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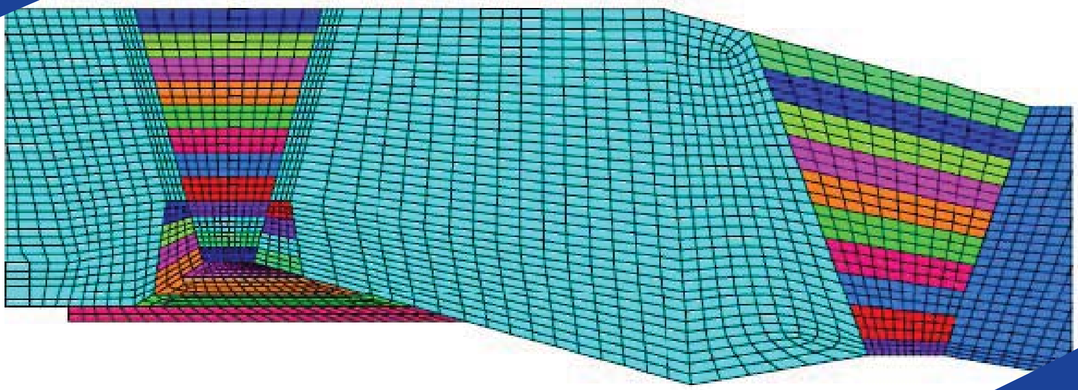
Materials Reliability Program: Primary Water Stress Corrosion Cracking (PWSCC) Flaw Evaluation Guidance (MRP-287)



Materials Reliability Program: Primary Water Stress Corrosion Cracking (PWSCC) Flaw Evaluation Guidance (MRP-287)

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ABSTRACT

Fracture mechanics-based evaluation to determine a flaw's acceptability to remain in service for a defined period of time is a well-established practice in the nuclear power industry. Rules for such analyses are contained in consensus standards to document acceptable procedures and criteria, yet may be broadly written to allow the analyst important latitude in selecting inputs and assumptions appropriate for a specific case. For example, ASME Boiler and Pressure Vessel (B&PV) Code, Section XI flaw evaluation guidance for piping states only that "appropriate experimental data on residual stress distributions for different pipe sizes should be used." Residual stress prediction or determination is imprecise at best but the dominant effect this rather "uncertain" attribute has on primary water stress corrosion cracking (PWSCC) growth calculations can control the evaluation outcome. Thus "latitude" in this case leaves the analyst to defend the fundamental credibility of the results without the "consensus" support for input selection typically derived from application of ASME Code rules. Practical and financial exigencies of a timely return to service for a nuclear power plant may make it expedient to opt for a costly and potentially unnecessary or hurried repair over the uncertainty of a potentially protracted defense of key analytical assumptions.

To address this problem, flaw evaluation experts representing industry and the U.S. Nuclear Regulatory Commission (NRC) staff held a workshop in late 2009 to review the Section XI flaw evaluation process and the required inputs specifically as applied to PWSCC-type flaws in Class 1 PWR piping systems. Consensus guidance was discussed emphasizing the attributes most important to achieving consistent results with greater inherent credibility. These results were distilled into the detailed written guidance presented in this report which has been reviewed by the original industry and regulatory participants and presented to the appropriate ASME Section XI Subgroups. This report supplements the requirements of ASME Section XI by providing detailed, peer-reviewed guidance for evaluation of PWSCC-type flaws in a consistent, technically defensible manner that will lend credibility to the results and facilitate their acceptance. However, it provides neither a cookbook approach nor guarantees automatic acceptance of the results in any technical or regulatory venue. Utilities should ensure PWSCC flaw evaluations for their plants incorporate the guidance contained in this report. They should also consider the recommendations for input data collection prior to planned inspections of PWSCC-susceptible components as a contingency to facilitate rapid evaluation of identified nondestructive evaluation (NDE) indications for acceptance, repair, or mitigation.

Keywords

Dissimilar metal butt-weld
Flaw evaluation
PWSCC (primary water stress corrosion cracking)
Welding residual stress

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INTRODUCTION / OBJECTIVE

With increased inspections being performed to address primary water stress corrosion cracking (PWSCC) susceptibility in Alloy 600 pressure boundary components and associated weldments [1, 2], the likelihood exists that crack-like indications will be detected which will be diagnosed as due to PWSCC, or for which PWSCC can't be eliminated as the potential cause. In many instances, disposition of such indications will involve some form of mitigation or repair, such as stress improvement or weld overlays. However, in some cases, it may be possible to disposition the indication(s) by flaw evaluation. The components in question are ASME Class 1, high energy piping and nozzle safe-ends, for which flaw evaluation rules and acceptance criteria are well documented in ASME Section XI [3]. However, detailed guidance is not provided for some aspects of flaw evaluations of PWSCC susceptible components, such as determination of appropriate residual stresses, for which Section XI states only that "appropriate experimental data on residual stress distributions for different pipe sizes should be used". This single attribute can have a dominant effect on PWSCC growth calculations and can thus control the outcome of an evaluation. The purpose of this document is to provide additional, peer-reviewed guidance on PWSCC flaw evaluation, including the topic of residual stresses, to facilitate the evaluation process and subsequent review of that process by the NRC. Another objective of this report is to outline steps that utilities can take in advance of the actual inspection outage, to expedite the evaluation process in the event that indications are detected that can be evaluated for continued operation without repair.

An overview of the Section XI flaw evaluation process is depicted in Figure 1-1. The two major aspects of the process are: establishment of an allowable, end-of-evaluation-period flaw size (horizontal dashed line in the figure), and calculation of projected future growth of the observed indication during continued service (solid curve in the figure). The intersection of these two lines represents the evaluation period. If this period is relatively long (e.g. ~10 yrs as illustrated in the figure), then flaw evaluation without mitigation or repair is a viable option. However, if the period is less than a fuel cycle, as can occur when analyzing PWSCC in high residual stress fields, especially at hot leg temperatures or greater, then acceptance of the indication by flaw evaluation is not generally practical, because reinspection would be required before the next scheduled refueling outage. In such cases, repair of the indication or some form of mitigation would likely be required. In these cases, the options for long term repair include removal of all or a portion of the detected flaw, reinforcement of the weld to increase the allowable flaw size, stress improvement to slow or halt the projected crack propagation rate, or combinations thereof. Under these options, key parameters in the evaluation, such as residual stress, flaw size or wall thickness, are physically modified so as to make a previously unacceptable evaluation acceptable (basically, extending the evaluation period to a practical inspection interval, typically the standard ASME Section XI ten year interval).

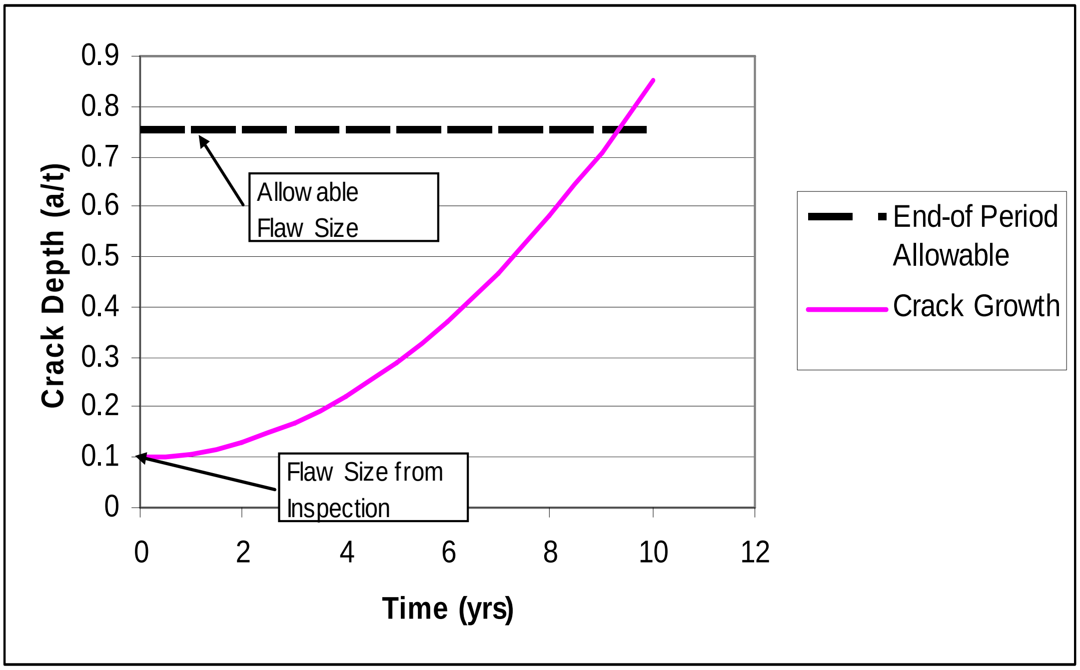


Figure 1-1
Schematic Illustration of ASME Section XI Flaw Evaluation Process

2

INPUT REQUIREMENTS

The first step in any flaw evaluation process is to collect the required input data. This step can be time consuming, since the input must be transmitted and verified in accordance with the Quality Assurance programs of the organizations involved (typically, the utility and the evaluation contractor). Involvement of the NSSS vendor may also be required (if that organization is not the evaluation contractor), since the necessary information is not generally in the public domain, and data releases may be needed, further lengthening the time required. Thus this activity should be considered a pre-outage preparation activity. In other cases the necessary data may already be in the utility's possession, and may be used as necessary to maintain their equipment.

Collecting the necessary data, and obtaining any releases that may be required for use of the data, are prudent steps that a utility can perform in advance of the inspection outage, once the specific locations to be inspected are known. Required input data for a flaw evaluation include:

- Vessel, nozzle and piping drawings, with sufficient dimensional details:
  - Necessary drawing information includes diameters, wall thicknesses, and materials for the vessel, nozzle, safe-end and piping.
  - It is important to know whether a safe-end is present and if so, the axial distance between the nozzle to safe-end weld (typically the dissimilar metal weld (DMW)) and the safe-end to pipe weld (typically the stainless steel weld (SSW))
  - Weld joint geometry for both DMW and SSW (butter, J-groove, single-V, double-V)
  - Weld process for both DMW and SSW (butter, root pass, was the ID machined and re-welded, any post-weld heat treatment (PWHT) performed, weld interpass temperature limits if available)
  - Welding sequence, i.e., whether the DMW was installed before or after any PWHT
- As-built dimensional information, if available:
  - Some of the above dimensional information may have been re-measured after construction. This information may be helpful in some aspects of the evaluation, such as residual stress analysis, but in general, the evaluation is performed with Design Report information which is based on minimum design dimensions. If a safe-end is present, as-built length of the safe-end has an important effect on residual stress analysis and should be obtained.
  - The construction process in many cases may have included some amount of cold-springing of the pipes for fit-up. However, the amount of cold-spring was rarely recorded or known. Nevertheless, it is reasonable to assume that welding residual stresses would overwhelm any elastic stresses due to cold spring, and thus cold-spring is not deemed to be a necessary input to the flaw evaluation.

