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Evaluation and Screening Criteria for the Dresden 2 and 3 Shrouds

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1.0 INTRODUCTION

In preparation for the Dresden 2 and 3 shroud inspections, Commonwealth Edison Company has requested GE to develop a screening criterion for indications that may be found at the shroud welds. Recently, indications have been discovered in some BWR shrouds as a result of in-vessel visual inspection (IVVI). When indications are found by IVVI, only the lengths of the indications are known. Given that non-destructive examination (NDE) of every visually detected indication would be difficult and time consuming, a method of screening indications for subsequent evaluation is required. This report presents such a screening criterion.

The guiding parameter used for the selection of the indications for further evaluation is the allowable through-wall flaw size, which already includes safety factors. If all of the visually detected indications are assumed to be through-wall, then the longest flaws, or combination of flaws, would have the limiting margin against the allowable through-wall flaw size. In reality, the indications are likely not through-wall, and therefore the criteria and methods presented in this report are conservative.

The result of this procedure will be the determination of the effective flaw lengths which will be used to compare against the allowable flaw size and selection of indications for more detailed evaluation. The determination of effective flaw length is based on ASME Code, Section XI, Subarticle IWA-3300 (1989 Edition) proximity criteria. These criteria provide the basis for the combination of neighboring indications depending on various geometric dimensions. Crack growth over a subsequent cycle is factored into the criteria.

The proximity rules described here also conservatively assume that there is interaction between two perpendicular flaws. It is assumed that circumferential and axial indications could increase the effective flaw length depending on the unflawed distance between them. This effective circumferential flaw length must be compared against the allowable circumferential flaw length. The effective axial flaw length would be compared against the allowable axial flaw length.

Flaws are considered in the same plane if the perpendicular distance between the planes is 4 inches or less. Any flaws which lie at an angle to the horizontal plane should be separated into a circumferential and axial component. These components can then be used separately in the determination of effective flaw lengths.

The selection of indications for further investigation can be performed by evaluating the resulting effective flaw lengths. **Indications with effective flaw lengths greater than the allowable flaw sizes would require further characterization by NDE or more detailed analysis.** The procedure described here is conservative, since all of the indications are assumed through-wall and are being compared against the allowable through-wall flaw size.

This report describes the following steps:

- Determination of effective flaw length including proximity criteria for adjacent flaws.
- Determination of allowable flaw sizes based on both linear elastic fracture mechanics (LEFM) and limit load criteria.
- Screening criteria.

The report covers the limiting stresses for all the shroud welds (H1 through H7 welds). Therefore, the screening criteria developed here cover all shroud weld indications. A list of conservative assumptions used in this evaluation is summarized in Table 1-1.

Table 1-1: Conservative Assumptions Included In Screening Evaluation

1. Postulated surface indications were assumed to be through-wall for analysis.
2. The bounding crack growth estimated for the next fuel cycle was included in postulated flaw lengths used for evaluation.
3. ASME Code primary pressure boundary safety margins were applied even though the shroud is not a primary pressure boundary.
4. ASME Code, Section XI proximity rules were applied.
5. A proximity rule to account for perpendicular flaws was applied, although not required by Section XI.
6. An additional proximity rule which accounts for fracture mechanics interaction between adjacent flaws was used.
7. Fracture toughness measured for similar materials having a higher fluence was used (fluence comparable to end-of-life prediction).
8. For welds H4 and H5, both LEFM and limit load analyses were applied, even though LEFM underestimates allowable flaw size, and is not required for austenitic materials.

2.0 DETERMINATION OF THE EFFECTIVE FLAW LENGTH

The effective flaw lengths are based on ASME Code, Section XI proximity criteria as presented in Subarticle IWA-3300. The procedure addresses both circumferential and axial flaws. Indications are considered to be in the same plane if the perpendicular distance between the planes is less than 4 inches. All flaws are considered to be through-wall. Therefore, indications on the inside and outside surface should be treated as if they are on the same surface. When two indications are close to each other, rules are established to combine them based on proximity. These rules are described here.

2.1 Proximity Rules

The flaw combination methodology used here is similar to the ASME Code, Section XI proximity rules concerning neighboring indications. Under the rules, if two surface indications are in the same plane (perpendicular distance between flaw planes < 4 inches) and are within two times the depth of the deepest indication, then the two indications must be considered as one indication.

In Figure 2-1, two adjacent flaws L1 and L2 are separated by a ligament S. Crack growth would cause the tips to be closer. Assuming a conservative crack growth rate of 5×10^{-5} in/hr, crack extension at each tip is 0.833 inches for 16,655 hours or one fuel cycle (24 month cycle with a 95% capacity factor). Therefore, combining the crack growth and proximity criteria, the flaws are assumed to be close enough to be considered as one continuous flaw if the ligament is less than (2 x 0.833 + 2 x shroud thickness). For a shroud thickness of 2.0 inches, this bounding ligament is 5.67 inches. Thus, if the ligament is less than 5.67 inches, the effective length is (L1 + L2 + S + 1.67"). Note that the addition of 1.67 inches is to include crack growth at the other (non-adjacent) end of each flaw (See Figure 2-2).

If the ligament is greater than 5.67 inches, then the effective flaw length is determined by adding the projected tip growth to each end of the flaw. For this example, $L1_{eff} = L1 + 1.67"$, and $L2_{eff} = L2 + 1.67"$.

A similar approach is used to combine flaws when a circumferential flaw is close to an axial flaw (See Figure 2-3). If the ligament between the flaws is less than 4.833 inches, then the effective flaw length for the circumferential flaw is $L_{eff} = L1 + S + 0.833"$ (the bounding ligament for these cases). If the ligament is greater than 4.833 inches, then the flaws are treated separately.

After the circumferential and axial flaws have been combined per the above criteria, a map of the effective flaws in the shroud can be made, and the effective flaw length can be used for subsequent fracture mechanics analysis.

To demonstrate the proximity criteria, three examples are shown in Table 2-1 and described below.

