June 13, 1994

Mr. William T. Russell, Director
Office of Nuclear Reactor Regulation
U.S. Nuclear Regulatory Commission
Washington, D. C. 20555

Attn: Document Control Desk

Subject: Analytical Evaluation of Cracking Identified at Quad Cities Nuclear Power Station Unit 1
NRC Docket No. 50-254

References:
(a) M. Lyster letter to T. Murley, dated June 6, 1994, Providing Response to Request for Additional Information Concerning Core Shroud Cracking at Dresden, Units 2 and 3, and Quad Cities, Units 1 and 2.

(b) General Electric Company Report GENE-523-02-0194, dated March 1994, Evaluation and Screening Criteria for the Quad Cities 1 and 2 Shrouds (Attachment 1).

(c) General Electric Company Report GENE-523-30-0294, Revision 1, dated June 1994, Recommended Inspection Criteria for the Quad Cities 1 and 2 Shrouds (Attachment 2).

(d) General Electric Company Report GENE-523-A79-0594, dated June 1994, Evaluation of the Indications Found at the H5 Weld Location in the Quad Cities Unit 1 Shroud (Attachment 3).

(e) Structural Integrity Report RAM-94-159, dated June 11, 1994, Evaluation of Flaws in Circumferential Core Shroud Welds at Quad Cities Unit 1 (Attachment 4).

(f) General Electric Company Letter GLS-94-11, dated June 8, 1994, Response to Commonwealth Edison Technical Audit Questions Regarding the H5 Weld Flaw Evaluations for Dresden Unit 3 and Quad Cities Unit 1.

Dear Mr. Russell:

In reference (a) Commonwealth Edison (ComEd) submitted the results of the core shroud visual examinations and supplemental ultrasonic examinations performed at Quad Cities, Unit 1. The analytical evaluation of the core shroud cracking consisted of structural margin assessments utilizing limit load and, where appropriate, linear elastic fracture mechanics at

A001

each horizontal weld location, H1 through H7 in accordance with ASME Section XI, IWB-3142.4. The purpose of this letter is to provide the results of the evaluations to the NRC staff for review in accordance with ASME Section XI, IWB-3144(b). The following is a synopsis of the evaluation results at each weld location. The detailed evaluations are contained in the reference (d) and (e) reports.

During the current refuel outage (Q1R13), visual inspections (VT) were performed on the core shroud welds H1 through H7. Subsequently, additional examinations using ultrasonics (UT) were performed to corroborate the results of the visual examinations.

Using ASME Section XI IWB-3142.4 Acceptance by Analytical Evaluation, the evaluations were performed to support operation, without repair of the shroud welds, for an 18 month operating cycle. The Screening Criteria, reference (b) forms the basis of the evaluation methodology in accordance with ASME Section XI. The Inspection Criteria, reference (c), is also based on the Screening Criteria and was developed prior to the performance of the visual inspections to provide the minimum acceptance standard for each weld, in the form of equally distributed unflawed material. Due to accessibility limitations and inspection results, additional analyses were performed to determine the actual structural margin based on ASME Code factor-of-safety. The analysis for welds H1, H2, H3, H4, H6 and H7 is documented in reference (e). For weld H5, the inspection and screening criteria was not met. Therefore, additional analysis was performed and is documented in reference (d).

The inspection results, previously transmitted per reference (a), were utilized as input to the evaluations and are summarized below.

Additional evaluations on the H1 and H2 welds were necessary because the spacing of unflawed material varied slightly from the Inspection Plan. No indications were observed visually. The H2 visual inspection results were confirmed by UT. Approximately 78% (539 inches) of H2 was UT examined. Indications were noted at 20% (139 inches) of the weld with a maximum depth of 0.35 inches, with a majority of the flaw depths at 0.20 inches. No flaws were detected in the areas visually examined.

The H3 weld meets the applicable Inspection Criteria. The visual inspection was performed on 100% of the weld ID and OD surfaces.

The H4 weld visual inspections covered 66° (116 inches) of the ID and 90° (162 inches) of the OD with a total of 15 inches of ID/OD overlap. Two 1/2 inch long flaws were observed on the ID surface by VT. These flaws are separated by ~30 inches. No flaws were observed during the OD visual inspection. The H4 weld ID inspection results were bounding when compared to the OD inspection and , hence were used in the evaluation.

The H5 visual inspection covered ~150° of the circumference and noted numerous, random linear indications in the ring material located below the weld at all locations inspected. The observed cracking is not connected but has distinct starts and stops. Subsequently, UT examination was performed at four (4) locations for a total of 112° (207 inches). The UT recorded three (3) flaws, with a maximum depth of 0.57 inches. An assumed conservative

flaw depth of 1.24 inches for 360° was used in the evaluation coupled with a conservative crack growth rate of $5x10^{-5}$ inches/hour. The results of the evaluation show an end of 18 month cycle flaw depth of 1.84 inches. This depth results in a structural margin factor of 9.7 when compared to an allowable crack depth of 2.88 inches using limit load analysis.

To aid in determining the root cause of the cracking, two (2) "boat" samples were removed from the H5 weld. The preliminary boat sample results are:

1. The cracking was caused by IGSCC.
2. The material composition is 304 stainless steel.
3. Irradiation effects were not observed.
4. Confirmed cold working depth up to 0.050 inches.

The H6 weld meets the applicable Inspection Criteria. The visual inspection was performed on the OD and covered 36% (231 inches) of the weld with one 7 inch flaw detected. The weld was also UT examined at four locations for a total of 6.5% (42 inches). One 2 inch flaw was detected on the ID. The UT examination was not performed in the area where the 7 inch flaw was detected. Therefore, the VT results were reduced by the UT results and used in the evaluation.

The H7 weld was evaluated because the areas inspected differed from the inspection plan due to accessibility. The visual inspection covered 23% (146 inches) of the weld. This weld was also UT examined at four locations for a total of 6.5% (42 inches). The UT areas coincided with the areas visually inspected. There were no recordable indications at H7.

The analytical evaluation of the core shroud cracking consisted of structural margin assessments utilizing limit load and, where appropriate, linear elastic fracture mechanics (LEFM) at each horizontal weld location, H1 through H7. The structural margin assessments determined the minimum factor-of-safety available in terms of required unflawed areas for a 18-month cycle of operation at each weld location. The operating margin consists of any margin above the Code required minimum factor-of-safety of 1.4 under faulted conditions. The following is a synopsis of the evaluation results at each weld location. The detailed evaluations are contained in the reference (d) and (e) reports. Also, the reference (f) letter provides the rationale for the structural analysis criteria and methods used in the reference (d) report.

A summary of the Code margins available at each location is as follows:

Weld Location	Limit Load Factor of Safety
H1	7.1
H2	5.8
H3	56.3
H4	5.6 (1.7 LEFM)
H5	> 9.7
H6	4.5
H7	1.5

In closing, the above evaluation results, coupled with the substantial conservatisms that were built into the flaw evaluations, demonstrate that the flaws observed in the core shroud welds represent no immediate safety concern, and that all applicable ASME Code safety margins will be maintained well beyond the end of the next operating cycle for Quad Cities Unit 1.

If there are any questions concerning this matter, please contact this office.

Respectfully,

R Walsh

Robert J. Walsh
Core Shroud Project Manager
Quad Cities Station

cc: J. B. Martin, Regional Administrator - RIII
C. Patel, Project Manager - NRR
C. Miller, Senior Resident Inspector - Quad Cities

ATTACHMENT 1

General Electric Company Report GENE-523-02-0194, dated March 1994, Evaluation and Screening Criteria for the Quad Cities 1 and 2 Shrouds.