- Vessel, nozzle, and piping stress reports containing design and operating loads and load combinations:
  - Normal & Upset loads (Service Levels A and B)
  - Emergency & Faulted loads (Service Levels C and D)
- Prior repair history, if available
- Applicable edition and addenda of ASME Section XI
- Current inspection reports specifying location, orientation and sizing of observed indication(s). (These of course cannot be obtained until after the inspections are performed, however, a useful pre-outage activity is to explicitly know the qualifications and limitations of the Inspectors and the Inspection process being utilized.)
- Prior inspection reports (if applicable).
- Material Properties – Several types of material properties are needed for a flaw evaluation:
  - For allowable flaw size calculations, the yield and ultimate tensile strengths of all structural materials in the components and welds are required. These may be obtained from component specific certified material test report (CMTRs) (if available), but as an alternative, ASME Code Section II minimums may be used. Use of Code minimums will generally result in significant conservatism, since the Code does not publish strength data for weld metals, and base metal properties are usually very conservative lower bounds of weld metal strength properties.
  - Some types of austenitic weld metals (SMAW or SAW) are considered to have limited toughness properties, in which case elastic plastic fracture mechanics (EPFM) rather than limit load methods must be used to determine allowable flaw size. Reference [4] contains an accepted EPFM approach, including the necessary material properties, for Alloy 82/182 weldments.
  - A wide range of material properties are required for residual stress analyses. These include complete, temperature dependent stress strain curves for all materials in the component (CS, LAS, SS, Cast SS, Alloy 82/182 weld metal, SS weld metal), as well as physical properties such as thermal expansion coefficient, thermal conductivity, and specific heat. For residual stress analyses, use of Code minimum strength properties may not be conservative, so the evaluator should confirm that his properties are consistent with CMTRs, and that the stress strain data and hardening laws have been benchmarked and validated generically for residual stress analysis (see Section 3.5, Attribute 5 below).
  - Other than CMTRs for the specific components, these properties are available from various sources, and generally do not need to be provided to organizations that perform Section XI flaw evaluations.

It is noteworthy that these same input data are required for most repair options, such as a weld overlay, in the event that the flaw evaluation is unsuccessful, so a utility that prepares in this manner is well-prepared no matter the outcome of the evaluation.

3
EVALUATION PROCESS

Flaw evaluations are performed in accordance with the requirements of ASME Section XI, IWB-3640, Evaluation Procedures and Acceptance Criteria for Flaws in Austenitic and Ferritic Piping [3]. The evaluation process summarized below is from Section XI Appendix C [3], a complementary, non-mandatory Appendix to Section XI that provides analysis details. Alternate analysis procedures, which demonstrate equivalent structural factors, are also permitted by Section XI (IWB-3644). However, in the U.S., the use of Appendix C has become essentially mandatory for this type of evaluation and if alternative methods are used, they must be justified and would likely be subject to a more intense and potentially more time-consuming level of regulatory review. In either case the analysis must be fully documented (including input, assumptions, analytical models and results), and, in accordance with Section XI [3], must be provided to the regulatory authority having jurisdiction at the plant site.

3.1 Flaw Characterization

Section XI Appendix C provides detailed guidance on how flaws are to be characterized for purposes of evaluation. The general approach is to bound the observed indication by a circumferential or rectangular planar area, as illustrated in Figure 3-1. Quantitative proximity rules are also provided for subsurface flaws that are very close to the surface (requiring them to be treated as surface flaws), and for multiple flaws in near proximity of one another (requiring them to be combined into a single, larger flaw that bounds the multiple flaws). Rules are also provided for projection of observed flaws into principal stress planes (axial or circumferential). The flaw characterization rules are well defined in Section XI, and do not need to be repeated here.

An inherent assumption in flaw characterization is that the inspection procedure was qualified for detection and sizing in accordance with Section XI, Appendix VIII, Supplement 10 [6]. Under that supplement, examination procedures, equipment and personnel are qualified for length and depth sizing to within specified RMS error limits, and therefore no allowance for sizing uncertainty needs to be added. (Note that Appendix VIII sizing qualification has not been achieved for some modes of examination performed, and thus a sizing uncertainty correction may be required if such examinations are not supplemented by other sizing methods for the flaw evaluation.)

3.2 Crack Growth Modeling

Section XI Appendix C requires that subcritical flaw growth be performed to determine the maximum depth and length (a_f and l_f) to which the observed flaw is projected to grow during the evaluation period. Flaw growth must be evaluated due the combined effects of stress corrosion cracking under sustained loads and fatigue due to cyclic loading. Appendix C explicitly states that residual stress effects shall be included in the evaluation of both mechanisms, and that appropriate data for residual stress distributions and flaw growth rates should be used. Detailed guidance on residual stress distributions for PWSCC evaluations is provided in Section 3.5 below.

A generally accepted source of PWSCC growth laws for Alloy 82/182 weld metals is MRP-115 [5] which has recently been incorporated into Section XI Appendix C [3]. These are temperature dependent, and guidance for adjusting the crack growth law to the applicable temperature is also provided. Figure 3-2 illustrates crack growth rates versus sustained stress intensity factor for some typical PWR operating temperatures, using values for Alloy 182 weld metal and the standard 75th percentile curve fit to the experimental data recommended for flaw evaluation in Ref. [5]. Note the significant temperature dependence, which translates directly into the flaw evaluation periods that will result from evaluations of components at various temperatures. Crack growth rates at typical hot leg temperatures are about a factor of 3.3 greater than those at cold leg temperatures, and crack growth rates at typical pressurizer temperatures are in turn about a factor of 3.5 greater than those at hot leg temperatures. MRP-115 also reports slower crack growth rates in certain circumstances (factor of 2.6 for Alloy 82 versus Alloy 182 and factor of 2 for crack propagation that is clearly perpendicular to the dendrite solidification direction for Alloys 182 and 82). So, if the DMW process, alloys and flaw location are known precisely, the evaluator may take advantage of these differences, but adequate justification must be provided if this approach is used.

Since the MRP-115 crack growth rates are specified in terms of stress intensity factor (K), the evaluator must compute stress intensity factors versus crack depth for all sustained stresses at the crack location. Equations are provided in Section XI Appendix C for K due to membrane and bending stress conditions, but not for more complex stress conditions such as residual stresses. More guidance on stress intensity factor calculations in complex stress fields is provided in Section 3.5.

Section XI Appendix C does not provide a recommended fatigue crack growth law for nickel-based alloys or their weld metals; however, it states that fatigue crack growth rates for materials not specifically covered in the Appendix may be obtained from other sources and that the growth rate curve should represent conservative values of fatigue crack growth rates for the appropriate environment, cyclic loading and R ratio. NUREG/CR-6907 [7] states that the fatigue crack growth rate of Alloy 82/182 in the PWR environment is a factor of ~5 higher than that of Alloy 600 in air under the same loading conditions. Thus, a fatigue crack growth rate for DMWs made of Alloy 82/182 filler metal equal to five times that for Alloy 600 in air may be used. A fatigue crack growth rate for Alloy 600 in air is published in NUREG/CR-6721 [8].

3.3 Allowable Flaw Size

Section XI, Appendix C [3] provides detailed screening criteria and procedures for allowable flaw size determination by Limit Load, EPFM, and LEFM. PWSCC evaluations generally fall into one of the first two categories, Limit Load or EPFM. For flaws in wrought base metal, non-flux welds, and cast products in which ferrite content is less than 20%, plastic collapse is the controlling failure mode, and limit load analysis, as prescribed in Article C-5000 of Ref. [3] may be applied. For flaws in flux welds, elastic plastic fracture mechanics (EPFM) methods as prescribed in Article C-6000 of Ref. [3] must be applied. Alloy 82 is a non-flux (GTAW) weld, while Alloy 182 is a flux (SMAW) weld. Most DMWs were fabricated with a combination of the two, and therefore the more conservative EPFM approach should generally be used.

For limit load calculations, the allowable flaw size is determined based on the ratio of the primary stresses at the weld location (Pm + Pb) to the material flow stress, defined as the average of the material yield and ultimate tensile strengths. The yield and ultimate tensile strengths may be obtained from ASME Section II, Part D for the pipe material and service temperature under evaluation, or, if actual (measured) material properties are known, the measured yield and ultimate strengths at the service temperature may be used. The allowable flaw size for limit load evaluation can be determined from tabular solutions provided in Article C-5000 of Section XI Appendix C, or alternatively by analytical solution to equations provided in that same article. In either approach, the evaluator must perform separate evaluations for Service Levels A through D, since the Code specifies different structural factors for each. An example of a typical flaw evaluation table is shown in Figure 3-3. The evaluator enters the table at the stress ratio listed in the first column, and scrolls over to the appropriate flaw length (normalized by pipe circumference), to determine the allowable flaw depth as a fraction of the pipe wall thickness. Note that ASME Section XI contains a maximum allowable flaw depth limit of 75% of the wall thickness, which often governs the allowable flaw depth in PWSCC flaw evaluations.

Allowable flaw size calculations for EPFM evaluations are addressed in Article C-6000 of Section XI Appendix C and may be performed using either tabular or analytical solutions. For EPFM evaluations, the applied stresses must include thermal expansion stresses for the various service levels, but with no structural factor applied (versus primary stresses for which the specified structural factors for each condition are to be applied), as well as Z-factors to account for non-limit load behavior. Review of Figure 3-3 illustrates that the same evaluation tables in Article C-5000 may be used for EPFM evaluations, using a modified stress ratio definition, as described in the footnotes.

Section XI Appendix C provides Z factor equations for austenitic weldments fabricated by shielded metal arc (SMAW) or submerged arc welds (SAW). However, these were developed for stainless steel weldments, and have been found to be overly-conservative for nickel-based alloy weldments. Alternative Z-factors for use with Alloy 82/182 weldments are reported in Reference [4].

Care must be taken in applying the allowable flaw size rules to DMWs to select the appropriate material properties for the evaluation based on the location of the flaw being evaluated. For flaws located on the carbon or low-alloy steel side of a dissimilar metal weldment, the Z-factor approach should be used, in conjunction with the material tensile properties of the Alloy 82/182 weldment. For flaws located on the stainless steel side of the DMW, limit load analysis may be used, but with the generally lower strength tensile properties applicable to the stainless steel material. Figure C-1100-1 of ASME Section XI Appendix C may be used to define the weld-base metal interface, using the weld centerline, as shown in that figure, to determine on which side of the weld the flaw is located. If the flaw is located near either fusion line of the weld, the analysis should consider the more conservative of the properties on either side of the fusion line.

3.4 Acceptance Criteria

Flaws evaluated using the above described analytical procedures are acceptable for continued service during the evaluated time period if the critical flaw parameters satisfy either of two acceptance criteria specified in Appendix C, Article C-2600.

The first acceptance criterion is based on flaw size. Under this criterion, the evaluator must demonstrate that:

$$a_f \leq a_{allow}$$

where:

a_f = maximum depth to which the detected flaw is calculated to grow by the end of the evaluation period

a_{allow} = maximum allowable flaw depth corresponding to the flaw length l_f and applied stresses

The allowable flaw depth is a function of the applied stresses plus applicable structural factors for each service level, and may be determined from a series of tables similar to that illustrated in Figure 3-3, or alternatively from analytical equations provided in Appendix C, Articles C-5000 or C-6000.

For axially oriented flaws, the final length of the flaw shall meet the following:

$$l_f \leq l_{allow}$$

where:

l_{allow} = allowable length limit for an axial through-wall flaw to remain stable under pressure loading.

l_f = maximum length to which the observed flaw is calculated to grow by the end of the evaluation period

This limit must also be established based on applicable structural factors for various service levels provided in Appendix C.

