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Evaluation of the Nine Mile Point Unit 2 Core Shroud Cracking

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1.0 INTRODUCTION

This report presents the support provided by Structural Integrity Associates (SI) for the disposition of the observed cracking in the Nine Mile Point Unit 2 (NMP2) core shroud. UT and visual inspection of the horizontal and vertical welds was performed as part of the inspection program during the NMP2 1998 outage. Indications were found in the H1, H2, H3, H4, H5, H7, and H8 welds. Significant cracking was observed at weld H7 and at the beltline welds, H4 and H5. Weld H6 had no indications. Minor cracking was found at all other horizontal welds. Based on the inspection, no indications associated with the vertical welds were found.

As part of this effort, SI performed a review of the GE Nuclear Energy (GE) fracture mechanics evaluations, including methodology. An important point during these evaluations was to verify that all methods were consistent with those documented in BWRVIP-01 [1] and Reference [2].

SI also performed a linear elastic fracture mechanics (LEFM) evaluation of welds H4 and H5 using detailed finite element analysis methods. The LEFM analysis for a compound crack described in this report was performed to provide additional assurance that margin existed at these welds. Existing solutions, as used in the GE analysis, required validation for direct application to the NMP2 shroud since the solution validity ranges were not met.

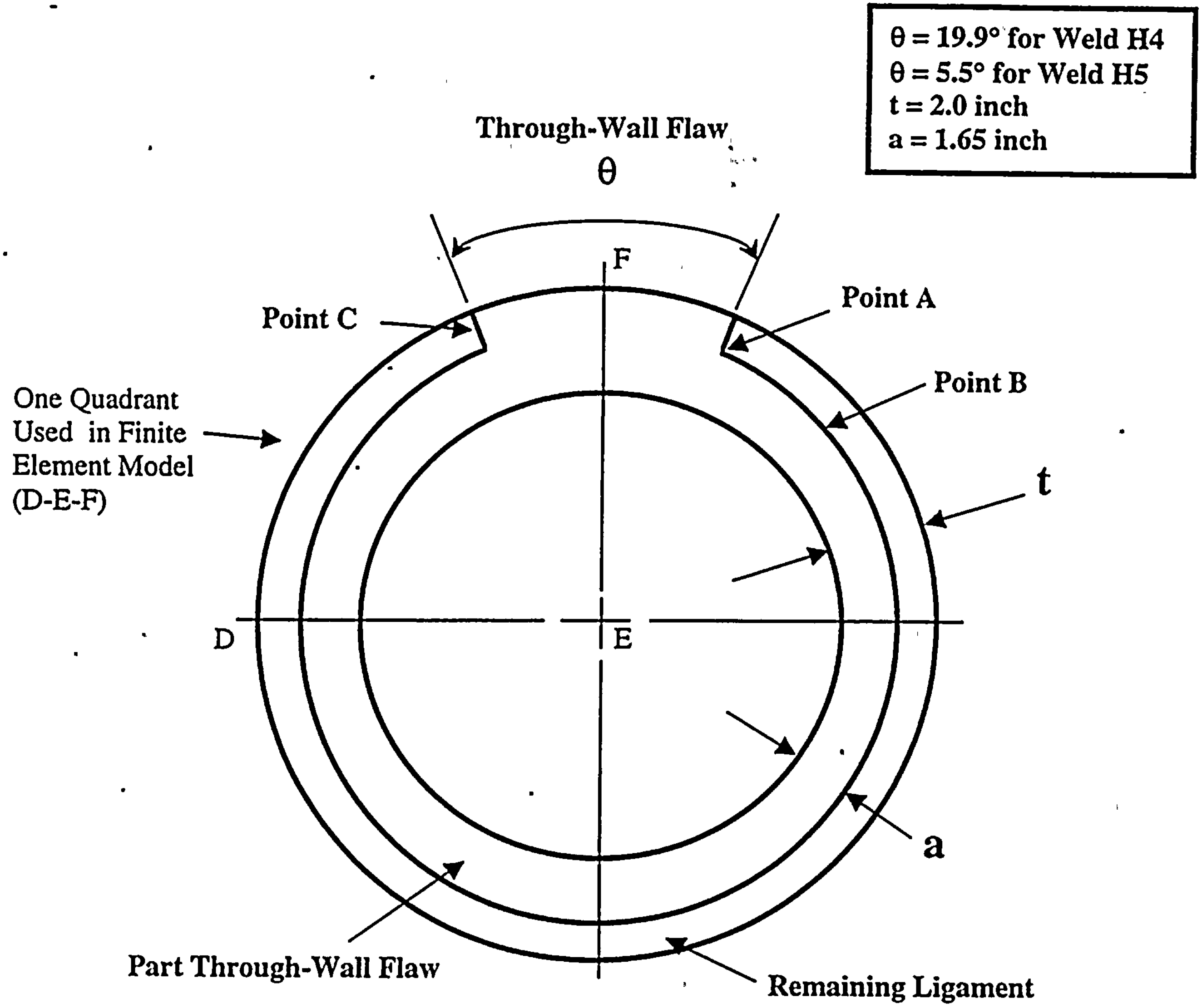
Based on the review of the GE evaluation, SI concurs with the conclusion that the observed cracking in the core shroud does not jeopardize structural integrity. The GE evaluation in combination with the weld H4 and H5 finite element results presented in this report comprise a technical justification for continued operation. Since the required safety factors in BWRVIP-01 are maintained, and the methods used are in compliance with BWRVIP-01 which uses ASME Code, Section XI as a guide, continued operation for at least the next operating cycle is justified.

