Phase 2b Finite Element Round Robin Results
Technical Letter Report

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Executive Summary

Weld residual stress (WRS) results from high thermal gradients, structural constraint, and thermal expansion mismatches of adjacent dissimilar materials during the welding process. These stresses remain present in the finished component even if no external loads are applied. WRS is known to be a significant driving force for subcritical crack growth mechanisms, such as primary water stress corrosion cracking and fatigue. It is important, therefore, to understand the capabilities and limitations of analytical prediction of WRS in safety-related nuclear components. As such, the U.S. Nuclear Regulatory Commission (NRC) and the Electric Power Research Institute (EPRI) undertook a cooperative research program under the auspices of a Memorandum of Understanding to compare finite element predictions of WRS to experimentally measured values. These studies involved measurements on both small-scale specimens (Phase 1) and full-scale mock-ups and ex-plant components (Phases 2a, 3 and 4). The results of this previous work showed a need to decrease analyst-to-analyst uncertainty in the predicted residual stress profiles. The subject of this document is the Phase 2b study, where the NRC built a new mockup of a pressurizer surge line nozzle and coordinated a double-blind finite element modeling study. The participants of the study did not have access to the measurement data. The objectives of the Phase 2b study were to:

- Determine if appropriate modeling guidance could be developed to reduce the previously-observed analyst-to-analyst uncertainty, and
- Develop acceptance criteria for comparing modeling predictions to measurement results

This document reports both raw and processed WRS data from the Phase 2b study. Data processing steps, which were needed to facilitate direct comparisons among the various data sources, included sorting, interpolating, and normalizing. The raw data is presented in both graphic and tabular format.

The measurement data included four deep hole drilling measurements and one contour measurement. The five measurements all showed similar through-wall trends for a given stress component, though the contour hoop stress data demonstrated less through-wall variation than the hole drilling data. At certain regions through the pipe wall, the contour data and hole drilling data lacked agreement in stress magnitude (see Section 3.1).

The modeling data is presented as axial and hoop stress versus through-wall position. While no quantitative evaluation of the data is offered in this document, qualitatively the Phase 2b modeling data still exhibited significant scatter. Outliers may be present in the Phase 2b round robin data set. Assessing and dispositioning modeling outliers is left for future work.

Finally, the measurement and modeling WRS profiles obtained in this study were used as inputs to flaw growth calculations. Similar analyses often form the basis of industry relief requests. The flaw growth calculations showed that time-to-leakage is sensitive to relatively small differences in predicted WRS. Since stress intensity factor is a function of flaw geometry and loading assumptions, both these factors must be considered in explaining flaw growth results. Future efforts will focus on understanding how subtle differences in WRS prediction affect flaw growth analyses.

This report is only a summary review of the data obtained during the Phase 2b round robin study. For future work, NRC staff will apply quantitative analysis tools to understand measurement and modeling uncertainty. This activity will aid the NRC in establishing acceptance criteria and, ultimately, guidance on WRS finite element analysis.

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1. Introduction

This report documents the results of the Phase 2b finite element round robin study. The previous research for this program, which motivated the need for Phase 2b, is documented in References [1-2]. In particular, this study is a follow on to the Phase 2a round robin effort, where a similar pressurizer surge line nozzle mock-up was studied. This work showed that, while on average finite element models provided reasonable predictions of the weld residual stress (WRS) measurements, there was significant analyst-to-analyst variability. It also provided an idea of which modeling parameters appreciably affected modeling uncertainty (e.g., hardening law) and which did not (e.g., weld bead shape). Uncertainty in WRS predictions can affect flaw growth calculations that sometimes form the basis for regulatory relief requests regarding inspection and repair/replacement activities at nuclear power plants. There was a need to perform a second double-blind round robin study to:

- Determine if model uncertainty can be reduced by formulating effective modeling guidance
- Inform formulation of appropriate acceptance criteria for weld residual stress predictions

While this document only presents results, the data contained herein will support NRC decision-making on a number of technical issues. Ultimately, the NRC will issue guidance on developing WRS inputs for regulatory purposes. To reach that goal, rigorous statistical methods must be applied to the Phase 2b data. These methods will allow for uncertainty quantification of both the measurements and the modeling data. After uncertainty quantification and comparison of measurement and modeling data, the NRC staff can make judgments about acceptance criteria for WRS modeling. The modeling guidance resulting from this work will be published in two forms: the American Society of Mechanical Engineers Boiler and Pressure Vessel Code (ASME Code) and an NRC NUREG. ASME Code guidance is developed in a consensus manner with both NRC and industry representatives.

The remainder of this document is dedicated to introducing results of the Phase 2b round robin study. Chapter 2 describes the round robin in detail, including mock-up fabrication and experimental setup. Chapter 3 presents the WRS results from Phase 2b and flaw growth calculations based upon those results. The raw WRS results are presented in tabular form in Appendix C. Chapter 4 describes future work for this research program.

2. Phase 2b Round Robin Study

The Phase 2b study involved measurements and modeling of a pressurizer surge line mock-up. The measurements were carried out prior to initiating the modeling round robin study, and the measurement data were kept secret until the analysts submitted their model results. This section details mock-up fabrication, WRS measurement, and modeling guidance development.

2.1 Mock-Up Fabrication

The geometry chosen for the Phase 2b round robin study was representative of a pressurizer surge nozzle. The overall geometry of the mock-up is shown in Figure 1.

