SAFETY ASSESSMENT ON THE ADVANCED FINITE ELEMENT ANALYSIS RELATED TO GROWTH OF POSTULATED PRIMARY WATER STRESS CORROSION CRACKING FLAWS IN PRESSURIZER NOZZLE DISSIMILAR METAL BUTT WELDS

1.0 Introduction

On October 13, 2006, the Wolf Creek Nuclear Operating Corporation performed pre-weld overlay inspections using ultrasonic testing (UT) techniques on the surge, spray, relief, and safety nozzle-to-safe end dissimilar metal and safe end-to-pipe stainless steel butt welds. The inspection identified five circumferential indications in the surge, relief, and safety nozzle-to-safe end dissimilar metal (DM) butt welds that the licensee attributed to primary water stress corrosion cracking (PWSCC) [1] and were significantly larger and more extensive than previously seen in the industry. During Refueling Outage 15 in October 2006, Wolf Creek completed its baseline pressurizer nozzle weld inspections and weld overlay repairs per industry guidance in MRP-139, “Primary System Piping Butt Weld Inspection and Evaluation Guidelines.” [2]

During public meetings with the industry on November 30, 2006, and December 20, 2006, the Nuclear Regulatory Commission (NRC) staff presented the results of a fracture mechanics based scoping study that assessed the safety significance of the UT indications found at Wolf Creek. As a result of these analyses, the staff concluded that there may be little or no time margin between the onset of leakage and rupture in pressurizer nozzle DM butt welds containing flaws similar to those found at Wolf Creek.

In March 2007 the NRC issued Confirmatory Action Letters (CALs) to licensees of 40 pressurized water reactor (PWR) nuclear power plants, confirming commitments from those licensees to resolve concerns regarding potential flaws in specific reactor coolant system (RCS) DM butt welds by the end of 2007. The remaining 29 PWR plants have either completed the requisite actions or do not have welds susceptible to these flaws.

Nine of the plants receiving CALs do not have outages scheduled in 2007. These plants committed to accelerate outages into 2007 if the industry was not able to demonstrate an adequate level of safety to the NRC. The nine plants are Braidwood 2, Comanche Peak 2, Diablo Canyon 2, Palo Verde 2, Seabrook, South Texas Project 1, V. C. Summer, Vogtle 1, and Waterford 3.

By letter dated February 14, 2007, the Nuclear Energy Institute (NEI) indicated that the Electric Power Research Institute Materials Reliability Program would be undertaking a task to refine the crack growth analyses pertaining to the Wolf Creek pressurizer DM weld ultrasonic indications. These additional analyses were performed to address the NRC staff’s concerns regarding the potential for rupture without prior evidence of leakage from circumferentially oriented PWSCC in pressurizer nozzle welds. The goal of these studies was to demonstrate that PWSCC in pressurizer DM butt welds will progress through-wall and exhibit detectable leakage prior to causing a possible rupture event, through reduction of conservatisms and uncertainties in previous analyses.

Industry completed these analyses and documented the results in MRP-216, Revision 1, “Advanced FEA Evaluation of Growth of Postulated Circumferential PWSCC Flaws in Pressurizer Nozzle Dissimilar Metal Welds: Evaluations Specific to Nine Subject Plants” [3].

These results were provided to the NRC staff by letter dated August 13, 2007. The NRC staff evaluation of this MRP report is contained in this safety assessment.

Enclosure 1 to this safety assessment (ML072470394) documents the NRC staff's confirmatory analyses performed by the NRC Office of Nuclear Regulatory Research, which provided extensive support to this review and evaluation effort. Enclosure 1 documents an extensive effort to evaluate the industry's analysis methodology and verify the acceptability of the results. The review and analyses documented in Enclosure 1 are referred to frequently in this safety assessment as the "NRC staff's analyses." Section 3 of this safety assessment contains a brief summary of the NRC staff's confirmatory analysis program.

2.0 Methodology and Analytical Assumptions

To assess the pressurizer nozzle integrity of the nine PWRs that had planned to perform PDI-qualified inspections or mitigations during their scheduled spring 2008 outages, the industry conducted fracture mechanics analyses using advanced finite element (FE) models and documented the entire effort in MRP-216, Revision 1. The industry's FE analysis will be referred to as the advanced FEA evaluation throughout this safety assessment. There are 51 pressurizer nozzles for the nine plants in the analysis, with different geometries, fabrication processes, and loadings. To explore the limiting geometry, residual stresses from fabrication, and piping loads for all 51 pressurizer nozzles and to model uncertainties in key parameters, the industry performed a sensitivity study with 119 analysis cases.

The advanced FEA evaluation maintains the approach used in the industry's 2006 December analysis [4] of allowing the flaw to grow through-wall and then circumferentially to rupture, as opposed to the ASME Code, Section XI, flaw evaluation rules for piping which do not permit flaws deeper than 75% of the pipe wall. However, the advanced FEA evaluation removed some conservatism which was embedded in the 2006 December analysis methodology. The industry made three improvements in the advanced FEA evaluation: (1) the scope was broadened from one plant (Wolf Creek) to nine plants, (2) the conservative semi-elliptical shape assumption for flaws was dropped so that the progressing surface flaw can take any shape determined by the analysis, and (3) the residual stresses were from pressurizer nozzle-specific FE modeling instead of from a previous generic study and the ASME Code. It should be noted that due to improvement (1), the flaws considered in the advanced FEA evaluation are now postulated rather than from inspection results because inspections of these nozzles have not been performed and it is not known whether flaws actually exist in any of the 51 pressurizer nozzles. The flaws detected in the Wolf Creek pressurizer nozzles are reference points to make more informed flaw size assumptions in the advanced FEA evaluation. Also, due to improvement (2), a new set of stress intensity factor (K) solutions were developed by the industry because the applied K solutions available in the literature for elliptical surface flaws in cylinders were no longer applicable. Determination of the applied K for a growing flaw is an essential part of the advanced FEA evaluation, because the PWSCC flaw growth rate is a function of the applied K. Determination of residual stresses across the DM weld is also an essential part of the advanced FEA evaluation, because the residual stresses contribute the most to the applied K and the subsequent flaw growth under PWSCC. The fracture mechanics modeling with the improvements discussed above results in more realistic crack geometry and growth, and the results produced conditions more representative of operating experience than previous models.

Improvement (2) required significant software development. Therefore, the advanced FEA evaluation was separated into two phases: a Phase-I effort was conducted to establish the feasibility of using these uniquely developed crack growth codes by re-analyzing the critical case from the NRC staff's scoping analysis [5]; the Phase-II effort was conducted to assess the pressurizer nozzle integrity of the nine PWRs through 119 sensitivity cases by varying nozzle specific loads, dimensions, geometries, weld residual stresses, PWSCC crack growth rates, initial flaw assumptions, etc. Since the Phase-I effort was initiated as a feasibility study prior to initiating a Phase-II effort, this safety assessment focuses on the Phase-II results. For additional information regarding the Phase-I effort, see Enclosure 1, Section 5.1. The fracture mechanics modeling for the applied K determination and the weld residual stress modeling are discussed in details in Sections 2.1 through 5.2.3 of this safety assessment.

As part of the NRC staff's review of the advanced FEA, the NRC staff considered the significance of the additional loading that could result from a seismic event. Because the duration of a seismic event is short, it will not produce any appreciable flaw extension unless a large flaw is preexisting at the time of the seismic event. The combination of a flaw growing to a large size in a pressurizer nozzle weld occurring at the same time as an earthquake was considered to be a very unlikely event. The NRC staff also reviewed the increase in loading that would result from a safe shutdown earthquake. As discussed below, the surge nozzle welds bound the safety/relief and spray nozzle welds from the point of view of available margin. The limiting surge nozzle weld loading under a seismic event represents an increase of only about 16% over the normal loading on the limiting surge nozzle weld. This increase is relatively small considering the margins specified by the NRC staff to address uncertainties. For these reasons, seismic loading was not considered in the advanced FEA calculations.