The alternative acceptance criteria are based on applied stresses. These require that the applied stresses meet the same analysis safety factors for the various service levels (Ref. [3] Article C-2620), relative to limiting stresses in the cracked section containing flaws equal to the final end-of-evaluation-period flaw sizes, a_f and l_f.

3.5 Residual Stress Modeling

As previously mentioned, residual stresses can have a dominant effect on PWSCC growth calculations and can thus control the outcome of a flaw evaluation. Yet little guidance is provided on residual stresses in Section XI Appendix C, other than to state that appropriate experimental data on residual stress distributions for different pipe sizes should be used. A major goal of this document is to provide supplementary guidance on residual stresses that will facilitate PWSCC flaw evaluations as well as USNRC review and acceptance of the same.

Finite element residual stress analysis procedures have been reported in the literature for many years [9-11]. In addition, experimental work has been performed to benchmark and validate analytical residual stress predictions [12-14], and a comprehensive residual stress measurement/analysis program is currently underway [15]. Appendix A summarizes the results of some of those programs.

The residual stress analysis process generally involves elastic-plastic two- or three-dimensional finite element modeling (FEM) which is used to simulate the steps of the fabrication and welding process. The first stage of the analysis is to develop the geometric model, which generally includes a portion of the vessel nozzle, nozzle buttering and cladding (if present), the DMW, the safe-end, safe-end to pipe weld and a portion of the piping (see Figure 3-4 for a typical FEM). Transient thermal analyses are performed with this model, simulating the sequential heating and cooling of the components as weld beads are applied. (A typical analysis sequence is illustrated in Figure 3-4.) The thermal analysis results are saved as a transient temperature history, and the model is then re-run in the elastic-plastic stress analysis mode to predict the transient thermal stress history of the components. Particular emphasis is given to the resulting stresses in the dissimilar metal weld, since that is the region of PWSCC susceptibility. Since elastic-plastic analyses are path-dependent, care must be taken to properly simulate the sequence of heating and cooling steps that take place during the welding, including the details and sequence of the welding and repair processes that govern the thermal history of the DMW. In most cases, two-dimensional (axisymmetric) models are used because the large number of elements in a three-dimensional model make elastic-plastic analysis very computer-time intensive. Nonetheless, some three-dimensional residual stress analyses have been performed. Material properties required for the analysis include temperature-dependent stress strain curves for all materials in the component (CS, LAS, SS, Cast SS, Alloy 82/182 weld metal, SS weld metal, as applicable), for temperatures ranging from room temperature to near the melting points of the materials, as well as physical properties such as coefficient of thermal expansion, thermal conductivity, and specific heat. In practice, material properties are generally not available over this entire temperature range, so the common practice is to interpolate linearly between the known properties at the highest temperature available, and appropriate assumptions for the properties at the material melting point (e.g. zero strength).

Because of the complexity of the process, most organizations that perform residual stress analyses have developed their own proprietary sets of methods and procedures. These procedures generally contain a number of approximations, such as ignoring creep and phase change effects, simplification of the actual welding pattern (bead sizes, start-stop effects, axisymmetric bead laydown versus simulating torch travel, etc.), as well as approximations in the heat transfer analysis (weld heat input, thermal efficiency factor, heat transfer boundary conditions, etc.). As such, verification and validation of these models can only be performed by comparison of various analysts' results and/or by comparisons to residual stress measurements performed on mockups. The latter approach has shown that there is significant variation between analysis and experimental results, as well as between experimental results obtained with different measurement techniques. An additional source of uncertainty is the significant effect of repairs performed on the weldment during the fabrication process (which may be either documented or undocumented in the fabrication records). However, by benchmarking the analysis method and performing sensitivity studies, as discussed in the Attributes section below, reasonably conservative residual stresses can be obtained that are appropriate for use in PWSCC flaw evaluations.

Some typical comparisons of analyses and measurements on mockups are presented in Appendix A, as well as a suggested validation criterion for analytical versus experimental comparisons. The results in Appendix A are presented at room temperature, because that is the temperature at which the residual stress measurements were taken. However, the analyst is cautioned that residual stress distributions for plant PWSCC evaluations must be adjusted to steady state operating temperature, and that stresses due to operating pressure and sustained applied loads must be added.

Review of the three mockup cases presented in Appendix A reveals some interesting insights into features of a weldment that can have a significant effect on the severity of the welding residual stresses. A summary of the ID surface stresses from these three cases (measured and average of the analytical results) is provided in Table 3-1.

Table 3-1
Summary of ID Surface Residual Stresses from Appendix A Mockup Cases

Case	Mockup Description	Measurements		Analysis	
		Hoop Stress (ksi)	Axial Stress (ksi)	Hoop Stress (ksi)	Axial Stress (ksi)
1	*European JRC Mockup (measured values extrapolated to surface)*	5.8[1]	-20.3[1]	-20.6	-32.3
2	*EPRI/NRC RPV Nozzle (Phase IV)*	20.6	-10.2	27.2	-11.7
2(a)	*Ph IV MU (Pre- SS Weld)*			93.6	65.0
3	*EPRI 36" Diameter OWOL*	90.0	92.0	96.5	63.0

1. *Note that the measured values for this case are based on the neutron diffraction (ND) measurement technique, which is considered to have significant uncertainty, especially at surfaces, for which they must be extrapolated.*

Case 1, the European JRC mockup, had no inside surface weld repair. The ID surface stresses in this mockup were compressive or low tension. PWSCC is unlikely in such a weld. Case 2, the EPRI/NRC Phase IV mockup, had an inside surface repair, but also had a stainless steel pipe-to-safe-end weld very close to the DMW (3.9 in. safe-end length). The SS weld relieved the highly tensile ID surface residual stresses from the ID repair, such that circumferential PWSCC would be unlikely (the axial stresses are compressive), but axial PWSCC might be expected (hoop stresses are moderately high tension). The last two rows of Table 3-1, Case 2(a), the EPRI/NRC Phase IV mockup analytical results prior to the SS weld and the EPRI 36" Diameter OWOL mockup are indicative of severe residual stress conditions for PWSCC – ID surface repairs coupled with no nearby SS safe-end welds. This condition produces very high tensile stresses in both the axial and hoop directions. In light of this observation, it is worth restating the importance of using the correct safe-end length when assessing the SS weld effect. A very long safe-end is expected to be the same as having no SSW at all, and would thus yield no beneficial effect of the SS weld. Although not quantified at this time, intermediate safe-end lengths are expected to have proportionately reduced stress relieving effects. However, if an extremely short safe-end is present, assuming a longer safe-end may also be non-conservative. Therefore, obtaining and using the as-built safe-end length in the residual stress analysis is highly advised.

It is also noteworthy that, in all four cases reported in Table 3-1, hoop stresses were consistently higher than axial stresses, leading to the observation that axial cracking is a more likely occurrence in these large diameter DMWs than circumferential cracking.

3.6 Attributes of an Acceptable Residual Stress Analysis

This section provides a list of attributes of an acceptable residual stress analysis for a PWSCC flaw evaluation, to ensure that weld residual stresses used in the evaluation are realistic or conservative. It does not provide a systematic description of the analytical method since it is assumed that individuals or organizations performing PWSCC flaw evaluations possess sufficient expertise to perform such analyses without step by step guidance.

1. Geometry and Materials: Diameters, thicknesses, lengths, tapers, etc. of the DMW and adjacent components (nozzle, safe-end, and pipe) must match or be reasonably close to those of the component being evaluated. Caution is advised when attempting to use analysis results from a different nozzle configuration than the nozzle under evaluation, unless the designs are essentially identical, or any relevant differences are reconciled with an appropriate technical justification. Material properties (mechanical and thermal) also need to be appropriately modeled.
2. Weld Configuration and Fabrication Sequence: Details of the DMW configuration are important to the residual stress analysis. Weld groove design and whether the nozzle and/or safe-end were buttered need to be modeled. In the case of buttering, if the nozzle was post weld heat treated (PWHT'd) after installation of the butter, and an ID weld repair or other form of ID welding is included in the analysis, then modeling of the butter welding process isn't necessary, but the exclusion of this step should be justified. Also, in Ref. [16], it was discovered that the inside surfaces of some surge nozzle welds were machined after completion of the welding, and a 360° fill-in weld was performed to facilitate fit-up with thermal sleeves in the nozzles. This process can have a similar effect on residual stresses as an ID surface weld repair (see item 3 below), and must be modeled if present. Any deviation in the modeling with respect to the actual weld configuration and fabrication sequence must be justified
3. ID Surface Repair: As illustrated by Case 1 in Table 3-1, without an ID surface repair or a weld buildup on the ID surface, residual stresses in many cases are expected to be relatively low (or compressive), and PWSCC would not be expected. Construction repairs (or some form of ID weld buildup) have generally been present when PWSCC has been observed, and therefore a conservative repair assumption should be included as part of the evaluation process.

   Records of construction repairs may be available in some cases, and thus a search of available construction repair and NDE records should be performed. It is also helpful to have knowledge of the fabrication practices and procedures of the shop where the DM weld was produced.

4. The following represents a set of conservative ID repair assumptions suggested by the NRC staff, which would be considered acceptable without further technical justification:

   a.) If no documented repairs are found, a repair depth of 50% through the DMW wall thickness at the location of the flaw should be assumed, with a repair length of 100% of the circumference (360°).

   b) If a documented repair is found, it must be demonstrated to be bounded by the above 50%, 360° repair assumption, by modeling (3D as necessary) or other means.. The more conservative of the two repair assumptions should be used in the flaw evaluation.

Information may become available that enables a defensible estimate to be made of a smaller repair depth than the above assumptions. If a less conservative repair assumption is used, it must be technically justified.

1. <u>Adjacent Safe-End to Pipe Weld</u>: As illustrated by Cases 2 and 2(a) in Table 3-1, the presence of an adjacent SS safe-end to pipe weld and the length of the safe-end can have a significant effect on residual stresses. The SS weld produces a stress relieving effect on the DMW residual stresses. This effect is, however, dependent upon safe-end length, thus mandating that accurate geometry information for this component be incorporated in the analysis (per attribute 1 above). Another consideration is that safe-ends were often field-trimmed to size during construction, such that design drawings might be inaccurate. The analyst is advised to check as-built drawings (if available) for this important dimension. MRP-139 [1] UT inspectability surveys are also a potential source of actual safe-end length. If actual safe-end length is not obtained and used in the analysis, justification must be provided demonstrating the effect of possible variations in safe-end length on the results of the evaluation. (See item 9 – Sensitivity Studies)

2. <u>Benchmarking and Validation</u>: Because of the numerous analytical details and assumptions required in a residual stress analysis, it is not practical to provide a complete set of detailed guidelines for performing such an analysis. Instead, it is recommended that the analysis technique be benchmarked and validated with respect to stress measurements on one or more well-characterized mockups, such as those described in Appendix A. The analysis should be demonstrated to provide reasonable predictions of the trends and stress magnitudes measured in the mockup(s). A mockup is not required for every analysis, since once the analytical method is validated on one geometry, it can be extended to the analysis of other geometries and welding conditions. However, the geometry, materials, residual stress measurement techniques and results for the mockup used for benchmarking should be documented, and the evaluator should justify its applicability to the subject flaw evaluation.