Table 2-1: Flaw Combinations Considered in Proximity Criteria

Case	Circumferential Flaw	Axial Flaw
A	Yes	No
B	Yes	Yes
C	No	Yes

2.1.1 Case A: Circumferential Flaw – No Axial Flaw

This case applies when two circumferential indications are considered. Figure 2-2a shows this condition. If the distance between the two surface flaw tips is less than 5.67 inches, the indications must be combined such that the effective length is (See Figure 2-2b):

$$L_{eff} = L1 + S + L2 + 1.67"$$

where: L1 = length of first circumferential indication
L2 = length of second circumferential indication
S = distance between two indications

If the distance between the two tips is greater than 5.67 inches, the effective flaw lengths are (See Figure 2-2c):

$$L1_{eff} = L1 + 1.67"$$
$$L2_{eff} = L2 + 1.67"$$

2.1.2 Case B: Circumferential Flaw -- Axial Flaw

This case applies when both a circumferential and an axial flaw are being considered. Figure 2-3a demonstrates this condition. For this case, only growth of the circumferential flaw is considered. If the distance between the circumferential indication tip and the axial indication is less than 4.833 inches, then the effective circumferential flaw length is (See Figure 2-3b):

$$L_{eff} = L1 + S + 0.833"$$

where: L1 = length of circumferential indication
S = distance between the circumferential tip and axial flaw.

and the effective axial length is (Figure 2-3b):

$$L_{eff} = L2 + 1.67"$$

where: L2 = length of axial indication

If the distance between the circumferential indication tip and the axial indication is greater than 4.833 inches, then the flaws are not combined (See Figure 2-3c) and the effective lengths are:

$$L1_{eff} = L1 + 1.67" \text{ (for circumferential flaw)}$$

$$L2_{eff} = L2 + 1.67" \text{ (for axial flaw)}$$

2.1.3 Case C: No Circumferential Flaw -- Axial Flaw

This case applies when only axial flaws are being considered. The effective length is determined in a manner similar to that used for Case A for circumferential flaws.

2.2 Application of Effective Flaw Length Criteria

The application of the effective length criteria is applied to two adjacent indications at a time. Figure 2-4 is a schematic which illustrates the process. For example, using the 0° azimuth as the starting location for a circumferential weld or plane, the general procedure would be as follows:

- Moving in the positive azimuthal direction, the first indication encountered is indication 1.
- The next indication is indication 2.
- Apply proximity rules to the pair of indications (indications 1 and 2). Combine the flaws if necessary (L1 + L2 + S). If the flaws are combined, the resulting flaw becomes indication 2.
- Continue along positive azimuthal direction until the next indication is encountered. This becomes indication 3.
- Apply proximity rules to indications 2 and 3.
- Continue proximity rule evaluation until all indications along the subject weld or plane have been considered.