2.1 Fracture Mechanics Modeling

2.1.1 Stress Intensity Factor (K) and the K-Based Crack Growth

The industry used three-dimensional, one quarter (two planes of symmetry) FE models to obtain the applied K. The industry's basic element for the FE model was the 8-node brick element, with collapsed-front crack-tip nodes. External forces were applied as pressures at the axial end of the model. External moments were applied as a pressure gradient. These external loads included dead weight, pressure, and normal thermal expansion loads. The through-wall residual stress distribution was applied to the FE model using differential thermal expansion between axial layers of nozzle elements so that the FE method-based residual stresses, which are discussed in Section 2.2 of this safety assessment, were developed at the DM weld location and diminished at locations away from the DM weld. For sensitivity cases with no weld repair, the residual stresses were applied to the FE model axisymmetrically.

Using the FE model described above, the industry obtained the applied K value from the calculated strain energy values readily available from the FEA output file. In this conversion, a plane strain equation for Mode I loading (cleavage) was used. Since the advanced FEA evaluation removed the constraint of the elliptical flaw assumption for the progressing flaws, the applied K values were calculated along the entire crack front. Based on these calculated applied K values for each intermediate crack shape, the crack growth at selected points along the crack front was calculated by post-processing software, and a new mesh for the next crack shape is generated automatically for the next step in the FEA.

The industry's indirect determination of applied K and PWSCC crack growth are consistent with the plant-specific and generic flaw evaluations for various piping, reactor pressure vessel penetrations, and pressurizer penetration nozzles that the NRC staff has reviewed and accepted in the past. Using differential thermal expansion so that the FE method-based residual stresses are developed at the DM weld location and diminish at locations away from the DM weld has not been discussed in previous NRC staff safety evaluations (SEs) on flaw evaluation of similar components. The NRC staff concludes that this assumption makes sense based on engineering experience with the attenuation of stress in other applications.

The Phase-II analyses involved a series of progressing cracks with arbitrary shapes whose applied K solutions were newly derived. Industry and NRC staff independently calculated applied K for the same semi-elliptical surface cracks and hypothetical crack shapes to verify similar results were being obtained and to ensure that the applied K solutions for the sensitivity cases were valid. The industry described the K verification process for hypothetical crack shapes in MRP-216, Revision 1, Section 4.5. This process is further discussed in Enclosure 1 Sections 3.2.1 and 3.2.2. The reasons for choosing the semi-elliptical surface cracks are that their shapes are analytically defined and a third source [6] is available for comparison. Although different fracture mechanics, post-processing software, and slightly different mathematical representations of the same residual stresses were used by the industry and the NRC staff, the comparison of their applied K solutions for all crack shapes selected for this verification is good, demonstrating that the industry and NRC staff are likely to generate reasonably close applied K solutions for the progressing cracks of an arbitrary shape and, subsequently, reasonably close crack growth calculations in their sensitivity cases. It should be noted that the hypothetical crack shapes selected encompassed the anticipated crack shapes for the sensitivity cases. Further, the crack growth calculations were sensitive to the refinement of growth steps. The industry performed a convergence study by using twice the normal step refinement and confirmed that the difference was insignificant. The NRC staff concurs with the finding.

The industry used the MRP-115 [7] crack growth rate to calculate the PWSCC crack growth as a function of K as the crack continued to grow through-wall. This rate was developed using a series of laboratory sized specimens under well controlled conditions, and represents a 75th percentile of the rates from the DM weld data considered. Consequently, there is uncertainty associated with this statistically determined rate.

Industry ran Cases 42-47 to study the effect of varying the crack growth rate in the calculations. Varying the crack growth rate from one case to another changes the time between leak and rupture but has little effect on crack shape. The limiting case, Case 42c is discussed in Section 5.2.2 of this safety assessment.

Uncertainties associated with use of the MRP-115 crack growth rate are summarized in Enclosure 1, Section 6.3.3. Since the MRP-115 crack growth rate has not been validated by field data, the staff takes a position similar to that taken previously on industry's use of the MRP-55 [8] crack growth rate for alloy 600 penetrations [9,10]. Specifically, the NRC staff will reassess any conclusions if the NRC staff becomes aware of data that significantly change the crack-growth formula in MRP-115.

2.1.2 Crack Stability Analysis

The industry's crack stability analysis was based on the net section collapse (NSC) equations for a complex-shaped crack in a thin-wall pipe. A complex-shaped crack is a crack with a portion that is only open to the inside surface and a portion that is open to both the inside and outside surfaces of the weld. Complex-shaped cracks are illustrated in MRP-216, Revision 1,

Figure 7-17. A correction factor known as a Z-factor was applied in the crack stability analysis to account for the possibility of an elastic-plastic fracture mechanics (EPFM) failure mode. The room-temperature certified material test report (CMTR) material properties used in the stability analysis were adjusted for the nozzle operating temperature of 650°F. Further, for each nozzle, the contributions to the loading from dead weight, pressure, and thermal expansion were combined; the three components of force were summed algebraically, and the three moment components were combined as vectors into an effective moment. When a crack grows past the cracked section's neutral axis, the industry's approach assumed that the crack will not take compressive loads.

The industry's NSC analysis using a Z-factor bounds both the fully plastic failure mode and the EPFM failure mode. The Z-factor based on Reference 11 was developed for stainless steel piping, not for piping with DM welds. Appropriate test data on DM welds would be needed to support a clear determination on whether inclusion of the Z-factor is necessary for NSC analysis of DM welds. However, because of the lack of test data, the NRC staff determined that use of the Z-factor from stainless steel piping in the current advanced FEA evaluation was necessary to address NRC staff concerns regarding calculation of load carrying capability in a cracked weld [12].

The use of the thin-wall equilibrium equation in the NSC analysis is supported by Reference 13, and the treatment of material properties and load combinations is consistent with the scoping analysis approach by both the NRC staff [5] and industry [4]. Finally, assuming that the crack will not take compressive loads when it grows past the section's neutral axis is conservative because absence of the additional compressive loads will lower the NSC loads. In other words, this assumption results in a decrease in the calculated load carrying capacity of the crack.

The industry's NSC results were verified by using software independently developed by another commercial organization, as discussed in MRP-216, Revision 1, Section 5.5. These steps offer assurance that the crack stability analysis using the NSC analysis for piping DM welds with complex-shape cracks was properly implemented. The critical flaw size from the stability analysis is used in calculating the time for a crack to grow from passing a detectable level of leakage until the critical flaw size is reached. This is discussed below.

Although the industry's and the NRC's fracture mechanic methodologies and analytical assumptions are similar and reasonably sound, there were some uncertainties in the analyses which were not fully accounted for because of lack of certain relevant experimental data. These are discussed in Enclosure 1. Due to these considerations, the NRC indicated in Reference 14 that adequate safety factors would need to be considered in the advanced FEA. In this safety assessment, safety factors and margin are used interchangeably.

2.2 Weld Residual Stress Modeling

The residual stresses for various pressurizer nozzles are used for crack growth calculations before leakage occurs and for calculation of the time margin between the onset of leakage and final rupture.

