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BWR Vessel and Internals Project Shroud Vertical Weld Inspection and Evaluation Guidelines (BWRVIP-63NP)

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BWR Vessel and Internals Project

Shroud Vertical Weld Inspection and Evaluation Guidelines (BWRVIP-63NP)

TR-113170NP

Final Report, January 2000

EPRI Project Manager
R. Carter

EPRI • 3412 Hillview Avenue, Palo Alto, California 94304 • PO Box 10412, Palo Alto, California 94303 • USA
800.313.3774 • 650.855.2121 • askepri@epri.com • www.epri.com

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CITATIONS

This report was prepared by

GE Nuclear Energy
175 Curtner Avenue
San Jose, CA 95125

Author
R. Stark

GE Principal Investigators:
R. Stark
S. Ranganath

Prepared for Boiling Water Reactor Vessel and Internals Project and EPRI.

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REPORT SUMMARY

The Boiling Water Reactor Vessel and Internals Project (BWRVIP), formed in June, 1994, is an association of utilities focused exclusively on BWR vessel and internals issues. This BWRVIP report provides guidelines for inspecting and evaluating vertical welds in BWR core shrouds.

Background
Core shroud cracking, first detected in 1990, has been found in a significant number of BWRs. Initially, the cracking was detected in circumferential welds. In response, the BWRVIP developed guidelines for inspecting, evaluating, and re-inspecting those welds. More recently, cracking has been observed in core shroud vertical welds. Comprehensive guidelines are needed for the inspection, evaluation, and re-inspection of vertical welds.

Objectives
To develop generic inspection recommendations and evaluation procedures for core shroud vertical welds in BWRs.

Approach
A group of utility and industry experts evaluated postulated cracking to determine the level of cracking in vertical welds that could be tolerated without jeopardizing the safety functions of the shroud. These evaluations included simple hand calculations as well as detailed, finite element structural analyses. Once the experts had determined the allowable amount of cracking, they developed an inspection strategy to ensure that the allowable level is not exceeded.

Results
One of the conclusions from the analytical evaluations was that vertical welds are not required for shroud integrity as long as circumferential welds are not severely cracked. Consequently, the guidelines present a set of screening criteria that can be applied to circumferential welds at each end of a vertical weld. If circumferential welds meet the screening criteria, no inspection of the vertical weld is required. In the event that the screening criteria are not met, the guidelines present a set of inspection requirements and acceptance criteria for the vertical weld. A re-inspection schedule is defined in the guidelines and is tied to the as-found condition of the vertical welds. The guidelines also present analytical methods for evaluating any cracking that may be found during inspection.

EPRI Perspective
These vertical weld inspection guidelines are to be used with the recommendations for inspecting circumferential welds found in reports BWRVIP-01 and BWRVIP-07. (Note: this report's recommendations supersede BWRVIP-07's recommendations for vertical weld inspection).

When implemented, the combined inspection recommendations will ensure that core shroud integrity is maintained with respect to all essential safety functions.

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Keywords
Boiling water reactor
Flaw evaluation
Inspection strategy
Core shroud
Stress corrosion cracking
Vessel and internals

ABSTRACT

Cracking has been observed in the vertical welds in core shrouds in a number of boiling water reactors (BWRs). This report provides inspection recommendations which, if implemented, will ensure that the essential safety functions of the shroud are maintained. Methods are also presented for the evaluation of any cracks that may be observed during the inspections.

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Bob Carter	EPRI
Rich Ciemiewicz	PECO
Dana Covill	GPUN
Glenn Gardner	NU
Dennis Girroir	VY
Kevin Groom	TVA
Ed Hartwig	TVA
George Inch	NMPC
Mike Jones	NMPC
John Langdon	CP&L
Steve Lewis	Entergy
Bruce McLeod	SNC
Keith Moser	CECO
Paul Norris	SNC
Priit Okas	NYPA
Albert Piha	PECO
Jim Powers	First Energy
Bud Syx	SNC
Lew Willertz	PP&L
Blane Wilton	CP&L

GE Principal Investigators:
Randy Stark
Sam Ranganath

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1 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 loss of coolant accident (LOCA). 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.

