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Evaluation and Screening Criteria for the Brunswick 1 Shroud Indications

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1.0 INTRODUCTION

Indications have been discovered in the Brunswick Unit 1 shroud as a result of in-vessel visual inspection (IVVI) performed recently. Since they were 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 the 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 (1986 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 axial flaw would be compared against the allowable axial flaw length.

Flaws are considered in the same plane if the perpendicular distance between the planes is 3" 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 H8 welds). Therefore, the screening criteria developed here cover all shroud weld indications. A list of conservatisms used in this evaluation is summarized in Table 1-1.

Table 1-1 Conservatisms Included In Screening Evaluation

1. All surface indications were assumed to be through-wall for analysis.

2. The highest stress computed for any single location was used for all locations.

3. The highest seismic moment computed for any single location, as applicable, was used for corresponding locations.

4. The bounding crack growth estimated for the next fuel cycle was included in flaw lengths used for evaluation.

5. ASME Code primary pressure boundary safety margins were applied even though the shroud is not a primary pressure boundary.

6. ASME Code, Section XI proximity rules were applied.

7. A proximity rule to account for perpendicular flaws was applied, although not required by Section XI.

8. An additional proximity rule which accounts for fracture mechanics interaction between adjacent flaws was used.

9. Fracture toughness measured for similar materials having a higher fluence was used (fluence comparable to end-of-life prediction).

10. Both LEFM and limit load analysis were applied, even though LEFM underestimates allowable flaw size, and is not required for austenitic materials.

11. The screening criteria limit one-fourth of allowable circumferential flaws to any arbitrary 90° sector.

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 3". 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 <3") 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 0.6 in. for 12,000 hours or one fuel cycle. 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 0.6 + 2 x shroud thickness). For a shroud thickness of 1.5 in., this bounding ligament is 4.2 in. Thus, if the ligament is less than 4.2 inches, the effective length is (L1+L2+S+1.2"). Note that the addition of 1.2 in. is to include crack growth at the other (non-adjacent) end of each flaw (See Figure 2-2).

If the ligament is greater than 4.2 in., then the effective flaw length is determined by adding the projected tip growth to each end of the flaw. For this example, $L1_{eff} = L1 + 1.2"$ and $L2_{eff} = L2 + 1.2"$.

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 3.6 inches, then the effective flaw length for the circumferential flaw is $L_{eff} = L1+S+0.6"$ (the bounding

ligament for these cases). If the ligament is greater than 3.6 in., 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.

In order 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 Crack

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 4.2", the indications must be combined such that the effective [illegible] (See Figure 2-2b):

$$L_{eff} = L1 + S + L2 + 1.2"$$

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 4.2", the effective flaw lengths are (See Figure 2-2c):

$$L1_{eff} = L1 + 1.2"$$
$$L2_{eff} = L2 + 1.2"$$

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 3.6", then the effective circumferential flaw length is (See Figure 2-3b):

$$L_{eff} = L1 + S + 0.6"$$

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

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

$$L_{eff} = L2 + 1.2"$$

where: L2 = length of axial indication

If the distance between the circumferential indication tip to the axial indication is greater than 3.6", then the flaws are not combined (See Figure 2-3c) and the effective lengths are:

$L1_{eff} = L1 + 1.2"$ (for circumferential flaw)
$L2_{eff} = L2 + 1.2"$ (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). Old indication 2 becomes new indication 1.
- Continue along positive azimuthal direction until the next indication is encountered. This becomes new indication 2.
- Apply proximity rules to new indications 1 and 2.
- Continue proximity rule evaluation until all indications along the subject weld or plane have been considered.