The industry used two-dimensional, axisymmetric FE models to perform the welding residual stress analysis. The low alloy steel nozzle, Alloy 82/182 butter and nozzle-to-safe end DM weld, stainless steel safe-end, and safe end-to-pipe stainless steel butt weld were all modeled in the FE analysis. The welding operation was simulated, alternating between thermal and structural analyses. The resulting welding was then subjected to weld repair if applicable, hydrostatic testing, and operating conditions to arrive at the DM weld residual stress distribution to be used in the applied K calculations discussed in Section 2.1 of this safety assessment. The industry's residual stress FE modeling for the pressurizer nozzle DM weld was consistent with, or more refined than the industry's prior residual stress FE modeling for the CRDM and incore instrumentation nozzle to vessel welds which were reviewed and accepted by the NRC in 2003 [9, 10]. Therefore, the industry's residual stress FE modeling for the pressurizer nozzle DM weld is also acceptable to the NRC. MRP-216, Revision 1, Figure 3-6 indicates that the DM weld of the surge nozzle was modeled by 12 layers; an inside diameter fill-in weld was modeled by 4 layers, and the associated stainless steel weld was modeled by 10 layers. However, unlike the CRDM and incore instrumentation nozzles, the pressurizer nozzles are part of some extensive piping systems and present additional modeling challenges in predicting residual stresses through the use of the FE method. As explained in Section 4.4 of Enclosure 1, the industry's and the NRC staff's independently derived residual stresses from the FE models without the stainless steel safe-end weld were similar, while moderate discrepancies exist between industry's and the NRC's residual stresses from the FE models with the stainless steel safe-end weld. It is suggested in Enclosure 1 that these discrepancies are due to the fact that NRC staff's analysis considered the compliance or flexibility of the piping system beyond the safe end of the nozzles while the industry did not. This discrepancy in residual stresses for nozzles with the stainless steel safe-end weld has no impact on the staff's evaluation for safety/relief and spray nozzles because the calculations using these FE-based residual stresses, whether the NRC staff's or the industry's calculations, led to crack arrest. For the safety/relief and spray nozzles, the ASME Code-based residual stresses used in the NRC scoping study [5] had to be assumed in order for the analysis to cause a simulated crack to grow through-wall. For surge nozzles, the differences in the industry and NRC staff's generated residual stresses affect the results somewhat, as indicated in Table 8 of Enclosure 1, but they are in reasonable agreement. This point is discussed further in Section 5.2 of this safety assessment.

Furthermore, the industry's overall pressurizer nozzle DM weld modeling adequacy for generating residual stresses was confirmed by the general agreement between the industry's axial stresses along the butter layer centerline and those calculated by other organizations as published in a paper by the European Commission Joint Research Center's (JRC) Institute for Research [15] . Although the JRC's stainless steel welded joint mockup is simpler than the pressurizer nozzle Alloy 182 DM weld with a stainless steel welded safe end, this comparison shows that the industry's FE modeling technique is at the same level of other organizations having the capability to predict residual stresses of a welded joint using FE modeling.

The NRC also performed similar calculations as part of this validation exercise with JRC data. This validation exercise was performed to better understand the uncertainties in weld residual stresses. The results of all of the weld residual stress calculations and the measured weld residual stress values are shown in Appendix A of Enclosure 1. A general agreement on residual stresses is again observed among all participants. This adds additional credibility to the residual stresses calculated by the industry and the NRC staff for the current application. However, it is evident that there are sizable differences in weld residual stress between the FE calculations and the measured results. These differences are also shown in Figure 3-27 of MRP-216, Revision 1 and are addressed in Section 5.2 of this safety assessment.

2.3 Leak Rate Modeling

The industry used the PICEP computer code [16] to perform the leak-rate calculations required in the advanced FEA evaluation. The PICEP code is based on the Henry-Fauske two-phase fluid model, which allows for non-equilibrium vapor generation as the fluid flows through the crack. PICEP has been used previously by licensees in their leak-before-break (LBB) applications. Unlike a typical LBB application where both crack-opening displacement (COD) and the leak rate were generated by PICEP, the advanced FEA evaluation generated CODs from various sensitivity cases and used them as inputs to PICEP to predict their leak rates. The industry report states that the PWSCC crack morphology parameters which were used in the leak-rate calculations were determined considering recent information regarding PWSCC developed under NRC staff sponsorship [17].

As part of leak-rate calculation verification, the industry used the Wolf Creek relief nozzle geometry and loading as a study case and performed leak-rate calculations for cracks ranging from 1 to 10 inches to compare the results from using PICEP with those from using the NRC sponsored code SQUIRT [18]. The verification study results show that the leak rates from using SQUIRT are 1% to 30% greater than the rates from using PICEP.

Although the industry report indicated that their PWSCC crack morphology parameters considered the recent NRC information in Reference 17, it did not clearly establish the equivalence of the industry's crack morphology parameters to those recommended in Reference 17. The NRC confirmatory study in Enclosure 1 used the SQUIRT code and the Reference 17 PWSCC crack morphology parameters. However, since both PICEP and SQUIRT are based on the Henry-Fauske two-phase fluid model, the discrepancy in calculated leak rates from the two codes is likely to result from reducing the set of more sophisticated crack morphology parameters for SQUIRT to an equivalent set for PICEP, other parameters such as the entrance loss coefficient, and those which define the changing crack area along the leakage path. To evaluate the impact on the leak-rate calculations due to each of these parameters is outside the scope of this evaluation. Nevertheless, the industry's leak rates were based on the results from PICEP which are lower than those from the NRC sponsored code SQUIRT. These lower leak rates are more conservative because they present more challenge to a plant's leak detection capability. Therefore, the NRC staff considered use of PICEP acceptable.

Compared with the fracture mechanics analysis using the FE method, the leakage analysis is not as accurate. As a result, a larger safety factor is usually used in the leakage estimation to account for the uncertainties associated with the non-equilibrium vapor generation, the flow path losses, the friction factors for tight cracks, and the potential for particulate plugging. Section 5.1 of this safety assessment discusses the appropriate safety factors to be applied to the fracture mechanics analysis and the leakage analysis.

3.0 The NRC Confirmatory Study

In response to the February 14, 2007 letter from NEI [19] that contained industry's proposal to conduct an advanced finite element analysis project, the NRC responded with a letter [14] on March 5, 2007, accepting industry's proposal to proceed with the project and provided a set of comments that identified key areas of regulatory interest that needed to be addressed. These key areas were addressed in subsequent interactions with industry during the implementation of industry's project plan. The NRC staff also provided a technical basis document [20] to industry to support its comments of March 5, 2007, on certain aspects of the calculation methodology.

NRC staff comments on the calculation methodology and the key areas of regulatory interest were discussed in numerous category 2 public meetings with industry's advanced FEA expert panel and resolved over the time period of this project [22-28]. Specifically, the NRC staff reached agreement with industry on the input data, modeling methodology and assumptions, matrix of sensitivity cases, and conduct of the actual calculations.

As an essential part of the NRC staff's review of the advanced FEA, the NRC staff established a large and essentially real time confirmatory study to review, benchmark, and verify the industry's advanced FEA results and the quality of their analyses. As such, the NRC independently developed an advanced FEA computer based model similar in approach to the industry's version which removed the semi-elliptical flaw constraint found in typical ASME Code, Section XI flaw evaluation procedures. The NRC staff used its independent computer codes to conduct its own calculations. The NRC staff benchmarked the industry sensitivity matrix cases using similar nozzle-specific geometries, operating loads, stress intensity factor (K) solutions, initial flaw assumptions, weld residual stress profiles, sub-critical crack growth analysis, critical crack size calculations, and leak rate models.

The industry evaluated 119 sensitivity cases in their advanced FEA project by systematically varying multiple model input parameters. The NRC confirmatory program evaluated a subset of cases that focused on a few representative and several limiting cases using realistic and conservative assumptions, respectively. In total, the NRC evaluated 31 sensitivity cases with 16 cases directly related to particular industry examined sensitivity cases and corresponding input parameters. Specifically, the NRC program confirmed 7 safety/relief, 3 spray, and 5 surge nozzle cases from the industry's sensitivity matrix. The remaining 16 cases were not directly addressed in the industry matrix and were examined to address uncertainties in the modeling methodologies and the sensitivity of the results to multiple input conservatisms.