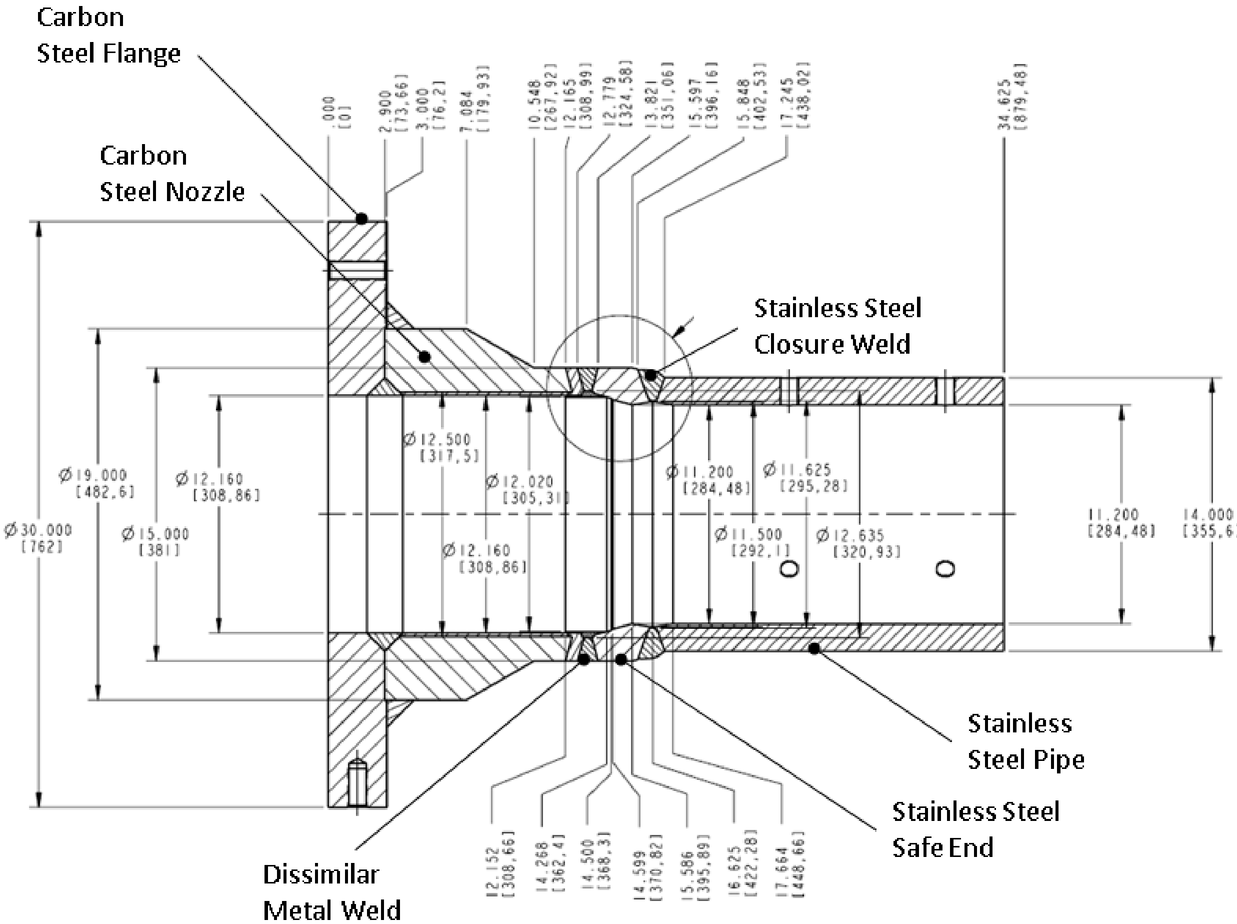


Figure 1: Phase 2b Mock-Up Geometry (Dimensions in in. [mm])

Detailed fabrication information, including welding parameters and bead map drawings, is found in Appendix A. The fabrication process consisted of the steps shown in Table 1.

Table 1: Mock-up Fabrication Steps

Step	Description	Purpose
1	A36 flange welded to SA182 nozzle	Simulates nozzle stiffness in service; not modeled
2	Alloy 82 buttering applied to nozzle	Allows for post-weld heat treat of low alloy steel and prepares dissimilar metal weld
3	Post weld heat treatment	Tempers martensite in low alloy steel and relieves residual stress
4	Buttered nozzle welded to F316L safe end with Alloy 182 filler metal	Simulates shop weld
5	Backchip and reweld	Simulates repair weld at inner diameter
6	Weld crown machine	Weld crowns from steps 4 and 5 removed
7	Safe end welded to TP316 pipe	Simulates field closure weld

The fabricators of the mock-up collected the following data during the welding process (also found in Appendix A).

- Thermocouple measurements for Steps 4, 5, and 7.
- Laser profilometry for Steps 4, 5, and 7.

2.2 Round Robin Participants

Ten participants submitted finite element model results to the round robin study, and the organizations that contributed to these submissions are shown in Figure 2. These participants represent a cross section of international industry, government, academic, and private contractor organizations. Some of these participants volunteered their services to this effort.

Figure 2: Participating Organizations

2.3 Weld Residual Stress Measurements

The residual stress measurements were performed by VEQTER, Ltd. in Bristol, UK and Hill Engineering, LLC in Rancho Cordova, CA. Two sets of measurements were carried out: hole drilling and contour (see Section 2.2.2 of [1] for more details). The hole drilling measurements consisted of a combination of deep hole drilling (DHD) and incremental deep hole drilling. The experimental setup of the hole drilling measurements, which provide hoop, axial, and shear stresses through the wall thickness, is shown in Figure 3. Four hole drilling measurements were taken at the dissimilar metal weld centerline starting at location B shown in Figure 3. Location B was located 22° from Location A, which is the weld start location. The other three measurements were made 90° apart from one another. Care was taken to avoid weld start/stop locations around the circumference. The hole drilling measurements were performed prior to the destructive contour measurements.

