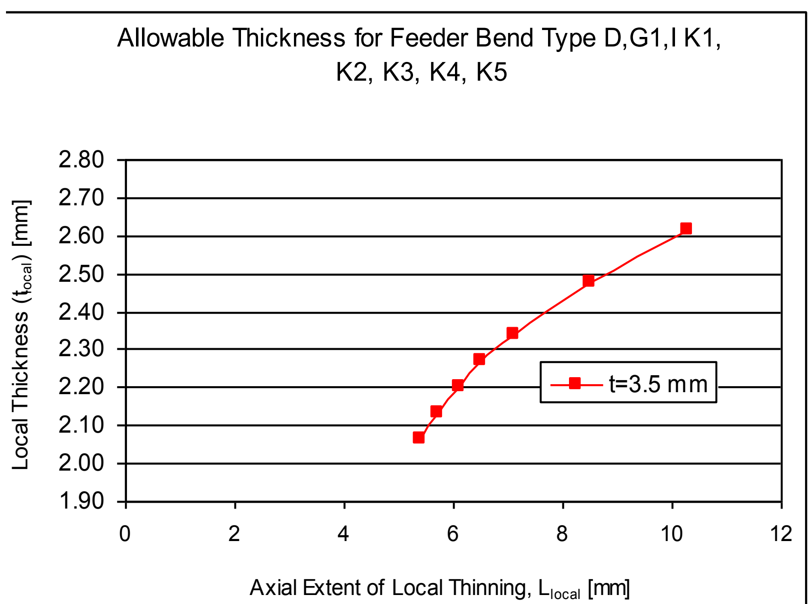

Figure 2 Variation of Axial Extent of Thinning Allowed for Localized Thickness Below Pressure Based Thickness for Feeder Bend Type D, G1, I, K with t = 3.5 mm.

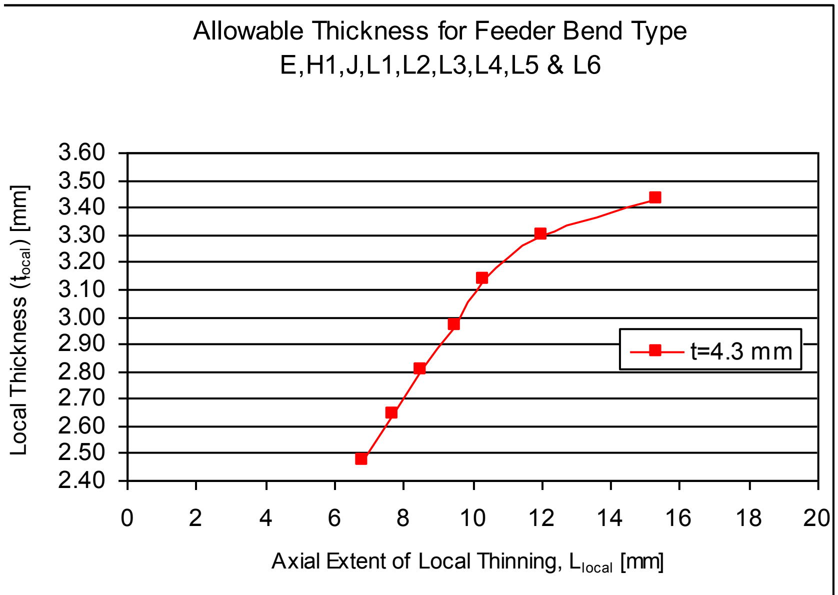

Figure 3 Variation of Axial Extent of Thinning Allowed for Localized Thickness Below Pressure Based Thickness for Feeder Bend Type E, H1, J, L with t = 4.3 mm.

