Letter Report
TLR-RES/DE/CIB-2020-07

BENCHMARK SOLUTIONS FOR XFEM ANALYSIS COMPARISONS

Date:
August 28, 2020

Prepared in response to Task B3 in User Need Request NRR-2020-004, by:
L. T. Hill
Engineering Mechanics Corporation of Columbus
F.W. Brust
Engineering Mechanics Corporation of Columbus
S. Kalyanam
Engineering Mechanics Corporation of Columbus

NRC Project Manager:
Giovanni Facco
Materials Engineer
Component Integrity Branch

Division of Engineering
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission
Washington, DC 20555–0001

DRAFT Final Report
On

Support for XFEM Component Integrity Analysis: Task 4 Benchmark Solutions for XFEM Analysis Comparisons

U.S. Nuclear Regulatory Commission
Prime Contract No.: NRC-HQ-25-14-E-0004
Task Order No. 31310019F0075
Emc^2 Project Number: 19-G121-01
As a Subcontractor to NUMARK Associates, Inc.

to

U.S. Nuclear Regulatory Commission
Washington, D.C. 20555-0001

by

L.T. Hill, F.W. Brust, and S. Kalyanam

Engineering Mechanics Corporation of Columbus
3518 Riverside Drive, Suite 202
Columbus, OH 43221
Phone/Fax (614) 459-3200/6800

July 28, 2020

As a Subcontractor to
NUMARK Associates, Inc.
1220 19th Street, NW, Suite 500
Washington, DC 20036

EXECUTIVE SUMMARY

This report represents the fourth, and final task, of the *Support for XFEM Component Integrity Analysis* program. The other reports are completed or undergoing final review at present. Task 1 (Literature Survey) provided a literature review of the eXtended Finite Element Method (XFEM) as well as a summary of the capabilities and limitations of other crack growth modeling techniques. Task 2 (Sensitivity Study of PWSCC-type Crack Growth in Abaqus XFEM) discussed the Abaqus implementation and explored optimum parameter definitions to provide the most appropriate solutions for simple fatigue and PWSCC (Primary Water Stress Corrosion Crack) crack growth analysis. The Task 2 report explored five crack geometry cases, from simple two-dimensional cases to the V. C. Summer PWSCC analysis for three-dimensional axial PWSCC growth and leakage. Sensitivity studies identified best practice to make likely success using the Abaqus XFEM implementation.

The Task 3 report (Evaluation of PWSCC-subcritical crack growth using Abaqus XFEM for complex geometries) provided detailed XFEM solutions for the VC Summer and control rod drive mechanism (CDRM) crack growth to leakage solutions. This report summarized the best Abaqus XFEM solution parameter definitions and compared the solutions to crack growth analyses performed in the past using other methods. This report also identified limitations in the analysis process and pitfalls possible, including 'core dumps' where the analysis may run for several days before stopping without completion due to Abaqus internal errors. Due to these Abaqus internal errors and the inherent instability of the XFEM approach at present the efforts in Tasks 2 and 3 were significant and required hundreds of unexpected analyses in order to identify the important Abaqus 'knobs' to turn to make an accurate solution or even a solution at all most likely.

In the previous tasks for this project, the built-in Abaqus XFEM capability was shown to adequately model relatively simple planar crack growth due to PWSCC and constant amplitude fatigue applications when prescribed modeling recommendations were followed. In addition, Abaqus XFEM analyses were performed to determine the applicability of these recommended modeling practices in complex geometries with planar crack growth relevant to the nuclear power industry. Specifically, the Abaqus XFEM crack propagation results were compared to several traditional PWSCC crack growth analyses for a control rod drive mechanism (CRDM) nozzle and reactor pressure vessel outlet nozzle.

This task 4 report is the final in this series on the use of Abaqus XFEM for subcritical crack growth, and provides a summary of solutions previously performed by the NRC staff and contractors, and other organizations that may be used in the future for further XFEM benchmarking. The solutions and predicted results presented here provide the references and necessary data needed to perform the XFEM analyses in order to validate the solutions against previous results. These solutions developed using either Advanced Finite Element Analysis (AFEA), or Finite Element Alternating Method (FEAM) include:

- Wolf Creek Nozzle PWSCC growth. Including 31 possible model configurations. These include safety and relief, spray, and surge lines as detailed in Section 3.2.1.
- North Anna axial PWSCC growth in a steam generator nozzle. This is a complex geometry with unique PWSCC pattern.
- European utility surge line, steam generator, safety/relief, and spray lines. These represent more than ten solutions for different size lines and include solutions for axial and circumferential PWSCC growth benchmarks. Some of these problems include PWSCC in complex weld joints including K-weld geometry in a steam generator.
- Hot leg Inlay PWSCC growth. This provides solutions for the inlay mitigation problem which involves complex crack growth (bubble shape) for crack growth growing from alloy 52 into alloy

182 weld regions. This type of problem will be difficult to solve using the current Abaqus 2020 XFEM version, but future versions should be able to handle this case. Approximately 10 configurations of this model could be compared against previous results.

- Natural crack growth in CRDM nozzles. Natural crack growth is considered to better approximate PWSCC growth in the field since the crack is grown at every location along the crack front like that with XFEM predictions. Benchmark solutions are provided for top dead center nozzle and maximum angle case (53-degree nozzle).
- Multiple stationary cracks in CRDM nozzles. This is a benchmark for evaluating interacting cracks and mixed mode conditions. This effort compared stress intensity factor solutions for stationary cracks with no crack growth predicted.

This report documents these problems as potential benchmarks to further evaluate the effectiveness of XFEM for general NRC usage.

Other cases can be added by considering recently updated weld residual stress (WRS) solutions and modeling PWSCC by using AFEA and/or FEAM approaches. In particular, CRDM WRS solutions were recently updated using full three-dimensional moving arc solutions without simplifying geometric assumptions and were compared with some measurements for WRS validation. These could be modeled using FEAM and/or AFEA methods to provide updated benchmark solutions for CRDM nozzles. While these problems were developed to validate the XFEM process they could likewise be used to validate xLPR deterministic PWSCC solutions.

TABLE OF CONTENTS

1 INTRODUCTION

The extended finite element method (XFEM) is a Finite Element Analysis (FEA) method that allows for mesh-independent analysis of discontinuities and singularities and can be used to simulate crack growth in complex geometries in a simplified manner. This capability is available in several commercial FEA codes, including Abaqus (2020), and is potentially a powerful tool for representing cracks and simulating crack growth in industry relevant models. Additionally, the Abaqus XFEM capabilities can be used to simulate fatigue and PWSCC crack growth analysis.

The objective of this task order project was to provide expert technical assistance services from the NUMARK/Emc^2 team on evaluation of advanced and simple fracture mechanics procedures for crack assessment of nuclear components. This is to augment the NRC's current capabilities in PWSCC analysis. XFEM is a more recently developed method which is now available in some commercial finite element codes and Department of Energy developed codes including Abaqus, MORFEO, GRIZZLY, and others. The objective of this program was to examine the XFEM approaches in the available codes and identify the best way for the NRC staff to use these codes. This includes identifying the limitations and best practices for use of XFEM in practical crack growth and instability assessment of nuclear components. This was performed by using the Abaqus version of XFEM implementation to perform sensitivity studies of several crack geometries and comparing the results of the analyses to conventional crack growth and fracture approaches. The goal was to assess simple (e.g. two-dimensional planar) and complex (e.g. CRDM) crack geometries and define parameters for optimum XFEM performance.

There have been three other reports produced as part of this effort. Task 1 *Literature Survey* (Hill, Brust, Kalyanam, Facco, et al 2020a) provided a literature review of the XFEM method which summarized the theoretical approach and capabilities of XFEM and compared them against other crack growth and instability analysis and currently in use. Task 2 *Sensitivity Study of PWSCC-type Crack Growth in Abaqus XFEM* (Hill, Brust, Kalyanam, Facco, et al 2020b) discussed the Abaqus implementation and explored parameter definitions to provide the most appropriate solutions for simple fatigue and PWSCC crack growth analyses. The sensitivity studies identified best practices for using the Abaqus XFEM implementation most likely to achieve reliable results. The Task 3 report *Evaluation of PWSCC-type Crack growth in Abaqus XFEM for Complex geometries* (Hill, Brust, Kalyanam, Facco, et al 2020c) provided detailed solutions for the VC Summer reactor vessel outlet nozzle and a characteristic CRDM penetration nozzle using XFEM based crack growth analyses to predict time to leakage. The Task 3 report also identified limitations in the analysis process and pitfalls possible, including 'core dumps' where the analysis may run for multiple days before stopping without completion due to Abaqus internal errors. Due to these Abaqus internal errors and the inherent instability of the XFEM approach, the efforts in Tasks 2 and 3 were significant and much greater than anticipated.

Utilizing the specified meshing parameters, the analysis parameters for calculating crack growth (growth tolerance, fracture criteria, general solution controls, etc.) should be set to the default or recommended values as summarized in the Task 2 report. However, with careful evaluation and benchmarking, other non-default parameters can be utilized to obtain robust, accurate solutions in a timely fashion.

In this report, benchmark problems are listed which permit assessment of XFEM solutions in the future using both Abaqus and other potential codes. Section 2 provides the NRC perspective on PWSCC modeling approaches – both historically and potentially in the future. Section 3 summarizes the benchmark problems, which can be used for validation purposes in future XFEM applications. This is followed by a recommendations section and conclusions.

2 NRC CRACK GROWTH MODELING OVERVIEW

Over the years the NRC staff and contractors have developed crack growth and instability methods and corresponding computer codes. Prior to discussing the potential future role of XFEM methods for crack growth and instability predictions below it is useful to review this work. These crack growth and instability procedures and corresponding computer codes are used by the NRC staff to perform confirmatory assessments of industry submittals including relief requests. Convenient and accurate assessments of crack growth and instability are important in order to quickly and reliably evaluate these flaws. The methods used at the NRC evolve over time in order to improve the quality of the results as well as the convenience of the analyses..

2.1 Crack Growth and Instability Analysis

Over the years the NRC has developed crack growth analysis and instability procedures that permit safety assessments of nuclear components. For elastic-plastic instability predictions J-estimation schemes and corresponding computer codes were developed (NRCPIPE, NRCPIPESC, SQUIRT, etc.) and are still used today for stable crack growth and instability predictions of surface and through wall cracked pipes; as well as, leak rate predictions (see for instance Wilkowski et al, 1992) and the many references cited therein). The ability of these codes to predict elastic-plastic crack growth and instability in piping systems were validated by comparison to extensive pipe tests over the years. However, for surface crack growth analysis crack growth is only permitted at the deepest point of the crack as the estimate of J is only available at this point within the NRC suite of J-estimation codes. These analysis capabilities within this suite of codes has been used by the U.S. NRC to perform safety assessments of nuclear piping and validate leak before break (LBB) assessments made by industry for Standard Review Plan (SRP) 800 (NRC (2013) Section 3.6.3 compliance (NUREG-0800).

2.2 PWSCC Crack Growth Analysis

2.2.1 Idealized Crack Growth Procedures

Idealized crack growth procedures and the corresponding modeling codes are traditional and are used by many industries including the nuclear industry and aerospace, for fatigue crack growth assessment (NASGRO, 2020) based on Raju and Newman (1980) stress intensity factor solutions for cylinders. The NRC has developed a deterministic flaw growth computer code, based on stress intensity factor solutions (Xu 2012, Shim 2014) called FES (Flaw Evaluation Software). For surface cracks, an elliptical crack shape is assumed, and the crack growth is prescribed at the deepest and surface points only, as shown with the yellow arrows in the left illustration in Figure 1. Therefore, the crack must remain elliptical in shape. For through wall cracks the crack is grown in the center of the crack and, after a transition phase, an idealized through wall crack shape is assumed. These codes are limited to simple geometries where the stress intensity factors can be compiled easily.

