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STRUCTURAL MARGIN ASSESSMENT TO SUPPORT CURRENT FUEL CYCLE OPERATION OF NINE MILE POINT UNIT 1 WITH SHROUD VERTICAL WELD INDICATIONS

Prepared for

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IMPORTANT NOTICE REGARDING

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EXECUTIVE SUMMARY

During the last refueling outage (RFO 14) at the Nine Mile Point Unit 1 (NMP-1) Station, cracking was detected in the vicinity of vertical welds of the core shroud. The cracking was detected by inspections performed in accordance with industry recommendations. Based on evaluations which used conservative crack sizing assumptions and used an upper bound plateau crack growth rate of 5×10^{-5} in/hr, continued operation was justified for 10,600 hours (Reference 1). The NRC reviewed the results and issued a Safety Evaluation Report (Reference 2) approving restart of the plant for 10,600 hours consistent with the analyses results.

In addition, the utility, Niagara Mohawk Power Corporation (NMPC) removed two boat samples in an effort to improve the understanding of the cracking and to provide a better basis for crack growth rate predictions. NMPC also put in place operational procedures to assure that the coolant chemistry was maintained at conductivity levels that would assure significantly lower crack growth rates than those used for the structural analyses used earlier to support continued operation, see Reference 3.

The basis of the new evaluation is a detailed structural assessment that shows vertical welds have higher margin than documented in the Reference 1 report and that the ASME Code structural margins can be maintained for the current fuel cycle operating period of 14,500 hot operating hours even with the conservative crack growth rate of 5×10^{-5} in/hr. The new analysis considers the vertical cracks with more reasonable assumptions regarding the level of cracking in the vertical welds. Specifically for V9 and V10, the use of a through wall crack instead of the part through crack assumed in Reference 1 simplifies the analysis and demonstrates higher crack tolerance. Additional analyses have also considered the UT data for both the H4 and H5 welds. These analyses have confirmed that the H4 and H5 welds will retain sufficient integrity considering 5×10^{-5} in/hr crack growth of existing horizontal cracks such that the V9 and V10 welds can be assumed 100% cracked through wall. The fracture model used for these analyses has been benchmarked by handbook solutions for a through crack in a finite width plate. The results of the fracture analysis are also supported by a separate independent analysis performed using the strain energy release technique.

The boat sample fluence measurement, and tensile tests have demonstrated that the limit load analysis is conservative for the V9 and V10 welds. The available equivalent ligament length after 14,500 hours for the V9 and V10 welds, including crack growth in depth and length at 5×10^{-5} in/hr, was re-calculated. The available ligament satisfies the limit load minimum required ligament with significant margin for the 14,500 hour interval.

The other vertical welds V3,V4,V15 and V16 are re-evaluated with a more reasonable assessment of the UT data which credits "far side detection". The UT inspection data has been reviewed by GE NDE and the far side coverage area verified. Crediting this additional coverage results in the operating interval 14,500 hours while maintaining all NRC/ASME Code structural margin requirements.

The structural analysis has clearly established that the NMP1 core shroud will maintain the required ASME code and NRC required safety factors even considering the extreme assumption of 5×10^{-5} in/hr crack growth rate. The conservatism in this structural evaluation is further supported by the crack growth rate analysis in the Reference 3 report which has established that the maximum crack growth rate which can be anticipated is over a factor of ten lower (4.2×10^{-6} in/hr). The analysis documented in this report has demonstrated by several analysis techniques that the NMP1 core shroud has multiple levels of margin which sufficiently bound any uncertainty regarding analysis assumptions.

This report provides new analyses that are based on more reasonable but still conservative assumptions in the structural analysis. It is shown that the 10,600 hour operating period in Reference 1 can be extended to over 14,500 hours while maintaining all ASME Code / NRC required safety factors.

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STRUCTURAL MARGIN ASSESSMENT TO SUPPORT CURRENT FUEL CYCLE OPERATION OF NINE MILE POINT UNIT 1 WITH SHROUD VERTICAL WELD INDICATIONS

1.0 INTRODUCTION

During the last refueling outage (RFO 14) at the Nine Mile Point Unit 1 (NMP-1) Station, cracking was detected in the vicinity of vertical welds of the core shroud. The cracking was detected by inspections performed in accordance with industry recommendations. Based on evaluations which used conservative crack sizing assumptions and used an upper bound plateau crack growth rate of 5×10^{-5} in/hr, continued operation was justified for 10,600 hours (Reference 1). Following some revisions to the UT depth data, the structural analysis was updated to reflect the new UT information and documented (Reference 4). The conclusions regarding continued operation for at least 10,600 hours remained unchanged. The NRC reviewed the results and issued a Safety Evaluation Report (Reference 2) approving restart of the plant for 10,600 hours consistent with the analyses results.

The areas of significant conservatism in the Reference 1 analysis which led to the conclusion that the period of continued operation was less than a full cycle are summarized as follows:

1. A detailed finite element analysis was performed with special crack tip elements, but the model included a part through crack. The assumption that crack initiation and subsequent crack growth occurred in those areas which were uncracked prior to return to operation led to part through wall cracks in the uncracked regions. The part through cracks caused discontinuities which overestimated the stress intensity factors. Therefore, the allowable flaw depths and the allowable operating period determined in Reference 1 were overly conservative.

2. All analyses were conducted based on the upper bound crack growth rate of 5×10^{-5} in/hr, that has been used regardless of the water chemistry conditions. The water conductivity at NMP1 has been excellent and the crack growth predictions based on the GE and the BWRVIP models for the NMP1 water chemistry have clearly shown that use of the conservative upper bound crack growth rate of 5×10^{-5} in/hr is overly conservative for NMP1.

3. Structural margin credit was taken only for areas which were inspected by UT on *both* sides of the weld and covered by all three search units - 45 shear wave, 60 longitudinal wave and the OD creeping wave . All other locations were assumed to have through thickness cracking. In particular, no credit was taken for the far side detection capability of the 60 degree L transducer. BWRVIP-03 qualification of this transducer has established the capability of this transducer to detect cracking on the far side of the weld from the transducer.

4. Metallography and fluence measurements of the V9 and V10 boat samples have demonstrated that the V9 and V10 cracking is not due to IASCC. This testing has also benchmarked the actual shroud material fluence analysis through retrospective dosimetry analysis and established that the lower third of the V9 and V10 welds are below the BWRVIP-01 threshold of 3×10^{20} n/cm ^{2} above which LEFM analyses is required. This testing has also established that the peak fluence at the ID surface is only nominally above the 3×10^{20} n/cm ^{2} threshold. The tensile testing of the boat sample material has also demonstrated that the shroud 304SS retains excellent ductility. Based on the average fluence being below the threshold and the ductile behavior of the material (as confirmed by the boat sample) , fracture mechanics analysis is not required. The overall conclusion based on the fluence measurements and the extensive testing is that the Limit Load analysis approach is a conservative analysis for the V9 and V10 welds.

This report evaluates three independent fracture mechanics cases for the V9 and V10 vertical welds. The primary case is presented in the base report with the second and third cases included in the appendices. The primary case takes no credit for the uncracked material located at the H4 and H5 weld locations. The second and third cases take credit for the structural integrity of the portions of the horizontal welds verified as being

uncracked by the UT. In all cases only regions examined by UT were credited in the analysis and no credit for far side detection was required.

The V9 and V10 Case 1 fracture analysis credits the end segments of the V9 and V10 welds based on UT data (no axial cracking) for both these locations. Supplemental EVT-1 examination of both the welds in the end segment region at the H4 location confirmed the UT determination that there was no cracking. The supplemental EVT-1 of the end segment near H5 did identify minor radial indications at the H5 location which the UT did not identify. The evaluation of the these visual indications concluded that the indications were short ¼ to ½ inch horizontal indications and not in the plane which the UT was oriented to optimally examine. The orientation of these indications is such that they have no impact on the vertical weld integrity and are likely extremely shallow. The Reference 1 and 4 analyses assumed incipient cracking for these segments of the V9 and V10 welds and then assumed that a crack grew from the OD surface at 5×10^{-5} in/hr.

The metallurgical examination of the V9 and V10 boat sample has been completed (References 5 and 8). These evaluations have concluded that the cracking is due to IGSCC. More importantly, the metallurgical examination has confirmed the accuracy of the UT depth data. The root cause evaluation has confirmed that the most likely cause of the IGSCC initiation was the cold working from fabrication grinding on the OD surface coupled with poor reactor water chemistry during the first 5 cycles of operation at NMP1. The cracking shows no evidence of an IASCC initiation or propagation mechanism (excessive branching, grain fall-out). Based on the confirmed UT data at the H4 and H5 end points, and the confirmed metallurgical evaluation of the cracking, the V9 and V10 Case 1 analysis relaxes the assumption of crack initiation in the uncracked material. This is considered consistent with BWRVIP-01 since these guidelines do not require this assumption. The assumption was made in the Reference 1 analysis as an interim conservative assumption which would be revisited based on further analysis. The re-evaluation of these locations has concluded that this assumption is not warranted. (References 3, 5, 8).

The boat sample fluence and tensile testing has established that the limit load considerations for the V9 and V10 welds are considered conservative and represent margin above that predicted by the fracture cases for the V9 and V10 welds. The V9 and V10 welds available equivalent ligament length after 14,500 hours, including crack growth in depth and length at 5×10^{-5} in/hr, is determined by the new analysis. This

analysis shows significant margin exists for the proposed operating interval of 14,500 hours.

The other vertical welds V3,V4,V15 and V16 do not require fracture analyses based on LEFM since these welds are below the threshold fluence of 3x 10^{20} n/cm^2. In accordance with BWRVIP-01 guidance, the safety margin is governed entirely by limit load considerations. For these welds the available ligament was evaluated based on a more reasonable assessment of the UT data which credits "far side detection". The UT inspection data has been reviewed by GE NDE and the far side coverage area verified.

The fracture analyses in Appendix A demonstrate that the H4 and/or H5 horizontal welds are capable of maintaining the shroud integrity even assuming 100% through-wall cracking on the entire V9 and V10 length, demonstrating that the horizontal welds are redundant to the vertical welds considering the vertical welds 100% through wall cracked. The analyses included as Appendix B considers only the available ligament on the horizontal welds in limit load analyses.

The vertical welds V3,V4,V15 and V16 are re-evaluated for limit load margins with a more reasonable assessment of the UT data which credits "far side detection". The UT inspection data has been reviewed by GE NDE and the far side coverage area verified. Crediting this additional coverage results in the operating interval 14,500 hours while maintaining all NRC/ASME Code structural margin requirements.

This report provides new analyses that are based on more reasonable but still conservative assumptions in the structural analysis. It is shown that the 10,600 hour operating period in References 1and 4 can be extended to over 14,500 hours while maintaining all ASME Code / NRC required safety factors. The reevaluation of the crack growth rates also leads to similar conclusions and is reported separately (Reference 3).

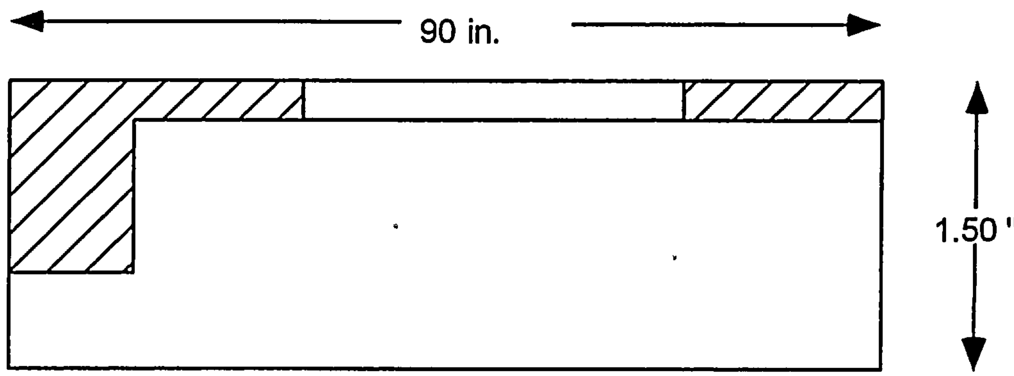
2.0 FRACTURE EVALUATION OF THE V9/V10 WELDS

The analysis presented in Reference 1, and the response to the NRC's request for additional information (RAI) documented in Reference 4 considered a through wall crack (after accounting for crack growth and crack depth and length uncertainty) for the length of V9 and V10 which

contained any cracking as identified by the EVT and UT inspections. In addition, it was assumed that the uncracked regions were just at the point of crack initiation. Essentially this meant that there was a part through crack after including initiation and subsequent crack growth. The part through crack when combined with the through wall crack created a compound crack as shown in Figure 2-1. As described in Reference 1, this crack was modeled with a finite element method (FEM) using special crack tip elements. Since the compound crack combines a part through crack with the through wall segment, an additional geometric discontinuity (over and above that of the crack) is created at the intersection of the part through and through wall cracks. Although the FEM model considered a radius for the crack front, the calculated stress intensity factor, K, at the intersection was high because of the discontinuity. Therefore the calculated K from the FEM analysis was over conservative. By eliminating the unreasonable assumption that uncracked sections are at incipient cracking and considering subsequent crack growth, the part through cracks can be avoided, thereby simplifying the analysis. This analysis considers a through wall crack as shown in Figure 2-2. This is the key difference between the present analysis and the analysis in Reference 1 and documented in the response to the NRC's RAI (Reference 4).

This case assumes a through wall flaw wherever cracking was identified in the limiting V9 weld. This case also assumes welds H4 and H5 are fully cracked (additional fracture analyses taking credit for the H4/H5 welds are described in Appendix A). The predicted crack growth at each crack tip is 14500 hours x 5 x 10^{-5} in/hour = 0.725 in. Adding the crack length uncertainty of 0.394 inch, the total crack lengthening at each crack tip is (0.725 + 0.394) = 1.119 in. This gives a predicted final crack length of 78.6 inches (see Figure 2-2). Considering the depth of the indication, the V9 weld is more limiting. But, if the length of the indication alone is considered, a through wall representation of the V10 weld may be somewhat longer. However, since the allowable flaw sizes determined in this analysis are much longer than the modeled through wall representation of either weld, the results are applicable to both welds, regardless of the slight difference in length. Special crack tip elements are included at the end of the modeled through wall crack in the V9 and V10 welds. Figure 2-3 shows a schematic of this case (referred to as Case 1 to distinguish this from the additional fracture analysis cases in Appendix A). The analysis was performed using the ANSYS finite element code.