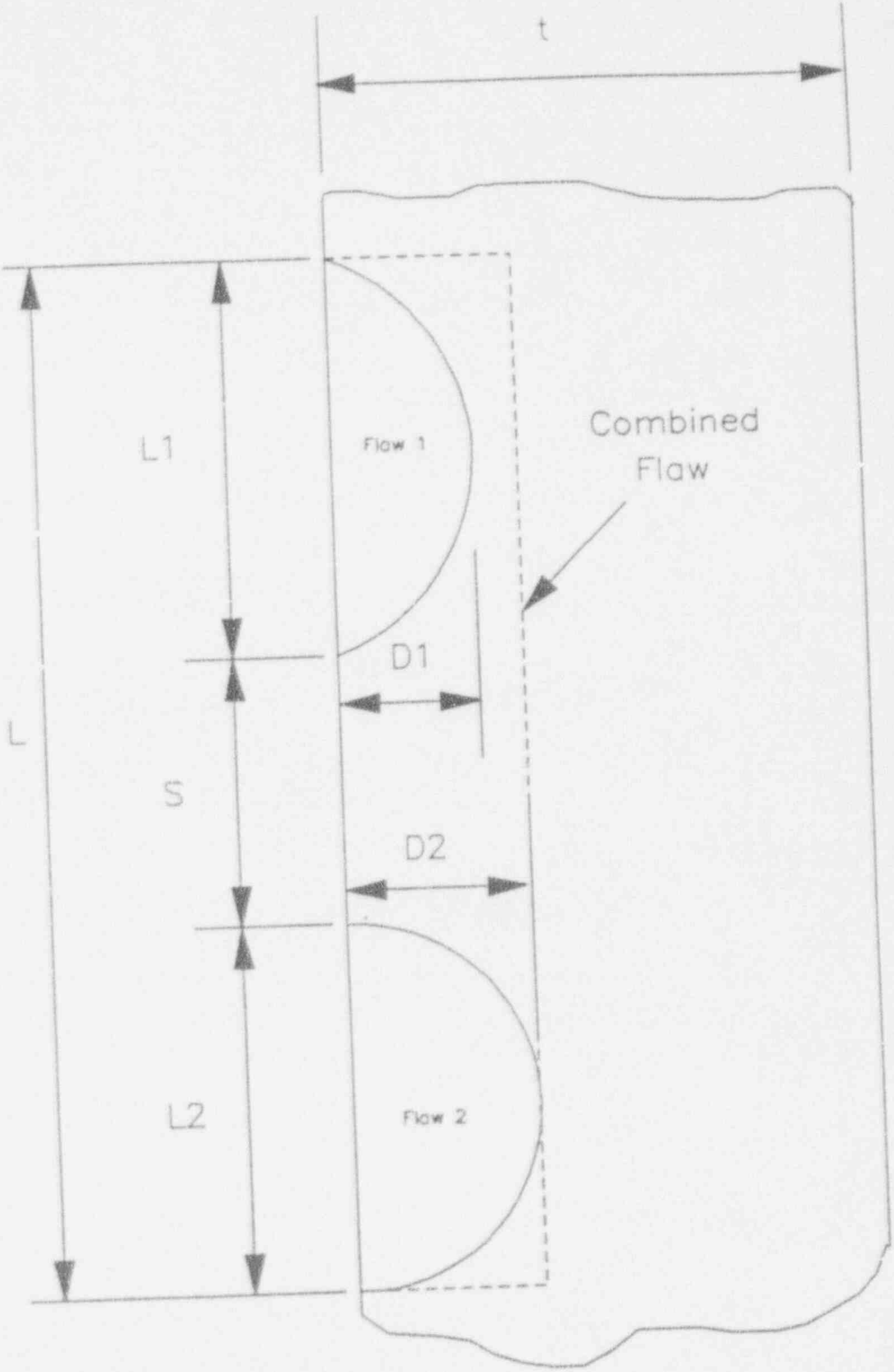

Figure 2–1 – ASME Code Proximity Criteria

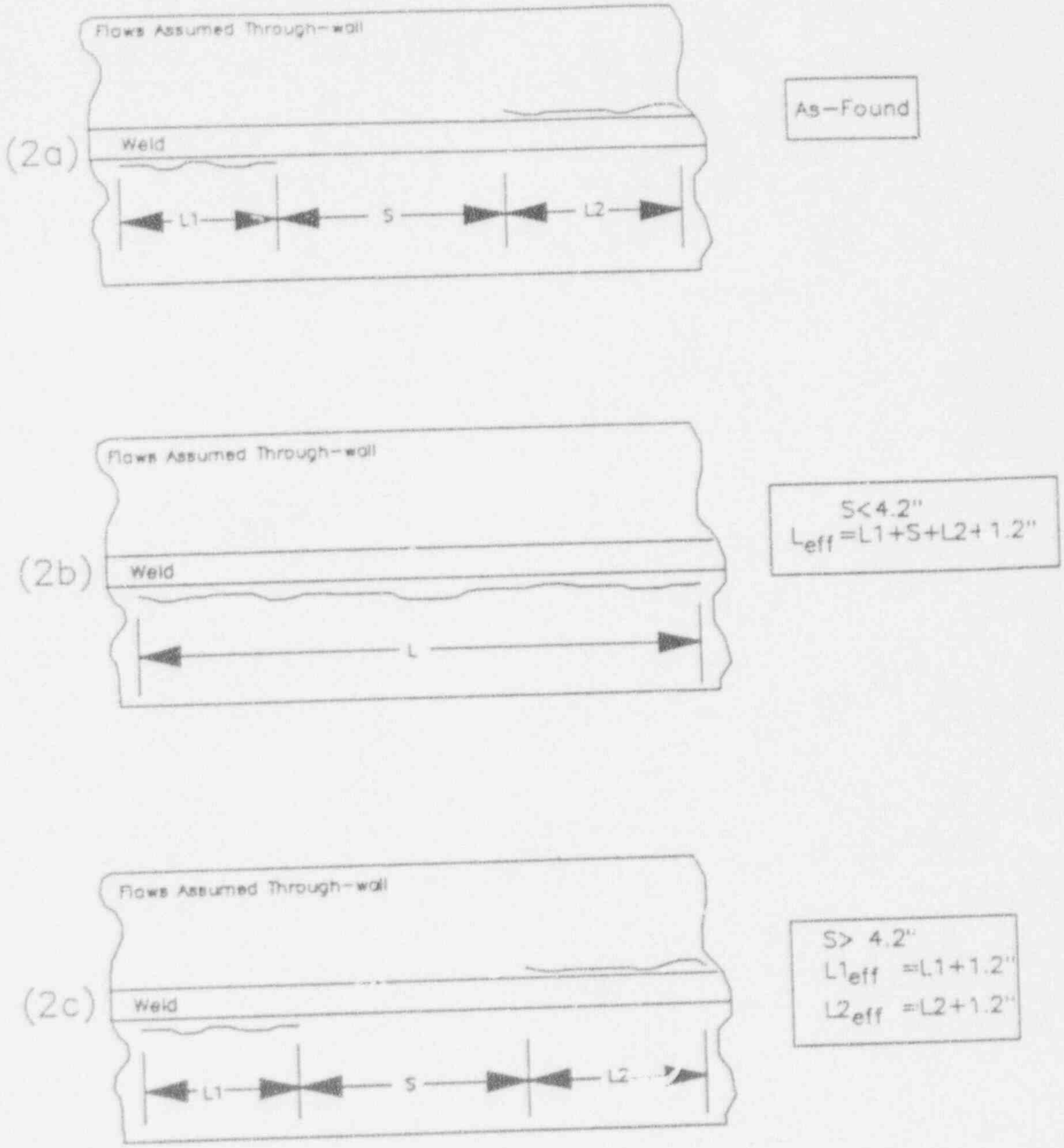

Figure 2-2 - APPLICATION OF PROXIMITY PROCEDURE TO NEIGHBORING CIRCUMFERENTIAL FLAWS

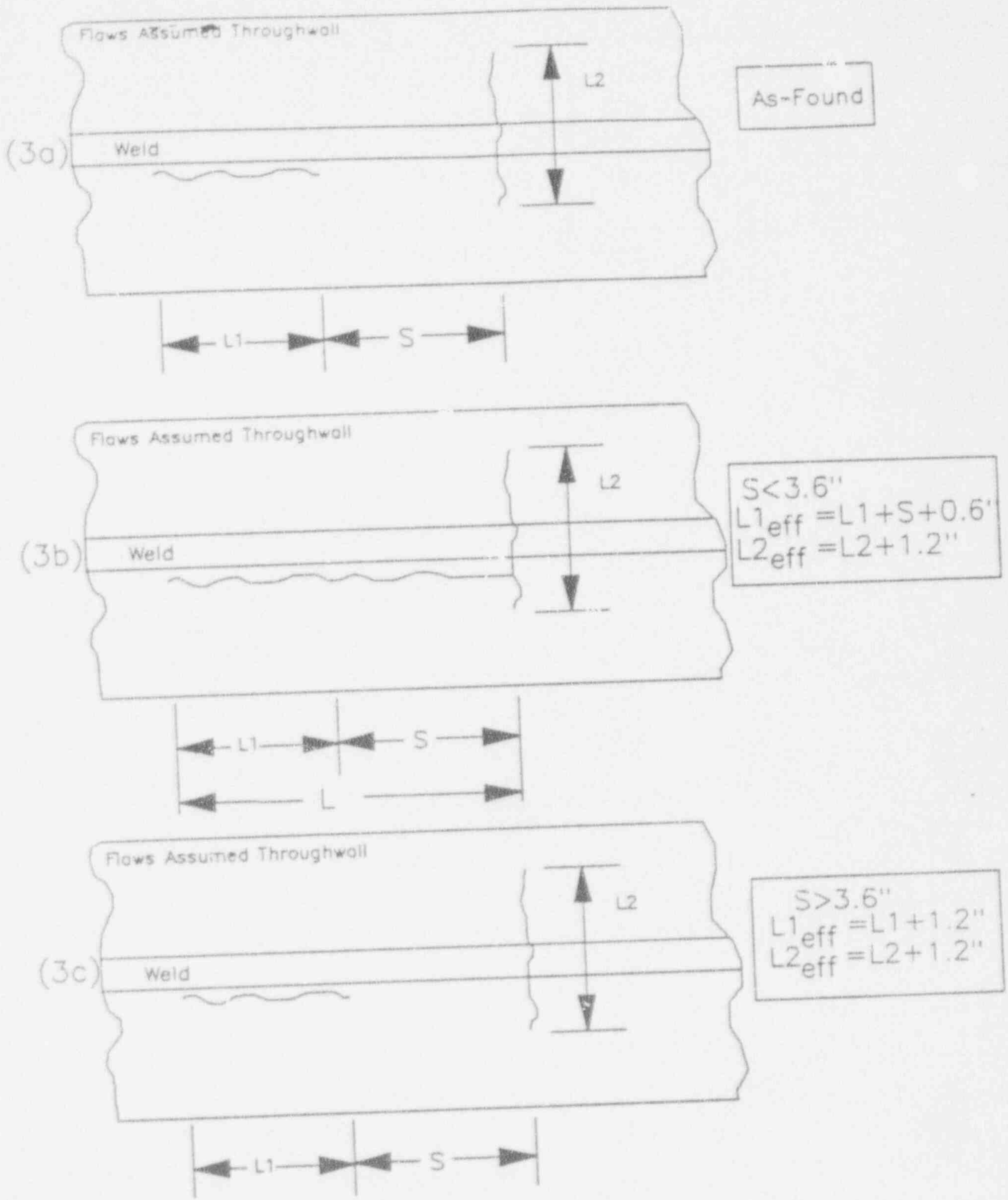

Figure 2–3 – APPLICATION OF PROXIMITY PROCEDURE TO NEIGHBORING AXIAL AND CIRCUMFERENTIAL FLAWS

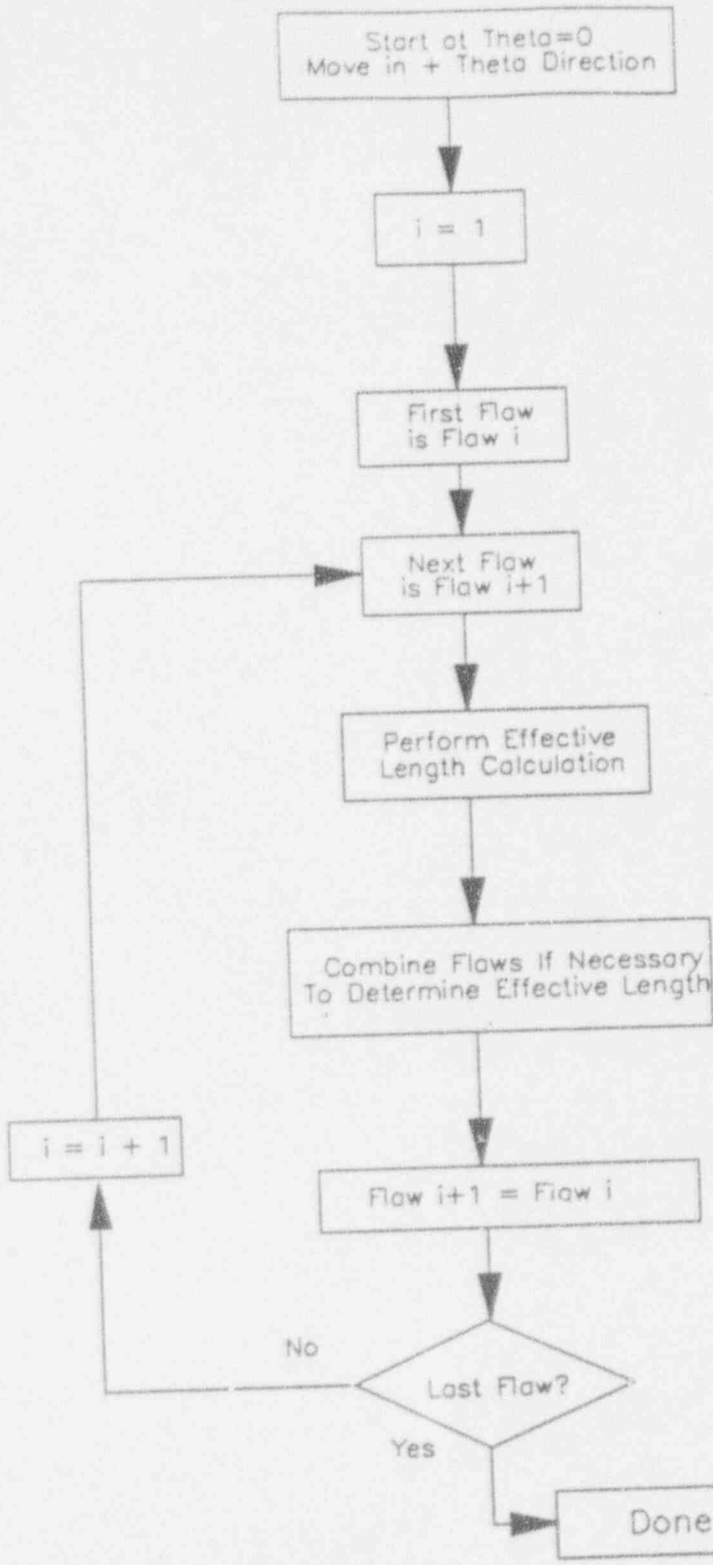

Figure 2-4 – PROCESS FOR DETERMINING EFFECTIVE CIRCUMFERENTIAL FLAW LENGTH

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: the determination of axial and circumferential stress magnitudes in the shroud, and 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 seismic. The seismic loads consist of a horizontal shear force at the top of the shroud and an overturning bending moment. The shear force produces a shear stress of insignificant magnitude, and 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 seismic stress analysis and system information reports. The nominal shroud radius and thickness (1.5 in.) were used to calculate the stresses from the applied loads. The stresses are essentially based on the strength of materials formulas. Since the bending stress due to seismic shear force varies with the elevation of a location, two conservative values of this stress were calculated: one applicable to shroud sections above the core plate and the other for sections below the core plate. Figure 3-1 shows the weld designation and relative locations in the shroud.