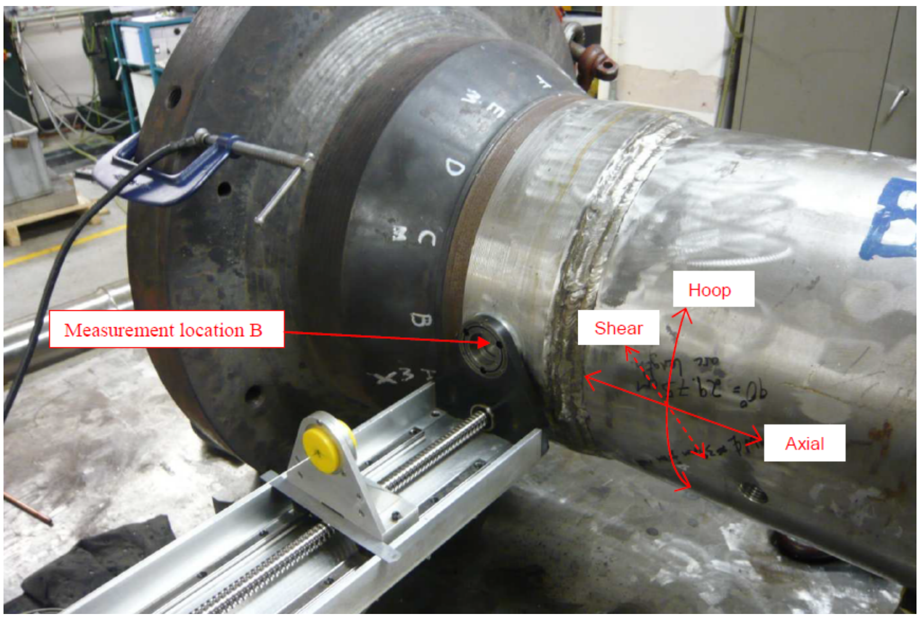


Figure 3: Deep Hole Drilling Measurement Setup

The contour measurements required a series of sectioning cuts. The first cut removed the thick part of the nozzle and a majority of the stainless steel pipe (section cut 1 in Figure 4). The next cut was a radial cut through the length on one side of the mock-up, as shown in Figure 5 as section cut 2. Finally, the specimen depicted in Figure 6 was cut out with section cuts 3. Figure 6 also shows a slitting measurement. The slitting measurement provided data only through half the wall thickness and is not discussed further here. Axial and hoop stresses were determined by two final cuts, as shown in Figure 6. A laser profilometer determined the displacements on the two surfaces resulting from the final contour method cuts. The calculation of residual stress accounted for the release of strain that occurred in each cutting operation.