Figure 2-1 Compound crack considered in Reference 4



Compound Crack

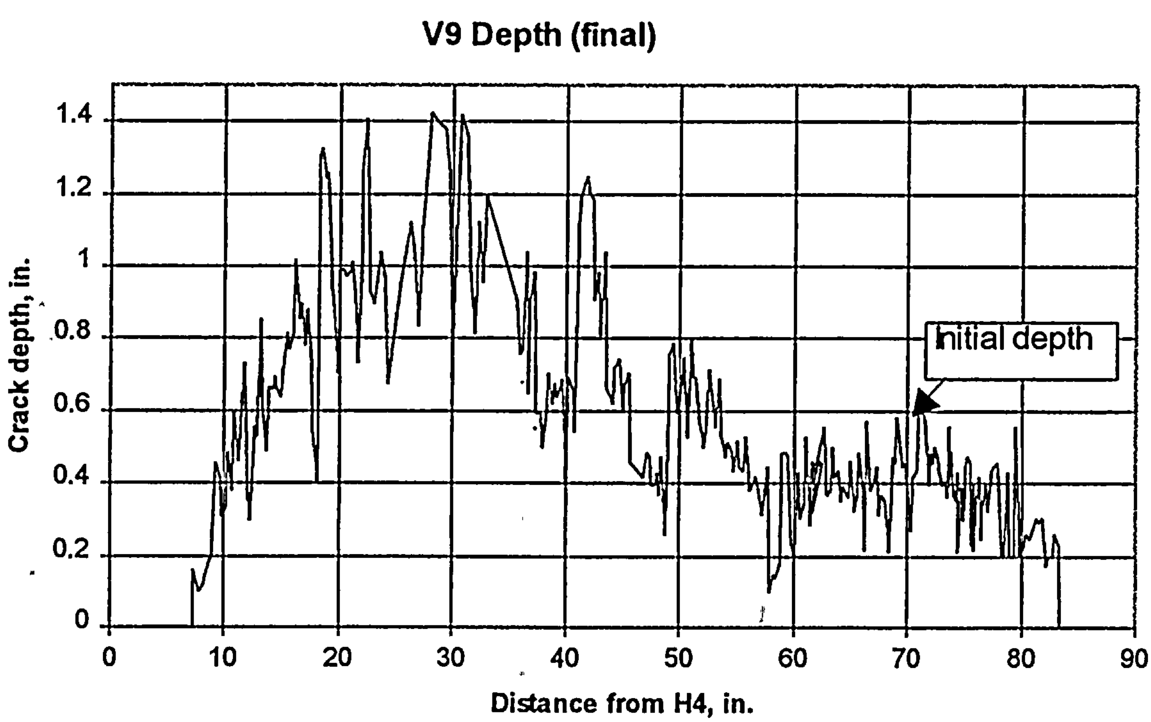
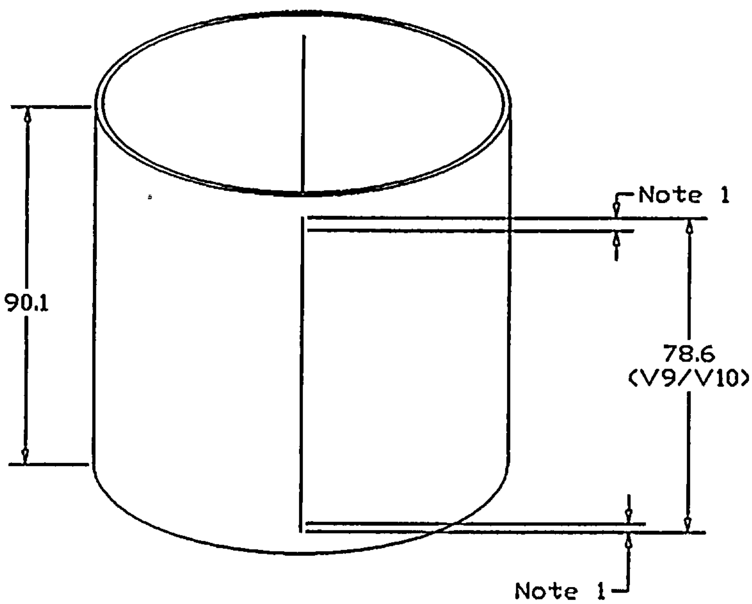


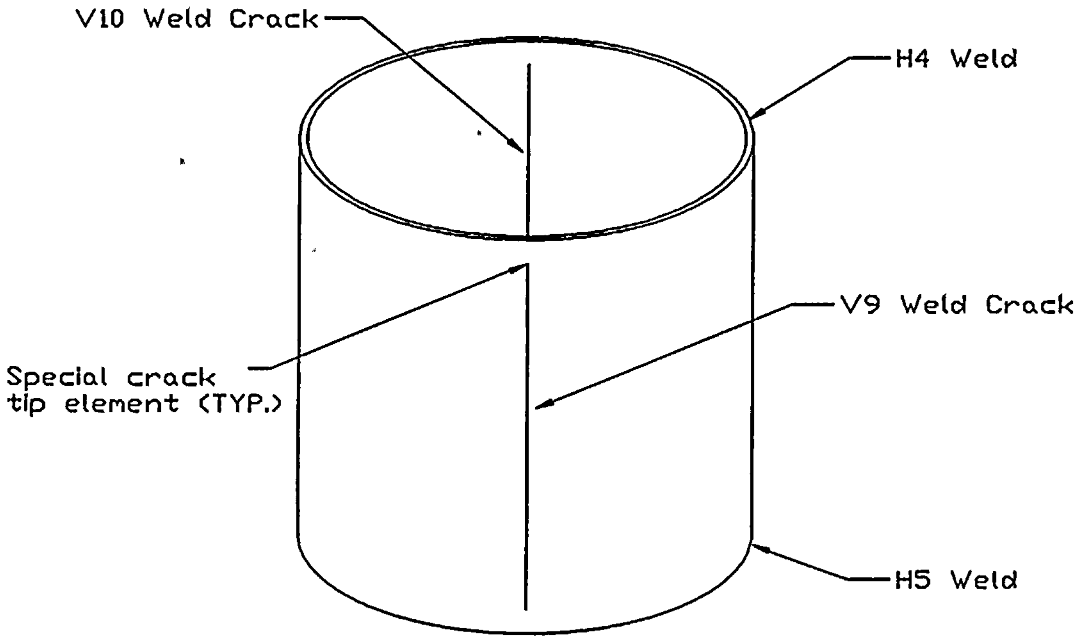
Figure 2-2 Through wall crack considered in the current analysis



Notes:

1. Crack Growth + UT Uncertainty
   (5e-5 in/hr x 14500 hrs + 0.394 in = 1.119 in)

Figure 2-3 Schematic of the fracture analysis case



3.0 RESULTS OF THE V9/V10 FRACTURE MECHANICS ASSESSMENT

The finite element code ANSYS Version 4.4 was used for the fracture analysis. Since ANSYS does not have crack tip shell elements, the shroud was modeled using three dimensional solid elements (Element 45). The crack tip was modeled with elements that simulate the crack tip singularity (Element 85) and provide the stress intensity factors directly. The internal pressure was set at 33 psi . This includes a safety factor of 1.5 on the accident condition pressure of 22 psi. The radial displacement boundary conditions at the top and bottom ends of the model were set to be free, except for one point to prevent rigid body motion.

Fracture mechanics solutions are available for a through wall axial crack in an infinite cylindrical shell under internal pressure. However, if the cylinder is assumed to be finite in length, the K calculations based on the infinite length shell can be non-conservative. Since there are no stress intensity solutions in the literature for a crack in a finite width cylinder, one way of accounting for this is to apply a finite width correction factor based on a plate solution. For example, the stress intensity factor for a through crack of length 2a, in an infinite plate under an external applied stress, σ, is given by $K = \sigma\sqrt{\pi}\ a$. However, if the crack is in a finite plate of width 2b, a correction factor of $\sqrt{(\sec \pi a/2b)}$ is applied. As the crack length approaches the width of the plate (i.e. 2a is close to 2b) the finite width correction factor increases rapidly. This factor was initially used in the Reference 1 analysis for evaluating the crack in a finite width cylinder (no credit for the H4 and H5 welds) but was dropped because of excessive conservatism and subsequently evaluated using the part through crack finite element model. The secant correction factor for a flat plate with a crack is accurate and therefore can be used to qualify the finite element model used here. To do this, two finite element models were developed. Figure 3-1 gives the FEM model used for the crack in the finite width cylindrical shell. The detail in Fig. 3-2 also shows a close-up of the special crack tip element used. To validate the results of the cylindrical shell case, a similar flat plate model shown Figure 3-2 was also developed. For both cases, the input loads included the hoop stress corresponding to an internal pressure of 33 psi. This pressure load is consistent with faulted conditions (steam line break) and includes a safety factor of 1.5. Since the pressure already includes the safety factors, the calculated stress intensity factors should be compared with the allowable K of 150 ksi-$\sqrt{\text{in}}$. Figure 3-3 shows the calculated stress intensity factor as a function of half crack length for several cases. The results are summarized below:

- For the flat plate case, the comparison of the theoretical closed form solution with the secant factor to the FEM predictions is excellent. The close agreement validates the FEM prediction.

- The FEM results for the finite cylindrical shell with a through wall crack show that for relatively long cracks (in excess of 85 inches) the calculated K is within the allowable value. The FEM calculations appear to be somewhat lower than the values determined by applying the secant finite width correction factor on the infinite shell solution. Since the FEM results for the plate are in good agreement with the secant factor for the finite width plate, it appears that the approximation of applying the flat plate finite width correction factor for the plate is overconservative. The FEM results are also in good agreement with the results from a strain energy release approach, which also found that the secant factor overestimates the K value for a finite width cylindrical shell. Both the strain energy release solution and the current FEM analysis show that cracks up to 85 inches can be tolerated without exceeding the 150 ksi-$\sqrt{in}$ toughness. Since the predicted crack length using the conservative NRC bounding crack growth rate value of 5×10^{-5} in/hr at the end of the current cycle is 78.6 inches (slightly higher for V10), the final length is within the allowable value of 85 inches. Therefore the fracture analysis results support continued operation for 14,500 hours of operation.

- The results of the analysis show that even with the most conservative assumptions (no contribution from H4 or H5) the allowable crack length exceeds the predicted length after 14500 hours. Higher margins can be demonstrated with the inclusion of credit for the remaining sections at welds H5 and H4. The analyses described in Appendix A show that even with the assumption that the <u>entire lengths</u> of the V9/V10 welds are cracked through wall, adequate fracture margin can be demonstrated by taking credit for the H4/H5 welds.

- The mechanical testing of the boat sample removed from the NMP1 shroud shows that the material behavior was essentially ductile. (Reference 7). Therefore, the actual fracture margin is much higher than that indicated here.