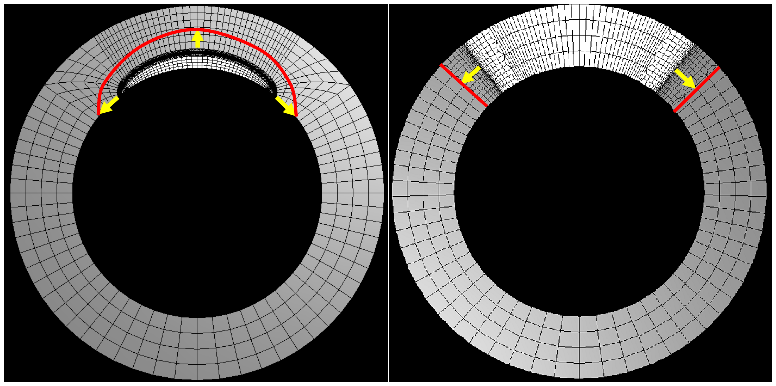

Figure 1 – Idealized crack growth procedure

The xLPR (eXtremely Low Probability of Rupture) computer code, developed jointly by NRC and EPRI and just released to the public (NRC and EPRI (2020)), is a probabilistic PWSCC and fatigue crack growth and instability code for LBB assessment. This code can be used to perform deterministic analyses with the cracks grown at the deepest and surface points as illustrated in Figure 1. Many of the deterministic modules within xLPR are based on earlier NRC work (Wilkowski et al, 1992). The xLPR code for deterministic crack growth and instability assessments accounts for the WRS contribution to stress intensity factors based on a unified weight function method which can model the exact WRS distribution through the nozzle. However, at present, xLPR can only handle pipe type geometries with axial or circumferential crack growth.

For complex geometries, the FEAM approach is quite convenient for use in analyzing growing cracks at the deepest and surface points (Brust, 2011). The advantage of this method is that the solution alternates between a closed form solution and the finite element solutions for *the uncracked geometry* which renders solutions extremely fast, simple to obtain, and convenient. However, crack growth using FEAM is usually performed at the deepest and surface points although this is not a restriction. Use of FEAM for crack growth modeling is more flexible than FES or xLPR because the crack shape can be any part of the ellipse and therefore the crack shape can be quite arbitrary. This method has been used by the NRC staff for PWSCC cracks growth in CRDM nozzles and many other complex geometries and for fatigue crack growth in industry.

2.2.2 Natural Crack Growth Procedures

One of the first applications of natural crack growth modeling as applied to PWSCC was performed as part of the Wolf Creek LBB assessment by Rudland, Shim, Zhang, and Wilkowski (2007) and Rudland, Shim, and Csontos (2008)[*]. With this approach the crack is permitted to grow as shown in Figure 2. The crack is grown an incremental amount based on the crack growth law and stress intensity factor at each point along the crack front and crack growth is perpendicular to the current crack tip. As opposed to idealized crack growth (Figure 2) this approach permits rather arbitrary crack shapes to develop during the PWSCC growth process with an example crack growth from the Wolf Creek analysis (Rudland et al 2007) shown in Figure 3. Both the time to leakage, the crack shape, and potential instability point of PWSCC between idealized growth and AFEA can all be different. The term AFEA is perhaps a misnomer since there are clearly more advanced forms of the finite element method that have been developed. However, it was first termed 'AFEA' during the Wolf Creek work (Rudland, Shim, Zhang, and Wilkowski (2007) and Rudland, Shim, and Csontos (2008) and in the corresponding industry assessments (MRP-

[*] Independent PWSCC analyses were also performed by industry and results compared reasonably between NRC and industry solutions.

216, 2007) of the Wolf Creek problem so the term is used here. From a technical standpoint it is thought that AFEA assessments are more accurate than growing the crack only at the deepest and surface points (as per Figure 1) because the emerging crack shape is more ‘natural’ rather than just being grown at two points. The AFEA procedure is performed within the framework of conventional Abaqus analyses by automatically developing crack meshes for each growth increment and obtaining the stress intensity factors, growing the crack more, etc., with this process managed by a Python script. For circumferential crack growth in a pipe this process can usually be performed overnight where the result of elastic Abaqus analyses are then used to automatically create new meshes with updated crack shapes and run a new analysis. This process is then automatically repeated until the desired condition is met. However, for complex geometries this automated procedure is not possible because the automatic mesh development code is not available for these geometries. For instance, the ‘balloon’ shape crack discussed in the next paragraph does not use an automatic mesh generation procedure since developing automatic mesh procedures for complex cracks is a complex development that has not been done yet. For such cases the mesh is developed by hand for each PWSCC growth increment.

A summary of all methods of PWSCC growth procedures using FES type analysis, FEAM analysis, and AFEA is described in detail in Brust et al (2011) along with an eleven-step process. The automated procedure of developing a new mesh (known as PipeFracCAE) for each increment of crack growth works rapidly for certain geometries such as circumferential cracks in pipe but is not automated for complex geometries. However, as seen in Brust et al (2011) this natural crack growth approach has been used for more complex geometries such as PWSCC through an inlay where the crack grows much slower in the alloy 52 inlay material and then much faster once the underlying alloy 82/182 material is reached by the crack (Figure 4). Numerous additional examples of ‘balloon’ crack PWSCC growth can be found in Rudland, Brust, Zhang, Shim, and Wilkowski (2010). The natural crack growth procedure for complex geometries and several PWSCC growth laws for different parts of the component is not automatic as each new mesh, after growth, must be developed manually. This process is time consuming. Using the XFEM capabilities of Abaqus natural crack growth is achieved without the need for these remeshing procedures and shows a potential great advantage in XFEM PWSCC analysis procedures.

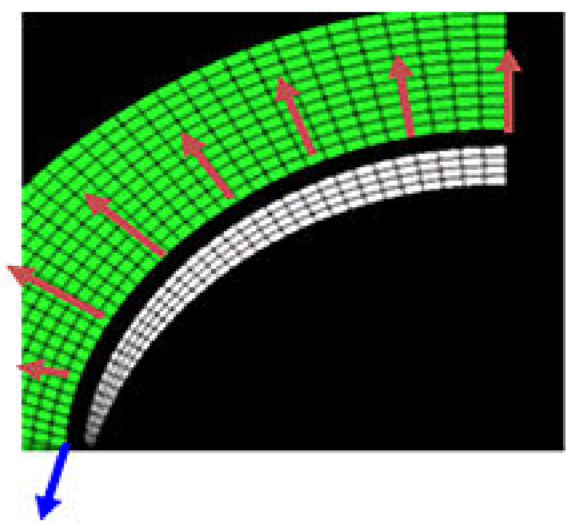

Figure 2 – Natural crack growth procedure

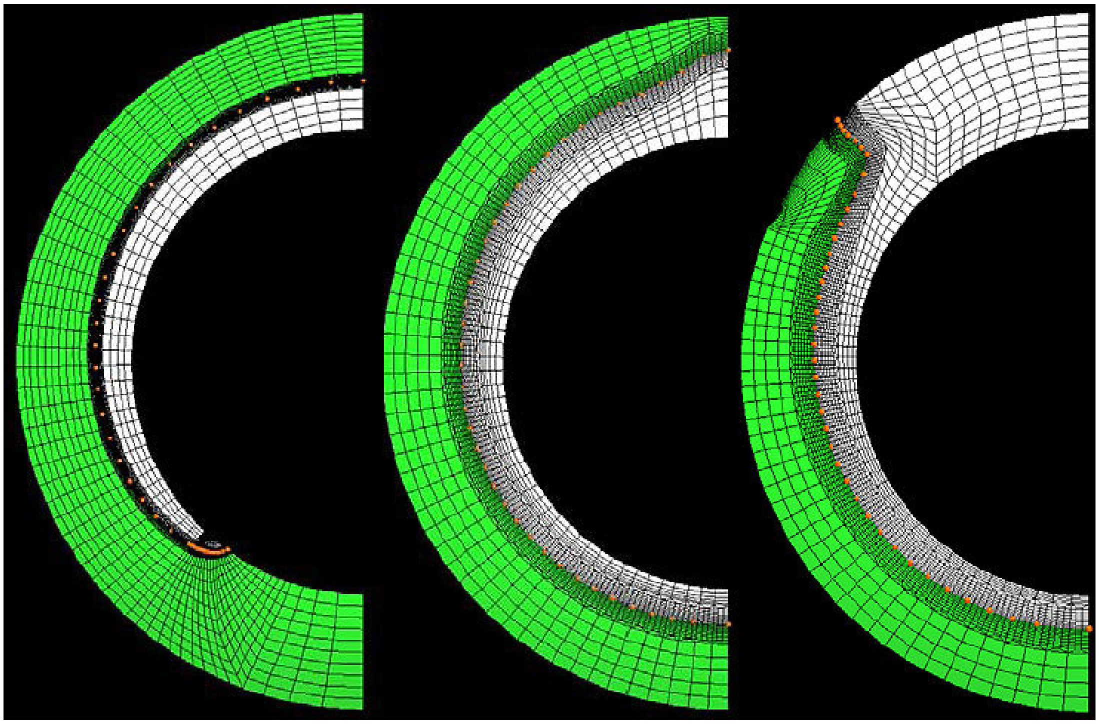

Figure 3 – Example of crack growth from natural crack growth or AFEA

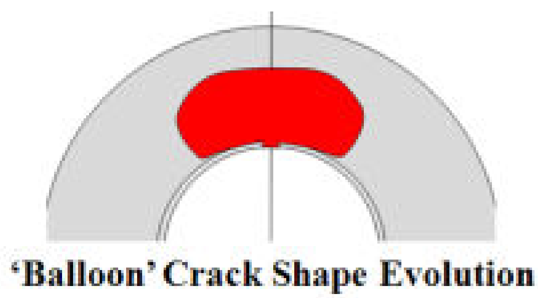

Figure 4 – 'Balloon' crack shape development in inlay nozzle using natural crack growth.

2.2.3 XFEM Based Natural Crack Growth Procedures

The Abaqus based XFEM natural crack growth procedures were fully documented in the Task 2 and Task 3 reports (Hill et al 2020b, 2020c) and will not be repeated here. An example of the predictions of natural PWSCC growth in a CRDM nozzle using Abaqus based XFEM is shown in Figure 5. The time to leakage from this analysis matched quite well compared to a similar analysis performed using the FEAM approach (see Task 3 report (Hill et al 2020c). The advantage of XFEM for PWSCC natural crack growth analysis is evident. However, at present there remain issues with guaranteeing convergence using the XFEM. Moreover, the crack growth shape and time to leakage can depend on the parameters used to control the Abaqus based XFEM analysis. The recommended parameters based on this work (Task 2 and Task 3 reports, Hill et al 2020b, 2020c) often lead to a solution. However, 30 to 40% of the analyses lead to problems or core dumps at present for complex geometries.

For this reason, it is recommended that analyses be performed using two methods to verify the XFEM solution. For instance, if a relief request came into NRC from a vendor or operator, it is suggested that an XFEM analysis be performed along with one of the other PWSCC assessment procedures. This might mean that for simple pipe geometries with circumferential crack growth the FES code or the automated

AFEA procedures might also be used to perform the PWSCC analysis and corresponding LBB assessment. For more complicated geometries an FEAM assessment along with XFEM might be performed to ensure consistency in results. Once XFEM is verified for a particular type of crack growth in a component and WRS field, then additional sensitivity analysis might be performed using XFEM alone. This is because it is not always known, for a particular problem, if the ABAQUS XFEM approach will converge.