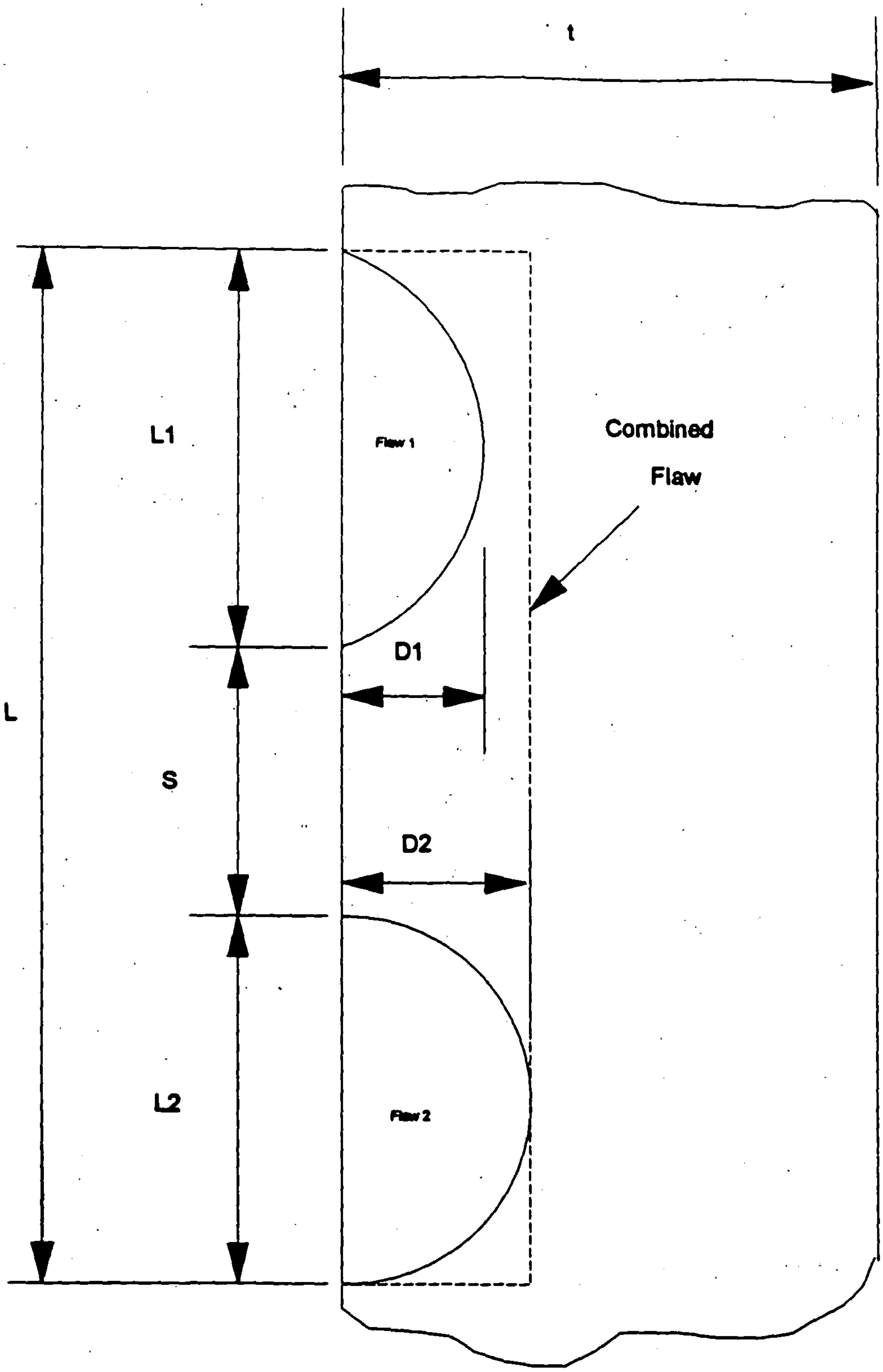


Figure 2-1: ASME Code Proximity Criteria

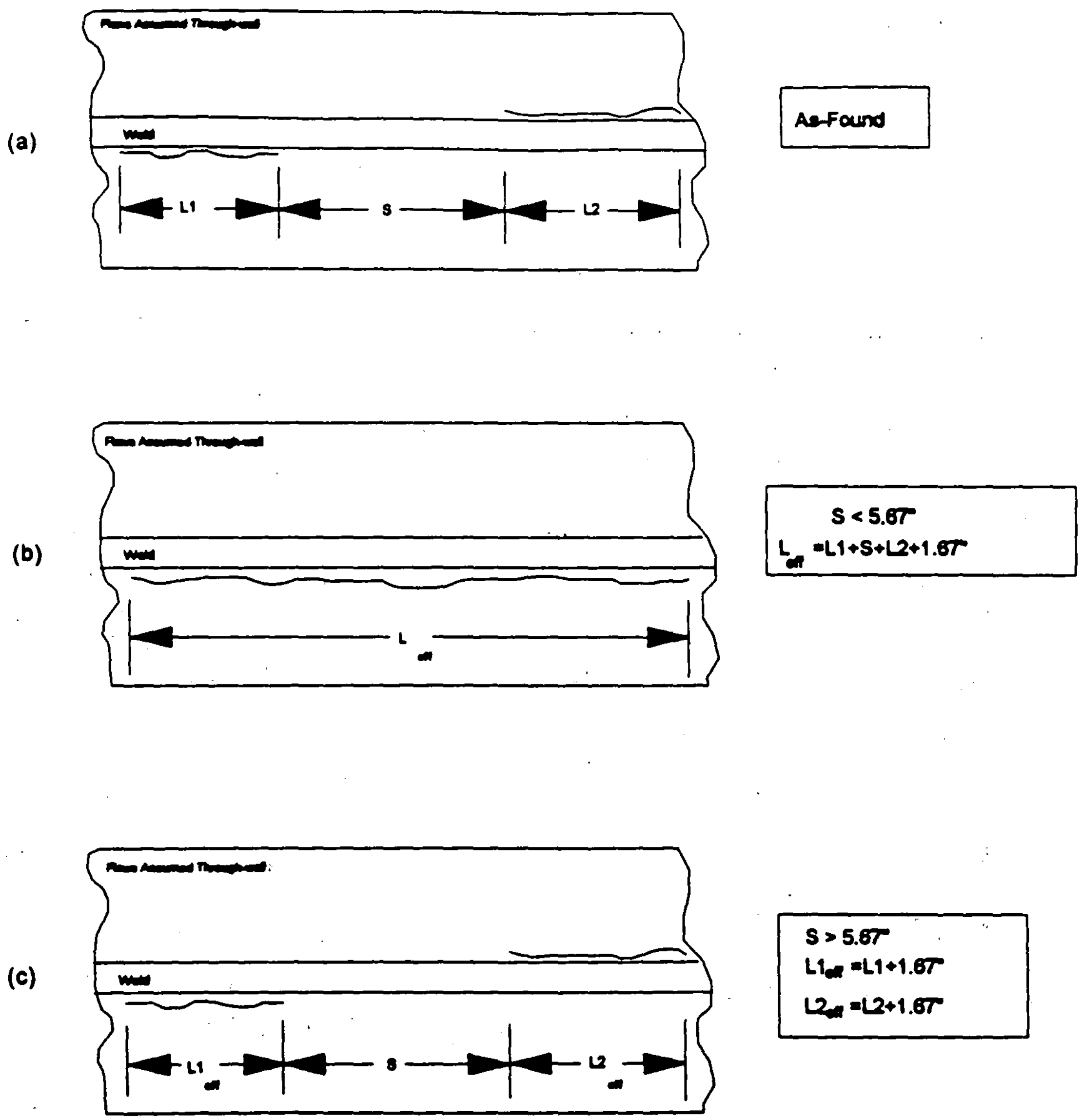


Figure 2-2: Application of Proximity Procedure to Neighboring Circumferential Flaws

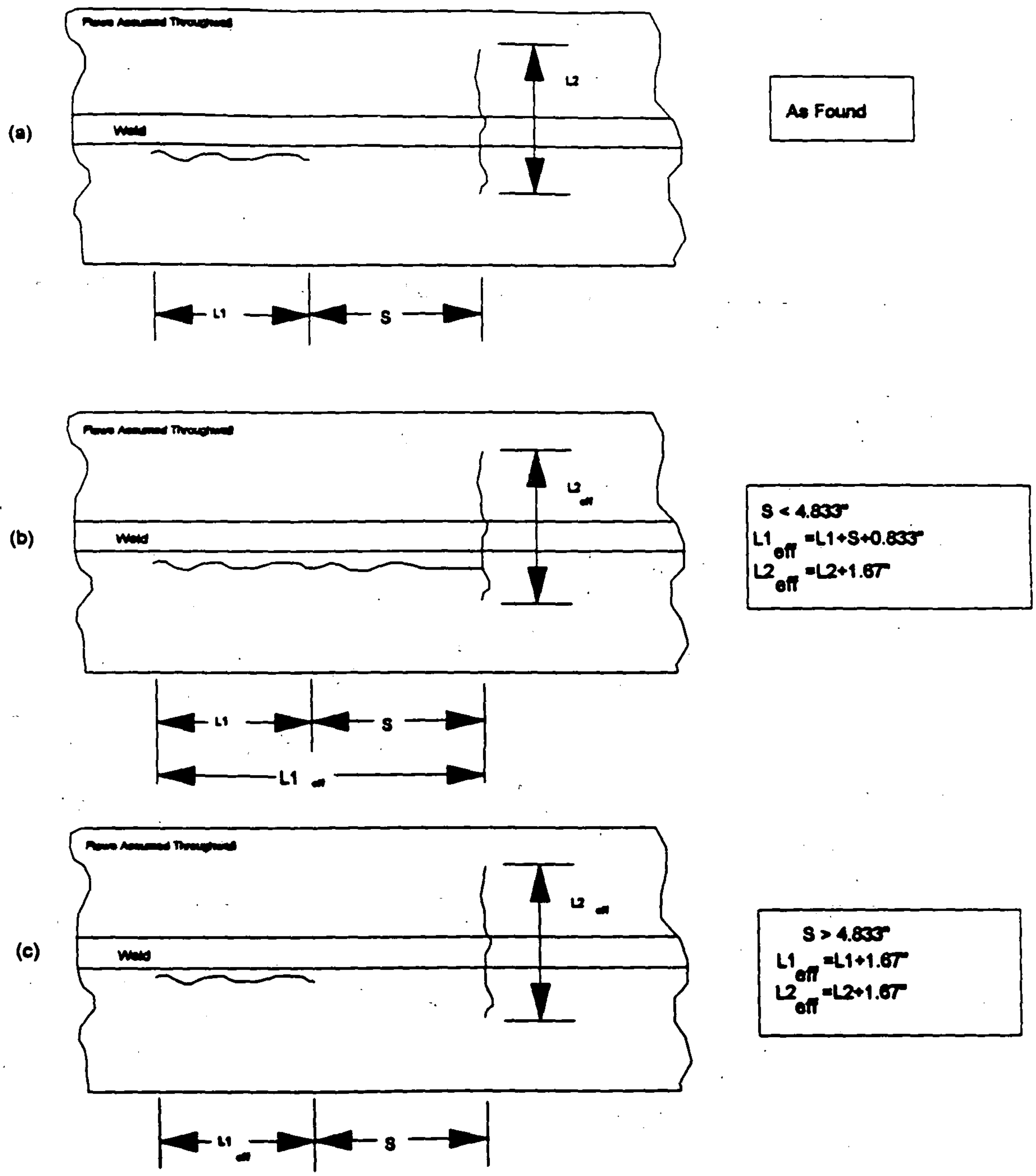


Figure 2-3: Application of Proximity Procedure to Neighboring Axial and Circumferential Flaws