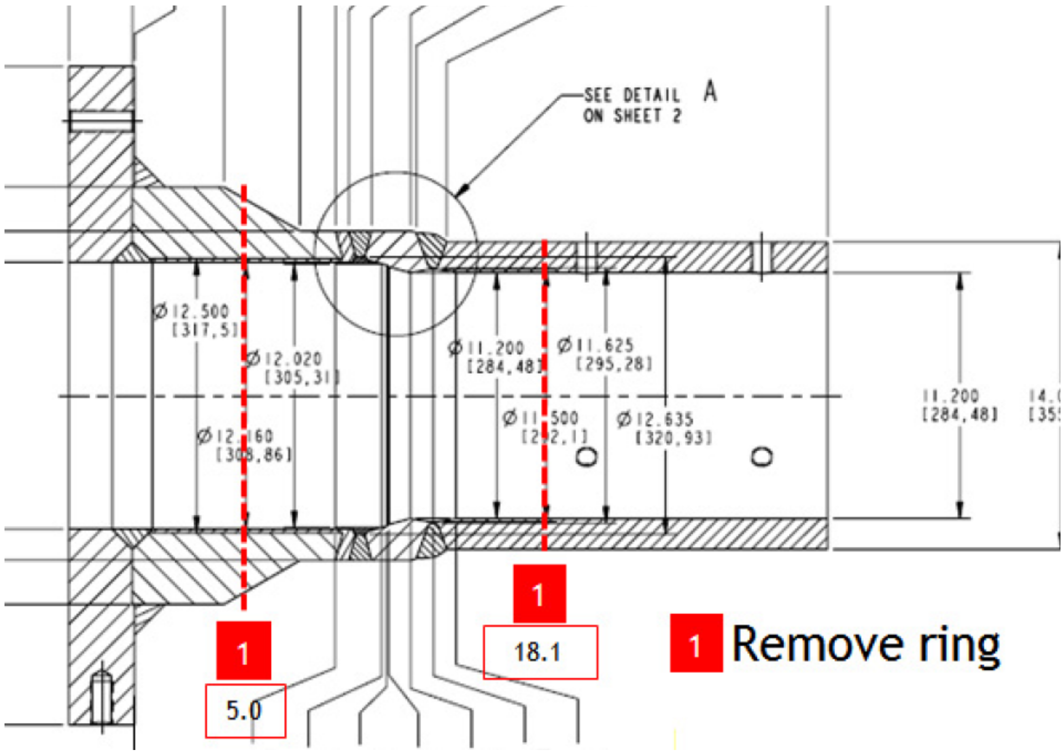


Figure 4: First Section Cut

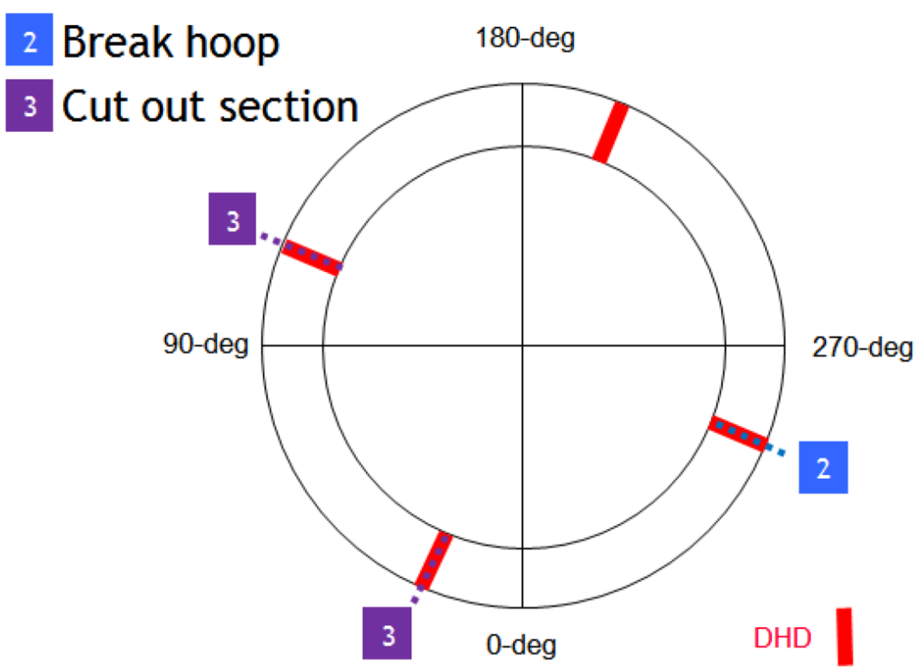


Figure 5: Section Cuts 2 and 3

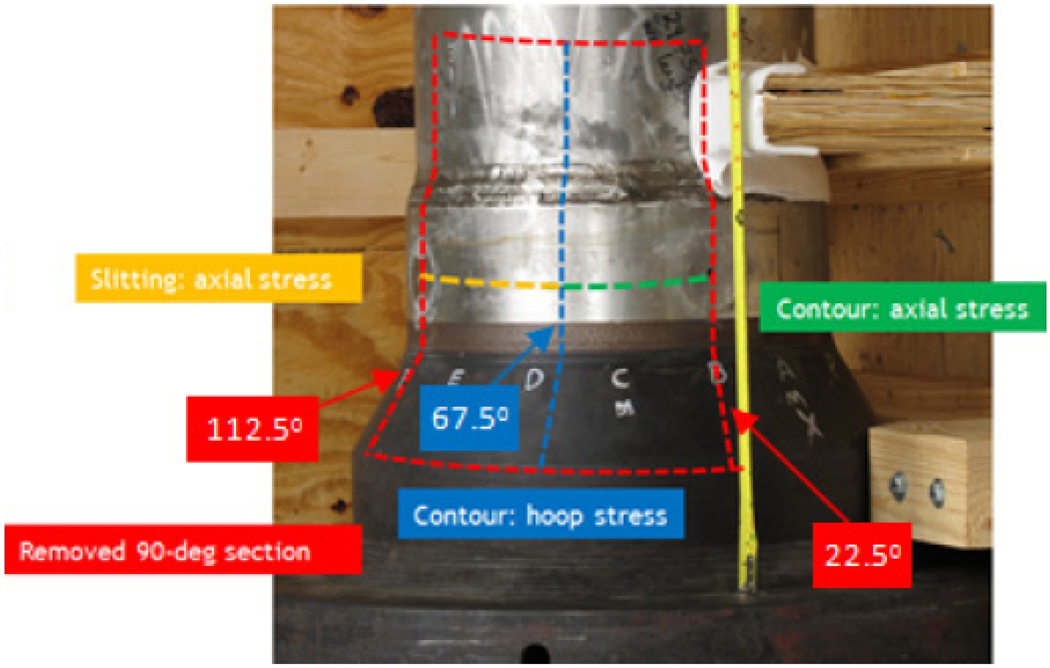


Figure 6: Specimen for Contour Measurement

2.4 Modeling Guidance

The written problem statement provided to the round robin participants is shown in Appendix B. This guidance was based upon modeling experience gained in previous work [1-4] and is summarized in Table 2. Participant deviation from the guidance, if applicable, was described by participants upon submission of their results.

Table 2: Model Guidance

Modeling Topic	Guidance Description
Hardening Law	Participants to complete two models: one assuming isotropic hardening, one assuming kinematic hardening. Material properties for each hardening law provided to the participants.
Weld Bead Geometry	Participants should model the specified number of weld passes and layers provided in the problem statement. Precise use of profilometry data was not required. Participants can use trapezoidal beads of approximately equal area.
Thermal Model Tuning	Material properties for heat transfer calculation provided to the particpants. Participants free to choose heat input model. Precise tuning of thermal model to thermocouple data optional, due to weak sensitivity on heat input. Participants should tune thermal model to approximate expected melt zone area. No guidance provided on interpass temperature.
Structural Boundary Conditions	Mock-up was not extensively constrained during fabrication. Participants should fix one single node (located away from welding areas) from displacement along the axial direction of the pipe.
Material Properties	Material properties for both the heat transfer and static stress analysis were provided to the particpants.
Post Processing	Particpants requested to define a path through the centerline of the dissimilar metal weld and extract data at 26 equally-spaced points along the path, including the inner and outer surfaces.
Pass Lumping and Bead Sequence	Participants requested not to lump weld beads. Participants requested to model the bead sequence specified in the problem statement.
Miscellaneous	Fine mesh of linear elements recommended. Mesh size of approximately 1.25 mm square in weld beads recommended. No triangular elements. Mesh density may coarsen away from weld areas.

3. Results

This section reports the basic set of results from the Phase 2b finite element round robin study. The results are first reported exactly as they were received from the measurement vendors and modelers. The data is then reported after sorting and interpolation, which was required for comparison purposes. When reporting modeling data, isotropic and kinematic hardening models are separated for the purposes of this report. Finally, flaw growth calculations are presented for reported residual stress profiles. The measurements and modeling results are not compared in this report, and no comment is made as to the validity of modeling results. All actions remaining for future work in this program are documented in Section 4.

3.1 Measurement Results

Figure 7 shows the raw hole drilling data for each of the four measurement locations around the circumference of the mock-up. The raw hole drilling data through the weld centerline are reported as a function of distance from the outer diameter (OD) surface, due to the nature of the hole drilling experiment (see Figure 3). The shear stress is approximately zero, indicating that the axial and hoop stresses are principal stresses. The axial and hoop stresses show a similar trend of tension at the OD and compression at the mid-thickness location. The axial stresses are more compressive at the inner diameter (ID) than the hoop stresses.