In general, the results from this NRC study confirm the industry's advanced FEA results and trends. The specific results, however, were slightly different between the NRC and industry analyses as would be expected from separately and independently developed models. The NRC advanced FEA program also confirmed that the semi-elliptical crack shape assumption is a major conservatism in typical ASME Section XI flaw evaluation procedures in component integrity calculations of PWSCC flaws in service.

4.0 Sensitivity Matrix

The industry developed a sensitivity matrix of 119 cases to assess the sensitivity of specific input parameters on the mechanical behavior of the nozzle-to-safe end DM weld. The parameters that were considered in the sensitivity matrix include weld residual stress profile, nozzle dimensions and geometry, initial crack shape, initial crack dimensions, operational loads, PWSCC crack growth rates, and the effects of plastic redistribution of forces. Safety/relief, spray, and surge nozzles are all addressed in the sensitivity cases. Separately, the NRC staff performed its independent evaluation on 31 cases to either validate the results by industry or to further evaluate the effects of certain parameters on the results.

The sensitivity study shows that the results are highly dependent upon the assumptions of the DM weld residual stress profile and the initially assumed flaw characteristics, with the results being most sensitive to changes in the DM weld residual stress profile. In turn, the DM weld residual stress profile was shown to be strongly dependent on the modeling of the field weld connecting the safe end to the stainless steel piping. The sensitivity cases demonstrate that an inner diameter (ID) repair would create high local tensile stresses, which cause a postulated crack to grow faster radially than circumferentially in the vicinity of the repair and eventually cause this flaw to grow through-wall around the location of the repair. As a result, leakage will occur before rupture of the pipe at the DM weld. Outer diameter (OD) repairs were not included in the sensitivity cases because, except for a deep OD repair about 75 percent of the wall thickness, they would create compressive stresses on the ID, i.e., a benign weld residual stress case for pipe rupture.

The 119 sensitivity cases contain 10 cases (designated as S-series cases) designed specifically to further study the effect of having multiple initial flaws in the surge nozzle welds. The S-series cases model the combination of three initial flaws or use the conservative assumption of an initial 360° 10% deep flaw and, except for two cases, do not model the effect of the field weld connecting the safe end to the piping. The effect of the field weld connecting the safe end to the piping is to add compressive stresses near the ID of the DM weld which beneficially retards crack initiation and/or growth. For plants with the stainless steel safe end weld located near the DM weld, modeling the analysis with and without the safe end weld was performed to address the differences between FE calculations and measured weld residual stresses, discussed in Section 2.2 above.

The industry's advanced FEA evaluation results are presented in MRP-216, Revision 1, Tables 7-4 to 7-6, and the staff's results from confirmatory analyses are presented in Enclosure 1, Table 7. A comparison of the industry's and the NRC staff's results can be found in Enclosure 1, Table 8.

Some general observations are as follows. One observation from Enclosure 1, Table 8 is that, in general, the industry's results are more conservative before the postulated crack becomes through-wall (designated as Stage 1) and produces a calculated leakage rate of 1 gpm (designated as Stage 2) while the NRC's results are more conservative from the 1 gpm leaking flaw to the critical crack length where unstable crack growth occurs (designated as Stage 3). Enclosure 1, Section 5.3.1 attributes this observation to the NRC staff's assumptions between first leakage to a 1 gpm leak rate size (Enclosure 1 Figure 58), which is caused, possibly, by the NRC staff's higher K values during the stages 2 and 3 crack growth.

Another observation from MRP-216, Revision 1, Tables 7-4 to 7-6, and Enclosure 1, Table 8, is that the NRC staff's and the industry's results (regardless of their differences) for the safety/relief and spray nozzles show much higher stability margins than those of the surge nozzles. MRP-216, Revision 1, Tables 7-4 to 7-6 indicate that the lowest stability margin for the safety/relief and spray nozzles at a leak rate of 1 gpm or higher is 1.57 (Case 42c) while the lowest stability margin for the surge nozzles at a leak rate of 1 gpm or higher is 1.03 (Case S1b). The NRC performed additional cases that were derived from Case 6c and Case S1b to further study these critical cases. Not surprisingly, some of the additional cases derived from Case S1b also show similar low margin results, as indicated in Enclosure 1, Table 7. Cases 42c and S1b will be examined in detail in Section 5.2 of this safety assessment.

From the NRC confirmatory analyses (Enclosure 1, Table 7) it can be observed that inclusion of the field weld connecting the safe end to the piping in the FE model has a large impact on the overall weld residual stress profile and, hence, the final results. Case S1b does not consider this field weld. As a result, some of the additional cases based on Case S1b and run by the NRC staff consider it. The Case S1b-based additional cases considering the field weld have either a margin about 1.5 at 1 gpm leak or a crack arrest. Since the effect of the field weld connecting the safe end to the piping is so significant, this was investigated further. The industry's and the NRC staff's residual stresses resulting from modeling the effect of the field weld connecting the safe end to the piping are different. Enclosure 1, Figure 52 shows that the NRC staff's and the industry's residual stresses at the inner diameter (ID) of the weld with the stainless steel safe end vary between -18 to +33 ksi. To investigate this, the NRC staff modified its residual stress for Case 17-6 by increasing the residual stress at the inner surface by 28 ksi to +10 ksi at the ID of the weld. This modified case is Case 17-7. Both Case 17-6 and Case 17-7 were analyzed with the stainless steel safe end to piping weld included and considered bounding loads for the surge nozzles. The results of both cases indicate that a postulated initial 360° 10% deep crack will arrest.

From a review of MRP-216, Revision 1, Section 2 and Appendix A, it can be observed that the fabrication practices for all nozzles falls under one of two categories identified as back-welded or machined. All the nozzles at a given plant fall into one category or the other. Plants A, B, C, F, and G had the back-welded fabrication, and plants D, E, H, and I were machined. The back-weld fabrication process consisted of a back-chipping process where the initial weld root pass was removed and the weld finished from the ID. The welding from the ID produced both tensile axial and hoop weld residual stresses on the ID with the axial stresses potentially promoting circumferential cracks. The weld residual stresses developed from ID welding were then shown to be somewhat mitigated by the safe end to piping stainless steel weld because of the proximity between the DM weld and stainless steel weld. In contrast, the machining step in the fabrication process reduced the residual stresses in the inside region of the weld. Cases 8, 9, 15, 16, 19, 20 and S8 were performed to address the machined category of plants. From a review of the results of these cases it can be seen that the analyses led to either arrest or high stability margins. Also, the results of the analyses of the back-weld category bound the results of the plants analyzed with machined nozzles.

5.0 Assessment of Results

5.1 Safety Factors and Acceptance Criteria

Developing appropriate safety factors and acceptance criteria for this advanced FEA evaluation for a limited-time consideration (approximately 6 additional months) was a first of a kind experience. The established safety factors and acceptance criteria in the ASME Code Section XI, Appendix C for piping flaw evaluation are for detected flaws (as opposed to postulated flaws) which are limited by Section XI requirements to grow to only 75% of the pipe wall. Therefore, they are not applicable to the advanced FEA evaluation for pressurizer nozzles which examines flaw growth until nozzle rupture occurs. However, there are established safety factors and acceptance criteria for fracture mechanics evaluations of certain nuclear components with postulated flaws, and insight can be gained by examining these evaluation processes. Three such cases are available: ASME Code Section XI, Appendix G for postulated flaws in reactor vessels under normal and upset conditions, ASME Code Section XI, Appendix K when the reactor vessel metal temperature is in the upper-shelf range, and Standard Review Plan (SRP) Section 3.6.3 leak-before-break (LBB) evaluation of postulated flaws in piping.