   The nature of the uncertainties and variability in both residual stress predictions and measurements render meaningful, point-by-point comparisons of analytical versus experimental results impractical. Because of this, and recognizing that the end use of the residual stresses in a flaw evaluation is for the prediction of crack growth rate, a validation approach is suggested in Appendix A which consists of comparing results based on stress intensity factor rather than based on point-by-point stresses. Deviations between the benchmark analyses and measurements are candidates for consideration in the sensitivity studies discussed in item 9 below. The benchmarking analysis and validation criteria are considered part of the evaluation, and should be documented in the evaluation report or in a companion stand-alone report.

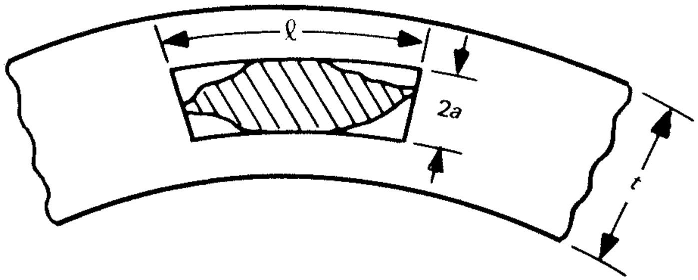
3. <u>Fracture Mechanics Modeling</u>: Fracture Mechanics modeling of stress intensity factors for complex stress fields such as residual stress profiles is a relatively well studied and documented science. Section XI Appendix A provides solutions based on curve fitting of relatively complex stress fields to a third order polynomial and the Code Committee is currently working on a revision to include 4th order polynomial curve fit K-solutions into Appendix A. Other similar solution methods are available in the literature. Caution is advised, however, when using such curve fitting techniques to ensure that the curve-fit is a good representation of the residual stress pattern in the region of interest. Weight function methods may be used as an alternative to curve fitting the stress distribution. Stress paths should be taken at the flaw location, or the bounding path of multiple locations within the DM weld should be chosen based on the highest Ks over the region of interest in the evaluation. Other relevant factors that should be included in the fracture mechanics

evaluation are depth and length crack growth considerations (unless one assumes a 360° circumferential crack or an axial crack that spans the entire length of PWSCC susceptible material, as applicable to the specific evaluation). This is typically done by calculating the stress intensity factor (K) at the major and minor axes of a semi-elliptical surface crack, and numerically integrating for the growth of both. Care must be taken to use small enough integration steps such that the calculated K doesn't change significantly during the step (i.e. to obtain a convergent solution).

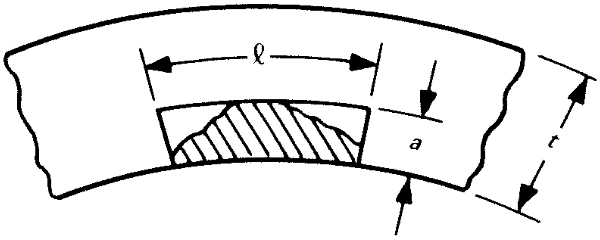
a) Operating Temperature and Pressure: Stresses (including residual at operating temperature) and pressure plus sustained piping loads must be used in PWSCC growth analyses. These can be obtained by adding steady state pressure and temperature loads at the end of the residual stress modeling process. It is also advisable to apply a hydrotest cycle and two or three loading cycles (from shutdown to operating temperature and pressure, and return) to incorporate any shakedown effects on the residual stress distributions. Alternatively, pressure and steady state piping load stresses from elastic solutions may be superimposed on the residual stress distribution providing the elastic models used to develop the pressure and thermal expansion stresses model the geometry and material properties of each material correctly. (Superposition is permissible in this case, even though residual stress analyses are highly non-linear, because residual stresses are localized and secondary (strain-controlled) in nature, and as such, superposition amounts to combining overall strains for use in a pseudo-elastic crack growth analysis.)

b) Consistency with Inspection Results: The crack growth calculations should be generally consistent with the presence of the observed flaw indication. For example, if a residual stress solution does not indicate that PWSCC of approximately the observed depth would occur, (e.g. Case 1 in Table 3-1), then it is not reasonable to use that residual stress distribution for the flaw evaluation. A more conservative residual stress distribution that is consistent with the observed cracking should be used.

c) Sensitivity Studies: Sensitivity analyses should be performed to address unknowns or uncertainties associated with the plant-specific information developed in items 1 - 8 above to demonstrate robustness of the analysis. Given the nature of the uncertainties discussed above, the analyst should be cognizant of how variations in the assumptions that go into the PWSCC crack growth prediction, such as the welding residual stress prediction and the crack growth rate, affect the final answer. There are some sensitivity studies that the NRC will do when reviewing a PWSCC calculation, so it is useful to know how the crack growth calculations will change when various sensitivity cases are considered, even if they aren't submitted. For example, one might want to address the effect of a deeper ID weld repair than the assumptions recommended above, or of uncertainties in UT sizing of the observed flaw. If the results are still acceptable, no further work on this topic is needed, but if they are unacceptable, one might strive to reduce other conservatisms in the analysis, such as critical flaw size or PWSCC crack growth rate (e.g. 50th instead of 75th percentile) to see if they compensate. Such sensitivity studies are informational, and not intended to impose additional constraints on predicted service times. However, they can be helpful in demonstrating the robustness of an evaluation.



(a) Subsurface Flaw



(b) Surface Flaw

Figure 3-1
ASME Section XI Flaw Characterization [3][1]

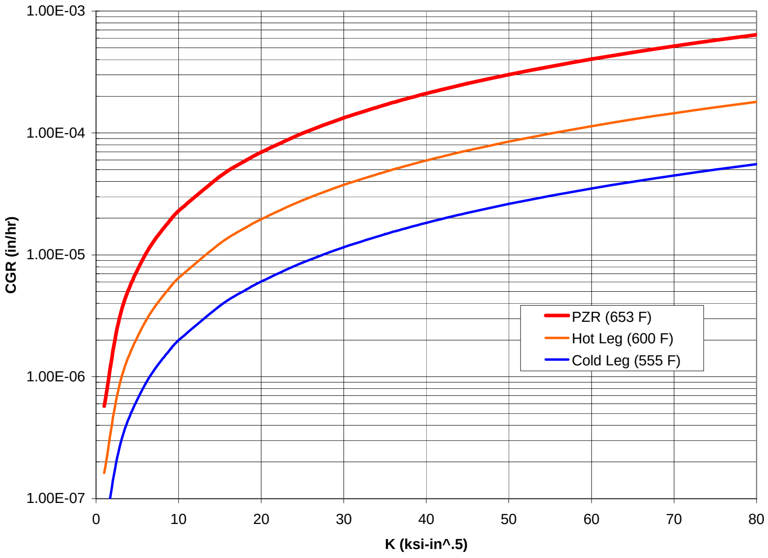


Figure 3-2
Differences in PWSCC Propagation Rates [5] for Alloy 182 at Typical Operating Temperatures

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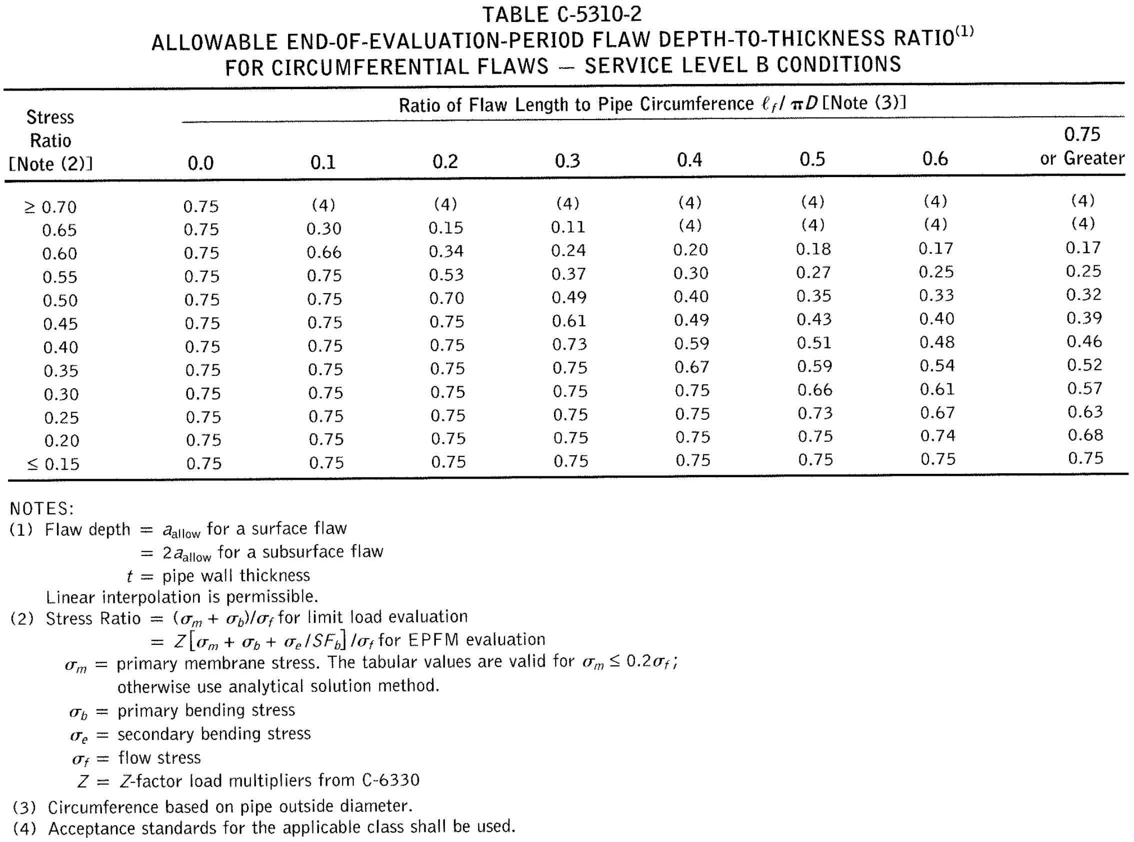

TABLE C-5310-2
ALLOWABLE END-OF-EVALUATION-PERIOD FLAW DEPTH-TO-THICKNESS RATIO(1)
FOR CIRCUMFERENTIAL FLAWS – SERVICE LEVEL B CONDITIONS

Stress Ratio [Note (2)]	Ratio of Flaw Length to Pipe Circumference $\ell_f / \pi D$ [Note (3)]							
	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.75 or Greater
≥ 0.70	0.75	(4)	(4)	(4)	(4)	(4)	(4)	(4)
0.65	0.75	0.30	0.15	0.11	(4)	(4)	(4)	(4)
0.60	0.75	0.66	0.34	0.24	0.20	0.18	0.17	0.17
0.55	0.75	0.75	0.53	0.37	0.30	0.27	0.25	0.25
0.50	0.75	0.75	0.70	0.49	0.40	0.35	0.33	0.32
0.45	0.75	0.75	0.75	0.61	0.49	0.43	0.40	0.39
0.40	0.75	0.75	0.75	0.73	0.59	0.51	0.48	0.46
0.35	0.75	0.75	0.75	0.75	0.67	0.59	0.54	0.52
0.30	0.75	0.75	0.75	0.75	0.75	0.66	0.61	0.57
0.25	0.75	0.75	0.75	0.75	0.75	0.73	0.67	0.63
0.20	0.75	0.75	0.75	0.75	0.75	0.75	0.74	0.68
≤ 0.15	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75

NOTES:

(1) Flaw depth = a_{allow} for a surface flaw
= $2a_{\text{allow}}$ for a subsurface flaw
t = pipe wall thickness
Linear interpolation is permissible.