2.0. FINITE ELEMENT ANALYSIS OF WELDS H4 AND H5

To support the disposition of cracking at the H4 and H5 welds, SI performed a detailed finite element analysis reflecting the results of the inspection for each of these welds. Based on the inspection report, certain regions of the H4 and H5 welds were not inspected. The conservative assumption that uninspected regions are through-wall cracked was maintained in this analysis. Reference [3] contains the UT inspection results which were the basis for the crack geometries analyzed in this section.

As part of the Niagara Mohawk Power Corporation (NMPC) effort to disposition cracking, calculations were performed using available solutions for similar geometries. In Reference [3], GE used a solution by Zahoor [4] for a compound crack. The compound crack is a crack geometry comprised of a through-wall crack merging with a 360° part through-wall crack. In the case of weld H4, the through-wall portion had a length equivalent to 19.9° of the shroud circumference, and the part through-wall portion had a depth of 1.65 inch. The 1.65 inch depth was determined by assuming an initial beginning-of-cycle flaw of 0.65 inch, and adding uncertainty {0.108 inch (Ref. [3])} and crack growth (0.85 inch based on a crack growth rate of 5×10^{-5} in/hr) for the next operating cycle (two years conservatively using 17,000 hrs.). This is conservative since a crack depth of 1.608 inch could have been used (0.65 + 0.85 + 0.108 = 1.608). The 0.65 inch initial flaw was the deepest indication at either weld H4 or H5. Note that this is considered conservative since the average crack depths are well below 0.65 inch (approximately 0.39 inch for H4 and H5). For weld H5, the through-wall portion was only 5.5° of the shroud circumference, and the part through-wall crack was assumed the same as that for weld H4.

The Zahoor solution is applicable to geometries with radius to thickness ratios (R/t) of 5 to 10. The NMP2 core shroud has a R/t ratio of 51. The finite element analysis was performed to verify the GE conclusion that the Zahoor compound crack solution was conservative. Note that the Zahoor solution is for a 360° crack growing from the inside surface, whereas in the NMP2 case, the cracking is connected to the outside diameter surface. However, for such large R/t ratios as 51, the solution is applicable to either ID or OD cracked geometries since it approaches a flat plate solution. Figure 2-1 is a schematic of the compound crack geometry being considered in this analysis.



Notes:

1. Finite element analysis models crack growing from ID. NMP2 flaw is on OD. For large R/t values, difference is not significant between ID or OD cracks since the solutions approach the flat plate solution.

2. Due to symmetry, finite element model, two through-wall flaws are modeled 180° opposite to through-wall flaw shown above.

