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ASSESSMENT OF CRACK GROWTH RATES APPLICABLE TO NINE MILE POINT-1 VERTICAL WELD INDICATIONS

Prepared for

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ASSESSMENT OF CRACK GROWTH RATES APPLICABLE TO NINE MILE POINT-1 VERTICAL WELD INDICATIONS

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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 (approximately 16 months).

In addition, 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. The utility also put in place operational procedures to assure that the coolant chemistry was maintained at conductivity levels that would lead to significantly lower crack growth rates than those used for the structural analyses used to support continued operation (reference 1).

The purpose of this report is to provide a revised crack growth rate basis for extending that 10,600 hour operating period to 14,500 hours. There are several factors that support this refined, yet still conservative assessment of crack growth rate. These are the following:

- The boat sample evaluations provide clear evidence that the cracks are intergranular stress corrosion cracking similar to that found in piping and in components that have been sensitized conventionally by the welding process.

- The boat sample metallography which revealed a highly cold worked layer on the shroud o.d., thick oxides on the crack surfaces and normal IGSCC features, is consistent with cracking that initiated early in the plant history, growing in depth over the early years of plant operation when the coolant conductivity was significantly higher and the cumulative fluence low (reference 2).

- Qualitative assessment of the material sensitization levels and EPR measurements of the NMP1 V9 and V10 boat samples (reference 21) have concluded that the V9 and V10 material is mildly sensitized consistent with crack growth rate analysis assumptions.

- The NMP1 V9 and V10 boat sample fluence measurements have confirmed the maximum ID fluence on the V9 specimen was ~3E20 n/cm^2. Based on this testing the mid wall fluence from 60 inches below the H4 to the H5 weld is bounded by the V10 mid wall measured fluence of 1.54E20 n/cm^2, (reference 22). This NMP1 specific measured data confirms the appropriateness of the application of the BWRVIP-14 disposition crack growth rate of 2.2 E-5 in/hr.

- The NMP1 V9 and V10 boat sample tensile tests have determined that the increase in yield strength is consistent with the expected change in yield strength for 304 SS with a fluence of 1.5E20 n/cm^2. The measured yield strength of approximately 50 ksi at 550 degrees F demonstrates the material remains ductile and correlates well with both the fluence measurements and the material sensitization evaluations.

- The boat samples confirmed that the UT measurements were consistent with the metallographically measured crack depths.

- A revised disposition crack growth rate of 2.2×10^{-5} inches per hour is appropriate for the NMP1 fracture mechanics analysis of through thickness crack growth that supports continued operation. The application of the disposition growth rate is justified based on the boat sample findings and the operational water chemistry currently being adhered to during operation of NMP-1.

- The currently available crack growth methodologies (references 3-9), using conservative estimates of stress intensity, water chemistry parameters and material condition, strongly support the application of the BWRVIP-14 disposition rate of 2.2×10^{-5} inches per hour (reference 3).

- The available field data and laboratory data on crack growth rates also strongly support the conservative nature of this bounding average rate of 2.2×10^{-5} in/hr (reference 3).

- Crack growth rate predictions made using the GE CR&D's comprehensive fundamental PLEDGE model and based on the actual operating conditions at NMP-1 predict that crack growth rates will be bounded by 2.2×10^{-5} in/hr.

- The PLEDGE assessment which includes consideration of water chemistry species and irradiation effects predicts the expected average rate to be at or below 4.2×10^{-6} in/hr for the specific cracks and components of concern. This representative predicted rate is based on excellent water chemistry being maintained over the cycle at or below a conductivity of 0.1 μS/cm with the total detrimental species (sulfate and chloride) kept at or below a 5 parts per billion (ppb) concentration.

- The crack growth rate required to support an operating period of 14,500 hot operating hours is 3.65×10^{-5} in/hr based on the reference 1 fracture mechanics analysis (CGR x 14,500 hrs = 0.53 inch). This crack growth rate is a factor of 1.5 conservative compared to the BWRVIP-14 disposition rate and a factor of 10 conservative compared to the pledge predicted crack growth rate.

The technical details that support these conclusions are presented in this report. Several complementary crack growth evaluations have been made. All establish the conservative nature of the revised analysis that justifies the longer period of continued operation. These analyses do require that NMP-1 be operated per the engineering procedures now in place. This is justified by the past record of operation at NMP-1 over the last ten years which clearly establishes that the unit has the current capability to maintain excellent water chemistry. The requirement to operate NMP1 within the EPRI water chemistry guidelines with the average conductivity below 0.19 μS/cm will be incorporated into NMP1 operational procedures which ensures that the analysis assumptions are maintained.