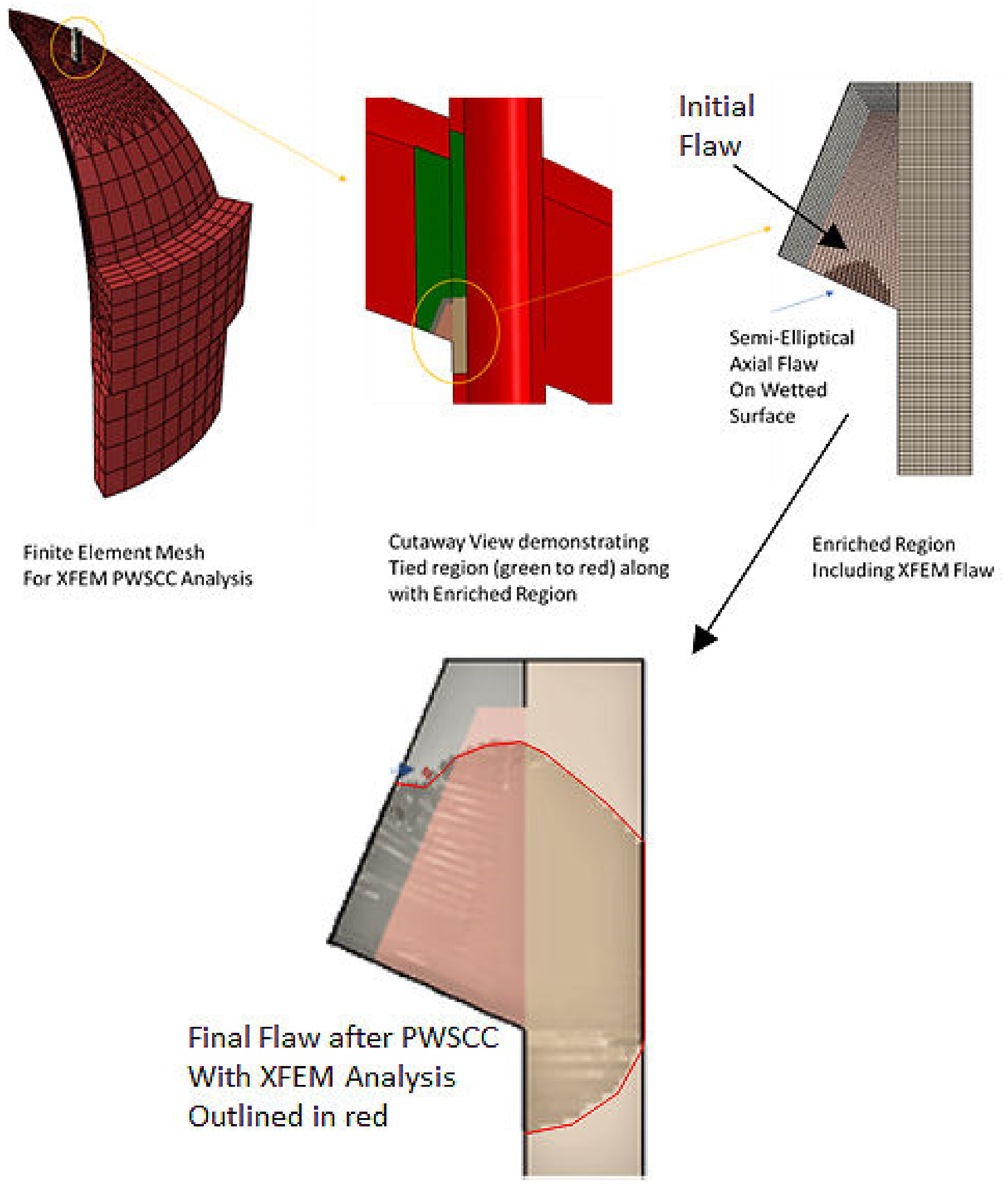

Figure 5 – Natural crack growth in CRDM nozzle using XFEM

3 POTENTIAL BENCHMARK SOLUTIONS WITH OPERATIONAL EXPERIENCE

This section provides a list and summary of some prior PWSCC analyses that have been performed by the NRC staff using a variety of methods. Results of these prior analyses using these other methods are also provided so that benchmarking of additional problems using XFEM may be performed in the future.

Abaqus is proposed for these potential analyses for several reasons:

- Abaqus now provides XFEM based crack growth analysis procedures.
- Weld residual stresses play an important role in PWSCC growth since tensile WRS increases the stress intensity factor which drives the crack. Most WRS modeling procedures used by the NRC staff are performed within the framework of Abaqus (both 2D and VFT based 3D although VFT analyses can now be performed within WARP3D).
- Abaqus has very robust field solution mapping procedures from one mesh to another. For XFEM assessment, one first performs the WRS analysis and then maps this field to an XFEM based Abaqus mesh, which has the enriched elements for crack modeling and is typically much more refined compared to the mesh used for weld modeling. This is very convenient.

It would be possible to use other codes, for instance GRIZZLY, that permit use of XFEM for these assessments. However, procedures for weld modeling within these codes would have to be developed and verified and the mapping procedures necessary for transferring results from one mesh to others would have to be developed and/or verified. This may be attempted in the future.

3.1 Benchmark Problems in Task 2 and 3

This section briefly summarizes solutions performed in the Task 2 and Task 3 reports that can be used for benchmarking.

- The VC Summer axial crack growth solution using XFEM was provided in the Task 3 report (Hill et al, 2020c). All necessary solution parameters and comparison to solutions using the AFEA procedure are included in this report. This represents a benchmark solution. Solutions using XFEM compared quite well with AFEA solutions both for crack evolution and time to leakage.
- A 25-deg hillside CRDM solution for PWSCC was performed in the Task 3 report (Hill et al 2020c). The reference solutions were performed in the past (Brust et al 2011) using the FEAM approach. The XFEM solution provided reasonable predictions of PWSCC evolution when compared to the FEAM results, and the time to leakage compared well. This also represents a benchmark solution.

3.2 Additional Benchmark Problems for XFEM

Here benchmark problems are presented as a starting point when looking to analyze the behavior of crack growth FEA models and compare them to published results. These solutions were performed in the past by NRC staff and contractors and are identified in references provided below. Each case is documented in different sections below.

3.2.1 Wolf Creek Pressurizer Nozzles – Circumferential Crack Growth

The following summary from the final Wolf Creek report to NRC (Rudland, Shim, Zhang, and Wilkowski (2007)) details the Wolf Creek issue followed by some benchmark analyses that were performed as part of that study. The examination of the Wolf Creek incident was the first application of AFEA and natural crack shape development for PWSCC growth in PWRs, so it makes sense to provide context for this first before providing benchmark problems.

In October 2006, NRC-RES informed Emc^2 of circumferential indications that had been located by ultrasonic testing in three of the pressurizer nozzle dissimilar metal welds (DMW) at the Wolf Creek nuclear power plant. The NRC staff tasked Emc^2 with analyzing these defects. Using conservative American Society of Mechanical Engineers (ASME) Section XI type analyses, Emc^2 estimated the times to both leakage and rupture for each indication. The results indicated that under certain conditions, no margin between leakage and rupture existed. The results from these analyses led the NRC staff to request that the inspection/mitigation program currently in place for the pressurizer nozzles be accelerated. This acceleration affected nine PWR plants in the U.S. fleet at that time.

In response, the industry embarked on a short-term technical program aimed at refining the crack growth analyses conducted by Emc^2 using ASME procedures. The main emphasis of the industry program was to use advanced finite element methods (AFEA) to remove the semi-elliptical flaw assumption that is typical in ASME Section XI type analyses. In addition, detailed sensitivity analyses were conducted to demonstrate that sufficient margins exists for the pressurizer nozzles that would be affected by the accelerated inspection request.

The work described in Rudland et al (2007) were two-fold. First, using similar techniques, confirmatory analyses were conducted by Emc^2 to verify the calculations conducted by the industry (MRP-216, 2007). Since both Emc^2 and the NRC staff worked very closely with the industry during that program, many of the technical issues were jointly discussed and agreed upon. Much of this report presented the confirmatory results for the stress intensity factor (K) solutions, the welding residual stress, and the leak/rupture margin analyses. Secondly, the applicability of this methodology for predicting leak/rupture margins was addressed by discussing the improvements to the standard methodology and the conservatisms, and uncertainties associated with this analysis. The PipeFracCAE automatic mesh generator was developed as part of this program which creates automatic spider type meshes for circumferential crack in pipe permitting natural crack growth analysis seamlessly as discussed by Rudland et al (2007). The industry used FEACrack for their AFEA analyses.

The Wolf Creek nozzles examined by Rudland et al (2007) provide a rich set of validation cases for comparison of XFEM results. The nozzle geometries considered are summarized in Table 5 of Rudland et al (2007) and shown below:

- **Safety and Relief** - R_{outer} = 3.875”, t=1.29”; R_{outer} = 3.875”, t=1.065”; R_{outer} = 4”, t=1.405” (total of eleven cases analyzed). Three nozzle type geometries were considered which resulted in different WRS fields.
- **Spray** - R_{outer} = 2.905”, t=0.9”; R_{outer} = 2.595”, t=1.045” (total of four cases analyzed). Two nozzle type geometries considered which resulted in different WRS fields.
- **Surge** - R_{outer} = 7.5”, t=1.58”; R_{outer} = 6.53”, t=1.470” (total of sixteen cases analyzed). Two nozzle type geometries considered which resulted in different WRS fields.

For each nozzle, the WRS field was specified. The WRS fields included welds with and without the stainless steel weld (neglecting the stainless steel weld increased the tensile WRS field near the ID) and

WRS fields that include repair welds. In addition, the nozzle internal pressure, temperature, operating axial load, and operating moment were specified in Table 6 of Rudland et al (2007).

The AFEA results for each of these 31 cases are provided in Table 7 of Rudland et al (2007). The results of interest to us in evaluating the usefulness of the XFEM procedure are the time to leakage as PWSCC crack evolution was not provided. These cases should be modeled using XFEM procedures and the time to leakage from the analyses compared to the times listed in Table 7 of Rudland et al (2007). This is a robust set of validation cases for XFEM for circumferential crack growth in pipe and nozzles. Because circumferential crack growth in pipe is very conveniently performed using the PipeFracCAE analysis system some of these could be redone as well using the latest version of PipeFracCAE. Some of these analyses were also compared to independent analyses performed by industry as well. In general, the predicted times to leakage made by Emc^2 were longer than those predicted by industry, but they were usually close to each other. In addition to comparison of time to first leak between AFEA and XFEM, the instability load margins could also be compared if desired.

These XFEM analyses of the 31 cases could be performed using the procedures discussed in the Task 3 report (Hill et al 2020c). The WRS fields listed in Rudland et al (2007) can be applied to a model using the thermal load analogy which mimics actual WRS fields accurately. Then these WRS fields can be mapped to the XFEM model and the crack growth assessments made. It might also be possible to apply the thermal gradient directly to the XFEM model to obtain the WRS fields, but this would have to be explored.

3.2.2 North Anna Axial Crack Growth

During a scheduled outage at the North Anna PWR plant the steam generator to hot leg DM nozzle welds had an overlay repair applied. This was a double V-groove weld which had both ID and OD repairs applied as seen below in Figure 6. During the machining process to even out the nozzle taper prior to overlay (see Figure 6) application a leak occurred. The leak occurred after removal of about 1" (25.4 mm) of material from the OD in the 5" (123 mm) thick nozzle, meaning about 80% of the original thickness at the DMW centerline remained. The leaks were caused by rather deep axial cracks. As summarized generically in Brust, Punch, Shim, Rathbun, and Rudland (2013) the WRS profiles were determined and then used to model the natural axial crack growth in the weld. This analysis provided information regarding crack growth evolution versus time. Moreover, since this nozzle weld had nondestructive examination performed in 2009 (with no indications found at that time) this analysis also assessed the possibility that an undetected crack at that time could grow to 80% through wall over the 33 months to this current outage[†].

This was a complex geometry and unique weld in that several large repair welds were made. Figure 6 shows the WRS finite element model of the nozzle where the overall finite element mesh is shown. The weld analysis procedure consisted of application of the butter layer, post weld heat treat, machining of the butter, application of the alloy 182 weld (blue outline in Figure 6 with a double vee groove geometry), machining of the repair grooves followed by application of the repair welds (red outline in Figure 6), and then finally application of the stainless steel safe-end weld. Note that the ID repair weld is quite large and offset from the original weld slightly. The butter application required 167 passes to

[†] It is noted that more details of this analysis were provided in Brust, F. W., Punch, E., Kurth, E., Shim, D. J., Xu, H., Wilkowski, G., Rudland, D., and Rathbun, H. (2012), "North Anna Weld Residual Stress and Crack Growth Analysis", Final Summary Letter Report to US NRC, June, 2012.

model. The butter was then post weld heat treated and was then machined (both of which are modeled). The weld is deposited next using 110 passes where the ID groove was applied first followed by the OD. Next, the repair grooves were machined, and the ID repair deposited using 62 passes followed by the smaller OD repair in 9 passes. The large ID repair weld produced the dominant effect on WRS. Finally, the stainless steel closure weld was applied in 50 passes. Because the stainless steel weld is far from the DM weld (~7-inch) and the nozzle has a large thickness (~ 5-inch) the stainless steel weld had a small influence in the final WRS state, which is shown in Figure 7. It is seen that the hoop WRS are rather large to about half thickness and then decrease, then increase again. This results in rapid PWSCC growth at first, followed a crack growth bottle neck near half thickness, then more rapid growth until leakage, as will be seen next.

