Quad Cities Units 1 & 2 Core Shroud Repair, Design Reliant Structures Inspection Requirements and Acceptance Criteria

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SARGENT & LUNDY CERTIFICATION OF REPORT NO. SL-4984

REV. 1

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I certify that this Design Document was prepared by me or under my supervision and that I am a Registered Engineer under the laws of the State of Illinois

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Table of Contents:

1.0 Introduction

This report documents the requirements and acceptance criteria developed for the inspection of the Quad Cities Unit 1&2 core shroud repair design reliant structures. It focuses on the core shroud components, structures and welds relied upon by the shroud repair to maintain its structural integrity.

1.1 Background

NRC Generic Letter 94-03 required an inspection plan to be developed for all shroud welds, i.e. "from attachments to the vessel to the top of the shroud," or provide justification for eliminating the weld from the inspection. It also required that this plan define the method of examination to be specified for those welds being examined. The required Quad Cities Station Unit 2 core shroud inspection plan was developed following the guidance of the Boiling Water Reactor Vessel & Internals Project (BWRVIP) as provided in the BWR Core Shroud Inspection and Flaw Evaluation Guidelines, Reference 3. From this guidance document, the Quad Cities Station has been determined to be a Category C plant, requiring a comprehensive inspection of the shroud welds. Since this inspection is being performed in conjunction with the core shroud repair for the horizontal welds, the vertical and ring segment welds and all other shroud components relied upon to satisfy the design basis requirements of the repair design require an inspection.

1.2 Inspection Objectives

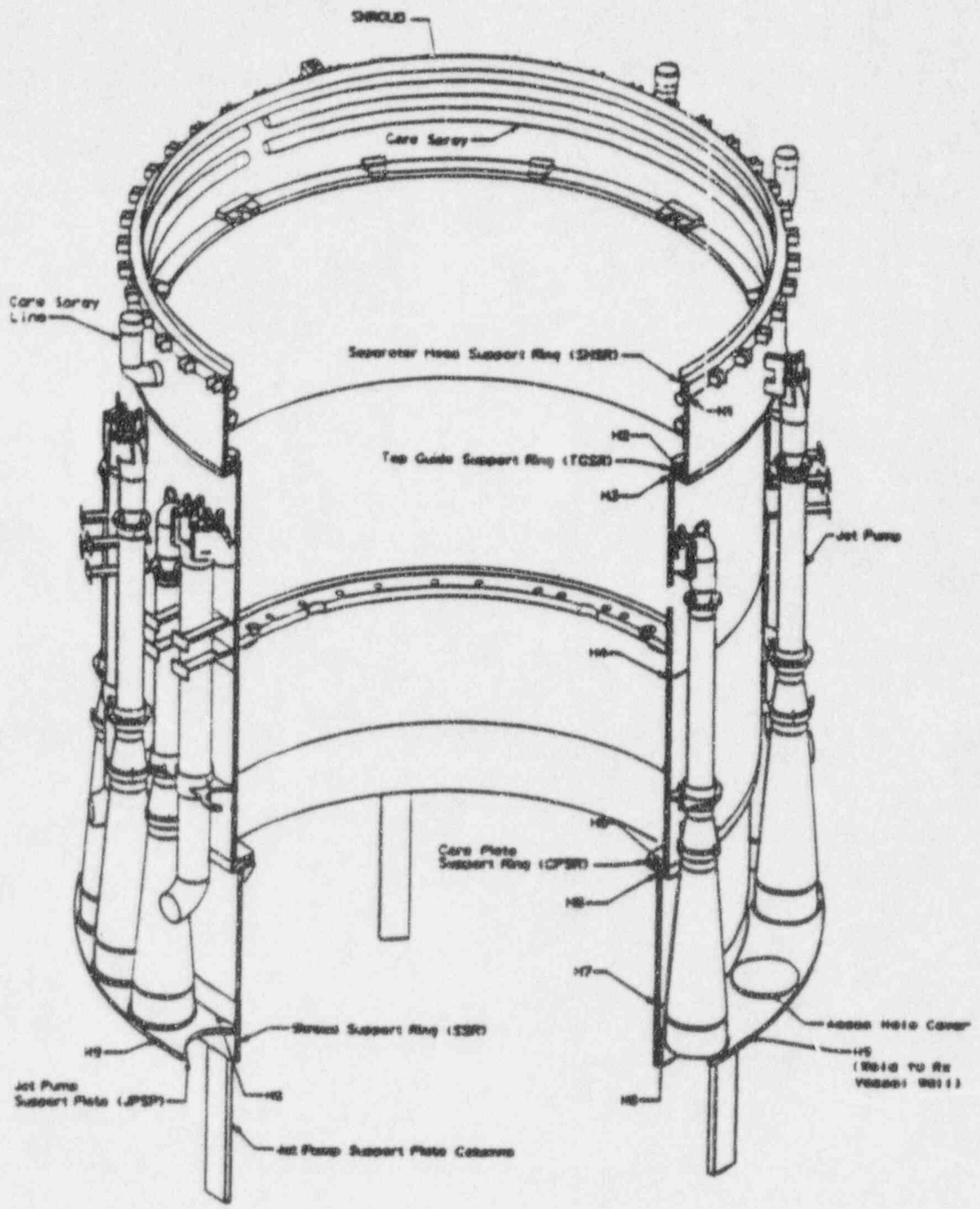
The installation of the core shroud repair hardware is intended to replace the structural functions of the horizontal welds, H1 through H7. The repair design, Reference 4, has concluded that the H1 through H7 welds are not required to maintain shroud functionality and they are assumed to be flawed through wall for the entire circumference of the shroud. Consequently, the horizontal welds H1 through H7 are not required to be examined. It also evaluated the requirements for the H8 weld and determined that rotational resistance at this weld is not required for the shroud support plate to perform its design function. It relies on the H8 connection to restrain the vertical and horizontal forces only. The repair design relies on the vertical and the ring segment welds, as well as the H9 weld and repair attachment points to remain