Shroud cracking, first detected in 1990, has been found in a significant number of BWRs. The majority of the cracking has been identified as intergrannular stress corrosion cracking (IGSCC) in the heat affected zone of the shroud welds. Cracking has been observed in core shrouds fabricated from both Type 304 and Type 304L stainless steel materials.

The overall goal of this report is to identify the inspections and associated evaluations that will insure shroud integrity and margins for safe operation in the presence of shroud vertical weld cracking. The inspection and evaluation strategies are based on technical analyses, which will also be outlined in this report. Due to the large crack tolerance in the vertical welds, it is possible, in some cases, to justify exemptions from inspecting large portions of the welds. Recommendation and justification for these exemptions are also included in these inspection and evaluation guidelines.

Note that the inspection and evaluation guidelines for vertical welds presented in this report supersede those previously described in BWRVIP-01 and BWRVIP-07.

An overview of the inspection philosophy is provided in Section 2. Section 3 provides the recommendations and related flaw acceptance criteria. Flaw evaluation methods are presented in Section 4.

This report was developed according to the applicable provisions of 10 CFR 50, Appendix B.

2
TECHNICAL APPROACH

2.1 Overview of Inspection Approach

Inspections of vertical welds are dependent on the degree of cracking in adjacent circumferential welds. An inspection approach was developed which "screens" each vertical weld based on the condition of adjacent circumferential welds. If the adjacent circumferential welds meet the screening criteria, the vertical welds between them will not require inspection. If the circumferential welds do not meet the screening criteria, the adjacent vertical welds must be inspected and the results of those inspections must meet specific acceptance criteria. If the acceptance criteria are not met, a plant specific evaluation must be performed. The screening criteria and the acceptance criteria are based on analytical evaluations described in this report.

Once a specific vertical weld has been inspected, or has been eliminated from inspection based on the screening criteria, a reinspection interval must be established. The time at which the next inspection is to be performed is designated as the "end of interval" (EOI). A unique EOI can be determined for each vertical weld. Each circumferential weld also has an EOI based on the inspections performed in accordance with BWRVIP-01 and BWRVIP-07.

If a vertical weld does not need to be inspected (because the adjacent circumferential satisfied the screening criteria), then the EOI for that vertical weld is equal to the shortest EOI of the adjacent circumferential welds. At that time, the circumferential weld with the shorter EOI will be reinspected (per BWRVIP-07) and the vertical weld will be reevaluated based on the new inspection results.

If the vertical weld does need to be inspected (because the adjacent circumferential weld did not satisfy the screening criteria), its EOI is determined differently.

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Following this process, each vertical weld will have an individual EOI based either on its as-found condition or on the EOI of adjacent circumferential welds. Reinspection of each vertical weld must be performed at or before its EOI is reached.

2.2 Inspection Methods

The acceptance criteria for vertical welds are based on the determination that a sufficient amount of uncracked weld exists to ensure its structural integrity.

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The specific inspection recommendations and acceptance criteria for vertical welds are described in Section 3. The analyses, which form the basis for the acceptance criteria, are detailed in Appendix A.

3 INSPECTION RECOMMENDATIONS

This section presents the inspection strategies for vertical welds in Category C repaired and unrepaired BWR core shrouds, and for radial ring welds in repaired shrouds. The inspection strategies for vertical welds in unrepaired and repaired core shrouds are presented in Sections 3.1 and 3.2, respectively, and are summarized in Figure 3-1 and Figure 3-2. These strategies are applicable to vertical welds lying between horizontal welds H1 and H7. The inspection strategy for radial ring welds in repaired shrouds is presented in Section 3.3.

The inspection strategy for vertical welds includes screening or sampling procedures to determine the vertical welds that need to be inspected. For welds that need to be inspected, acceptance criteria are provided to determine if the vertical welds have sufficient structural capacity for continued operation.

The acceptance criteria are based on the projected extent of cracking at EOI. The projected cracking is to be based on the as found inspection results and an acceptable crack growth rate. The following guidelines shall be used to determine the crack depth and length at EOI:

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3.1 Vertical Welds in Unrepaired Shrouds

3.1.1 Screening of Horizontal Welds

Structural evaluations have determined that shroud integrity can be demonstrated in the presence of vertical weld cracking, given that cracking in intersecting horizontal welds is not significant.