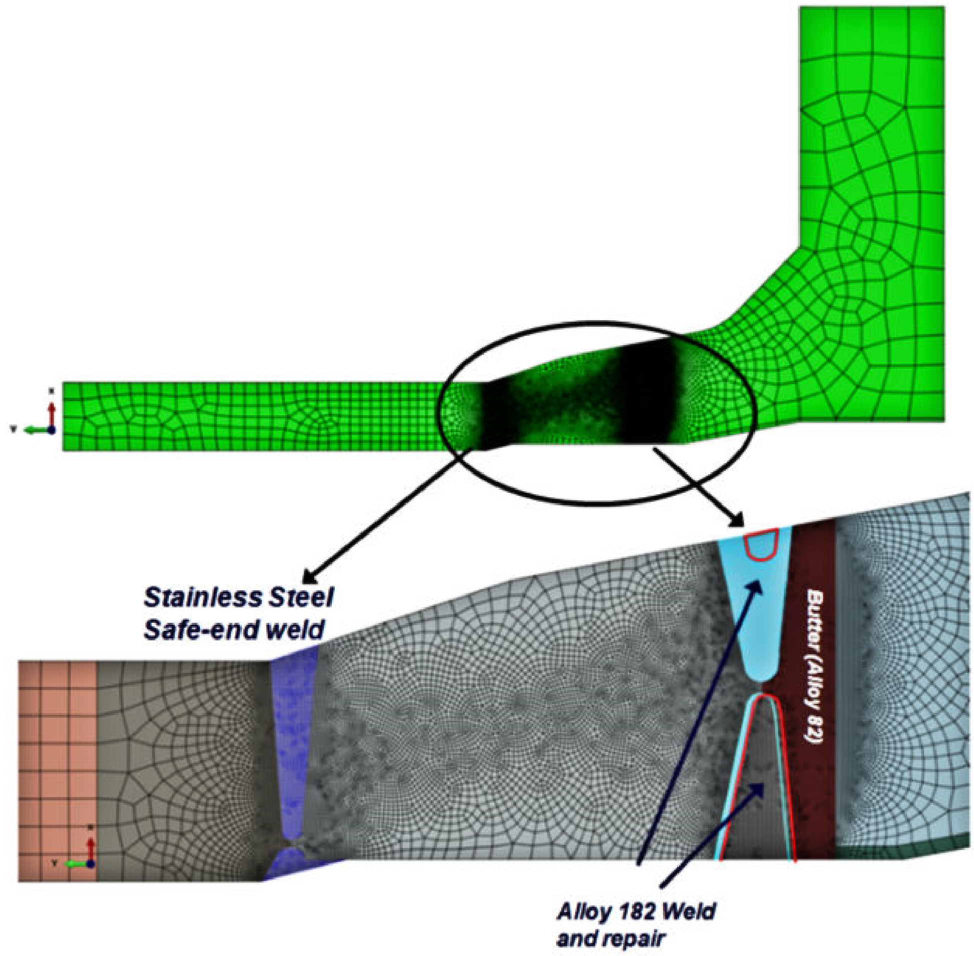

Figure 6 – North Anna nozzle illustrating the double vee groove geometry and repair welds

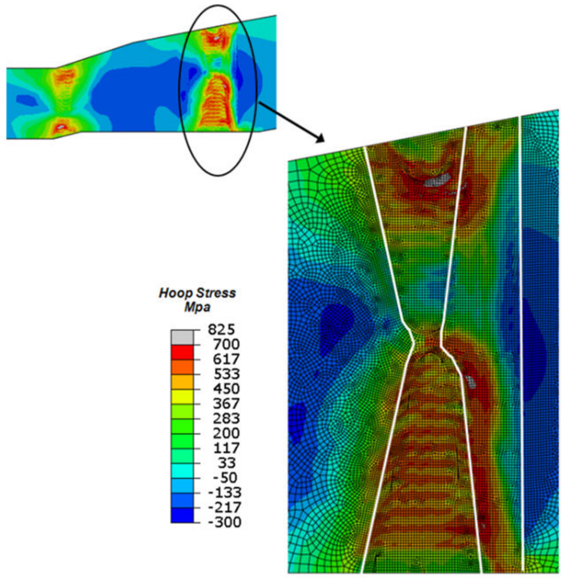

Figure 7 – WRS field in North Anna steam generator (SG) nozzle at operation temperature (322.5 C)

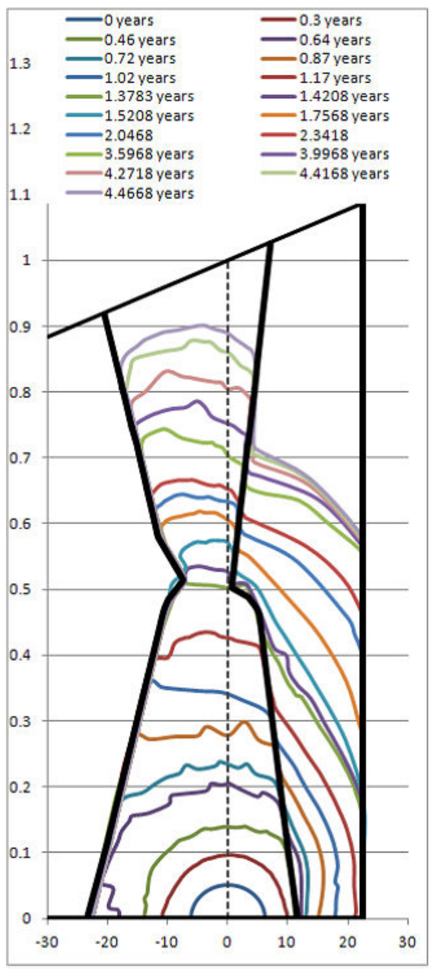

Figure 8 – Axial crack growth evolution in North Anna

The AFEA method was used to model crack growth to 92% of the thickness as seen in Figure 8. This can then be modeled using XFEM using the procedures in the Task 2 report (Hill et al 2020b) as an excellent validation case for a complex geometry with a complex residual stress field and complex PWSCC growth pattern. The evolution of crack shape versus time from the XFEM analysis will be compared to the results shown in Figure 8 for this validation case. This included circumferential and axial crack growth cases for a surge line size DMW, safety/relief line, and spray line.

3.2.3 AFEA of Pressurizer Surge Line Nozzle

Several AFEA analyses were performed for a European utility as summarized in Shim et al (2010)[‡]. The outer diameter and thickness of the surge nozzle were 387.2 mm and 41.1 mm.

3.2.3.1 Circumferential Crack Growth in Pressurizer Surge Line Nozzle

The operating conditions consisted of temperature of 345 °C, internal pressure 15.59 MPa, axial tension 39.51 MPa, and maximum bending stress of 74.54 MPa, along with a residual stress field shown in Figure 9. This came from a full WRS analysis using non-linear kinematic hardening (NLKN) and this represents the average WRS field within the weld region. NLKN was used because it was deemed to produce the fastest growing crack to leakage compared to isotropic hardening. The thermal analogy was used to impose the WRS field in the AFEA model and the service loads were included for growth crack growth.

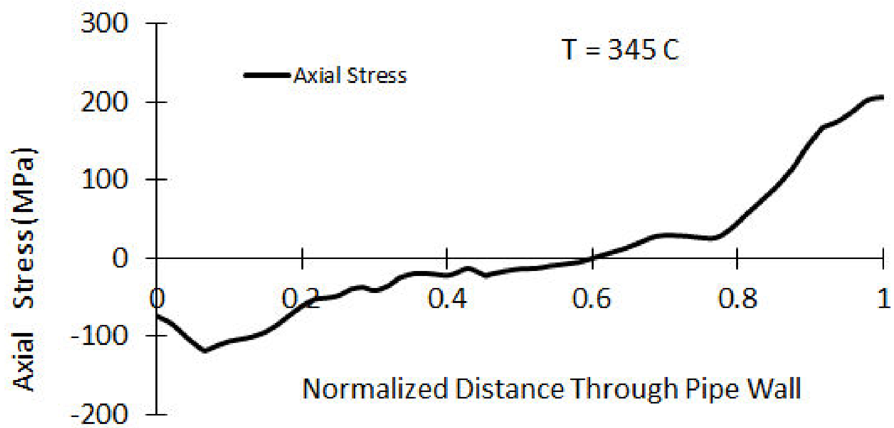

Figure 9 – Axial WRS field for surge circumferential AFEA crack growth modeling

The AFEA model and crack growth shape after 3.4 years of growth are illustrated in Figure 10. Three different initial flaw sizes were considered for these AFEA analyses. For all cases a_i/t (initial flaw depth over thickness) was 0.2 and three different initial crack lengths were considered ($2c_i/a_i$ = 20, 10, 7). The AFEA predicted crack growth shapes are shown in Figure 11. The actual years to leakage and growth of the through wall crack are available for XFEM validation purposes although Shim et al (2011) normalized all times to the time to leakage due to the sensitive nature of the actual leak time numbers.

[‡] Many more details of this assessment are available in the contractor reports to European utility if needed.

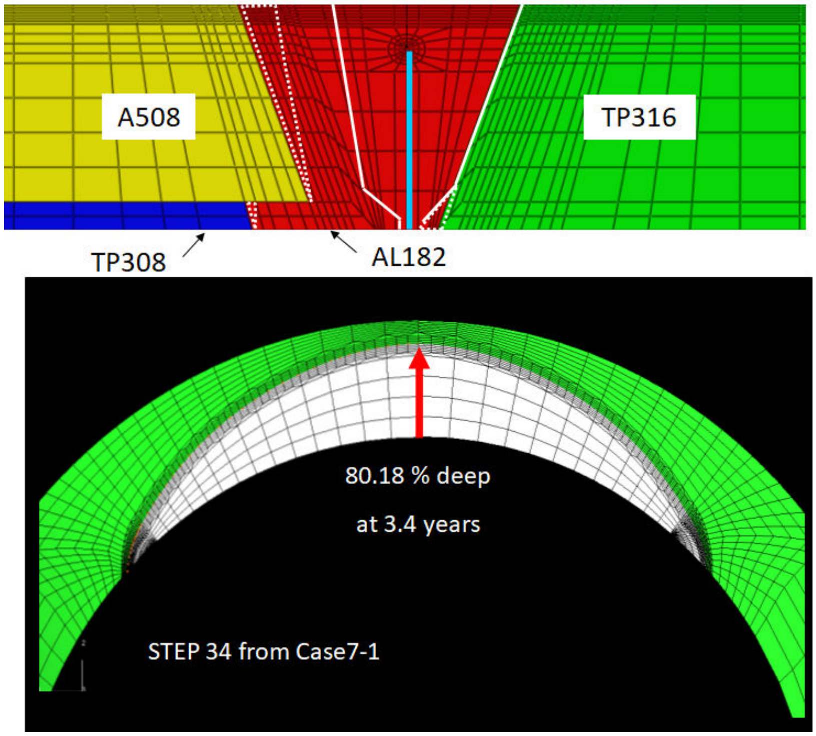

Figure 10 – AFEA model (top) and crack shape after 3.4 years

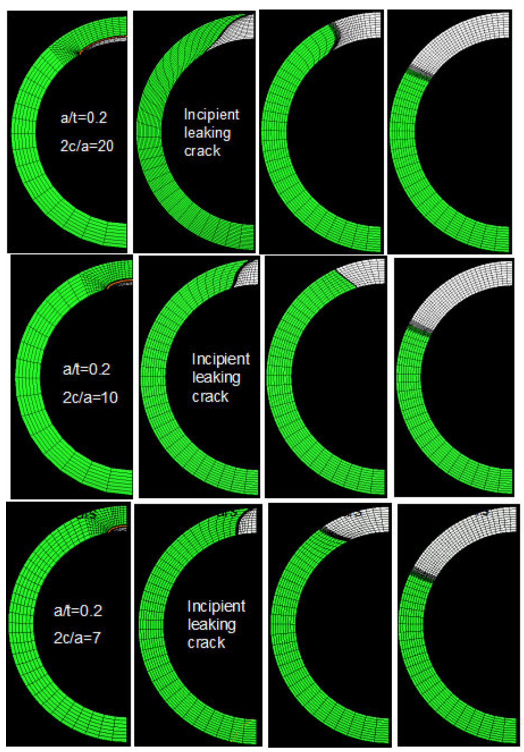

Figure 11 – AFEA model PWSCC growth for the three initial flaw sizes

This is an excellent example to examine the capabilities of XFEM because the surface crack growth and the through wall crack growth can be compared between AFEA and XFEM for three different initial crack sizes. The crack growth equation used is:

$$\frac{da}{dt} = C(K_I)^{\beta}$$

For surge temperature is 345 C, and C = 0.1102 mm/year with β = 1.6.

3.2.3.2 Axial Crack Growth in Pressurizer Surge Line

The hoop WRS field for the surge is shown in Figure 12 at 345 C (upper illustration). This is for the isotropic hardening analysis since, for axial crack growth, isotropic hardening produces the fastest time to leakage. The lower illustration is the crack mesh for the initial flaw with the WRS field mapped from the weld model (upper) to the lower crack mesh. PWSCC axial crack growth is limited to the weld metal. Figure 13 provides the crack growth pattern normalized by the time to leakage because results were sensitive. However, the actual times for each crack shape are available.