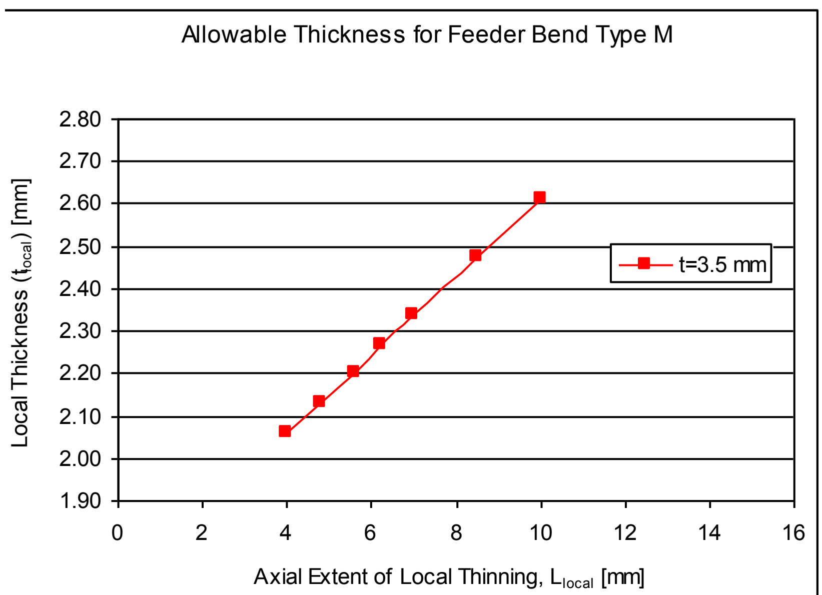

Figure 4 Variation of Axial Extent of Thinning Allowed for Localized Thickness Below Pressure Based Thickness for Feeder Bend Type M with t = 3.5 mm.

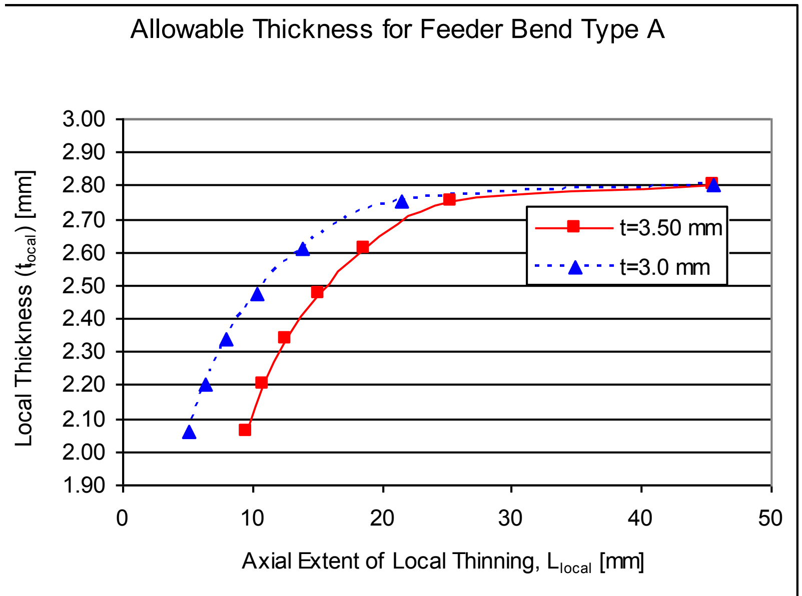

Figure 5 **Variation of Axial Extent of Thinning Allowed for Localized Thickness Below Pressure Based Thickness for Feeder Bend Type A with t = 3.5 and 3.0 mm**

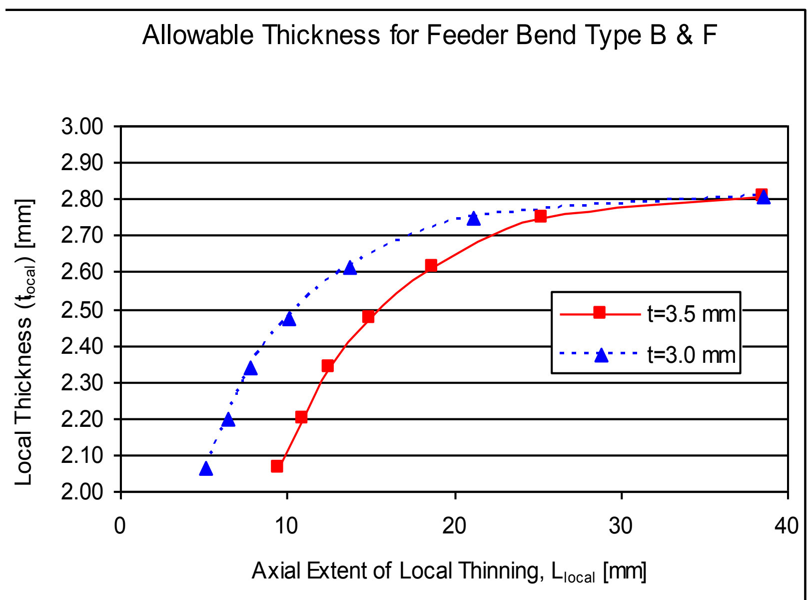

Figure 6 **Variation of Axial Extent of Thinning Allowed for Localized Thickness Below Pressure Based Thickness for Feeder Bend Type B with t = 3.5 and 3.0 mm.**