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The screening process defined in this section is applicable only for horizontal welds where the inspections required by BWRVIP-01 have been completed. The screening process is not applicable if the horizontal welds have not been inspected per the requirements of BWRVIP-01. If the horizontal welds have not been inspected, then the vertical welds shall be inspected as described in Section 3.1.2.

No inspection of a particular vertical weld is required if <u>any</u> of the following is true for each of the horizontal welds at each end of the vertical weld, where the EOI for each horizontal weld has been determined in accordance with BWRVIP-07.

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Vertical welds that intersect a horizontal weld that does not meet at least one of the three horizontal weld-screening criteria must be inspected. The inspection regions for these vertical welds are defined in Section 3.1.2.

3.1.2 Inspection Requirements for Vertical Welds

One hundred percent of the accessible region of the vertical weld must be inspected.

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3.1.3 Acceptance Standards for Vertical Welds

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Plant specific evaluation should include structural considerations, and if through-wall cracking is observed during the inspection, the evaluation should include leakage considerations. Relevant inspection data can also be used to demonstrate the acceptability of the vertical weld. A number of methodologies for evaluation of through-wall and part-through-wall cracking are presented in Section 4.

Each vertical weld shall be re-evaluated at or before its EOI is reached. This re-evaluation may take the form of a screening process based on new information regarding the horizontal welds or it may include inspection of the vertical welds.

3.2 Vertical Welds in Repaired Shrouds

Inspection is not required for horizontal or vertical welds that are structurally replaced by a repair. At some plants a shroud repair may not include all relevant horizontal welds. In this instance, any vertical weld that runs between two unrepaired horizontal welds will be evaluated according to the guidelines in Section 3.1. Any vertical weld that intersects a repaired horizontal weld will be evaluated using the guidelines in this section.

Either of two options may be used to define the scope for the vertical weld inspection.

Option A – Sampling of Vertical Welds

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Option B – Screening of Horizontal Welds

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3.3 Radial Ring Welds

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Figure 3-1
Inspection Strategy for Vertical Welds in Category C Repaired and Unrepaired Shrouds

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Figure 3-2
Acceptance Standards for Vertical Welds in Category C Repaired and Unrepaired Shrouds

4
EVALUATION OF VERTICAL WELD INDICATIONS

In the event that the acceptance standards in Section 3 are not met, methods for the evaluation and dispositioning of flaws are required. This section describes the suggested procedures for evaluating indications found in the vertical welds. Different methods are proposed for varying degrees of cracking. For vertical weld indications that do not intersect a circumferential weld, the evaluation can be done using closed form solutions, assuming a free standing cylinder. For indications that intersect the circumferential welds, more extensive hand calculations are required.

The methodologies for the closed form solutions which cover a broad range of cracking scenarios are outlined in this section. For cracking scenarios which are not bounded by the cases presented here, evaluations will have to be performed on a plant-specific basis and may include more detailed hand calculations or finite element analyses.

The structural analyses described in this section consider both LEFM and limit load margins. The methodology is conservative, but consistent with BWRVIP-01 and NRC approved methods. The allowable axial flaw size is dependent only on the pressure stress. The analysis is applicable to both normal/upset and emergency/faulted conditions as long as the appropriate safety factor is used.

The allowable flaw size analysis described here is based on structural considerations only. If through-wall cracks in vertical welds were observed during the inspection, leakage from vertical weld cracking must also be evaluated. Leakage is further discussed in Section 4.3.