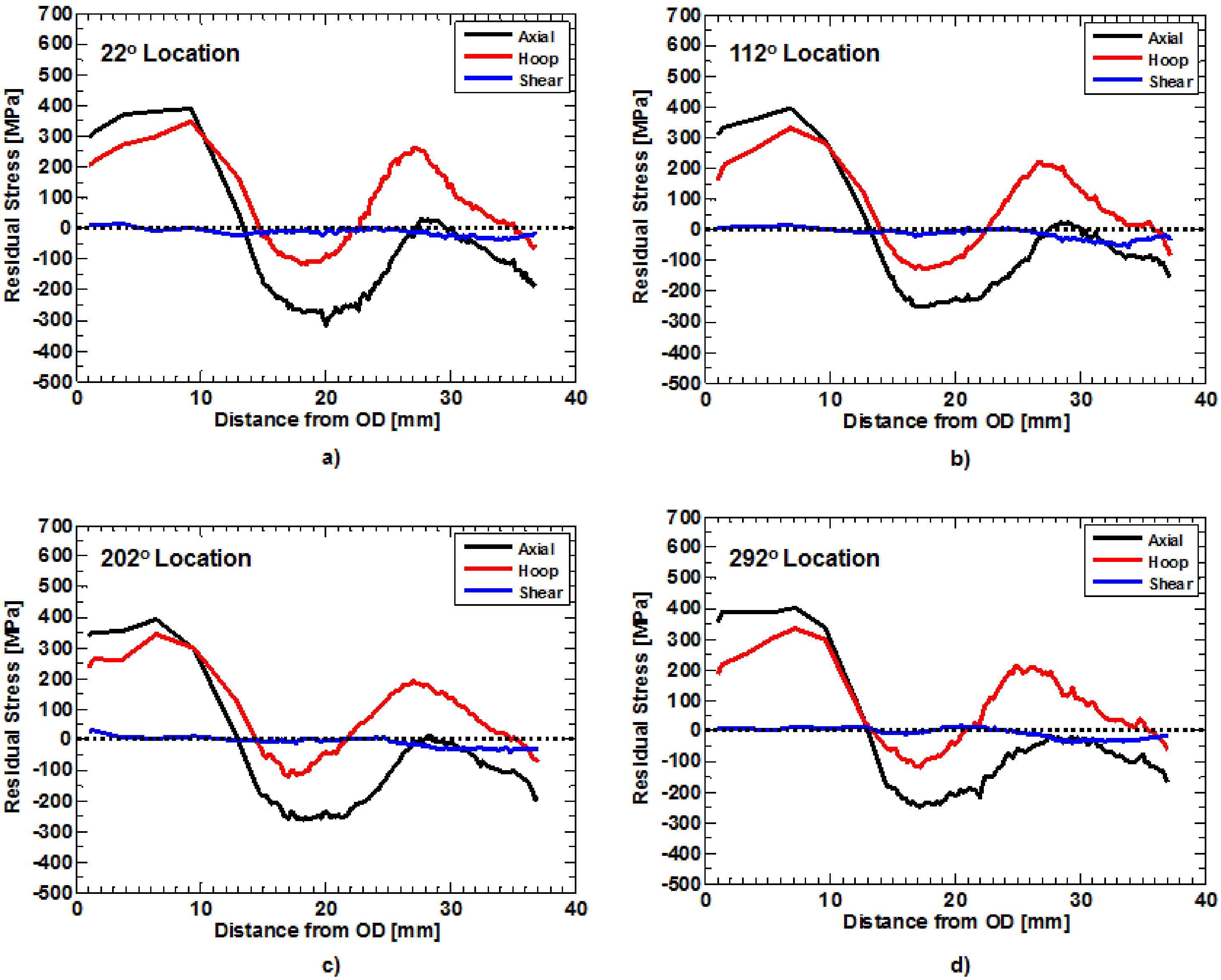


Figure 7: Hole Drilling Data: a) 22°, b) 112°, c) 202°, d) 292°

The raw contour data is shown in Figure 8 and Figure 9. The path data from the contour measurements were reported as a function of distance from the ID, in contrast to the hole drilling measurements. The axial stress contour data was determined on a plane through the centerline of the weld, and the stress variation around the circumference of the weld could be observed (Figure 8b). The hoop stress data was obtained along a plane through the pipe axis, and the axial variation of the through-wall stress profile was observed (Figure 9b). The raw measurement data is reported in tabular form in Appendix C.