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1.0 BACKGROUND

Following the detection of intergranular stress corrosion cracking (IGSCC) in the large diameter piping in the BWR recirculation system, efforts were undertaken to develop crack growth rate data and to use the data to develop a crack growth model that could be used to predict the amount of crack growth that would take place during future periods of operation. The efforts resulted in NUREG-0313, rev.2 (reference 10) which put forth a methodology for dispositioning IGSCC in piping (reference 11). This understanding of IGSCC also led to its use in setting inspection intervals for austenitic recirculation piping in Generic Letter 88-01 (reference 12). With the discovery of IGSCC in core shrouds, the NRC made use of that data to develop a more conservative bounding approach for estimating the rate of growth in these components. The existing data from NUREG-0313 was again used as the basis for this bounding approach. It was used to establish a plateau rate of 5 x 10^{-5} in/hr for estimating future crack growth at these locations. This conservative approach was simplified: it did not consider the impact of the residual stresses in the components nor the effects of water chemistry improvements in reducing the actual rates of extension.

Examination of the data used to develop the crack growth rate information that is the basis of the NRC bounding rate shows that it was all produced in laboratory facilities where the conductivity of the high temperature water used covered a wide range from 0.3 µS/cm to 0.7 µS/cm for tests conducted in 288°C, 200 ppb oxygenated water to 0.5 to 1.5 µS/cm for tests conducted in 288°C, 6000 ppb oxygen saturated water. (reference 13). The conductivity of the water resulted from actual additions of sulfate species to the water. These species are known to accelerate crack growth in a similar manner to chloride species in high purity water. The impurity levels that were required to achieve the high conductivity levels associated with the laboratory tests required the addition of ~90 to >200 ppb sulfate. However, in currently operating BWRs, sulfate and chloride species are nominally very low (< 5 ppb) under normal operation and their levels are restricted to a maximum level of 20 ppb before operating procedures require action. The total conductivity in the NMP-1 plant, for example, is mainly attributable to H+, OH- and other species such as nitrates which have much less effect on the crack growth rates. Therefore, the data used to develop the NRC disposition line presented in NUREG-0313 and the 5 x 10^{-5} in/hr bounding rate can be assumed to be very conservative for normal operation, particularly at a plant such as NMP-1.

The second critical consideration is the stress intensity factor that is associated with the bounding crack growth rate (5 x 10^{-5} in/hr). The majority of tests were performed at values of ~25 ksi-in$^{1/2}$. For existing shroud cracks with a depth beyond 25% of the shroud thickness, the residual stresses in the shroud produce a crack tip stress intensity factor that is significantly lower than this value used in the tests. There is continuing confirmation that residual stress patterns in thick wall components that have resulted from double sided welding such as for the shroud (>1.0 inch) become sufficiently compressive at mid-wall to markedly reduce the stress intensity driving force for crack growth. The lower stress intensity has a very large effect on crack growth rate. These patterns are consistent with the majority of the length of vertical weld cracking in the NMP1 V9 and V10 welds which is integral to the through thickness evaluation of structural margin.

NMP1 has performed specific V9 and V10 residual stress studies which define a potential shift in the mid wall compressive region due to fabrication practices such that the stress intensity could remain in the range of 10 to 20 ksi$\sqrt{\text{in}}$ for OD initiated cracking. This postulated shift in the mid wall residual stress pattern has been proposed as a possible explanation for the deeper V9 cracks. The PLEDGE crack growth studies confirm the maximum crack growth rate is bounded by the BWRVIP-14 growth rate. These studies have assumed initial constant through-wall stress intensity levels of 10 ksi and 20 ksi which clearly bounds this postulated condition.

Another factor affecting the high crack growth rate in the data used to set the NRC bounding rate was the level of sensitization of the laboratory test specimens. This level was, in many cases, fully furnace sensitized. The sensitization level would be expected to bound the sensitization level found in the core shroud, even after operation introduced irradiation contributions to sensitization. With this background, it is appropriate to re-visit the crack growth rate values used in the shroud vertical weld analysis. The purpose of this report is to establish that a lower value of 2.2 x 10^{-5} in/hr be used as a bounding crack growth rate in structural assessments. There is now a large amount of understanding of crack growth rate dependencies. The critical role of anionic species on crack growth has been investigated for over 15 years.

Additionally, there is also improved understanding of the effects of irradiation on the key factors controlling IGSCC. Its effect on water chemistry, material sensitization and residual stress patterns allow its effect to also be included in crack growth modeling.

