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BWR CORE SHROUD INSPECTION AND FLAW EVALUATION GUIDELINES

Prepared for the BWR
Vessel and Internals Project
Assessment Subcommittee

Prepared by: T A Caine

T. A. Caine, Principal Engineer
Reactor Internals Management Projects

T A Caine for

H. S. Mehta, Principal Engineer
Structural Mechanics Projects

Verified by: [signature] for

G. L. Stevens, Senior Engineer
Structural Mechanics Projects

Approved by: [signature] for

S. Ranganath, Projects Manager
Engineering and Licensing
Consulting Services

GE Nuclear Energy

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EXECUTIVE SUMMARY

Cracking has been observed in the vicinity of core shroud welds at several domestic and overseas boiling water reactors (BWRs). Visual (VT) and ultrasonic (UT) test examinations of the shroud weld areas have shown both circumferential and axial indications, mostly associated with the heat affected zones of the circumferential shroud welds. In April 1994, the Boiling Water Reactor Owners' Group (BWROG) published a document entitled "BWR Core Shroud Evaluation" (Report No. GE-NE-523-148-1193). This document provided a conservative generic methodology to evaluate core shroud flaw indications on a plant-specific basis. However, shroud inspections conducted in the Spring of 1994 using VT and UT methods revealed that the shroud cracking is more extensive and less predictable than originally anticipated.

The BWR Vessel and Internals Project (VIP), formed in response to heightened industry concern on shroud cracking, committed to supply a generic inspection and flaw evaluation criteria for use by plants in the upcoming Fall 1994 outages. This report meets that commitment, and reflects the new information gained from the Spring 1994 inspections. The objectives of this report are to present a generic inspection strategy, and to define a flaw evaluation methodology that includes appropriate levels of conservatism to assure shroud integrity while optimizing the overall impact on outage schedules, resources and exposure.

The inspection strategy, combined with the flaw evaluation methodology, is intended to provide guidance on "what" to inspect and "how much". The recommended weld inspections are based on SCC susceptibility by plant and additionally on field experience by weld. The strategy identifies the minimum required inspection and analysis scopes needed to satisfy safety margins, including allowances for crack growth and inspection method uncertainty. Plants are categorized as needing no inspection, limited inspection or comprehensive inspection of circumferential welds, depending on factors such as age, water chemistry history and materials of construction. Inspection scope expansion criteria are provided as well. The strategy provided here is intended to serve as a guide in developing plant-specific inspection plans which will be appropriate and conservative for all BWRs, and supersedes inspection recommendations in SIL 572, Revision 1.

The flaw evaluation methodology allows the utility to make the conservative assumption that regions which are either uninspected, or where cracking is detected but not sized, are fully cracked. When this very conservative approach cannot be used to meet acceptance criteria, the flaw evaluation methodology allows evaluation of actual inspection results, considering both uncracked and partially cracked regions.

This report is intended to be a living document. Therefore, new information obtained from future core shroud inspections, qualification testing of NDE techniques, additional research to quantify more realistic crack growth rates, etc., will be factored into subsequent revisions of this report.

1.0 INTRODUCTION

1.1 Background

Boiling water reactors (BWRs) designated BWR/2 through BWR/6 were designed with a core shroud. The core shroud is a stepped cylinder which directs flow through the core. It performs the safety functions of helping to maintain fuel alignment such that control rods can be inserted and forming part of the boundary to maintain water level in the core after a LOCA (loss of coolant accident). Due to its large size and varying diameters, the shroud is an assembly of welded plates and rings, made from 304 or 304L stainless steel. The design configuration of the core shroud differs from plant to plant depending on the fabricator and BWR product line. As a result, there are different designations for the various circumferential welds (H1, H2, H3, etc.) and vertical welds (V1, V2, V3, etc.) in the shroud assembly. For purposes of discussion in this report, the circumferential weld configuration shown in Figure 1-1 will be followed.

Shroud cracking, first detected in 1990, has been found in a significant number of BWRs in 1993 and 1994, predominantly and most significantly in circumferential welds. Owners were apprised of the cracking through GE SILs and RICSILs and NRC Information Notices [1-1 through 1-5]. As a result of the increased shroud crack findings, the BWR Owners' Group (BWROG) published a report entitled "BWR Core Shroud Evaluation" [1-6]. This report provided a conservative, generic screening methodology to evaluate core shroud flaw indications on a plant-specific basis. It emphasized a statistical sampling method of inspection, where initial inspections of H3 (top guide support ring) and H4 (core beltline) were to be used to indicate whether expansion to other circumferential welds was warranted. However, several Spring 1994 shroud inspections using VT and UT methods revealed that the shroud cracking is more extensive and less predictable than originally anticipated. Specifically, significant cracking, assumed to be 360°, at the H5 (core plate support ring) weld was found at several plants where the H3 and H4 cracking was less extensive.

The difficulty of predicting shroud cracking led to heightened NRC concern and actions on the shroud issues. The BWR Owners had previously responded to the industry concern on shroud-related issues by forming the BWR Vessel and Internals Project (VIP), managed by BWR utility executives. The VIP formed Subcommittees on Inspection, Assessment, Mitigation and Repair, as well as an Integration Subcommittee and an

Executive Oversight Committee to provide consistency in the VIP's activities. An urgent activity of the Assessment Subcommittee has lead to the generation of this report, in time to support Fall 1994 outages. The report presents current inspection strategies and flaw evaluation methodologies that take into consideration recent plant-specific analysis approaches and experiences as well as the guidance of the BWROG report [1-6].

1.2 Objectives

The overall goal of the inspection program is to identify the inspections and associated evaluations that will insure shroud integrity and margins for safe operation. With that in mind, the basic technical objectives of this report are twofold:

1. Provide VIP members with an inspection strategy which identifies which shroud welds need to be inspected, and identifies varying benefits associated with different inspection methods (details on inspection methods are being provided separately by the VIP Inspection Subcommittee). The method and extent of inspection of a given shroud weld identified in this report is expected to depend on various plant-specific criteria, so the method and extent will be determined and justified by individual plants, using the Assessment and Inspection Subcommittee documents for guidance.

2. Provide VIP members with a flaw evaluation methodology that is technically sound and has appropriate, but not excessive, conservatism to assure adequate margins of safety during subsequent operation. The underlying reasoning in optimizing conservatism is to have a cost-effective flaw evaluation methodology that minimizes the need for plant-specific analyses which deviate in methodology from the guidance in this report. This will standardize analyses, thus minimizing the extent of plant-specific NRC reviews needed in justifying return to operation with shroud cracking.

This report supersedes the inspection recommendations of SIL 572, Revision 1, and is intended to be a living document. Therefore, new information obtained from future core shroud inspections, qualification testing of NDE techniques, additional research to quantify more realistic crack growth rates, etc., will be factored into subsequent revisions of this report.

1.3 References

[1-1] GE RICSIL 054, Revision 1, "Core Shroud Cracks," July 1993.

[1-2] GE SIL 572, Revision 1, "Core Shroud Cracks," October 1993.

[1-3] GE RICSIL 068, Revision 2, "Update on Core Shroud Cracking," May 1994.

[1-4] NRC Information Notice 93-79, "Core Shroud Cracking at Beltline Region Welds in BWRs," September 1993.

[1-5] NRC Information Notice 94-42 and Supplement 1, "Cracking in the Lower Region of the Core Shroud in BWRs," July 1994.

[1-6] "BWR Core Shroud Evaluation," Report No. GE-NE-523-148-1193, April 1994.

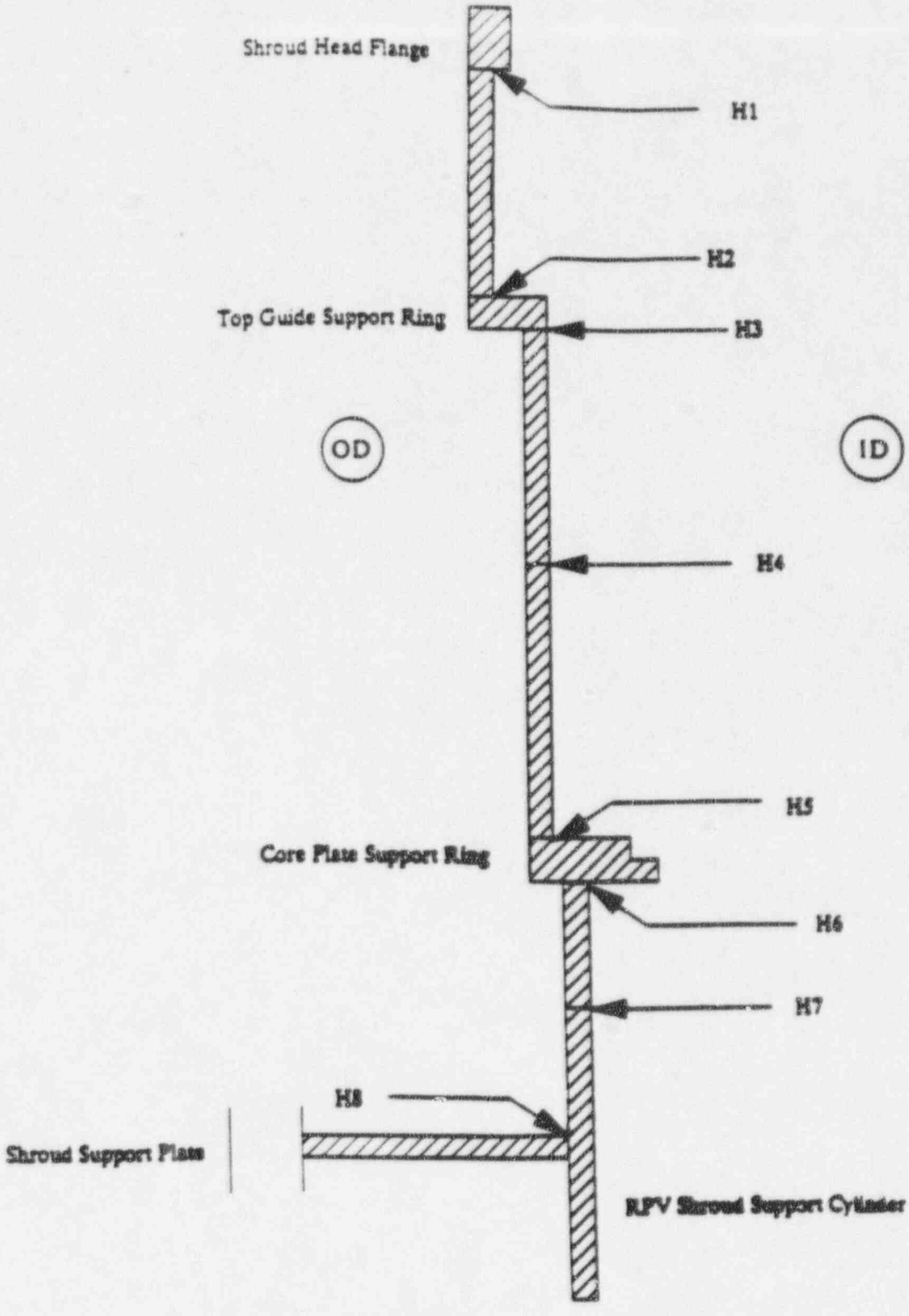


Figure 1-1 Example of Core Shroud (Design is Plant Specific)

2.0 CORE SHROUD DESIGN INFORMATION

The core shroud is an austenitic stainless steel cylinder assembly which provides a partition to separate the upward flow of coolant through the core from the downward recirculation flow. This partition separates the core region from the downcomer annulus, thus providing a floodable region for a postulated recirculation line break.

The core shroud is typically composed of three cylindrical shell sections and three rings. The three rings are the shroud head flange, top guide support ring and core plate support ring. The top cylindrical shell connects the shroud head flange to the top guide support ring. The longest cylindrical portion connects the top guide support ring to the core plate support ring. The bottom cylindrical shell connects the core plate support ring to the shroud support cylinder which is typically made from Alloy 600 material. The shroud support legs are located at the bottom edge of the shroud support cylinder (a few plants, supported on the cantilever principle, do not have support legs).

Some of the significant differences between core shroud designs and fabrication conditions are:

- Diameter of shroud (diameter varies in some plants)
- Thickness of shroud wall (in some cases varying thickness along shroud height)
- Number of horizontal welds in the core beltline
- Number of vertical welds connecting the cylindrical shells
- Material (Type 304 vs. 304L)
- Carbon content
- Fabrication of rings (single piece forging vs. segmented welded plate pieces)
- Tapered lower cylindrical shell vs. straight lower cylindrical shell

Figure 1-1 shows a schematic of one type of shroud design. There are variations in the number of welds with different plant designs. Reference [2-1] provides sketches of the various shroud configurations. For the purposes of the generic discussions and guidance in this report, the weld designations in Figure 1-1 will be used.

The shroud base materials are 304L (carbon content 0.04 wt.% or less) or 304. Carbon content for Type 304 shroud plates varies from 0.045 wt.% to 0.074 wt.%. Hardness is in the range of Rockwell B hardness of 90 for Type 304 and Rockwell B hardness of 92 for Type 304L. The rings are fabricated from welded plate segments or from forgings. While welded-plate rings follow the carbon ranges of 304 or 304L, the forged rings in some 304 shrouds have low carbon.

The horizontal and vertical welds are typically made by submerged arc automatic welding. Weld filler material is Type 308 or Type 308L. Typically, shroud seam weld prep surfaces were prepared by machining the base metal. In cases where seam welds were the double groove geometry, the second groove was prepared for welding by grinding or gouging, followed by liquid penetrant examination. Final surfaces of the welds were also inspected by liquid penetrant examination.

The weld between the stainless steel lower cylinder and the Alloy 600 shroud support cylinder is typically Alloy 182 material. The weld prep is typically single beveled with or without a backing ring.

The austenitic stainless steel material is typically purchased in the solution annealed condition. No solution annealing was performed after welding of the various shroud parts, although BWR/6 shroud assemblies may have received a low temperature stress relief to reduce peak weld residual stresses.

During assembly and shipment of the core shroud, braces, jacks and temporarily welded supports were used to help in meeting design geometric tolerances. In many cases there is no recorded documentation of these practices, but it is likely that they did occur. Since these temporary welds were not full penetration welds, the likelihood of developing through-wall flaws is less than that for other welds.

2.1 Susceptibility Factors

The pattern of cracking indicated from field inspections appears consistent with the SCC susceptibility criteria (Water Chemistry, Material Carbon Content, Fabrication History, Neutron Fluence and Hot Operating Time) described in SIL 572, Revision 1 and the BWROG report [1-6] and discussed briefly below:

1. Fabrication History

Fabrication history can have a significant influence on SCC susceptibility and, in particular, in the extent of circumferential cracking. As was shown in the BWROG Generic Safety Assessment [2-2], the shroud weld locations exhibiting the greatest extent of circumferential cracking (> 200 inches effective crack length) are all associated with ring to shell welds, i.e. H1, H2, H3 and H5. The various support rings present above and below the top guide and at the core plate elevation were fabricated from forgings at some plants, whereas in most cases they were fabricated from arcs cut from rolled plate and welded into a ring configuration followed by machining to size. This process for the welded-plate rings exposes the short transverse "end grain" orientation to the coolant, and can result in the presence of a relatively deep layer of surface cold work. Analysis of boat samples containing shroud cracking at Brunswick-1, Dresden-3 and Quad Cities-1 indicated that the depth of the cold worked layer can range from 0.010 inches to as deep as 0.060 inches.