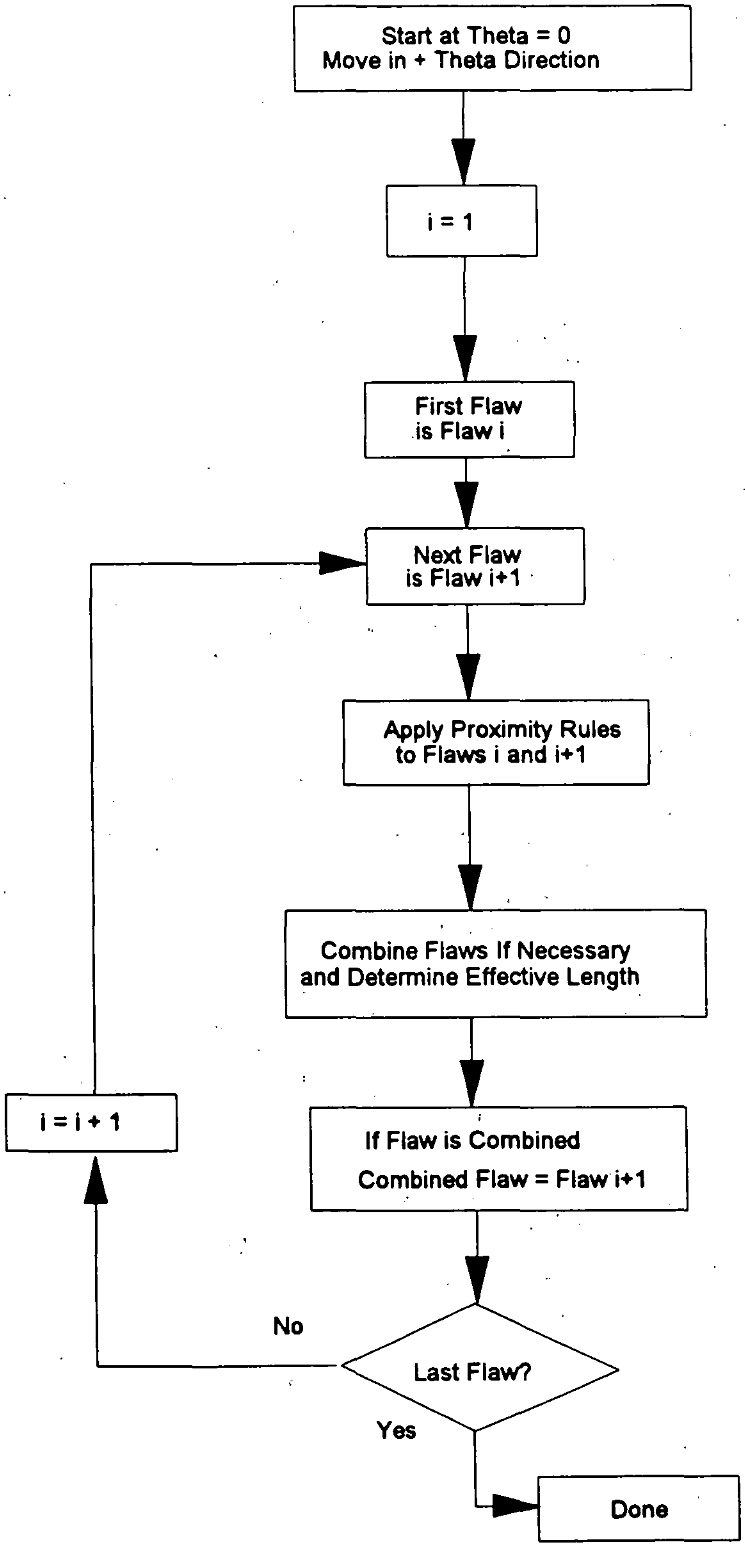


Figure 2-4: Process for Determining Effective Circumferential Flaw Length

3.0 STRUCTURAL ANALYSIS

The preceding section of this report described the determination of effective flaw lengths from the IVVI results. These effective flaw lengths have to be compared to the allowable flaw lengths to assess the structural integrity of the shroud. This section describes the details and the results of the structural analysis performed to determine the allowable flaw lengths. The structural analysis consists of two steps: (1) the determination of axial and circumferential stress magnitudes in the shroud, and (2) the calculation of the allowable flaw lengths. Both the fracture mechanics and limit load methods are used in the calculation of allowable flaw lengths.

3.1 Applied Loads and Calculated Stresses

The applied loads on the shroud consist of internal differential pressure, weight, and dynamic. The dynamic loads consist of a horizontal shear force and an overturning bending moment. The shear force acts in a direction which does not influence crack growth significantly, so it is not considered. The bending moment stress at a shroud cross-section varies as a function of its vertical distance from the top of the shroud. Because of the inherent ductility of the material (which will be discussed in Section 3.2 of this report), residual stresses and other secondary stresses do not affect structural margin. Thus, they need not be considered in the analysis.

The magnitudes of the applied loads were obtained from the dynamic stress analysis (Reference 3-1) and Final Safety Analysis Report (FSAR, Reference 3-2). The nominal shroud radius and thickness (Reference 3-3) were used to calculate the stresses from the applied loads. Stresses are calculated based on strength of materials formulas. Figure 3-1 shows the weld designation and relative locations in the shroud. Table 3-1 shows the calculated dynamic bending stress magnitudes for both the upset and faulted conditions. The appropriate pressure differences for the normal/upset and faulted conditions are shown in Table 3-2. Axial membrane stresses are calculated based on these pressure differences, as well as cumulative weight (Table 3-3), vertical seismic (0.067 g's OBE, 0.134 g's DBE), and buoyancy. Shear forces are given in Table 3-3, but, as mentioned above, are not used in the analysis.