(2) Stress Ratio = $(\sigma_m + \sigma_b)/\sigma_f$ for limit load evaluation
= $Z[\sigma_m + \sigma_b + \sigma_e/SF_b]/\sigma_f$ for EPFM evaluation
σ_m = primary membrane stress. The tabular values are valid for $\sigma_m \leq 0.2\sigma_f$; otherwise use analytical solution method.
σ_b = primary bending stress
σ_e = secondary bending stress
σ_f = flow stress
Z = Z-factor load multipliers from C-6330

(3) Circumference based on pipe outside diameter.

(4) Acceptance standards for the applicable class shall be used.

Figure 3-3
Typical End-of-Period Flaw Evaluation Table from Section XI Appendix C [3][2]

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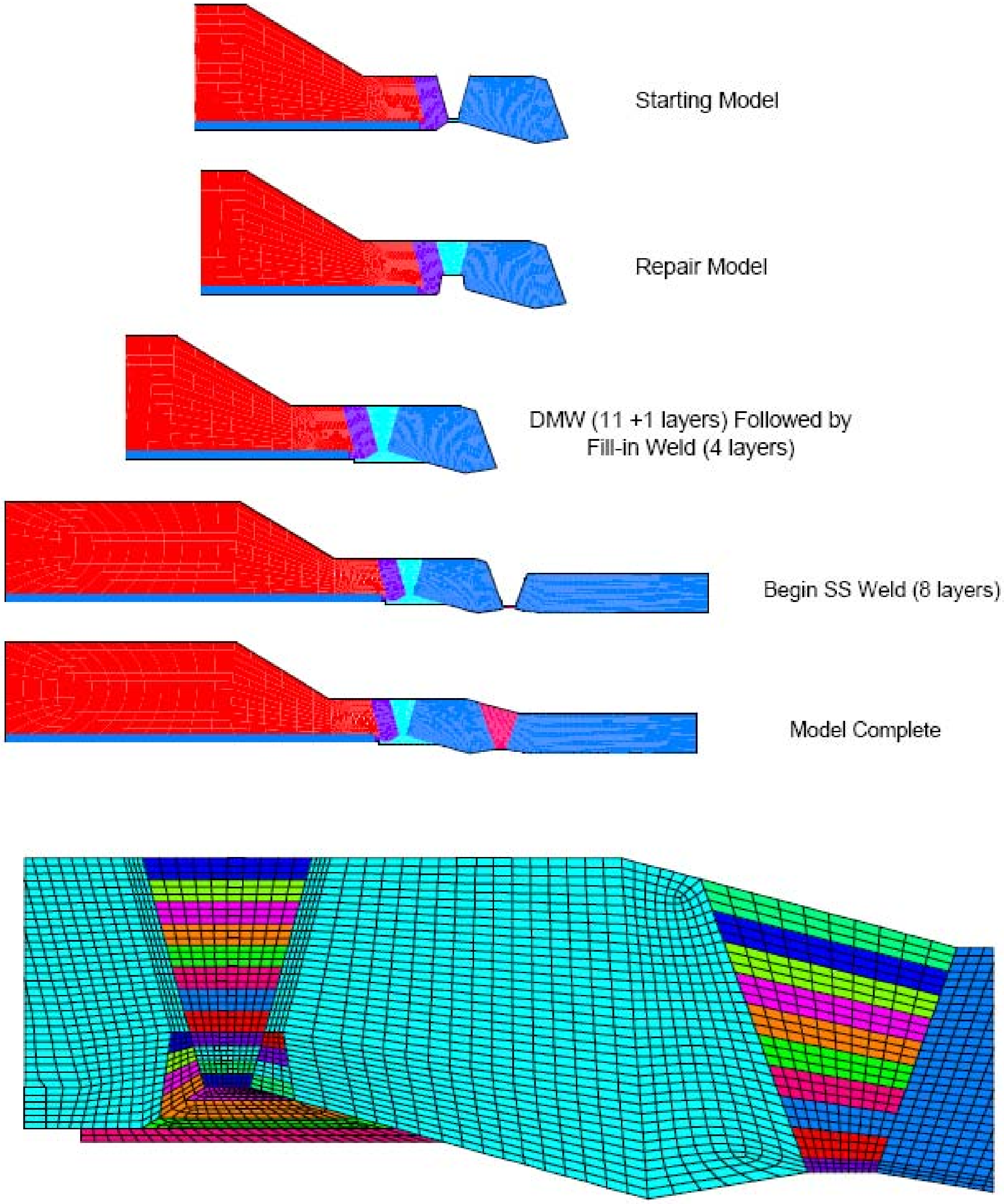

Figure 3-4
Typical Modeling Sequence and Resulting FEM for Nozzle/Safe-End Residual Stress Analysis (from [16])

4

SUMMARY / CONCLUSIONS

This document provides a summary of important considerations when performing ASME Section XI flaw evaluations of inservice inspection indications believed to be PWSCC in Alloy 600/82/182 dissimilar metal welds in PWR primary coolant system piping and components. Guidance is provided which expands upon that contained in ASME Section XI, Appendix C, especially in the area of residual stress calculations, for which the Code guidance is relatively sparse. The document has been peer reviewed, and thus if followed, should facilitate the flaw evaluation process and subsequent review of the evaluation by the NRC. It also provides useful information to utilities preparing for outages in which PWSCC inspections will be performed, outlining steps they can perform in advance of the outage to expedite the evaluation process, should one be required.

5
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A

APPENDIX: ANALYTICAL VERSUS EXPERIMENTAL RESIDUAL STRESS COMPARISONS

This Appendix presents a series of analytical versus experimental residual stress comparisons based on a group of benchmark analyses of the type recommended for residual stress methodology in the body of this report. In some cases, the comparisons are quite good, indicating an acceptable residual stress analysis technique for crack growth analyses, while in other cases the results appear to be non-conservative. Finally, a validation criterion for acceptance of analytical methodology based on such comparisons is suggested.

A.1 European JRC Mockup

Figure A-1 presents results of several analyses performed on a mockup fabricated on behalf of the European Commission Joint Research Centre's (JRC) Institute for Energy [14], in which through-wall residual stress distributions were measured by the Neutron Diffraction (ND) technique and compared to analyzed residual stresses. The project investigated a stainless steel weld joining two piping spool pieces, each approximately 500 mm (20 inches) long, one made of Type 316L stainless steel and one from A508 low alloy steel. Nominal outside diameter of the mockup was 453 mm (17.8 in.). The initial A508 spool piece was 64 mm (2.5 inches) thick, and the initial Type 316L spool piece was 73 mm (2.9 inches) thick. Figure A-1 presents through-wall stress distributions from several European analysis organizations, plus analyses performed by Dominion Engineering, as reported in [14]. The results exhibit reasonable agreement among the various analyst's results in terms of axial stress predictions (lower plot), as well as reasonable agreement with the overall trend of the measured axial stresses (although most of the analyses under-predicted axial residual stresses near the inside surface; i.e. the right hand side of the plot). The hoop stress results (upper plot) compare less favorably, with greater deviation among the various analyses and greater deviation of the analytical predictions from the measurements. It is fair to point out, however, that the measurements in this experiment don't necessarily represent ground truth. More recent work [15] has shown that there is a fair amount of uncertainty associated with ND measurements of residual stress. Both the analyses and measurements indicated a trend towards compression near the inside surface of this weldment, which is not atypical for a butt weld of this type with no inside surface repair. Indeed, without an ID surface repair, or some other form of detrimental ID surface condition, such welds would not be expected to crack due to SCC.

A.2 EPRI/NRC RPV Nozzle (Phase IV) Mockup

Figure A-2 presents a finite element residual stress model of a large diameter mockup prepared for the NRC by EPRI, as part of an ongoing EPRI/NRC cooperative research program [13]. In this case, the mockup consisted of a large diameter (nominally 35 in. OD with a 2.9 in. wall thickness at the DMW) reactor vessel main coolant loop nozzle (LAS) and safe-end (SS) harvested from a cancelled PWR plant in the US. As illustrated in Figure A-2, the mockup included both an Alloy 82/182 DMW and a stainless steel pipe to safe-end weld, at the end of a relatively short, 3.9 in. long safe-end. EPRI performed a 30° partial arc, ID surface repair ~25% thru wall in the DMW before making the stainless steel weld to a SS piping spool piece. Residual stresses were measured by a number of techniques[3] at this point in the fabrication sequence. Eventually, a weld overlay was applied to the mockup, and the residual stress measurements were repeated after application of the overlay; but this report will focus on the pre-WOL analyses and measurements that would be of interest in a flaw evaluation.

Figure A-3 presents the measured residual stress profiles compared to results of analyses performed by several U.S. organizations. It is seen that the agreement in this case is quite good, both among the various organizations and in comparison to the measurements. The measurements were performed at several azimuthal locations, including 180°, which was at the center of the partial arc repair. As expected, the residual stress data at the repair azimuth (red curves and data points) were higher than at other, non-repaired azimuths. Since the analyses were two-dimensional (axisymmetric), the repair was modeled as 360° rather than as its actual 30° circumferential length, and there was thus no ability to distinguish between repair versus non-repair azimuths in the analyses. However, the analytical results are in reasonable agreement with the measured stresses in the higher-stressed, repaired azimuth (180°) and would thus be conservative for use in a PWSCC flaw evaluation. In comparison to the European JRC mockup case, it is seen that the Phase IV mockup exhibits higher (tensile) stresses near the ID surface, especially in the hoop direction.

A.3 EPRI 36" Diameter OWOL Mockup

A 36" diameter simulated nozzle to pipe weld mockup was constructed by EPRI, the primary purpose of which was WOL NDE qualification [12]. However, the mockup was also instrumented to confirm the residual stress benefits of the OWOL and to validate residual stress analysis techniques used to design overlays. ID surface residual stress measurements were obtained on this mockup before and after application of the OWOL. The construction weld was performed, NDE targets were installed, and an inside surface weld repair during construction was simulated. Strain gauge measurements of inside surface residual stresses were taken at this point in the process, using the incremental hole drilling approach. An OWOL was then applied to the mockup, and the residual stress measurements were repeated to determine the benefits of the OWOL. Two and three-dimensional residual stress analyses of this mockup were performed by one vendor. The pre-overlay measurements and analyses are of primary interest to this report.

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[3] deep hole drilling and incremental deep hole drilling for through-wall stresses and surface hole drilling plus X-ray diffraction for surface stresses

Figure A-4 illustrates the mockup and associated finite element model (unmeshed). It is noted that the mockup did not have any safe-end, but rather, simulated a DMW directly from a stainless steel pipe to a clad carbon steel elbow (such as may be used in a main coolant pump nozzle). The mockup also possessed some inside surface features that would be expected to make it very severe from a residual stress standpoint: notably, a partial arc ID repair to a depth of 25% of the wall thickness, followed by a 360° counterbore fill-in weld. The resulting, pre-overlay through-wall residual stress profiles for this mockup weld are illustrated in Figure A-5. The measurement results for this case are only reported near the ID surface, since no through-wall measurements were performed. However, they agree reasonably well with the analytical predictions at the ID surface, so the through-wall analytical stress profiles are validated at least to some extent. This mockup yielded very high tensile residual stresses in both the hoop and axial directions, and compared to the prior mockup cases, a weldment of this type would be expected to have a high propensity for PWSCC in service.