All of this understanding has been used to develop a documented basis for the lower plateau crack growth rate. This basis which is presented in the remainder of the report, is given in several parts: first, this basis can be justified using all of the currently proposed crack growth models including that proposed in BWRVIP-14 and the PLEDGE model that is used by the GENE and GE CR&D. These modeling efforts can also incorporate the important, confirmatory understanding derived from the two NMP-1 boat samples taken from the V-9 and V-10 vertical shroud welds to predict even lower expected rates. Finally, the modeling efforts can use the assessment of the current depth of cracking in the vertical welds, verified by the boat sample metallography, to benchmark the choice of modeling parameters.

2.0 CRACK GROWTH RATE FACTORS for NMP-1 ASSESSMENT

There have been significant efforts made to understand the rates of growth in Type 304 stainless steel in BWR environments including measurements of actual crack growth rates in laboratory and plant water chemistry environments. They have identified the key factors that control crack growth that are directly related to the three factors controlling SCC: material susceptibility, applied and residual stresses, and the environmental parameters. Even though there are different methodologies that are capable of modeling crack growth and in turn can be used in an appropriate conservative manner to disposition existing crack indications, these factors are common to all. It is also clear that these factors are now understood for the NMP-1 shroud welds to a level that justifies the use of a lower dispositioning crack growth rate. The next sections discuss these factors and assign appropriate values to NMP-1 vertical shroud welds.

2.1 Key Inputs to Crack Growth Modeling for the NMP-1 Shroud

The key factors controlling crack growth in the NMP-1 V-10 and V-9 shroud welds have been determined through review of the materials records for the shroud, the boat sample evaluation of the actual material condition in the vicinity of the cracking, the inspection efforts during the last outage, the water chemistry records and the operational guidelines being placed on current and future operation. This summary of the understanding of the ingredients that control crack growth is focused on the key material and water chemistry parameters in efforts to bound the rate of crack growth during the current operating cycle.

2.1.1 Current Understanding of NMP-1 Shroud Vertical Weld Materials

The materials that were used for the different shroud plates were typical Type 304 stainless steel with carbon levels between 0.047 and 0.062w/o (reference 14). The plates were solution annealed and then cold formed into shape. The cylinders were welded together using vertical welds that were double sided welds. The inner half of the weld was manufactured first, the root was then back gouged and the weld was completed on the outside of the shroud (reference 15). This process would be expected to impart surface cold work and HAZ sensitization which is controlled by the weld process as well as the mid-spec range in carbon level.

Examination of the boat samples provided more quantitative evidence of key factors important to both SCC initiation and subsequent crack growth. The crack initiated in the HAZ adjacent to the weld (Figure 3.3 from the Boat Sample Report). There was a heavy cold work layer on the V-10 boat sample, taken from the outside of the core shroud. The peak hardness was 380 HV Vickers Hardness (Figure 3.10 from the Boat Sample Report). The metallography revealed moderate sensitization in the HAZ and at the current crack tip location. Based on comparison with other metallography, the sensitization level is consistent with an EPR value of 6 to 8 C/cm^2 (references 16 and 21). (Figure 3.19 from the metallography report details the moderate level of ditching at the crack tip location). Similarly, it should be noted that the V-9 sample taken from the inside of the shroud was not as severely cold worked or sensitized, consistent with the absence of cracking in this region.

The boat sample evaluation substantiated that the cracking was IGSCC. The location of the cracking is consistent with the location of the weld HAZ, the location of sensitization and the location of higher weld residual stresses. The cracking did not exhibit broad intergranular branching that might be expected if the role of irradiation on material susceptibility was dominant. These features support the use of existing models or correlations to predict future crack growth.

2.1.2 Current Water Chemistry at NMP-1

The water chemistry at the NMP-1 unit is also an important factor in the crack growth process. The key parameters are the electrochemical corrosion potential (ECP) as well as the anionic species in the coolant that contribute to the cracking process. The latter is often treated as directly related to the conductivity in many modeling approaches. This is a good first order approach; however, the presence of specific species such as sulfates and chlorides are largely responsible for accelerating the SCC processes in normal water chemistry (NWC). Table 1 displays the yearly average conductivity as well as the yearly chloride and sulfate levels (sulfate measurements were not recorded in the first years of operation.) The conductivity levels were high with corresponding high chloride levels (reference 17). Figure 1 displays day to day details of the water chemistry history over the last cycle. It is apparent that the purity of the coolant has undergone a dramatic change. The averaged conductivity over the last cycle was 0.086 μS/cm. The average sulfate and chloride levels were 2.9 and 0.5 ppb, respectively. This represents excellent operation, and environmental conditions that would slow SCC processes.