Table 3-1: Dynamic Bending Stresses at Shroud Welds

Weld Designation	Moment, (in-kip) Upset	Moment, (in-kip) Faulted	Stress, (ksi) Upset	Stress, (ksi) Faulted
H1	3.24×10^3	6.48×10^3	0.04	0.09
H2	6.78×10^3	1.36×10^4	0.09	0.18
H3	7.22×10^3	1.44×10^4	0.11	0.22
H4	2.34×10^4	4.67×10^4	0.35	0.71
H5	4.01×10^4	8.02×10^4	0.61	1.21
H6	4.14×10^4	8.28×10^4	0.67	1.33
H7	6.03×10^4	1.21×10^5	0.97	1.94

Table 3-2: Pressure Differences

Component	Pressure Differences (psi) Normal/Upset Condition	Pressure Differences (psi) Faulted Condition
Shroud Head and Upper Shroud	7	12
Core Plate	17	20
Lower Shroud	25	30

Table 3-3: Shroud Weight and Seismic Shear Loads

Weld Designation	Effective Wt.* (kips) OBE	Effective Wt.* (kips) DBE	Shear (kips) OBE
H1	177.77	163.04	25
H2	201.10	184.43	186
H3	202.24	185.48	186
H4	259.06	237.59	193
H5	334.48	306.76	327
H6	336.02	308.18	327
H7	351.36	322.24	366

* These are cumulative weights, not lumped masses. Buoyancy and vertical seismic effects are included.

The structural analysis for the indications uses two methods; linear elastic fracture mechanics (LEFM) and limit load analysis. Both the limit load and the LEFM methods were used in determining the allowable flaw sizes in the shroud. Since the limit load is concerned with the gross failure of the section, the allowable flaw length based on this approach may be used for comparison with the sum of the effective flaw lengths, determined in Section 2.2, of all the flaws at a cross-section. On the other hand, the LEFM approach considers the flaw tip fracture toughness and thus, the allowable flaw length based on this approach may be used for comparison with the largest effective flaw length, determined in Section 2.2, at a cross-section. The fluence levels at welds H1, H2, H3, H6, and H7 are such that no significant embrittlement effects are expected. Therefore, only the limit load approach was used at these welds. The technical approach for the two methods is described next.

3.2 LEFM Analysis

The shroud material (austenitic stainless steel) is inherently ductile and it can be argued that the structural integrity analysis can be performed entirely on the basis of limit load. In fact, J-R curve measurements (Figure 3-2) made on a core shroud sample taken from an overseas plant having higher fluence ($8x10^{20}$ n/cm^2) showed stable crack extension and ductile failure. The ASME Code recognizes this fact in using only limit load techniques in Section XI, Subsubarticle IWB-3640 analysis. Nevertheless, a conservative fracture mechanics evaluation was performed using an equivalent K_{jc} corresponding to the material J_{Ic}. The K_{jc} for the overseas plant shroud was approximately $150 ksi\sqrt{in}$. Use of this equivalence is extremely conservative since:

i) The actual fluences for Dresden 2 and 3 are lower than that for the overseas plant from which J-R curves were obtained.

ii) The J-R curves show J_{max} values well above the J_{Ic}, confirming that there is load capability well beyond crack initiation (See Figure 3-2).

Also, K_{jc} is divided by ASME Code safety factor: 3.16 for normal and upset condition stresses, and 1.4 for faulted condition stresses. For the analysis presented here, the LEFM analysis is confined to welds H4 and H5. The fluence corresponding to welds at and below the core plate and above the top guide is an order of magnitude lower and the associated fracture toughness is comparable to that of the unirradiated material. For those locations, only the limit load analysis is used.

An additional consideration that applies only to the fracture mechanics analysis is the question, "When is a flaw independent of an adjacent flaw?" The ASME Code proximity rule described in Section 2 considers how flaws can link up and become a single flaw as a result of proximity. However, even when two flaws are separated by a ligament that exceeds 5.67 inches, they may not be considered totally independent of each other. That is, the flaw tip stress intensity factor may be affected by the presence of the adjacent flaw. This can be accounted for by using the finite width correction factor for a flaw in a finite plate. For a through-wall flaw in an "infinite" plate, the stress intensity factor is:

$$K = \sigma\sqrt{(\pi a)}$$

For a finite plate, the K value is higher as determined by the finite width correction factor, F. In this screening evaluation it is assumed that the plate is "infinite" if the correction factor F is less than 1.1. As seen in Figure 3-3, if the width of the plate exceeds 2.5(L1 + 1.67) (or a/b less than 0.4), then there would be no interaction due to plate end edge effects. If this same condition is applied to two neighboring flaws, then there will be no interaction between the two indications if the tips are at least 0.75(L1 + L2 + 3.33) apart. Thus, if the distance between indications is greater than 0.75(L1 + L2 + 3.33), then they may be considered as two separate flaws. If however, they are closer, for the purpose of fracture analysis, the equivalent flaw length is the sum of the two individual flaws including crack growth. Alternately, the precise equations using specific assumed flaw lengths and actual applied stresses may be compared to the appropriate allowables to account for interaction.

3.3 Limit Load Analysis

A through-wall circumferential flaw was assumed in this calculation. Limit load calculations were conducted using the approach outlined in Subsubarticle IWB-3640 and Appendix C of Section XI of the ASME Code. The flow stress was taken as $3S_m$. The S_m value for the shroud material (Type 304 stainless steel) is 16.9 ksi at the approximate normal operating temperature of 550°F.

Safety factors from the ASME Code (for circumferential flaws - 2.8 for normal and upset and 1.4 for emergency and faulted, and for axial flaws - 3.0 for normal and upset and 1.5 for emergency and faulted) were used in the analysis. Separate criteria are prepared for each weld, based on location-specific stresses.

3.4 Shroud Thickness Considerations

A shroud thickness of 2.0 inches was used in developing the screening criteria. However, there are locations in the shroud with wall thickness greater than 2.0 inches. Therefore, it must be determined if the use of 2.0 inches is applicable to all other shroud locations.

The screening criteria based on the 2.0 inches thickness is considered applicable to locations of greater thickness since stresses were determined based on the 2.0 inch thickness. This results in conservative stress values when applied to locations with thickness greater than 2.0 inches, such as the weld between the 2.0 inch shroud cylinder and 2.5 inch top guide support ring.