structurally intact for the repair to function as intended. Consequently, the vertical shell course, ring segment, H8 and H9 welds and attachment points of the core shroud will be examined to the extent necessary to satisfy the core shroud repair design requirements. The requirements for this inspection and the inspection acceptance criteria are determined based on the design reliant functions of the welds and structures. Table 1 provides a comprehensive review of the design reliant functions and inspection requirements for the core shroud design reliant structures and welds. Figure 1 presents the core shroud vertical shell course, ring segments and horizontal weld locations.

Table 1: Quad Cities Unit 2 Core Shroud Repair Design Reliant Functions

Weld/Component Description	Design Reliant Function	Extent & Type Of Required Inspection
H1-H7	• None	• None • Horizontal Welds Structurally Replaced By Repair Hardware
H8	• Vertical & Horizontal Restraint for Jet Pump Support Plate Connection to the Shroud	• VT at Four Attachment Locations
H9	• Vertical, Rotational & Horizontal Restraint for Jet Pump Support Plate Connection to the RPV	• VT at Four Attachment Locations
Vertical Shroud Welds Between • H1-H2 • H3-H4 • H4-H5 • H6-H7	• Resistance to Differential Pressures & Hoop Stresses • Lateral Stability of Shroud Cylinder	• VT and/or UT of the Welds
Ring Segment Welds • Shroud Head Flange Ring • Top Guide Support Ring • Core Plate Support Ring	• Resistance to Differential Pressures & Hoop Stresses • Distribute Bending Stresses • Lateral Stability of Shroud Cylinder	• VT of the Welds
Repair Attachment Locations • Shroud Head Flange Ring • Jet Pump Support Plate	• Structural Connection of Shroud Repair Hardware	• VT of Attachment Points

Figure 1: Core Shroud Configuration



2.0 Inspection Acceptance Criteria Methodology

The inspection acceptance criteria is based on a structural evaluation for the stated design reliant functions of the vertical shell course welds, the ring segment welds, the H8 and H9 welds and the repair hardware attachment points. The structural evaluation is performed using the flaw evaluation methods specified in the BWRVIP inspection and evaluation guidelines, Reference 3. Limit load and linear elastic fracture mechanics methods are used to establish the acceptance criteria (i.e., the minimum length of uncracked material necessary to meet the structural requirements) for each location. Providing this acceptance criteria is met, the condition of those areas not examined will not affect the design reliant function of the welds, and may conservatively be assumed to be cracked. In addition to the flaw evaluations, a stress evaluation using the ASME B&PV Code, Subsection NG is performed to calculate the minimum length of uncracked material required for the normal, upset, emergency and faulted condition stress limits. This additional evaluation is performed to ensure the structural margins inherent in the original design of the shroud are maintained.