4.1 Vertical Weld Cracks that Do Not Intersect Circumferential Welds

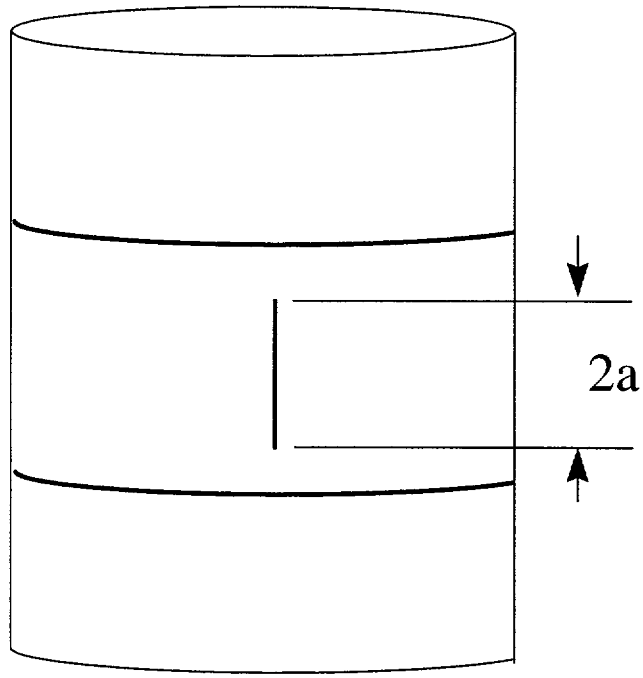

Figure 4-1
Vertical Weld Cracks that Do Not Intersect Circumferential Welds

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4.2 Vertical Weld Cracks that Intersect Circumferential Welds

The previous evaluation methodology dealt with indications in the vertical weld that do not intersect the circumferential weld. For the case of intersecting indications in the vertical and circumferential weld, the analyses are more extensive. Several methodologies can be used to assess vertical weld indications that intersect circumferential weld indications. These methodologies are outlined in the following sections.

4.2.1 360 Degree Through-Wall Flaw in Intersecting Circumferential Weld; Part Through-Wall Flaw in Vertical Weld

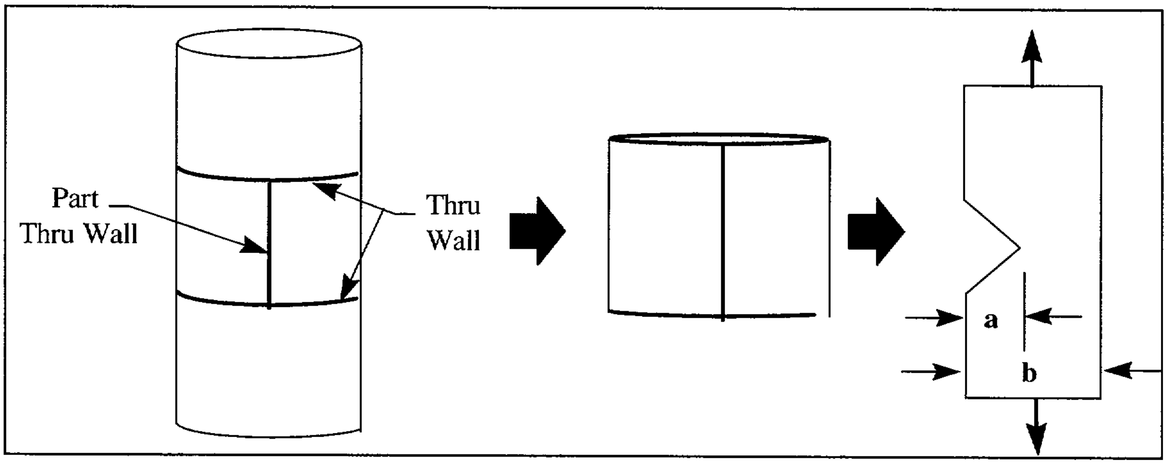

Figure 4-2
360 Degree Through-Wall Flaw in Intersecting Circumferential Weld; Part Through-Wall Flaw in Vertical Weld

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Figure 4-3
Compound Crack

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4.2.2 360 Degree Part Through-Wall Flaw in Circumferential Weld; Through-Wall Flaw in Intersecting Vertical Weld