3.5 References

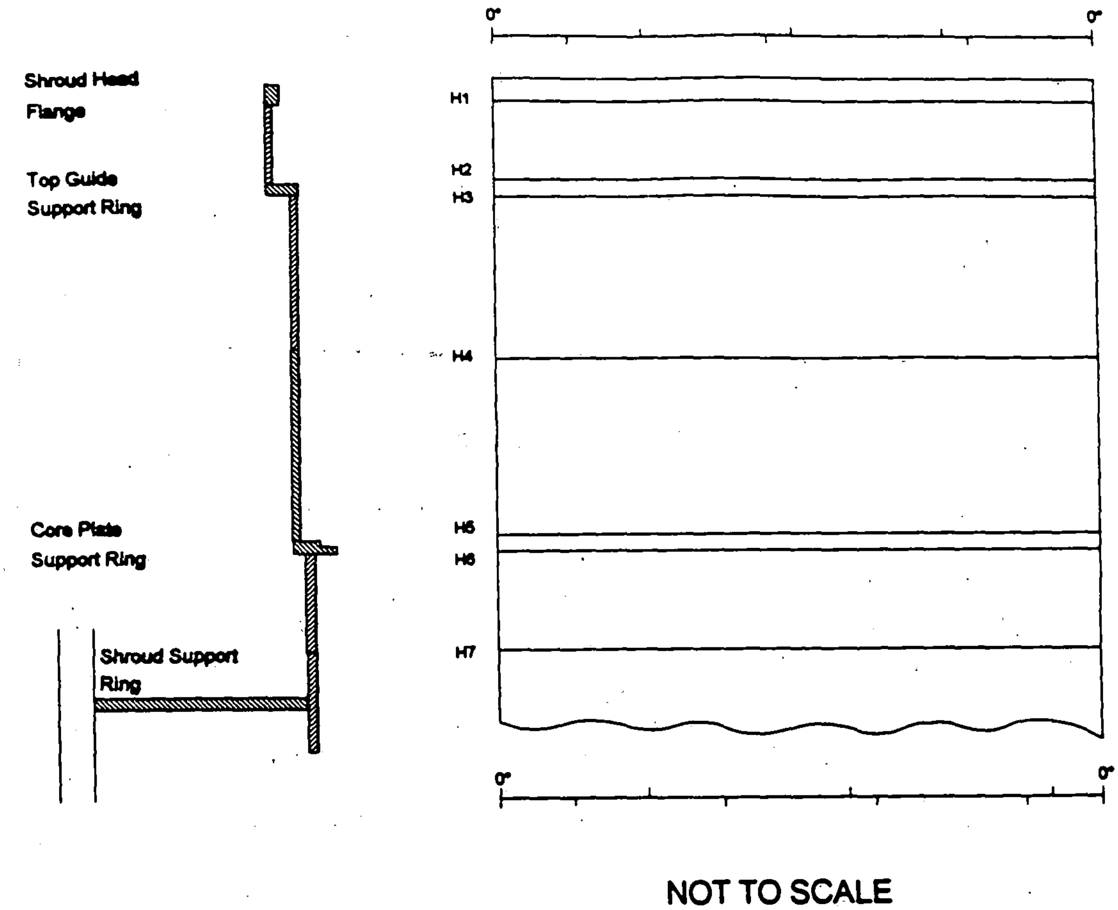
3-1. Letter WFW9408 Rev. 1, from W. F. Weitze (GE) to Hien Do (CECo) dated February 17, 1994, "Shroud Seismic Loads for Dresden and Quad Cities."

3-2. Dresden 2 and 3 Final Safety Analysis Report (FSAR).

3-3. **GE Drawings:**

a. 718E861, Rev. 6, "Shroud - Spec. Control," Part 1, GE-NED, San Jose, CA.

b. 885D660, Rev. 6, "Reactor Vessel - Spec. Control," Part 1, GE-APED, San Jose, CA.



Note: Vertical weld locations are not shown for clarity.

Figure 3-1: Sketch Showing Circumferential Welds in the Core Shroud

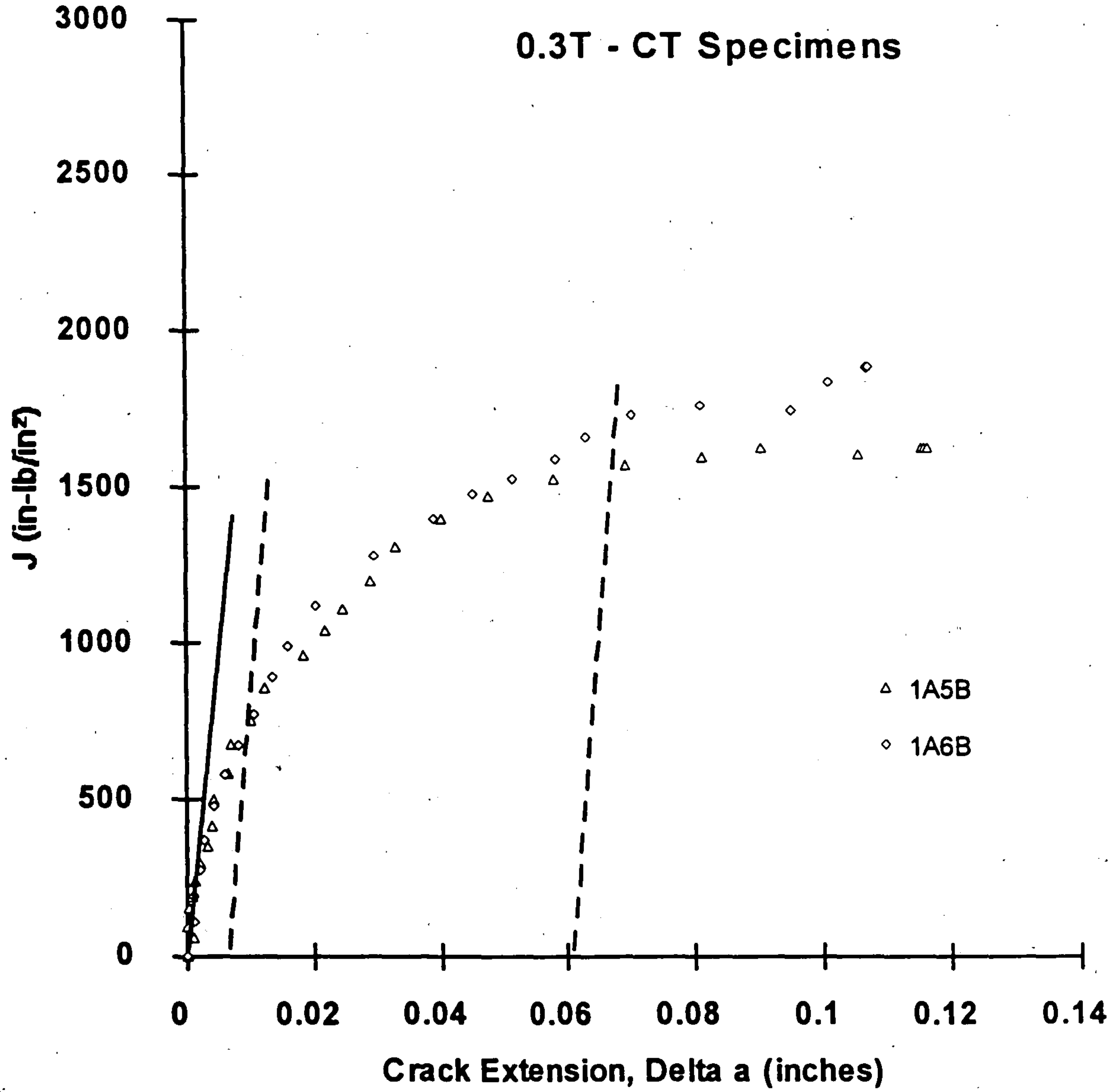
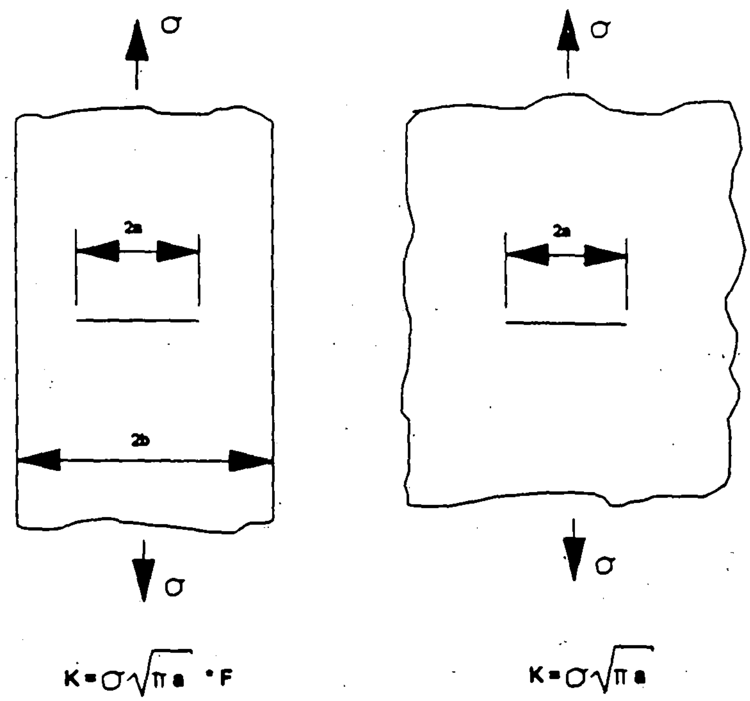