A.4 Suggested Analytical versus Experimental Validation Criteria

The nature of the uncertainties and variability in both residual stress predictions and measurements render meaningful, point-by-point comparisons of analytical versus experimental results impractical. Because of this, and recognizing that the end use of the residual stresses in a flaw evaluation is for the prediction of crack growth rate, a validation approach is suggested which consists of comparing results based on stress intensity factor rather than based on point-by-point stresses. Figure A-6 illustrates this process, using the EPRI/NRC RPV Nozzle (Phase IV) Mockup case as an example. The experimental residual stress profiles from Figure A-3 (180° repair section azimuth, i.e. red curves and data points) were curve-fit by a third order polynomial and stress intensity factor was then calculated using an appropriate flaw model for each case (360° circumferential crack for axial stresses and 2:1 finite aspect ratio axial crack for hoop stresses). The resulting "measured" stress intensity factors versus crack depth are shown by the solid black curves in Figure A-6. ±10 ksi√in error bands are also shown on these curves. The same stress intensity factor solutions were then applied to each of the analytical curves in Figure A-3, and the results are presented as the dashed curves in Figure A-6.

This figure suggests one possible validation criterion for residual stress calculation methodology, namely to apply a ±10 ksi√in error band to the stress intensity factor results. If the computed Ks for the analytical and measured stress distributions, at crack depths of interest in the flaw evaluation, are within 10 ksi√in of each other, or if the deviation is greater than 10 ksi√in, but the analytical Ks are higher than the measured Ks, then the residual stress approach would be considered to be appropriately benchmarked for the flaw evaluation. In accordance with this suggested criterion, all three of the axial crack solutions (i.e. hoop stresses in Figure A-3) and two of the three circumferential crack solutions (i.e. axial stresses in Figure A-3) would be qualified for flaw evaluation over essentially the entire crack depth range in Figure A-6 (0 to 1.4 inches).

Figure A-7 addresses the potential effects of the suggested ±10 ksi√in error band on a typical crack growth evaluation. Evaluation of the circumferential crack case is not fruitful for this exercise, because the Ks are negative over a large portion of the crack depth range, and all of the solutions would predict eventual crack arrest. Crack growth evaluation of an axial flaw is meaningful, however, and Figure A-7 presents predicted PWSCC growth rates for an initial 10% crack using the measured K and the measured K minus 10 ksi√in solutions. Crack growth was evaluated using the 75th percentile crack growth rate for Alloy 182 at 560°F [3, 5]. It is seen from this figure that the crack growth rate based on the measured K minus 10 ksi√in solution is about half that of the measured solution, (~14 years for a 10% defect to grow to approximately mid-wall of the nozzle, versus 7.5 years for the measured solution without the 10 ksi√in adjustment). It is emphasized that the above 10 ksi√in error band is only a suggestion of one possible validation criterion, which has not been agreed to or accepted by NRC or industry reviewers of this document. The benchmarking analysis and validation criterion are the responsibility of the evaluator, including justification of the specific validation criterion used via sensitivity studies or some other approach.

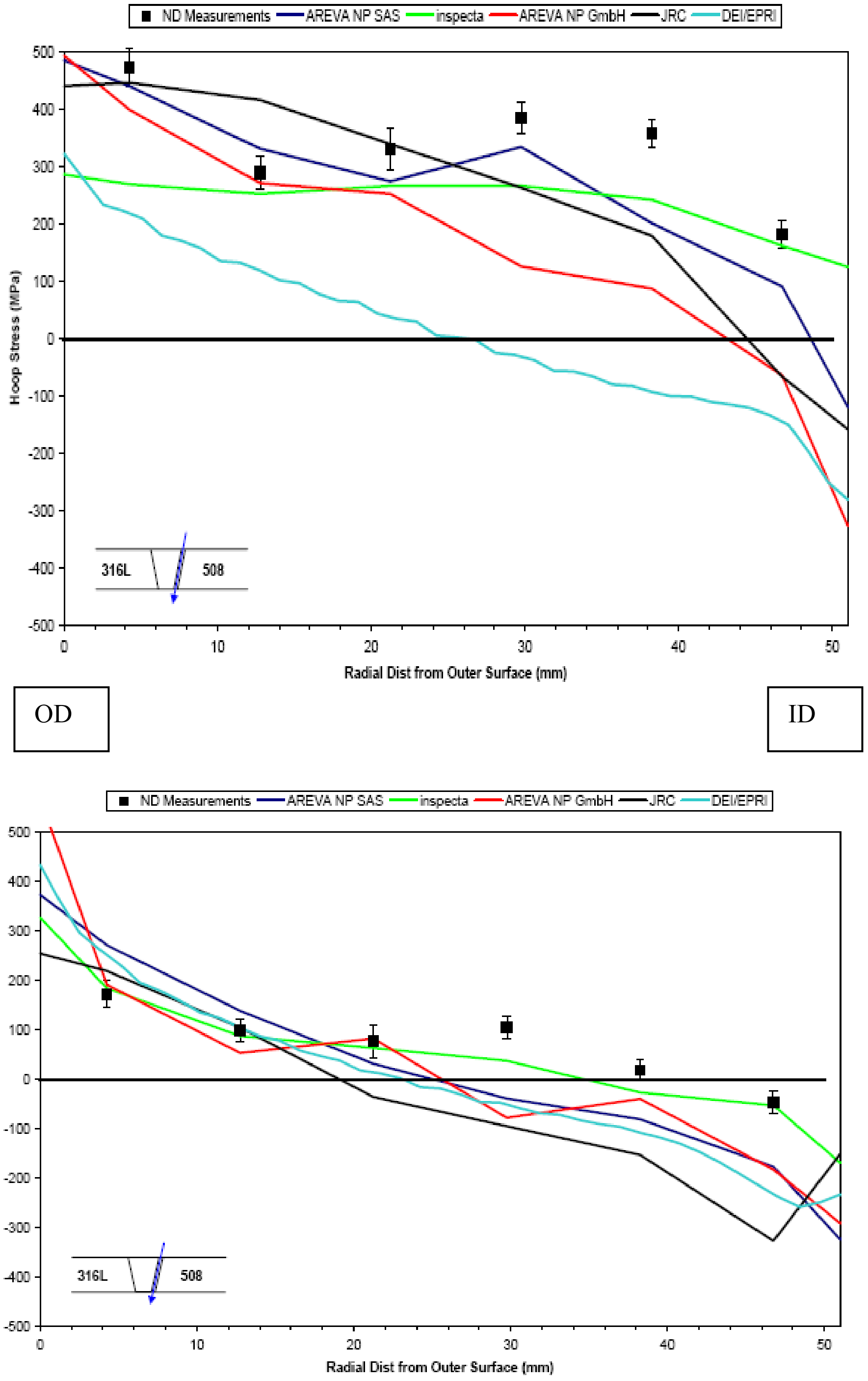


Figure A-1
Through-Wall Analytical vs. Measured Residual Stress Profiles at Room Temperature (OD to ID) from European Commission Joint Research Centre (JRC) Round Robin Study [16]

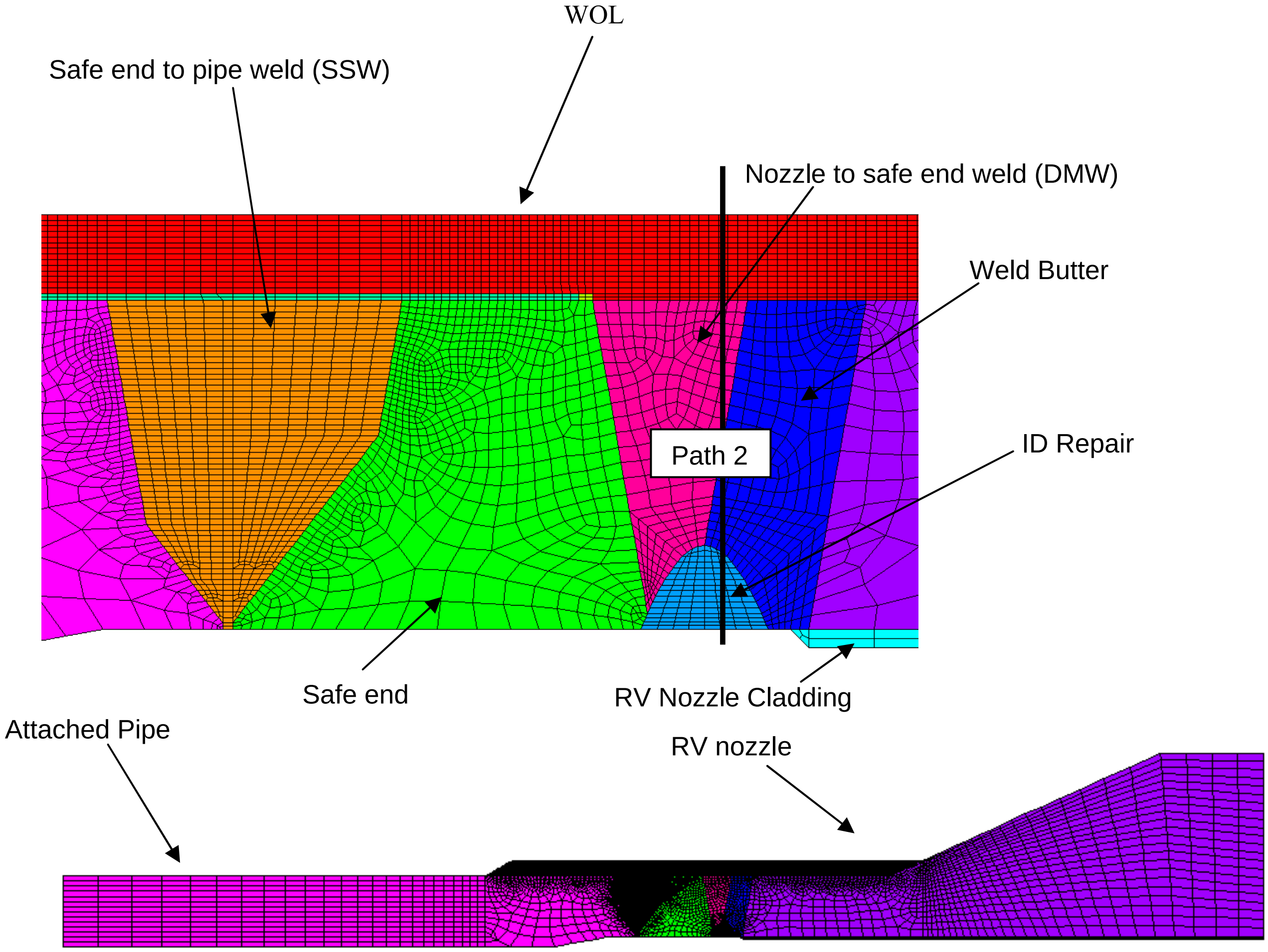
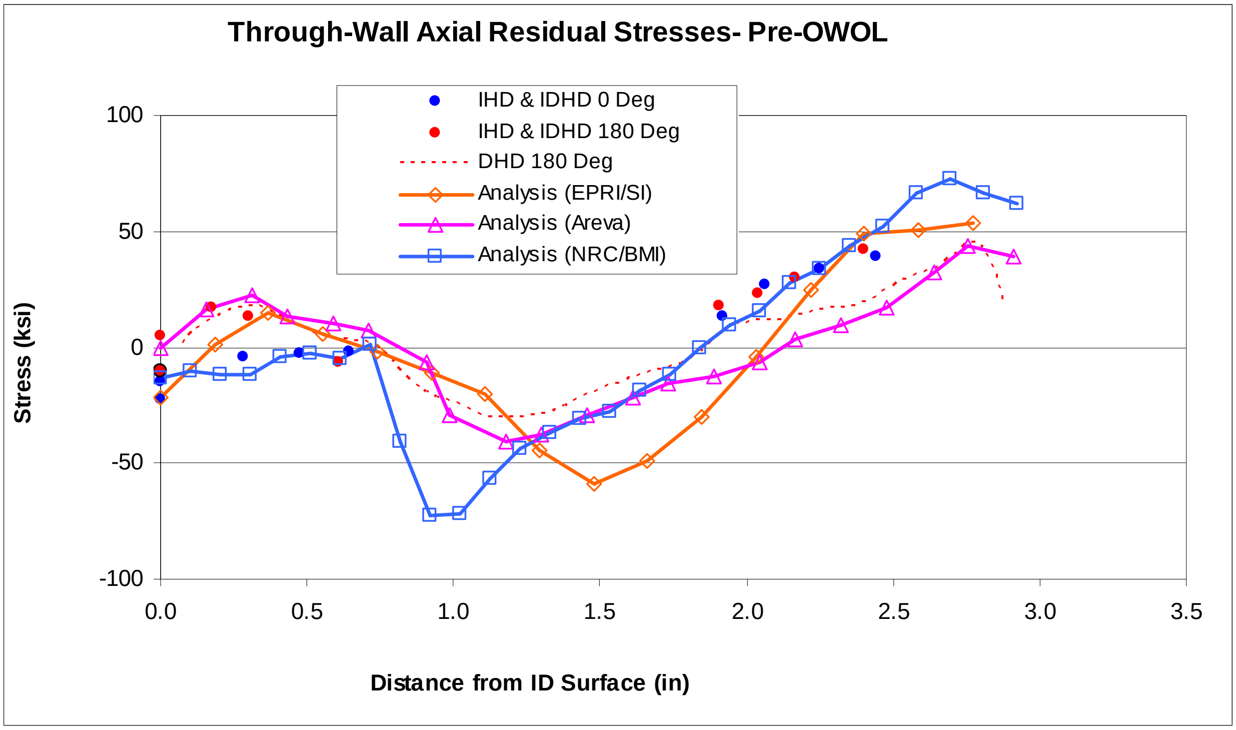