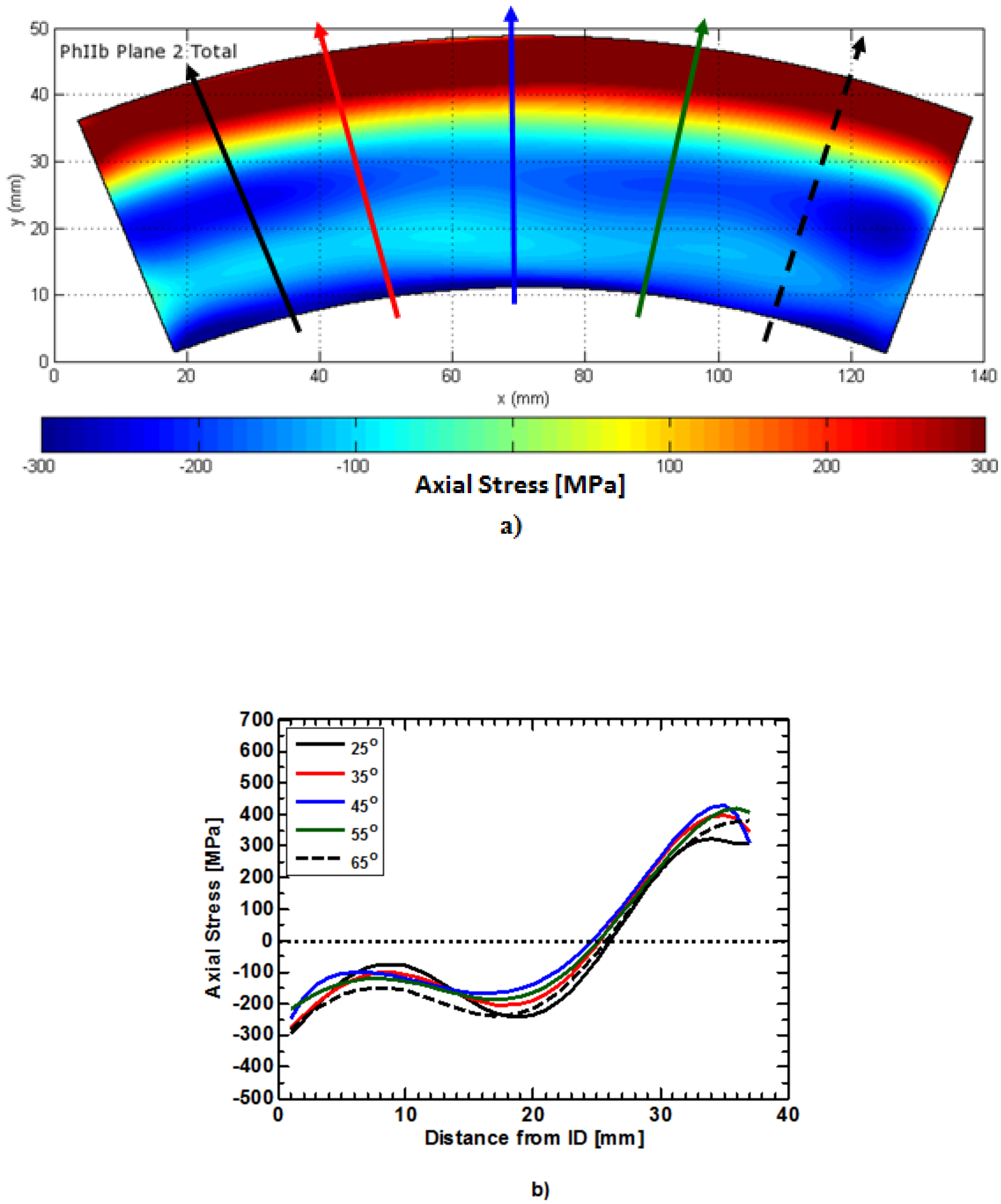
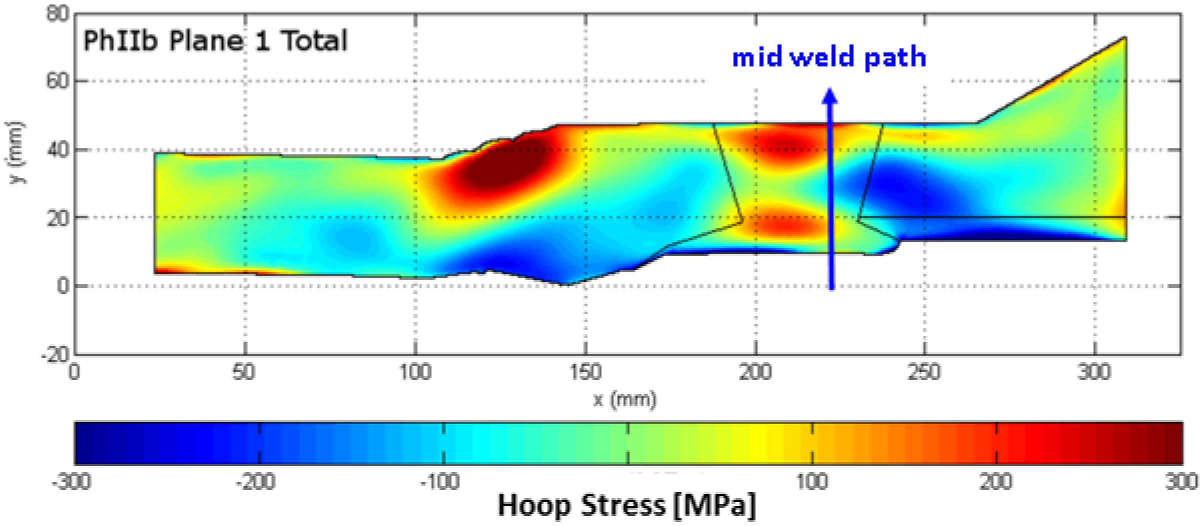
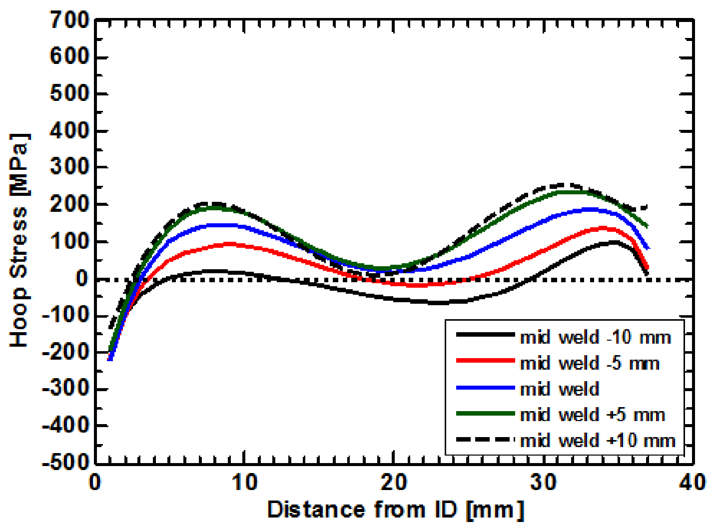


Figure 8: Axial Stress Contour Data: a) contours, b) path data



a)



b)

Figure 9: Hoop Stress Contour Data: a) contours, b) path data

Comparison of these data sets with each other (and, in future, with the modeling results) requires sorting, linear interpolation, and normalization of the through-wall position with respect to the thickness of the pipe. Each measurement shows stress data to slightly different through-wall positions x (e.g., 36.8 mm from the OD for one hole drilling measurement and 37.0 mm from the ID for the contour measurement). The nominal thickness of the weld, according to fabrication drawings, was 37.8 mm. For the purpose of comparison, the through-wall position was normalized with respect to the final position reported in each individual measurement (x/t). In addition, comparison of the two data sets requires contour data along the weld centerline. As such, the axial stress data in Figure 8b were averaged, and only the mid weld hoop stress data in Figure 9b were considered for this purpose. The measurement data after sorting ID to OD, interpolating, and normalizing are shown in Figure 10.