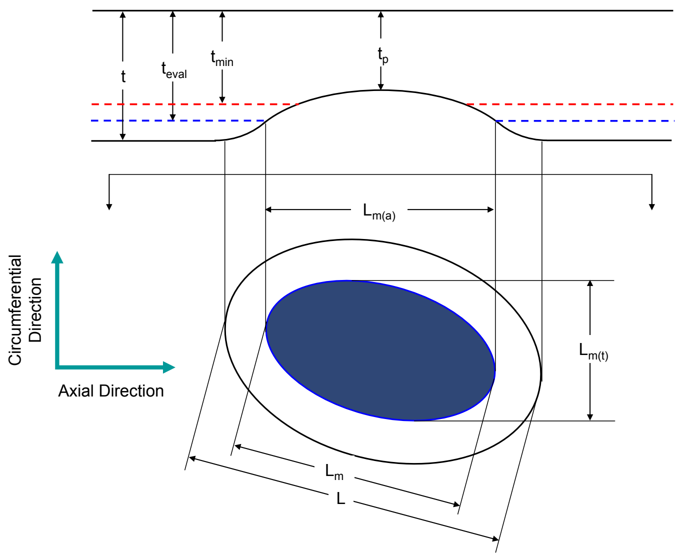

Figure 7 Illustration of Local Thinned Region

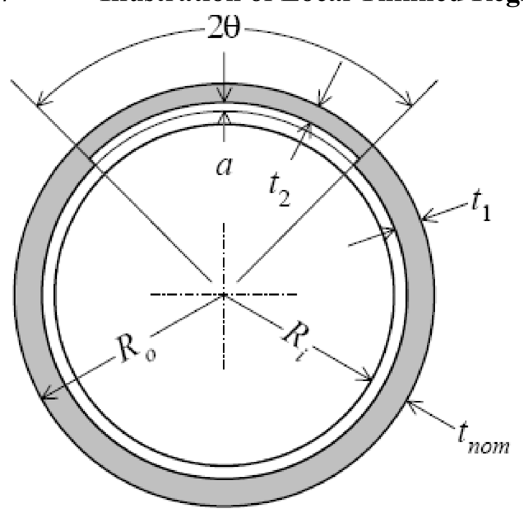

Figure 8 Characterized Feeder Cross-Section