Figure A-2
Finite Element Model of Large Diameter RPV Coolant Loop Nozzle Mockup (Phase IV) of Ongoing EPRI/NRC Cooperative Research Program



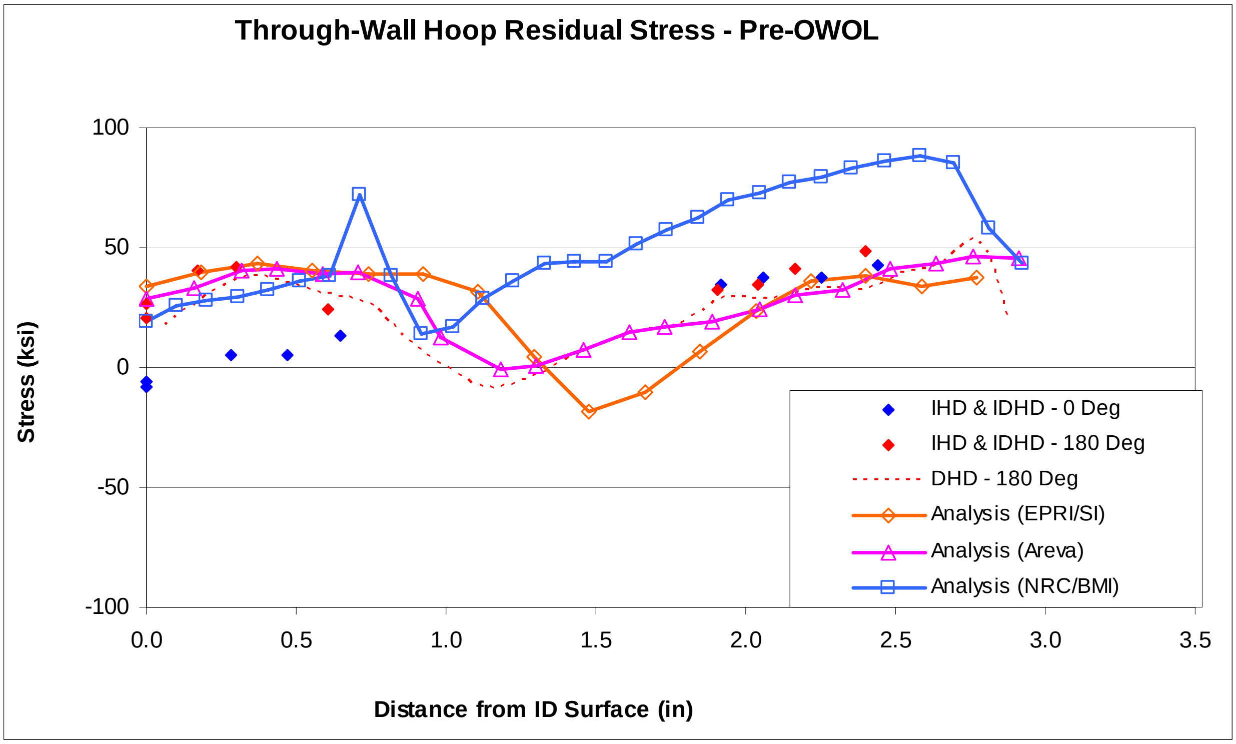


Figure A-3
Through-Wall Analytical vs. Measured Residual Stress Profiles at Room Temperature (ID to OD) from Large Diameter RPV Coolant Loop Nozzle Mockup (Phase IV)

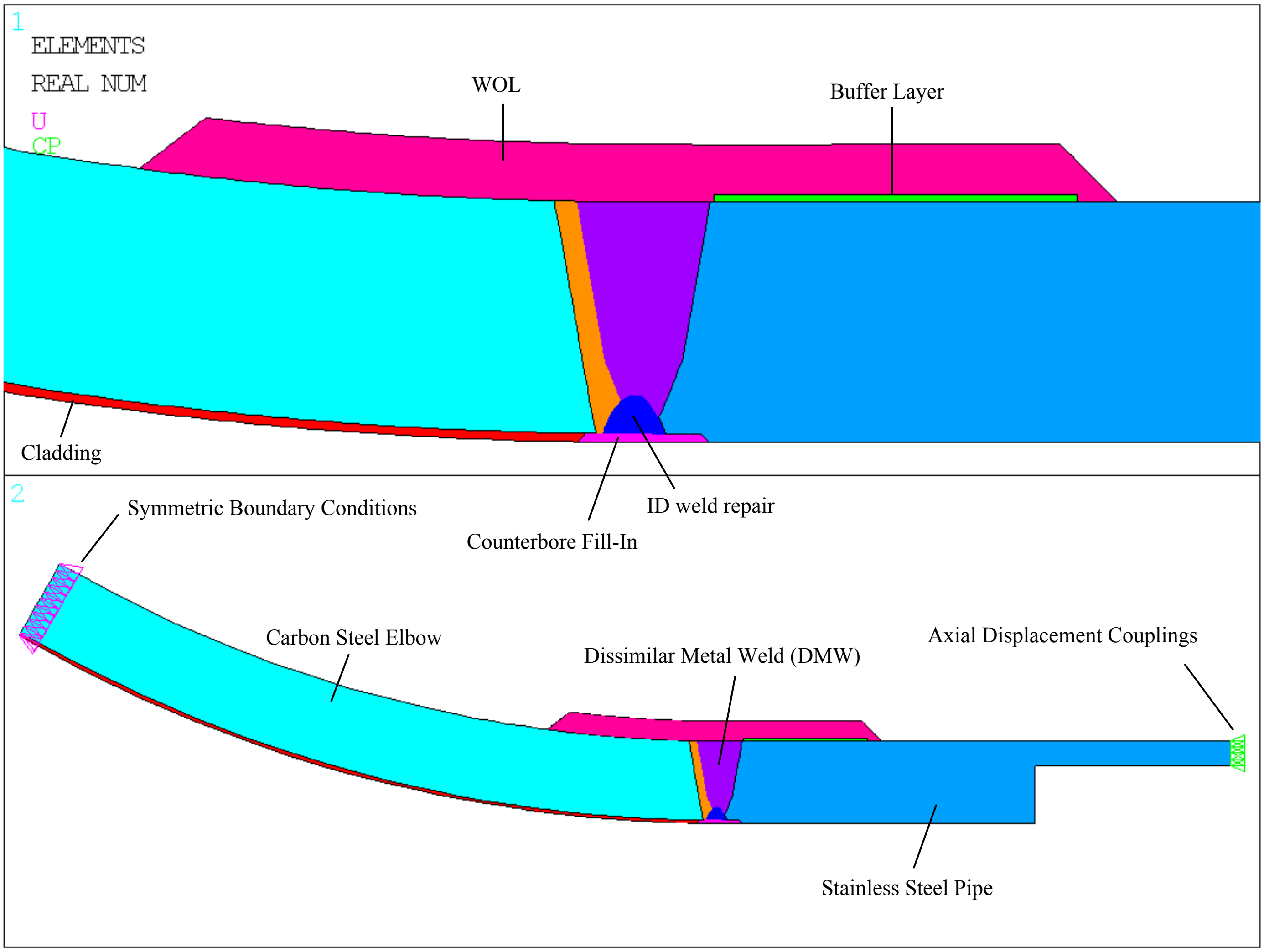
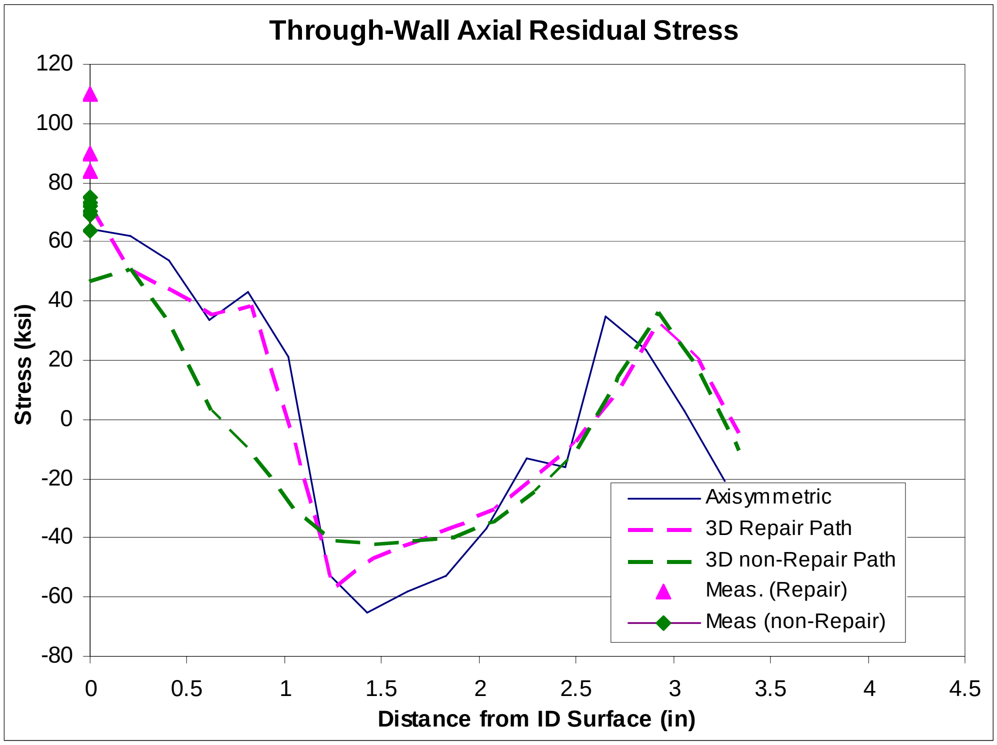