Figure 2-1. Compound Crack Configuration Used in Finite Element Analysis of Welds H4 and H5

2.1 Finite Element Analysis

The finite element model was developed using the ANSYS finite element program, Revision 5.3 [5]. Reference [6] was used to obtain the necessary geometry information needed to construct the model. The shroud was modeled as an assemblage of finite elements with appropriate loading and boundary conditions. The 20-node isoparametric quadrilateral brick element (STIF95) from the ANSYS element library was used to model the crack tips, and the STIF45 element was used to model the remainder of the shroud. The crack tip singularity was modeled by moving the mid-side nodes in the vicinity of the crack tip to the quarter point. Details of this element type and method are described in Reference [5]. The geometry of the model is shown in Figure 2-1, and the finite element model mesh is shown in Figure 2-2. Close-up plots of the crack tip region in the vicinity of the corner where the through-wall crack and the part through-wall crack intersect are shown in Figures 2-3 and 2-4. The finite element model was constructed such that the crack tip region is sufficiently detailed for the stress intensity factor calculation.

One quarter of the core shroud was modeled using symmetry so that the geometry being modeled actually includes two through-wall cracks opposite to each other. However, the stress field for these two through-wall cracks do not interact and in fact, the addition of the second through-wall crack will increase the overall stress adding some conservatism to the solution. The finite element model of the shroud was made long enough to represent the remote tension loading condition.

The finite element approach to determine the stress intensity factors (which are directly calculated by ANSYS) was validated by comparing this approach with known solutions. Cases were evaluated to confirm that the methodology could repeat the solution assuming a through-wall flaw only, part through-wall flaw only, and edge-cracked plate. Results of this comparison showed that the finite element method duplicated the results from the available solutions within a few percent. Reference [7] contains this validation.

The cracking observed at welds H4 and H5 includes areas which were not inspected, areas that had little or no cracking, and some isolated areas with deeper cracking. This finite element

analysis simplified the problem by assuming a 360° part through-wall flaw with a depth equal to the deepest observed flaw and a through-wall flaw with a length equal to the longest uninspected length. The results of this simplified finite element model are appropriate to model the actual condition of the welds since the finite element results will bound that for the actual configuration.

Two compound crack finite element models were developed as noted below: Case 1 represents the flaw geometry for weld H4, and Case 2 represents the flaw geometry from weld H5 (see Figure 2-1).

Case 1:	Part through-wall flaw depth = 1.65 inch Through-wall flaw length = 19.9°
Case 2:	Part through-wall flaw depth = 1.65 inch Through-wall flaw length = 5.5°

The through-wall length corresponds to the largest uninspected region at each weld.

2.2 Loads and Boundary Conditions

The remote tension load is applied as a 1 ksi pressure load on the top of the model. Note that this conservatively assumes that the loading (including bending) is entirely membrane tension. Thus, the actual stress condition can be obtained by multiplying the unit load results by an appropriate factor of the applied stress in ksi units.

Symmetry boundary conditions are applied at the uncracked ligament at the bottom of the model, which represents the location of the H4 or H5 weld. Symmetry boundary conditions are also applied at the circumferential symmetry faces of the quarter cylinder model which results in the simulation of a 360° cylinder.

The loading and boundary conditions are illustrated in Figure 2-2.

2.3 Results

The ANSYS finite element model results were evaluated for the two different cases. The stress intensity factor (K_I) varies significantly along the crack tip in the vicinity of the corner where the part through-wall and through-wall flaws meet (see Point A in Figure 2-1). Thus, the maximum value in the corner region from the unit load case was used to determine the actual K_I value. The K_I along the part through-wall flaw away from the corner stabilizes to a constant value (see Point B in Figure 2-1).

The average K_I along the through-wall portion of the crack (see Point C in Figure 2-1) was compared against that of a single through-wall crack in a cylinder. The results compared within a few percent, adding additional validity to the finite element modeling.