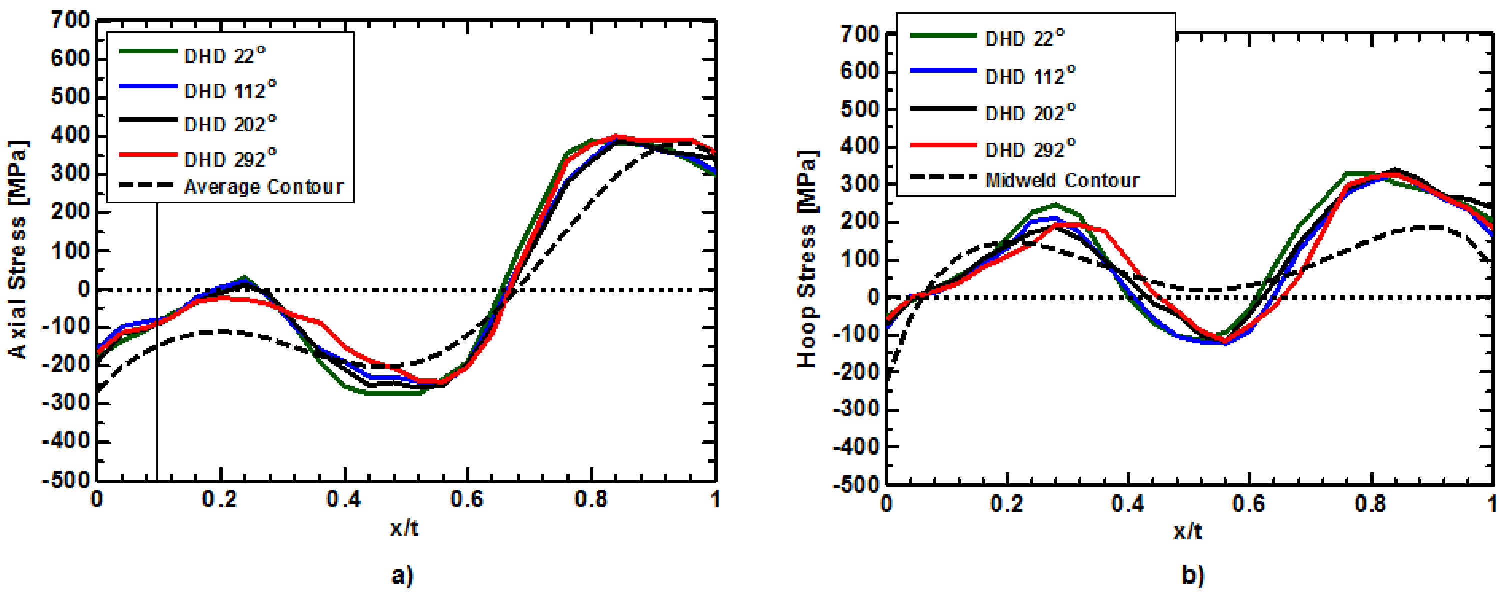


Figure 10: Modified Measurement Data: a) axial, b) hoop

While all the measurement data showed similar through-wall trends, the contour data exhibited some different features than the hole drilling data. For axial stresses, the average contour data showed higher-magnitude compressive stresses for $0 \le x/t \le 0.35$ and lower-magnitude tensile stresses for $0.7 \le x/t \le 0.9$. For hoop stresses, the contour method showed less through-wall variation than the hole drilling measurements and higher compression near the ID.

3.2 Modeling Results

An example mesh from one of the finite element round robin participants is shown in Figure 11. The participants extracted the data at a path going through the weld centerline. The figure also illustrates major geometry features that were modeled by the participants.

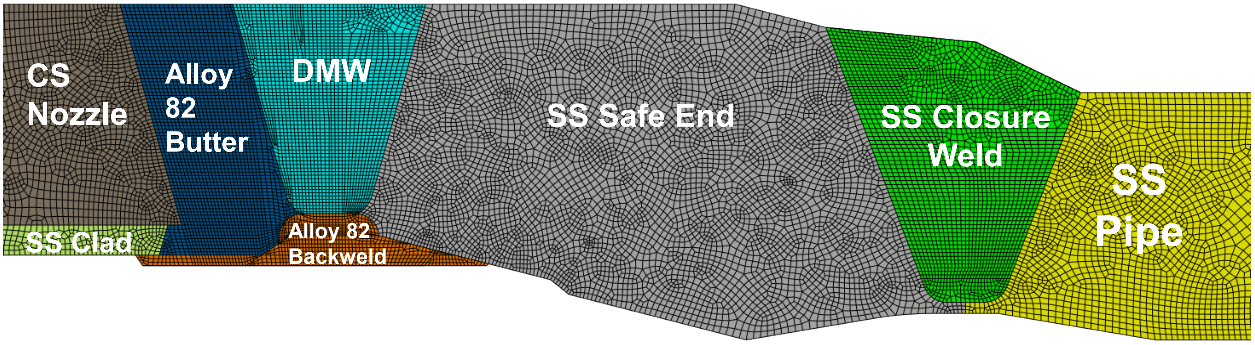


Figure 11: Example Mesh

Figure 12 and Figure 13 show the isotropic and kinematic hardening results, respectively. In general, the predictions based upon the nonlinear kinematic hardening rule show less variation through the wall thickness than the isotropic predictions. The raw modeling data is reported in tabular form in Appendix C.