The location of the shroud welds within the core region certainly does also establish that the ECP would be high. The crack surfaces exhibited residual oxides (Figure 3.25 from the Boat Sample Report) consistent with the oxidizing nature of the environment. This is consistent with metallography of other core shroud samples. The expected ECP would be in the 150 to 200 mV_{she} range (reference 18).

3.0 SUPPORTING CRACK GROWTH RATE ASSESSMENTS

Current efforts by both the BWRVIP and the Swedish SKI as well as the on-going efforts by GE CR&D have led to models that can be used to evaluate crack growth rates. These correlative or fundamental models can be used to disposition cracks. They can also be used to predict expected cracking behavior. Both types of evaluations are useful in justifying a lower bounding crack growth rate to be used in the justification for continued operation with the shroud vertical weld cracking. A lower rate is warranted by the excellent operating coolant water chemistry at NMP-1. The higher bounding rate used in the original safety assessment (reference 1) is typical of the higher conductivity levels associated with BWR operation a decade ago when large diameter pipe cracking occurred. The following sections provide the support for using 2.2 x $\cdot 10^{-5}$ in/hr in crack growth assessments. The assessments taken together lend high confidence that the lower rate is justified.

3.1 BWRVIP-14 Based Evaluation

The BWRVIP has documented a methodology for evaluating crack growth behavior in core internal components (reference 3). The effort included the important compilations of crack growth rate data, crack growth rates determined from re-inspection data from core shrouds, and through-wall residual stress measurements for shrouds. The stainless steel crack growth data was used to establish a three tiered approach for assessing crack growth rates. The easiest and most conservative approach was the use of a plateau rate of 2.2 x 10^{-5} in/hr in the dispositioning of cracking in core internals constructed of stainless steel. The compendium of laboratory crack growth data established that for existing cracks, such as those in the NMP1 core shroud, the cumulative impact of good water chemistry and favorable residual stress patterns supported the use of this bounding rate, a rate approximately one half of the currently used value.

The residual stresses measured in actual shroud weld regions verify that the stresses become compressive in the mid-wall location (Figure 4-7 from BWRVIP-14), thereby leading to a reduction in the stress intensity factor and to a lowering of the driving force for further crack deepening (Figure 5-3 from BWRVIP-14). The average depth of cracking found in the V9 and V10 welds support the applicability as well.

The BWRVIP report also provided additional UT-determined data from shroud re-inspections which also supports this bounding rate. While none of the laboratory tests were

made using irradiated material, the UT data was taken from Type 304 stainless steel core shroud welds that had experienced a range of fluence. This included data that was taken for an H4 weld exposed to a higher fluence than that for the NMP-1 vertical welds. The rates of deepening were less than the 2.2 x 10^{-5} in/hr (Pages I-29 through I-32 from BWRVIP-14).

3.2 GE PLEDGE Crack Growth Rate Assessments

The PLEDGE model was developed by GE CR&D over 15 years ago for sensitized stainless steel, then later extended to non-sensitized, then irradiated stainless steel. It can be used to predict both crack growth rates as well as crack growth in different austenitic stainless steel structural components including core internal welded structures (references 4-8). The specific details were also given in Appendix B of the previous NMP-1 vertical crack assessment report (reference 1). The PLEDGE model is unique in that it has been benchmarked using both un-irradiated and irradiated crack growth rate data (references 4, 19, 20). Because of its ability to use all specific material and environmental information, the model is well suited to predicting the future crack growth in the vertical welds in the NMP-1 core shroud, particularly where there is significant flux and cumulative fluence that will be expected to have effects on the shroud material. The model requires inputs of the material susceptibility which is based on the initial sensitization and can account for the cumulative effects of neutron fluence. It also requires inputs of the residual and operating stress profile or the stress intensity level that results. The stress parameters are influenced by irradiation that leads to significant relaxation at higher fluences (also discussed in Appendix B of reference 1). The final inputs are the water chemistry variables that include (1) the ECP (corrosion potential) which depends on the level of oxidizing species in the core region adjacent to the core shroud, and (2) the conductivity. The effective conductivity used in the model accounts for the specific anionic species that promote IGSCC. While the material susceptibility and water chemistry parameters have already been discussed, the ECP value, measured directly for laboratory tests, must be assigned a value based on radiolysis modeling understanding and direct measurements made at similar reactors in the core region of interest. For this effort, the value is based on a review of current GE modeling efforts and actual in-reactor ECP measurements that establish the value to be 150 to 200 mV_{she}.