Recognizing the potentially higher SCC susceptibility of the welded-plate rings, the shroud SIL specifically identified the top guide and core plate support rings as areas where more extensive cracking may be found. To date, consistent with the SIL, the most extensive cracking has occurred in the plate ring material in and near the weld HAZ. In all cases to date where cracking has exceeded 180° of circumference, the cracking has occurred at the top guide or core plate support rings, where the rings were fabricated from plate material rather than forgings. The distinction between welded-plate ring cracking and other shroud cracking (in forged ring or shell regions) can be seen in the inspection results in Figure 2-1, where welded-plate ring cracking is, in most cases, considerably more extensive. Since the welded-plate ring versus forged ring fabrication history is known for most plants, this aspect of shroud fabrication was selected as a factor in developing susceptibility groupings in [2-2].

2. Water Chemistry

Extensive SCC testing has shown that SCC initiation and growth is strongly dependent on the electrochemical corrosion potential (ECP) on the surface of a component. ECP depends on the level of oxidants, such as oxygen and peroxide, in the reactor water. However, there is no historical data base of ECP or the levels of oxidants at the shroud surfaces, so ECP cannot be used as a factor for susceptibility grouping.

One variable of water chemistry that has been measured regularly during operation at all BWRs is conductivity. Laboratory SCC tests and field experience with recirculation pipe cracking and shroud head bolt cracking have shown a definite correlation of conductivity with initiation and growth of SCC. Therefore, conductivity was investigated as a factor for susceptibility grouping.

Because of the significant cold work and short transverse orientation present in the welded-plate rings, it is believed that SCC initiation occurred very early in plant life. This is supported by the observation that cold worked bent beam and pressurized tube SCC specimens exposed in-reactor were found to exhibit SCC in less than one fuel cycle. Therefore, the conductivity history for early plant hot operation is expected to have a significant effect on SCC initiation and crack growth. The shroud inspection results were evaluated against the mean conductivity for the first five fuel cycles, as shown in Figure 2-1. The five cycle mean value was chosen to represent early operating conductivity after reviewing the conductivity history of the Brunswick plants. It is used here for generic evaluation, recognizing that a different value may be appropriate for a particular plant. The comparison of early operating conductivity with extent of observed cracking, shown in Figure 2-1, indicates that early conductivity influences expected extent of cracking. Therefore, mean conductivity for the first five cycles was selected as a factor for susceptibility grouping in [2-2].

3. <u>Material Carbon Content</u>

Although cracking has been detected in core shroud material having a range of reported carbon contents from greater that 0.06 wt.% to as low as 0.023 wt.%, all incidents where cracking has exceeded 180° of circumference have occurred in ring plate material with carbon content equal to or greater than 0.06 wt.%. This is consistent with current understanding of weld HAZ degree of sensitization and resultant expected IGSCC susceptibility.

In the absence of surface cold work and/or crevices, cracking in L-grade material was not expected until the neutron fluence exceeded the IASCC threshold value of 3 to 5×10^{20} n/cm^2 (E> 1 Mev). The SIL and BWROG did recommend inspection of all plants with L-grade shroud materials following eight on-line years of operation. This recommendation appears conservative based on inspections to date at ten plants with

L-grade core shrouds. Significant (but < 180 degree) SCC in L-grade shrouds has been reported at two plants where the on-line time equaled or exceeded 10 years. Other than the very minor (~1 inch vertical) crack lengths detected at Fermi-2, inspected L-grade shrouds with as much as 8.4 on-line years have shown no cracking. Since the focus in [2-2] was consideration of 360° cracking, it was appropriate to select carbon content (generically 304 versus 304L) as a factor for susceptibility grouping.

4. Neutron Fluence

It is evident that core shroud weld cracking can occur by IGSCC in the absence of significant fluence as evidenced by the indications found at several plants at the H-1 welds and the core plate support ring welds where the fluence, f, is very low ($f<1x10^{18}$ n/cm^2). However, a fluence effect on cracking susceptibility (IASCC at $f>3$ to $5x10^{20}$ n/cm^2) or a synergistic interaction of fluence in already sensitized material (IGSCC at $f>1x10^{19}$ n/cm^2) is expected and has been verified with boat samples taken from Brunswick-1 and KKM. Inspection results do not indicate that fluence is a primary contributor to extensive cracking, so it was not selected for susceptibility grouping in [2-2].

5. Hot Operating Time

As with any stress corrosion phenomenon, the frequency and extent of core shroud weld cracking would be expected to correlate with hot operating time. In addition, fluence increases with operating time leading to increased susceptibility at some welds. Hot operating time, defined as the time spent with reactor coolant above 200°F, is not readily available data, so extent of cracking is plotted in Figure 2-2 versus on-line years, which is a close approximation. The plot indicates that cracking in excess of 180° is unlikely until a plant accumulates 10 on-line years of operation. While plants were not grouped in [2-2] by hot operating time, this conclusion provides helpful information for newer BWRs, which have also experienced lower early conductivities as a result of lessons learned from recirculation pipe cracking in older BWRs.

Several conclusions can be drawn from the inspection results available to date when compared to the susceptibility grouping factors:

- There is a clear distinction that 360° cracking can occur in 304 welded-plate shroud rings, but is extremely unlikely, in the near term, in shrouds with 304 forged rings or 304L materials.
- There is a tendency in welded-plate rings for cracking extent to be greater with higher early (e.g., first 5 cycles) conductivity.
- 360° cracking has not occurred in any of the eight plants inspected with less than 9.5 years of hot operation, and is therefore very unlikely in other plants with less than 9.5 hot operating years.

Based on the susceptibility considerations described above, Reference [2-2] placed the various BWR shrouds into seven categories:

(1) Type 304 shrouds with welded plate rings and highest conductivity
(2) Type 304 shrouds with forged rings and highest conductivity
(3) Type 304L shrouds with highest conductivity
(4) Type 304 shrouds with mid-range conductivity
(5) Type 304L shrouds with mid-range conductivity
(6) Type 304 shrouds with lowest conductivity
(7) Type 304L shrouds with lowest conductivity

These rankings were focused on the susceptibility to extensive, 360° cracking for purposes of a basis for safe continued operation of uninspected plants. For the purpose of categorizing plants for inspection, susceptibility to *any* cracking is significant. As a result, inspection categories, described in Section 3.1, are somewhat different from those shown above.

2.2 References

[2-1] "Responses to NRC Questions on Core Shroud and Reactor Internals," GE Report for BWROG, GENE-523-A114P-0894, August 1994 (Proprietary).

[2-2] "BWR Shroud Cracking Generic Safety Assessment," GE Report for BWROG, GENE-523-A107P-0794, August 1994 (Proprietary).

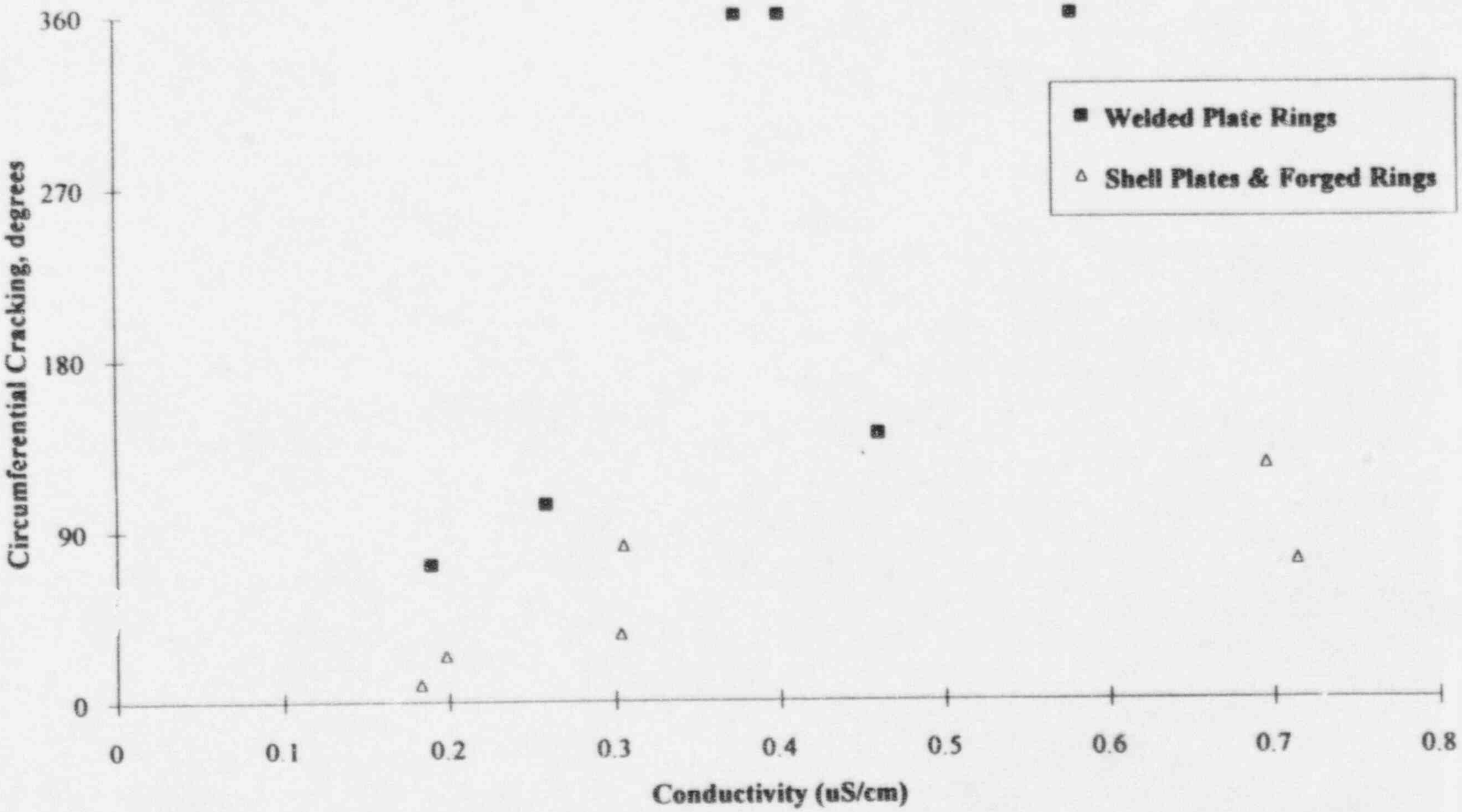


Figure 2-1. Extent of Cracking versus Conductivity

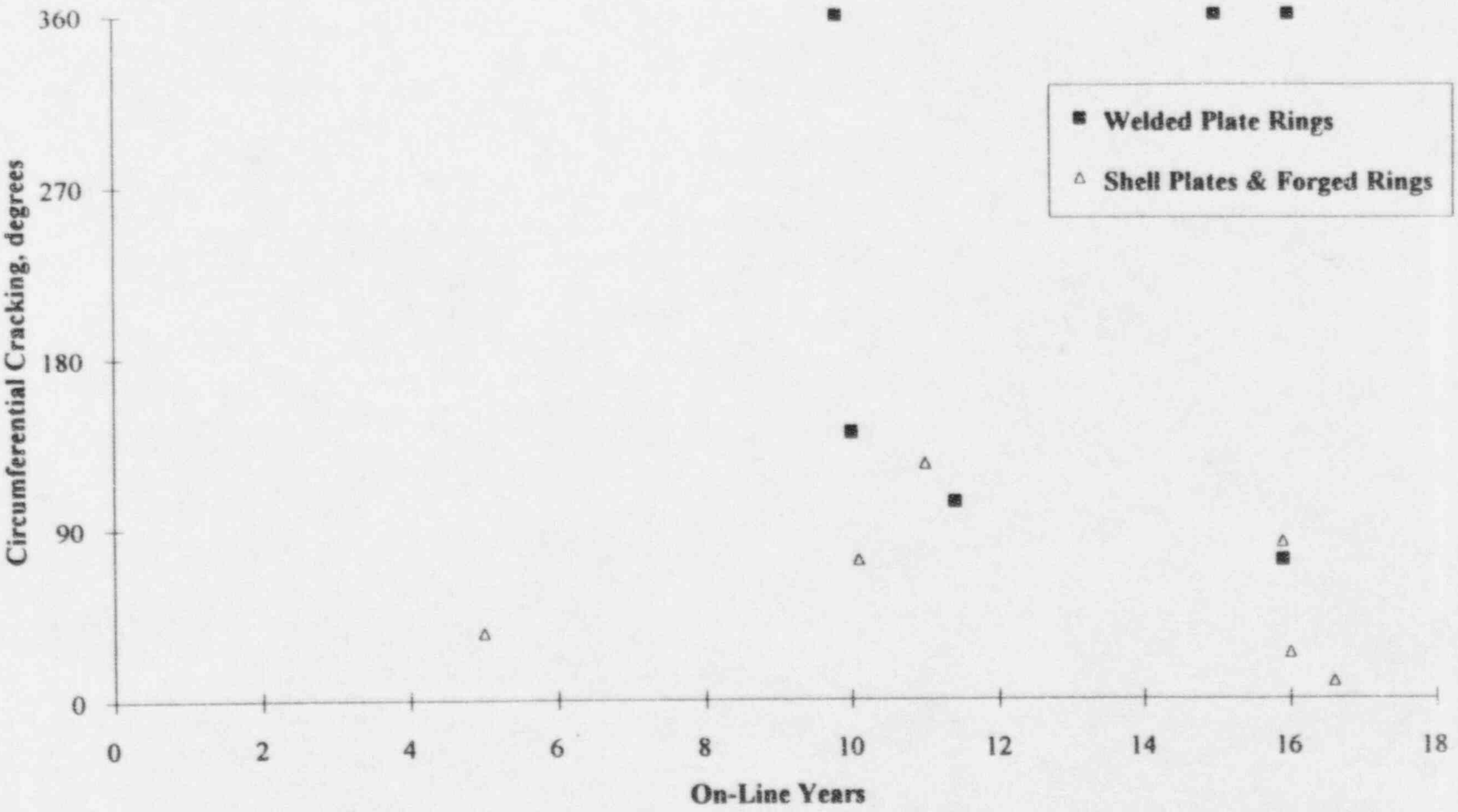


Figure 2-2. Extent of Cracking versus On-Line Years

3.0 INSPECTION STRATEGY

The objective of inspecting the shroud is to assure core shroud structural integrity for a specified period of operation, using a cost-effective combination of inspection scope and NDE techniques while considering manrem exposure and outage schedule impact. The inspection strategy is designed to accomplish this objective by outlining stages of inspection effort and associated analyses which logically expand, as needed, to meet structural integrity criteria.