Table 2-1 shows the unit load stress intensity factors at Point A:

Table 2-1 Unit Load Stress Intensity Factor Results

Case	Unit Load Stress Intensity Factor (ksi $\sqrt{in}$)
Case 1	23.1
Case 2	12.4

Multiplying the Case 1 results by the weld H4 stress, and Case 2 by the weld H5 stress gives the specific K_I values necessary to compare against the allowable stress intensity factor. The applied stress given in Table 2-2 is the sum of the pressure membrane stress and bending stress from Table 5-1 of Reference [3]. The allowable stress intensity factor is 54.15 ksi $\sqrt{in}$ · (from BWRVIP-01, 150 ksi $\sqrt{in}$ /2.77). Table 2-2 shows the specific weld H4 and H5 results. The safety factor of 2.77 is used since the upset condition is limiting.

Table 2-2 Stress Intensity Factor Results

Weld	Applied Stress (ksi)	Maximum Stress Intensity Factor (ksi $\sqrt{in}$)
H4	1.62	37.4
H5	2.54	31.5

Comparing the K_I values with the allowable value of 54.15 ksi $\sqrt{in}$ demonstrates that the required safety factors are maintained throughout the next operating cycle (17,000 hours).

2.4 Tracker Placement Uncertainty

The results described in Section 2.3 for the unit load cases can be used to illustrate margin in the definition of the uninspected region start-stop locations. This also serves to demonstrate that uncertainty in the tracker placement, and crack growth from uninspected regions, is not critical to the acceptance of the cracking at the H4 and H5 welds.

Multiplying the unit load results (Case 1 and Case 2 in Table 2-1) by the appropriate stresses gives the K_I for flaws of 5.5° and 19.9° at welds H4 and H5. This can be done since the basic geometry of the weld H4 and H5 locations is identical (shroud radius and thickness).

Table 2-3 Stress Intensity Factor Results

Weld	Stress Intensity Factor (ksi$\sqrt{in}$)		
	Length of Uninspected Zone (degrees)		Allowable (ksi $\sqrt{in}$)
	5.5	19.9	
H4	20.1	37.4	54.15
H5	31.5	58.7	54.15

Note that the 19.9° through-wall flaw case K_I of 58.7 ksi $\sqrt{in}$ for weld H5 slightly exceeds the allowable of 54.15 ksi $\sqrt{in}$, but it can be used here to illustrate existing margin. Evaluation of the

results also shows that for weld H5, a through-wall crack length slightly smaller than 19.9° would meet the allowable limit of 54.15 ksi $\sqrt{in}$. A margin of at least 10° (the difference between 5.5° and the angle which makes K_I equivalent to the allowable which is slightly less than 19.90) of the shroud length is present for the H5 weld after maintaining the BWRVIP-01 required safety factors. Likewise, for weld H4, the margin (in degrees) between K_I and the allowable is at least 10° of the shroud circumference (represented by the additional angle for the K_I to increase from 37.4 ksi $\sqrt{in}$ to the allowable of 54.15 ksi $\sqrt{in}$). The 10° margin bounds estimates for crack growth and length uncertainty.

2.5 Analysis Conservatisms

Several conservatisms were included in the finite element analysis presented in the previous sections. The conservatisms are listed below:

1. All uninspected weld lengths were assumed to be through-wall cracked.
2. A bounding crack growth rate of 5 x 10^{-5} in/hr was used for the part through-wall crack growth prediction.
3. Crack growth was estimated assuming a cycle length of 17,000 hours.
4. A 360° part through-wall crack was assumed with a uniform initial depth of 0.65 inch.
5. Applied stress was assumed all membrane.

Assumption 1 is conservative since based on inspection of 77.1% of weld H4 and 92.5% of weld H5, no through-wall cracking was found. A more reasonable assumption would be to assume that the uninspected zones had an initial depth of 0.65 inch.

Assumption 2 is conservative since a lower crack growth rate could probably be used. Assumption 3 increased the final depth by 5% since the actual cycle length is 15,500 hours. In fact, if a growth rate of 2.2x10^{-5} in/hr and 15,500 hours for the next cycle is considered, the end-of-cycle depth would be 1.1 inch (including 0.108 inch depth uncertainty and initial depth of 0.65 inch). This would be reduced even further to 0.84 inch if the average depth were used for

the initial 360° part through-wall flaw depth. This compares against the end-of-cycle depth of 1.65 inch used in the analysis.