Figure 3-1 FEM model for a crack in a finite width cylindrical shell

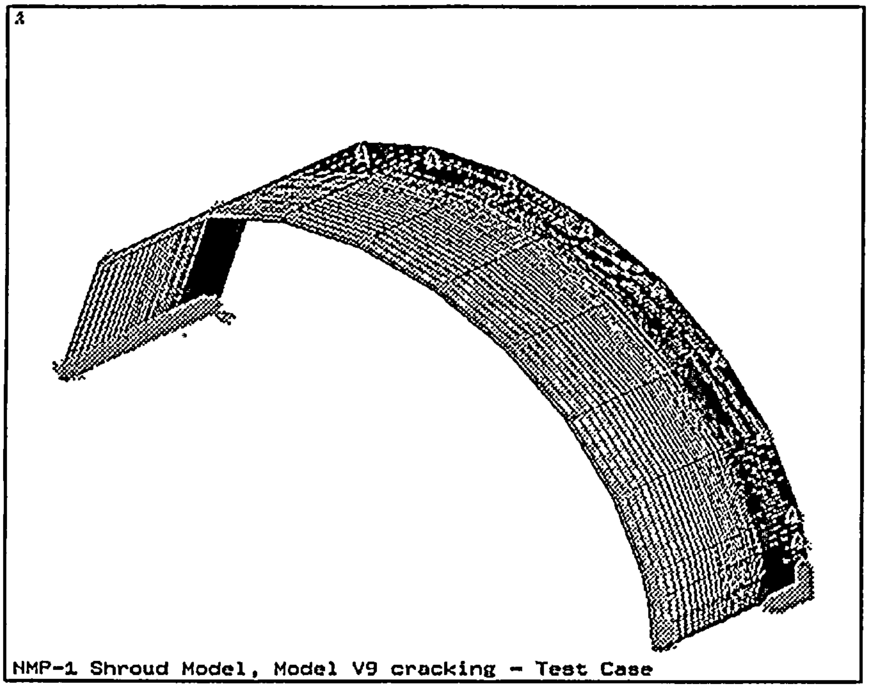


Figure 3-2 FEM model for a crack in a finite plate

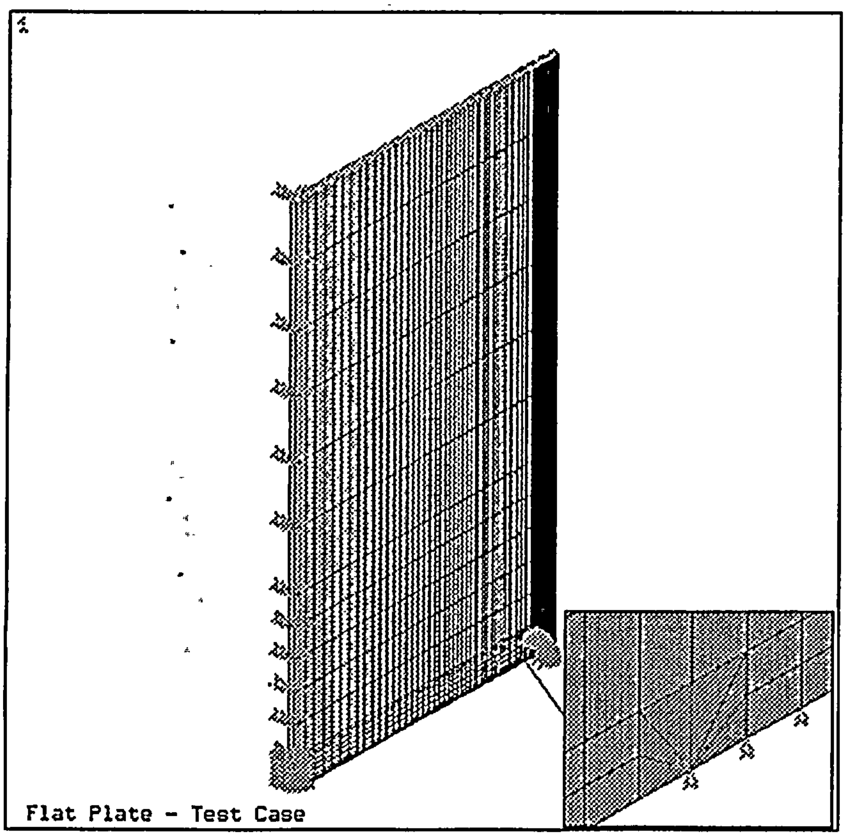
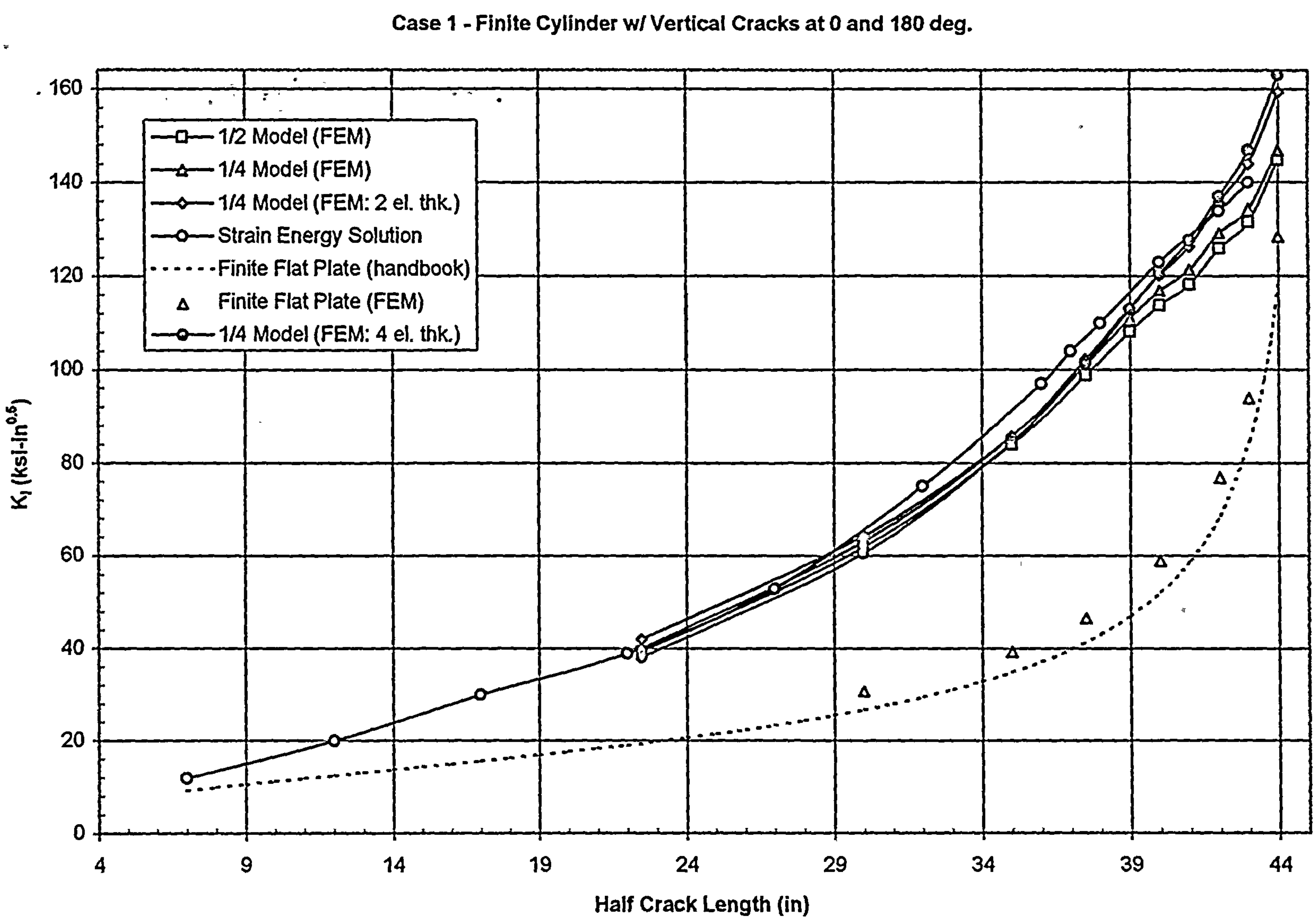


Figure 3-3 Stress Intensity Factor as a function of half crack length



4.0 LIMIT LOAD ANALYSES FOR V4, V4, V15 AND V16

For welds with fluence below the threshold fluence of 3x 10^{20} n/cm^2, the safety margin is governed entirely by limit load consideration. Welds V3, V4, V15 and V16 are below the threshold fluence and can therefore be evaluated by limit load analysis only. Since V4 was more limiting and specifically shown to be acceptable for 10,600 hours in Reference 1, the re-evaluation of V4 is considered separately in Section 4.1. The evaluation of the other welds (V3, V15 and V16) is described in Section 4.2.

4.1 Limit Load Analysis of the V4 Weld

Limit load analysis margins have to be demonstrated for all vertical welds regardless of location. In cases where the fluence effects are not significant, the limit load allowables are governing. In the Reference 1 analysis, all the welds except the V4 weld had sufficient limit load margins considering crack growth for the entire cycle. The evaluation of the UT results (for V4 as well as the other welds) in Reference 1 was overly conservative for the following reasons:

1. All uninspected regions of the weld were assumed to have through wall cracking.

2. In order to take credit for the inspection results, inspection had to be covered by **all three** search units (45° shear, 60° longitudinal and creeping wave) and should be based on inspection from **both sides.**

3. Where inspection results are available, the remaining cross section is determined by:
a) increasing the crack length at each crack tip by 1.119 in (equivalent to crack growth of 14,500 x 5 x 10^{-5} = 0.725 in and a *length* uncertainty factor of 0.394 in), and b) increasing the average depth by 0.833 in. (crack growth increment of 0.725 in. and a *depth* uncertainty factor of 0.108 in.).

The first assumption is unavoidable if there is no inspection at all for a given region. The second assumption is overly conservative especially if there are inspection results from one side and the inspection is such that the search unit covers the far side of the weld. Clearly, if the ability to confirm the condition of the weld on the far side is validated, then one can take credit for the composite result verifying the condition of the weld on both sides. The third assumption on crack growth and the uncertainty factor on length and depth is conservative but is unavoidable. The

focus of the evaluation of the V4 UT results was to reexamine the UT coverage for the V4 weld. The results of the reexamination of the V4 UT data are summarized below.

Vertical weld V4 was examined from the left side of the weld from 4.50 inches through 17.75 inches from circumferential weld H1, and on the right side from 6.50 inches through 30.9 inches from weld circumferential H1. Obstructions at the OD surface prevented the examination of the complete length of weld V4 from either side of the weld. The ultrasonic examination data from the right side of weld V4 revealed cracking along almost the entire examined length of the weld. The ultrasonic data from the left side of weld V4 revealed cracking for 1.50 inches along the examined length of the weld. Figure 4-1 shows the inspection results.

The core shroud vertical welds were examined using the GE trimodal search unit which included three transducers: 45° shear wave, 60° longitudinal wave and surface creeping wave. The key issue is the effectiveness of the inspection of the far side regions which are accessed by ultrasound transmission though the weld metal. Figure 4-2 describes the surface regions that were examined using the search unit containing the three transducers. The transducers which have been demonstrated by qualification to be effective for the far side detection of ID and OD surface flaws are the 60° longitudinal and creeping wave devices, respectively. The 45° shear wave transducer cannot reliably penetrate the weld metal, but is very effective for near side base metal examinations. The creeping wave transducer has been shown by qualification to not be reliable for the detection of all OD-connected far side flaws, but all flaws which exceed 0.25 in. (from the OD surface) will be detected. The 60° longitudinal wave transducer has been shown by qualification to be reliable for the detection of (unmasked) ID-connected far side flaws.

The OD obstructions limited the examination of weld V4 to one-side (from the right side) over most of the examined length. Additionally, flaws were detected on the right side of weld V4. The presence of these flaws serves also to limit the effective examination of the far side of the weld, since these flaws mask the regions behind them which are in line with the projected central angle of the ultrasound. Figure 4-3 illustrates the examination coverage of the far side of the weld. The triangular-shaped area on the bottom side of the weld has been masked by the flaw on the left side of the weld. The average flaw height of 0.57 inch (based on the detailed depth data) has been calculated and inserted into the above sketch. The position of the flaw in the above sketch has been so chosen since IGSCC generally follows the weld heat-affected zone adjacent to the weld. For the purpose of depicting the masked region of the surface adjacent to the weld, this position affords a conservative flaw placement, since the closer to the weld centerline a flaw resides, the larger the masked surface on the far side of the weld. Considering the average flaw height and the

central beam of the 60° longitudinal wave transducer, 0.64 in. of the required ID surface on the far side of the weld is unmasked and can be inspected from the far side.

Based upon the demonstrated capabilities of the examination techniques employed on site, the following may be concluded:

1) Based upon the creeping wave examination from the left side of the weld (6.35 inches through 17.75 inches from circumferential weld H1) the left side OD surface of weld V4 does not contain flaws. Based upon the creeping wave examination from the right side of the weld, (8.35 inches through 30.9 inches from circumferential weld H1), the right side OD surface of weld V4 does not contain flaws. Essentially, this says that in the examined areas, there is no OD cracking. It is reasonable to extend this to conclude that there is no OD cracking in areas where inspection was performed either from the right or the left side of the weld, or from 6.35 inches to 30.9 inches.

2) A combination of the 60° longitudinal wave examination from the right side of the weld (7.4 inches through 29.95 inches from circumferential weld H1), and the 60° longitudinal wave examination from the left side of the weld (5.4 inches through 16.8 inches from circumferential weld H1), results in coverage of the weld V4 from 5.4 inches to 29.95 inches in the unmasked portion of ID surface "C". Essentially, this means that the inspection results from both sides can be superimposed and used to represent the condition of the whole weld.

Figure 4-4 shows the results of the V4 inspections. The cracking is confined to the ID. Over the combined inspection length of 4.5 in. to 30.9 in. (from either the left side or the right side) there is one crack on the left side 1.5 in. long and 0.75 in. deep and a near continuous crack on the right side from 8.35 in. to 29.8 in. The uninspected region covers the region from 0 to 6.35 in. and 29.95 in. to 31.25 in (the 60 degree L wave coverage started at 5.4 in, which was conservatively not credited). Allowing for crack growth for 14,500 hours (0.725 in.) and length and depth uncertainty of 0.394 in. and 0.108 in. respectively, the remaining area after 14,500 hours can be determined. Figure 4-5 shows a schematic that describes the uncracked area available at the end of the current cycle. The available area after excluding uninspected regions, accounting for crack growth, and allowing for length and depth uncertainty is calculated to be $(7.1-6.35)\text{x}1.5+(29.95-10.8)\text{x}0.09 = 2.85 \text{ in}^2$. This is equivalent to an uncracked length of $2.85/1.5 = 1.9$ in. after 14,500 hours.

In Reference 1 the required equivalent length (including the safety factor of 1.5) at the end of the cycle was determined to be 1.28 in. The available equivalent length as described above is 1.9 inches which exceeds the required value. Therefore sufficient structural margin will be maintained throughout the current cycle for the V4 weld.

Appendix B describes an alternate limit load evaluation where it is assumed that all vertical welds are fully cracked (through wall and over the entire length). It is shown that with a ligament of just 0.125 inch over the entire circumference, sufficient structural margin can be demonstrated.

4.2 Limit Load Analysis for the V3, V15 and V16 welds

In Reference 1, the evaluation of the V3, V15 and V16 welds had shown that continued operation for the full cycle was justified. However, the analysis was updated later (Reference 4) with new UT information based on a re-evaluation of the UT data and it was shown that even with the new depth data, continued operation could be justified for the 10,600 hours approved by the NRC. The evaluation described here shows that even with the updated UT data, continued operation can be justified for at least 14,500 hours.

The analysis of the V3, V15, and V16 welds was limited by UT extending over a part of the weld (due to access restrictions) coupled with three conservative analysis assumptions: 1) no credit was taken for uninspected regions i.e. through thickness crack assumed, 2) three transducers with inspection from both sides with overlapping coverage was required to verify unflawed material, 3) ASME Code proximity rules were applied. The re-analysis of V15 was performed by relaxing the second or third assumptions using less conservative, but more reasonable criteria. Specifically the new analysis removes the proximity rule application (while still retaining the crack growth and UT uncertainty factors). Analysis is also performed with and without taking credit for the far side UT coverage for some of these welds.

The proximity criteria in the ASME Code are really intended for fracture mechanics analysis to account for the fact that a crack in the stress field of an adjacent crack might have an effective K value that is higher than that calculated individually. In other words, the proximity rules account for the effect of interaction between two cracks on the stress intensity factor. However, for limit load analysis, no proximity rules are needed (as long as crack growth and crack length uncertainty is included) since the governing factor is merely the available area, not the calculated stress intensity factor. The analysis of these welds was performed removing this conservatism.

UT depth Uncertainty plus crack growth:

The depth and length uncertainties need to be added to the UT reported crack depths and lengths. For the depth direction, the uncertainty value is 0.108 inch, based on probe 60° longitudinal, scan type 1 in Table 4.4.17-2 of BWRVIP-03. Thus, the crack depth adder including the crack growth for 14,500 hours is (0.725+0.108) or 0.833 inch.

UT Length Uncertainty and length growth assumptions:

For the length direction, the uncertainty value was assumed as 0.364 inch, based on probe 60° longitudinal, scan type 1 (same) in Table 4.4.17-2 of BWRVIP-03. This value envelopes the uncertainty values for the 45° shear (0.336 inch) and the OD creeper (0.19 inch). In addition, the uncertainty factor due to the delivery system (suction cup scanner) was added to this value. The BWRVIP-03 (Page 4-42 for GE Suction cup scanner system) specifies this value as 0.25% of the scanner interval which is 11.4 inches. The uncertainty due to scanner location is (11.4x0.0025) or 0.03 inch. Adding together the two uncertainty factors, we obtain a total of (0.364+0.03) or 0.394 inch. The crack growth is 0.725 inch and, therefore, the crack growth plus UT uncertainty adds up to (0.394+0.725) or 1.119 inch which is the crack length increment added to each end of a crack..