The first stage of effort is to inspect for a length or lengths of uncracked ligament which meet limit load, and when appropriate LEFM/EPFM, acceptance criteria for the design basis loading conditions. The required lengths of uncracked ligament include a conservative margin to accommodate crack growth and inspection uncertainty. When the required amount of uncracked ligament is found, the rest of the weld may be assumed to be cracked through-wall, and shroud integrity will be assured for the specified operating cycle. Additional inspections may be done, but are not required.

Inspection techniques are outlined for each weld (Tables 3-2 and 3-3), according to the accessibility of both the ID and OD surfaces. Current UT techniques may not detect cracking initiating from the examination surface. VT or ET must be used in combination with UT to confirm the absence of cracking initiating from the examination surface, in order to have a reinspection frequency of two cycles. Otherwise, examination is currently required every cycle. Development of UT techniques for surface detection of flaws may eliminate the need to supplement UT exams with VT or ET for extended cycle operation.

The required inspection scope for each weld is defined as that number of crack-free ligaments that are large enough to provide adequate structural margin, taking into account the necessary safety factors, inspection uncertainties and future crack growth. The length and number of ligaments required is determined for each shroud horizontal weld such that structural margins applicable to limit load, and where applicable LEFM, methodology are realized.

The combination of number of ligaments and required ligament lengths is that which is needed to satisfy the limit load, and where applicable LEFM, approach plus an amount to allow for two cycles (regardless of one- or two-cycle inspection frequency) of crack growth from cracking assumed to be adjacent to both sides of the ligament, plus an amount to account for the uncertainty associated with the inspection method.

$$l_{min} = l_{calc} + 2CG + 2U \qquad (3\text{-}1)$$

where: l_{calc} = minimum required ligament length, as calculated by limit load/LEFM/EPFM approach
CG = crack growth for two operating cycles
U = length added for NDE method uncertainty
l_{min} = minimum required inspection length

The CG rate used to establish l_{min} should have a sound technical basis and an appropriate degree of conservatism. The VIP intends to further develop appropriate CG rates in the future, but for analyses supporting the Fall 1994 outage inspections, a CG rate of 5×10^{-5} inches/hour is consistent with previous NRC-approved shroud submittals.

Determination of inspection uncertainties (U) by the VIP Inspection Subcommittee is underway. For analyses supporting Fall 1994 outage inspections, engineering judgment based on limited information on inspection method accuracy has been used to estimate U. A value of twice the shroud thickness, 2t, has been selected, which means that l_{min} includes six to eight inches of length *in each ligament* to account for uncertainties.

If it is not possible to find sufficient *length* of uncracked ligament, then the next stage of the process is to utilize *depth* sizing. The length and depth data are then evaluated in accordance with the flaw evaluation methodology in Section 4.0. Accessibility limitations may preclude inspecting sufficient portions of a weld to perform a quantitative assessment. In these cases, a qualitative assessment must be done, using data from the inspected portions and plant-specific history, if appropriate. If the structural integrity of the shroud cannot be established, then a repair must be implemented prior to restart.

In summary, the inspection strategy provides a cost-effective approach of integrated inspection and assessment. The approach is designed to quantitatively demonstrate, within the constraints of accessibility and existing NDE technology, the necessary structural margins (including safety factors) for a defined period of time. The strategy is based on current knowledge of the shroud cracking issue and inspection experience at various plants. As more inspections are performed, and as the understanding of technical issues such as crack growth rate improve, some of the specifics of the approach may be further refined.

The strategy provided here is intended to serve as a guide in developing plant-specific inspection plans which will be appropriate and conservative for all BWRs. It is intended to provide guidance on inspection which supersedes SIL 572, Revision 1.

3.1 Inspection Scope

The extent of inspection required has been determined based on three susceptibility factors which can be readily evaluated: hot operating time, conductivity and shroud material type. The seven categories from Section 2.1, which were established relative to the likelihood of *extensive 360°* cracking, were condensed into three categories when considering the likelihood of *any* cracking. The three categories are described below, in order of increasing susceptibility:

Category A: Plants with hot operating time of less than 6 years for 304 shroud material, or less than 8 years for 304L shroud material and with average conductivity for the first five fuel cycles at or below the BWR Water Chemistry Guidelines [3-1] Action Level 1 value of 0.30 μS/cm. Such plants have shown very low likelihood of cracking, demonstrated by field experience with the shroud and other components.

Category B: Plants with 304L shroud material, with hot operating time of 8 years or more but with average conductivity for the first five fuel cycles at or below the BWR Water Chemistry Guidelines [3-1] Action Level 1 value of 0.30 μS/cm. Numerous plants which meet these criteria have performed inspections and found no cracking.

Category C: Plants with 6 or more hot operating years with 304 shroud material and plants beyond 8 hot operating years with 304L shroud material and average conductivity for the first five fuel cycles above 0.30 μS/cm.

Evaluation of the BWRs according to the logic in the Figure 3-1 flowchart leads to the plant groupings shown in Table 3-1.

3.1.1 *Comprehensive Inspection Scope*

The scope included in the near term for generic shroud inspection is H1-H7 for BWR/2-6s and H8 for BWR/2s.

Inspection of other shroud support attachment welds is less urgent, based on the judgment that these welds are relatively less susceptible to SCC. Inspection of these welds will be addressed in the future, as well as development of inspection tooling, if needed. The relative SCC susceptibility judgment is based on the following:

- The Alloy 182 welds attach Alloy 600 base material (H7 in BWR/3-6 and H8 in BWR/2 are Alloy 182, but are bimetallic welds). The shroud support welds are uncreviced. While some cracking of uncreviced Alloy 182 has occurred, most cracking experience with Alloy 182, such as in access hole covers and shroud head bolts, has involved creviced Alloy 600.

- Vessel assembly sequence information reviewed indicates that many of the shroud support assemblies, including H8, H9, etc., were already installed in the vessel bottom heads of US BWRs when the bottom head assembly welds were post-weld heat treated (PWHT) at 1150°F. While PWHT at this temperature does not completely relieve Alloy 182 residual stresses, it does significantly decrease the peaks of the residual stress, which should slow SCC initiation and growth.

There are other welds and welded components attached to the shroud, such as vertical welds, ring segment welds, and attachment welds for core spray piping, LPCI piping, lugs and other cases where welded attachments may have been removed, such as alignment supports for installation and vibration test equipment fixtures. Core spray piping is already covered by inspection requirements intended to detect SCC. For other welded shroud attachments, the welded region is small enough that even if through-wall SCC were to develop, the safety consequences due to leakage from the core region into the shroud annulus region would be considerably less significant than the scenarios evaluated for circumferential welds. There would be no significant safety concerns resulting from cracking of these welds for any operating condition, given that the structural margins of the circumferential welds are maintained. Therefore, inspection of these welds is not currently required.

For the specific case of the shroud vertical welds, it has been shown in previous analyses that the allowable crack length for these axial welds is longer than the height of the plate material used in the shroud fabrication. Based on this, it is not expected that axial flaws would exceed allowable flaw lengths. Leakage through a fully cracked vertical weld has also been shown to be acceptably small. Therefore, examination of vertical welds is not necessary for demonstrating structural margins if structural integrity of the horizontal welds is assured, which would be the case when returning to operation after inspection. If hardware has been installed to repair the shroud, and that repair hardware design assumes that the vertical welds (or ring segment welds) remain intact to some degree, then the vertical and ring segment welds will need to be inspected to whatever degree needed to satisfy the design assumptions for the repair.

3.1.2 *Plant Categorization*

Category A: No Inspection Required

A Category A plant is not expected to experience shroud cracking in the near term due to its low operating time and low early years conductivity. Therefore, inspection is not considered necessary. In addition to the guidance of SIL 572, Rev. 1, hot operating time < 6 years for 304 plants or < 8 years for 304L plants, early conductivity is used as a screen for this category. Several plants in this category have done limited shroud inspections. The inspection results support exemption for such plants.

Category B: Limited Inspection Required

A Category B plant has some limited, but low, potential for shroud cracking. In general, Category B plants have exceeded the initial screen for operating time, but are significantly less susceptible to cracking than Category C plants. This is due to better-than-average water chemistry (early conductivity averaging 0.3 μS/cm or less) and the use of low carbon materials in fabrication. Therefore, inspection of only a limited number of shroud welds is considered necessary. The welds chosen for inspection are those representative of each region of the shroud where significant cracking has been seen to date, namely H3, H4 and H5. In addition, H7 is included, due to its unique combination of a bimetallic weld with, in some cases, a backing ring crevice. The philosophy being applied for this category is that cracking is not likely and a limited inspection can be performed to verify this. Since limited inspection may be done in any of these welds to confirm the necessary distributed uncracked ligament length, detection of any cracking during the limited inspection shall result in expanding the inspection scope to meet the Category C scope prior to restart. The inspection implementation approach for a Category B plant is given in Table 3-2.

Category C: Comprehensive Inspection Required

A Category C plant has a relatively high potential for some amount of shroud cracking. Category C plants have high carbon materials or early conductivity averaging greater than 0.3 μS/cm. Therefore, inspection of shroud welds H1 through H7 (and H8 for BWR/2s) to demonstrate structural margin is considered necessary. The inspection implementation approach for a Category C plant is given in Table 3-3.

3.2 Inspection Implementation Approach

Based on the distributed ligament approach described above, the following progressive steps would be followed in developing an inspection plan:

1. Determine the plant inspection category (A, B or C).

2. Evaluate the accessibility limitations.

3. Based on inspection category (B or C), accessibility, reinspection frequency desired and other outage-related constraints, select the appropriate NDE method(s) to be used and establish an inspection plan.

4. Perform a limit load, and where required LEFM/EPFM, analysis for the preliminary inspection scope for each weld to be inspected. Establish the length, number and location of uncracked ligaments needed to meet the requirements for structural margin, crack growth and inspection uncertainty. The inspection method(s) and associated inspection frequency for a given weld should conform with those shown in Tables 3-2 and 3-3.

   The initial distribution of ligaments may be symmetric (four at 90°, eight at 45°, etc.) or non-symmetric, and ligaments may be of different lengths. In developing the inspection plan, consideration for scope expansion and the associated activities, such as in-vessel work and fuel movement, should be included in outage planning.

5. If the initial inspection fails to identify the number and length of uncracked ligaments specified in (4) for any given weld, additional weld length shall be inspected. Inspection scope will be expanded until:

   - Acceptance criteria have been met with inspection results from uncracked ligament lengths (requires only characterization of ligament lengths), or

   - Acceptance criteria have been met with inspection results for the "as-found" ligament distribution in cracked and uncracked regions from partial inspection (requires characterization of ligament lengths and depths), or

   - Data from all accessible portions of the weld have been obtained for use in a quantitative or qualitative assessment.

6. In some instances it may not be possible to inspect sufficient portions of a weld to quantitatively assess the structural integrity, due to accessibility limitations or the constraints of the existing inspection technology. In such instances, inspection of all accessible regions with the best available, qualified technology should be performed. A qualitative assessment of the structural integrity of the weld will be performed, based upon the results. If a qualitative assessment must be performed for a given weld, that weld must be re-examined during the next refueling outage.

3.3 References

[3-1] "BWR Water Chemistry Guidelines - 1993 Revision; Normal and Hydrogen Water Chemistry," EPRI TR-103515, February 1994.

Figure 3-1
Inspection Strategy Flowchart

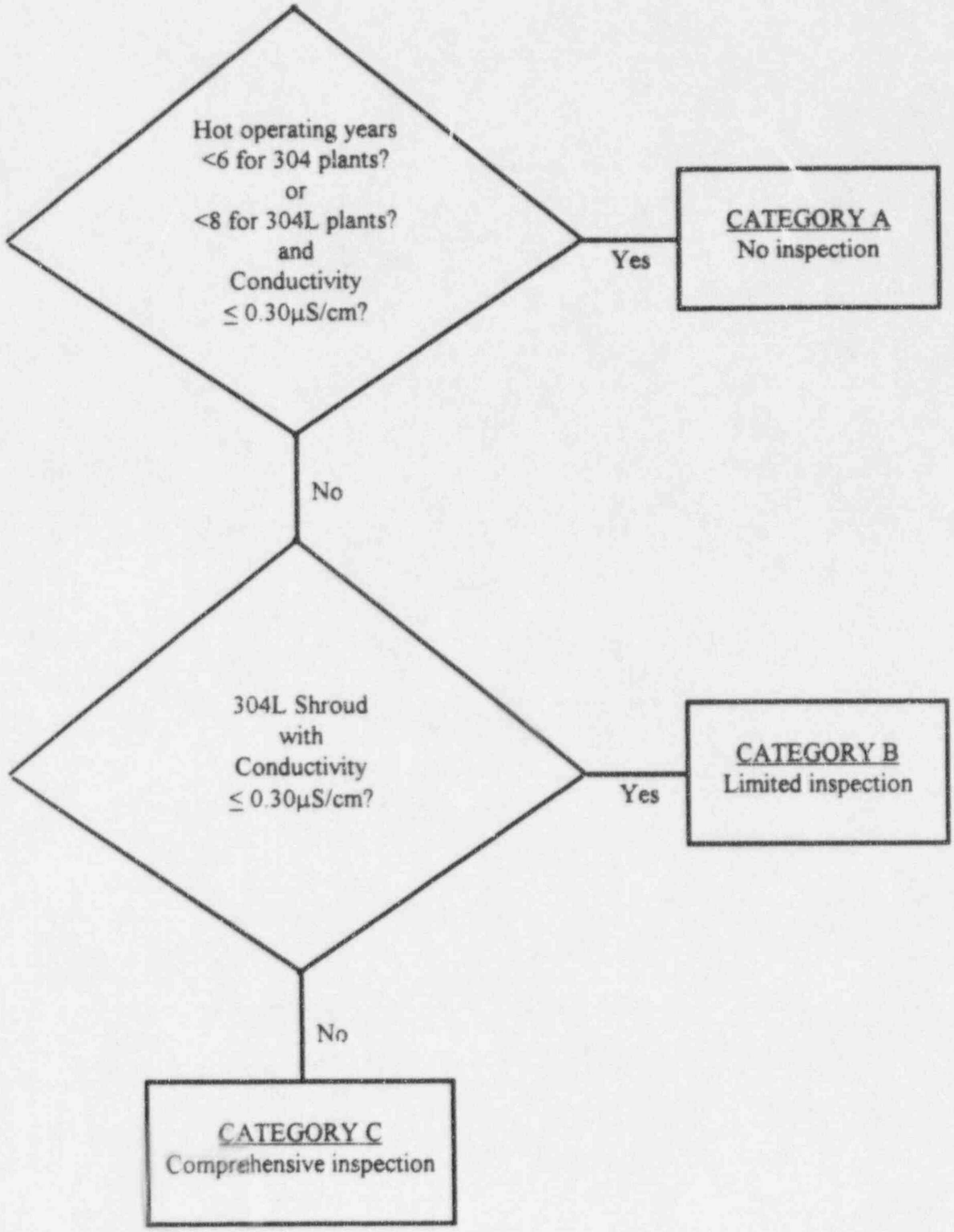


Table 3-1
Inspection Categories

Category	Description	Plant Characteristics	Plants[1]
A	No Inspections Required	a. 304 plants < 6 hot operating years and average conductivity ≤ 0.30 μS/cm during first 5 cycles of operation	None
		b. 304L plants < 8 hot operating years and average conductivity ≤ 0.30 μS/cm during first 5 cycles of operation	Clinton, Fermi 2, Hope Creek, Limerick 2, Nine Mile Point 2, Perry, River Bend, WNP-2
B	Limited Inspection	304L plants with ≥ 8 hot operating years and average conductivity ≤ 0.30 μS/cm during first 5 cycles of operation	Grand Gulf, LaSalle 1 and 2, Limerick 1, Susquehanna 1 and 2
C	Comprehensive Inspection	a. 304 plants with ≥ 6 hot operating years, regardless of conductivity.	Plants with welded-plate rings: Brunswick 1 and 2, Cooper, Dresden 2 and 3, FitzPatrick, Hatch 1, Millstone, Nine Mile Point 1, Oyster Creek, Pilgrim, Quad Cities 1 and 2 Plants with forged rings: Browns Ferry 1, 2 and 3, Monticello, Peach Bottom 2 and 3, Vermont Yankee
		b. 304L plants with ≥ 8 hot operating years and average conductivity > 0.30 μS/cm during first 5 cycles	Duane Arnold, Hatch 2

Notes: 1. Categorization above is based on best estimate of hot operating years at next outage. Individual plants should confirm their categorization.