Table 3-1 shows the calculated seismic stress magnitudes for both the upset (Operating Basis Earthquake - OBE) and faulted conditions (Design Basis Earthquake - DBE). The appropriate pressure differences for the normal and faulted conditions are shown in Table 3-2.

Table 3-1 Seismic Axial Stresses at Shroud Welds

Weld Designation	DBE Moment (in-lb)	Stress (ksi)	
		DBE	OBE
H1	$27x10^6$	0.65	0.36
H2	$36x10^6$	0.87	0.48
H3	$38x10^6$	1.04	0.58
H4	$58x10^6$	1.59	0.88
H5	$110x10^6$	3.01	1.67
H6A	$134x10^6$	3.67	2.04
H6B	$138x10^6$	3.78	2.10
H7	$181x10^6$	5.34	2.97
H8	$202x10^6$	4.50	2.50

Table 3-2 Pressure Differences

Component	Pressure Differences (psi)	
	Normal Condition	Faulted Condition
Shroud Head and Upper Shroud	7.9	29.0
Core Plate Support Ring and Lower Shroud	27.7	48.0

The structural analysis for the indications uses two methods; linear elastic fracture mechanics 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 lengths 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 at a cross-section. The technical approach for the two methods is described below.

3.2 Fracture Mechanics 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√in. Use of this equivalence is extremely conservative since:

i) The actual fluence for Brunswick Unit 1 is much 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).

Using the ASME Code safety factor of 3, which is applicable for normal and upset conditions of pressure boundary components, the allowable K_{Ic} value becomes 50 ksi√in. For the analysis presented here, the LEFM analysis is confined to the H5 weld and above. The fluence corresponding to welds at and below the core plate elevation is an order of magnitude lower and the associated fracture toughness is comparable to that of the unirradiated material. For those locations, 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 4.2 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 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 2.5L (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) apart. If the distance

between indications is greater than 0.75(L1+L2), 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.

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 normal operating temperature of 550°F.

Safety factors similar to those used in the ASME Code (2.8 for normal and upset and 1.4 for emergency and faulted) were used in the analysis. The highest seismic stress was used for the limit load calculations and is shown in Table 3-1. Similarly, the highest axial pressure stress corresponding to the lower shroud was used. Thus, the analytical results are applicable for all welds since limiting values are used.

3.4 Shroud Thickness Considerations

A shroud thickness of 1.5" was used in developing the screening criteria. However, there are locations in the shroud with wall thickness greater than 1.5". Therefore, it must be determined if the use of 1.5" is applicable to all other shroud locations.

The screening criteria based on the 1.5" thickness is considered applicable to locations of greater thickness since stresses were determined based on the 1.5" thickness. This results in conservative stress values when applied to locations with thickness greater than 1.5", such as the weld between the 1.5" shroud cylinder and 3" top guide support ring.

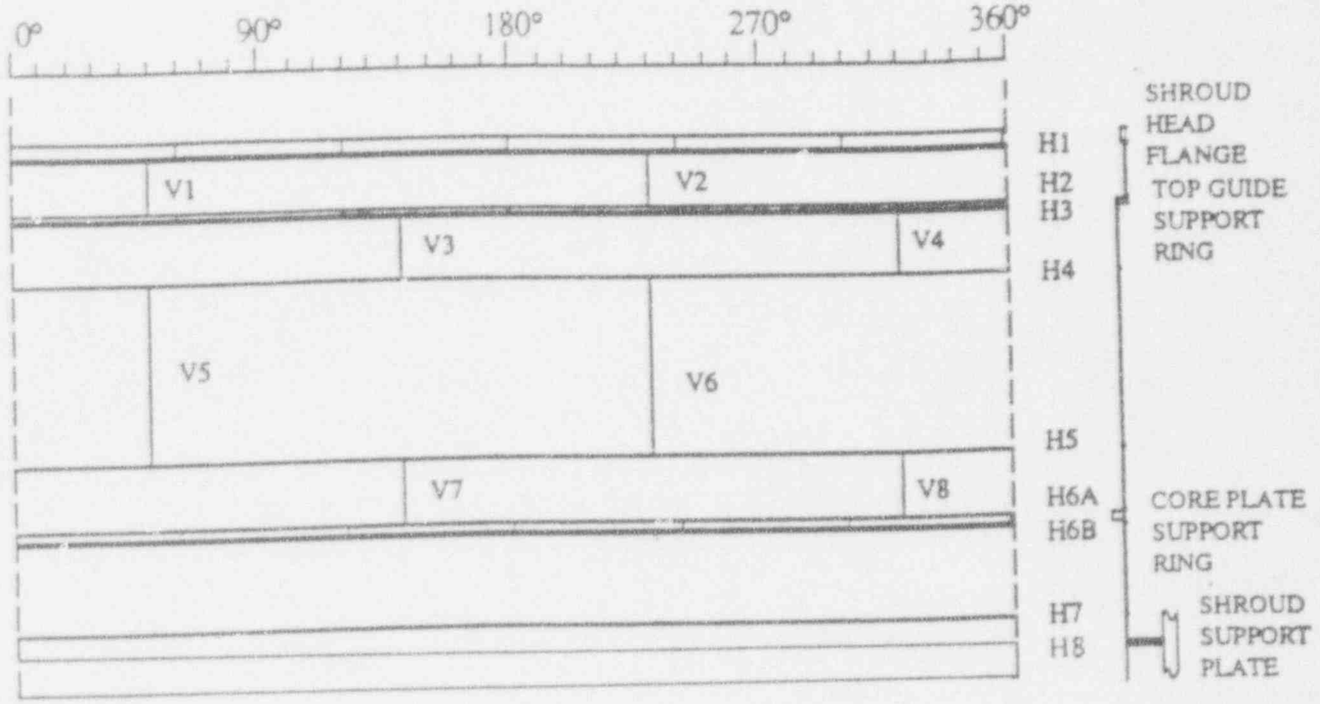

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Figure 3-1. Sketch Showing typical Welds in the Core Shroud