Figure 3-2: Comparison of J-R Curves Developed for Two Irradiated Stainless Steel Specimens



a/b	F
0.0	1.0
0.1	1.006
0.2	1.0246
0.3	1.0577
0.4	1.1094
0.5	1.1867

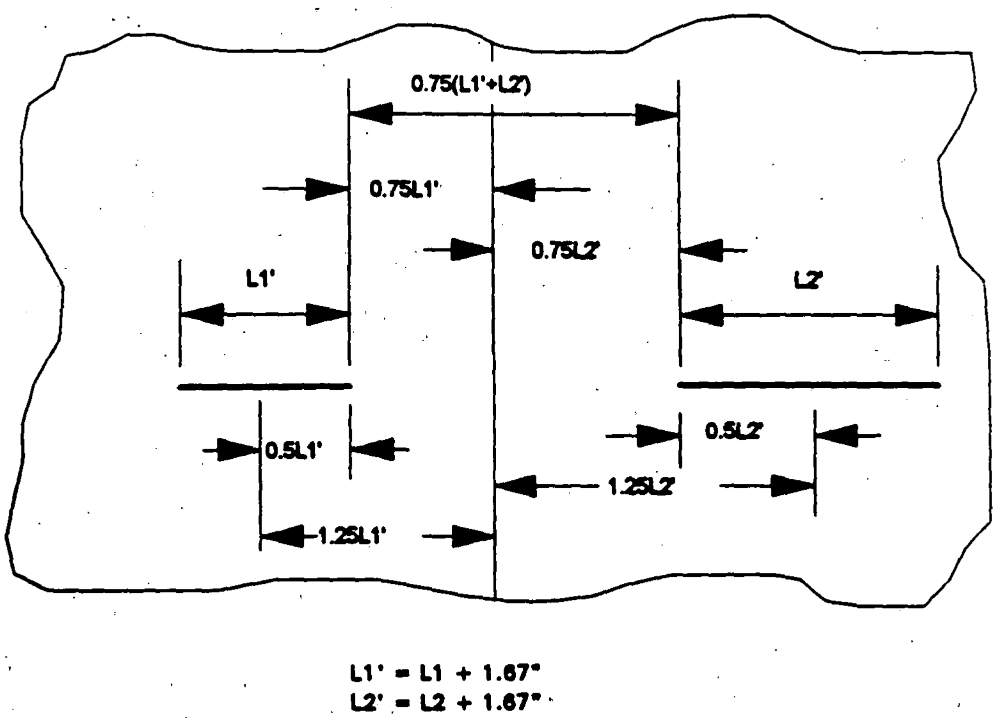


Figure 3-3: Schematic Illustrating Flaw Interaction

4.0 ALLOWABLE THROUGH-WALL FLAWS

Allowable through-wall flaw sizes were determined using both fracture mechanics and limit load techniques for both circumferential and axial flaws. It should be emphasized that the allowable through-wall flaws are based on many conservative assumptions and are intended for use only in the screening criteria. More detailed analysis can be performed to justify larger flaws (both through-wall or part-through when measured flaw depths are available). However, since the intent of the screening criteria is to determine when additional evaluation or NDE characterization is needed, a conservative bounding approach is utilized.

4.1 Allowable Through-Wall Circumferential Flaw Size

Both the LEFM and limit load methods were used to evaluate the allowable through-wall flaws. At welds H4 and H5, LEFM and limit load analysis methods were used, and the limiting locations for through-wall cracking occurred at the H5 weld. For the limit load analysis, the governing case is the H7 weld location where the pressure and dynamic stresses are high.

4.1.1 LEFM Analysis

The total axial weight, pressure, and dynamic stresses are 0.35 ksi (weld H4) and 0.61 ksi (weld H5) for the upset condition and 0.83 ksi (weld H4) and 1.28 ksi (weld H5) for the faulted condition. Using the ASME Code safety factors for fracture analysis (3.16 for normal and upset and 1.4 for faulted), the faulted condition is limiting for H4 and upset is limiting for H5.