GE Nuclear Energy

TECHNICAL SERVICES BUSINESS
GE Nuclear Energy
175 Curtner Avenue, San Jose, CA 95125

GENE-523-02-0194
DRF 137-0010-7
Class II
March 1994

Evaluation and Screening Criteria for the Quad Cities 1 and 2 Shrouds

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1.0 INTRODUCTION

In preparation for the Quad Cities 1 and 2 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, the crack extension, Δa, at each tip is 0.625 inches for an 18 month fuel cycle (12,492 hours using a 95% capacity factor), and 0.833 inches for a 24 month fuel cycle (16,655 hours using 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 ($2 \times \Delta a + 2 \times$ shroud thickness). For a shroud thickness of 2.0 inches, this bounding ligament is 5.25 inches for an 18 month fuel cycle and 5.67 inches for a 24 month fuel cycle. Thus, if the ligament is less than $2\Delta a + 2t$, the effective length is ($L1 + L2 + S + 2\Delta a$). Note that the addition of $2\Delta a$ 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 $2\Delta a + 2t$, then the effective flaw length is determined by adding the projected tip growth to each end of the flaw. For this example, $L1_{eff} = L1 + 2\Delta a$, and $L2_{eff} = L2 + 2\Delta a$.

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 $\Delta a + 2t$, then the

effective flaw length for the circumferential flaw is $L_{eff} = L1 + S + \Delta a$ (the bounding ligament for these cases). If the ligament is greater than $\Delta a + 2t$, 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 $2\Delta a + 2t$, the indications must be combined such that the effective length is (See Figure 2-2b):

$$L_{eff} = L1 + S + L2 + 2\Delta a$$

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 $2\Delta a + 2t$, the effective flaw lengths are (See Figure 2-2c):

$$L1_{eff} = L1 + 2\Delta a$$
$$L2_{eff} = L2 + 2\Delta a$$

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 $\Delta a + 2t$, then the effective circumferential flaw length is (See Figure 2-3b):

$$L_{eff} = L1 + S + \Delta a$$

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

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

$$L_{eff} = L2 + 2\Delta a$$

where: L2 = length of axial indication

If the distance between the circumferential indication tip and the axial indication is greater than $\Delta a + 2t$, then the flaws are not combined (See Figure 2-3c) and the effective lengths are:

$$L1_{eff} = L1 + 2\Delta a \quad \text{(for circumferential flaw)}$$

$$L2_{eff} = L2 + 2\Delta a \quad \text{(for axial flaw)}$$

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.