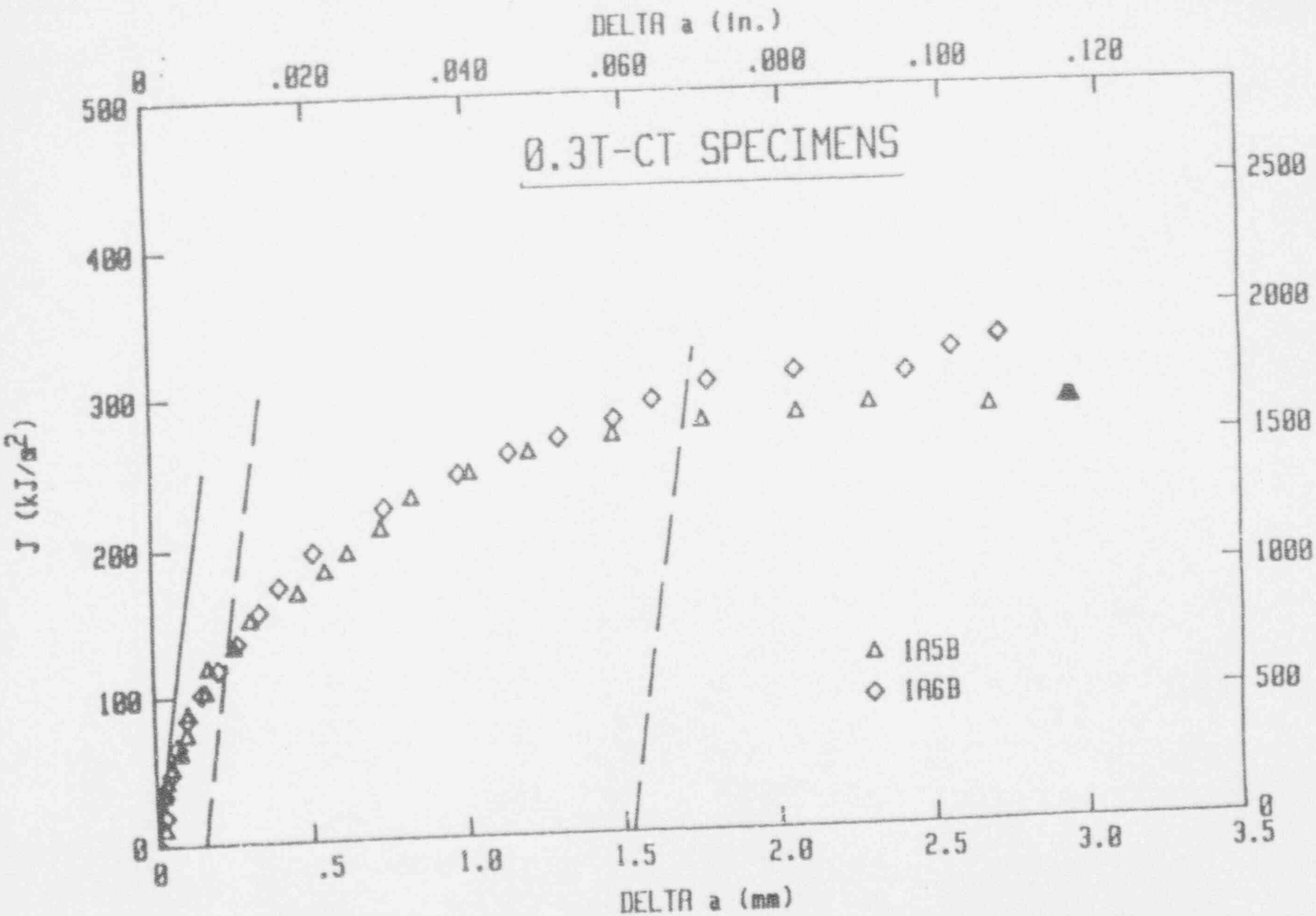
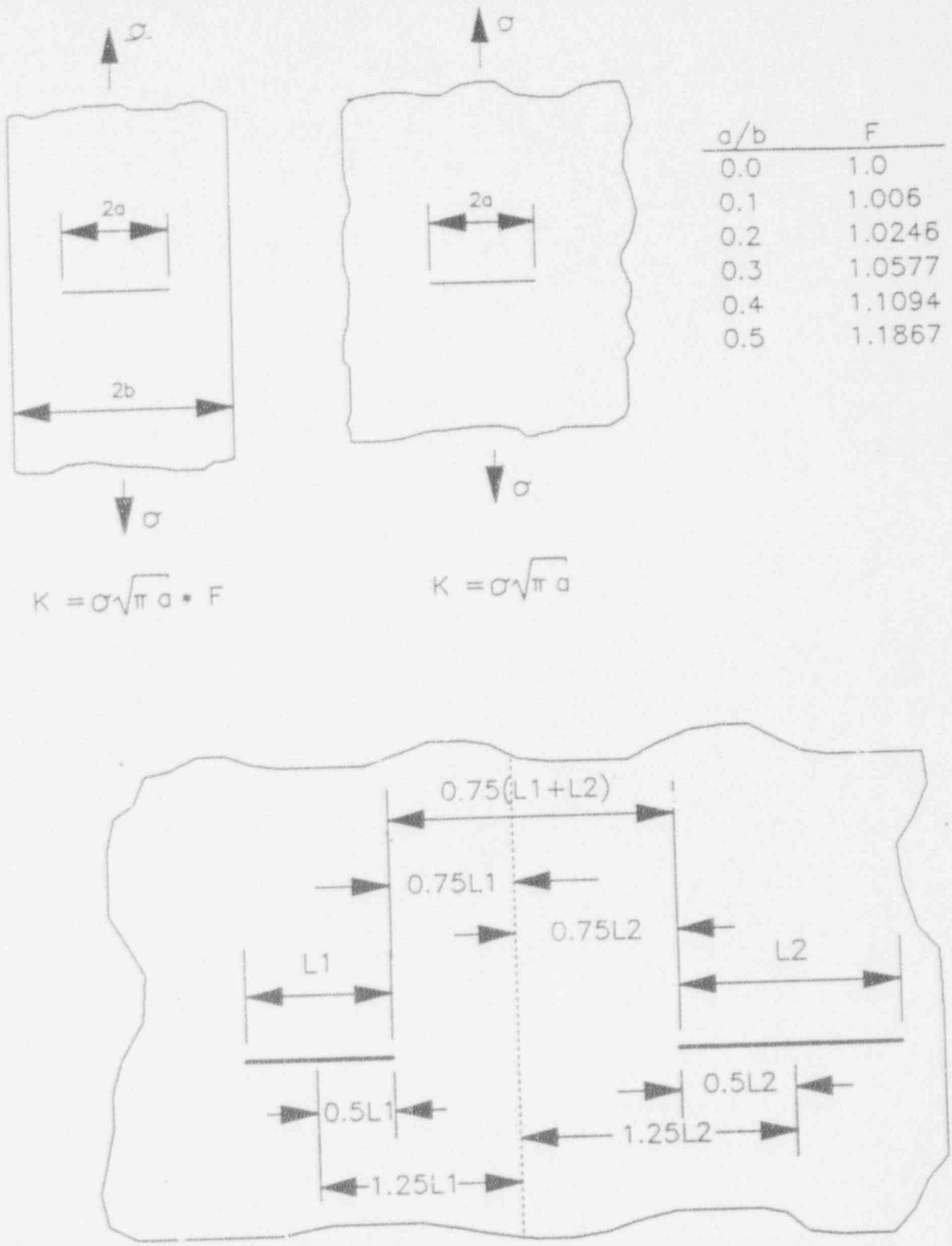


Figure 3-2. Comparison of J-R curves developed for two irradiated stainless steel specimens.