As required by the repair evaluation (Reference 4) the inspection of the repair attachment points to the shroud head flange ring segment and the shroud support ledge is intended to establish the localized integrity of these attachment points. These points are required to maintain the vertical load capacity of the repair tie rod. Additionally, the inspection of the H8 and H9 welds in the vicinity of the repair attachment is to establish the load carrying capability of these welds. The repair evaluation requires the H8 weld to act as a pinned connection and resist vertical and horizontal loads. It requires the H9 weld to resist vertical and horizontal loads as well as the bending moment. For the H9 and hardware attachment points, an evaluation will be performed using IWB-3600 of the ASME B&PV Code, Section XI, to ensure the structural integrity of these components if crack indications are found during the examination.

These evaluations are based on conservative combinations of the postulated flaw sizes and locations and do not consider the as found flaw distribution or part through wall flaw conditions. Consequently, actual inspection results not meeting these criteria may be evaluated separately and found to be acceptable.

2.1 Vertical Shell Course and Ring Segment Loading

The flaws being evaluated in the vertical shell course and ring segment welds will be oriented in a plane formed by the radial and vertical directions because the weld residual stress is acting in a direction normal to this plane. Vertical, radial or localized bending stresses will not contribute substantially to cracking for flaws in this plane. Consequently, the critical axial flaw size is governed primarily by the hoop stress caused by pressure loads. This conclusion is also supported by the BWRVIP inspection and evaluation guideline, Reference 3. The pressures used in these evaluations are listed in Table 2. They are the maximum pressure differentials to occur for the normal, upset, emergency and faulted conditions of the vessel. Although a pressure drop exists along the vertical axis of the shroud, constant maximum pressures above and below the core plate are conservatively used for these evaluations. The pressures utilized are the bounding values from Tables 3.9-18 and 3.9-20 of the USFAR and the results of the TRACG main steam line break analysis, Reference 9.

Table 2: Quad Cities Units 1 & 2 Maximum Differential Pressures for the Core Shroud

Weld Locations	Normal Operating/Upset Condition Pressure - psid	Emergency/Faulted Condition Pressure - psid
Above H5	8.0	20.0
Below H5	26.8	43.0

In addition to the pressure load, the finite element stress analysis results, Reference 10, prepared for the core shroud repair design qualification include the effects of the seismic and LOCA loads on the hoop stress. The effects of these loads on the hoop stress are highly localized in the shell at the shroud head, top guide and core plate rings and are caused by the conservative seismic and LOCA load application methods during the analyses. However, these conservative hoop stresses for the combined normal/upset and faulted conditions are used for the critical flaw length calculations.

2.2 Critical Flaw Length Evaluations

The critical flaw lengths are calculated for each set of vertical shell course and ring segment welds using the limit load and linear elastic fracture mechanics approaches as recommended by the BWRVIP in Reference 3. For each of these approaches, the horizontal welds above and below the vertical plate or ring segment being evaluated, are conservatively assumed to be cracked through wall for the entire circumference. The axial flaw is assumed to be through wall anywhere along the vertical weld and is evaluated as a semi-infinite plate loaded in tension. These evaluations also use the ASME B & PV code Section XI safety factors of 2.77 for the normal/upset conditions and 1.39 for the emergency/faulted condition to maintain the margins established by the original design.

The critical flaw length for the limit load evaluation was determined by solving the following equation.

$$\sigma_h = \sigma_f \,(1 - a/L)/SF$$

Where σ_h is the hoop stress, σ_f is the flow stress defined as 3 S_m, L is the total length of the vertical weld, a is the total flaw length and SF is the appropriate safety factor. The S_m used for these evaluations is 16.9 ksi for Type 304 stainless steel at 550°F.

As indicated in Reference 3, the linear elastic fracture mechanics evaluation is only required where high fluence levels, greater than 3 $\times 10^{20}$ n/cm^2, may reduce the material toughness of the core shroud. This is only a concern for the vertical welds between the H3 and H5 welds, therefore the LEFM evaluation is limited to these vertical welds. The critical flaw length for the linear elastic fracture mechanics evaluation was determined by the formulation for a center or double edge cracked panel under uniform tension. The applied stress intensity is calculated using the following equation with the same terms as described for the limit load equation.

$$K_{I applied} = \sigma_h \left((2L/\pi a) \tan(\pi a/2L)\, \pi a/2\right)^{1/2}$$

The fracture toughness, K_{Ic}, for radiation embrittled Type 304 stainless steel is conservatively estimated to be 150 ksi $\sqrt{\text{in}}$. The critical flaw length is calculated by setting the applied stress intensity equal to the fracture toughness divided by the appropriate safety factor. The fracture toughness, K_{Ic}, for the normal/upset condition is 53.6 ksi $\sqrt{\text{in}}$ and for the emergency/faulted condition, 107.1 ksi $\sqrt{\text{in}}$.