The analysis for the V3, V15 and V16 welds are performed for both of the following inspection result conditions: i) taking credit only for areas with coverage on both sides with the three transducers and ii) taking credit for far side inspections. Results for both cases are presented here.

Evaluation of the V3 Weld

Figure 4-6 shows a plot of the UT data (solid line). The dotted line shows the predicted indication depths after accounting for UT uncertainty and 14,500 hours of crack growth.

The area available for load carrying is the following:

$$\begin{aligned} A &= (12.019-8.35)(1.5-1.203)+(14.919-12.019)(1.5-0.973)+(17.9-14.919)1.5 \\ &= 7.0895 \text{ in}^2 \end{aligned}$$

The equivalent full thickness length is then, (7.0895/1.5) or 4.726 inches. This exceeds the required minimum length of 1.28 inches (see Reference 1). Thus, it is acceptable for continued operation through 14,500 hours.

Evaluation of the V15 Weld

The V15 weld is limited by inspection data. The tie rod support attachment bracket prevented complete UT coverage of the V15 weld. The Reference 1 analysis credited only regions covered by 3 transducers from both sides of the weld. As discussed for the V4 analysis, credit for far side detection can be justified.

The V15 weld is located below the core plate. This weld is a low fluence weld, and is only required to be analyzed based on limit load. As discussed previously, the Reference 1 analysis applied the ASME Code proximity criteria when analyzing the V15 indication. Removing this overly conservative assumption and taking credit for uncracked metal verified by triple transducer coverage from both sides, sufficient remaining ligament can be demonstrated for 14,500 hours even with the NRC bounding crack growth rate. Figure 4-7 shows a plot of the UT depths. The dotted line shows the predicted indication depths after accounting for UT uncertainty and 14,500 hours of crack growth.

The area available for load carrying is the following:

$$A = (8.419-6.4)(1.5-0.883) + (9.281-8.419)1.5 + (11.9-9.281)(1.5-0.883)$$
$$= 4.155 \text{ in}^2$$

The equivalent full thickness length is then, (4.155/1.5) or 2.77 inches. This exceeds the required minimum length of 2.46 inches. Thus, continued operation for 14,500 hours is justified.

When far side detection is credited for this weld including proximity criteria, the effective inspected length extends from 2.35 in. to 15.55 in. The corresponding area is 8.57 in^2 and the equivalent full thickness length is 5.7 inches which also exceeds the minimum required length of 2.46 inches.

Evaluation of the V16 Weld

Figure 4-8 shows a plot of the UT data (solid line). The dotted line shows the predicted indication depths after accounting for UT uncertainty and 14,500 hours of crack growth.

The area available for load carrying is the following:

$$A= (7.019-2.45)(1.5-1.133) + (7.519-7.019)(1.5-0.933) + (10.5-7.519)1.5$$
$$= 6.432 \text{ in}^2$$

The equivalent full thickness length is then, (6.432/1.5) or 4.288 inches. This exceeds the required minimum length of 2.46 inches. Thus, continued operation is justified for 14,500 hours.

If credit is taken for the far side inspection capability, the effective inspection length is from 2.35 in. to 19.8 in. The available equivalent area considering far side inspection is 19.6 in^2. The corresponding equivalent length is 13 inches which is well in excess of the minimum required length of 2.46 inches.

4.3 Limit Load Evaluation of V9 and V10 Weld

The boat sample analysis of the V9 and V10 welds have been completed. These analyses have measured the V10 fluence at the shroud OD surface approximately 60 inches down from the H4 weld (Reference 6). The OD fluence was $\approx 1.11 \times 10^{20}$ n/cm^2 on the OD surface and $\approx 1.54 \times 10^{20}$ n/cm^2 at approximately the plate mid-wall. The V9 boat sample was taken approximately 25 inches down from the H4 weld location from the ID surface. This location was chosen based on analysis which predicted this location to have the highest neutron fluence. The measured ID surface fluence for this location was 3.088×10^{20} n/cm^2 and the mid plane fluence was measured at $\approx 2.27 \times 10^{20}$ n/cm^2. It is evident from these analyses that for the majority of the V9 and V10 weld located below the V10 boat sample location that the fluence is below the BWRVIP-01 threshold of 3×10^{20} n/cm^2, below which LEFM analyses are not required. These measurements also demonstrate that the maximum ID fluence for the V9 weld is only nominally above the LEFM threshold. The ID fluence values for the V9 and V10 welds near the H4 locations are only marginally above the 3×10^{20} n/cm^2 threshold, while the lower half of the V9 and V10 welds are

below the threshold. The V9 and V10 tensile testing has demonstrated that the shroud 304SS material at the V9 and V10 welds retains a high ductility, see Reference 7.

Evaluation of the V9 Weld

The available equivalent ligament length including crack growth considering the same ligament as applied in the LEFM analyses demonstrates adequate ligament for a full 24 month fuel cycle. The available equivalent uncracked ligament length after 14,500 hours is (90.12-78.6) = 11.5 inches. This exceeds the required uncracked length of 3.51 inches (Reference 1). Therefore V9 is acceptable for at least 14,500 hours considering limit load, also.

Evaluation of the V10 Weld

The effective crack length for V10 is slightly longer than V9 - 80 inches after considering crack growth and UT uncertainty. This still leaves an uncracked ligament of (90.12-80.0) = 10.12 inches which exceeds the required value of 3.51 inches for limit load margin. Continued operation for at least 14,500 hours is justified.

4.4 Conclusions from the Limit Load Analysis

The results of the limit load analysis are summarized in Table 4-1. It is seen that the available uncracked ligament after accounting for crack growth in both the length and depth direction and allowing for UT uncertainty exceeds the required value in all cases. Thus continued operation for at least 14,500 hours is justified. In fact, based on the measurements, the average through thickness fluence is less than the BWRVIP-01 threshold value of 3×10^{20} n/cm^2 over the entire length of the shroud. Thus, in theory, only the limit load analysis is necessary. The analyses described here and in Appendix B show significant margins relative to the required uncracked lengths. This coupled with the fracture analysis described in Section 3 as well as Appendix A provide confirmation that all NRC required structural margins will be maintained through the current cycle.

Table 4-1

Allowable Flaw Sizes for the Nine Mile Point Unit 1 Shroud Vertical Welds

Weld ID	Weld Length, in	Allowable Through wall crack length, in. (Limit Load)	Minimum required ligament, in.	Avail. Equiv. Ligament Length including crack growth for 14,500 Hours and Inspection Uncertainty, in.
V3, V4	31.25	29.97	1.28	4.73 (V3) 1.9 (V4)
V9, V10	90.12	86.61	3.51	11.5 (V9) 10.12 (V10)
V15, V16	22.13	19.53	2.46	2.77 (V15) 4.29 (V16)