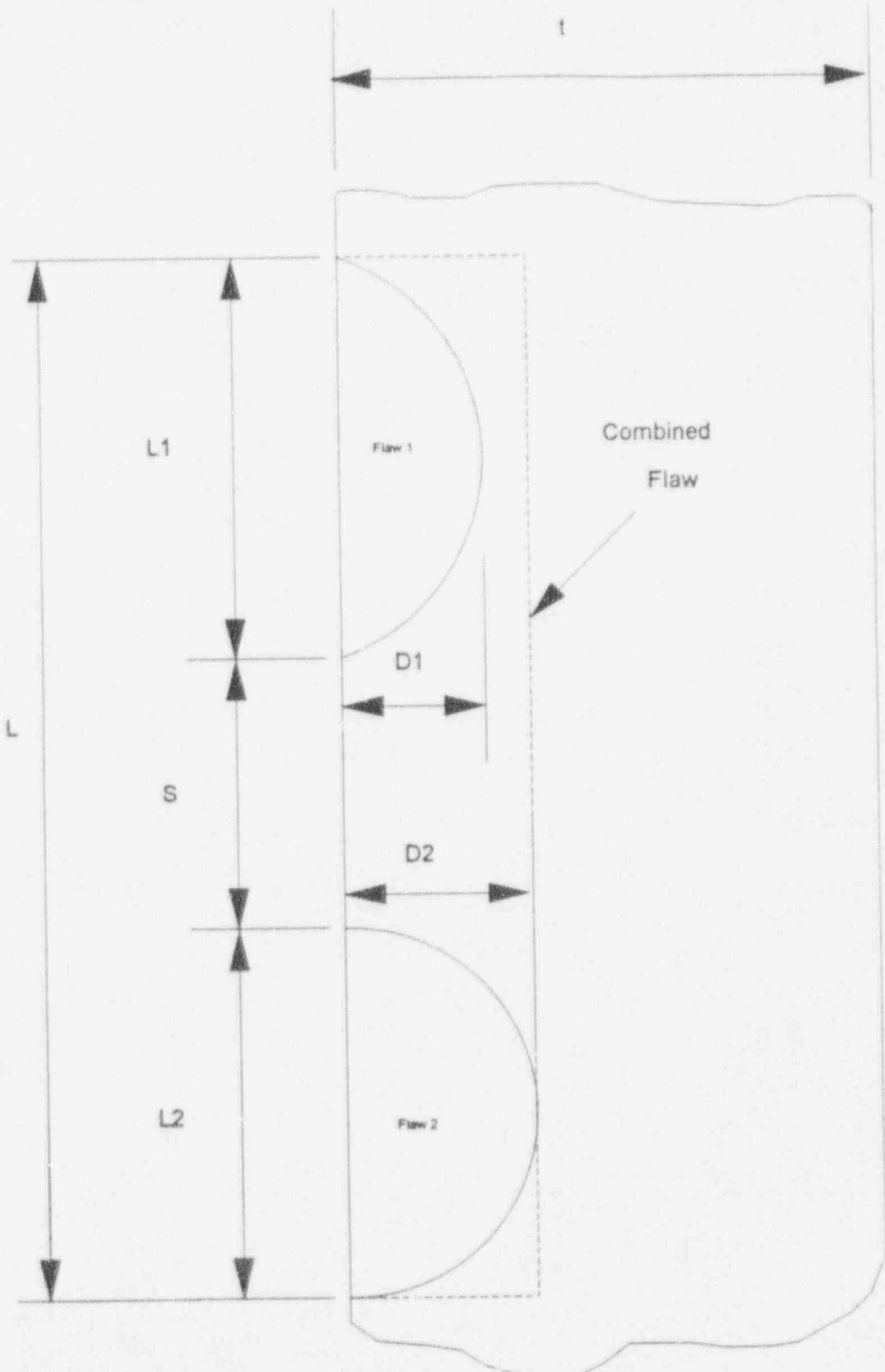


Figure 2-1: ASME Code Proximity Criteria

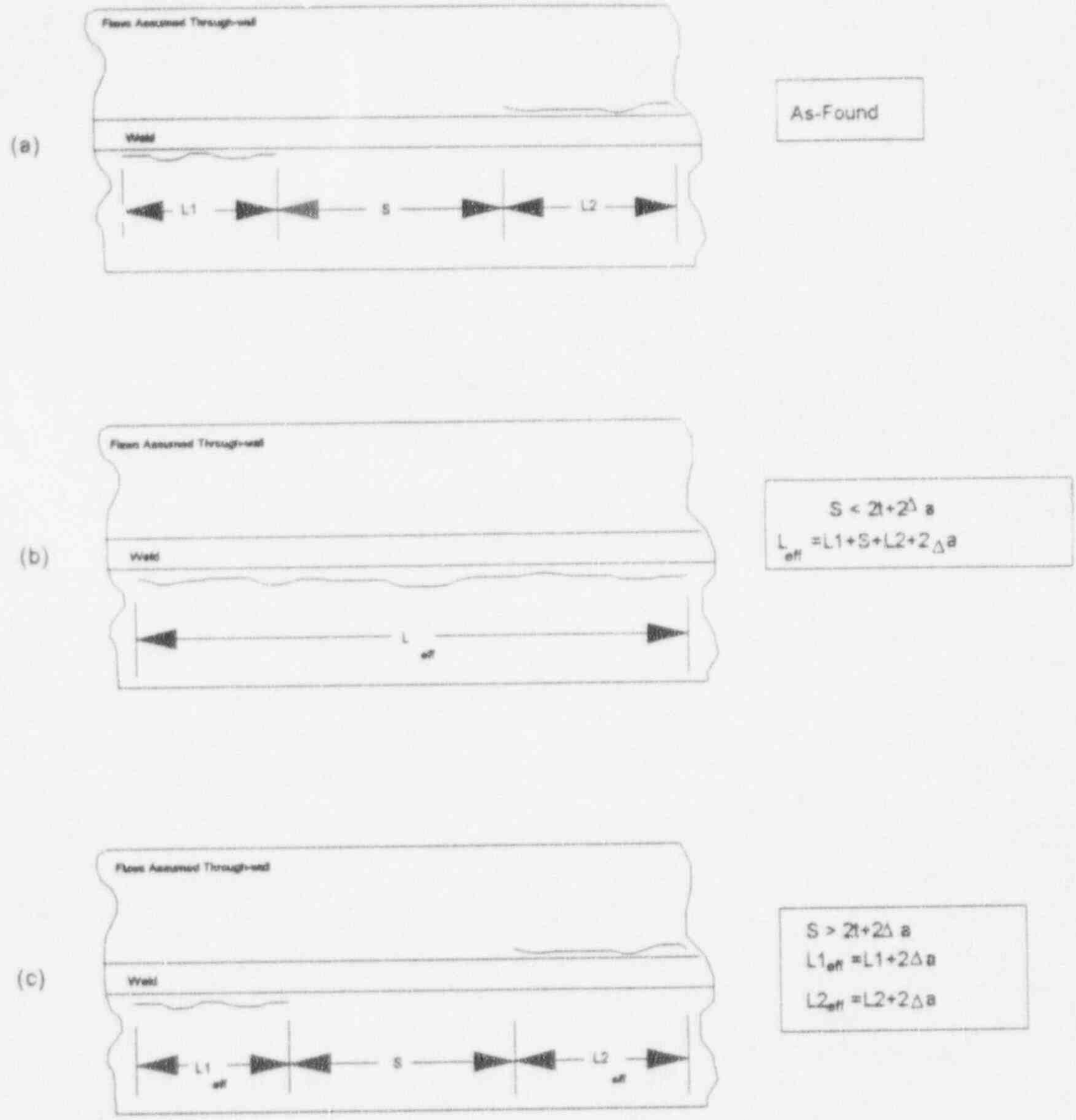


Figure 2-2: Application of Proximity Procedure to Neighboring Circumferential Flaws

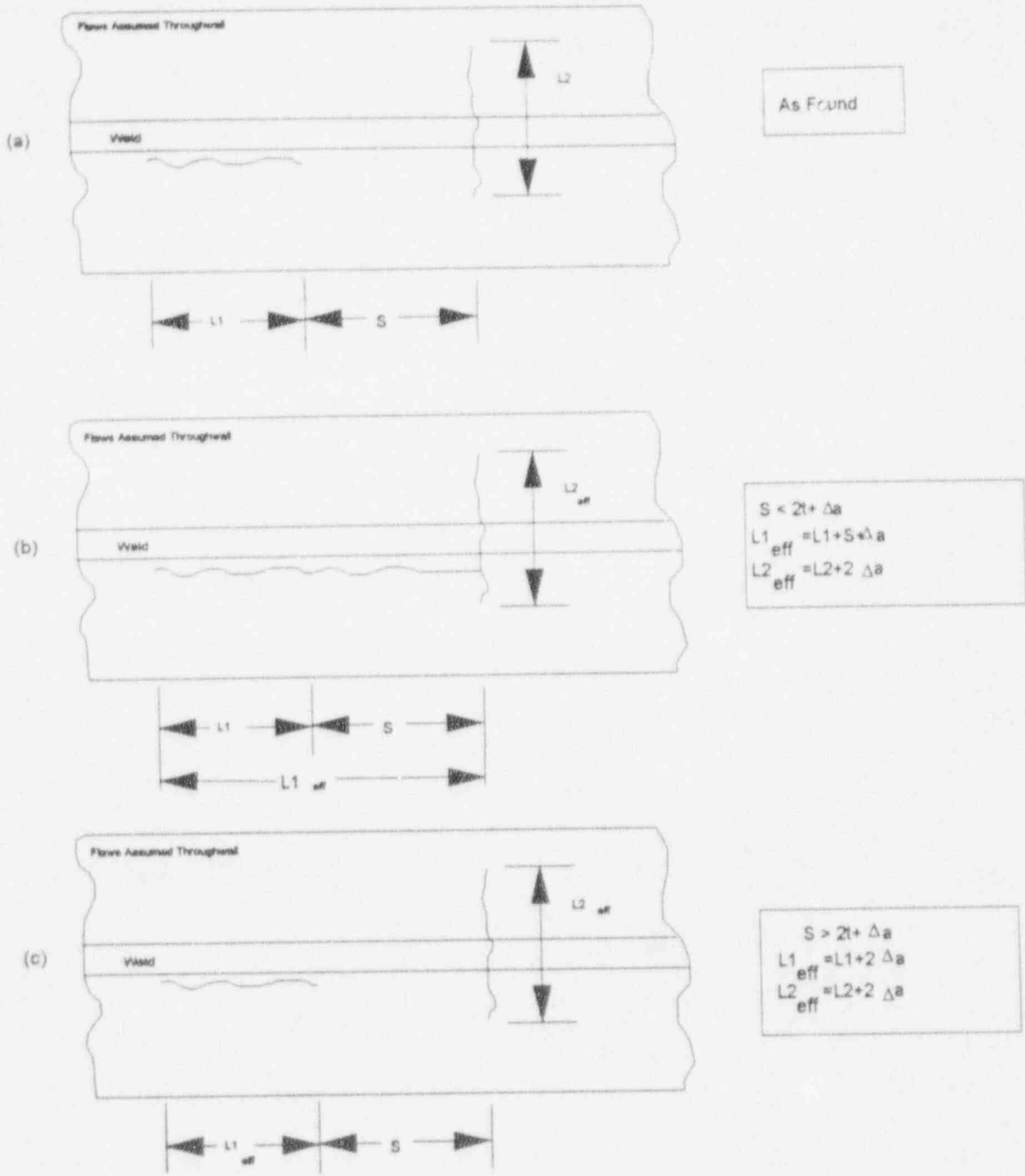


Figure 2-3: Application of Proximity Procedure to Neighboring Axial and Circumferential Flaws