The understanding of the residual stresses and the K levels is based on previous measurements as discussed for the BWRVIP approach as well as previous understanding of

cracking. The standard through wall residual stress distribution is also very broadly similar to the large diameter pipe distribution, tension-compression-tension, and is supported by the generally observed behavior over the majority of the length of the vertical welds (references 1, 3). Therefore, this distribution (combined with the operating stresses) was used as the basis for setting upper bound stress intensity levels upon which to make crack depth evaluations of the NMP-1 shroud.

A critical parameter used in these calculations was the conductivity.

Both un-irradiated PLEDGE and irradiated PLEDGE (which accounts for all fluence induced changes in the material and in the residual stresses) evaluations were made. Crack growth rate calculations were made making use of all of the NMP-1 material, water chemistry and fluence information.

Crack growth rates were determined using unirradiated PLEDGE and irradiated PLEDGE for different initial stress intensities as well as different conductivity levels. The rates, given in µ-inch/hour (1 x 10^{-6} in/hr), are displayed in Table 2. These calculations were made for initial stress intensity levels as well as for three fluence levels which would be representative of a 0.6 inch deep crack in the V9 or V10 weld at the start of the evaluation. This depth is consistent with the average depth for the V9 and V10 welds in the locations key to the structural margin assessment (reference 1).

Four conductivity levels are presented: 0.1 µS/cm,

and the conductivity leading to a crack growth rate of 22 µ -in./hr (the same as 2.2 x 10^{-5} in/hr). Two initial K levels were used: 10 ksi-in$^{1/2}$ and 20 ksi-in$^{1/2}$. In addition to various crack growth enhancements induced by irradiation, irradiation also leads to stress relaxation (and reduced stress intensity as is shown) as well.

Reviewing the results given in Table 2, it can be seen that for the most conservative case of an initial K of 20 ksi-in$^{1/2}$, an ECP of 200mV$_{she}$ and an EPRo of 10.8 C/cm^2, the predicted crack growth case of 2.2 x 10^{-5} in/hr is only reached in one of the cases if the conductivity of 0.19 µS/cm is The other lower ECP cases (150 mV, she), particularly at the lower K value show that this rate is still not exceeded at the Action level 1 conductivity of 0.3 µ S/cm Therefore, setting 0.19 µS/cm as an operational bound on conductivity will restrict any predicted rate from exceeding 2.2 x 10^{-5} in/hr under all of these conditions. Recognizing that the actual operating conductivity at NMP1 is ~0.09 µS/cm, the actual crack growth rate would be far lower than this bounding value.

3.3 GE Modeling of Expected Crack Growth Rates in High Purity, Low Conductivity Water at NMP-1

The PLEDGE model can be used to support the development of a strong basis for the use of a bounding crack growth rate which has been presented in section 3.2. The PLEDGE model can also use the understanding gained from the boat sample and the current water chemistry to make "best" estimates of the future average crack growth rate and predict the extension of the existing cracks. Using this approach with these realistic inputs, the PLEDGE model was used to make these calculations. As stated earlier, the level of initial sensitization in the boat sample level has been estimated to be 6 -8 C/cm^2 at the current crack tip location, a location in the outer region of the weld HAZ. The applied stress intensity based on the information given in reference 3 is expected to be no greater than

The water chemistry conductivity is currently projected to maintain an average value between 0.09 and 0.1 µS/cm, with sulfate and chloride concentrations at 3 and 0.5 ppb, respectively. The ECP must be assigned a value of 200 mV $_{she}$ over the length of the shroud outside surface. Using these inputs, the values of crack growth rate were determined using PLEDGE (with and without irradiation considerations). The rates are given in Table 3. It can be seen that the expected growth rate is between 1.2 and 4.2 µ-inches/hr (4.2 x 10-6 in/hr). Integrated over the entire 24 month period, this growth rate would lead to 0.07 inches of added depth. Integrated over the actual hot operating period of 14,500 hours would lead to an added depth of .06 inches. While some cusps of the crack could grow more due to higher sensitization and localized increases in residual stress, the expected rate establishes a factor of 10 over the BWRVIP-14 disposition rate of 2.2 x 10^{-5} in/hr.

3.4 SKI Based Assessment

The Swedish Inspectorate has also established crack growth relationships for austenitic stainless steel (reference 9). These simple, easy to use relationships are based on a subset of the un-irradiated crack growth rate data compiled in the BWRVIP effort. The disposition lines incorporate a stress intensity dependence that is based on PLEDGE, thereby making use of the code's fundamental relationships between crack growth and stress intensity. Different curves are recommended for good and bad water chemistry, consistent with the fundamental principles of crack growth rate understanding. The curves are given in Figure 2. The predicted growth rates again support the use of a lower disposition rate for the core shrouds when appropriate stress intensity values are used. This approach is consistent with PLEDGE as well as the second tier disposition curve presented in BWRVIP-14.