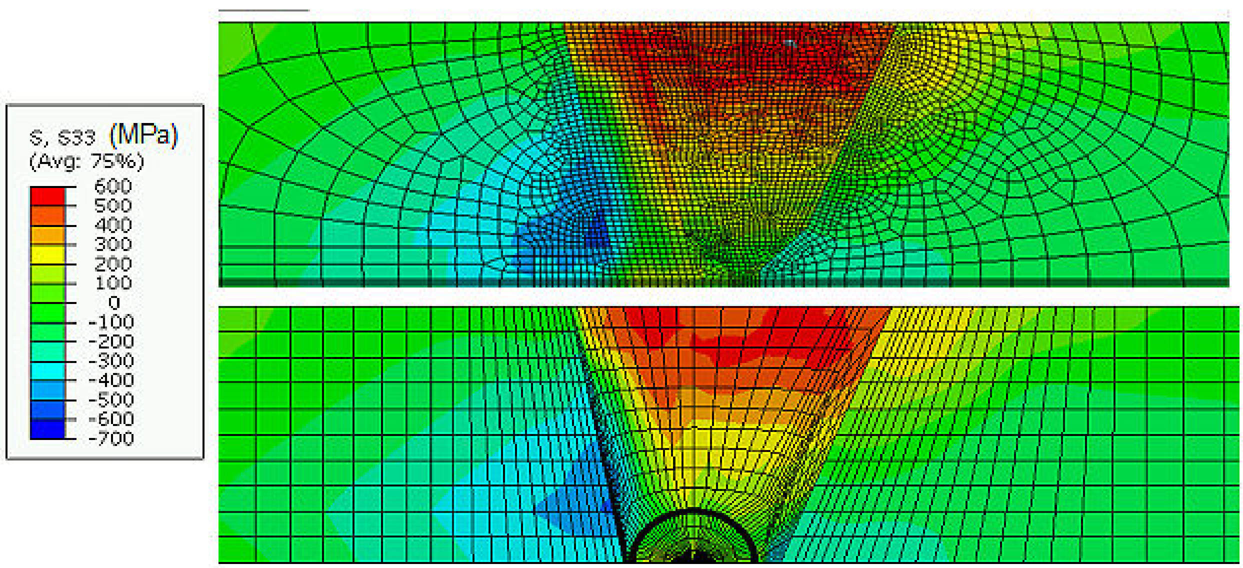

Figure 12 – Hoop WRS field in surge (isotropic hardening) at 345 C.

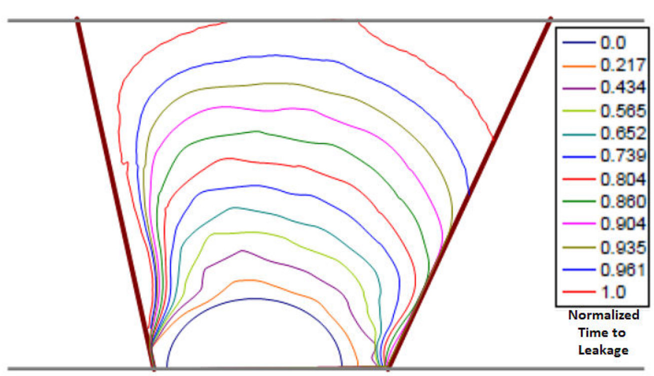

Figure 13 – Axial crack evolution growth patterns for surge for normalized time

This is a good problem to test the XFEM growth process for a complicated geometry. Note the crack does not grow very deep on the left side because the WRS field is low and even compressive along the butter/ferritic material interface. This may tax the XFEM approach and is a good check.

3.2.4 Axial Crack Growth in SG Nozzle K-Groove Weld

The SG validation case recommended here is interesting because the weld is a 'K-weld' as seen in Figure 14. The weld has an OD of 964.6 mm and thickness of 88.45 mm. The initial flaw depth is 6 mm and is circular as seen in the bottom illustration of Figure 14 and the WRS and crack growth analysis results are presented in Shim et al (2010)

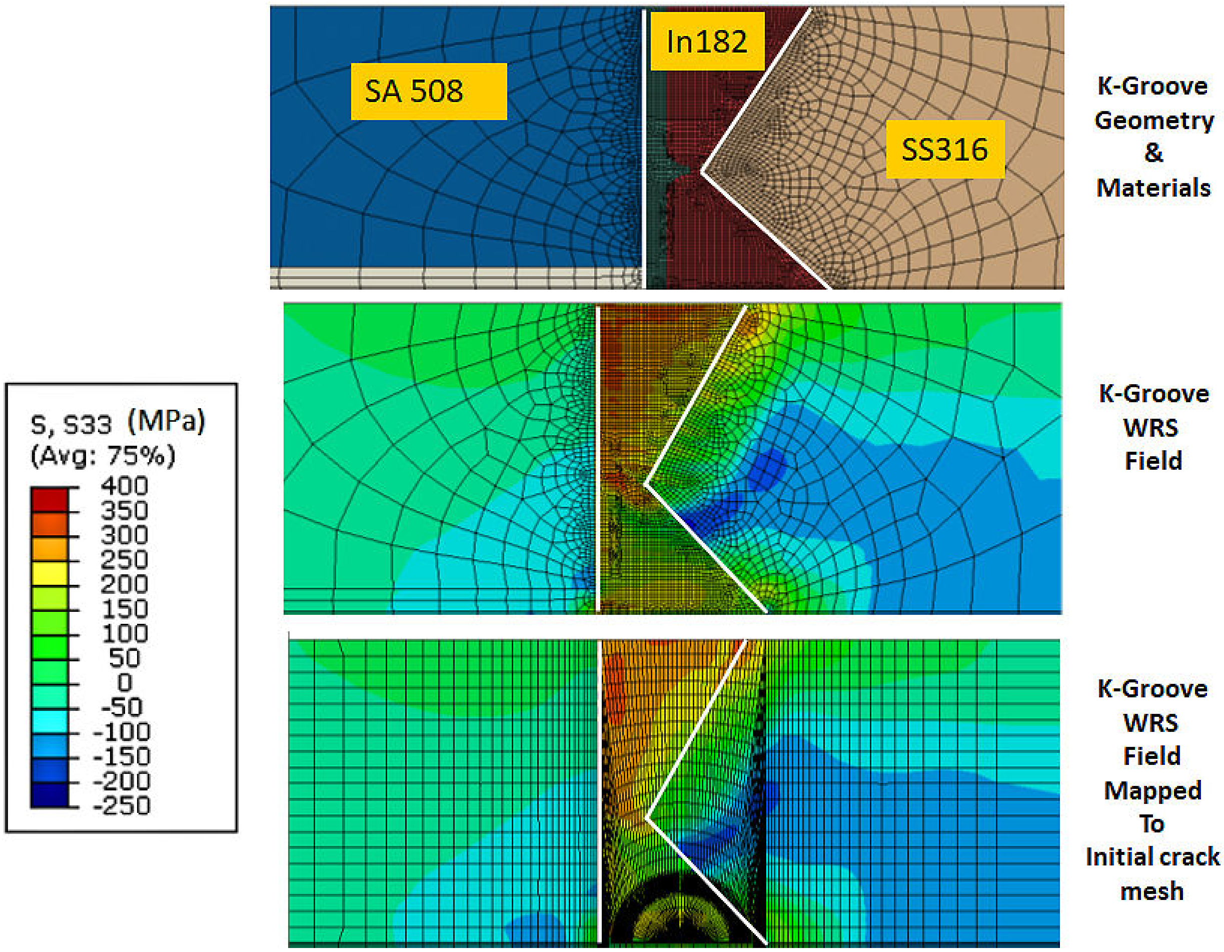

Figure 14 – SG K-Weld (top) and WRS fields (325 C) for AFEA and mapped to crack mesh

The operating conditions consisted of temperature of 325 C, internal pressure 15.68 MPa, axial tension 31.42 MPa, and maximum bending stress of 57.04 MPa, along with a residual stress field shown in Figure 14. The crack growth equation used is:

$$\frac{da}{dt} = C(K_I)^{\beta}$$

Here C = 0.0473 mm/year with β = 1.6.

The evolution of the crack shape is shown in Figure 15 from AFEA analysis. This is a good check case for XFEM because the geometry is difficult with the K-groove. The nozzle is also very thick as well. While Figure 15 normalized the time for each crack shape by the time to leakage, the actual times are available for the XFEM assessment.

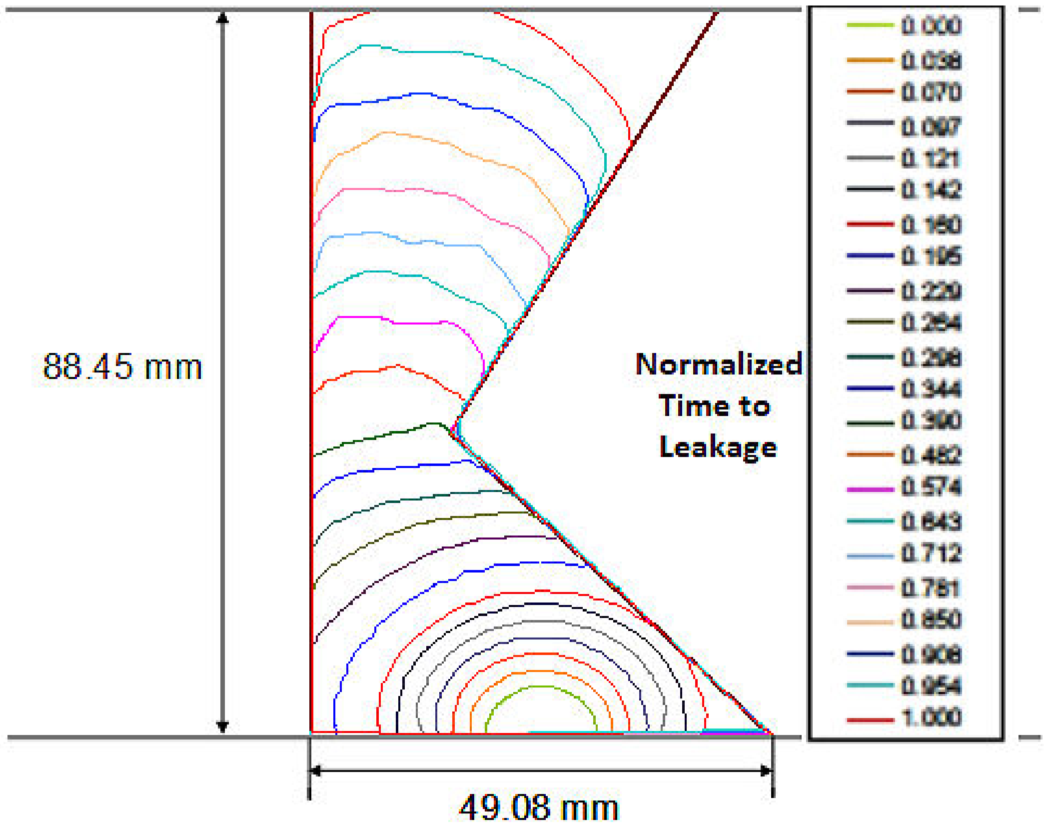

Figure 15 – Axial crack evolution growth patterns for SG for normalized time

3.2.5 Circumferential and Axial Safety/Relief and Spray Nozzle AFEA Crack Growth

There were two additional nozzles that were studied in Emc^2 (2010). These were not formally published in a publication but in the contractor reports. These cases could be considered as well for modeling by XFEM with permission from the utility. The safety/relief nozzle had ID of 138.2 mm with thickness of 32.65 mm. The spray nozzle had ID of 102.2 mm with thickness of 20.2 mm. Both axial and circumferential cracks were evaluated using AFEA. These could be good check cases because the thickness is lower compared to the cases considered above. The WRS fields are available for all cases. The crack growth evolution for the circumferential crack growth is also available for comparison to XFEM results up to and beyond leakage. Moreover, for both nozzles the axial cracks arrested and, therefore, through wall leakage was not predicted in the analyses. The axial cracks were predicted to grow only a short distance before crack arrest occurred. This is a good case to check XFEM predictions to see if crack arrest can be predicted with this approach.

3.2.6 Crack Growth in Inlay in a Hot Let Nozzle

AFEA based natural crack growth assessments were made for an inlay repair case. Apparently, the XFEM implementation within Abaqus does not permit multiple material crack growth modeling at present. However there may be alternate modeling strategies that would allow for this analysis using Abaqus XFEM even at present. Alternatively, future updates of the Abaqus XFEM implementation might overcome this limitation.. Therefore, the description for this type of a crack growth analysis is included for completeness. Figure 16 illustrates the geometry for an inlay repair with details provided in Rudland, Brust, Zhang, Shim, and Wilkowski (2010). The fabrication process is complicated. Buttering is applied followed by deposition of the alloy 182 weld metal, then deposition of the stainless steel weld. Next the area for the inlay (black in Figure 16) is machined away and alloy 52 inlay material is deposited using temper bead weld process which requires the deposition of very small weld layers. This requires a very fine mesh in the inlay region. There were a number of cases considered with varying repair depth and therefore WRS fields. The case in Figure 16 represents a 50% repair being made before application of the stainless steel weld although other cases were considered as well.