Fig. 4-1 V4 Inspection Results

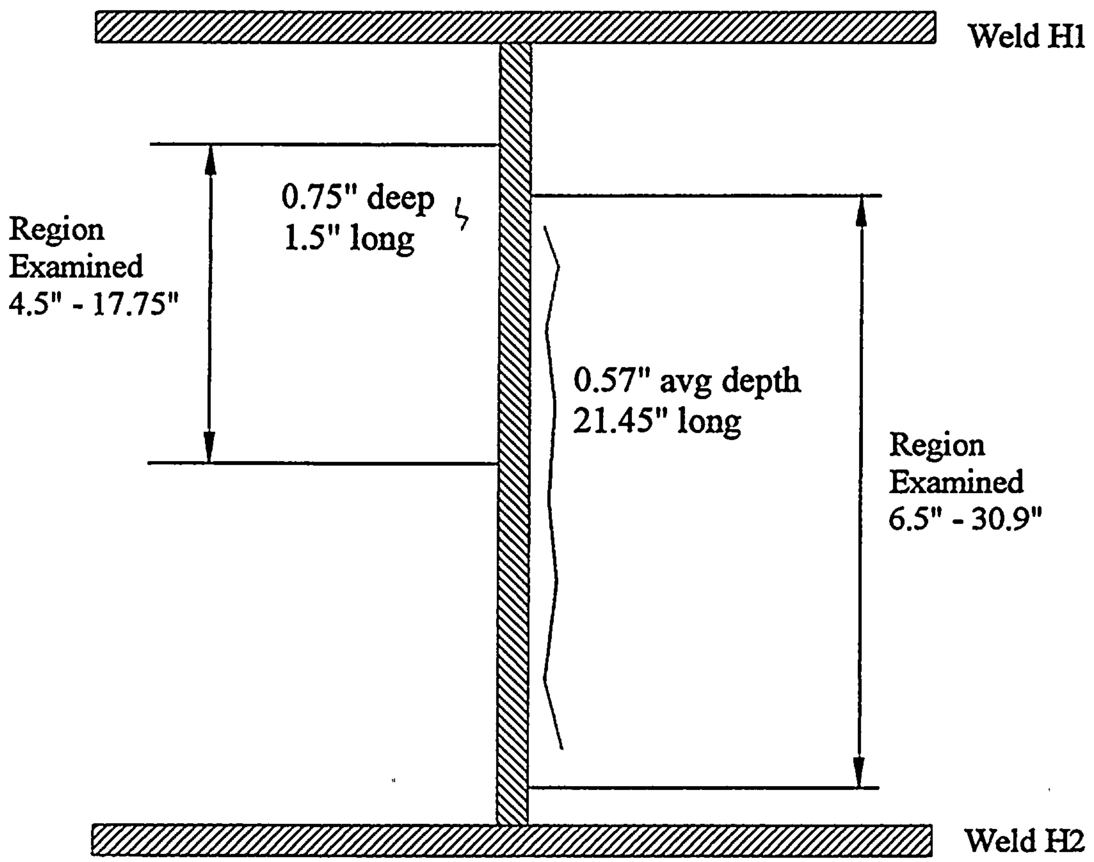


Figure 4-2 Required Examination Areas for the V4 weld

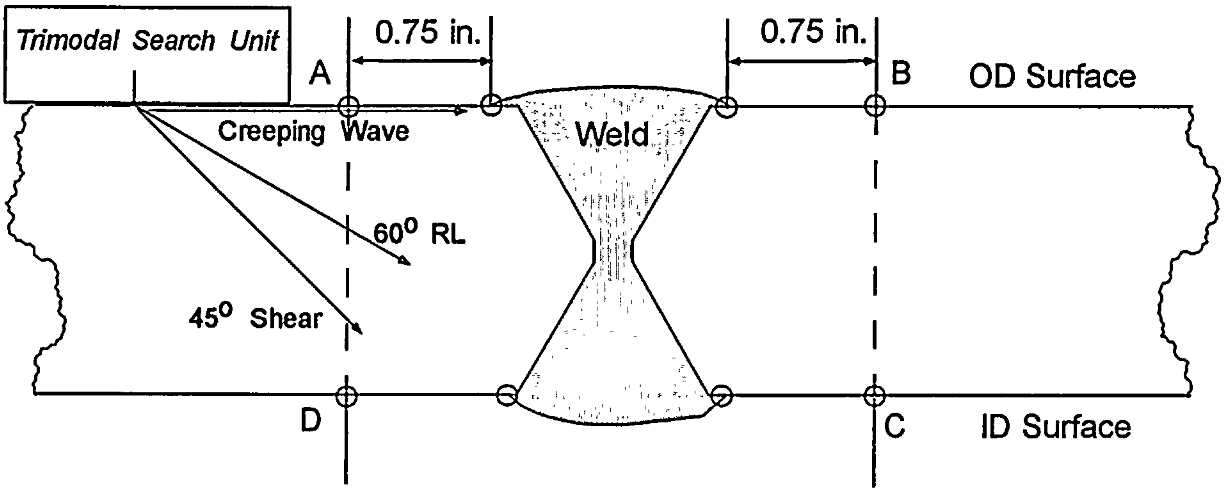


Figure 4-3 Weld V4 Examination Coverage on the Far side of the weld

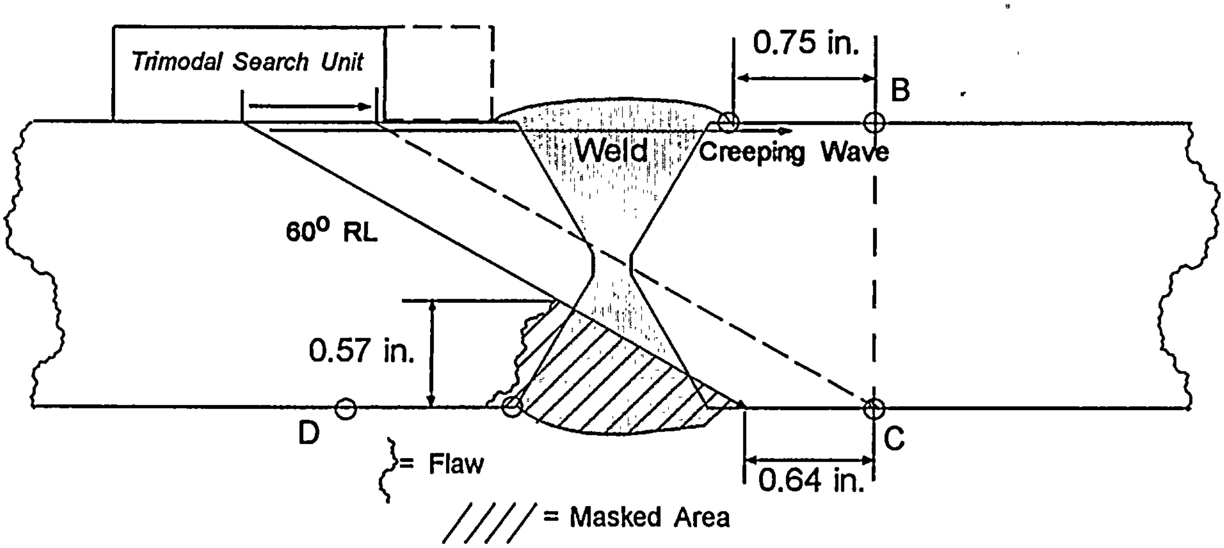


Fig. 4-4 V4 Inspection Data: Depth from the Right and Left Side

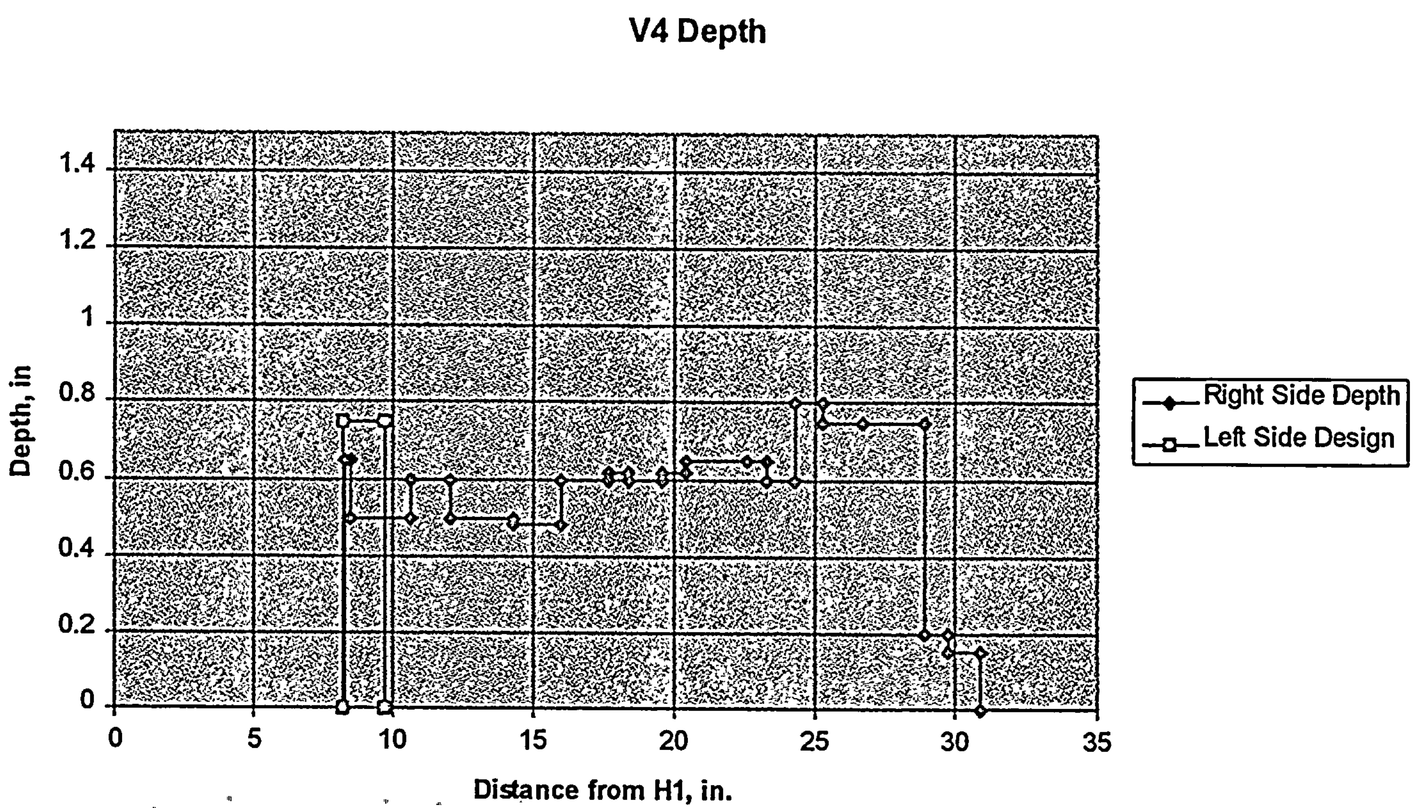


Fig. 4-5 Available uncracked area after 14,500 hours of operation

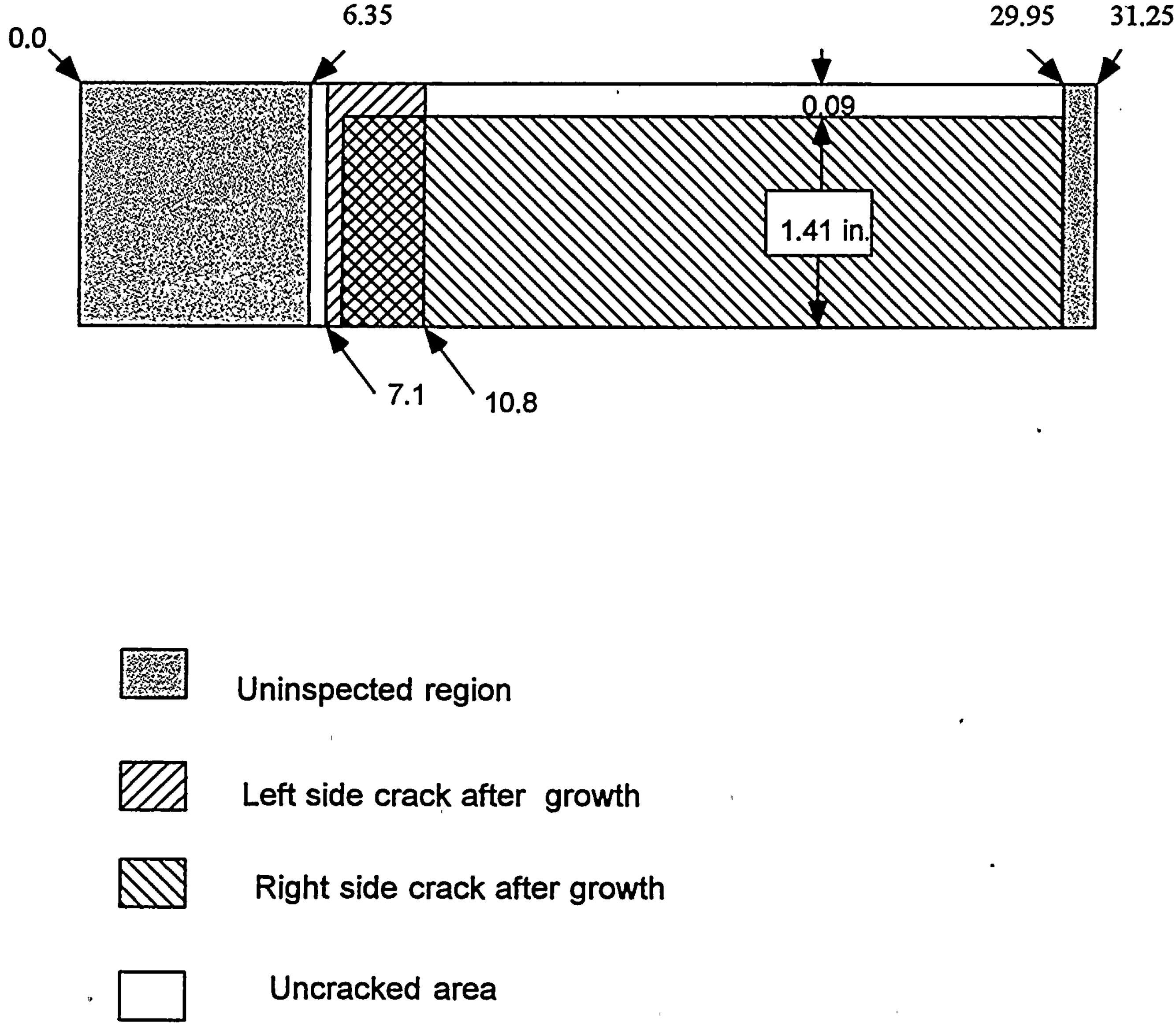


Figure 4-6 Weld V3 data

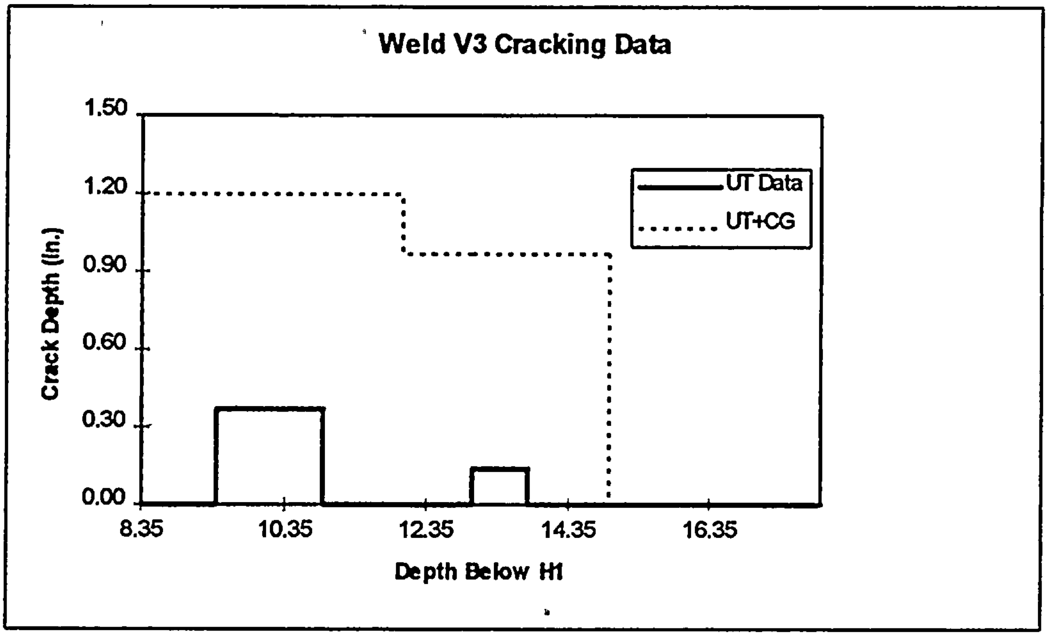


Figure 4-7 Weld V15 data

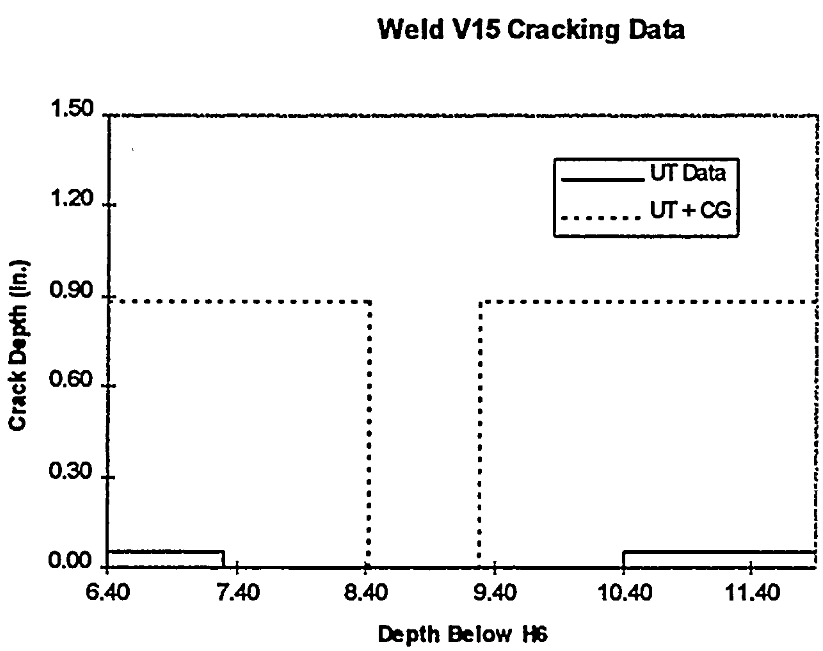
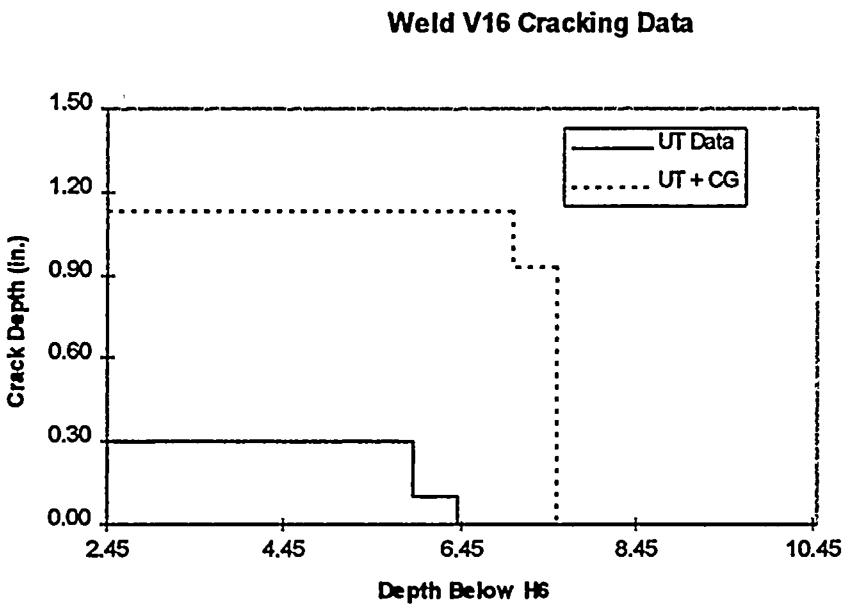


Figure 4-8 Weld V16 data



5.0 CONCLUSIONS

The structural analysis has established that the NMP1 core shroud will maintain the required ASME Code and NRC required safety factors considering the extreme assumption of a 5×10^{-5} in/hr crack growth rate for at least 14,500 hours. This crack growth rate is considered an extreme assumption based on the Reference 3 report, which has established that the maximum crack growth rate which can be anticipated at NMP 1 is less than 4.2×10^{-6} in/hr. The analysis has demonstrated by multiple methods (fracture mechanics, limit load) that structural margin is maintained. These combined analyses have established that significant structural margins exist which account for the uncertainties regarding new crack initiation and or inspection coverage limitations.

All the approaches established that the fracture mechanics analysis in Reference 1 was very conservative due to modeling assumptions. The results of the analysis for the V9/V10 welds show that even with the most conservative assumptions (no contribution from H4 or H5) the allowable crack length exceeds the calculated length after 14,500 hours. The results of the analyses described in Appendices A and B show that even higher margin can be demonstrated by taking credit for the remaining uncracked segments of the horizontal welds. The review of the application of limit load analyses for the V9 and V10 welds has concluded that limit load is a conservative analysis.

The results of the limit load assessment for the V3,V4,V15, and V16 welds show that even after assuming that all uninspected areas are fully cracked, after including uncertainty factors for depth and length and after including crack growth at the upper bound crack growth rate of 5×10^{-5} in/hr for 14,500 hours, the remaining equivalent uncracked lengths are still in excess of the required values.