3.5 Confirmation of Modeling Assessments

The last evaluation serves to validate the choice of modeling parameters through the use of the PLEDGE model to evaluate crack growth over the entire time of operation at NMP1. This assessment must account for the early initiation, the actual water chemistry over the history of operation, the cumulative effects of irradiation, and accordingly grow the crack to its current depth. It can also predict the amount of crack deepening that will occur over the next several cycles based on different water chemistry assumptions. This adds confidence in the margin against rapid deepening.

One scenario evaluated was designed to grow an initiated crack to a depth of from 0.6-inch to 0.7 inch by 202 months (the current point in time). The conditions that were used for these calculations included a standard symmetrical residual stress profile

Since early plant conductivity values were fairly high and included substantial quantities of deleterious species, no "discounting" (adjustment) of conductivity was performed for those inputs.

Other parameters used in these calculations included:

Plant conductivity

After 202 operating months, two "futures" were calculated to represent:

Continued operation at 0.1 µS/cm

Operate continuously at EPRI Action Level 1

Figure 3 clearly displays that the initial crack growth rates were higher due to poor water chemistry and the higher residual stresses on the outside diameter of the shroud. The rate continued to diminish and future crack extension is expected to be small, even if the water chemistry was assumed to be near the typical Action 1 operational limits.

4.0 CONCLUSIONS

The objective of this crack growth evaluation has been to re-assess the crack growth rate that can be used in evaluating the vertical cracks in the NMP–1 shroud. This evaluation has used all existing understanding of the NMP-1 shroud condition as well as the understanding of crack growth rates in Type 304 stainless steel. The primary basis of this new understanding are the results of the NMP-1 V-10 and V-9 weld boat samples as well analyses performed using the PLEDGE code that is capable of incorporating all of the important IGSCC variables. It should be noted that the NMP-1 boat sample evaluation provides clear evidence that the cracks are intergranular stress corrosion cracking, with a crack morphology, and pattern and degree of sensitization similar to that found in piping and in components that have been sensitized conventionally by the welding process. It also contained a surface cold work layer and thick oxides that are fully consistent with cracking that initiated early in the plant history, growing in depth over the early years of plant operation when the coolant conductivity was significantly higher.

The following conclusions can be drawn.

1. A revised bounding crack growth rate of 2.2 x 10^{-5} inches per hour can now be used in the fracture mechanics analysis of through wall crack growth that supports continued operation. The bounding growth rate is justified based on the boat sample findings and the operational water chemistry currently being adhered to during operation of NMP-1.
2. The currently available crack growth methodologies (references 2-4), using conservative estimates of stress intensity, water chemistry parameters and material condition, support the use of this bounding rate. In particular, this rate is the same as the bounding through wall rate proposed by the BWRVIP for use to disposition core internals and currently under review by the NRC.
3. The available field data and laboratory data on crack growth rates support the conservative nature of this bounding average rate of 2.2 x 10^{-5} in/hr.
4. Crack growth rate predictions made using the GE CR&D's comprehensive fundamental PLEDGE model and based on the actual operating conditions at NMP-1 predict that the crack growth rate will be bounded by 2.2 x 10^{-5} in/hr for bounding assumptions of stress intensity and conservative assumptions regarding degradation of the material by irradiation. This bounding rate does assume that NMP-1 will maintain an average conductivity below 0.19 μS/cm for the entire operating cycle.

5. The maximum allowable crack growth considering the operating period of 14,500 hours required to complete the NMP1 cycle 13 operating cycle is 3.65×10^{-5} in/hr based on the reference 1 fracture mechanics analysis. This represents a conservative margin of 1.6 to the BWRVIP-14 disposition rate of 2.2×10^{-5} in/hr.
6. The PLEDGE assessment which includes consideration of water chemistry species and irradiation effects predicts the expected average rate to be at or below 4.2×10^{-6} in/hr. This representative predicted rate is based on excellent water chemistry being maintained below a conductivity of 0.1 μS/cm with the total detrimental species (sulfate and chloride) held below 4 parts per billion(ppb) concentration. This rate is approximately a factor of 10 lower than the acceptable fracture mechanics analysis required crack growth rate. This translates directly into an equivalent factor of 10 conservative margin.