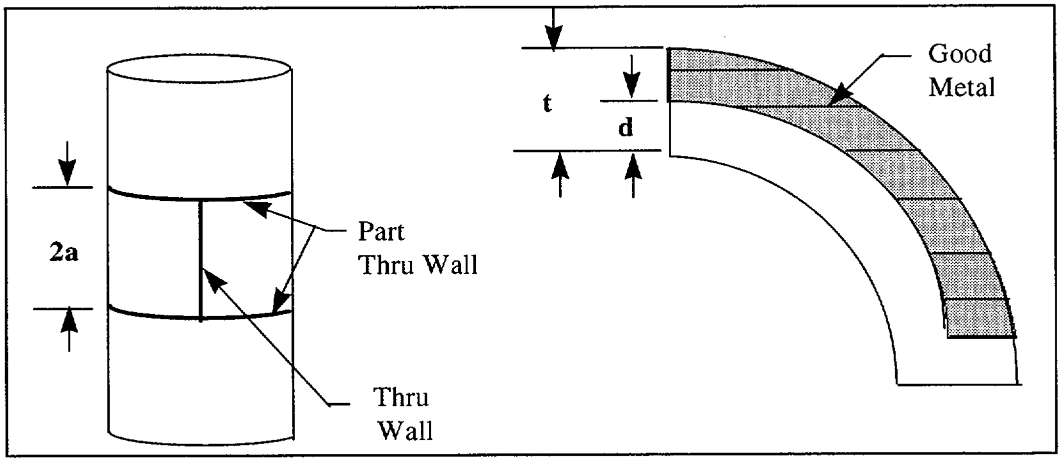

Figure 4-4
360 Degree Part Through-Wall Flaw in Circumferential Weld; Through-Wall Flaw in Intersecting Vertical Weld

For this case, the entire circumferential weld is assumed to be cracked to a part through-wall depth. The vertical weld is assumed to be cracked through-wall. The LEFM and limit load analyses for this case is provided below.

LEFM Analysis

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Limit Load Analysis

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4.3 Leakage

To this point, the flaw evaluation has outlined the analyses used to evaluate the structural margin of the flaw indications.

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Figure 4-5
Leak Rate vs. Axial Crack Length

4.4 Flaw Evaluation Assumptions for Cracking in Uninspected Regions

In performing plant specific evaluations, assumptions must be made regarding the amount of cracking in uninspected regions of the weld. For purposes of these evaluations, the defect rates shown in Table 4-1 should be assumed. The table shows the length of cracking that should be assumed in the uninspected region as a function of the length observed in the inspected region.

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Table 4-1
Defect Rates in Uninspected Regions of Core Shroud Vertical Welds

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4.5 Conclusions

The methodologies presented in this section provide closed form solutions to evaluate cracking in a vertical weld. The methodologies differ according to the severity of the cracking in the vertical weld. It should be noted that in some cases, due to the severity of cracking in the vertical weld, the simplified solutions will not yield acceptable results. For these cases, more detailed, plant specific finite element analyses may be used. Guidance on performing these detailed analyses is provided in Appendix B.

5
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A
ANALYTICAL BASIS FOR SCREENING AND ACCEPTANCE CRITERIA

This Appendix outlines the generic analyses which were performed in order to determine the inspection strategies given in Section 3. Included in this Appendix are four cases. The first case (Case A) provides an allowable through-wall flaw in a vertical weld. This is intended to show the amount of uncracked ligament needed in the vertical weld, given no credit for the circumferential weld. The second case (Case B) provides an allowable through-wall flaw in the circumferential weld at the intersection with the vertical weld, given no credit for the vertical weld. The final two cases provide allowable flaws while taking credit for partial through-wall cracking in either the vertical weld (Case C) or the circumferential weld (Case D).

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Case A: Allowable Through-Wall Flaw in Vertical Weld (Through-Wall Crack in Circumferential Weld over Entire Length)

This case, shown in Figure A-1, calculates the allowable through-wall flaw in the vertical weld, taking no credit for the integrity of the circumferential weld (cracks are represented in the figures by bold lines). The technical purpose of this case was to show how much through-wall cracking could occur in the vertical weld, while still maintaining structural margin. For this case, it was assumed that there was no cracking in the vertical weld at the intersection with the circumferential weld. Both LEFM and limit load methodologies were used to determine the allowable cracking. The technical basis and the results are included in the following.