Although not required by the current design basis for the core shroud, a primary stress check following the criteria of Subsection NG of the ASME B&PV Code was also performed. This evaluation was performed by calculating the length of the remaining ligament necessary to meet the NG 3000 primary stress criteria of S_m for the normal/upset condition and 2.0 x S_m for the faulted condition pressure differentials.

The critical flaw lengths calculated from the limit load and LEFM evaluations were used to determine the largest remaining ligament required by each approach. For conservatism, these ligament lengths were compared with the remaining ligament required by the primary stress check and the largest length was chosen as the required remaining ligament for the shroud section being analyzed.

For the localized inspections of the repair attachment points and the H9 weld any identified crack indications will be evaluated per the requirements of IWB-3600. Because the H8 weld is only required to resist vertical and horizontal (bearing) stresses, the inspection must verify that, if cracking exists, the separation between the ledge and shroud support is limited by the clearance required for the 2" thick ledge to bind on the shroud support when moving in a vertical direction. Additionally, the vertical load on the ledge will be resisted by the frictional force generated by the difference in the thermal expansion of the carbon steel vessel and the Inconel Alloy 600 support ledge. The acceptance criteria for the H8 weld examination is no visible separation between the support plate and the shroud support.

2.3 Required Remaining Ligament

Table 3 presents the results of the critical flaw length evaluations and the remaining unflawed ligament required to maintain the stability of the shroud. The required remaining ligament is the minimum required material length anywhere along the weld being examined.

Table 3: Remaining Ligament Requirements to Meet Weld Structural Integrity

Vertical Plate Weld	Critical Flaw Length	Required Remaining Unflawed Ligament	Length of Weld
Between H1 &H2	28.53"	4.97"	33.5"
Between H3 & H4	84.63"	4.37"	89"
Between H4 & H5	70.61"	4.64"	75.25"
Between H6 & H7	50.86"	4.76"	55.625"

Ring Segment Weld	Thickness of Plate	Length of Weld	Required Area of Unflawed Ligament (in^2)
Shroud Head Flange Ring	4.0"	6"	2.6
Top Guide Ring	2.5"	8.44"	4.2
Core Plate Support	4"	10.685"	4.3

3.0 Inspection Criteria

3.1 Requirements for Bounding Acceptance Criteria

The potential crack growth estimated to occur between inspections and the inspection uncertainty has been combined with the required remaining ligament to establish the required effective remaining ligament (i.e., acceptance criteria) for the inspection. Crack growth occurs along the crack tip at each end of the postulated flaw. Consequently, the effective remaining ligament is required to be increased by two times the estimated crack growth plus the inspection uncertainty factor. The crack

growth rate is based on 5×10^{-5} in/hr for hot operating hours above 200°F. For an inspection interval of every other fuel cycle, the hot operating hours are estimated to be 32000.0 hours, i.e. 91% availability for 48 months, yielding an estimated crack growth of 1.6 inches.

The inspection uncertainty used to determine the effective remaining ligament is dependent on the inspection method employed. The inspection uncertainty used here is based on the recommended evaluation factors for the nondestructive examination (NDE) technique and the delivery system provided by the BWRVIP Inspection Subcommittee in Reference 7. For a visual examination, the total inspection uncertainty of 1.25" is recommended for each end of the flaw. For ultrasonic examinations on the same side of the weld, the technique evaluation factor of 0.4", at each end of the flaw, is recommended for flaws identified on the near or far surface. For ultrasonic examinations on the opposite side of the weld, i.e. the transducer is on one side of the weld and is examining a flaw on the other side of the weld, the technique evaluation factor of 2 x t, at each end of the flaw, is recommended for flaws identified on the near or far surface. The delivery system evaluation factor for an area scanner is recommended to be 0" if the flaw length is determined without moving the scanner and 1.25", at each end of the flaw, if the scanner is moved any number of times. The inspection uncertainty for ultrasonic examinations is the summation of the inspection technique and delivery system evaluation factors.

It should be noted that these uncertainty factors apply to the prequalified flaw sizing techniques. If new techniques are applied (e.g., lasar measurement or video pixel measurement), the uncertainties demonstrated for those specific techniques shall apply.