Table 3-2
Category B Inspection Requirements
(Limited Inspection)

Weld	Inspection Required[1,2,3]	Interim Inspection Recommendations [4]
H3	a. VT = l_{min} on both sides	a. Re-inspect every other outage.
	b. UT = l_{min} from outside and VT/ET[5] = l_{min} on outside	b. Re-inspect every other outage.
	c. UT = l_{min} from outside	c. Re-inspect every outage.
H4	a. VT = l_{min} on both sides	a. Re-inspect every other outage
	b. UT = l_{min} from outside and VT/ET[5]= l_{min} on outside	b. Re-inspect every other outage
	c. UT = l_{min} from outside	c. Re-inspect every outage
H5	a. UT = l_{min} from outside and VT/ET[5]= l_{min} on outside	a. Re-inspect every other outage
	b. UT = l_{min} from outside	b. Re-inspect every outage
H7[6] with backing ring	UT = l_{min} from outside	Re-inspect every outage
H7[6] without backing ring	a. UT = l_{min} from outside and VT/ET[5]= l_{min} on outside	a. Re-inspect every other outage
	b. UT = l_{min} from outside	b. Re-inspect every outage

See next page for notes.

Table 3-2
Category B Inspection Requirements -- cont'd
(Limited Inspection)

Notes:

1. If a crack-like indication is identified at any weld location, then Category C inspection requirements shall be applied prior to restart.

2. VT or ET required for near surface detection.

3. The following notation is used:

$$l_{min} = l_{calc} + 2CG + 4t$$

where:

l_{calc} = minimum required ligament length, as calculated by limit load/LEFM/EPFM approach.

CG = crack growth for two operating cycles

t = nominal shroud thickness

l_{min} = minimum required inspection length

4. Inspection frequency is based on the current, very conservative crack growth rate assumed. Frequency may be lowered based on improved estimate of crack growth rate based, for example, on measured ECP values or other mitigation efforts for which credit may be taken.

5. ET results can be used to provide the basis for reinspection every other refueling outage once the ET technique has been qualified.

6. Accessibility limitations and/or examination techniques may not allow a fully quantitative assessment.

Table 3-3
Category C Inspection Requirements
(Comprehensive Inspection)

Weld	Inspection Required[1,2]	Interim Inspection Recommendations [3]
H1	a. UT = l_{min} from outside and VT/ET[4] = l_{min} on outside	a. Re-inspect every other outage
	b. UT = l_{min} from outside	b. Re-inspect every outage
H2	a. UT = l_{min} from outside and VT/ET[4] = l_{min} on outside	a. Re-inspect every other outage
	b. UT = l_{min} from outside	b. Re-inspect every outage
H3	a. VT = l_{min} on both sides	a. Re-inspect every other outage
	b. UT = l_{min} from outside and VT/ET[4] = l_{min} on outside	b. Re-inspect every other outage
	c. UT = l_{min} from outside	c. Re-inspect every outage
H4	a. VT = l_{min} on both sides	a. Re-inspect every other outage
	b. UT = l_{min} from outside and VT/ET[4] = l_{min} on outside	b. Re-inspect every other outage
	c. UT = l_{min} from outside	c. Re-inspect every outage
H5	a. UT = l_{min} from outside and VT/ET[4] = l_{min} on outside	a. Re-inspect every other outage
	b. UT = l_{min} from outside	b. Re-inspect every outage

Table 3-3
Category C Inspection Requirements - cont'd
(Comprehensive Inspection)

Weld	Inspection Required[1,2]	Interim Inspection Recommendations [3]
H6[5]	a. UT = l_{min} from outside and VT/ET[4] = l_{min} on outside	a. Re-inspect every other outage
	b. UT = l_{min} from outside	b. Re-inspect every outage
H7[5] with backing ring	UT = l_{min} from outside	Re-inspect every outage
H7[5] without backing ring	a. UT = l_{min} from outside and VT/ET[4] = l_{min} on outside	a. Re-inspect every other outage
	b. UT = l_{min} from outside	b. Re-inspect every outage
[illegible] (BWR/2)	a. UT = l_{min} from outside and VT/ET[4] = l_{min} on outside	a. Re-inspect every other outage
	b. UT = l_{min} from outside	b. Re-inspect every outage

Notes:
1. VT or ET required for near surface detection.
2. The following notation is used:

$$l_{min} = l_{calc} + 2CG + 4t$$

where:
- l_{calc} = minimum required ligament length, as calculated by limit load/LEFM/EPFM approach.
- CG = crack growth for two operating cycles
- t = nominal shroud thickness
- l_{min} = minimum required inspection length

Table 3-3
Category C Inspection Requirements - cont'd
(Comprehensive Inspection)

Notes:

3. Inspection frequency is based on the current, very conservative crack growth rate assumed. Frequency may be lowered based on improved estimate of crack growth rate based, for example, on measured ECP values or other mitigation efforts for which credit may be taken.

4. ET results can be used to provide the basis for reinspection every other refueling outage once the ET technique has been qualified.

5. Accessibility limitations and/or examination techniques may not allow a fully quantitative assessment.

4.0 FLAW EVALUATION METHODOLOGY

This section provides the methodology and guidance which can be used to determine the uncracked ligament lengths needed at the circumferential welds to ensure adequate structural margins. Ideally, the azimuths of the ligament lengths may be symmetric in the plane of the weld. However, access limitations may cause the ligament lengths available for inspection to be distributed randomly along the weld (e.g., see Figure 4-1). Therefore, the methodology and guidance provided in this section describe the general case that covers all possible distributions of ligament, incorporates the conservative assumption that the areas other than the inspected ligament lengths are assumed to be cracked through wall, and considers proximity rules (see Appendix B). Finally, should the uncracked ligament length criteria not be satisfied, methodology to analyze the as-found condition is also provided.

To account for the effects of irradiation, three different fracture mechanics techniques are employed to determine the required ligament lengths or to determine whether the given ligament configuration satisfies the structural safety margins. The three techniques are: (1) limit load, (2) linear elastic fracture mechanics (LEFM), and (3) elastic-plastic fracture mechanics (EPFM).

A brief description of these techniques is first provided followed by a detailed description of the procedure for evaluation.

4.1 Fluence Levels and Fracture Mechanics Methods

The shroud material (austenitic stainless steel) is inherently ductile and, therefore, in most cases the structural integrity analysis can be performed entirely on the basis of limit load. The only case for the use of other techniques such as LEFM or EPFM would be when the irradiation-induced changes in the material fracture toughness properties are judged to be significant. Properties relevant to material fracture toughness include yield and ultimate tensile strengths, uniform elongation and upper-shelf Charpy energy. Therefore, the trends in these properties as a function of fluence level were reviewed to determine a fluence value above which the use of LEFM/EPFM techniques would be necessary.

References 4-1 and 4-2 contain data showing trends in yield strength, reduction in area and uniform elongation as a function of fluence at irradiation and test temperatures of

550°F. A review of this data indicates that the yield strength increases occur at a significant rate beyond 3 to $5x10^{20}$ n/cm^2. Further, the data reveal significant changes in the uniform elongation percentage between fluence levels of $1x10^{20}$ and $5x10^{20}$ n/cm^2. The conclusion from these data is that the $5x10^{20}$ n/cm^2 fluence level is an upper bound cut-off for the use of limit load as the sole flaw evaluation method.

The material stress-strain curve is generally characterized by the following equation:

$$\sigma = A \bullet (\varepsilon)^n \qquad (4\text{-}1)$$

where, σ and ε are true stress and strain, respectively. The strain hardening exponent, n, is one of the indicators of ductility which in turn is a good measure of fracture toughness. Reference 4-1 shows the strain hardening exponent values as a function of fluence. From the data it can be seen that changes in the strain hardening exponent begin at approximately $1x10^{20}$ n/cm^2 with significant changes beyond $3x10^{20}$ n/cm^2. Additionally, the data indicates that beyond a fluence level of $2x10^{21}$ n/cm^2, the exponent value is close to zero (i.e., the yield strength is very close to the ultimate strength).

While data in References 4-1 and 4-2 indicate significant ductility changes may be expected beyond $3x10^{20}$ to $5x10^{20}$ n/cm^2 fluence, other data indicates significant ductility is still expected beyond this range. In fact, J-R curve measurements (Figure 4-2) made on a core shroud sample taken from an overseas plant having a fluence of $8x10^{20}$ n/cm^2 showed stable crack extension and ductile failure when tested. Based on this data, the limit load approach would still be applicable beyond the fluence level of $5x10^{20}$ n/cm^2. In fact, the limit load approach should be used at all fluence levels since it deals with the gross structural integrity of the shroud including all of the indications at a weld, whereas the LEFM approach only accounts for the single largest flaw.

Based on the preceding review of irradiated stainless steel data, the following conclusions are made regarding flaw evaluation methods:

- Limit load should be used at all fluence levels since it deals with the gross structural integrity of the shroud, including all of the indications at a weld, whereas the LEFM approach only accounts for the single largest flaw.

- Review of data indicates changes in ductility (based on changes in yield strength and percentage elongation), begin at approximately $1x10^{20}$ n/cm^2. Most data show significant changes beyond $5x10^{20}$ n/cm^2, with notable exception based on recent field data that shows stable crack extension and ductile failure at $8x10^{20}$ n/cm^2. Using the data and applying reasonable conservatisms, possible changes in ductility due to irradiation will be addressed by the use of LEFM/EPFM above fluences of $3x10^{20}$ n/cm^2.

- The trends in data show that the uniform elongation magnitudes and corresponding ductility may be limited beyond the fluence level of $1x10^{21}$ n/cm^2. Therefore, the use of EPFM is not justified, and LEFM will be used in conjunction with limit load at and beyond the fluence level of $1x10^{21}$ n/cm^2.

Based on the preceding discussion, the applicable fluence ranges for the various fracture mechanics procedures are the following:

Limit Load only	$\leq 3x10^{20}$ n/cm^2
LEFM/EPFM with Limit Load	$3x10^{20} < \phi < 1x10^{21}$ n/cm^2
LEFM with Limit Load	$\geq 1x10^{21}$ n/cm^2

Based on the current accumulated fluence information on file with GE, it is estimated that only the shroud 'barrel' welds in the active fuel region (i.e., H4, Figure 1-1) would exceed the fluence level threshold requiring the use of LEFM or EPFM.

4.2 Limit Load Method

Figure 4-1 shows a schematic representative plan view of an asymmetric distributed uncracked ligament. It is assumed that there are 1,2,...i,.... n ligament lengths and that the i^{th} length is of thickness 't_i' and extends from an azimuth of θ_{i1} to θ_{i2}. The ligament length 'l_i' of the ith ligament is related to azimuth angles θ_{i1} and θ_{i2} by the following relationship:

$$l_i = (D/2) \bullet (\theta_{i1} - \theta_{i2}) \qquad (4\text{-}2)$$

where, D is the diameter of the shroud. The calculation of moment 'M' that this ligament configuration can resist, is somewhat complicated since it is not a priori clear as to which azimuthal orientation of the neutral/central axis would produce the least value of bending moment, 'M'. Therefore, the value of 'M' is calculated for various orientations of the central axis from 0° to 360°. This calculation is performed in two steps:

(1) In this step, a central axis orientation, α, is first selected. The location of the neutral axis (which is parallel to the central axis) at a distance δ from the central axis is determined using the following (see Figure 4-1):

$$\int_{-(\pi-\alpha+\beta)}^{\alpha+\beta} Rt(\theta)d\theta - \int_{\alpha+\beta}^{-(\pi-\alpha+\beta)} Rt(\theta)d\theta = (\sigma_m/\sigma_f)(2\pi R t_n) \qquad (4\text{-}3)$$

where,

α	=	Assumed azimuth angle of the central axis
β	=	Angle of the neutral axis with respect to central axis, or $\sin^{-1}(\delta/R)$
δ	=	Distance between the central axis and the neutral axis
R	=	Mean radius of the shroud
$t(\theta)$	=	t_i (thickness of the ith ligament), if angle θ is such that $\theta_{i1} < \theta < \theta_{I2}$, or 0 otherwise.
t_n	=	Nominal thickness of shroud
σ_m	=	Membrane stress
σ_f	=	Material flow stress = $3S_m$

Thus, this step helps define the location of the neutral axis when the central axis is assumed to be at an azimuth angle of α.

(2) Once the location of the neutral axis relative to the central axis is determined, the moment, M_α, is then obtained by integrating the bending moment contributions from individual ligament lengths. The mathematical expression used is the following:

$$M_\alpha = \int_0^{2\pi} \sigma_f R^2 A\, t(\theta) \operatorname{Sin}(\alpha - \theta)\, d\theta \qquad (4\text{-}4)$$

where, A = 1.0, if $-(\pi-\alpha+\beta) < \theta < \alpha+\beta$, or
-1.0, if $\alpha+\beta < \theta < -(\pi-\alpha+\beta)$

The orientation 'α' that produces the least value of M is called 'α,min' and defines the axis capable of resisting the limiting moment. Whether the specified set of uncracked ligament lengths provides the required structural margin is verified by the following:

$$M_{\alpha,min}/Z + P_m \geq SF(P_m + P_b) \quad (4\text{-}5)$$

where,

	Z	=	Section modulus of the shroud based on uncracked cross section
	P_m	=	Applied membrane stress
	P_b	=	Applied bending stress
	SF	=	Safety factor

If the fluence level at a circumferential weld is greater than 3×10^{20} n/cm^2, the specified uncracked ligament length configuration must also satisfy the LEFM/EPFM criteria. If the LEFM/EPFM criteria is not satisfied, the lengths of the some of the uncracked ligament lengths would have to be increased until the criteria is satisfied.