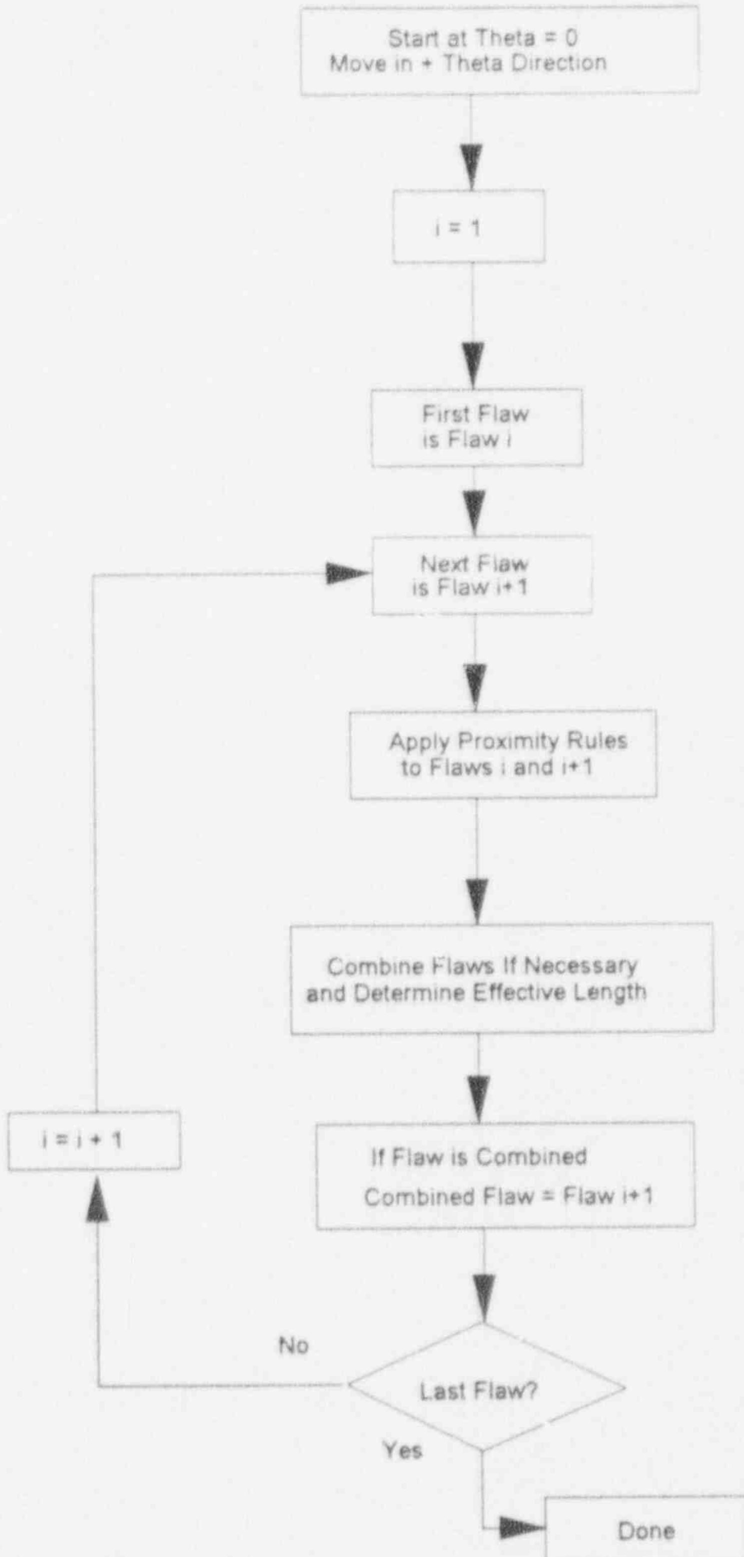


Figure 2-4: Process for Determining Effective Flaw Length

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 Updated Final Safety Analysis Report (UFSAR, 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 (0.08 g's OBE, 0.16 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)		Stress, (ksi)	
	Upset	Faulted	Upset	Faulted
H1	5.19×10^3	1.04×10^4	0.07	0.14
H2	1.16×10^4	2.31×10^4	0.15	0.31
H3	1.24×10^4	2.47×10^4	0.19	0.37
H4	4.31×10^4	8.61×10^4	0.65	1.30
H5	7.72×10^4	1.54×10^5	1.17	2.34
H6	7.96×10^4	1.59×10^5	1.28	2.56
H7	1.13×10^5	2.26×10^5	1.82	3.63

Table 3-2: Pressure Differences

Component	Pressure Differences (psi)	
	Normal/Upset Condition	Faulted Condition
Shroud Head and Upper Shroud	8	20
Core Plate	17	30
Lower Shroud	25	43

Table 3-3: Shroud Weight and Seismic Shear Loads

Weld Designation	Effective Wt.* (kips) OBE	Effective Wt.* (kips) DBE	Shear (kips) OBE
H1	174.91	157.32	43
H2	197.87	177.97	338
H3	198.99	178.98	338
H4	254.89	229.26	415
H5	329.10	296.00	604
H6	330.62	297.37	604
H7	345.71	310.94	592

* 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 Quad Cities 1 and 2 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 $2\Delta a + 2t$, 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 + 2Δa) (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 + 4Δa) apart. Thus, if the distance between indications is greater than 0.75(L1 + L2 + 4Δa), 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

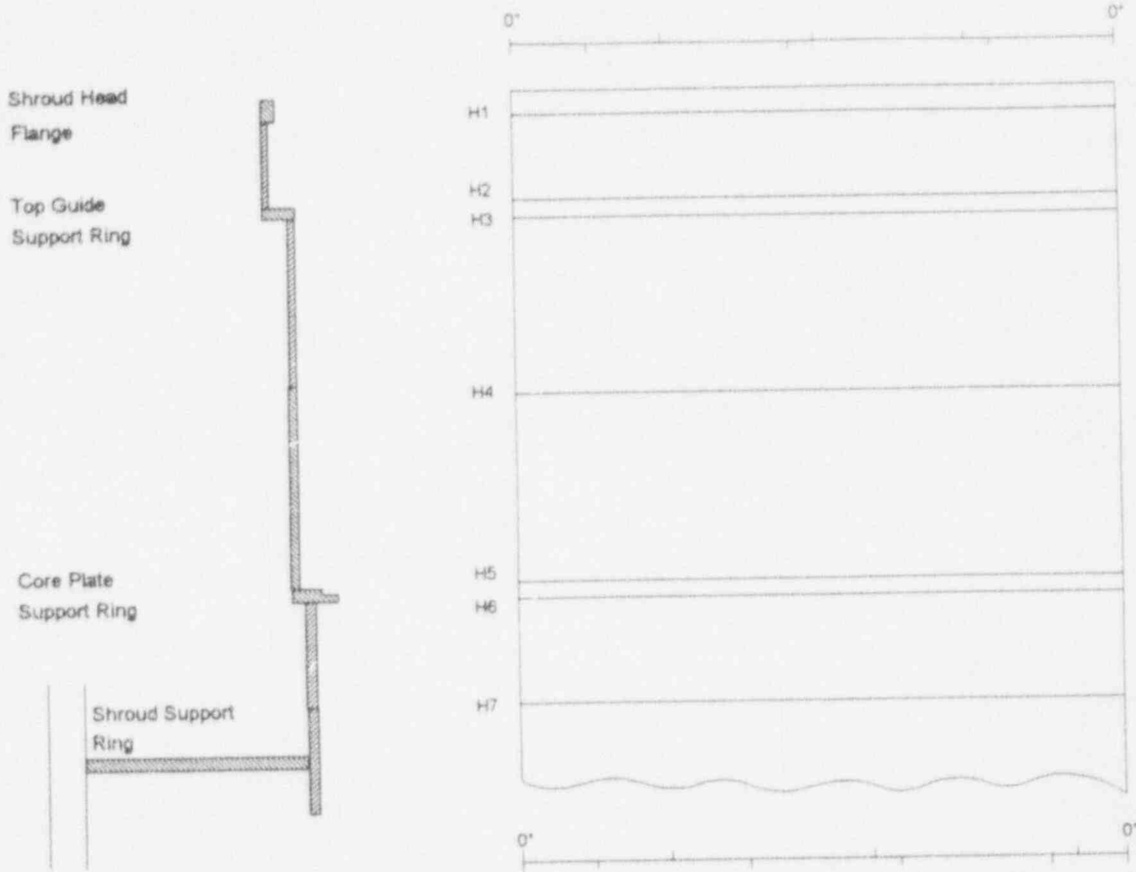
3-1. Letter PBS9401 from P. B. Shah (GE) to Hien Do (CECo) dated March 16, 1994, "Shroud Seismic Loads for Quad Cities."

3-2. Quad Cities 1 and 2 Updated Final Safety Analysis Report (UFSAR).

3-3. **GE Drawings:**

a. 718E861, Rev. 6, "Shroud - Spec. Control," Part 2, GE-NED, San Jose, CA.

b. 886D485, Rev. 4, "Reactor Vessel - Spec. Control," Part 1, GE-APED, San Jose, CA.



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Note: Vertical weld locations are not shown for clarity.