Table 4: Inspection Uncertainty at One End of A Flaw - Used to Determine the Effective Remaining Ligament Requirements

Vertical Plate Welds	VT Examination[1]	UT Examination - Same Side of Weld		UT Examination - Opposite Side of Weld	
		Single Placement	Multiple Placements	Single Placement	Multiple Placement
NDE Technique	1.25"	0.4"	0.4"	4.0"	4.0"
Delivery System	0"	0.0"	1.25"	0.0"	1.25"
Total Inspection Uncertainty	1.25"	0.4"	1.65"	4.0"	5.25"

Note 1: The VT Examination inspection uncertainty is also applicable to the ring segment inspections

An additional consideration for the effective remaining ligament is the minimum flaw separation criteria specified in section XI of the ASME B & PV Code. This criteria requires that the minimum distance between flaws in the same plane be at least two times the depth of the deeper flaw. For flaws assumed to be through wall, i.e. without depth sizing, the separation criteria would be two times the plate thickness. This separation criteria must also consider the potential crack growth at the adjacent crack tips, therefore the separation criteria for two flaws with undetermined depth is given by

$$S = 2\,CG + 2\,t\,,$$

where S is the distance separating two flaws, CG is the estimated crack growth associated with the inspection interval and t is the plate thickness. When the remaining ligament is less than the value of S above, a single continuous flaw must be assumed. Consequently, the minimum remaining ligament must be greater than the flaw separation criteria.

3.2 Inspection Requirements and Acceptance Criteria

The acceptance criteria required for the inspection of the vertical shell course and ring segment welds are established by combining the estimated crack growth of 5×10^{-5} in/hr for 2 fuel cycles (i.e., 48 months of operation at 91% availability) and inspection uncertainty with the required remaining ligament lengths. These results are presented for the inspection type and weld lengths in Tables 5 and 6. The inspection types have been recommended to verify the absence of cracking on both surfaces. The notes added to these tables clarify the intent of the examination and the alternatives. A note has also been added to each table to specify the length of additional material required to compensate for the estimated crack growth and inspection uncertainty. For those welds which are inaccessible for examination or do not meet the acceptance criteria, the structural stability of the plate or ring segment can be demonstrated by verifying the integrity of the horizontal weld above or below the vertical or ring segment weld. The required segment of horizontal material must start within 18" of the weld and is required on both sides of the weld at the top or the bottom of the plate/ring. Alternatively, the material is required within 18" of one side of the vertical weld at the top of the plate/ring and 18" of the other side of the weld at the bottom of the plate/ring.

Table 5: Vertical Shell Course Weld Inspection Requirements and Acceptance Criteria

Vertical Weld [5]	Inspection Type	Bounding Acceptance Criteria [3, 4, 5] for the Specified Inspection Type					Length of Weld
		VT	UT Same Side		UT Opposite Side		
			Single Place.	Multiple Place.	Single Place.	Multiple Place.	
Between H1-H2	VT [1] and UT [2] from outside	10.7"/ 15.6" [5]	9.0"/ 13.9" [5]	11.5"/ 16.4" [5]	16.2"/ 21.1" [5]	18.7"/ 23.6" [5]	33.5"
Between H3-H4	VT [1] and UT [2]	10.1"/ 14.4" [5]	8.4" / 12.7" [5]	10.9"/ 15.2" [5]	15.6"/ 19.9" [5]	18.1"/ 22.4" [5]	89"
Between H4-H5	VT [1] and UT [2]	10.3"/ 15.0" [5]	8.6" / 13.3" [5]	11.1"/ 15.8" [5]	15.8"/ 20.5" [5]	18.3"/ 23.0" [5]	75.25"
Between H6-H7	VT [1] and UT [2] from outside	10.5"/ 15.2" [5]	8.8"/ 13.5" [5]	11.3"/ 16.0" [5]	16.0"/ 20.7" [5]	18.5"/ 23.2" [5]	55.625"

1) VT not required if UT method is capable of detecting near surface flaws.

2) UT method must be capable of far surface flaw detection.

3) This is the required material at any location along the weld.

4) This dimension includes the postulated crack growth for 48 months of 1.6" and the inspection uncertainty specified in Table 4 multiplied by 2 to account for each crack tip.

5) For vertical welds which are inaccessible for examination or do not meet the acceptance criteria, an examination of the horizontal weld near the vertical weld is required to maintain shell stability. The minimum required material specified for this note, given the NDE technique actually employed, is required in the horizontal weld and must start within 18" of the vertical weld. The minimum required material is required to be on both sides of the vertical weld at the top or bottom of the plate or on one side of the vertical weld at the top of the plate and on the other side of the vertical weld at the bottom of the plate.