To determine the allowable flaw size based on LEFM methods, the conservatively estimated irradiated material fracture toughness K_{Ic} value of $150 ksi\sqrt{in}$ was used. Applying a safety factor of 1.4 for the faulted condition, the allowable K_I of $\sim 107 ksi\sqrt{in}$ was obtained. The allowable flaw size was calculated using the following equation:

$$K_I = G_m \sigma \sqrt{(\pi a)}$$

where G_m is a curvature correction factor as defined in (Reference 4-1), σ is the axial membrane stress, and 'a' is the half flaw length. The bending correction factor G_b, which varies through the wall from a positive to a negative value, and has an average of zero, was not used since the objective is to obtain the average K_I through the thickness. The allowable through-wall circumferential flaw length (2a) was determined as ≅ 489 inches for H4 and 326 inches for H5.

4.1.2 Limit Load Analysis

A through-wall circumferential flaw was assumed in this calculation. The limit load calculations were conducted using the approach outlined in Subsubarticle IWB-3640 and Appendix C of Section XI of the ASME Code. The flow stress was taken as $3S_m$. The S_m value for the shroud material is 16.9 ksi at the approximate normal operating temperature of 550°F.

The stresses and allowable flaw length for the limit load analysis are shown in the table below. The allowable flaw length is based on the faulted condition, which was found to be limiting for each weld, and includes the ASME Code, Section XI safety factors.

Table 4-1: Stresses and Allowable Flaw Lengths at Shroud Welds

Weld	Axial Force Stress (ksi)		Bending Moment Stress (ksi)		Allowable Flaw
	Upset	Faulted	Upset	Faulted	Length (in)
H1	0.06	0.21	0.04	0.09	571
H2	0.04	0.19	0.09	0.18	565
H3	0.02	0.16	0.11	0.22	532
H4	0.00*	0.12	0.35	0.71	505
H5	0.00*	0.07	0.61	1.21	484
H6	0.10	0.29	0.67	1.33	453
H7	0.09	0.27	0.97	1.94	435

* The calculated values are negative and, therefore, conservatively assumed to be zero for allowable flaw calculations.

4.2 Allowable Axial Flaw Size

4.2.1 LEFM Analysis

The allowable axial flaw size is governed entirely by the pressure hoop stress. As with the circumferential flaw case, the allowable axial flaw size was determined assuming a through-wall flaw. For a through-wall flaw of length 2a in the shroud, the applied stress intensity factor is given by:

$$K = M * \sigma_h * \sqrt{\pi a}$$

where M is the curvature correction factor given by:

$$M = [1 + 1.61a^2/(Rt)]^{0.5} \qquad \text{(from Reference 4-2)}$$

In the above expression, the allowable flaw length 2a can be determined by equating the calculated K to the fracture toughness of $150 \text{ksi}\sqrt{\text{in}}$. The hoop stress for the upset condition is 0.36 ksi; the ASME safety factor of 3.16 is applied and the result is used in the previous equation.

The allowable flaw length was conservatively determined to be 2a = 176 inches above the core plate.

4.2.2 Limit Load

An alternate approach to determining the allowable flaw size is to use limit load techniques. The allowable flaw length is given by the equation:

$$\sigma_h = \sigma_f / (M * SF)$$

where M is a curvature correction factor as defined above, $\sigma_f = 3S_m$ is the flow stress, SF is the safety factor of 3.0 for upset conditions, and σ_h = the hoop stress corresponding to the upset ΔP of 7 psi above the core plate and 25 psi below the core plate. The allowable flaw length based on the limit load analysis is 1010 inches above the core plate (using the limiting shroud diameter at welds H1 and H2) and 294 inches below the core plate. Since the value above the core plate exceeds the LEFM value, the allowable axial through-wall flaw length is 176 inches between H3 and H5.

4.3 References

4-1. Rooke, D.P. and Cartwright, D.J., "Compendium of Stress Intensity Factors," The Hillingdon Press (1976).

4-2. Ranganath, S., Mehta, H.S. and Norris, D.M., "Structural Evaluation of Flaws in Power Plant Piping," ASME PVP Volume No. 94 (1984).

5.0 SCREENING CRITERIA

The determination of the allowable through-wall flaws has been described in Section 4. The objective was to use the allowable flaw size as the basis for the screening criteria. Since the screening rules represent the first step in the evaluation, they are by definition conservative. If the criteria are exceeded, the option of doing further detailed evaluation or performing additional NDE remains. The allowable through-wall flaws were:

- Circumferential Flaws
  - H1: 571 inches (limit load only)
  - H2: 565 inches (limit load only)
  - H3: 532 inches (limit load only)
  - H4: 505 inches (limit load), 489 inches (LEFM)
  - H5: 484 inches (limit load), 326 inches (LEFM)
  - H6: 453 inches (limit load only)
  - H7: 435 inches (limit load only)

- Axial Flaws
  - Above Core Plate: 1010 inches (limit load), 176 inches (LEFM)
  - Below Core Plate: 294 inches (limit load)

A conservative approach in developing the screening rule is to include both the LEFM and limit load analysis. For circumferential flaws, LEFM provides the limit on an **effective single flaw length** for H4 and H5, while the limit load analysis provides the limit on **effective cumulative flaw length**. For axial flaws, the allowable flaw length is 1010 inches between H1 and H3, 176 inches between H3 and H5 (LEFM), and 294 inches below the core plate (limit load).

For circumferential flaws at welds H4 and H5, the limits are applied as follows. At weld H5, for example, the fracture mechanics based limit for a single effective flaw length, as determined in Section 2.2, is 326 inches. This in itself is not sufficient, since there could be several flaws (each less than 326 inches) in a circumferential plane that cumulatively add up to greater than 484 inches (the allowable circumferential flaw size based on limit load analysis). Thus, the sum of the effective flaw lengths, as determined in Section 2.2, should be less than 484 inches.

When considering LEFM based evaluations, the crack interaction criteria described in Section 3.2 must be applied in comparing against the allowable lengths. For example, for adjacent flaws where the spacing, S, is less than 0.75 (L1 + L2 + 3.33), the length L = L1' + L2' is used for comparison with the LEFM based allowable flaw length. The lengths L1' and L2' are as determined in Figure 3-3.

The criteria presented in this report are conservative in that continuous flaws (for limit load) were assumed. Additional analysis assuming the flaws are non-continuous (that is, distributed around the circumference of the shroud) or part-through wall will yield larger cumulative flaw lengths.