The Appendix G methodology, which is based on linear elastic fracture mechanics (LEFM), used a safety factor of 2 for pressure induced K (or stresses) and 1 for the thermal K, giving an average safety factor of 1.5 when equal weight is applied to these two sources of stress. Appendix G concerns only normal and upset loading conditions and recommends that emergency and faulted loading conditions be considered on an individual case basis. The Appendix K methodology, which is based on EPFM, used a safety factor for crack initiation of 1.15 for pressure loading and 1 for the thermal loading and used a safety factor for crack extension of 1.25 for pressure loading and 1 for the thermal loading under normal and upset loading conditions. The SRP 3.6.3 LBB evaluation, which is based on limit load analysis considering the Z-factor (discussed in Section 2.1.2 above), uses a safety factor of 1.4 on loads if they are summed algebraically, a safety factor of 2.0 on flaw size, and a safety factor of 10 on leakage. Unlike the Appendix G methodology, the SRP 3.6.3 LBB evaluation concerns only emergency and faulted loading conditions. It should be noted that in SRP 3.6.3, these safety factors are referred to as margin on load, margin on flaw size, and margin on leakage. If the leakage evaluation and the flaw evaluation in the SRP 3.6.3 LBB evaluation are treated as separate issues, then the two safety factors related to the flaw evaluation (1.4 on loads and 2.0 on flaw size) can be combined into a single safety factor on loads, or load safety factor based on fracture mechanics principles by multiplying the margin on load by the square root of the margin on flaw size, i.e., $1.4 \times \sqrt{2}$ or 2. After application of safety factors, the acceptance criterion for the Appendix G, Appendix K, and LBB applications can be expressed as:

the postulated flaw size < the critical flaw size

In the SRP 3.6.3 LBB evaluation, the postulated flaw size is the leakage flaw size based on a safety factor on leakage, or leakage safety factor, of 10. The SRP 3.6.3 LBB evaluation is far more conservative than the other two approaches. This is appropriate because the SRP 3.6.3 LBB flaw evaluation is a flaw tolerance evaluation based on an idealized through-wall flaw which spans an arc between two crack fronts that extend radially from ID to OD, and, therefore, requires large safety factors to cover uncertainties caused by this idealization. Also, NRC staff approval of an LBB application is for the life of the plant. The advanced FEA evaluation applies to a condition for a limited time where the leakage flaw and the critical flaw are of a complex-shape. The flaws in the advanced FEA are based on representative and conservatively postulated initial flaws. Based on these considerations, the NRC determined that using a load safety factor of 1.5 similar to the Appendix G approach in the current application is appropriate. Although both the Appendix K and the advanced FEA evaluation are based on EPFM, the staff did not adopt the Appendix K safety factors for this safety assessment because they are too low to be considered appropriate for an evaluation having many new aspects of methodology development.

For the leakage safety factor, the NRC staff reexamined the calculated and measured leakage rates published in the PICEP code document [16] and the SQUIRT code document [21]. The NRC staff concluded from a review of the data that when the calculated leakage rate is about 1 gpm, the corresponding measured value is bounded by 0.5 gpm. This suggests a leakage safety factor of 2. Considering additional margin that is needed to cover the difference between the well-controlled laboratory leakage measurements and the plant leakage measurements and the uncertainty regarding PWSCC morphology parameters, the NRC believes that use of a leakage safety factor of 5 for this application is appropriate.

In summary, the NRC determined that using a load safety factor of 1.5 and a leakage safety factor of 5 in the advanced FEA evaluation is appropriate. In the following sections of this safety assessment they are referred to as “the safety factors specified by the NRC staff.” The safety factors specified by the NRC staff are used to cover uncertainties in (1) the fracture mechanics methodology and analytical assumptions mentioned in Section 2.1.2 of this safety assessment, (2) residual stresses caused by FE modeling differences, and (3) leakage calculations. This covers the range of uncertainties discussed in Enclosure 1. However, like any flaw evaluation analysis, this set of safety factors is intended for a deterministic evaluation with assumptions that are not highly biased. Applying them strictly to all 119 sensitivity cases may be inappropriate because some of the sensitivity cases are based on multiple coinciding conservative assumptions which result in a bias in the unfavorable direction. Such cases were included in the sensitivity study to explore the sensitivity of the results to these assumptions. It should be noted that for a typical probabilistic fracture mechanics (PFM) analysis, the worst cases are determined by a Monte-Carlo simulation considering a combination of many randomly chosen parameters with no safety factors applied.

5.2 Evaluation of Results

5.2.1 Baseline Cases for All Nozzles

The industry's advanced FEA evaluation results are presented in MRP-216, Revision 1, Tables 7-4 to 7-6. These results are also presented graphically in Figures 7-18 to 7-21. Some of the limiting sensitivity cases are further illustrated in Figures 7-22 to 7-41, which plot the load safety factor (i.e., the stability margin) and the leak rate associated with an advancing complex-shaped crack as a function of time from first evidence of leakage to rupture. It was mentioned in Section 5.1 of this safety assessment that the safety factors specified by the NRC are intended to be applied to those advanced FEA sensitivity cases which are not highly biased. Sensitivity Cases 1 to 20 fit this category because these cases merely cover the design dimensions for each of the design configurations provided by Westinghouse and cover the range of applied membrane and bending loads for each geometry. They can be considered as baseline cases because all the remaining sensitivity cases are derived from them. Although the assumptions on the initial flaw shapes, i.e., a 360° 10% depth flaw and a 21:1 aspect ratio 26% deep surface flaw may be conservative, MRP-216, Revision 1, Table 7-5 show that all 20 sensitivity cases meet the safety factors specified by the NRC for the advanced FEA evaluation. In MRP-216, Revision 1, Table 7-5, the "Stability Margin Factor" has the same meaning as the load safety factor used in this safety assessment, and a "Leak Rate" of 1 gpm is equivalent to a leakage safety factor of 4. This is because the CALs require plant shutdown if reactor coolant system unidentified leakage increases above approximately 0.25 gpm. The NRC staff examined MRP-216, Revision 1, Figure 7-22 (Case 6c), the worst case among the 20 baseline sensitivity cases, and verified that at the time when the progressing crack meets the load safety factor of 1.5, the corresponding leakage is 2 gpm, meeting the leakage safety factor of 5. For this case, the calculated plant response time (between 1.25 gpm to 2 gpm) is approximately 16 days, which is more than adequate time for the plant to take actions.

5.2.2 Limiting Cases for Safety/Relief and Spray Nozzles

One important observation from MRP-216, Revision 1, Table 7-1 is that for the sensitivity cases regarding the safety/relief nozzles where the weld residual stresses were derived from nozzle-specific thermal-structural FE analysis without weld repairs, crack arrest occurred in all cases. With the FE calculated weld residual stresses, the industry had to assume ID repairs to make the crack (Cases 21a to 24a) grow through-wall. As a result, the industry applied the more conservative modified ASME Code residual stresses to all sensitivity cases for safety/relief nozzles, including the baseline cases discussed above, so that the postulated crack would grow to leakage and rupture. The NRC staff found the industry's use of the modified ASME Code residual stresses in the sensitivity cases for safety/relief nozzles to be very conservative because the modified ASME Code residual stresses have a deeper tensile region near the ID than the residual stresses calculated by FEA. Further discussion on this conservatism is given below.

In Section 2.2 of this safety assessment, the NRC staff mentioned the need to consider the sizable discrepancy between the residual stresses based on FE calculations and the measured results. The industry's report did not address this specifically. The NRC staff considers the industry's use of the Code residual stresses a conservative way to address this discrepancy. This staff determination is based on the MRP-216, Revision 1, Figure 3-18 comparison of the Code residual stresses with those from the FE thermal-structural analyses using plant-specific pressurizer nozzle welding and fabrication records. MRP-216, Revision 1, Figure 3-18 showed that the FE-based residual stresses have a much higher compressive portion in a much larger compressive zone, extending approximately from 10% to 60% of the pipe wall, which is why all the sensitivity cases for safety/relief nozzles using the FE-based residual stresses (except for those with ID repairs) result in crack arrest.