6.0 REFERENCES

1. "Assessment of the Vertical Weld Cracking on the NMP1 Shroud" GENE Report GENE-523-01869-043, GE Nuclear Energy, April 1997

2. "Safety Evaluation by the Office of Nuclear Reactor Regulation Regarding Results of the Reinspection of the Core Shroud, Niagara Mohawk Power Corporation Nine Mile Point Nuclear Station, Unit 1" Docket No. 50-220, United States Nuclear Regulatory Commission

3. "Assessment of Crack Growth Rates Applicable for the NMP1 Shroud Vertical Weld Indications ", GENE Report GENE -523-B13-01869-113.

4. Letter report from NMPC provided in response to NRC Request for Additional Information

5. "Part I Metallography Nine Mile Point Unit 1 Boat Sample Analysis", RDD:98:55863-002-000:01 B&W Nuclear Environmental Services, Inc. September 1997.

6. "Fluence Analysis Report for Boat Samples - Nine Mile Pt. 1, Jan 1998, Framatome Technologies Inc. 86-1266298-00

7. "Part III Tension Tests Nine Mile Point Unit 1 Boat Sample Analysis", McDermott Technologies, RDD:98:55863-004-000:02, March 1998.

8. "Interpretive Metallurgical Report on Core Shroud Vertical Weld Boat Samples from Nine Mile Point Unit 1", Altran Technical Report No. 97181-TR-02, revision 0, February 1998

APPENDIX A : ADDITIONAL FRACTURE ANALYSIS

A-1. Introduction

The fracture analysis presented in this report assumes a full through wall flaw in the limiting V9/V10 welds. In addition, it also assumes that welds H4 and H5 are fully cracked. For convenience, this case is referred to as Case 1. Taking no credit for the horizontal welds adds additional conservatism to the analysis. In this appendix, results are presented for three additional cases with less limiting assumptions. It provides a measure of the added conservatism in the analysis. The three fracture analysis cases considered here are:

1. The two cases (Case 2a and Case 2b) consider through wall cracking of the cracked sections of the V9/V10 welds. H4 is assumed to be fully cracked and H5 is partially cracked (i.e. credit for uncracked segments of H5 only) in Case 2a and is shown schematically in Figure A-1. In Case 2b, both H4 and H5 are assumed to be partially cracked (i.e. credit for uncracked segments of both H4 and H5) as shown in Figure A-2.

2. In this case (Case 3), the entire lengths of the V9/V10 welds are assumed to have through wall cracking, but credit is taken for the uncracked portions of H4 and H5. This is in a way the converse of the assumptions in the main report (Case 1) where it is assumed that H4/H5 are fully cracked over the entire circumference and the V9/V10 welds are assumed to have through wall cracking over a finite length. In Case 3, the <u>entire length</u> of V9/V10 is assumed to have through cracks, but H4 and H5 are assumed to be partially cracked (i.e. through thickness cracking over part of the circumference) as shown in Figure A-3.

A-2. Fracture Analysis Results

In all cases the finite element code ANSYS Version 4.4 was used. Since ANSYS does not have crack tip shell elements, the shroud was modeled using three dimensional solid elements (Element 45). The crack tip was modeled with elements that simulate the crack tip singularity (Element 85) and provide the stress intensity factors directly. The internal pressure was set at 33 psi. The effect of the vertical blow-off load was conservatively included. The radial displacement boundary conditions at the top and bottom ends of the model were set to be free, except for one point to prevent rigid body motion.

Case 2: Through Wall Cracking of the cracked sections of the V9/V10 welds and Partial H4/H5 weld cracking

Case 2a shown in Figure A-1 assumes that H4 is fully cracked and H5 is partially cracked (i.e. credit for uncracked segments of H5 only. Case 2b shown in Figure A-2 assumes partial cracking in both H4 and H5 (i.e. credit for uncracked segments in both H4 and H5). The degree of cracking assumed is consistent with the UT results and crack growth (5×10^{-5} in/hr for the full cycle) at each crack tip is included plus UT uncertainty and any uninspected portions of H4 and H5 are assumed to be cracked through wall. The V9 and V10 welds are assumed to have through wall lengths consistent with that in Figure 2-3 for Case 1 in the main report. Since the intent is to determine the K value at the vertical weld crack tips only, special crack tip elements are included at the end of the through wall crack in the V9 and V10. As in Case 1, the pressure (33 psi) used in the analysis already includes the safety factor of 1.5 and the calculated stress intensity factors can be directly compared with the fracture toughness of 150 ksi$\sqrt{\text{in}}$.

Case 2a Results

Figures A-4 shows the FEM model used for Case 2a. Figure A-5 gives the calculated K values for V9 and V10 at both the top and bottom weld locations. The finite cylinder (Case 1) results are also shown for comparison. As expected, taking credit for H5 results in a significant reduction in the calculated stress intensity factor at the bottom of the crack for both the V9 and V10 weld cracks. At the top crack tip where there is no benefit from H4, the stress intensity reduces by approximately 5% when compared to the finite cylinder solution (Case 1).

Case 2b Results

Figure A-6 shows the FEM model used for this case. Figure A-7 gives the calculated K values for V9 and V10 at both the top and bottom weld locations. The finite cylinder (Case 1) results are also shown for comparison. The added structural reinforcement from H4 further reduces the calculated stress intensity at all locations including the top of the V9 crack. But since H4 had more extensive cracking, and in fact had a through thickness crack at the intersection with V9, the overall benefit at the top is somewhat lower than at the bottom tip of the crack. In all cases, as expected, the calculated K values are lower than those for Case 1 with the finite width cylinder.

Case 3: Through wall cracking of the full length of the V9/V10 vertical weld with partial credit for H4 and H5 welds

In this case (Fig. A-3), the entire V9 and V10 welds are assumed to be fully cracked. The objective is to show that the uncracked ligaments in H4 and H5 are sufficient to resist the internal pressure. Figure A-8 shows the cracked and the uncracked regions of the H4 and H5 welds used in the analysis. This figure includes crack growth at each crack tip and assumes through wall cracking in uninspected regions. Also, all cracked regions were assumed to be through wall cracks regardless of the depth. At the intersection of the V9 weld with H4, there is a postulated through wall crack in both welds, leaving essentially a corner flap which could open up under the pressure loading. For this condition, it is necessary to show that there will not be any 'unzipping' of the crack under fracture crack extension. Therefore it is necessary to show that the stress intensity factor at the end of the horizontal crack is within acceptable values. Thus crack tip elements are used at the ends of the horizontal cracks. Figure A-9 shows the finite element model.

Table A-1 Calculated Stress Intensity Factors for Case 3

Crack Tip Location	Calculated Stress Intensity (ksi-√in)
A (10° on H4 adjacent to V9)	91.1 ksi-√in
B(0° on H4 adjacent to V9)	64.7 ksi-√in
C (190° on H4 adjacent to V10)	88.7 ksi-√in
D (180° on H4 adjacent to V10)	79.3 ksi-√in

Table A-1 gives the calculated stress intensity (K_I) levels for each of the critical locations on the two welds The differences in the calculated K values are due the location and extent of the cracking near V9 and V10. In all cases the calculate K_I does not exceed 92 ksi-$\sqrt{in}$. Based on the above analysis the K values for the horizontal crack tips are within the allowables and therefore unzipping of the crack will not occur.

A-3. Conclusions from the Additional Fracture Analysis

The following conclusions can be drawn from the fracture analysis for the three cases:

1. All approaches established that the earlier work in Reference 1 was very conservative due to modeling assumptions. The additional fracture analyses also confirm, as expected, the conservatism of the Case 1 analysis.

2. All approaches support continued operation for the current cycle.

3. With the inclusion of credit for remaining sections at welds H5 and/or H4, the stress intensity at end of cycle is further reduced to less than 110 ksi-$\sqrt{in}$.

4. The final case established that even with flap formation due to the assumption of complete through wall cracking of the V9 and V10 welds, the stress intensity at the ends of the H4 would not exceed 92 ksi-$\sqrt{in}$. Thus, even if the V9/V10 welds are cracked through wall for the entire length of the weld, still acceptable margins are maintained.