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 (e.g. using the limiting stress for all welds) 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. Above the core plate, LEFM and limit load analysis methods were used, with the limiting location for through-wall cracking at the H5 weld (with the combination of the highest fluence and seismic stress). For the limit load analysis (i.e., low fluence levels), the governing case is the H7 weld where the pressure and seismic stresses are highest. The H8 weld has higher seismic moments but since the thickness is greater, the H7 weld is still the limiting case. Furthermore, the H8 weld involves Alloy 600 which has higher S_m values and therefore has higher limit load capability.

4.1.1 Fracture Mechanics Analysis

The total axial pressure and seismic stress corresponding to the upset condition is 1.9 ksi, and 3.86 ksi for the faulted (Loss-of-Coolant Accident and Design Basis Earthquake) condition. Using the ASME Code safety factors for fracture analysis, the normal and upset condition is limiting.

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 3.0 for the upset condition, the allowable K_I of 50 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 Figure 4-1 (Reference 4-1), σ is the axial stress, and 'a' is the half flaw length. The allowable through-wall circumferential flaw length (2a) was determined as ≅ 110 inches.

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 normal operating temperature of 550°F.

The stresses for the limit load analysis for the upset condition consisted of an axial force stress of 0.52 ksi, and a bending moment stress of 2.97 ksi (corresponding to the H7 weld).

Similarly for the faulted condition, the axial force stress was 0.88 ksi, and the bending moment stress was 5.34 ksi. The allowable flaw length was approximately 300 in., including the ASME Code, Section XI safety factors.

4.2 Allowable Axial Flaw Size

4.2.1 Fracture Mechanics Analysis

The allowable axial flaw size is governed entirely by the pressure hoop stress. Similar to 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. M is given by:

$$M = G_m + G_b \qquad \text{(Figure 4-2, from Reference 4-1)}$$

In the above expression, the allowable flaw length 2a can be determined by equating the calculated K to the fracture toughness divided by the safety factor of 3. The hoop stress

is 1.78 ksi and the allowable K = 150/3 (where 150 ksi$\sqrt{in}$ represents a conservative estimate of the material toughness and 3 is the safety factor).

The allowable flaw length was conservatively determined to be 2a = 50 in.

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:

$$\sigma_h = \sigma_f/(M_1 * SF)$$

where M_1 is a curvature correction factor (which is a function of the flaw length (Reference 4-2)), $\sigma_f = 3S_m$ is the flow stress, SF is the safety factor of 2.8 for upset conditions, and σ_h = the hoop stress corresponding to the upset ΔP of 30 psi. The allowable flaw length based on the limit analysis is 170 in., which exceeds that determined by LEFM. Thus, the allowable axial through-wall flaw length is 50 in.

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).

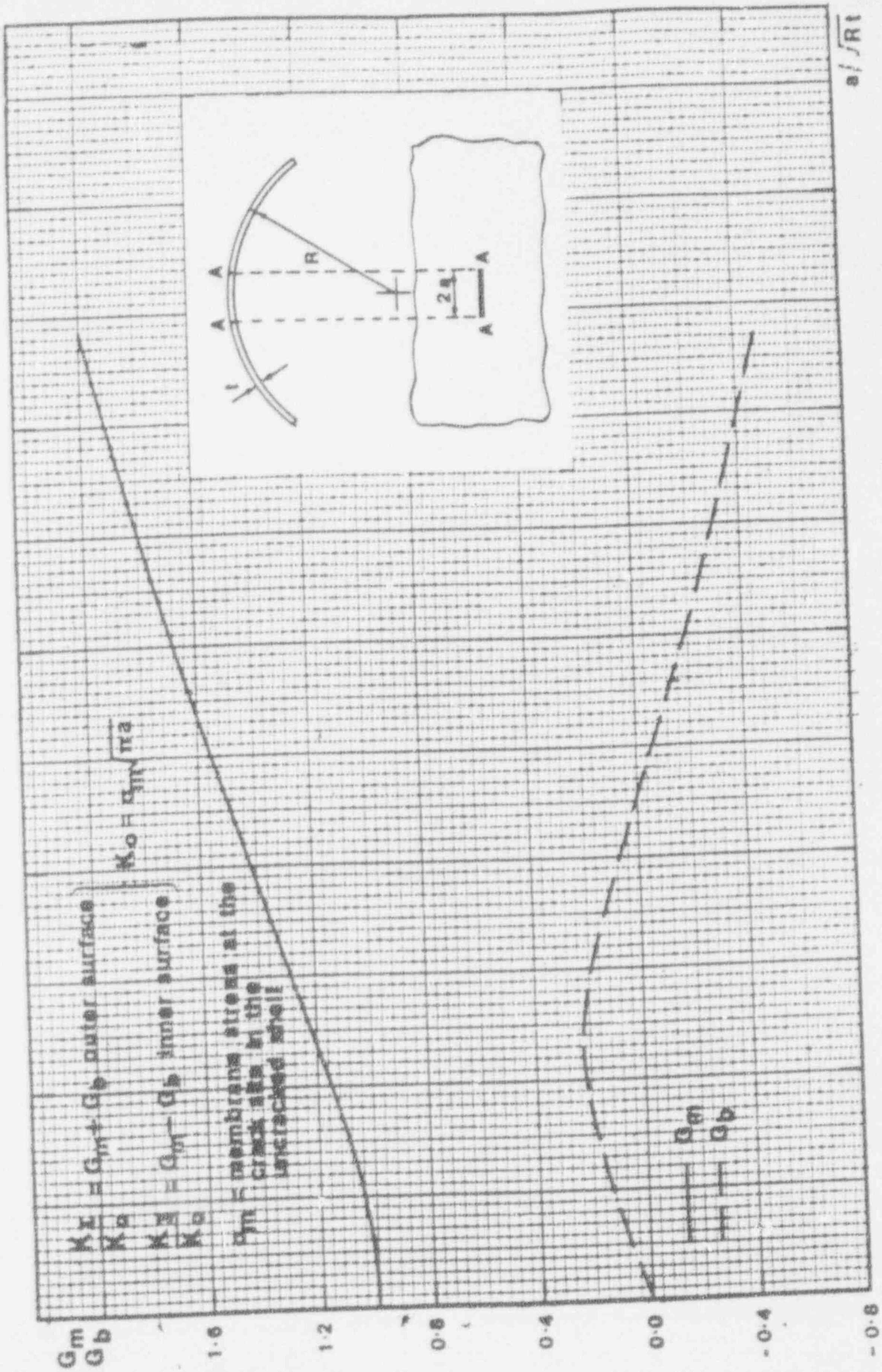


Figure 4-1. K_I for point A of a circumferential flaw in a cylindrical shell subjected to a uniform membrane stress