The safety/relief nozzle analyses bound the spray nozzle analyses. The safety/relief nozzle analysis with the lowest margin is Case 42c, which showed a load safety factor of 1.57 at 1 gpm. The plot for this case of load safety factor and the leak rate as a function of time after first leakage is shown in MRP-216, Revision 1, Figure 7-32. This figure shows that the safety factors specified by the NRC staff are maintained at a leakage of 1.25 gpm, but the load safety factor of 1.5 would not be met beyond this point of time. As stated in Section 5.1 of this safety assessment, the NRC staff considers it inappropriate to apply the safety factors specified by the NRC to all sensitivity cases because some sensitivity cases are highly biased with multiple conservatisms to explore the combined sensitivity of the results to these assumptions. Case 42c was designed by the industry to explore the effect of changing the MRP-115 crack growth equation. The effect of this change to the crack growth equation is a factor of 10 increase in the MRP-115 crack growth rate. The staff considers this case highly unlikely. Because of the multiple conservative assumptions in Case 42c, it is appropriate to allow the progressing crack to grow to a size corresponding to a slightly lower load safety factor. By doing so, the calculated plant response time would be adequate for the plant to take actions.

In summary, based on the NRC staff's evaluation of MRP-216, Revision 1, and on the NRC staff's confirmatory analyses, the NRC staff determined that the analyses for the nine pressurizer safety/relief and spray nozzle DM welds demonstrate an adequate level of safety for operation beyond December 31, 2007. The NRC staff does not believe that the pressurizer safety/relief and spray nozzle welds are seriously degraded; however, if a PWSCC flaw were to initiate and grow in one of these nozzle DM welds before the Spring 2008 refueling outages, there is reasonable assurance that detectable leakage would occur and that adequate time would be available to safely shutdown the plant prior to rupture of the nozzle with the leaking flaw.

5.2.3 Limiting Cases for Surge Nozzles

While there are nine plants addressed by this safety assessment, the surge nozzle weld for one plant has already been mitigated by application of a weld overlay. For the pressurizer surge nozzles for the remaining 8 plants, it can be seen from MRP-216, Revision 1, Table 7-5 and the supporting plots of load safety factor and leak rate versus time that all the sensitivity cases except for Case 29b and some S-series cases meet the safety factors specified by the NRC staff. Case 29b was designed to study the effect of applied moment on the final results. As a result, the applied moment was increased from its corresponding baseline Case 18b by a factor of 1.43. MRP-216, Revision 1, Table 7-5 shows that the load safety factor for Case 29b is only 1.38 at an initial leak rate of 4.05 gpm. The low margin results associated with this case are due to the following conservative assumptions: (1) the applied moment is 1.43 times the value for the base case, (2) the residual stresses are axisymmetric while actual weld residual stresses are unlikely to be fully axisymmetric, (3) the FE model does not consider the actual presence of the stainless steel welded safe end, and (4) the initial flaw is 360° 10% deep. Based on these multiple coinciding conservative assumptions, the staff determined it is inappropriate to apply a load safety factor of 1.5. Based on the industry specified load safety factor of 1.2, MRP-216, Revision 1, Figure 7-29, shows a plant response time of 12 days, which is adequate time for the plant to take actions. It should be noted that the initial leak rate of 4.05 gpm is more than 5 times the plant detectable leakage rate of 0.25 gpm.

For the 10 S-series cases, 2 cases exhibit crack arrest, leaving 8 S-series cases to consider. These 8 S-series cases are variations of baseline Case 17. This baseline case has a 21:1 26% deep initial surface flaw with the stainless steel welded safe end. Case 17 has the highest applied moment among all surge nozzle sensitivity cases. With one exception the 8 S-series cases are variations of Case 17, except that all 8 S-series cases are modeled without the stainless steel welded safe end and most have more conservative initial flaw assumptions than Case 17. Since 5 of these 8 S-series cases have load safety factors greater than 1.43 at an initial leak of 2.55 gpm, very close to the NRC staff specified safety factors, the NRC staff focused on the most limiting of the three remaining cases, Cases S1b. MRP-216, Revision 1, Table 7-5 shows that the load safety factor for Case S1b, which assumes an initial 360° 10% flaw, is only 1.03 at an initial leak rate of 7.39 gpm. To assess the biasing effect of the multiple conservative assumptions used for Case S1b, the staff identified the sources of conservatism in this case. These sources of conservatism are (1) the weld residual stresses are modeled in the analyses as axisymmetric, (2) the FE model does not consider the actual presence of the stainless steel welded safe end, (3) the initial flaw is assumed to be 360° 10% deep, (4) the reduction of secondary piping loads due to crack-induced piping compliance change, as documented in Appendices B and C of MRP-216, Revision 1, is not considered, (5) using the equivalent flow stress assuming that the crack is close to the nozzle stainless steel safe-end weld, and (6) the 75th percentile of the laboratory developed PWSCC crack growth rates, while it has not been validated by field data, is typically faster than indicated by operational data.

Regarding factor (1), the degree of conservatism introduced by treating the residual stresses as completely axisymmetric cannot be assessed quantitatively at this time. Given the steps involved in making welds, it is likely that the welding process would typically introduce some degree of asymmetry. For example, certain repairs can be made during the welding process that are not documented. It is apparent from the repair cases analyzed by industry (Cases 21-26) and by the NRC staff (Case 17-11) that repairs result in asymmetric residual stresses that promote through-wall crack development and larger stability margins at leakage. No credit is taken in this safety assessment for this factor.

Factor (2) was used to cover the uncertainty between calculated and measured weld residual stresses for surge nozzles. As discussed before for the safety/relief and spray nozzles, the NRC staff considers industry's use of the ASME Code residual stresses a very conservative way to address the discrepancy between FE-based residual stresses and the measured residual stresses. For the surge nozzles, industry did not use a similar approach. Rather, the safe end-to-piping weld was omitted from the analysis. Since the presence of the safe end-to-piping weld adds compressive stresses to the DM weld near the ID, not modeling the safe end is one way to account for the discrepancy between calculated and measured weld residual stresses for surge nozzles. As an alternative means of addressing this, the NRC staff ran its Case 17-7, which included the stainless steel welded safe end but used a weld residual stress modified by increasing the ID surface weld residual stress to +10 ksi. The increase in weld residual stress at the ID represents an increase of about 28 ksi over the FE calculated weld residual stress with the stainless steel safe-end to piping weld and is shown in Enclosure 1, Figure 52. This case was analyzed with a 360° 10% uniform depth initial flaw shape. This analysis case resulted in arrest of the initial flaw.

For factor (3) industry approached the results of Case S1b by running additional cases which it believed represented more realistic yet conservative initial flaw assumptions. These industry cases are Cases S4b through S7b as depicted in MRP-216, Revision 1, Figure 7-14. These cases superimpose pairs of surface flaws assumed to initiate and grow in a similar time frame as a 21:1 initial flaw located at the point of highest bending stress. The superimposed flaws are located at various symmetric locations around the pipe circumference. The analysis checked the stability of this weld with multiple flaws at a point in time when the flaw located at the point of highest bending stress has been leaking greater than 1 gpm for 7 days. The stability margin for all but one case at 1 gpm was close to the NRC staff specified load safety factor of 1.5.

For factor (4) the reduction of secondary piping loads due to the change in piping compliance induced by growth of a crack was documented in Appendices B and C of MRP-216, Revision 1. By agreement with industry before the sensitivity cases were calculated, this phenomenon was not considered in either the industry's analyses or the majority of NRC staff's confirmatory analyses. At the time of this agreement it was unclear what level of reduction would be appropriate. Industry performed additional analyses based on elasticity theory, LEFM and EPFM which are documented in Appendices B and C. The NRC staff concluded that these analyses provide an acceptable basis for a 40 to 50% reduction in the secondary stresses after the crack exhibits leakage, i.e., reduction in the contribution of secondary stresses to crack instability.