The PWSCC growth rate in the alloy 52 material is about 1/100 of that in the alloy 82 material as discussed in Rudland, Brust, Shim, Wilkowski (2011). For axial crack growth this means that the crack will grow much slower in the alloy 52 compared to the alloy 82. This leads to a 'bubble' crack growth shape once the flaw enters the alloy 82 material beyond the inlay and begins growing much faster within this material as was previously illustrated in Figure 16.

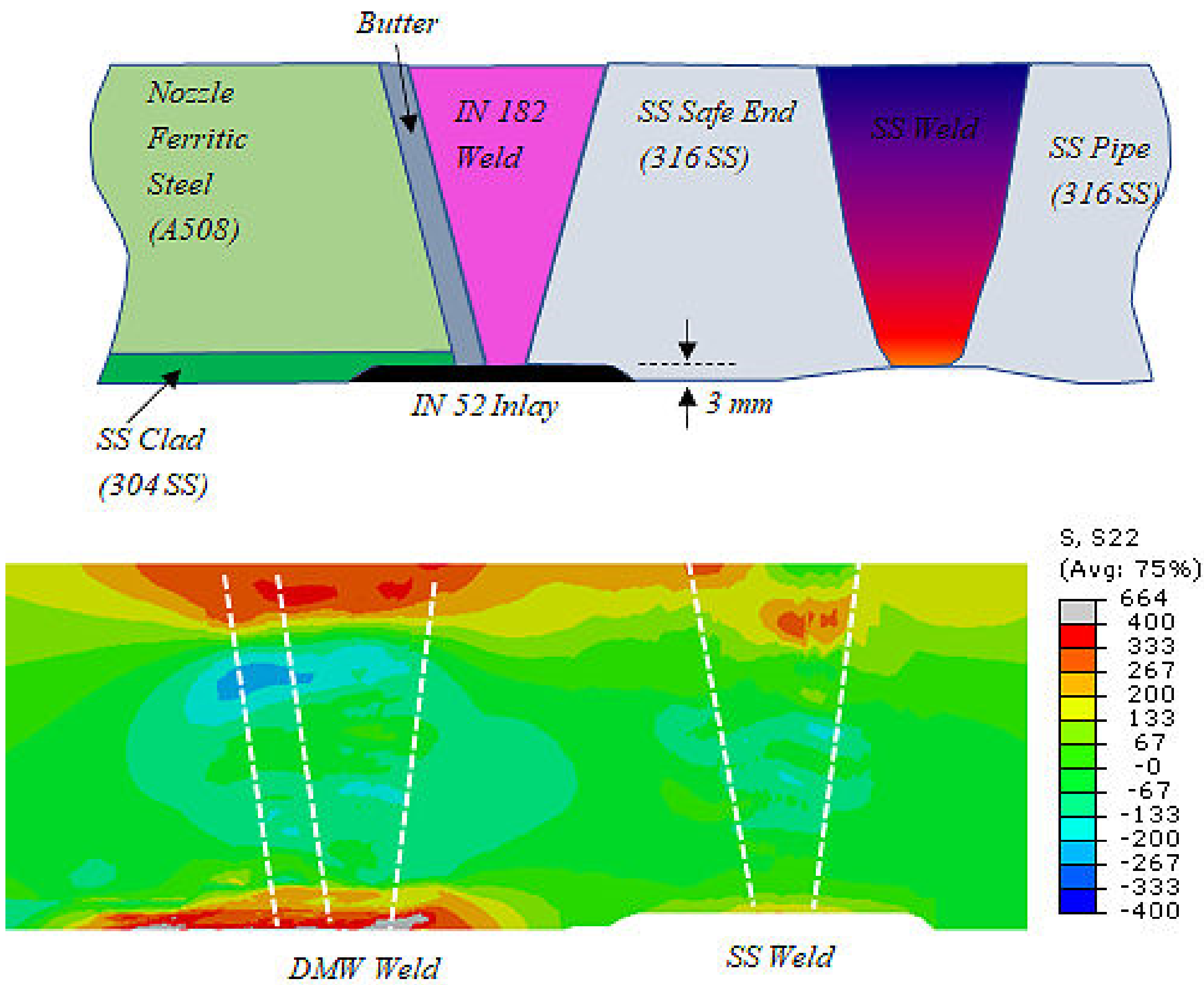

Figure 16 – Inlay geometry and axial WRS field for Hot Leg (326 C)

As seen in the bottom illustration in Figure 16, the inlay deposition leads to high tensile stresses at the ID of the nozzle. The OD for this hot leg nozzle is 872 mm with thickness of 68 mm. In addition to the WRS field, the crack growth was performed with internal pressure of 15.5 MPa, axial stress of 38.6 MPa, bending stress of 96.5 MPa at a temperature of 326 C and the effects of crack face pressure were included. The details of the modeling are provided in Rudland, Brust, Zhang, Shim, and Wilkowski (2010) and Rudland, Brust, Shim, Wilkowski (2011), including crack growth profiles to compare with.

The evolution of the crack shape is shown in Figure 17. It takes 31.5 years for a leak to occur and 34.2 years for crack instability to be predicted. Because of the WRS field, the crack slows down in the middle. The 'bubble' shape of the crack is evident just before leakage (green curve). The evolution of the crack is shown in more detail in the references. The other cases, with different WRS fields because of the different repair scenarios, show quite different times to leakage and crack evolution. In one particular case which considers a 50% repair to have occurred prior to application of the inlay, the predicted leakage occurs at 11.6 years. Both cases could be considered for XFEM assessment along with a number of other solutions shown in Rudland et al (2011).

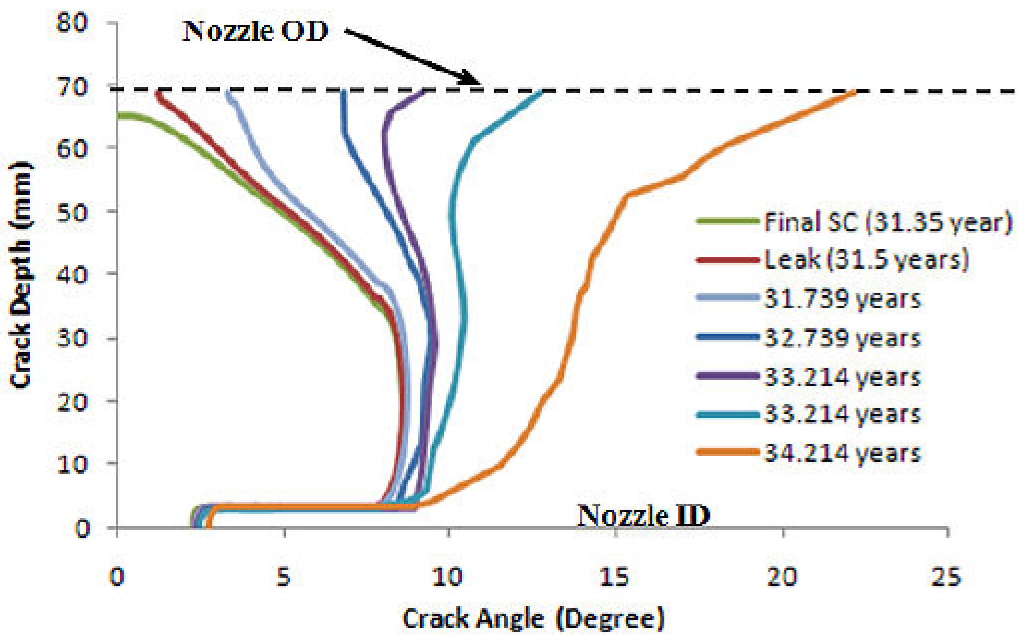

Figure 17 – Inlay AFEA crack growth for Hot Leg (326 C) (Case 1)

3.2.7 Natural Crack Growth in CRDMs

In February 2001, a U.S. plant operator discovered two long circumferential cracks above the J-groove welds of a CRDM nozzle in the upper head of their reactor pressure vessel. Both cracks lengths were 165 degrees around the outside diameter circumference, with one of them having a pinhole leak on the ID surface and the other having a small through wall leaking crack on the ID surface. The cracks initiated on the OD of the tubes. Because of the concern for possible tube ejection crack growth assessments were made using idealized crack shape modeling to develop inspection intervals to prevent the possibility of tube ejection. Here AFEA of a center hill and 53-degree nozzle were made to determine the validity of the idealized crack growth. These analyses can be used as an XFEM validation case. The details of this analysis are provided by Shim, Punch, Wilkowski, and Brust (2011).

The circumferential cracking on the OD surface occurred due to water leaking through separate through wall axial cracks in the tubes. The water within the annular region between the tube and head created a highly corrosive environment. During manufacturing of the head, the tubes are shrink fit into the reactor pressure vessel (RPV) hole, but at operating temperature and pressure there can be a very small annular gap. As water boiled/leaked out of the annular gap region, a higher concentration of boric acid may occur near the J-weld. Therefore, the concentration of boric acid in that region is much higher and may be a more severe cracking environment than created by the water inside the RPV. The precise composition of the water chemistry in the annular space is not known, but in the MRP-55 report, they suggested using a factor of 1.5 to 2 on the crack growth rate to account for this environment. The severe environment may also affect the crack initiation time and threshold stress intensity factor. A question of concern was that if leakage were detected, how long could the plant operate until an insufficient margin against failure was reached. These actions helped plants schedule detailed volumetric inspections, and initiate repairs or replacements of whole RPV heads.

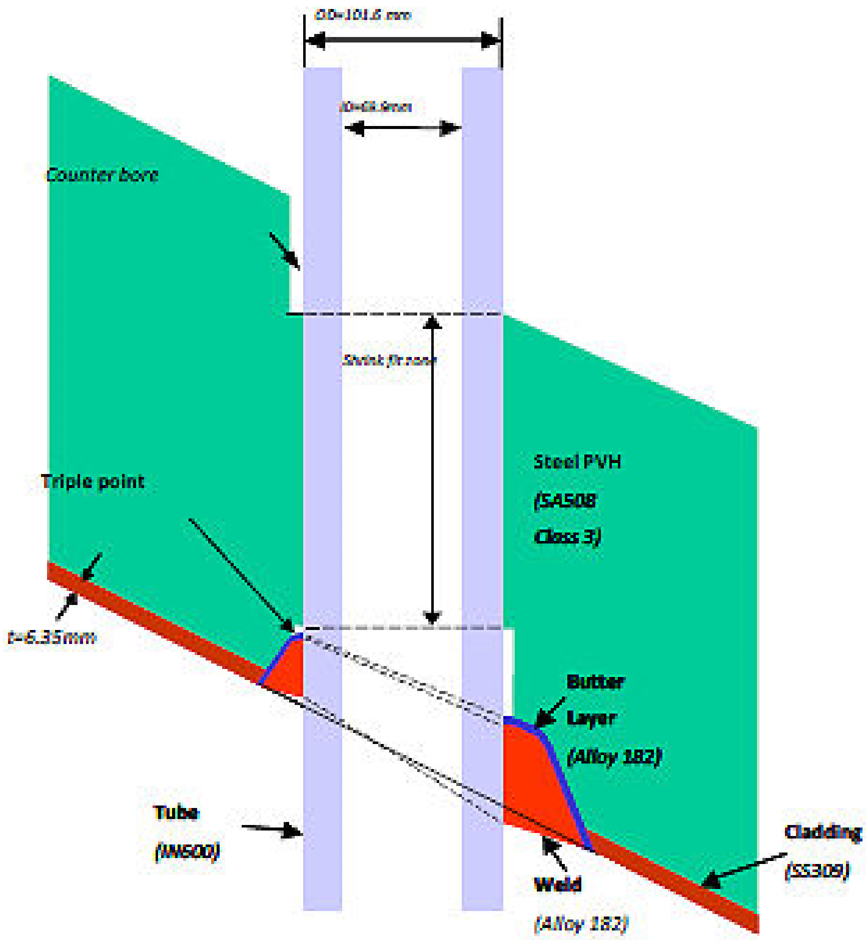

Figure 18 – Typical CRDM reactor vessel head J-groove weld

3.2.7.1 Center Hole Case

The Combustion Engineering head considered here is illustrated in Figure 19 where the center hole is shown. The side hill case of steepest angle hole, 53-degree, is considered next. The tube OD is 101.6 mm and thickness 15.875 mm.