Figure A-4
Components and Overview of Finite Element Model of EPRI 36” Diameter OWOL Mockup



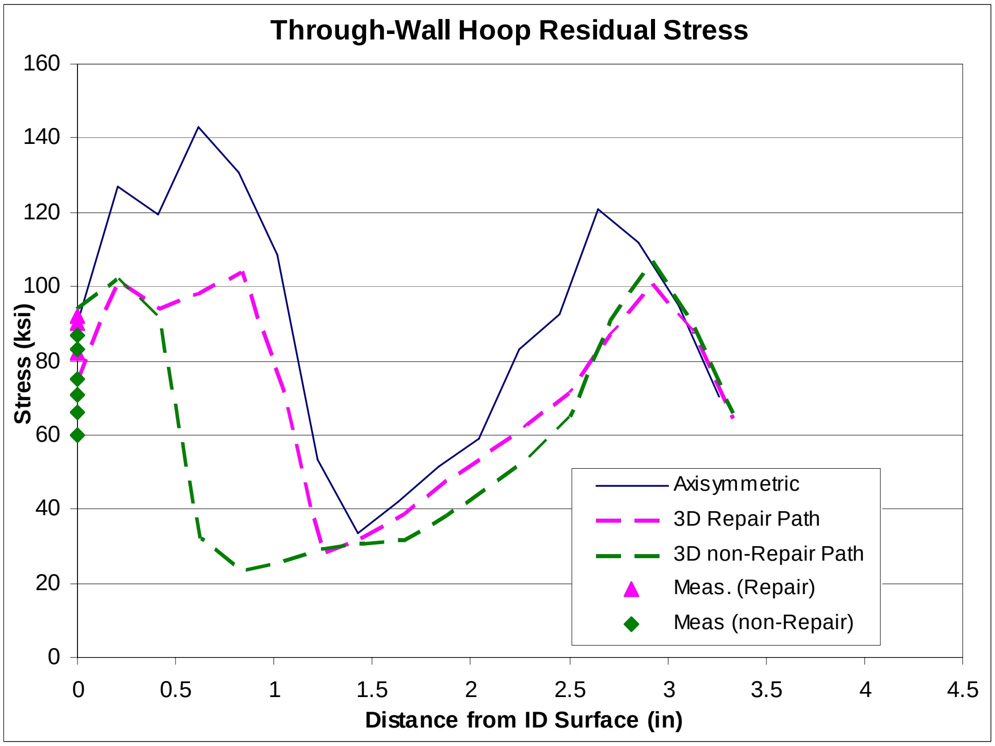


Figure A-5
Pre-Overlay Through-Wall Residual Stress Profiles at Room Temperature from Two- and Three-Dimensional Analyses of EPRI 36” Diameter OWOL Mockup. ID Surface Measurements Also Shown for Comparison

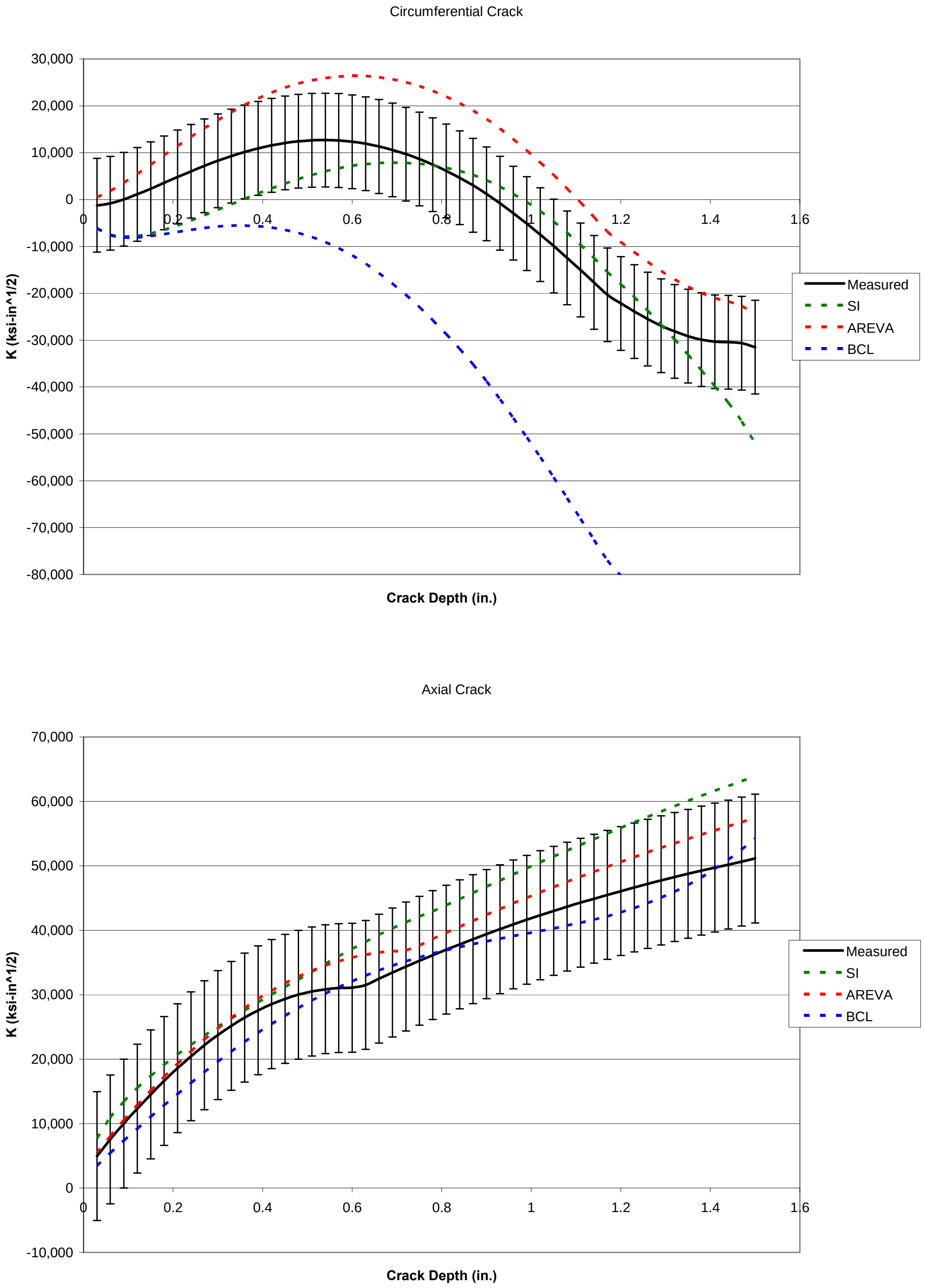


Figure A-6
Stress Intensity Factor Comparison of Analytical Versus Measured Residual Stress Results on Phase IV Mockup (±10 ksi√in error band shown on measurement curve)

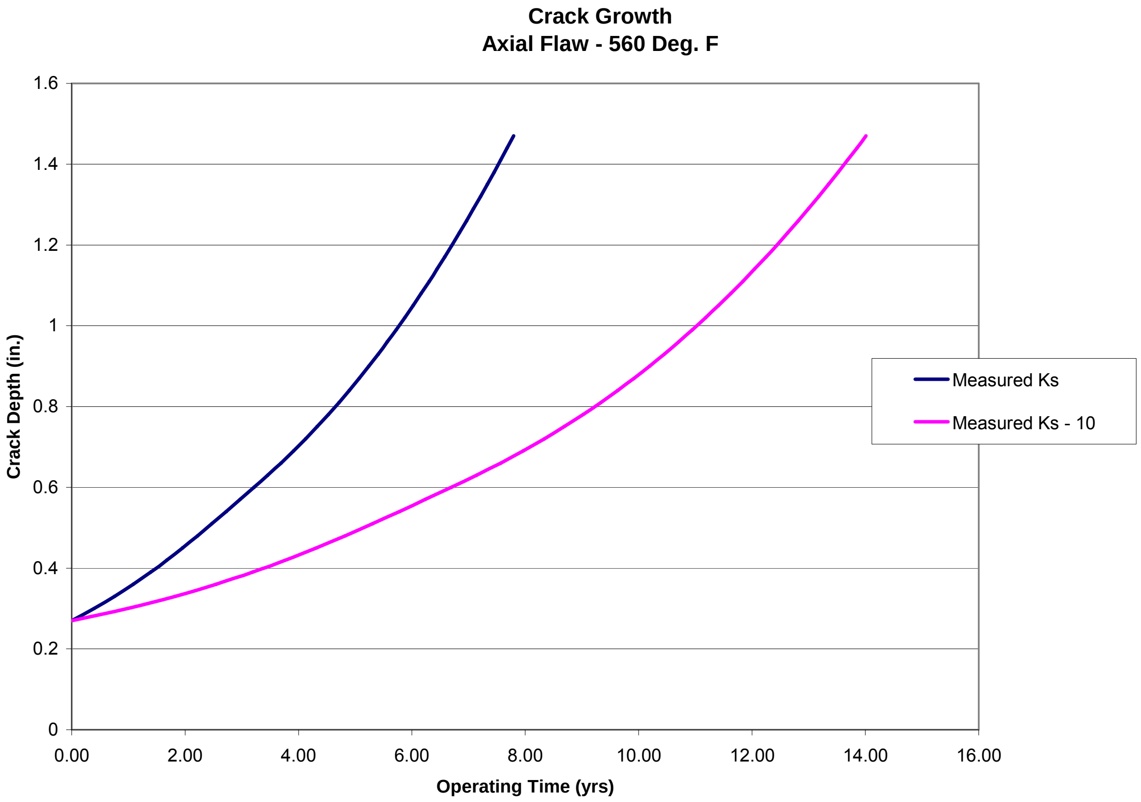


Figure A-7
Crack Growth Comparison of Measured Residual Stress Case versus Lower Bound (Measured Case -10 ksi√in)

Program:

Materials Reliability Program

1021023

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