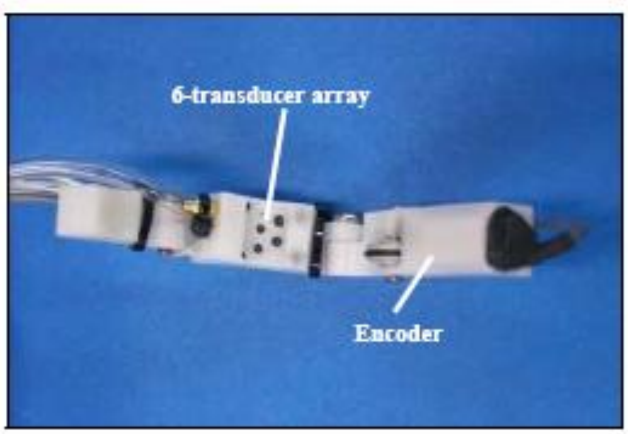

Figure 9 6-Pack Outrigger

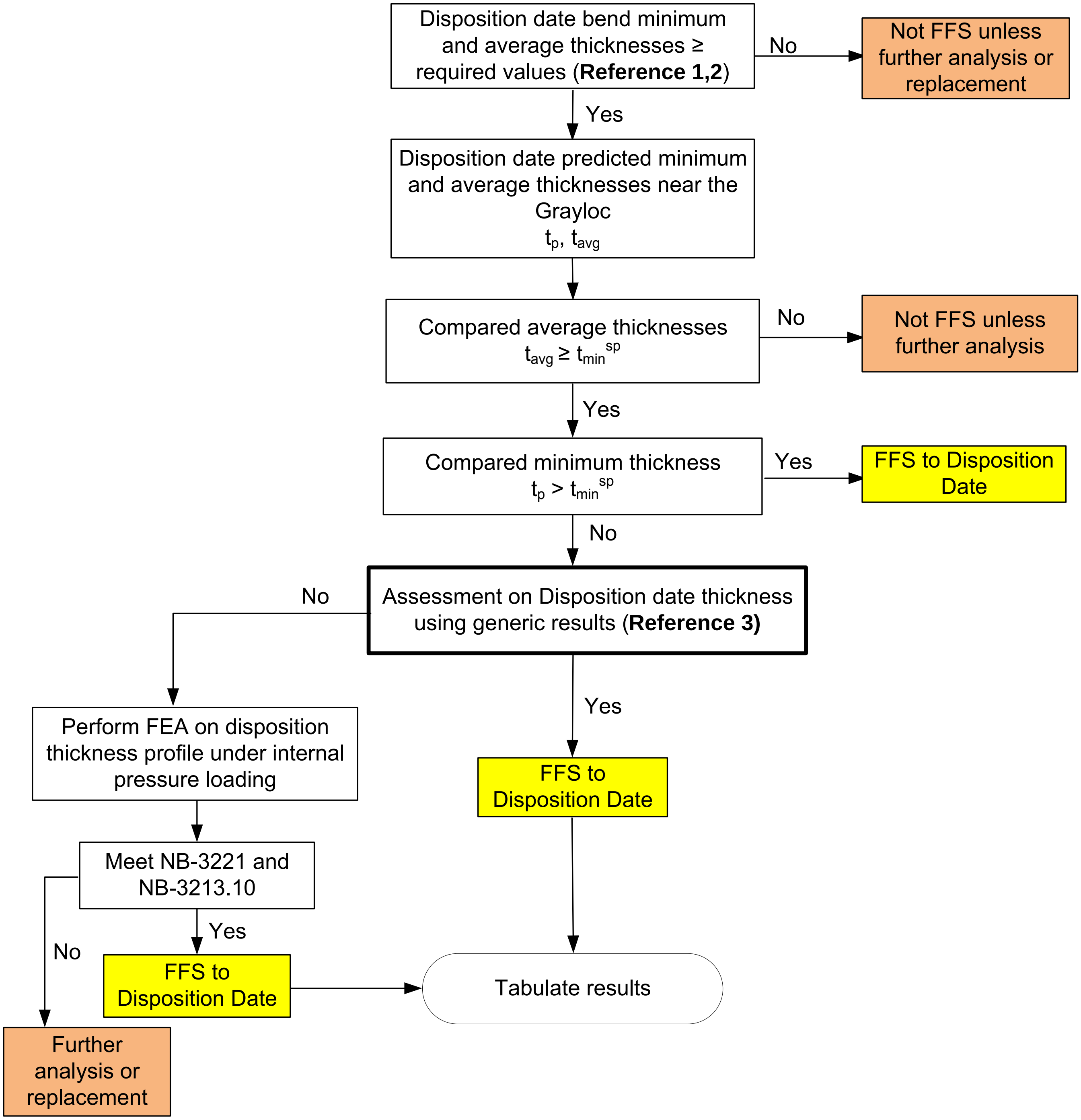

Figure 10 Flowchart of ASME III Assessment

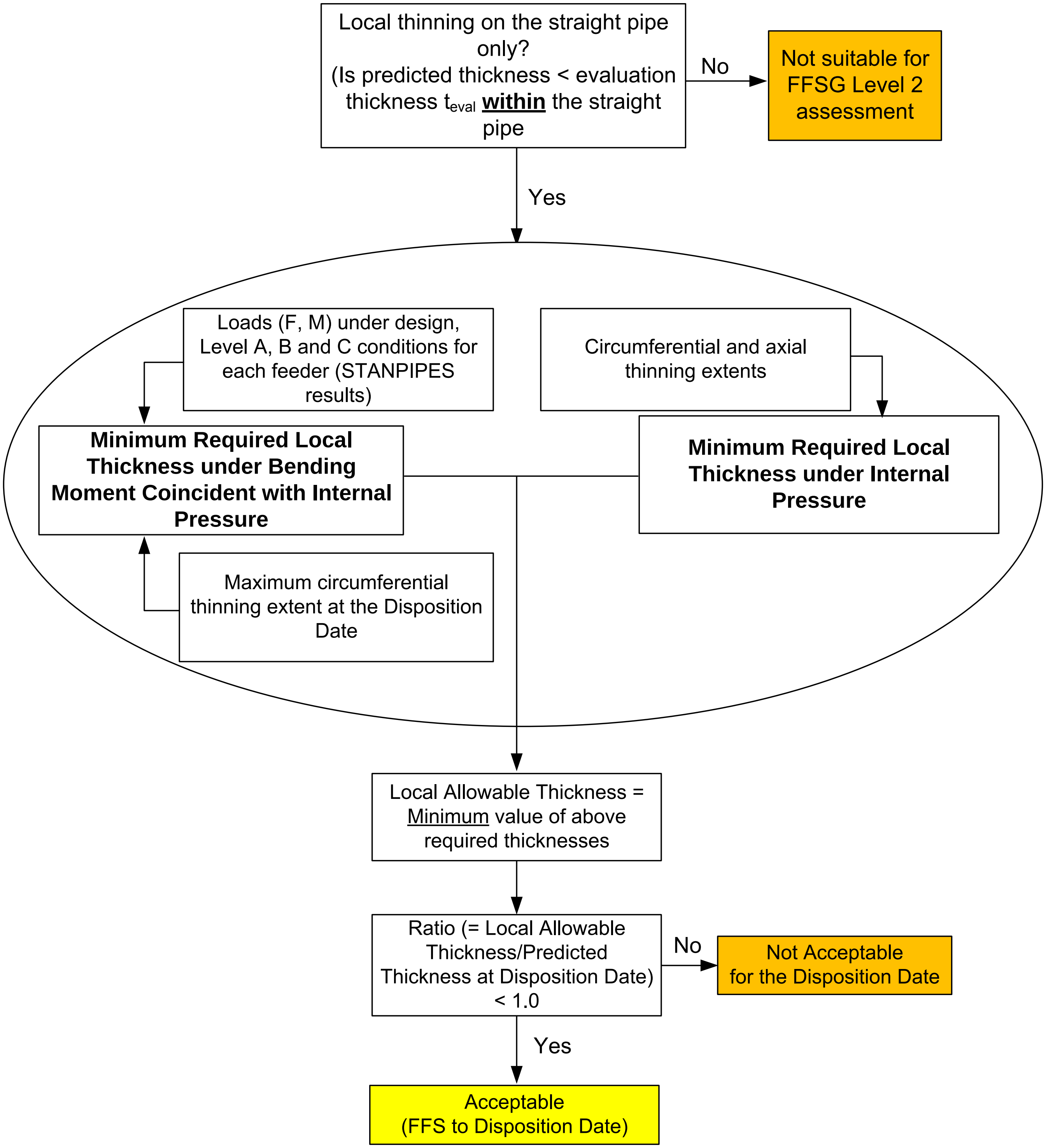