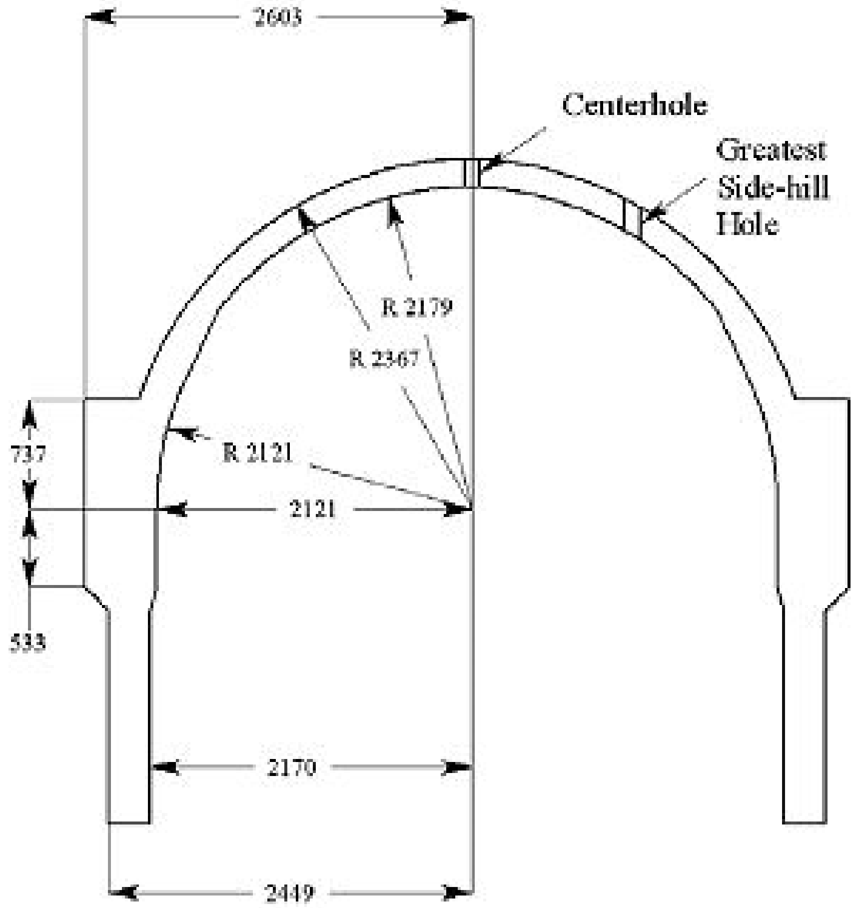

Figure 19 – Combustion Engineering CRDM head geometry (dimensions in mm)

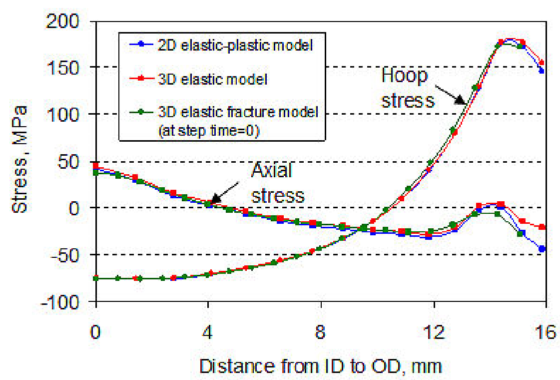

Figure 20 – WRS field in center hole tube (2D weld model, 3D revolved, and fracture model)

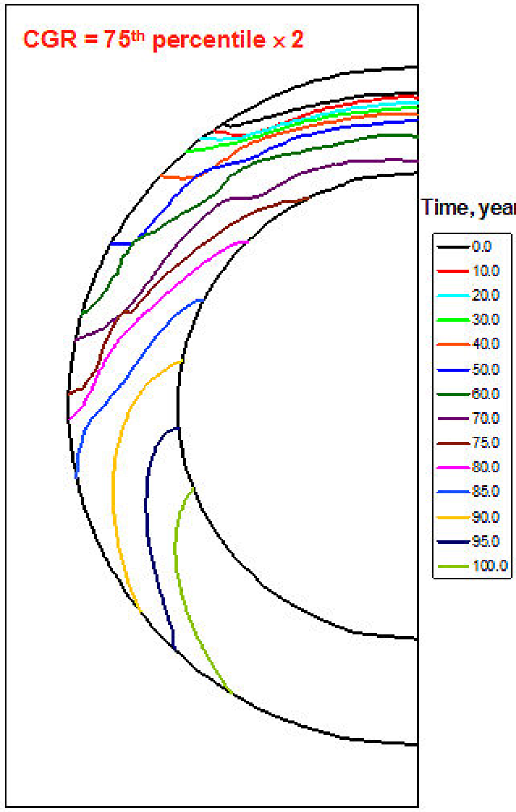

Figure 21 – Crack growth evolution for center hole case. Initial flaw a/t = 0.25, 2c/πD = 0.188.

The crack growth rate equation used here is:

$$\frac{da}{dt} = 2C\left(K_{eq} - K_{th}\right)^{\beta}$$

with C = 1.9576 E-12, β = 1.16, and K_{th} = 9 (MPa-m$^{.5}$). Because tube growth in an angled tube is mixed mode, K_{eq} here is the equivalent stress intensity factor determined from J to account for mixed mode ($K_{eq}=(JE)^{0.5}$). For the center hill case $K_{eq} = K_I$. The factor of '2' in the growth rate equation is to account for the increase in PWSCC in annular space environment. Note also that there is a threshold value of K_{th} in this equation.

The weld model consisted of a 2D axisymmetric model where the shrink fit between the head and tube if first modeled, followed by weld modeling, hydrotest, and operating temperature of 318 C. The model is then revolved to 3D and mapped to the crack model where PWSCC is modeled. The WRS field used to drive the tube axial PWSCC is shown in Figure 20 and PWSCC evolution in Figure 21. This case can be modeled with XFEM and compared to these AFEA results. The K values estimated in the AFEA analysis (Shim et al 2011) can be also compared to XFEM predictions.

3.2.7.2 Maximum (53-degree) Side Hill Case

The finite element model for the PWSCC analysis for this case for the initial crack size is shown in Figures 22 and 23. The crack is inserted on the downhill side and kept 1 mm above the triple point. The WRS field for this case was shown in Shim et al (2011).

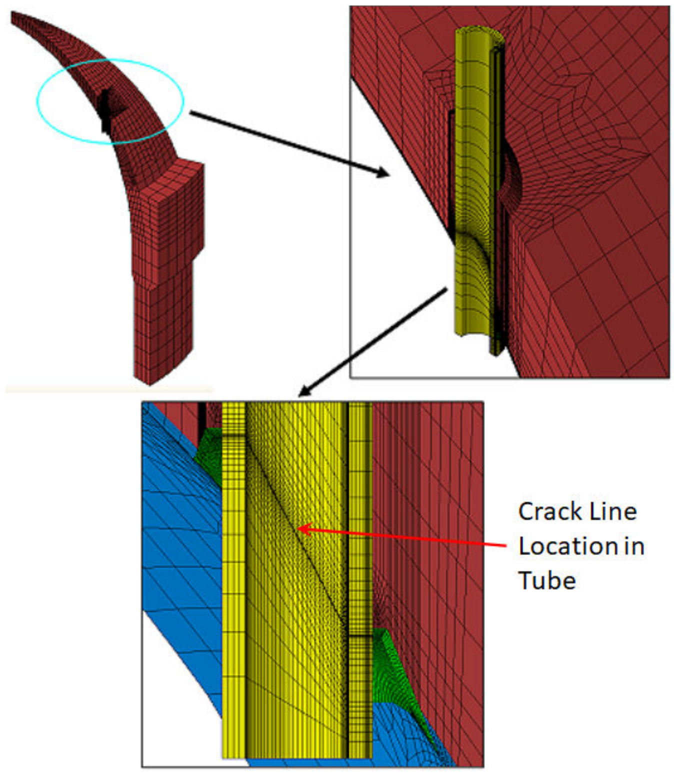

Figure 22 –Crack finite element model for 53-degree CRDM case.

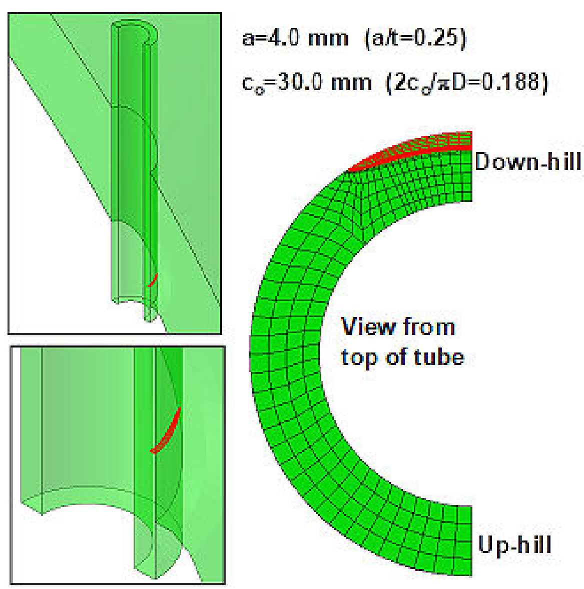

Figure 23 –Initial crack size and location for 53-degree CRDM nozzle

The crack growth evolution is seen in Figure 24 where the left illustration included a threshold value of K while the right illustration did not. This is a good validation case for XFEM since mixed mode K is involved here. There are additional PWSCC cases that can be considered also within Shim et al (2011).

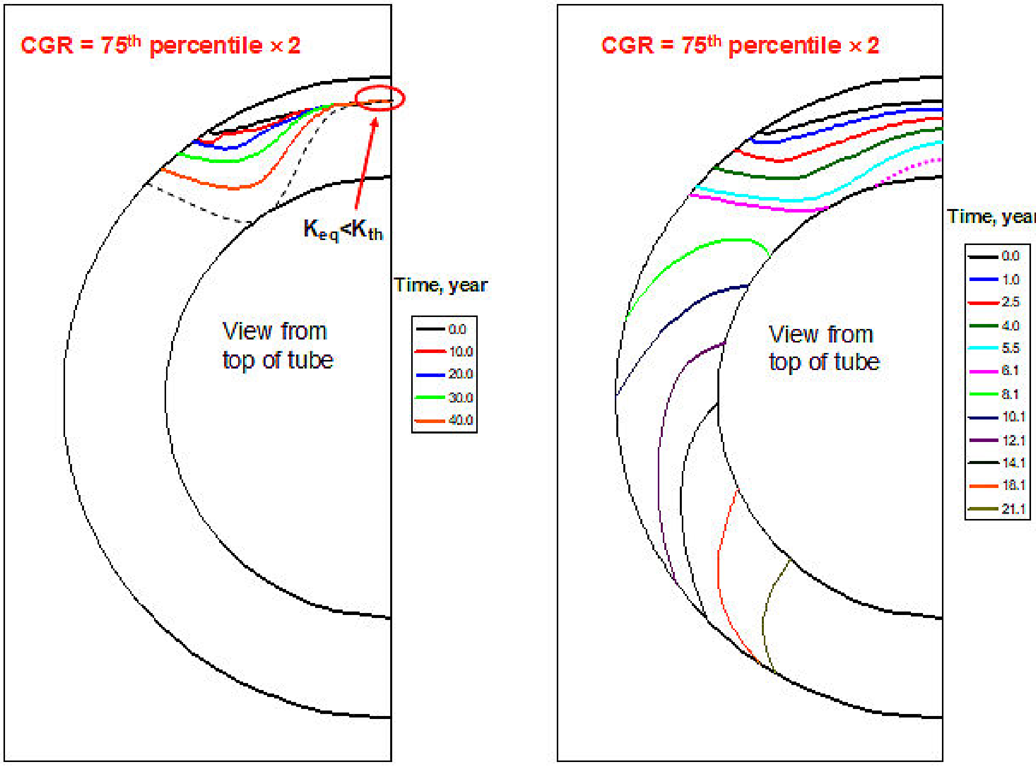

Figure 24 –Crack growth evolution for 53-degree crack (left including K_{th}; right K_{th}=0)

3.2.8 Multiple Flaws in CRDMs with FEAM

Brust, Zhang, Shim, and Wilkowski (2010) and Zhang, Brust, Wilkowski, and Rudland (2009) developed stress intensity factors for multiple flaws in CRDM heads based on multiple indications found in some heads. An example of the indications found in service for a particular head (discussed in Brust et al (2010) is seen in Figure 25. The details of the WRS analysis and mixed mode stress intensity factors calculated using the FEAM approach are provided in the references. This is a good check case for XFEM because multiple cracks and crack interaction along with mixed mode stress intensity factors can be checked.

In addition, there are additional multiple crack solutions in Delieu, P., Lacroix, V., Shim, D. J., and Brust (2015) that can be used to compared a variety of geometries and crack interaction distances which include mixed mode behavior. These solutions were made using both XFEM and FEAM methods.