4.3 LEFM Method

For a through-wall flaw in an "infinite" plate, the stress intensity factor K is given by the following:

$$K = \sigma\sqrt{(\pi a)} \quad (4\text{-}6)$$

where, σ is the remote membrane stress and a is the half crack length. The shroud is a cylinder and therefore, a curvature correction factor, G_m, needs to be applied to the above calculated value of K based on the infinite plate solution.. The values of G_m are given in Figure 4-3 (Reference 4-3) as a function of the non-dimensional parameter, $a/\sqrt{(Rt)}$. The behavior of G_m for $a/\sqrt{(Rt)}$ greater than 4.5 can be linearly extrapolated based on data from Reference 4-8. The coefficient G_b was not used since only the average value of the stress intensity factor across the crack tip is required.

The ligament length may be small enough that there is some interaction between the crack tips, leading to a higher value of K than that given by the above equation. This interaction effect was conservatively accounted for in the screening criteria approach (Reference 1-1).

A more reasonable yet conservative approach is used here by considering a classical solution for a series of flaws, given in Reference 4-4.

Figure 4-4 from Reference 4-4 shows the geometry and the K solution for a series of equi-length, equi-distant through wall flaws in an infinite plate subjected to remote tension. The K solution is given by:

$$K = \sigma \bullet \sqrt{\{W \tan(\pi a/W)\}} \qquad (4\text{-}7)$$

where,

	σ	=	applied tension stress ($P_m + P_b$)
	a	=	one-half crack length (see Figure 4-4)
	W	=	distance between mid-points of two adjacent ligaments (see Figure 4-4)

Since the shroud is a curved shell, the preceding K value should be multiplied by the curvature correction factor, G_m, described earlier. Thus, the analytical expression for K for use in the LEFM calculations is:

$$K = \sigma \bullet G_m \bullet \sqrt{\{W \tan(\pi a/W)\}} \qquad (4\text{-}8)$$

The ligament length, l, is related to the quantities 'a' and 'W' above by the following relationship:

$$l = W-2a \qquad (4\text{-}9)$$

The K calculation should be done for a case where the 'a' and 'W' combination is such that the value of K is maximized. The value of σ for use in the above equation is the sum of P_m and P_b, the membrane and bending stresses calculated using the nominal shroud cross-section properties. The calculated value of K should be less than K_{Ic} with the appropriate safety factor:

$$K < K_{Ic}/SF \qquad (4\text{-}10)$$

SF is the safety factor appropriate for the operating condition being evaluated. Subsection 4.6 provides the values of safety factors to be used for various operating conditions. A conservative K_{Ic} value of 150 ksi√in, based on the material J-R curve of Figure 4-2, can be used in this evaluation.

4.4 EPFM Methodology

The EPFM based concepts developed by Paris and Hutchinson and incorporated into EPRI handbooks [4-5,4-6,4-7] can be used in lieu of the conservative LEFM approach in which only the crack initiation is considered. The EPFM approach considers ductile crack extension in determining the load carrying capability of a cracked structure. The EPFM based approach is also called a J-integral tearing stability approach or a J/T approach. Two key concepts in this approach are : (1) the J-integral which characterizes the intensity of the plastic stress-strain field surrounding the crack tip and (2) the tearing stability theory which examines the stability of ductile crack growth.

Figure 4-5 schematically illustrates the J/T methodology. The material (J/T) curve or R-curve in Figure 4-5 represents the material's resistance to ductile crack extension. Any value of J falling on the material R-curve is denoted as J_{mat} and is a function solely of the increase in crack length Δa. Also defined in Figure 4-5 is the 'applied' J, which for given stress-strain properties and overall component geometry, is a function of the applied load P and the current crack length, a. The following two non-dimensional parameters are then defined:

$$T_{applied} = (E/\sigma_f^2) \bullet (\partial J_{applied}/\partial a) \qquad (4\text{-}11)$$
$$T_{mat} = (E/\sigma_f^2) \bullet (dJ_{mat}/da) \qquad (4\text{-}12)$$

where, E is Young's modulus and σ_f is an appropriate flow stress. The intersection point of the material and applied (J/T) curves denotes the instability point. The load at instability is determined from the J versus load plot also shown schematically in Figure 4-5. Thus, the three key curves in the tearing stability evaluation are: $J_{applied}$ versus $T_{applied}$, J_{mat} versus T_{mat}, and $J_{applied}$ versus load.

The J_{mat} versus T_{mat} curve or the material (J/T) curve can be derived in a straight forward manner from the material J-R curve (such as the one shown in Figure 4-2) and using equation (4-11). The $J_{applied}$ - $T_{applied}$ or the (J/T) applied curve can be generated through iteration in the crack length once the $J_{applied}$ versus load information is available for different crack lengths.

The calculation of $J_{applied}$ for a given load and crack geometry, can be performed using the estimation scheme procedures if the non-dimensional 'h_1' functions are available. The EPRI handbooks [4-5, 4-6, 4-7] give 'h_1' functions for several pressure vessel and piping geometries with a single crack. For uncracked ligament length configurations such as that shown in Figure 4-1, a finite element analysis would be necessary to calculate the value of $J_{applied}$.

4.5 Evaluation of Part-Through Wall Cracks

If it is not possible to find sufficient lengths of uncracked ligaments, then evaluation of a combination of uncracked ligaments and part through-wall cracks may be required to assess structural margins. For this case, the angular location of the uncracked ligaments, and the depth of the flaws, must be determined. Proximity rules are used to determine effective flaw length. The depth determination must also include any uncertainty associated with the NDE method used. Allowances for crack growth are also factored in, including effects on both length of uncracked ligaments, and depth of flawed portions of the area examined. This information can then be analyzed in accordance with previously outlined methods.

The maximum observed depth sizing error to date has been 0.3 inches. Based on this, the uncertainty assigned to depth measurements is 0.3 inches, until better information can be obtained. The Inspection Subcommittee of the VIP, along with EPRI, is actively pursuing further evaluation of the uncertainty associated with NDE techniques.

It may be possible to conservatively simplify the above approach by assuming a flaw of 360° at the maximum observed depth, a. Figure 4-6 shows a schematic of a 360° crack of depth 'a' at a shroud weld. The depth 'a' should include any uncertainty associated with the NDE method used. The fluence levels where this type of cracking has been observed, are typically well below the threshold value of 3×10^{20} n/cm^2. When this is the case, only the limit load approach need be used in conducting the structural margin assessment.

The required minimum 360° ligament at a circumferential weld can be determined by iteratively calculating the allowable crack depth, 'd' using the following equations (Reference 4-9):

$$\beta = \{\pi(1-d/t_n-P_m/\sigma_f)\}/(2-d/t_n)$$
$$P_b' = (2\sigma_f/\pi)(2-d/t_n)\sin\beta \qquad (4\text{-}13)$$
$$(P_m+P_b)SF = P_b' + P_m$$

where,

P_m = Primary membrane stress at the subject weld

P_b = Primary bending stress at the subject weld

d = Allowable crack depth

t_n = Shroud wall thickness (away from a fillet weld), or shroud wall thickness + fillet weld leg (t_{fw} in Figure 4-6) if the fillet weld can be shown crack free (see Section 5.0)

SF = Safety factor appropriate for the operating condition being evaluated

σ_f = Material flow stress (= $3S_m$)

It should be noted that the stresses, P_m and P_b, are calculated using the nominal shroud thickness. The current crack depth 'a' is acceptable if the projected crack depth, after accounting for crack growth until the next inspection, is less than the allowable crack depth 'd' calculated in Equation (4-13). This criteria is given by the following equation:

$$(a + CG) < d \qquad (4\text{-}14)$$

where, CG is the projected crack growth until the next inspection (projected at 5×10^{-5} in/hr per Section 3).

4.6 Safety Factors

In the screening criteria document (Reference 1-1), safety factors of 2.77 for normal (Level A) / upset (Level B) conditions and 1.39 for emergency (Level C)/ faulted (Level D) conditions were used in the evaluation of circumferential welds. These safety factor values are consistent with Section XI values. However, for many older BWRs the FSARs of these plants include specific safety factor values to be used for various operating conditions. In such cases, the safety factors specified in the plant FSAR can be used.

There are several conservatisms used in the flaw evaluation methodology described in this section in addition to the safety factors used in the structural margin evaluation. Table 4-1 presents a list of these conservatisms.

4.7 References

[4-1] "Design Criteria for Irradiated Type-304 Stainless Steel in BWR Applications," GE Report No. NEDE-20364, June 1974.

[4-2] "Evaluation of BWR Top-Guide Integrity," EPRI Report No. NP-4767, November 1986.

[4-3] Rooke, D.P. and Cartwright, D.J., "Compendium of Stress Intensity Factors," The Hillingdon Press (1976)

[4-4] Tada, H., Paris, P. and Irwin, G., "The Stress Analysis of Cracks Handbook," Del Research Corporation (1985).

[4-5] "An Engineering Approach for Elastic-Plastic Fracture Analysis," EPRI Report No. NP-1931, July 1981.

[4-6] "Advances in Elastic-Plastic Fracture Analysis," EPRI Report No. NP-3607, August 1984.

[4-7] "Elastic-Plastic Fracture Analysis of Through-Wall and Surface Flaws in Cylinders," EPRI Report No. NP-5596, January 1988.

[4-8] R.S. Barsoum, R.W. Loomis and B.D. Stewart, " Analysis of Through Cracks in Cylindrical Shells by the Quarter Point Elements," International Journal of Fracture, Vol. 15, No.3, June 1979.

[4-9] S. Ranganath and H.S. Mehta, "Engineering Methods for the Assessment of Ductile Fracture Margin in Nuclear Power Plant Piping," ASTM STP 803 (1983)

Table 4-1

Conservatisms Included in Flaw Evaluation Methodology

1. All VT or ET identified surface indications are assumed to be through-wall for analysis for uncracked ligament length.
2. ASME Code Section XI primary pressure boundary safety margins were applied even though the shroud is not a primary pressure boundary.
3. ASME Code, Section XI proximity rules were applied.
4. A proximity rule to account for perpendicular flaws was applied, although not required by Section XI.
5. The bounding crack growth rate was included in flaw lengths and depths used for evaluation.
6. Two cycles of crack growth are applied for uncracked ligament length, even in those instances where only one cycle of operation would be permitted.
7. A factor of '4t' is applied for uncracked ligament length, to account for inspection uncertainty.
8. For quantitative analysis, areas which are not or can not be inspected are assumed to be fully cracked.

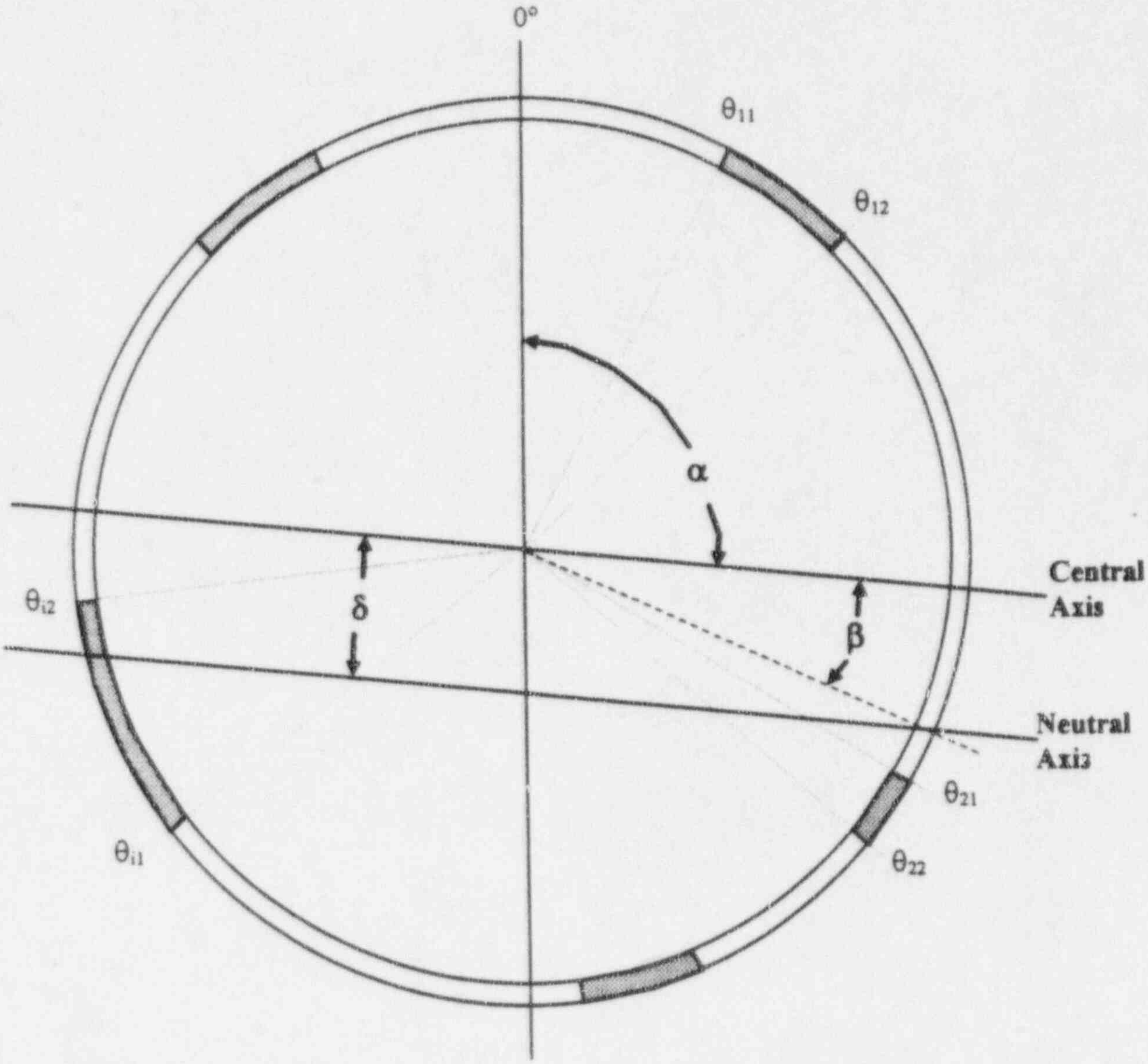
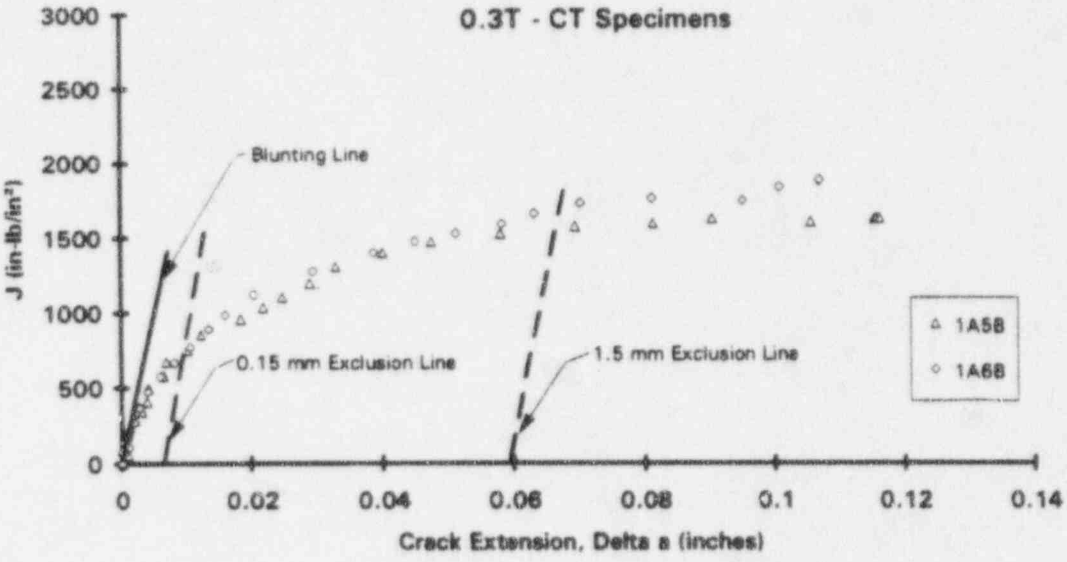