Figure A-1 Schematic of Case 2a

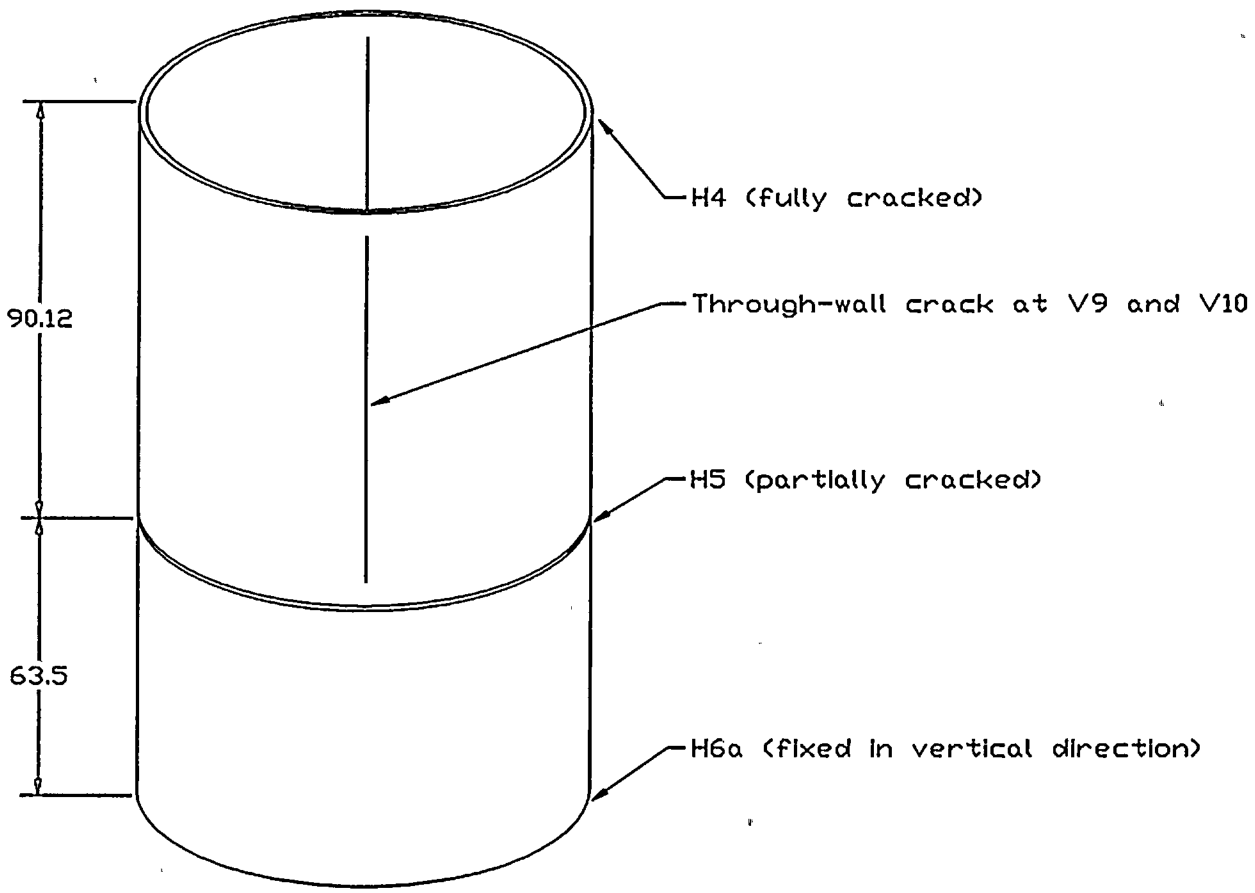


Figure A-2 Schematic of Case 2b

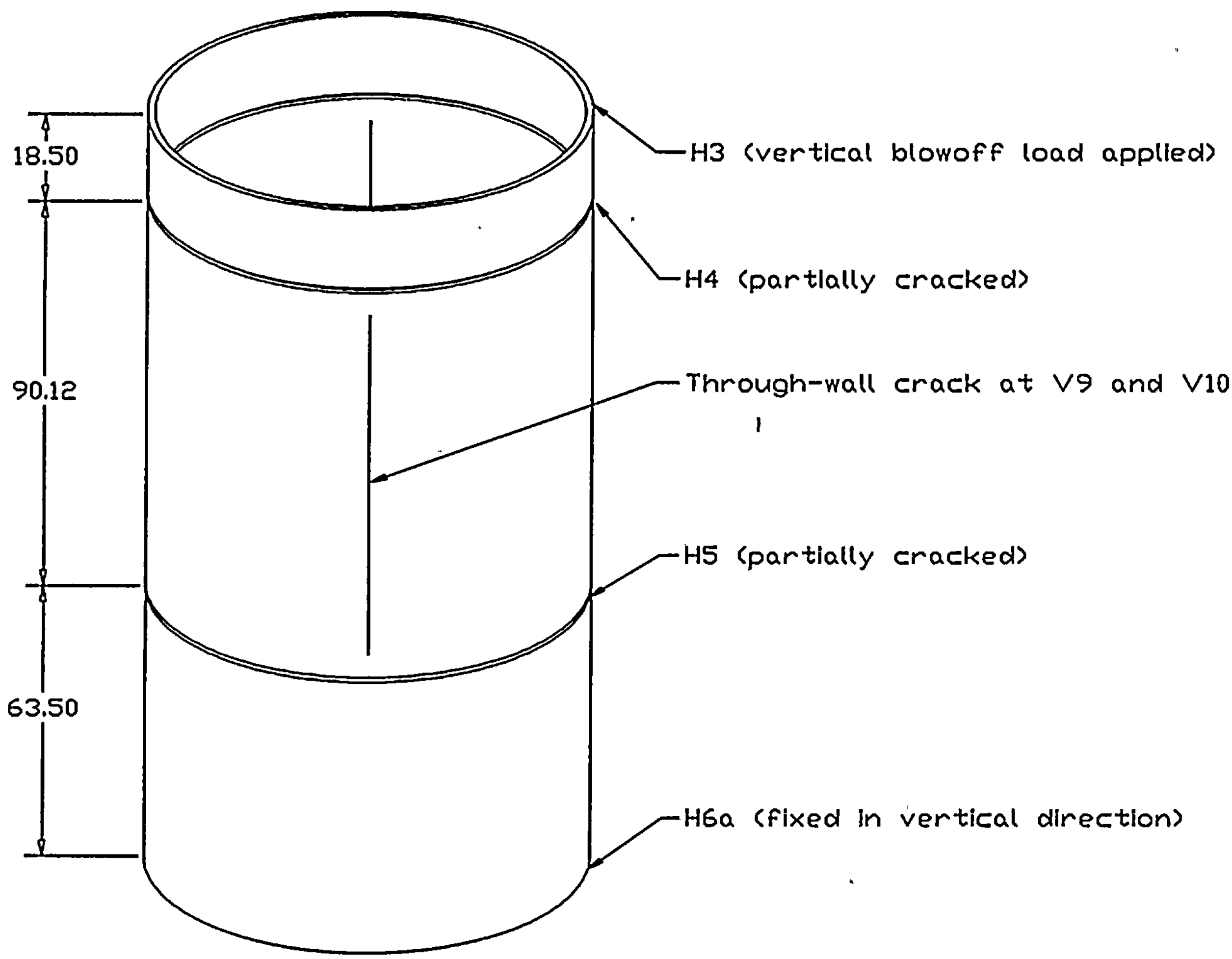


Figure A-3 Schematic of Case 3

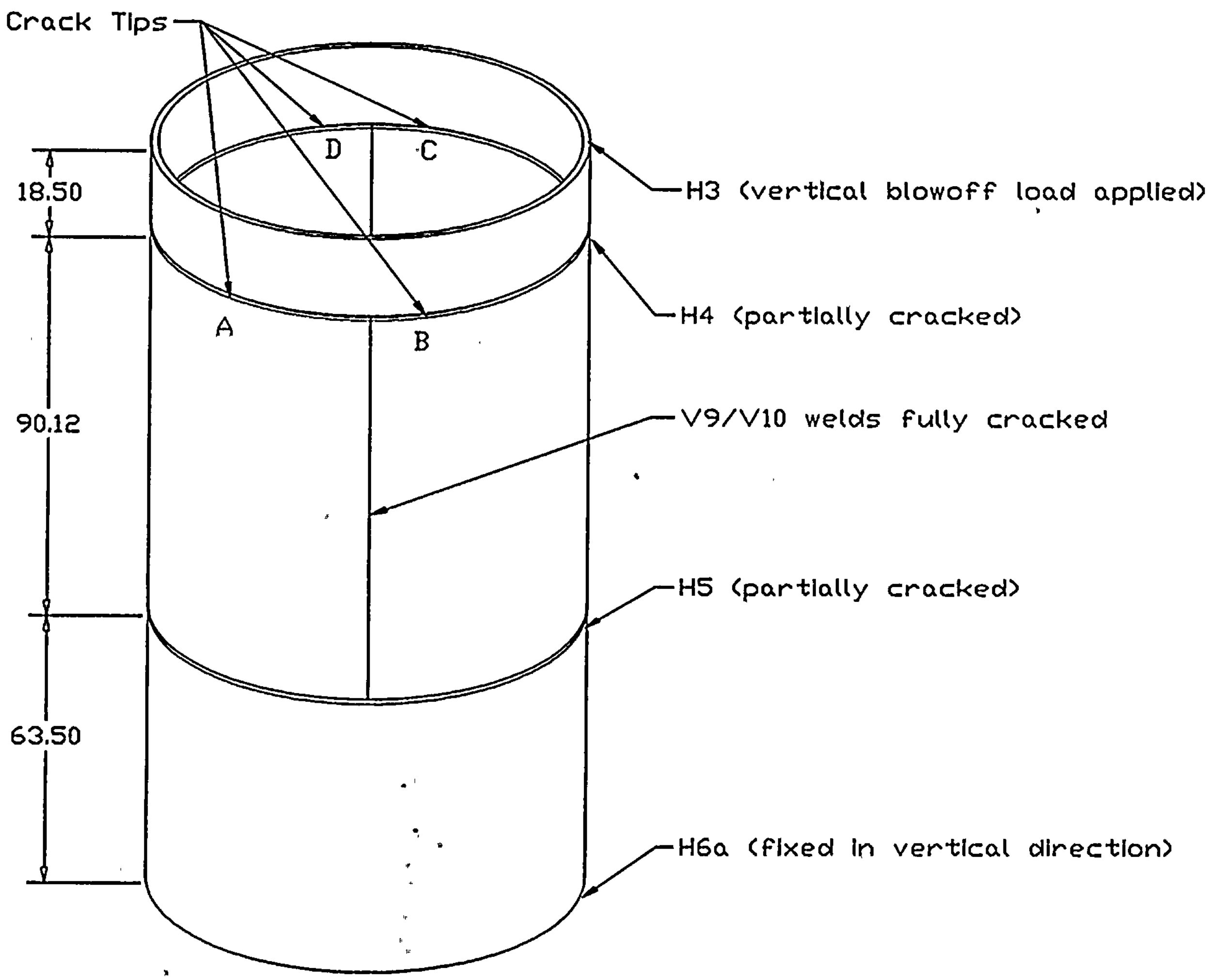


Figure A-4 FEM Model for Case 2a (Partial credit for H5 and no H4 credit)

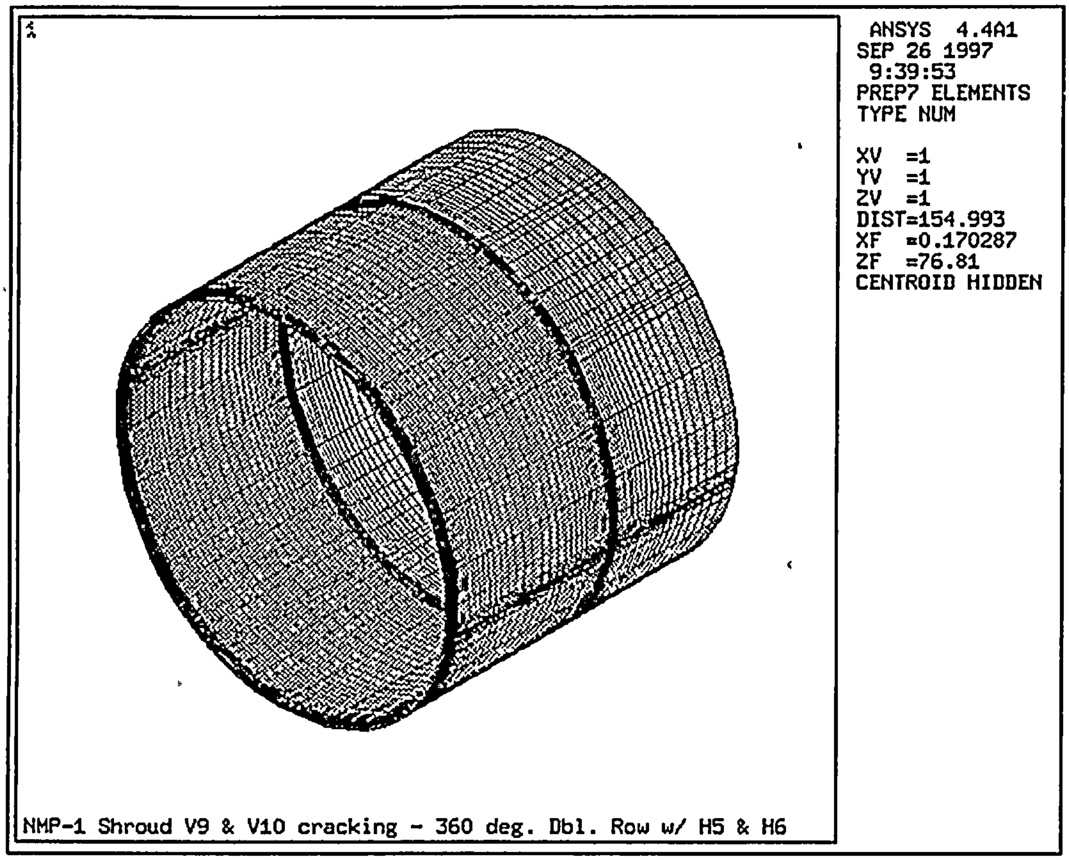


Figure A-5 Stress Intensity Factors as a function of half crack Case 2a

Case 2 - Full Model w/ H5 Ligaments and No H4 Credit

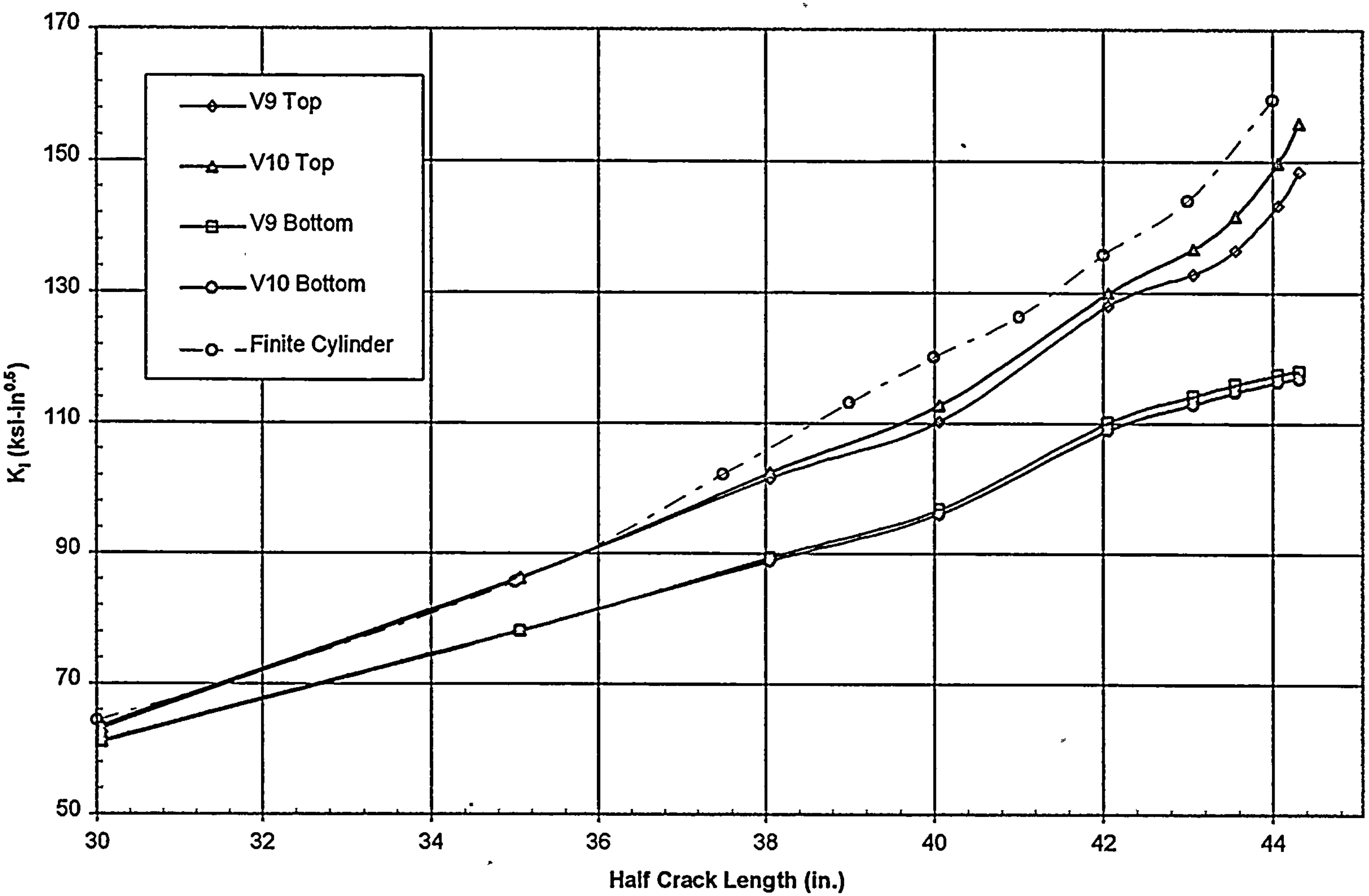


Figure A-6 FEM Model for Case 2b

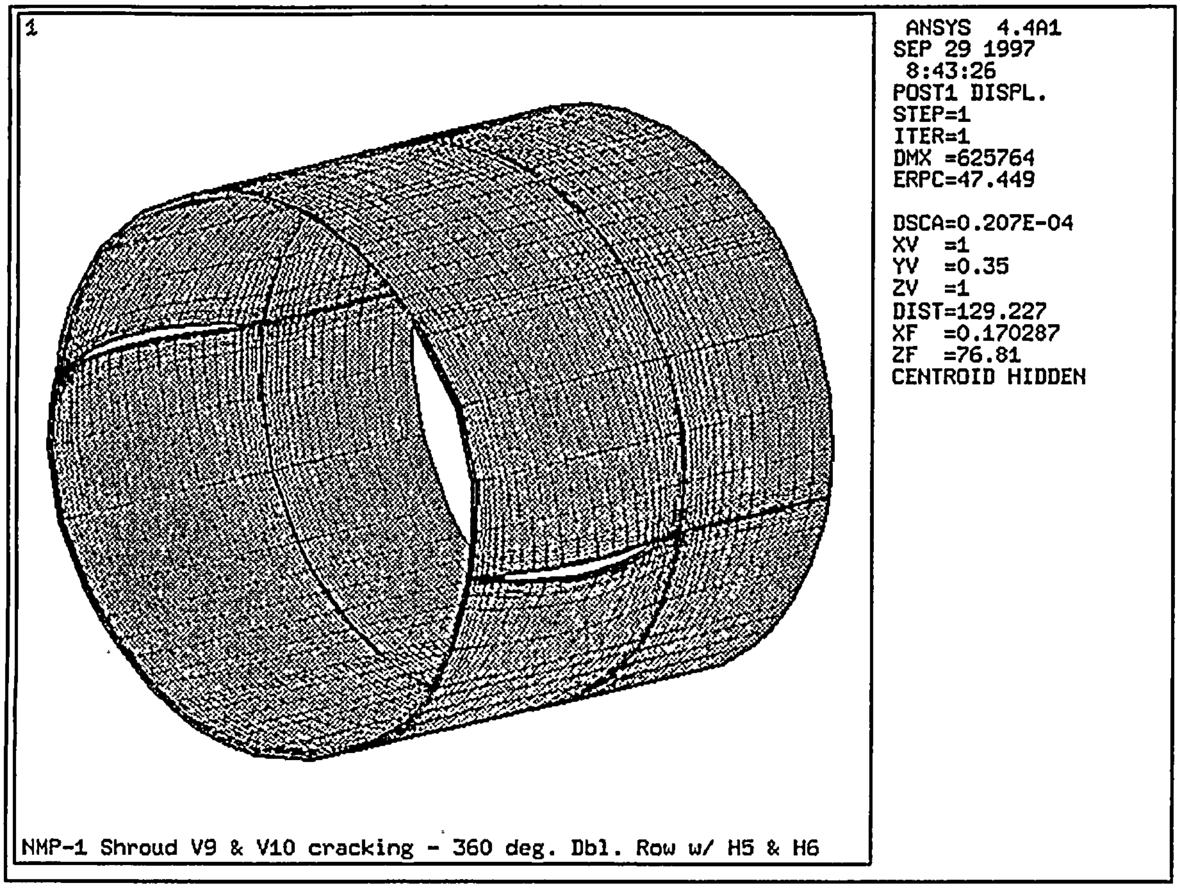


Figure A-7 Stress Intensity Factors as a function of half crack Case 2b

Case 2b - Full Model w/ H4 and H5 Ligaments (Including Vertical Load)