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Table 1: NMP-1 Cycle and Yearly Water Chemistry Conductivity Averages

Plant	Cycle	RW Cond		Plant	Year	RW Cond	Cl (ppb)	SO4 (ppb)
NMP1	1	0.432		NMP1	1969	0.453	36.25	
NMP1	2	0.525		NMP1	1970	0.340	32.92	
NMP1	3	0.591		NMP1	1971	0.446	30.18	
NMP1	4	0.445		NMP1	1972	0.522	28.18	
NMP1	5	0.291		NMP1	1973	0.466	38.16	
NMP1	6	0.225		NMP1	1974	0.656	62.72	
NMP1	7	0.181		NMP1	1975	0.522	52.24	
NMP1	8	0.133		NMP1	1976	0.433	44.53	
NMP1	9	0.087		NMP1	1977	0.263	31.62	
NMP1	10	0.082		NMP1	1978	0.290	32.48	
NMP1	11	0.079		NMP1	1979	0.193	31.56	
NMP1	12	0.092		NMP1	1980	0.261	25.97	
				NMP1	1981	0.225	26.72	
				NMP1	1982	0.198	25.18	
				NMP1	1983	0.149	24.81	
				NMP1	1984	0.138	24.62	
				NMP1	1985	0.127	24.44	
				NMP1	1986	0.100	25.44	
				NMP1	1987	0.084	12.85	
				NMP1	1988	0.086		
				NMP1	1989	0.079		
				NMP1	1990	0.081	1.01	
				NMP1	1991	0.079	1.02	
				NMP1	1992	0.094	1.08	1.20
				NMP1	1993	0.081	1.03	2.11
				NMP1	1994	0.079	0.69	1.52
				NMP1	1995	0.094	0.56	2.59
				NMP1	1996	0.089	0.57	2.98
				NMP1	1997	0.086	0.51	2.06

Table 2: Crack Growth Rate Calculations for NMP-1

These are calculations from PLEDGE and Irradiated PLEDGE for the following conditions with the rates given in micro-inches/hour (μ-in/hr):

A.

Neutron fluence: 1.5×10^{20} n/cm^2, 2.7×10^{20} n/cm^2 and 4.0×10^{20} n/cm^2.
Stress intensity: 10 & 20 ksi-in$^{1/2}$, also irradiation relaxed values.
Sensitization EPRo = 10.8 C/cm

	Initial K: PLEDGE	
	10 ksi-in$^{1/2}$	20 ksi-in$^{1/2}$
0.1 μS/cm	0.7 μin/hr	5.0 μin/hr
	1.7 μin/hr	11.1 μin/hr
	20.0 μin/hr	81.6 μin/hr
For 22 μ-in/hr		

	Initial K: PLEDGE	
	10 ksi-in$^{1/2}$	20 ksi-in$^{1/2}$
0.1 μS/cm	0.7 μin/hr	5.0 μin/hr
	1.7 μin/hr	11.1 μin/hr
	20.0 μin/hr	81.6 μin/hr
For 22 μ-in/hr		

	Initial K: PLEDGE	
	10 ksi-in$^{1/2}$	20 ksi-in$^{1/2}$
0.1 μS/cm	0.7 μin/hr	5.0 μin/hr
	1.7 μin/hr	11.1 μin/hr
	20.0 μin/hr	81.6 μin/hr
For 22 μ-in/hr		

Table 2 (cont.): Crack Growth Rate Calculations for NMP-1

These are calculations from PLEDGE and Irradiated PLEDGE for the following conditions with the rates given in micro-inches/hour (μ-in/hr):

B.

Neutron fluence: 1.5×10^{20} n/cm^2, 2.7×10^{20} n/cm^2 and 4.0×10^{20} n/cm^2
Stress intensity: 10 & 20 ksi-in$^{1/2}$,
Sensitization EPRo = 10.8 C/cm^2

	Initial K: PLEDGE	
	10 ksi-in$^{1/2}$	20 ksi-in$^{1/2}$
0.1 μS/cm	1.3 μin/hr	8.8 μin/hr
	3.2 μin/hr	18.3 μin/hr
	25.7 μin/hr	100 μin/hr
For 22 μ-in/hr		

	Initial K: PLEDGE	
	10 ksi-in$^{1/2}$	20 ksi-in$^{1/2}$
0.1 μS/cm	1.3 μin/hr	8.8 μin/hr
	3.2 μin/hr	18.3 μin/hr
	25.7 μin/hr	100 μin/hr
For 22 μ-in/hr		