Figure 4-1 Schematic of Non-Symmetric Ligament Distribution



Per ASTM Standard E813

Figure 4-2 J-R Curves for Two Irradiated Stainless Steel Specimens at Fluence of $8x10^{20}$ n/cm^2

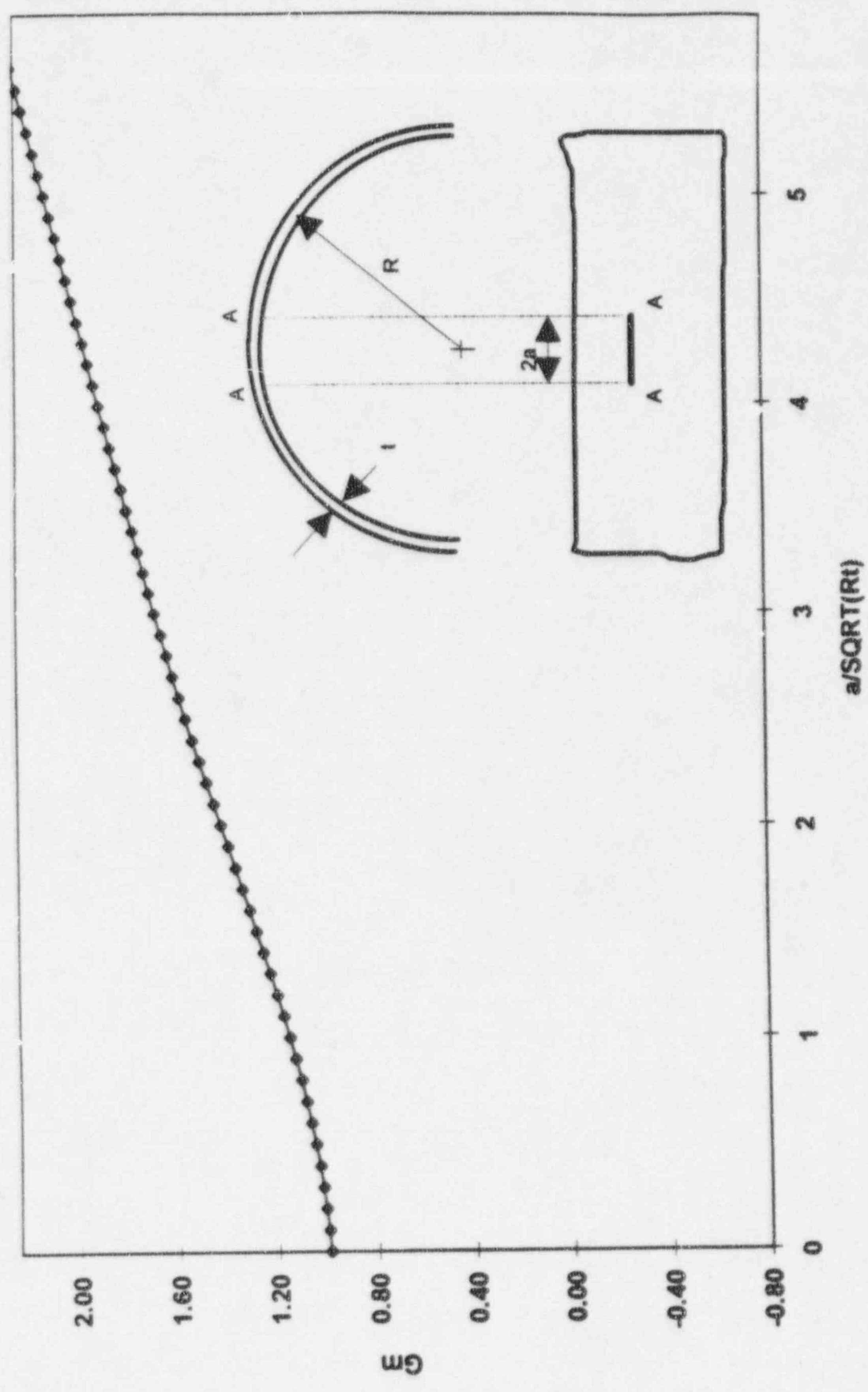
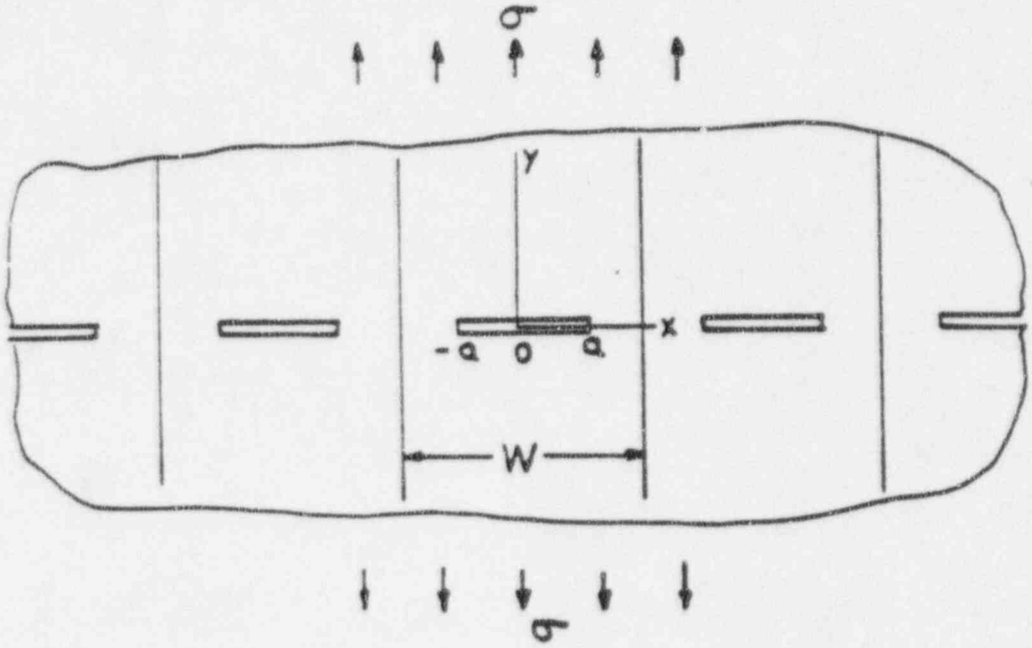


Figure 4-3 Curvature Correction Factor G_m for Circumferential Flaw



$$K_I = \sigma \sqrt{\{W \tan(\pi a/W)\}}$$

Figure 4-4 Solution for Equi-Distant Equi-Length Flaws

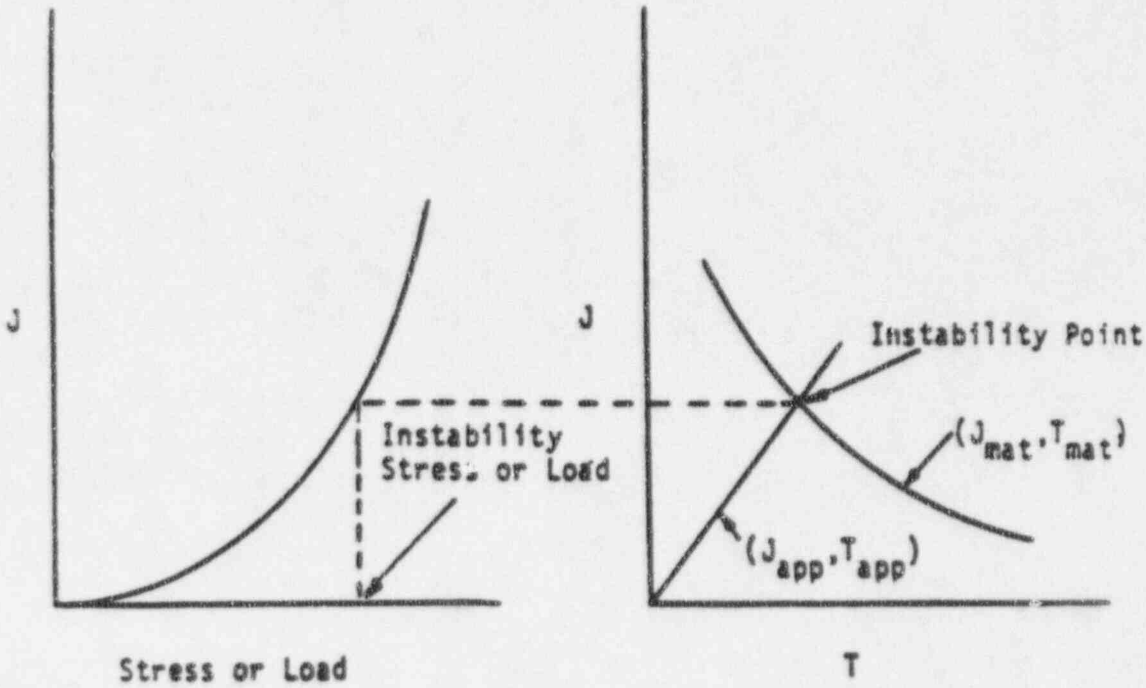


Figure 4-5 Schematic of (J/T) Approach

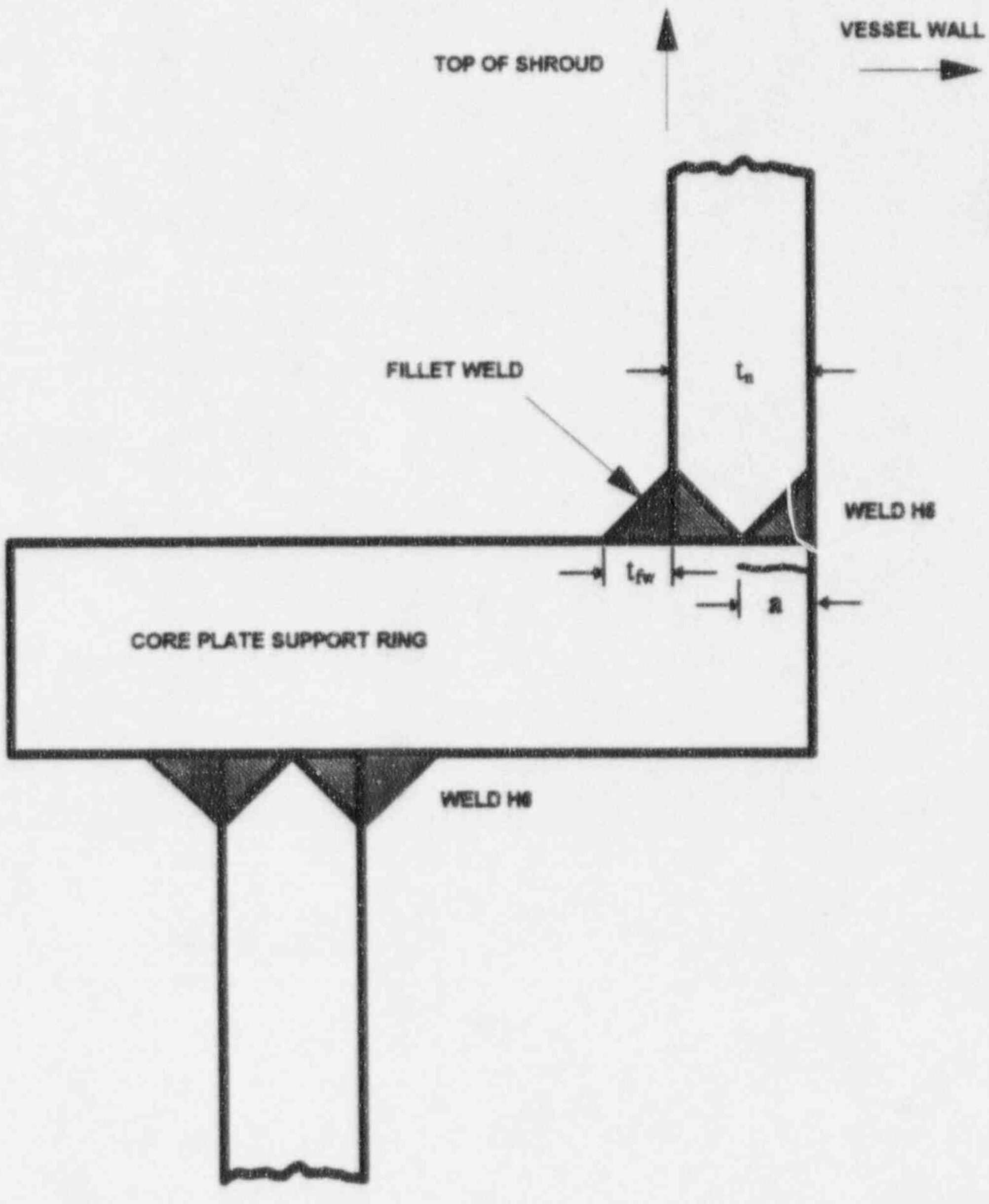


Figure 4-6 Shroud Weld with 360° Crack

5.0 USE OF FILLET WELD FOR ESTABLISHING ALLOWABLE FLAW DEPTH

5.1 Issue

Complete circumferential cracking at varying depths has been observed in 304 stainless steel shrouds in the top guide support ring H3 weld region and the core plate support ring H5 weld region in several BWRs. Such cracking has been mainly in the welded plate rings and has been attributed to a combination of cold work and unfavorable end grain orientation. Figure 5-1 shows typical cracking observed in the ring. In most cases, the ring is welded to the shroud cylinder with a full penetration weld and a fillet weld. The fillet weld is important, not from the perspective of strength contribution, but from crack growth considerations. Credit is not taken for the fillet weld when determining the stresses which apply at a given location. However, since cracking in the rings is expected to follow the weld heat affected zone, the total crack extension that can be tolerated before the crack leads to shroud separation is the shroud wall thickness, t_{shroud}, plus the length of the fillet weld leg, t_{fillet}. Finite element analysis has shown that with the crack extending parallel to the plane of the ring, the required wall ligament is less than 10% of the total available length. Given the extremely conservative crack growth rate being assumed, 5×10^{-5} in/hr, crack growth of as much as 0.8 inches can be postulated for a two-year fuel cycle. Justification for crack growth extending into the region between the fillet weld and ring improves a plant's ability to accommodate the multiple conservatisms in the analysis done assuming the presence of a 360° flaw.