The limiting industry case for the surge line, Case S1b, is related to Plant G. Enclosure 1, Figure 59 showed that by considering the reduction of the secondary loads by 40 percent after the crack exhibited leakage, the NRC staff's load safety factor would be approximately 1.38 at 1.25 gpm (Case 17-10) instead of 1.00 (Case 17 or Case S1b), and there would be 17 days of plant response time available between this point (i.e., 1.25 gpm leak) and when the load safety factor decreased to 1.2. Use of this lower load safety factor is justified considering the conservatisms contained in the assumptions discussed in this section.

For factor (5), using the equivalent flow stress assuming that the crack is close to the nozzle stainless steel safe-end weld was assumed for conservatism. No theoretical or experimental evidence indicated that the need for this assumption. If a neutral or unbiased assumption is used, i.e., the crack is located at the center of the DM weld (including the butter), the load safety factor would become 1.54 at 1.25 gpm, fall to about 1.5 after a week, and decrease to about 1.36 towards the end of the 17 days of plant response time. The flow stress is discussed in Section 6.2.1 and the impact of different flow stresses on load safety factor is shown in Figure 59 of Enclosure 1.

Enclosure 1, Table 7 also presented Case 17-5, another variation of Case 17-10 related to Plant G. This case assumed that the center line of a 21:1 26% deep initial crack was located opposite the location of highest tensile bending stresses (i.e., at the location of the highest compressive bending stresses). The NRC staff performed this calculation to understand how the crack growth shape evolved as a function of time, not because it considered this was a reasonable or realistic initial flaw assumption. Due to the compressive bending stresses, this initial crack grew in the circumferential direction rather than the depth direction until the crack fully encompassed the inner circumference. The reason this case showed lower margin than Case S1b is because the initial flaw shape resulted in lower remaining ligament. If a crack were to initiate only in this location, the fracture mechanics modeling relied upon for this assessment would demonstrate that development of such a shape could not occur. Specifically, a shallow crack initiating in this location would grow primarily in the circumferential direction and would not reach a depth of 26% with a 21:1 aspect ratio. Therefore, the NRC staff did not consider it necessary to give any additional consideration to this case.

As noted in Section 2.1.2 of this safety assessment, industry and the NRC staff considered the contributions to the loading from dead weight, pressure, and thermal expansion in the crack stability calculations. The NRC staff considered another case related to Case S1b to investigate the stability of a crack under the limiting transient thermal loading. The transient thermal loads are caused by thermal stratification during plant startup and shutdown. These loads are transient in nature and may lead to fatigue crack growth rather than growth by stress corrosion cracking. Therefore, for the purposes of this assessment, the transient thermal loads are only considered in the stability calculations. In addition to the conservatisms in Case S1b, noted above, assessment of this case under transient thermal loading assumes a crack has grown near to the point of leakage at the same time that the limiting transient thermal loads occur. The limiting transient thermal loading that needs to be considered is for a plant with the back-welded fabrication since the analyses for plants with back-welded fabrication bound plants with machined fabrication. Based on Figure 2-9 of MRP-216, Revision 1, the limiting plant in this case is Plant C. The transient thermal loading for plant C is slightly larger than the normal loading for Plant G, to which Case S1b applied. The NRC calculations for this case are shown in Enclosure 1, Appendix B, Figure 13 as Case 17-12. The results of this calculation show slightly lower margin (1.35 versus 1.54) than those for Case 17-10. The load safety factor for this case decreases slightly within the first week after first leakage (from 1.35 to 1.3) and the leak rate increases from about 1.2 gpm to greater than 3 gpm during this time period. Given the conservatisms noted above, the NRC staff concluded that the calculated safety factors are adequate. Evaluation of this bounding case demonstrates that all plants have adequate safety factors for transient thermal loading.

Therefore, by evaluation of the conservatisms inherent in the assumptions used to calculate Case S1b, the NRC staff concludes that the NRC staff specified safety factors are met with adequate response time to shut down the reactor in the event of surge nozzle weld through-wall leakage.

In summary, based on the NRC staff's evaluation of MRP-216, Revision 1, and on the NRC staff's confirmatory analyses, the NRC staff determined that the analyses for the eight pressurizer surge nozzle DM welds demonstrate an adequate level of safety for operation beyond December 31, 2007. The NRC staff does not believe that the pressurizer surge nozzle welds are seriously degraded; however, if a PWSCC flaw were to initiate and grow in one of these nozzle DM welds before the Spring 2008 refueling outages, there is reasonable assurance that detectable leakage would occur and that adequate time would be available to safely shutdown the plant prior to rupture of the leaking flaw.

6.0 Probabilistic Study

The industry performed a nozzle failure probabilistic study based on PFM. MRP-216, Revision 1, Appendix E, Table E-5 shows a nozzle failure probability per plant per reactor-year of 1.6×10^{-3} to 4×10^{-3} before Spring 2008 depending on the assumed complementary cumulative distribution of the criticality factor (CF) for inspection data compiled by the industry. Here, industry defines CF as the percentage of the cracked area to the nozzle cross section area. MRP-216, Revision 1, Appendix E further assumed that the probability of a rupture with undetected leakage among all failures is 1/500. Considering this factor, the per plant probability of nozzle rupture with undetected leakage per plant per reactor-year becomes 3.2×10^{-6} to 8×10^{-6} before Spring 2008.

Because of the complexity of the advanced FEA evaluation, several engineering assumptions, which deviate from a conventional PFM approach, had to be made to carry out the PFM analysis. One engineering assumption is that all nozzles can be treated as one generic nozzle and all nozzle data can be treated as coming from the same population. This may be conservative because in the industry's PFM analysis, the high surge nozzle applied stresses in MRP-216, Revision 1, Figure E-5 and E-6 were selected randomly and were considered applicable to the generic nozzle while in a more typical PFM approach they would be applicable only to the surge nozzles. Another engineering assumption was the use of the criticality factor (CF) as the sole parameter to represent a flaw. This may be non-conservative because the MRP-216, Revision 1, Table 7-5 Case S1b results demonstrate that a 360° 10% deep initial flaw assumption produces a low margin result if it is combined with other conservative assumptions. However, a 21:1 26% deep initial surface flaw with everything else unchanged (Case 17b) has substantial margin. Both cases have similar CF. The third engineering assumption is the use of two unrelated sets of information, the pressurizer nozzle DM weld design loads and the NRC degraded stainless steel piping test data [11], to develop the fragility curve (or the failure curve). During the advanced FEA evaluation program, the NRC and the industry used Reference 11 only to gain qualitatively insights. Using the degraded piping test data quantitatively here may not be fully justifiable because none of the welds in the NRC degraded piping test are DM welds. The last engineering assumption is the use of the area growth rate as a random variable in the PFM analysis and the use of the area growth rate distribution based on the sensitivity cases results. As indicated in MRP-216, Revision 1, Tables 7-4 to 7-6 calculated crack growth years before and after leakage are very much case dependent (or K dependent). The approach in MRP-216, Revision 1, Appendix E, however, randomly selected an area growth rate for a generic nozzle without referencing applied loads. Due to limited information, it is hard for the NRC staff to judge whether the last two assumptions are conservative or non-conservative.

In addition to the engineering assumptions mentioned above, MRP-216, Revision 1, Appendix E further assumed that the probability of a rupture with undetected leakage among all failures is 1/500. The basis for this assumption is not clear to the NRC staff. Based on this evaluation, the NRC staff found it difficult to develop a basis for accepting the probability of failure estimates in Appendix E and, therefore, based its conclusions on its evaluation of the deterministic results.

7.0 Conclusions

The principal conclusions resulting from this safety assessment are as follows.