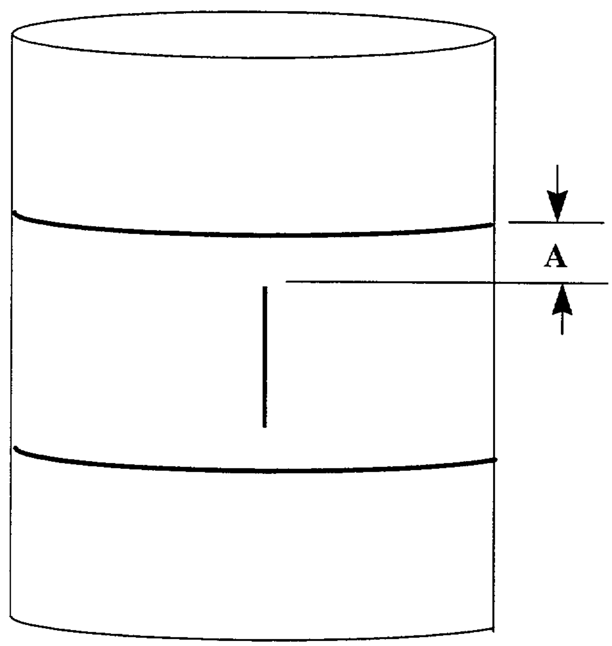

**Figure A-1
Case A**

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Case B: Allowable Through-Wall Flaw in Circumferential Weld (Through-Wall Crack in Vertical Weld over Entire Length)

Similar to Case A, this analysis, shown in Figure A-2, assumes no intersecting cracking at the vertical/circumferential weld intersection. The purpose of this analysis is to show how much uncracked ligament must exist at the intersection, given that the vertical weld is entirely cracked, and the remaining circumferential weld is cracked through-wall. The LEFM and limit load technical bases and results are included in the following.

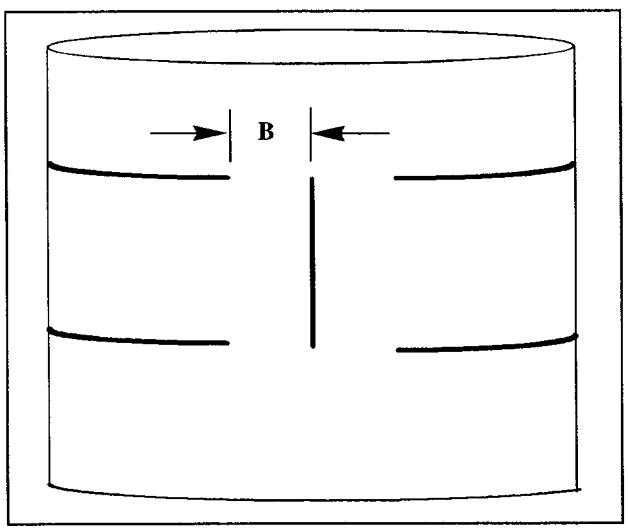

Figure A-2
Case B

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Case C: Allowable Part Through-Wall Flaw in Vertical Weld (Through-Wall Crack in Circumferential Weld over Entire Length)

This case was performed to address cracking in the intersection of the circumferential and vertical welds. For this case, partial credit was taken for part through-wall cracking in the vertical weld. This would allow for cracking to occur at the intersection, provided that the flaw depths do not exceed a specified amount. The allowable flaw depth is calculated over the entire length of the vertical weld. Similar to Case A, no credit was taken for the circumferential weld for this case.