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

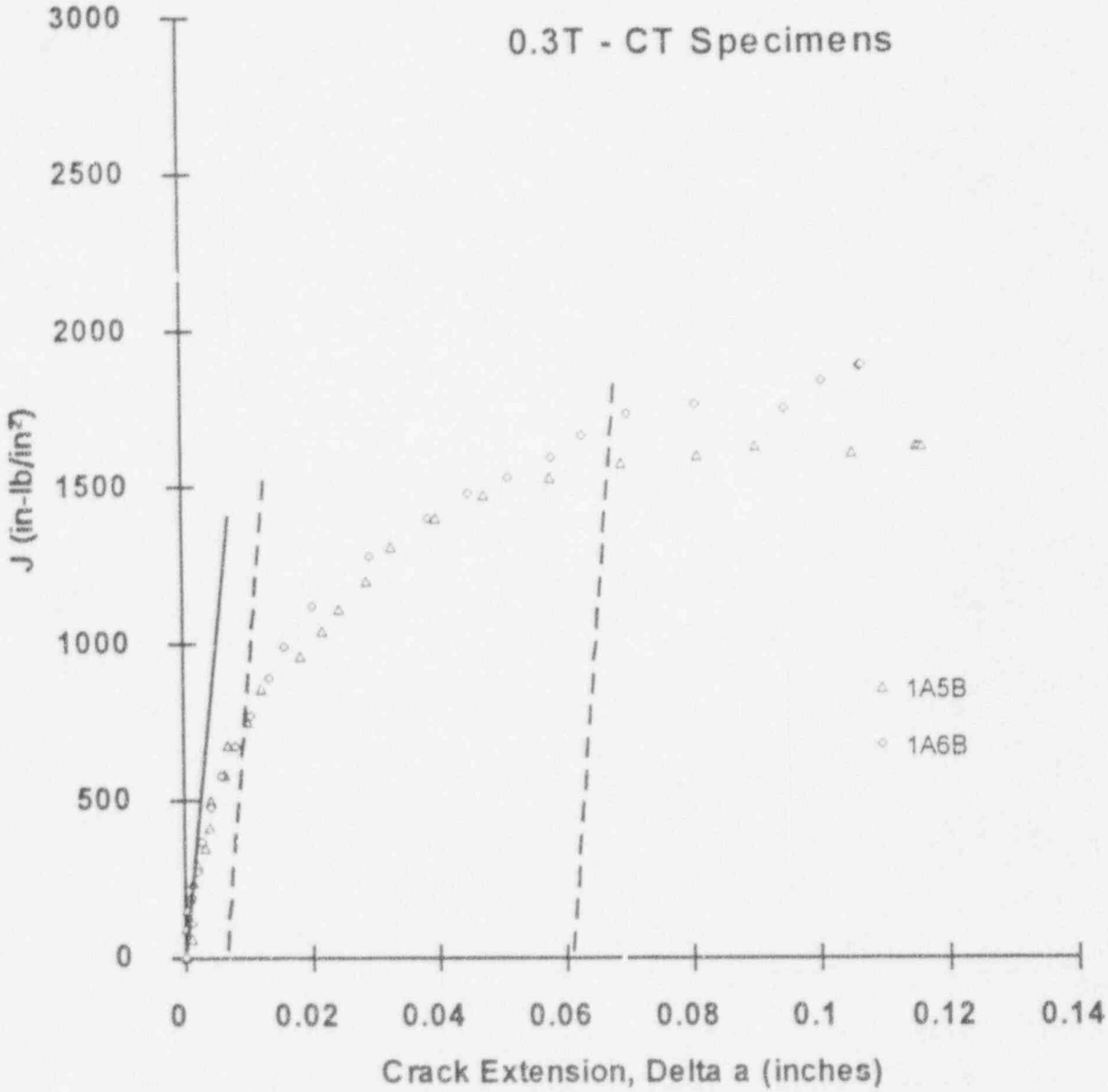
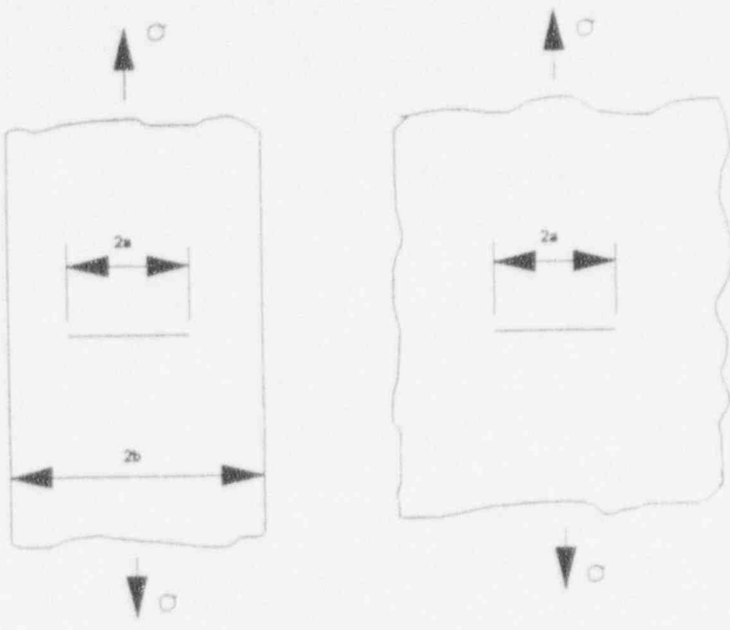


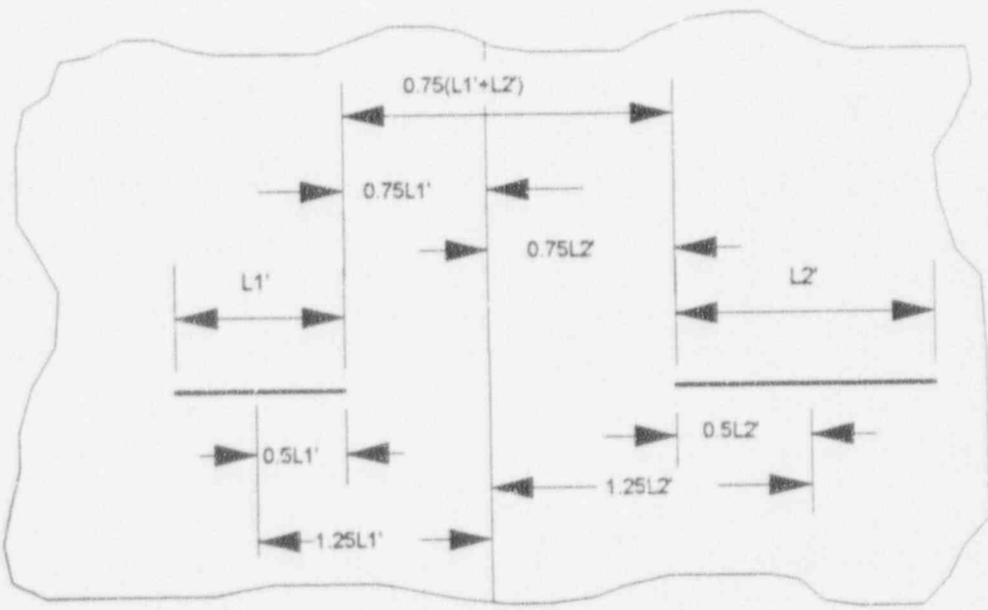
Figure 3-2: Comparison of J-R Curves Developed for Two Irradiated Stainless Steel Specimens



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

$K = \sigma\sqrt{\pi a} * F$

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



$L1' = L1 + 2\Delta a$
$L2' = L2 + 2\Delta a$

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 0.66 ksi (weld H4) and 1.17 ksi (weld H5) for the upset condition and 1.63 ksi (weld H4) and 2.62 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 $150 \text{ksi}\sqrt{\text{in}}$ was used. Applying a safety factor of 1.4 for the faulted condition, the allowable K_I of $\sim 107 \text{ksi}\sqrt{\text{in}}$ 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 ≅ 281 inches for H4 and 183 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 Length (in)
	Upset	Faulted	Upset	Faulted	
H1	0.09	0.43	0.07	0.14	541
H2	0.07	0.41	0.15	0.31	532
H3	0.05	0.37	0.19	0.37	501
H4	0.01	0.33	0.65	1.30	466
H5	0.00*	0.28	1.17	2.34	438
H6	0.13	0.61	1.28	2.56	407
H7	0.12	0.60	1.82	3.63	388

* The calculated value is 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 $150 ksi\sqrt{in}$. The hoop stress for the faulted condition is 1.04 ksi; the ASME safety factor of 1.4 is applied and the result is used in the previous equation.