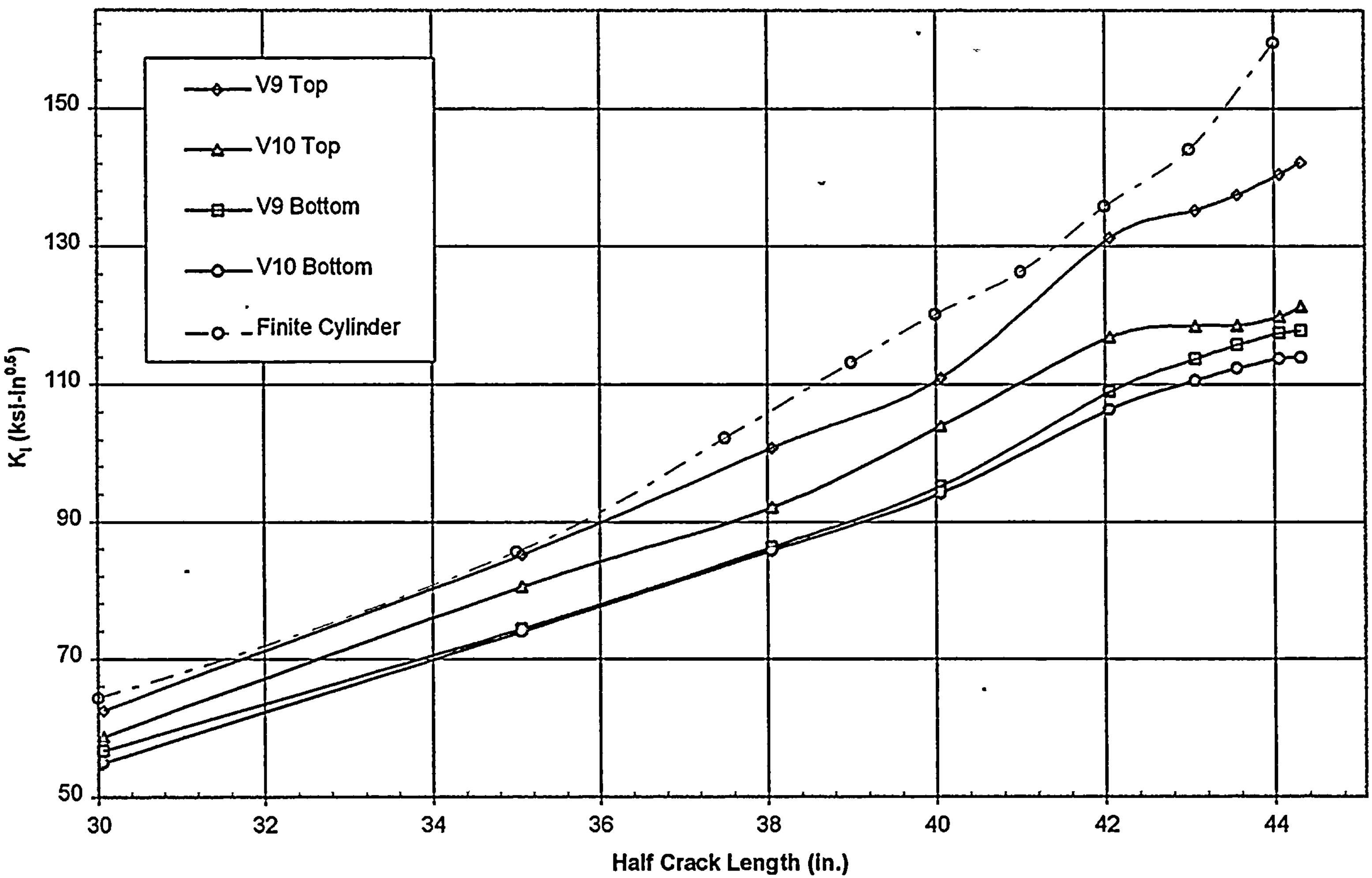


Figure A-8 Uncracked Regions of H4 and H5 welds

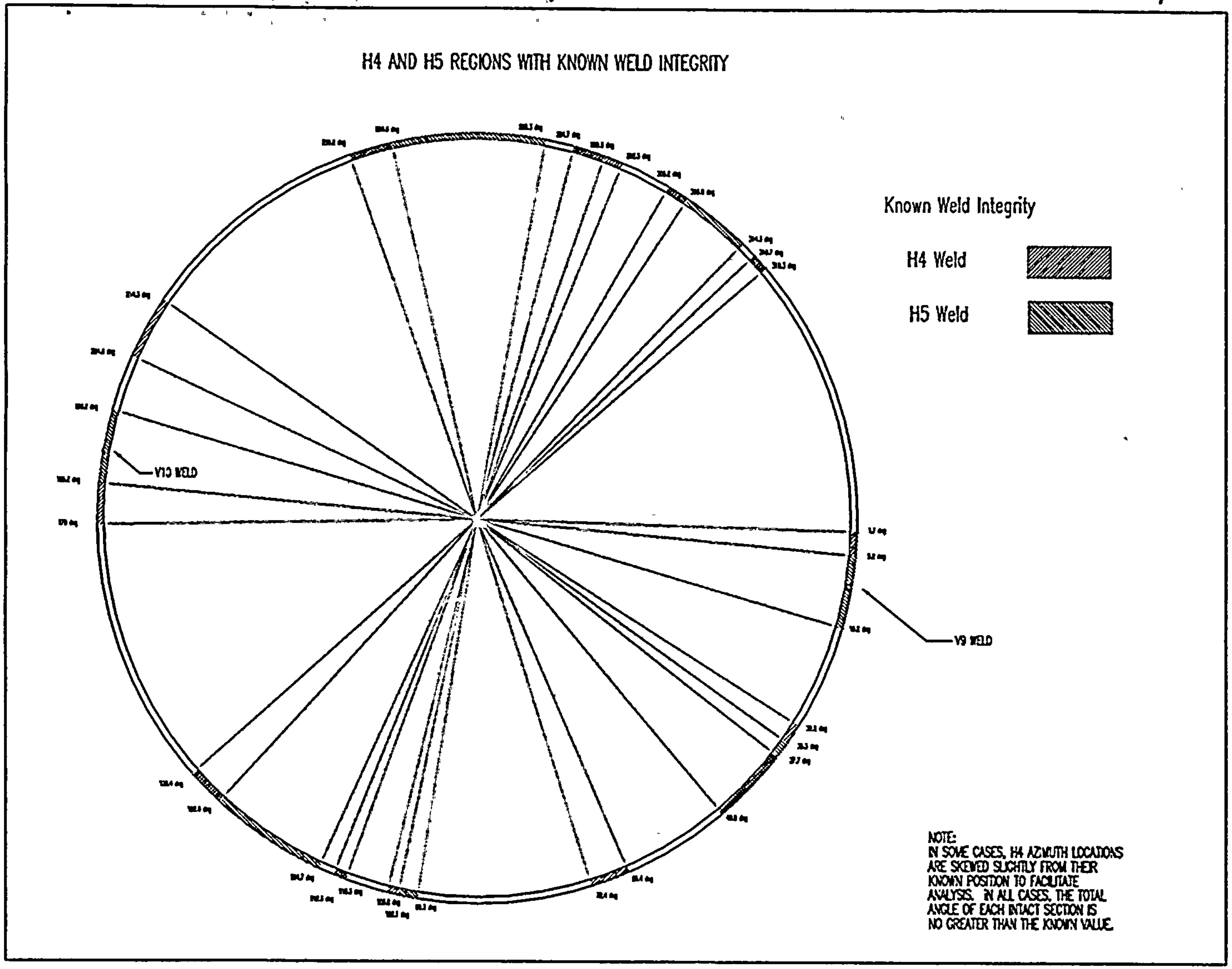
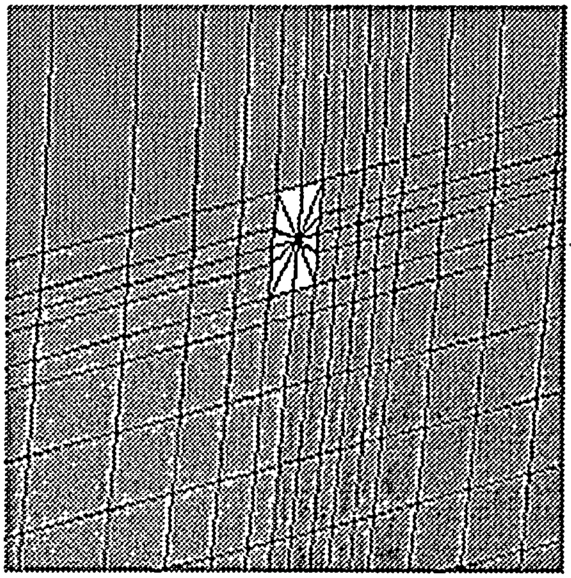
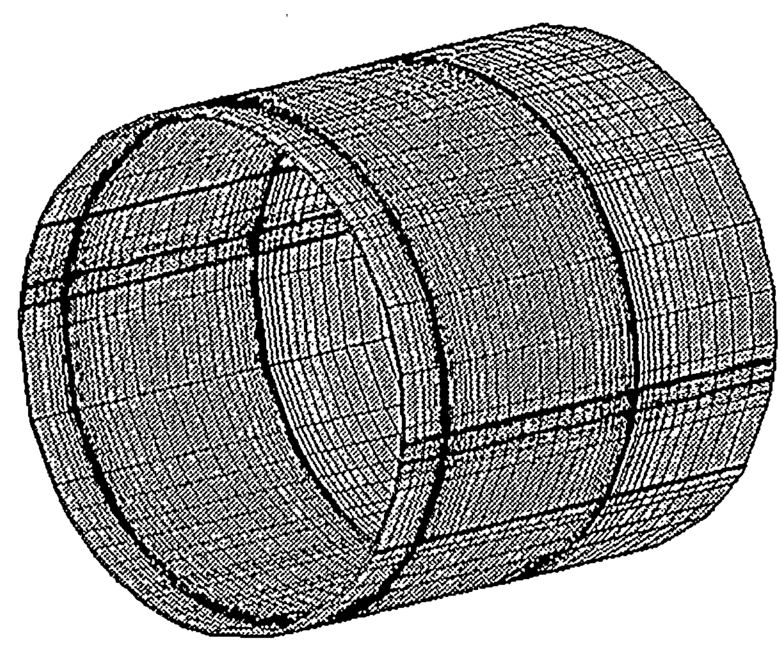


Figure A-9 FEM Model for Case 3



Close up of crack tip



NMP-1 Shroud V9 & V10 cracking - 360 deg. Dbl. Row w/ H4,H5,H6

APPENDIX B : LIMIT LOAD ANALYSIS

B-1. Introduction

The fracture analysis of the V9/V10 welds discussed Appendix A so far addresses failure margins under non-ductile behavior. It is also necessary to demonstrate limit load margin. This is particularly important since the mechanical testing of the boat sample removed from the NMP1 shroud shows that the material behavior was essentially ductile (Reference 7). Thus limit load margins may be governing.

Limit analysis margins have to be demonstrated for all vertical welds regardless of location. One problem with the inspection results for many of the non-beltline region welds such as the V3/V4 and V15/V16 welds was that there were segments that could not get UT coverage from both sides (and with all three transducers) because of access limitations. Demonstration of adequate margins for the entire cycle would be difficult if these uninspected segments are assumed to be cracked through wall and additional conservatisms, such as the NRC bounding crack growth rate and limiting UT uncertainty,are also used. An alternate approach is to assume that all vertical welds are fully cracked and show that the horizontal welds have sufficient uncracked ligaments to take up the pressure load. This Appendix describes the results of the evaluation of the limit load margin taking credit for the horizontal welds.

B-2 Bounding Limit Load Analysis

For this bounding limit load analysis, a finite element model of the entire shroud from H1 through H7 was developed (Fig. B-1). All vertical welds (except V7 and V8 which were found to be uncracked during inspections) were assumed to have through wall cracking over the entire length of the weld. Since information on cracking was limited for several horizontal welds, an average crack depth (based on the measured depths in regions where inspections were performed) was used for the analysis. A conservative estimate of the <u>average</u> depth is 0.5 inch. Adding to this, the incremental crack growth of 0.725 inches during the current cycle (14,500 hours at 5×10^{-5} in/hr) and UT uncertainty of depth of 0.1 inch, the remaining ligament is still in excess of 0.125 inch. Therefore, the analysis was performed assuming all horizontal welds were cracked 360° to a remaining ligament of 0.125 in. Since the analysis was directed at limit load margins, no special

crack tip elements were needed. This means that at the crack tips there will be a stress discontinuity. This is not a concern since the objective of the limit load analysis is to determine the average stress in the ligament and compare it with the flow stress. Table B-1 shows the average ligament stresses. It is seen that the ligament stresses in all the horizontal welds are within 3Sm. This confirms that even with assumed through wall cracking in most vertical welds and 360° cracking to a point where the remaining ligament thickness in all horizontal welds is only 0.125 inch, the required structural margins are maintained and the remaining ligaments are still sufficient to carry the pressure load, essentially substituting for the vertical weld.

B-3. Conclusions from the Bounding Limit analysis

Based on this analysis it is concluded that sufficient limit load margins are assured for the current cycle even if one assumes that all vertical welds (except V7 and V8 which were found to be uncracked during inspections) are fully cracked, but credit is taken for the horizontal welds. It indicates that the uninspected regions of the vertical weld do not have any significant impact on the ability to transfer the pressure loads.

Table B-1 Ligament Stress intensity Values in the Limit Load Evaluation

Section	Avg. Ligament SI	Flow Stress	Avg.<Allow
H1	4093	50700	OK
H2	21744	50700	OK
H3	7298	50700	OK
H4	10811	50700	OK
H5	22100	50700	OK
H6A	14098	50700	OK
H6B	12819	50700	OK

Figure B-1 FEM Model used for the limit load assessment