Assumption 4 is conservative since a bounding crack profile was considered. This simplified the application of crack proximity criteria, length uncertainty and crack growth. The UT data showed that the crack significantly varied in depth around the shroud circumference. Many shallow flaws sized using creeping wave were conservatively sized as 0.25 inch deep flaws. Other locations that had no cracking as indicated by the UT inspection were considered flawed to simplify the analysis. For comparison, the average crack depth in the inspected region for weld H4 and H5 was approximately 0.39 inch. Clearly it is conservative to assume that a 360° part through-wall flaw exists with a uniform depth equal to 1.65 inch. Recall that the actual predicted end-of-cycle flaw depth (using 17,000 hour cycle length and initial depth of 0.65 inch) was 1.608 inch but was conservatively increased to 1.65 inch.

Assumption 5 is considered conservative since the K_I solution for membrane loading bounds the solution for bending loading. The bending portion of the stress was the primary contributor to the total applied stress.

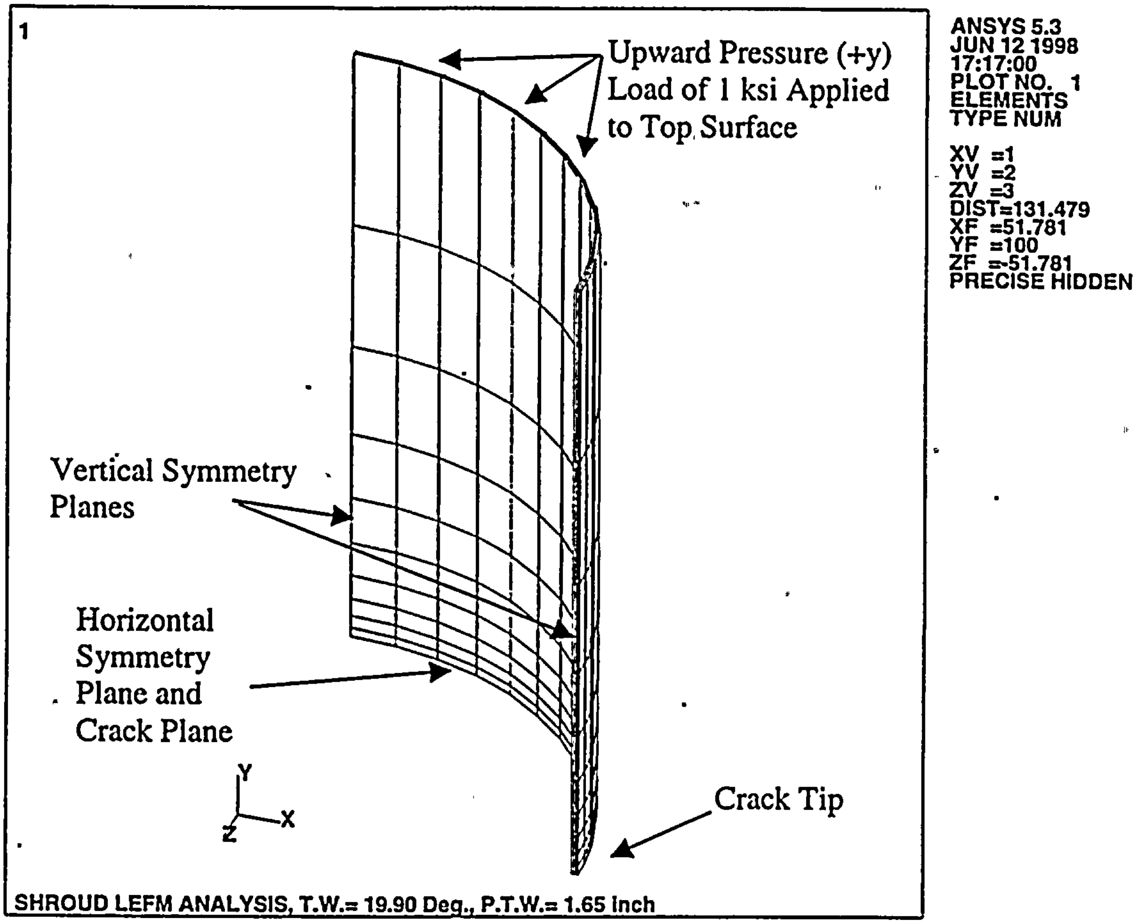


Figure 2-2. Finite Element Model

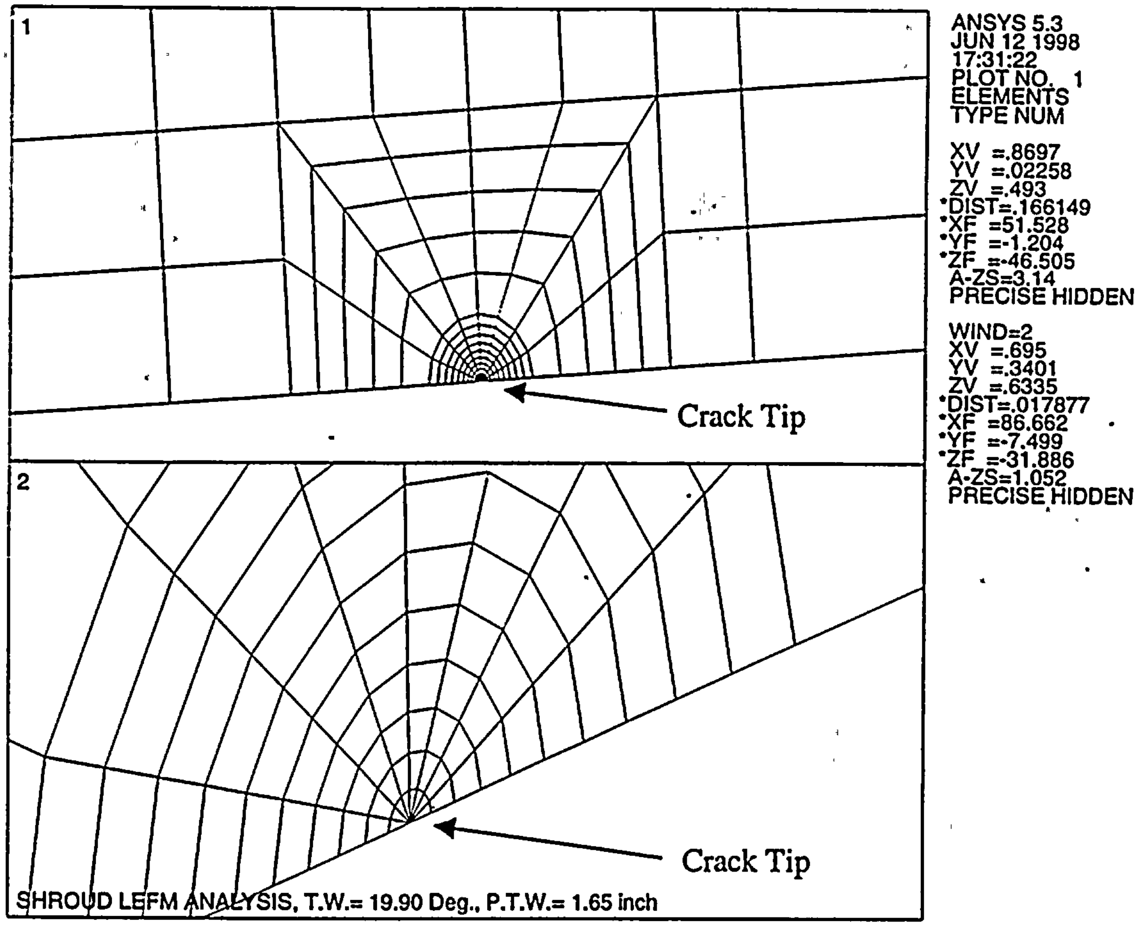


Figure 2-3. Close-Up View of Crack Tip Area

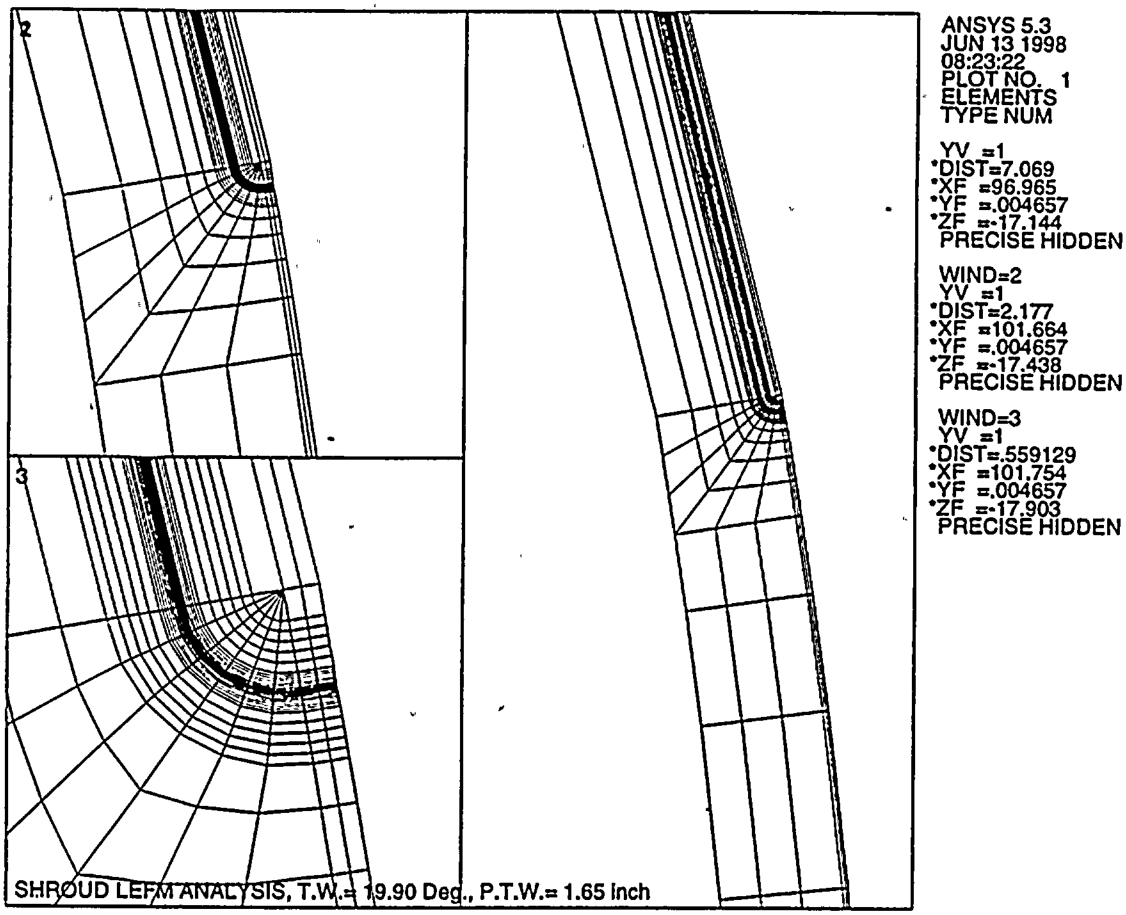


Figure 2-4. Close-Up View of Crack Tip Area Showing Corner Modeling

3.0 THIRD PARTY REVIEW OF GE'S SHROUD ANALYSES

This section presents the summary of the SI review of the GE evaluation of the cracking in the NMP2 shroud welds. Reference [3] was reviewed to assure the following:

1. Compliance with BWRVIP-01, Rev. 1 and Reference [2] technical approach.
2. Assure that the use of the methods was properly implemented into the analysis.
3. When new solutions were used, that they were consistent with the intention of BWRVIP-01, Rev. 1 and Reference [2].
4. Reasonable results.
5. Consistency with results obtained for other plants.
6. Appropriate benchmarking of solutions.
7. Correct implementation of inspection results.
8. Clear presentation of the results in a concise report.