- Based on operating experience with circumferentially and axially oriented indications of PWSCC, the NRC staff does not believe that the pressurizer nozzle DM welds are seriously degraded but if circumferential flaws were to occur, the NRC staff does not expect such flaws to grow to rupture without exhibiting leakage.
- Weld fabrication practices fall into one of two categories, back-welded and machined. The results of analyses for plants with back-welded fabrication bound the results for plants with machined fabrication. The plants with back-welded fabrication are plants A, B, C, F, and G. The plants with machined fabrication are plants D, E, H, and I.
- For the safety, relief, and spray nozzles, the results of the analyses showed crack arrest for all cases based on weld residual stresses from the finite element calculations. Through-wall crack growth resulted from analyses based on conservatively applying an ASME Code residual stress. The limiting cases from these analyses demonstrated acceptable safety factors. The results of these analyses demonstrated that safety factors on crack stability for the safety, relief, and spray nozzle welds are larger than the safety factors on stability for the surge nozzles.
- Analyses performed with non-axisymmetric weld residual stresses due to local inside diameter repairs demonstrated high safety factors since local repairs promote through-wall crack growth in the area of the repair. Plants A and B have documented inside diameter repairs of the surge nozzle weld.
- Analyses of the surge nozzle sensitivity cases showed that safety factors for almost all cases met the NRC staff specified safety factors. Quantitative evaluation of conservatisms inherent in those few sensitivity cases with low safety factors demonstrates that all surge nozzle analyses have adequate factors of safety.
- All nine plants have adequate safety factors for non-normal thermal loading.
- Based on the preceding, the NRC staff has concluded that there is reasonable assurance that the nine plants addressed by this evaluation can operate safely until their next scheduled refueling outages in the Spring of 2008.

8.0 References

1 Garrett, T. J. Letter to the NRC Staff, “Response to Request for Additional Information Relating to Pre-Weld Overlay Examination of Pressurizer Nozzle to Safe-End Dissimilar Metal Welds,” November 29, 2006 (ML063380456).

2 “Primary System Piping Butt Weld Inspection and Evaluation Guidelines (MRP-139),” EPRI, Palo Alto, CA, July 2005 (ML052150196).

3 “Advanced FEA Evaluation of Growth of Postulated Circumferential PWSCC Flaws in Pressurizer Nozzle Dissimilar Metal Welds (MRP-216, Revision 1): Evaluation Specific to Nine Subject Plants,” EPRI, Palo Alto, CA, 2007 (ML072410235).

4 “Review and Refinement of NRC Crack Growth Calculation for Relief Nozzle,” Section 5 in “Implications of Wolf Creek Pressurizer Butt Weld Indications Relative to Safety Assessment and Inspection Requirements,” MRP 2007-003, Attachment 1, January 2007 (ML070240159).

5 Rudland, D., Shim, D-J., Xu, H., and Wilkowski, G., “Evaluation of Circumferential Indications in Pressurizer Nozzle Dissimilar Metal Welds at the Wolf Creek Power Plant,” Summary Report to the NRC, April 2007 (ML071560398).

6 Anderson, T. L., et al., “Stress Intensity Solutions for Surface Cracks and Buried Cracks in Cylinders, Spheres, and Flat Plates,” Structural Reliability Technology final report to The Material Property Council, Inc., March 14, 2000.

7 “Material Reliability Program (MRP) Crack Growth Rates for Evaluating Primary Water Stress Corrosion Cracking (PWSCC) of Alloy 82, 182, and 132 Welds (MRP-115),” EPRI, Palo Alto, CA. 2007 (ML051450555).

8 “Material Reliability Program (MRP) Crack Growth Rates for Evaluating Primary Water Stress Corrosion Cracking (PWSCC) of Thick-Wall Alloy 600 Material (MRP-55),” EPRI, Palo Alto, CA, 2002 (ML023010510).

9 NRC Safety Evaluation, “Arkansas Nuclear One, Unit 2 (ANO-2) - Relaxation Request from U.S. Nuclear Regulatory Commission (NRC) Order EA-03-009 for the Control Element Drive Mechanism Nozzles (TAC No. MB9542),” October 9, 2003 (ML032820552).

10 NRC Safety Evaluation, “Arkansas Nuclear One, Unit 2 (ANO-2) - Relaxation Request from U.S. Nuclear Regulatory Commission (NRC) Order EA-03-009 for the Incore Instrumentation Nozzles (TAC No. MC0640),” October 9, 2003 (ML032860043).

11 “Summary of Technical Results and Their Significance to Leak-Before-Break and In-Service Flaw Acceptance Criteria,” NUREG/CR-4082, Volume 8, March 1984 - January 1989.

12 Evans, M.G. Letter to Marion, A., “Concerns Regarding Industry’s Phase I Wolf Creek Calculations,” April 4, 2007 (ML070940186).

13 Rahman, S., and Wilkowski, G., “Net-Section-Collapse Analysis of Circumferentially Cracked Cylinders—Part I: Arbitrary-Shaped Cracks and Generalized Equations,” Engineering Fracture Mechanics, Vol. 61, pp. 191-211, 1998.

14 Dyer, J.E. Letter to Thayer, J., “Comments on Industry Advanced 3-Dimensional Finite Element Analyses,” March 5, 2007 (ML070640401).

15 “Assessment of Dissimilar Metal Weld Integrity: Final Report of the NESC-III Project,” EUR 22510 EN, European Commission Joint Research Centre, 2006 (ML072400203).

16 PICEP Computer Code (NP-3596-SR): Pipe Crack Evaluation Program (Revision 1), EPRI, Palo Alto, CA, 1987.

17 Rudland, D., Wolterman, R., Wilkowski, G., and Tregoning, R., “Impact of PWSCC and Current Leak Detection on Leak-Before-Break,” Vessel Head Penetration Inspection, Cracking, and Repairs Conference, Gaithersburg, MD, 2003.

18 SQUIRT Computer Code User’s Manual (Windows Version 1.1): Seepage Quantification of Upsets In Reactor Tubes, Battelle, Columbus, OH, 2003.

19 Thayer, J., Letter to Dyer, J.E., "Refined Crack Growth Calculations Supporting Industry Response to Wolf Creek Pressurizer Dissimilar Metal Weld Indications February 14, 2007, (ML070600672).

20 Wilkowski, G., Rudland, D., Shim, D.-J., and Xu, H., "Technical Note On Critical Crack Size Evaluations for Circumferential Cracks in Dissimilar Metal Welds," June 20, 2007, (ML071560385).

21 Scott, P., Ghadiali, N., Paul, D., Morbitzer, R., Rudland, D., and Wilkowski, G., "Technical Development of Loss of Coolant Accident Frequency Distribution Program, Subtask 1a: Finalize and QA SQUIRT Code," Final report to Nuclear Regulatory Commission, March 2003.

22 Mensah, T.M., Memorandum to Rosenberg, S.L., Summary of March 7, 2007, Public Meeting, March 20, 2007 (ML070790257).

23 Gutierrez, M., Memorandum to Hardies, R., Summary of May 1, 2007, Public Meeting, May 14, 2007 (ML071360367).

24 Mensah, T.M., Memorandum to Rosenberg, S.L., Summary of May 8, 2007, Public Meeting, April 17, 2007, (ML071580239).

25 Guitierrez, M., Memorandum to Uhle, J., Summary of May 31 – June 1, 2007, Public Meeting, June 12, 2007, (ML071620384).

26 Guitierrez, M., Memorandum to Uhle, J., Summary of June 19 – 20, 2007, Public Meeting, July 5, 2007, (ML071860664).

27 Guitierrez, M., Memorandum to Uhle, J., Summary of July 17, 2007, Public Meeting, July 25, 2007, (ML072060132).

28 Mensah, T.M., Memorandum to Rosenberg, S.L., Summary of August 9, 2007, Public Meeting, (ML072410354)

Date: August 31, 2007

Principal Contributors: Simon Sheng
Aladar Csontos
Timothy Lupold
Edmund Sullivan