The allowable flaw length was conservatively determined to be 2a = 150 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 (3.0 for upset conditions, 1.5 for faulted), and σ_h = the hoop stress corresponding to the ΔP of 20 psi (faulted) above the core plate and 25 psi (upset) below the core plate. The allowable flaw length based on the limit load analysis is 706 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 150 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: 541 inches (limit load only)
  - H2: 532 inches (limit load only)
  - H3: 501 inches (limit load only)
  - H4: 466 inches (limit load), 281 inches (LEFM)
  - H5: 438 inches (limit load), 183 inches (LEFM)
  - H6: 407 inches (limit load only)
  - H7: 388 inches (limit load only)

- Axial Flaws
  - Above Core Plate: 706 inches (limit load), 150 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 706 inches between H1 and H3, 150 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 183 inches. This in itself is not sufficient, since there could be several flaws (each less than 183 inches) in a circumferential plane that cumulatively add up to greater than 438 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 438 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 + 4Δa), 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.

ATTACHMENT 2

General Electric Company Report GENE-523-30-0294, Revision 1, dated June 1994, Recommended Inspection Criteria for the Quad Cities 1 and 2 Shrouds.

GE Nuclear Energy

TECHNICAL SERVICES BUSINESS
GE Nuclear Energy
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GENE-523-30-0294
Revision 1
DRF 137-0010-7
Class II
June 1994

Recommended Inspection Criteria for the Quad Cities 1 and 2 Shrouds

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CONTENTS OF THIS REPORT

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1

IMAGE EVALUATION TEST TARGET (MT-3)

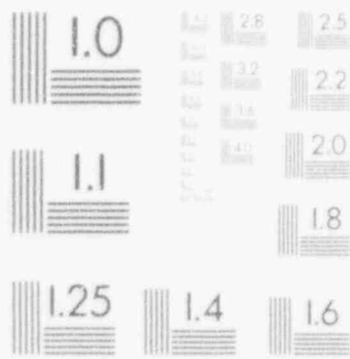

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IMAGE EVALUATION TEST TARGET (MT-3)

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IMAGE EVALUATION TEST TARGET (MT-3)

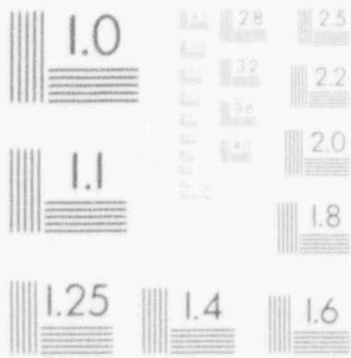

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IMAGE EVALUATION TEST TARGET (MT-3)

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1.0 BACKGROUND

The purpose of this report is to develop inspection criteria for the Quad Cities 1 and 2 shrouds in accordance with recommendations presented in GE Services Information Letter (SIL) Number 572, Revision 1 (SIL 572).

SIL 572 recommends examinations of accessible areas on both the inside diameter (ID) and outside diameter (OD) surfaces of the core shroud at the next scheduled refueling outages for all plants with Type 304 stainless steel shrouds with six or more years of power operation, and for all plants with L-Grade stainless steel shrouds with eight or more years of power operation. Power operation is defined as operation where the reactor is above 200°F. The Quad Cities 1 and 2 shrouds are fabricated from 304 stainless steel, and each plant has more than 6 years of power operation; therefore, inspection of the shrouds is warranted during the next scheduled refueling outages. SIL 572 recommends that any visual examinations be performed with an enhanced VT-1 system that can resolve a standard one (1) mil wire on the inspection surface. If no cracks are observed, it is recommended that the shroud be re-examined at every second refueling outage. If cracking is observed, the shroud should be re-examined during each refueling outage, and a structural margin analysis should be performed to assess operability. The inspection sample should be based upon a statistically significant sampling of the accessible areas.

Figure 1 shows, in a flow diagram format, the steps involved in the evaluation of the inspection results. The Reference 1 report documents screening criteria which may be used as a basis for dispositioning flaws discovered in the shroud during inspection, as suggested by the "COMPARE AGAINST VISUAL SCREENING CRITERIA" box in Figure 1. Reference 1 uses limit load and linear elastic fracture mechanics (LEFM) techniques to determine allowable flaw sizes assuming continuous length flaws. Alternate screening criteria are presented in this report which use similar methodology to that used in Reference 1, but take account for non-continuous flaws (i.e., separate uncracked regions distributed around the shroud circumference). This alternate approach is based on the premise that inspection times may be significantly shorter if the objective is to find the minimum amount of material needed to maintain structural margins rather than determining the full extent of any cracking which might be present.

The alternate approach described here, along with SIL 572, provide a basis for the plant-specific recommendations made for Quad Cities 1 and 2. The recommended inspection plan that follows can be performed by using enhanced visual examination, ultrasonic examination or some

combination thereof. There are distinct advantages and disadvantages associated with each of these inspection techniques which should be considered before selecting the inspection method, such as the cost to perform each type of exam and the associated impact on critical path time. The relative merits of each inspection technique are not discussed in this report.

2.0 TECHNICAL APPROACH

In this section, inspection criteria are developed which are used as a basis for the inspection recommendations which follow. The methodology used here is consistent with the limit load and LEFM techniques presented in Reference 1. However, the criteria developed here take into account distribution of uncracked material around the circumference of the shroud. This approach is less restrictive than that used in Reference 1, where it was assumed in the limit load approach that cracks were continuous. Therefore, the technical approach used here is to find the minimum amount of uncracked material at each weld location to meet the necessary structural margins (including safety factors). The condition of the uninspected locations of each weld remains unknown with this approach; in fact, much of it may be uncracked. However, for this conservative approach, it is assumed that they could be cracked. This assumption has no consequence to the structural adequacy of the shroud if it can be shown that the inspected regions are adequate from a structural standpoint, taking into account the necessary safety factors and future crack growth.

The limit load approach used here is depicted in Figure 2. In this figure, four equally distributed uncracked regions have been assumed. The length of each of these regions is to be determined for each shroud horizontal weld such that structural margins applicable to limit load methodology are realized and, where applicable, margins resulting from a LEFM approach are realized as well. From Reference 1, crack growth, Δa, is estimated to be 0.625 inch for an 18-month fuel cycle and 0.833 inch for a 24-month cycle. Therefore, the analyzed length of each uncracked section used in this evaluation was assumed to differ from the minimum required inspection length by twice the crack growth (i.e., $2 \times \Delta a$, assuming crack growth from both ends of the uncracked region). The same methodology applies for any other number of equally-spaced uncracked regions.

The neutral axis shown in Figure 2 is first determined by equilibrating the force resulting from the applied membrane stress, P_m, in the uncracked cross section with the force resulting from a stress equal to the flow stress in each of the uncracked regions. The flow stress of the

material is taken to be $3S_m$. Once the stress distribution in the uncracked regions is determined, the resulting moment about the centroidal axis is calculated, and this is used to determine an equivalent bending stress, P_b', in the cracked section. Finally, consistent with ASME Code, Section XI, IWB-3640 procedures, $P_b' + P_m$ is compared to the following:

$$(P_b + P_m) * S.F.$$

where:

P_b = Applied bending stress in uncracked section.

P_m = Applied membrane stress in uncracked section.

S.F. = Safety factor consistent with Appendix C of Section XI of the ASME Code.
= 1.4 for faulted conditions
= 2.8 for normal/upset conditions

The lengths of equally spaced, uncracked locations is structurally adequate if $(P_b + P_m) * S.F.$ is less than $P_b' + P_m$. As a final step, verification that the length obtained from this limit load approach exceeds the proximity criteria for adjacent flaws (from Reference 1) is performed.