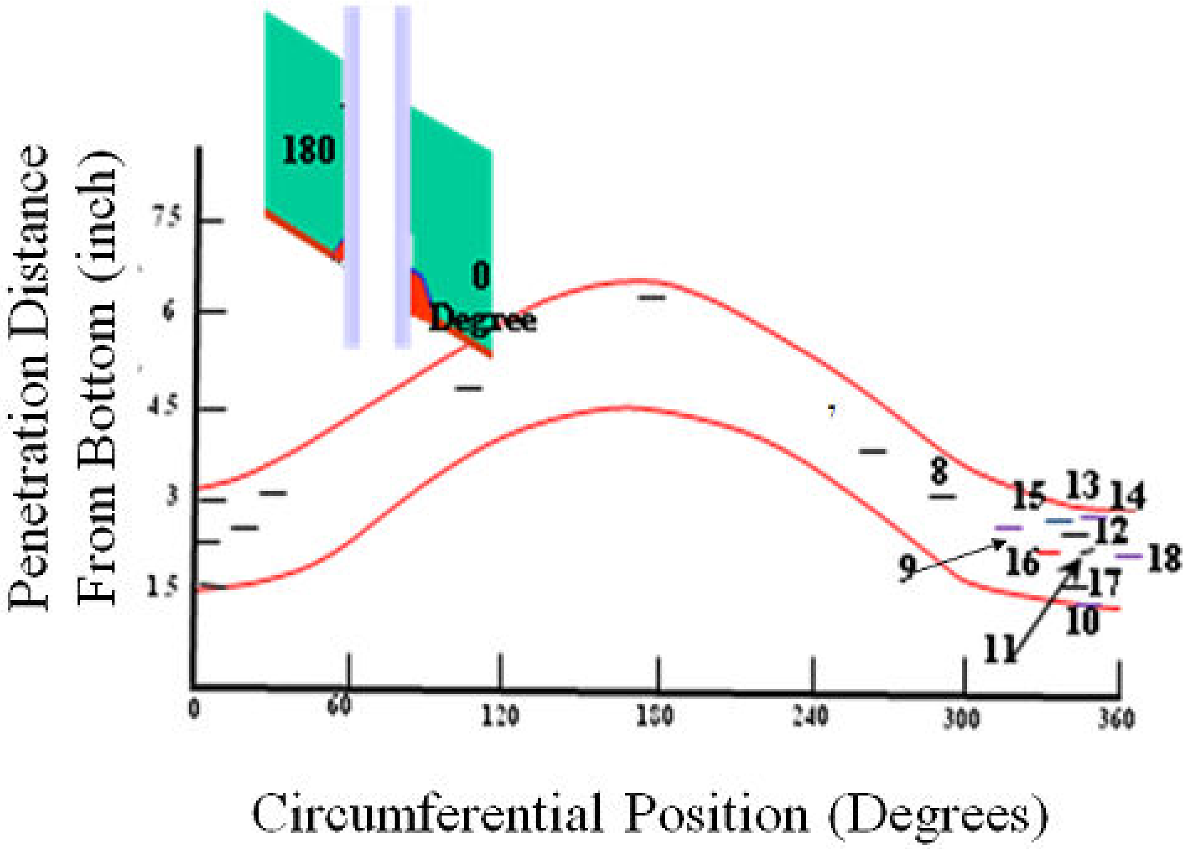

Figure 25 –Multiple crack indications found in CRDM for analysis

4 RECOMMENDATIONS AND CONCLUSIONS

During the course of the project, the built-in Abaqus XFEM capability was shown to adequately model relatively simple planar crack growth PWSCC and constant amplitude fatigue applications when prescribed modeling recommendations were followed. In addition, Abaqus XFEM analyses were performed to determine the applicability of these recommended modeling practices in complex geometries with planar crack growth relevant to the nuclear power industry. Specifically, the Abaqus XFEM crack propagation results were compared to several traditional PWSCC crack growth analyses for a CRDM nozzle and RPV outlet nozzle.

Still for this built-in Abaqus XFEM capability, solution stability remains a concern which may require sensitivity runs to obtain a solution. However, the built-in Abaqus XFEM capability for this application can be performed with reasonable results predicted if convergence occurs. However, it is recommended that analyses be performed using two methods to verify the Abaqus XFEM solution and to ensure a converged solution. For instance, if a relief request came into NRC from a vendor or operator, it is suggested that an Abaqus XFEM analysis be performed along with one of the other PWSCC assessment procedures. This might mean that for simple pipe geometries with circumferential crack growth the FES code or the automated AFEA procedures might also be used to perform the PWSCC analysis and corresponding LBB assessment. For more complicated geometries an FEAM assessment along with Abaqus XFEM might be performed to ensure consistency in results. Once XFEM is verified for a particular type of crack growth in a component and WRS field, then additional sensitivity analysis might be performed using Abaqus XFEM alone.

If an XFEM capability code other than Abaqus is utilized, it is recommended to start with the semi-elliptical flaw in a flat plate subjected to cyclic membrane fatigue loading analysis that was described in Task 2. In addition to allowing the user to understand the nuances of that code, it serves as a natural surrogate for circumferential and axial flaws albeit with infinite radius. After that, the user can proceed to the PWSSCC Compact Tension and then to complex geometries.

Regardless of XFEM code utilized, a wealth of potential benchmark solutions that have been described in Section 3 of the report provides a summary of ten solutions performed by the NRC staff, contractors and nuclear industry. The benchmark solutions presented here provide references along with other data necessary to perform Abaqus XFEM solutions and predicted results using other PWSCC growth methods for benchmark comparisons. Depending on the precise needs of the intended final application, a suitable PWSCC benchmark will likely be available.

REFERENCES

1) S. X. Xu, D. A. Scarth and R. C. Cipolla, "Calculation of Stress Intensity Factor for Surface Flaws Using Weight Functions with Piece-Wise Cubic Stress Interpolation ASME Section XI Appendix A," Proceedings of the 2012 ASME Pressure Vessel & Piping Division Conference, PVP2012-78236, 2012.

2) D.J. Shim, S. Xu, D. Lee, "Closed-Form Stress Intensity Factor Solutions for Circumferential Through-Wall Cracks in Cylinder," paper # PVP2014-28049, Proceedings of the ASME 2014 Pressure Vessels & Piping Division Conference - PVP2014, July 20-24, 2014.

3) Anderson, T.L., "Stress Intensity and Crack Opening Area Solutions for Through-wall Cracks in Cylinders, and Spheres," Structural Reliability Technology final report to The Materials Property Council, Inc., January 29, 2003.

4) Brust, F.W., Zhang, T., Shim, D.-J., Wilkowski, G. and Rudland, D. (2011), "Modeling Crack Growth in Weld Residual Stress Fields using the Finite Element Alternating Method," 2011 ASME Pressure Vessels and Piping Division Conference, Baltimore, MD, USA.

5) Brust, F. W., Shim, D. J., Wilkowski, G., and Rudland, D. (2011), "PWSCC Crack Growth Modeling Approaches," Proc. ASME PVP conference, July 17-21, Baltimore, MD.

6) Brust, F. W., Punch, E., Shim, D. J., Rudland, D., and Rathbun, H. (2013), "Weld Residual Stress Analysis and Axial PWSCC Predictions in a Double Vee Groove Large Diameter Nozzle," Proc. ASME 2013 PVP conference, Paris, France, paper PVP2013-98065, July.

7) Brust, F. W., Punch, E., Kurth, E., Shim, D. J., Xu, H., Wilkowski, G., Rudland, D., and Rathbun, H. (2012), "North Anna Weld Residual Stress and Crack Growth Analysis," Final Summary Letter Report to US NRC, June, 2012.

8) Brust, F. W., Zhang, T., Shim, D. J., and Wilkowski, G. (2010), "Evaluation of Fabrication Related Indications in Reactor Upper Head Penetrations," Summary Report to US NRC as part of the Component Integrity Program, July 27.

9) Dassault Systèmes (2020). Abaqus/Standard 2020 User's Manual. Providence, RI, USA.

10) Dulieu, P., Lacroix, V., Shim, D. J., and Brust, F. W. (2015), "Benchmark for the Calculation of Quasi-Laminar Elliptical Cracks Interaction Under Bi-Axial Loading," Proc. ASME PVP Conference, Boston, MA, paper PVP2015-45788, July.

11) Emc^2 Final Reports to European Utility (2010), "Analyses for Sizewell B Power Station Nozzle Welds," Three Report Series for WRS, circumferential, and axial crack growth, 2010.

12) Hill, L.T., Brust, F.W. and Kalyanam, S., Facco, G. (2020a), "Support for XFEM Component Integrity: Task 1 Literature Survey," Submitted to U.S. Nuclear Regulatory Commission as part of Prime Contract NRC-HQ-25-14-E-0004 Task Order 31310019F0075, March 2020.

13) Hill, L.T., Brust, F.W. and Kalyanam, S., Facco, G. (2020b), "Support for XFEM Component Integrity: Task 2 Sensitivity Study of PWSCC-type Crack Growth in Abaqus XFEM," Submitted to U.S. Nuclear Regulatory Commission as part of Prime Contract NRC-HQ-25-14-E-0004 Task Order 31310019F0075, Draft 6/19/2020.

14) Hill, L.T., Brust, F.W. and Kalyanam, S., Facco, G. (2020c), "Support for XFEM Component Integrity: Task 3 Evaluation of PWSCC-type Crack Growth in Abaqus XFEM for Complex

Geometries," Submitted to U.S. Nuclear Regulatory Commission as part of Prime Contract NRC-HQ-25-14-E-0004 Task Order 31310019F0075, Draft July 2020.

15) Materials Reliability Program (2007), "Advanced FEA Evaluation of Growth of Postulated Circumferential PWSCC Flaws in Pressurizer Nozzle Dissimilar Metal Welds," MRP-216, Rev. 1, EPRI, Palo Alto, CA.

16) NASGRO, 2020, "NASGRO Fracture Mechanics & Fatigue Crack Growth Software," Southwest Research Institute (SWRI), San Antonio, TX.

17) NRC and EPRI (2020), "eXtremely Low Probability of Rupture (xLPR) code," NRC and EPRI, just released version 2, May.

18) Raju, I. S., and Newman, J. C. 1980, "Stress Intensity Factors for Internal Surface Cracks in Cylindrical Pressure Vessels", journal of Pressure Vessel Technology, 102 (4).

19) Rudland, D.L., Shim, D.J., Zhang, T., and Wilkowski, G. (2007), "Implications of Wolf Creek Indications – Final Report," Program final report to the NRC, August. ADAMS ML072470394.

20) Rudland, D., Shim, D. J., Csontos, A. (2008), Natural Flaw Shape Development Due to Stress Corrosion Cracking," Proc. 2008 ASME PVP conference, July 27-31, Chicago, Illinois.

21) Rudland, D., Brust, F. W., Zhang, T., Shim, D-J., and Wilkowski, G. M., "Evaluation of the Inlay Process as a Mitigation Strategy for PWSCC in Pressurized Water Reactors," Final NRC Report ML 101260554, April, 2010.

22) Rudland, Brust, Shim, Wilkowski (2011), "PWSCC Crack Growth Mitigation With Inlay," Proc. ASME PVP conference, Baltimore, MD, Paper PVP2011-57954, July.

23) Rudland, Brust, Zhang, Shim, Wilkowski (2010), "Evaluation of The Inlay Process as a Mitigation Strategy for Primary Water Stress Corrosion Cracking in Pressurized Water Reactors," NRC Report, ADAMS ML101260554.

24) Shim D. J., Kalyanam, S., Punch, E., Zhang, T., Brust, F. W., Wilkowski, G., Goodfellow, A., and Smith, M. (2010), "Advanced Finite Element Analysis (AFEA) Evaluation for Circumferential and Axial PWSCC Defects," Proceedings of the ASME 2010 Pressure Vessels & Piping Division, K-PVP Conference, PVP2010-25162.

25) Shim, D-J., Punch, E., Wilkowski, G., and Brust, F. W. (2011), "Natural Crack Growth of PWSCC in Control Rod Drive Mechanism Tubes," Draft letter report to US NRC on Emc^2 Project Number 09-S44-05, September.

26) US Nuclear Regulatory Commission, Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants: LWR Edition (NUREG-0800, Formerly issues as NUREG-75/087), 2013.

27) Zhang, T., Brust, F. W., Wilkowski, G., Rudland, D. L., and Csontos, A. (2009), "Welding Residual Stress and Multiple Flaw Evaluation for Reactor Pressure Vessel Head Replacement Welds with Alloy 52," Proc. ASME PVP conference, Prague, Czech Republic, Paper PVP2009-78112, July.