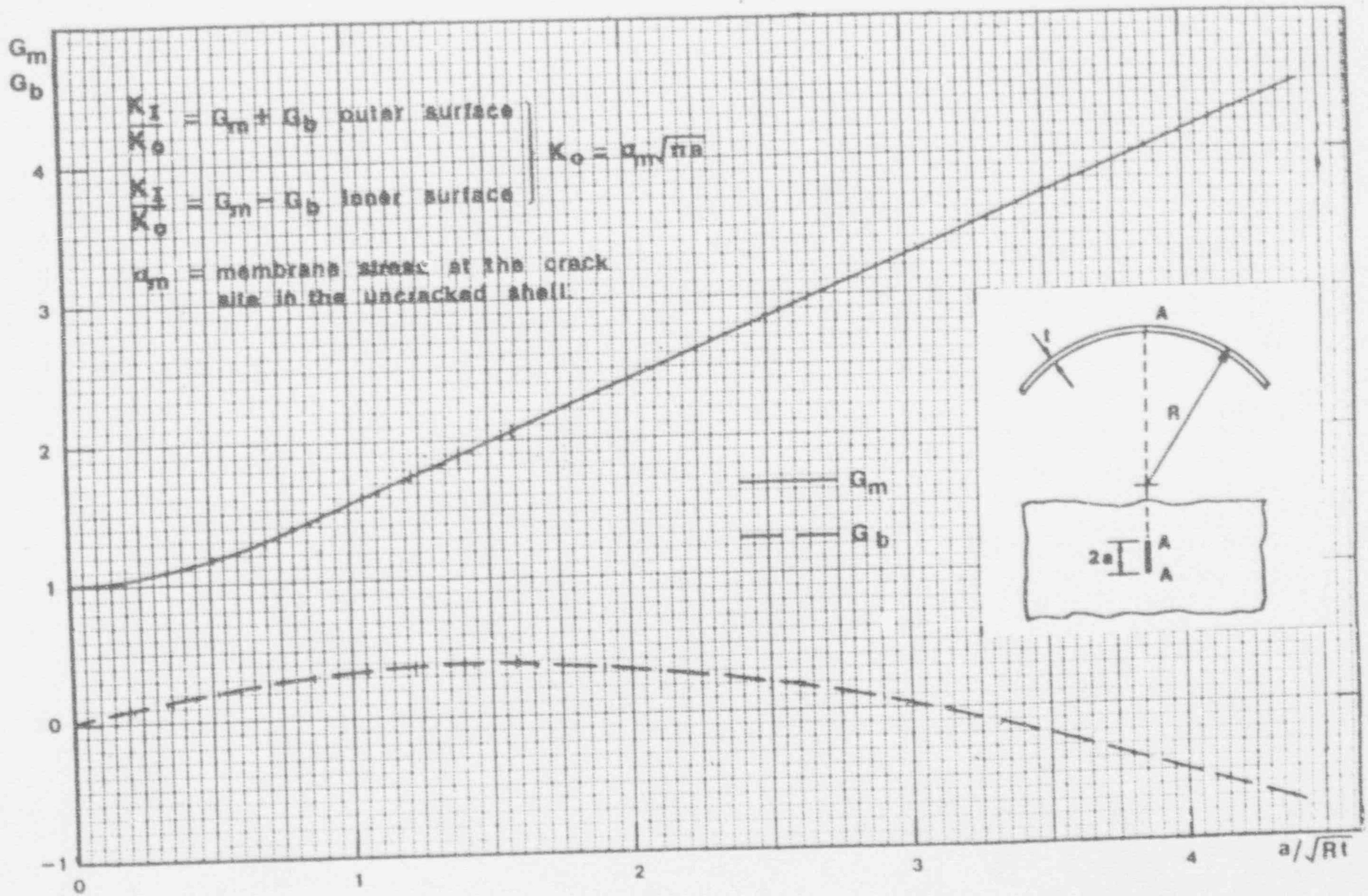


Figure 4-2. K_I for point A of a longitudinal flaw in a cylindrical shell subjected to a uniform membrane stress

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
  - 110 in. using LEFM
  - 300 in. using limit load

- Axial Flaws
  - 50 in. using LEFM
  - 170 in. using limit load

A conservative approach in developing the screening rule is to include both the LEFM and limit load analysis. For axial flaws, the allowable flaw length based on the LEFM controls, and the screening limit is 50 in.

For circumferential flaws the fracture mechanics based limit for a single flaw is 110 in. This in itself is not sufficient since there could be several flaws (each less than 110 in.) in a circumferential plane that cumulatively add up to greater than 300 in. (the allowable circumferential flaw size based on limit load analysis). Thus, the cumulative flaw length should be less than 300 inches. While this fully assures the ASME Code margins, an additional conservatism is included in the screening. **This states that the cumulative flaw length cannot be more than 300/4 = 75 in. in any 90 degree sector of the shroud.** This is a conservative restriction that assures that long continuous flaws are not admissible. With the provision that the cumulative flaw length cannot exceed 75 in. in any 90° sector of the shroud, this criterion becomes more limiting than the fracture mechanics limit of 110 in. The approach used here for the 75 inch limit for circumferential flaws is to assume a template with a moving window equal to the 90° sector. The cumulative length of flaws that appear in the window should be less than 75 in. This is shown graphically in Figure 5-1. A similar restriction based on limit loads is not needed for axial flaws since they are associated only with circumferential welds and are unlikely to be aligned in the same plane.

It should be noted that 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 ($L1_{eff}$ + $L2_{eff}$), the length $L = L1_{eff} + L2_{eff}$ is used for comparison with the LEFM based allowable flaw length.