Consistent with Reference 1, LEFM proximity limits must also be satisfied for welds H4 and H5. Calculations were performed for welds H4 and H5 to account for the LEFM effect adjacent flaws have on each other to ensure that flaws separated by the uncracked region length are acceptable (assuming the entire distance between uncracked regions was cracked). These calculations resulted in a minimum distance between flaws such that the stress intensity, K, (including the appropriate safety factor) was within the allowable material toughness value of 150 $ksi\sqrt{inch}$ used in Reference 1. The minimum spacing between flaws at these locations is the limiting (i.e., greater) result of both the limit load and LEFM methodologies.

Based on the loading described in Reference 1, the results of the limit load approach (as well as the LEFM approach for H4 and H5) described above are given in Table 1 for each weld for the next fuel cycle (18-month cycle). Based on Commonwealth Edison Company's intention of switching to a 24-month fuel cycle after the next cycle, results are also given in Table 2 for the next two fuel cycles (one 18-month cycle and one 24-month cycle). The weld locations are as identified in Reference 1. These results demonstrate that equally spaced uncracked regions, with quantities and lengths corresponding to that shown in Tables 1 and 2, provide adequate material to maintain all structural margins.

Table 1: Limit Load/LEFM Results for the Next Fuel Cycle

Weld	Limiting Condition	Number of Equally-Spaced, Uncracked Regions	Minimum Required Inspection Length per Uncracked Region(1) (inches)
H1	Faulted	4	5.25
H2	Faulted	4	5.25
H3	Faulted	4	5.25
H4	Faulted	4	18.75(2,3)
H4 (alternate)	Faulted	8	5.25(2)
H5	Upset	8	7.75(2,3)
H6	Faulted	4	13.25
H7	Faulted	see note 4	see note 4

NOTE: (1) From Reference 1, crack growth is estimated to be 0.625 inch for an 18-month fuel cycle. Therefore, the length of each uncracked section used in the evaluation was assumed to be the minimum inspection length reported here less crack growth from both sides of the uncracked region. Additionally, this length must be greater than the proximity criteria spacing requirement of Reference 1. Thus, the following was used in the evaluation for weld H1:

Proximity criteria spacing requirement from Reference 1 = 5.25"
Length used in evaluation = 3.00"
Inspection length = Length + crack growth = 3.00" + 2(0.625")
= 4.25"
Thus, the minimum required inspection length is 5.25"

(2) For these locations, LEFM techniques are applicable due to fluence considerations.

(3) The LEFM proximity criteria produced more limiting results than the limit load criteria, so the LEFM limits are tabulated at this location.

(4) Due to access restrictions at the H7 weld, the following distribution of uncracked regions was evaluated (refer to Figure 2): 34.25" at 90° and 270°, and 7.25" at 15°, 45°, 135°, 195°, 225° and 315°. These lengths are inspected lengths, so the actual lengths analyzed took into account crack growth, as per note 1.

Table 2: Limit Load/LEFM Results for the Next Two Fuel Cycles

Weld	Limiting Condition	Number of Equally-Spaced, Uncracked Regions	Minimum Required Inspection Length per Uncracked Region(1) (inches)
H1	Faulted	4	6.92
H2	Faulted	4	6.92
H3	Faulted	4	6.92
H4	Faulted	4	20.42(2,3)
H4 (alternate)	Faulted	8	6.92(2)
H5	Upset	8	9.42(2,3)
H6	Faulted	4	14.92
H7	Faulted	see note 4	see note 4

NOTE: (1) From Reference 1, crack growth is estimated to be 0.625 inch for an 18-month fuel cycle and 0.833 inch for a 24-month fuel cycle. Therefore, the length of each uncracked section used in the evaluation was assumed to be the minimum inspection length reported here less crack growth from both sides of the uncracked region. Additionally, this length must be greater than the proximity criteria spacing requirement of Reference 1. Thus, the following was used in the evaluation for weld H1:

Proximity criteria spacing requirement = 4.0+2(0.625"+0.833") = 6.92"
Length used in evaluation = 3.00"
Inspection length = Length + crack growth = 3.00" + 2(0.625"+0.833")
= 5.92"
Thus, the minimum required inspection length is 6.92"

(2) For these locations, LEFM techniques are applicable due to fluence considerations.

(3) The LEFM proximity criteria produced more limiting results than the limit load criteria, so the LEFM limits are tabulated at this location.

(4) Due to access restrictions at the H7 weld, the following distribution of uncracked regions was evaluated (refer to Figure 2): 35.92" at 90° and 270°, and 8.92" at 15°, 45°, 135°, 195°, 225° and 315°. These lengths are inspected lengths, so the actual lengths analyzed took into account crack growth, as per note 1.

3.0 INSPECTION CRITERIA

Based on the limit load/LEFM approach described in Section 2.0, the recommended inspection criteria for Quad Cities 1 and 2 are summarized below:

1. Based on the results of Tables 1 and 2, inspect equally spaced regions around the circumference of the shroud for *each* of the horizontal welds H1 - H7 (except as noted for H7), in quantities as noted in Tables 1 or 2. The length of each inspected region should be at least equal to that shown in Tables 1 or 2 in order for all structural margins to be met. Since the approach used here is to identify regions which have uncracked material, inspection of accessible areas that meet the criteria presented here should be performed for both the ID and OD surfaces, if accessible, to verify the absence of cracking. However, considering the various factors (end grain effects, fluence, environment/water chemistry and potential inaccessibility), it is recognized that the examination of the H1 OD, H2 OD, H3 ID, H4 ID, H5 OD, H6 OD and H7 OD surfaces will provide the most critical data for use with this examination approach (e.g., the areas noted are judged to be more susceptible to crack initiation).

2. If the extent of uncracked material identified in step (1) is insufficient to meet the limit load/LEFM results presented in Tables 1 or 2 for any given weld, additional areas of that weld must be examined in order to demonstrate structural margin through analysis.[a] The extent of the additional examination is dependent upon the amount of uncracked material identified in the initial regions. Using an approach similar to that described in Section 2.0, additional regions distributed around the circumference can be identified for further inspection with the intent of locating an amount of distributed, uncracked material which satisfies structural margins (limit load for all welds as well as LEFM for welds H4 and H5). This iterative approach will be pursued by Commonwealth Edison Company during the shroud inspection based on the results achieved.

3. From Reference 1, the allowable crack length for axial welds is longer than the width of the plate material used in the shroud fabrication. Based on this, it is not possible that axial flaws would exceed allowable flaw lengths. Therefore, examination of vertical welds is not necessary for demonstrating structural margins.

4. In addition to the areas identified above, inspection of additional areas of the shroud should be considered based on a review of the fabrication records contained in Reference 2. The information contained in Reference 2 suggests actions may have been taken which would cause local areas of cold work on the shroud. Because of the known susceptibility of such areas to IGSCC, inspection of these areas is appropriate. However, the areas of cold work were not identified in Reference 2. Based on this, a location-specific inspection recommendation cannot be provided. However, if cold worked locations are identified during the inspection, it is recommended that visual inspection of these local areas also be performed.

NOTE: (a) It is recognized that access limitations at the H7 weld may preclude the possibility of identifying sufficient uncracked material to positively demonstrate structural margin through limit load analysis. Should this prove to be the case, a conclusion as to the integrity of the weld may be based upon the results of the examinations performed.

4.0 REFERENCES

[1] GENE-523-02-0194, Revision 0, "Evaluation and Screening Criteria for the Quad Cities 1 and 2 Shrouds," W.F. Weitze, GE Nuclear Energy, San Jose, CA, March 1994.

[2] GENE-771-04-0194, Revision 0, "Shroud Fabrication and Operational History Data, Quad Cities 1," G. L. Hodson, GE Nuclear Energy, San Jose, CA, March 1994.