SI was also in frequent contact with GE and NMPC personnel to assure that the evaluation was proceeding in the appropriate and quickest direction. Following is a summary of the SI observations regarding the GE analyses.

The appropriate analyses were performed for the weld flaws (LEFM and/or Limit Load). The finite element analyses which is presented in Section 2.0 of this report established that the Zahoor correction factors used by GE are conservative for the NMP2 shroud geometry.

The methodology used was generally conservative, especially the processing of the flaw data. The average depth for weld H4 was approximately 0.39 inch compared to the 0.65 inch flaw which was used as the initial flaw depth in the analysis.

Although crack growth from the uninspected zones was not considered in the analysis, the use of the SI finite element analysis demonstrated that this was not critical to the conclusions. The GE

analysis results conservatively show that the weld H4 safety factors are close to the allowable (2.96 versus required 2.77). The SI finite element analysis indicated significantly higher margins with respect to the required safety factors.

SI believes that due to the substantial amount of shroud inspection coverage, the use of a 360° part though-wall flaw of 1.65 inch is a reasonable approach. Sufficient coverage was achieved on the H4 and H5 welds to justify use of this alternate approach.

In conclusion, SI concurs with the GE results, provided that the results of the SI finite element analysis (Section 2.0 of this report) are also incorporated into the justification. The final justification is consistent with the BWRVIP-01, Rev. 1 document and Reference [2], and thus provides an acceptable technical justification for continued operation with the detected flaws present.

4.0 SUMMARY

This report presents the support provided by Structural Integrity Associates for the disposition of the observed cracking in the Nine Mile Point Unit 2 core shroud. UT and visual inspection of the horizontal and vertical welds was performed as part of the inspection program during the NMP2 1998 outage. Indications were found in the H1, H2, H3, H4, H5, H7, and H8 welds. Significant cracking was observed at weld H7 and at the beltline welds, H4 and H5. No indications were detected at weld H6. Minor cracking was found at all other horizontal welds. Based on the inspection, no indications associated with the vertical welds were found.

As part of this effort, SI performed a review of the GE fracture mechanics evaluations, including methodology. Of special importance in this evaluation was to verify that all methods were consistent with those in BWRVIP-01. SI also performed a linear elastic fracture mechanics evaluation of welds H4 and H5 using detailed finite element analysis methods.

Based on the review of the GE evaluation, SI concurs with the conclusion that the observed cracking in the core shroud does not jeopardize structural integrity. The GE evaluation in combination with the weld H4 and H5 finite element analysis results presented in this report comprise a technical justification for continued operation. Since the required safety factors in BWRVIP-01 are maintained, and the methods used comply with BWRVIP-01, continued operation for at least the next operating cycle is justified.

5.0 REFERENCES

1. BWRVIP-01, Rev. 1, "BWR Core Shroud Inspection and Flaw Evaluation Guideline," March 1995.
2. Evaluation of "BWR Core Shroud Inspection and Evaluation Guidelines," GENE-523-113-0894, Revision 1, Dated March 1995, and "BWRVIP Core Shroud NDE Uncertainty & Procedure Standard," Dated November 22, 1994; USNRC, June 16, 1995.
3. GENE-B13-01920-63, Rev. 2, "The Evaluation of Nine Mile Point Unit 2 Shroud Cracking for at Least One Fuel Cycle of Operation Following RF06," GE Nuclear Energy, June 1998.
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5. ANSYS LinearPlus/Thermal, Revision 5.3, Second Release, ANSYS Inc., October 1996.
6. GENE-771-47-1293, DRF A00-05838, Index 2, "Shroud Fabrication and Operational History Data, Nine Mile Point 2," GE Nuclear Energy, December 1993.
7. SI File No. PPL-12Q-307, "Stress Intensity Factors Calculation by Finite Element Analysis, Compound Flaw," Structural Integrity Associates, Inc., November 1996.