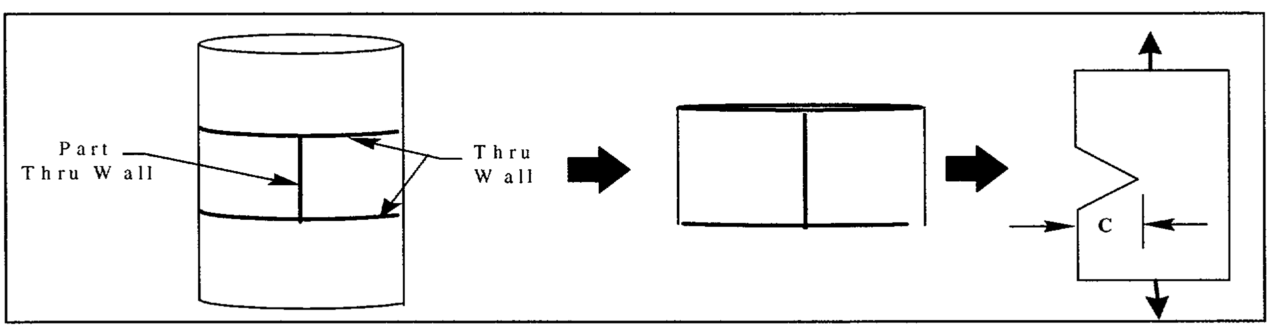

Figure A-3
Case C

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Case D: Allowable Part Through-Wall Flaw in Circumferential Weld (Through-Wall Crack in Vertical Weld over Entire Length)

This analysis assumes a part through-wall flaw in the circumferential weld and a complete through-wall flaw in the vertical weld. Consequently, the evaluation determines the allowable crack depth of the circumferential weld.

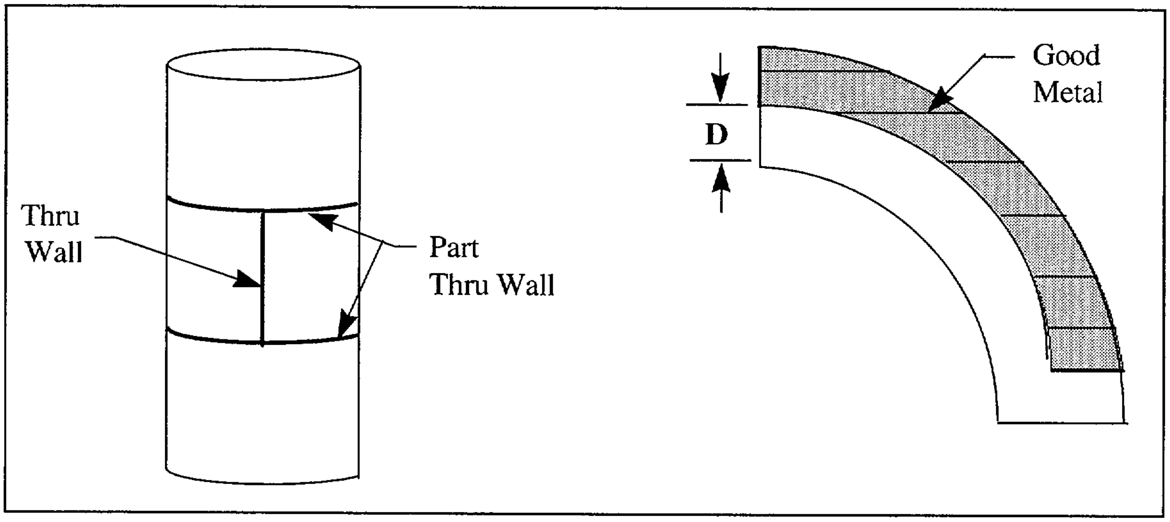

Figure A-4
Case D

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B
PLANT SPECIFIC FLAW EVALUATION METHODOLOGY

This Appendix provides additional guidelines and fundamental criteria for plant specific flaw evaluation outside the bounds of the three cases presented in Section 4.

The closed form solutions presented in Section 4 ensure that the vertical welds satisfy three basic criteria:

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Plant specific analysis is required when the generic acceptance criteria presented in Section 3 can not be met. The plant specific analyses must meet the following criteria:

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Some examples of the application of plant specific analyses follow.

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C
CALCULATION OF AVERAGE CRACK DEPTH

This appendix provides an example of the calculation of "average crack depth at EOI (End of Interval)" as defined in Section 3.

Assume the following:

Total length of vertical weld	90"
Inspected length (L_I)	50"
Shroud thickness	2"
EOI	6 years (8000 hr/year assumed)
Cracks observed (L_i, d_i):	

Crack	Length (in)	Depth (in)
1	12	0.2
2	8	0.1 to 0.2
3	6	1.0

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