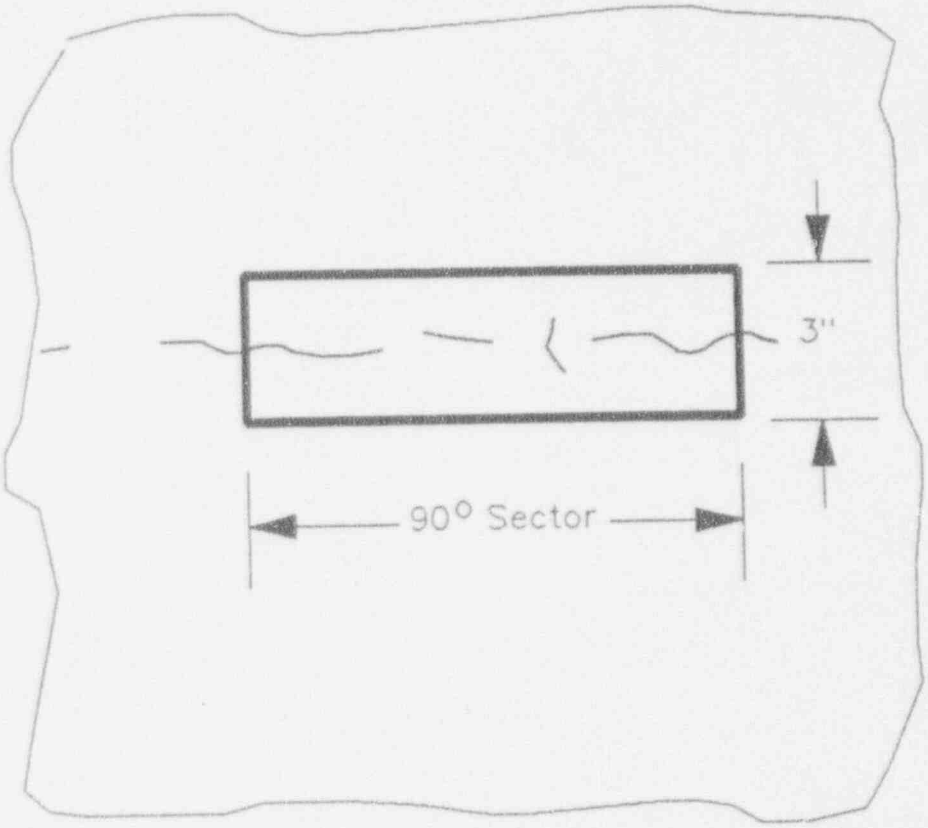


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Figure 5-1 SCHEMATIC ILLUSTRATING CUMULATIVE EFFECTIVE FLAW CRITERION

6.0 SUMMARY OF SCREENING CRITERIA

The screening criteria is schematically shown in Figure 6-1. The first step is to map the flaw indications observed by IVVI. Next the proximity rules are applied to the flaw map to develop effective flaw lengths. The results of the effective flaw lengths are also mapped.

For axial flaws, two neighboring flaws must be summed if $S < 0.75(L1_{eff}+L2_{eff})$. If the longest resulting flaw is less than 50 inches, then the screening limit is met for axial flaws.

For circumferential flaws, all flaws are summed in any 90° sector using a template. The total flaw length in the 90° window must be less then 75 inches to meet the screening criteria. The next step is the LEFM based comparison using the interaction criteria. If $S < 0.75\ (L1_{eff} + L2_{eff})$, then the length $L = L1_{eff} + L2_{eff}$ should be compared with the LEFM limit of 110 in. for circumferential flaws.

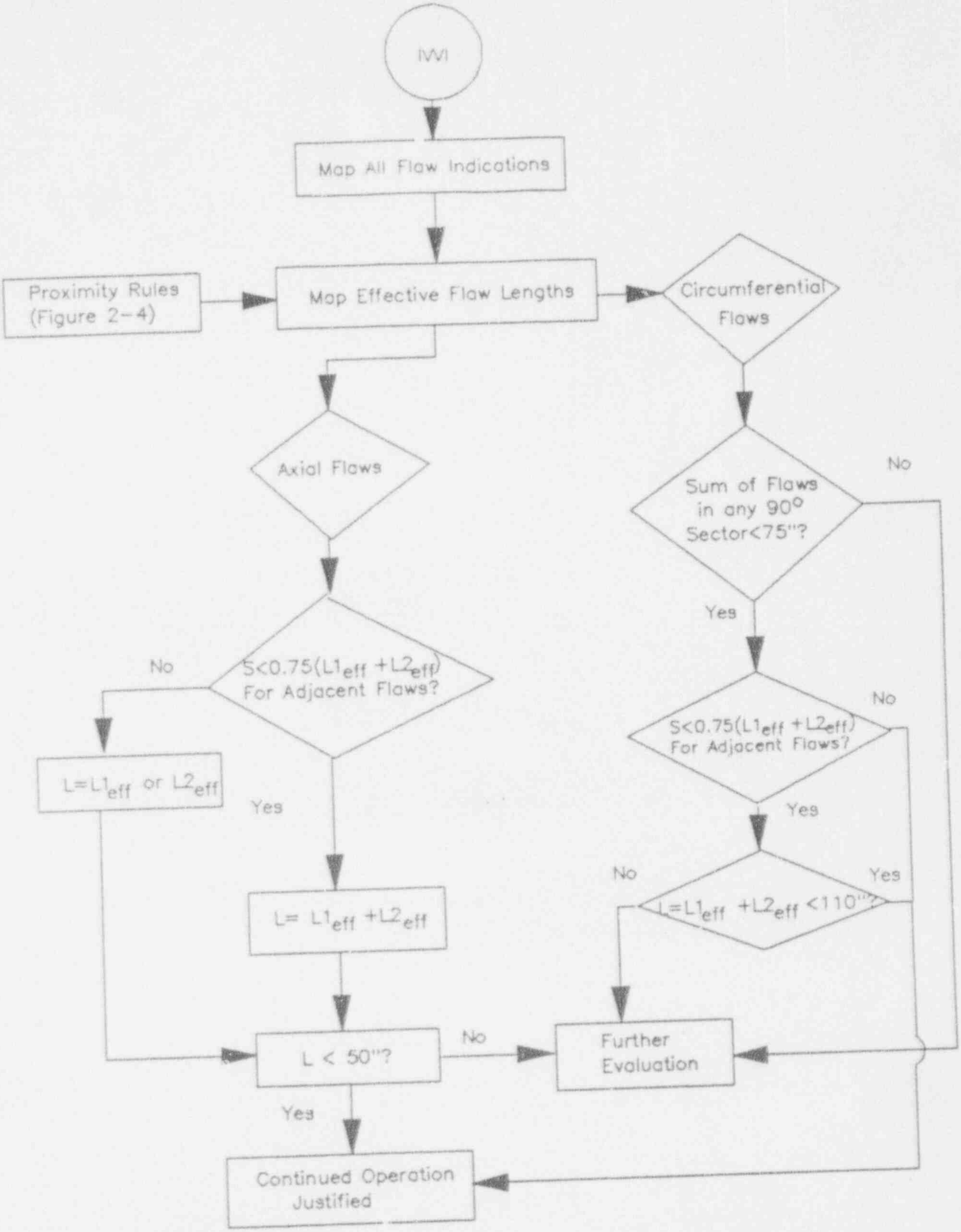

Figure 6-1 SCHEMATIC OF SCREENING CRITERIA