Figure 11 **Flowchart of FFSG Appendix E Level 2 Assessment**

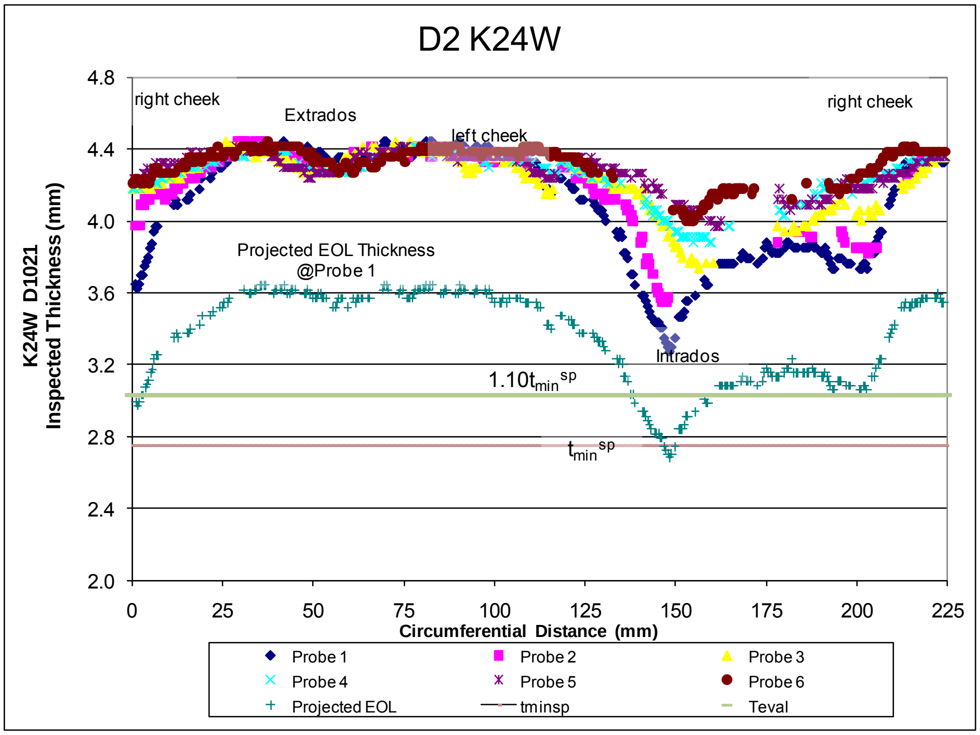

Figure 12 **Inspected and Predicted Thickness Profile of D2 K24W Near the Grayloc**