Table 6: Ring Segment Weld Inspection Requirements and Acceptance Criteria

Ring Segment Location	Inspection Type	Bounding Acceptance Criteria	Length of Weld
Shroud Head Flange Ring	VT	No Cracking	6"
Top Guide Ring [1]	VT	No Cracking	8.44"[1]
Core Plate Support Ring [1]	VT	No Cracking	10.685"[1]

1) This is the length of weld in the radial direction.

For ring segment welds which can not be examined or exhibit cracking, an examination of the horizontal weld near the ring segment weld is required to maintain plate stability. The minimum required material specified in Table 7 is required to be within 18" of the ring segment weld. The minimum required material is required to be on both sides of the ring segment weld at the top or bottom of the ring segment or on one side of the ring segment weld at the top of the ring segment and on the other side of the ring segment weld at the bottom of the ring.

Table 7: Ring Segment Horizontal Weld Inspection Requirements and Acceptance Criteria for Inaccessible or Unacceptable Ring Segment Welds

Ring Segment Location	Inspection Type	Bounding Acceptance Criteria [3, 4] for the Specified Inspection Type					Length of Weld
		VT	UT Same Side		UT Opposite Side		
			Single Place.	Multiple Place.	Single Place.	Multiple Place.	
Shroud Head Flange Ring	VT [1] and UT [2] from outside	8.3"	7.2"[4]	9.1"	13.8"	16.3"	6"
Top Guide Ring	VT [1] and UT [2] from outside	9.9"	8.2"	10.7"	15.4"	17.9"	8.44"
Core Plate Support Ring	VT [1] and UT [2] from outside	10.0"	8.3"	10.8"	15.5"	18.0"	10.685"

1) VT not required if UT method is capable of detecting near surface flaws.

2) UT method must be capable of far surface flaw detection.

3) This dimension includes the postulated crack growth for 48 months of 1.6" and the inspection uncertainty specified in Table 4 multiplied by 2 to account for each crack tip.

4) Based on the minimum flaw separation criteria, the acceptance criteria is 7.2"

As specified previously, any cracking identified at the repair attachment points and the H9 weld will be evaluated per the methods specified in IWB-3600 of the ASME B&PV Code, Reference 8. The examination requirements are presented below in Table 8.

Table 8: Repair Attachment Site Inspection Requirements

Location	Inspection Type	Flaw Length Permitted
Shroud Head Flange Ring Notches	VT Cut and Machined Surfaces	No Cracking [1]
Shroud Support Ledge Attachment	VT Upper Surface and Holes	No Cracking [1]
H8 Weld	VT [3]	No Minimum [2]
H9 Weld	VT [3]	No Cracking [1]

1) ASME Section XI IWB-3600 evaluation will be required for any indications found during the inspection.

2) This inspection is required to verify no separation of the two sides of the joint.

3) This visual examination is limited to the vicinity of the repair attachment sites.

4.0 References

1. NRC Generic Letter 94-03, "Intergranular Stress Corrosion Cracking of Core Shrouds in Boiling Water Reactors"

2. Quad Cities Station Unit 2 Core Shroud Inspection Plan (1/16/95)

3. BWRVIP document GENE-523-113-0894, "BWR Core Shroud Inspection and Evaluation Guidelines," September 1994.

4. GENE-771-69-1094, Rev. 0, "Backup Calculations for Quad Cities Shroud Repair Shroud Stress Report," January 1995

5. GENE Drawing 105E1415A, Rev 0, April 12, 1994

6. SL-4975, Rev 0, "Response To U. S. NRC Staff Request for Additional Information (Dated November 14, 1994) Concerning Core Shroud Cracking at Dresden Units 2 and 3 and Quad Cities Units 1 and 2," December 12, 1994

7. BWRVIP Inspection Subcommittee Report, "BWRVIP Core Shroud NDE Uncertainty & Procedures Standard", November 21, 1995.

8. ASME B&PV, Section XI, 1989 Edition

9. GENE-523-A163-1194, "Quad Cities and Dresden Main Steam Line Break Analysis with TRACG Model," November 9, 1994

10. GENE DRF B13-01740, ANSYS Finite Element Analysis Results

11. "Core Shroud Vertical Weld Flaw Evaluation for Inspection Acceptance Criteria", CMED-059111, Revision 1, April 10, 1995

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