	Initial K: PLEDGE	
	10 ksi-in$^{1/2}$	20 ksi-in$^{1/2}$
0.1 μS/cm	1.3 μin/hr	8.8 μin/hr
	3.2 μin/hr	18.3 μin/hr
	25.7 μin/hr	100 μin/hr
For 22 μ-in/hr		

Table 3: Expected Crack Growth Rates: Calculated using PLEDGE

A. Expected Crack Growth Rates for Unirradiated PLEDGE

Model Parameters: The calculation for growth rate for K = , +200 mV_{she}, 0.1 μS/cm with two EPRo assumptions: EPRo= 6 and 8:

EPRo = 6 C/cm^2	EPRo = 8 C/cm^2
1.2 μin/hr	2.0 μin/hr

B. Expected Crack Growth Rates for Irradiated PLEDGE

Model Parameters: The calculation for growth rate for K = , +200 mV_{she}, 0.1 μS/cm with two EPRo assumptions: EPRo= 6 and 8 with two fluences:

Fluence (nvt)	K (ksi-in$^{1/2}$)	EPRo = 6 C/cm^2	EPRo = 8 C/cm^2
1.5×10^{20} (mid- wall)		2.5 μin/hr	4.1 μin/hr
2.7×10^{20} (75% wall)		2.4 μin/hr	3.9 μin/hr
4.0×10^{20} (inside wall)		2.5 μin/hr	4.2 μin/hr

Figure 1: NMP-1 Daily Water Chemistry: Last Operating Cycle: Conductivity and Species vs. Cycle day

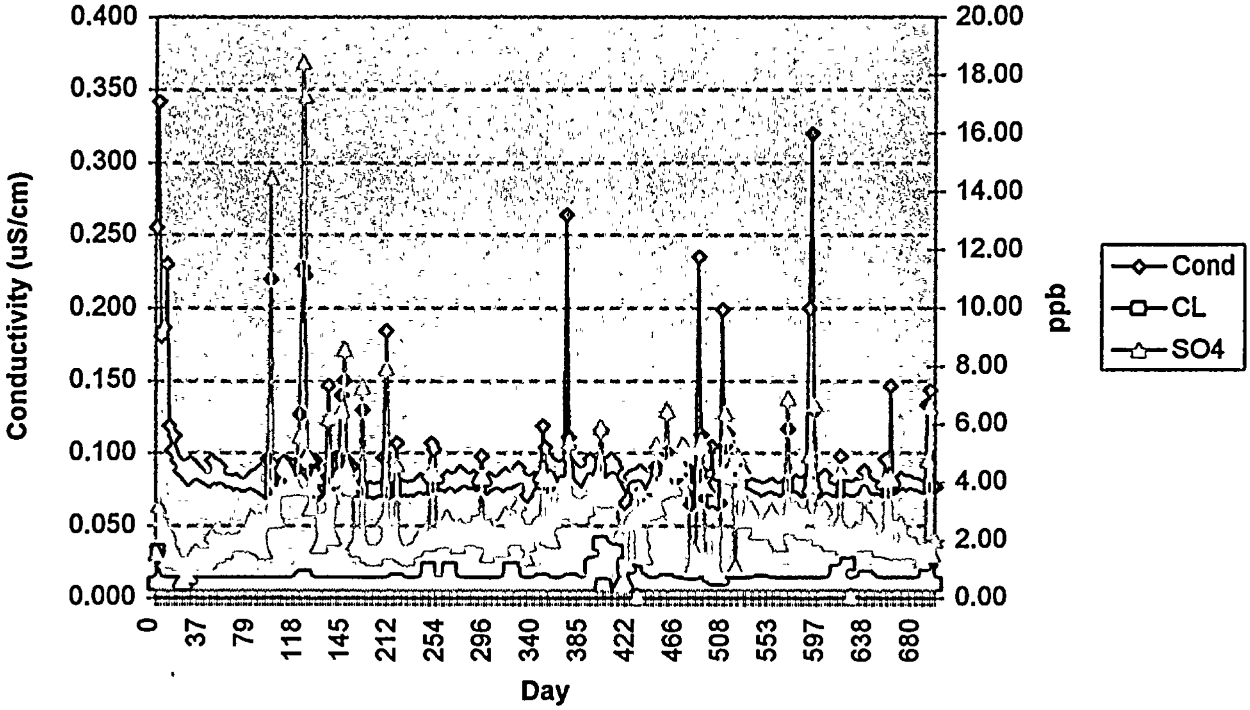

Figure 2: SKI Crack Growth Rate vs. Stress Intensity for Austenitic Stainless Steel in NWC