5.2 Crack-Free Fillet Weld Confirmation

Microstructurally, the weld metal is expected to be significantly more resistant to SCC initiation and growth than the base material HAZ. Field experience with shroud cracking confirms this. In order to take credit for the presence of a fillet weld, confirmation by inspection is needed to accomplish two things:

1. Inspection will determine the degree of cracking, if any, at the toe of the fillet weld or in the fillet weld itself.

2. Inspection will confirm the existence and size of the fillet weld.

The fillet weld size and crack-free condition must be confirmed before the available ligament can be increased by t_{fillet}. First, the existence and size of the fillet weld must be determined. In some cases, such as for H1, H2, H5 and H6, the fillet weld may not be visually accessible. Design or even as-built drawings may not accurately represent the fillet weld size, so the actual weld sizing is important. For accessible fillet welds, the size can be confirmed by VT. Visually inaccessible fillet welds can be sized by UT. Past inspection results have shown that the toes of the fillet weld can be consistently seen by UT, and can be distinguished from far-side cracking. If, due to a certain geometric configuration, the fillet weld size cannot be confirmed by any inspection method, only the shroud wall thickness shall be assumed as available ligament material.

At a plant with assumed 360° cracking at the H5 weld, there was one small area of detected cracking initiating at the upper toe of the fillet weld (adjacent to the shroud shell, not the ring). While this demonstrates that cracking can initiate at the fillet weld, it also demonstrates that such cracking is detectable by UT. Techniques in use for SCC detection, such as 45° and 60° shear wave UT transmission, allow full examination of the fillet weld region, even in the presence of significant cracking from the side of the ring opposite the fillet weld. At the same plant mentioned above, which had a near side crack assumed to be over one inch deep, the intersection of the toe of the fillet weld and the ring was readily apparent from the UT data, as were reflections from minor surface irregularities such as machining marks on the ring. Such evidence demonstrates the high sensitivity for crack detection. Level III UT analysts agree that SCC in the fillet weld toe region would be reliably detected.

SCC initiating at the fillet weld could be expected to grow close to the fillet weld fusion line in the HAZ. Concerns have been raised in the past on the possibility of such cracking being undetected by UT. There are established techniques which readily detect SCC shadowing the weld root and/or fusion line. Such techniques, properly demonstrated and qualified on calibration mockups, will reliably detect cracking initiating at the toe of the fillet weld.

If the fillet size and degree of cracking near the fillet weld can be demonstrated by inspection, then the fillet weld leg length (reduced appropriately if cracking is found) shall be assumed as available ligament material. If, due to geometric constraints or the large depth of the near side crack, the size of and degree of cracking near the fillet weld cannot be demonstrated during inspection, only the shroud wall thickness shall be assumed as available ligament material.

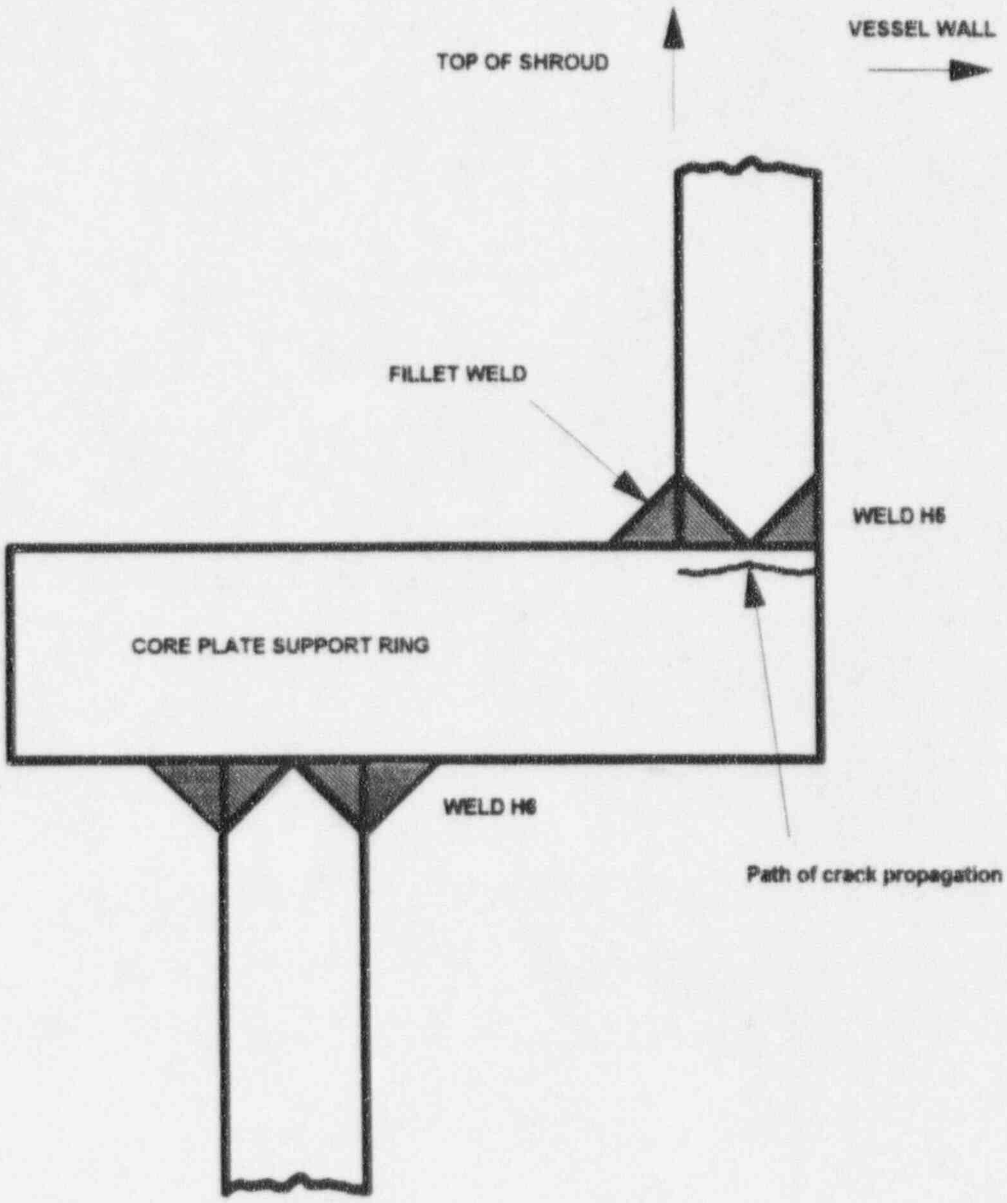


Figure 5-1. Schematic of Anticipated Crack Growth in Shroud Ring

APPENDIX A

TECHNICAL BASIS FOR EXEMPTING INSPECTION OF VERTICAL WELDS IN THE SHROUD

Background

A corollary to conducting the shroud in-service inspections of the horizontal welds is whether the vertical welds should also be inspected. Field data from the shroud inspections conducted so far at several BWR plants have been reviewed and fracture mechanics calculations are conducted to develop a sound technical justification that backs the assumption that the inspection of the vertical welds is not necessary.

Field Data

As a part of the shroud examination, several BWR plants have visually examined one or more vertical seams in the shroud. The shroud inspection results in GE's data file were reviewed for reported lengths of axial indications. The review indicated that most of the reported axial indications are at the circumferential welds in the shroud and not along the vertical seam welds. Most of these indications are less than 3 inches in length.

Among the indications reported along the vertical seam welds, most were minor in length (less than 3-inches). Only at one BWR plant, the reported lengths of the indications along a vertical weld were 4- and 15-inches. Thus, most of the indications found on the vertical weld seams are less than 4-inches. In this connection, it should be noted that the only locations in the shroud where long intermittent or continuous cracking had been found were at the circumferential welds. However, there are significant differences between these welds and the axial seam welds from the point of view of stress corrosion cracking (SCC) susceptibility, as discussed next.

At the H3 and H5 circumferential welds, factors such as the end grain effect and the presence of cold work, are considered to have played a major role in the observed long cracking. These factors are not present at the vertical seam welds in the shroud. Furthermore, the weld residual stress, a significant parameter for SCC initiation and growth, is expected to be lower at the vertical seam welds compared to circumferential welds due primarily to difference in constraint.

Based on the preceding review of field inspection results and discussion, it is clear that the likelihood of a long axial indication extending over the full height of the plate is highly unlikely. The vertical welds in the various plates constituting the shroud are staggered and thus, the longest crack that can be reasonably postulated is equal to the height of the plate.

Fracture Mechanics Evaluation

Critical flaw lengths are calculated using the limit load and the linear elastic fracture mechanics (LEFM) approaches. The LEFM approach is appropriate for vertical welds between the H3 and H5 welds. The smaller of the two critical flaw lengths determined by the two approaches is used in the evaluation. The critical axial flaw size is governed entirely by the pressure hoop stress. A through-wall flaw is assumed. For a through-wall flaw of length 2a in the shroud, the applied stress intensity factor for the LEFM approach is given by:

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

where σ_h is the hoop stress and M is the curvature correction factor given by:

$$M = [1 + 1.61a^2/(Rt)]^{0.5}$$

In the above expression, the critical flaw length 2a can be determined by equating the calculated K to the fracture toughness of 150 ksi$\sqrt{\text{in}}$ (representing a conservative estimate of the material toughness). The hoop stress σ_h was calculated using the following shroud geometry and the faulted condition internal pressure:

Internal Diameter:	174.5 in.
Thickness	1.5 in.
Internal pressure	32 psig

Based on the preceding values, the critical flaw length was calculated as 108 inches.

The critical crack length based on the limit load technique is given by the equation:

$$\sigma_h = \sigma_f / M$$

where M is the curvature correction factor (as defined previously), $\sigma_f = 3S_m$ is the flow stress and σ_h = the hoop stress (same as in the LEFM calculation). The S_m value was taken as 14.4 ksi, corresponding to an L-Grade material. The critical flaw length was calculated as 414 inches.

A comparison of the two critical flaw lengths shows that the LEFM based value of 108 inches is considerably smaller than the limit load based value.

The preceding calculations are applicable to shroud vertical welds above the core plate. The internal pressure for the vertical welds below the core plate is higher (approx. 49 psi). However, the fluence in the region below core plate is very low such that only the limit load based calculation needs to be used. This gives a calculated critical flaw length in excess of 180 inches. Therefore, only the LEFM based critical flaw length of 108 inches for the above core plate case is used in the discussion presented next.

Discussion

The length of a single vertical seam weld in a shroud is typically in the range of 80 inches. The LEFM based critical flaw length using the faulted condition pressure is 108 inches. Thus, the critical crack length value exceeds the potential length of a vertical seam weld. Thus, it can be concluded that even if an indication extending the full vertical length of the weld were to be present (highly unlikely in view of the field inspection data), it would not lead to instability or large crack opening areas even when faulted or LOCA condition loads are considered.

Conclusion

Given that the reported axial indication lengths at the vertical seam welds are small and the fact that the critical crack length exceeds the height of a typical vertical seam weld, it is reasonable to do no inspection of the vertical welds.

APPENDIX B

PROXIMITY RULES FOR PLANT-SPECIFIC FLAW EVALUATION

This Appendix describes the flaw proximity rules that can be used to determine the effective flaw lengths from the shroud inspection data. The rules specifically treat the circumferential welds.

B.1 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. Indications are considered to be in the same plane if the perpendicular distance between the planes is less than two times the shroud thickness (2T). When two indications are close to each other, rules are established to combine them based on proximity. These rules are described here.

B.2 Proximity Rules

The flaw combination methodology used here is based on the ASME Code, Section XI proximity rules concerning neighboring indications. Under the rules, if two surface indications are in the same plane and are within two times the depth of the deepest indication, then the two indications must be considered as one indication.

In Figure B-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 the crack growth rate multiplied by the number of hot operating hours above 200°F for the next two fuel cycles (conservative if a plant is inspecting every outage). The crack growth at each tip is thus, CG. 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 (2CG + 2t). If the ligament is less than (2CG + 2t), the effective length is (L1+L2+S+2CG). Note that the addition of 2CG is to include crack growth at the other (non-adjacent) end of each flaw (See Figure B-2).

If the ligament is greater than (2CG + 2T), then the effective flaw length is determined by adding the projected tip growth to each end of the flaw.

$$L1_{eff} = L1 + 2CG$$
$$L2_{eff} = L2 + 2CG$$

A similar approach is used to combine flaws when a circumferential flaw is close to an axial flaw (See Figure B-3). (An axial flaw could be detected while examining a circumferential weld.) If the ligament between the flaws is less than (2t + CG), then the effective flaw length for the circumferential flaw is Leff = L1+S+CG (the bounding ligament for these cases). If the ligament is greater than (2t + CG), then the flaws are treated separately. The effective flaw length can be used for subsequent fracture mechanics analysis.

To demonstrate the application of proximity criteria, two examples are shown in Table B-1 and described below.

Table B-1
Flaw Combinations Considered in Proximity Criteria

Case	Circumferential Flaw	Axial Flaw
A	Yes	No
B	Yes	Yes

Case A: Circumferential Flaw - No Axial Flaw

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

$$L_{eff} = L1 + S + L2 + 2CG$$

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 (2t + 2CG), the effective flaw lengths are (See Figure B-2c):

$$L1_{eff} = L1 + 2CG$$
$$L2_{eff} = L2 + 2CG$$

Case B: Circumferential Flaw - Axial Flaw

This case applies when both a circumferential and an axial flaw are being considered. Figure B-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 (2t + CG), then the effective circumferential flaw length is (see Figure B-3b):

$$L_{eff} = L1 + S + CG$$

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

If the distance between the circumferential indication tip to the axial indication is greater than (2t + CG), then the flaws are not combined (see Figure B-3c) and the effective length is:

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

B.3 Application of Effective Flaw Length Criteria

The application of the effective length criteria is applied to two adjacent indications at a time. Figure B-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 flaw is combined, the flaw becomes indication 2.

- Continue along positive azimuthal direction until the next indication is encountered. This becomes indication 3.

- Apply proximity rules to new indications 2 and 3.

- Continue proximity rule evaluation until all indications along the subject weld or plane have been considered.