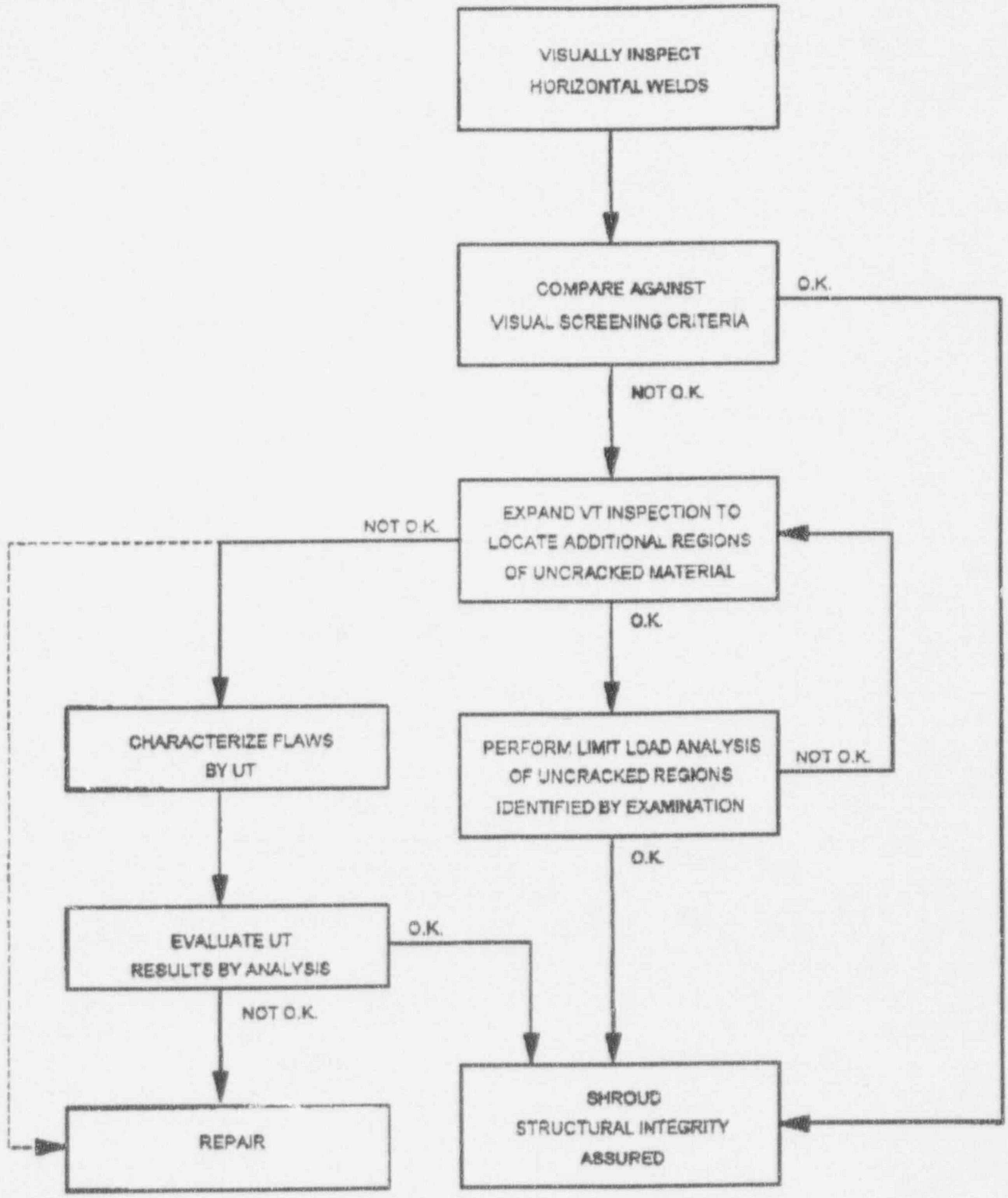

Figure 1: Shroud Inspection Flow Diagram

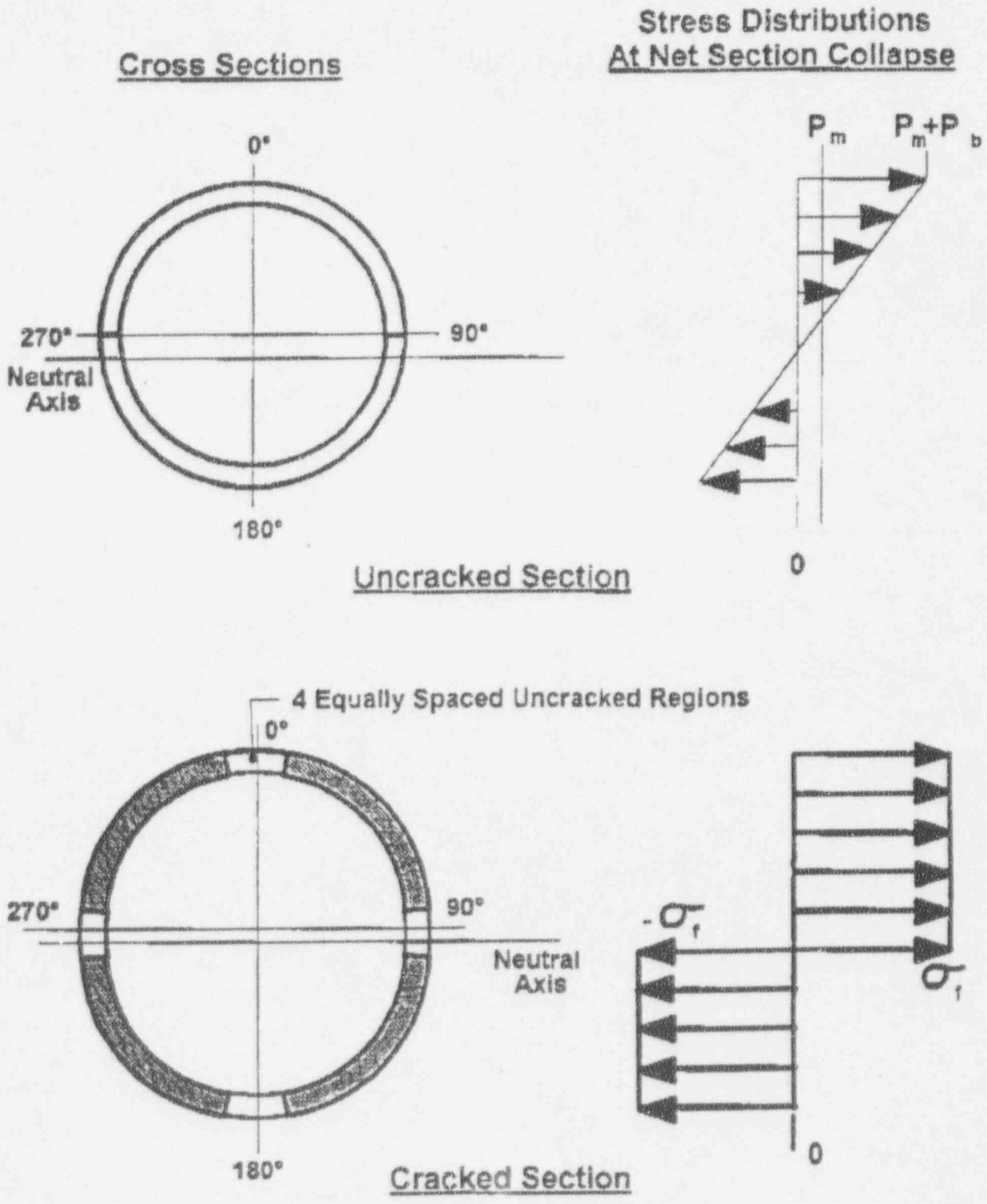

Figure 2: Limit Load Approach

ATTACHMENT [illegible]

General Electric Company Report GENE-523-A79-0594, dated June 1994, Evaluation of the Indications Found at the H5 Weld Location in the Quad Cities Unit 1 Shroud.