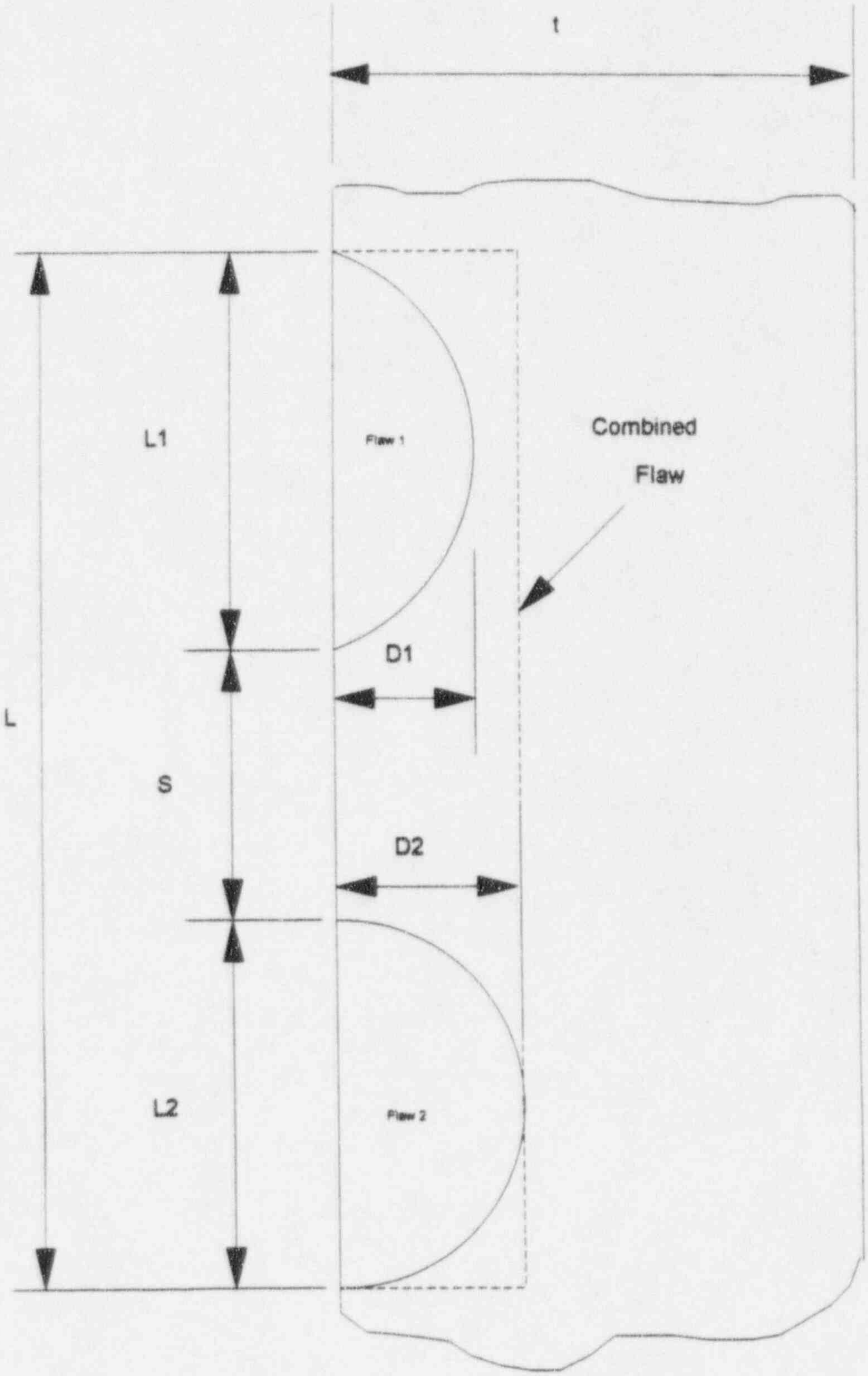


Figure B-1. ASME Code Proximity Criteria

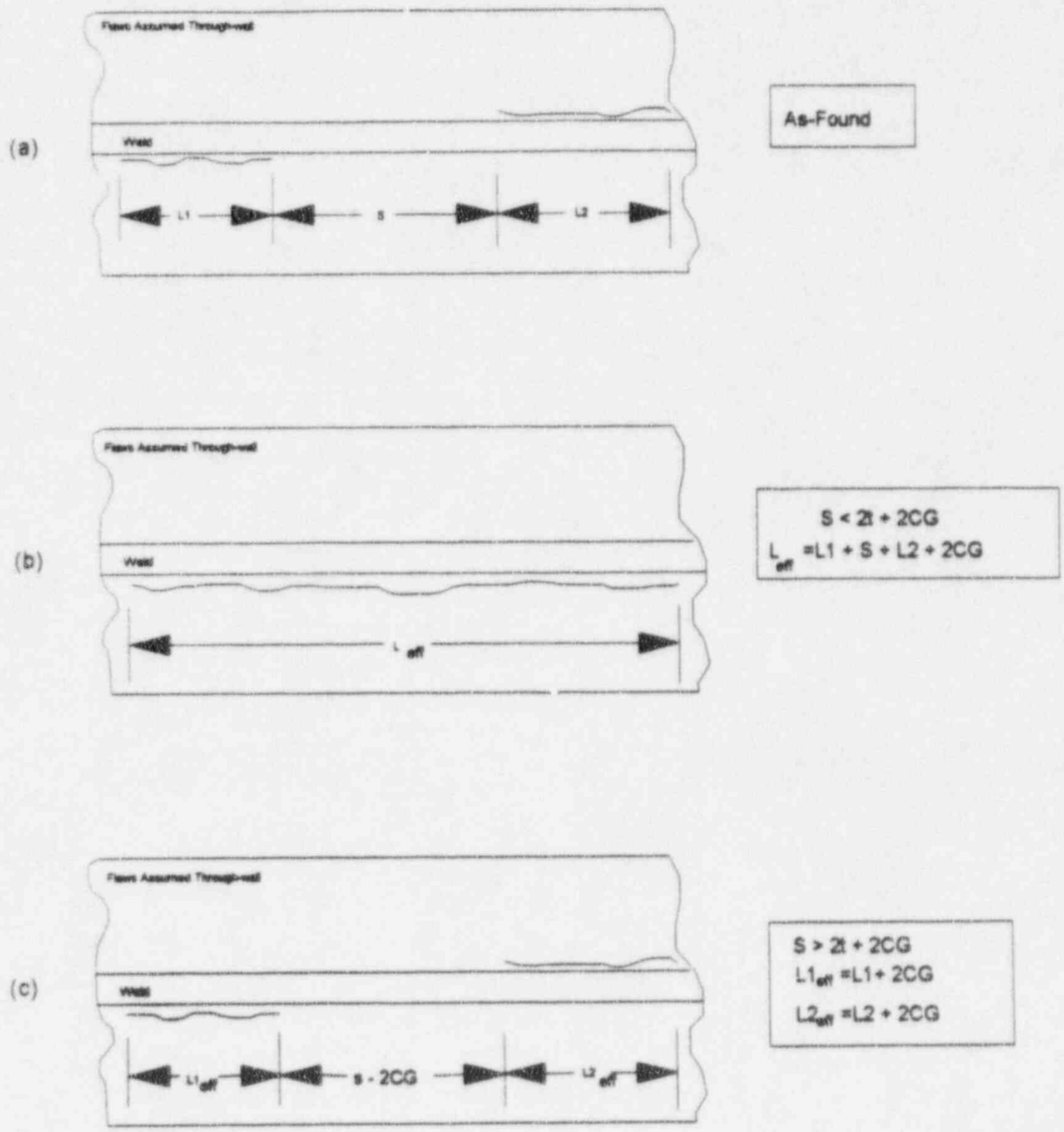


Figure B-2. Application of Proximity Procedure to Neighboring Circumferential Flaws

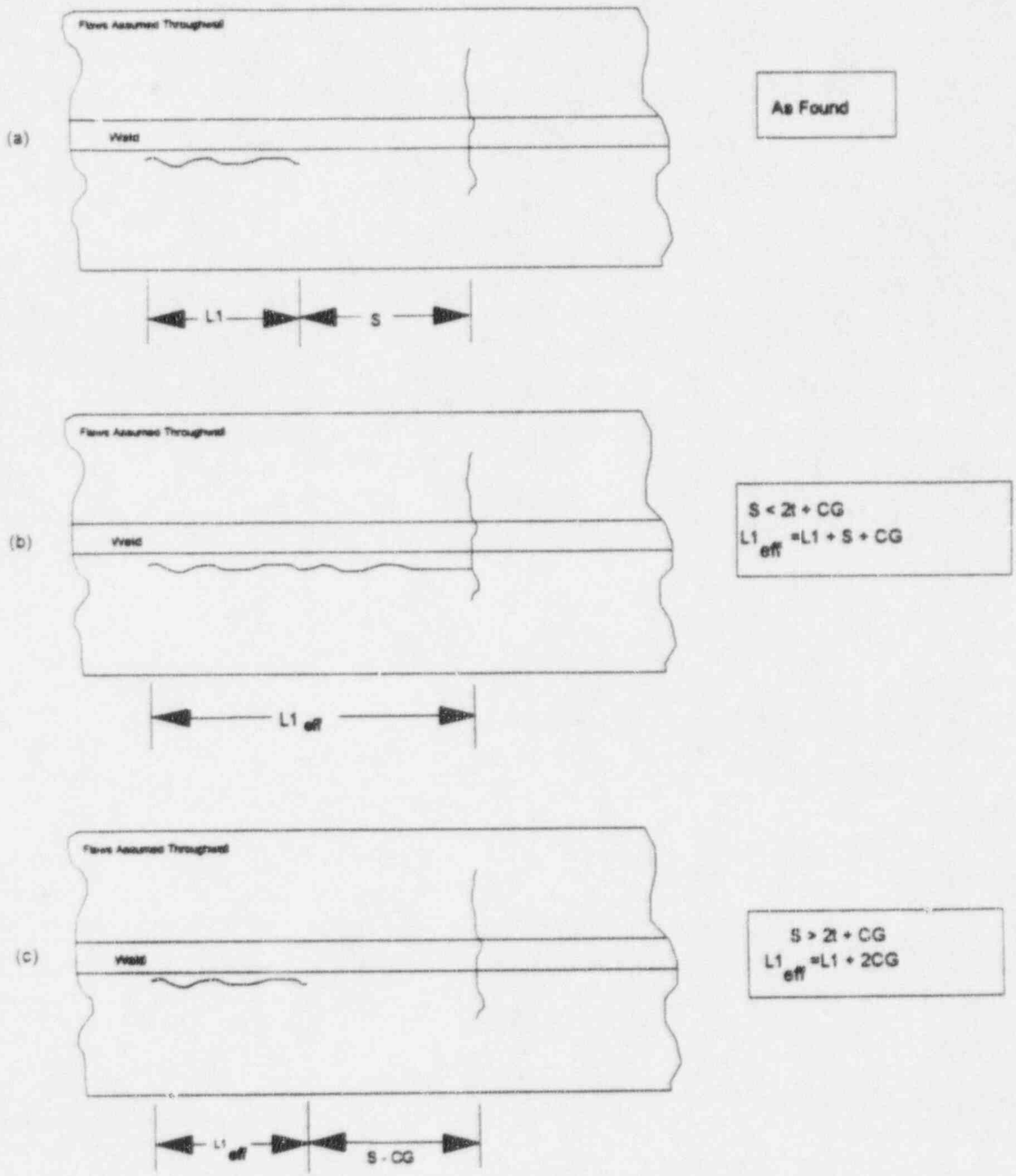


Figure B-3. Application of Proximity Procedure to Neighboring Axial and Circumferential Flaws

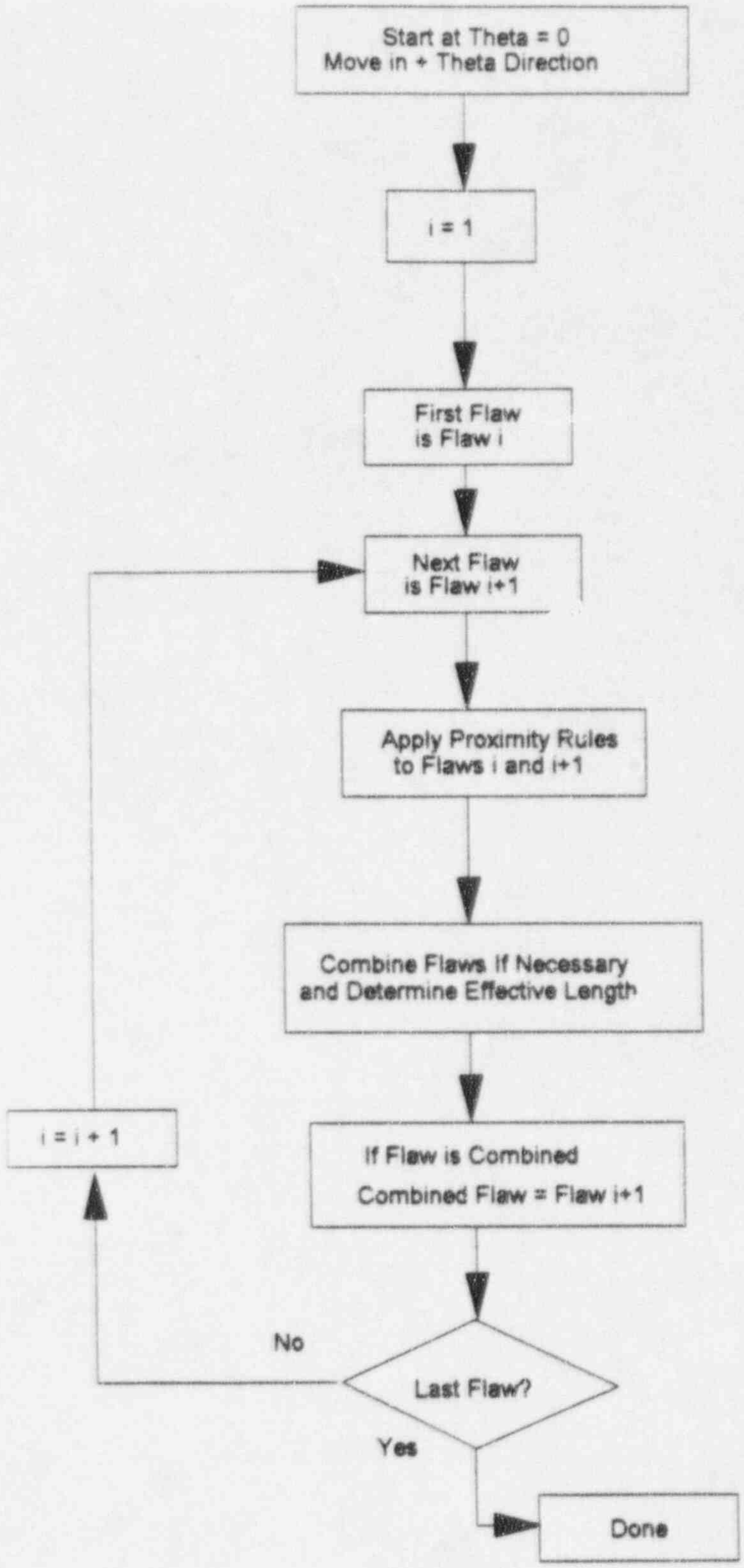


Figure B-4. Process for Determining Effective Circumferential Flaw Length