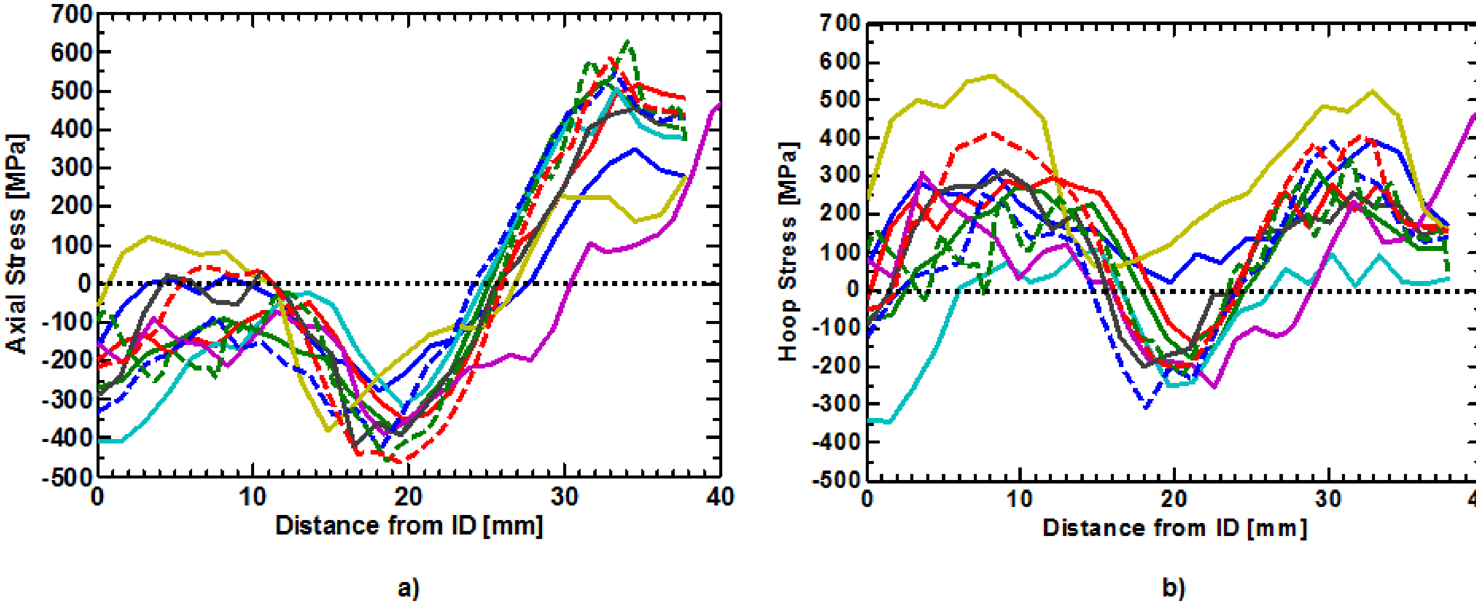
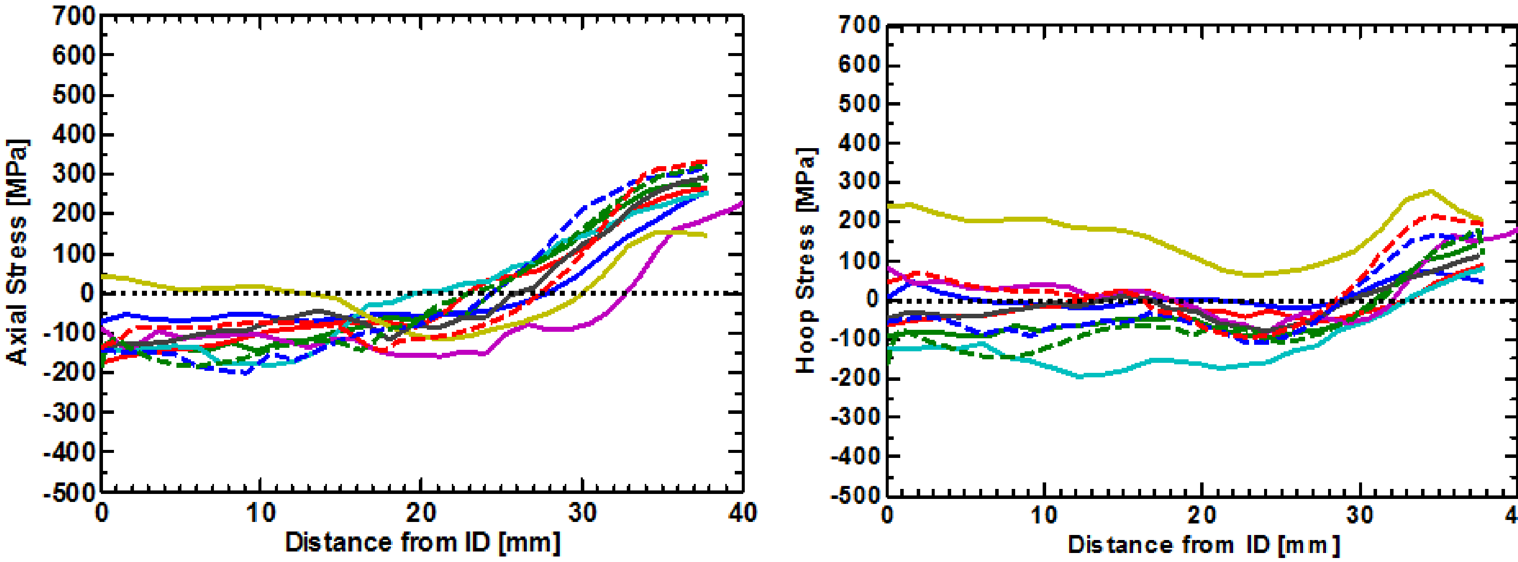


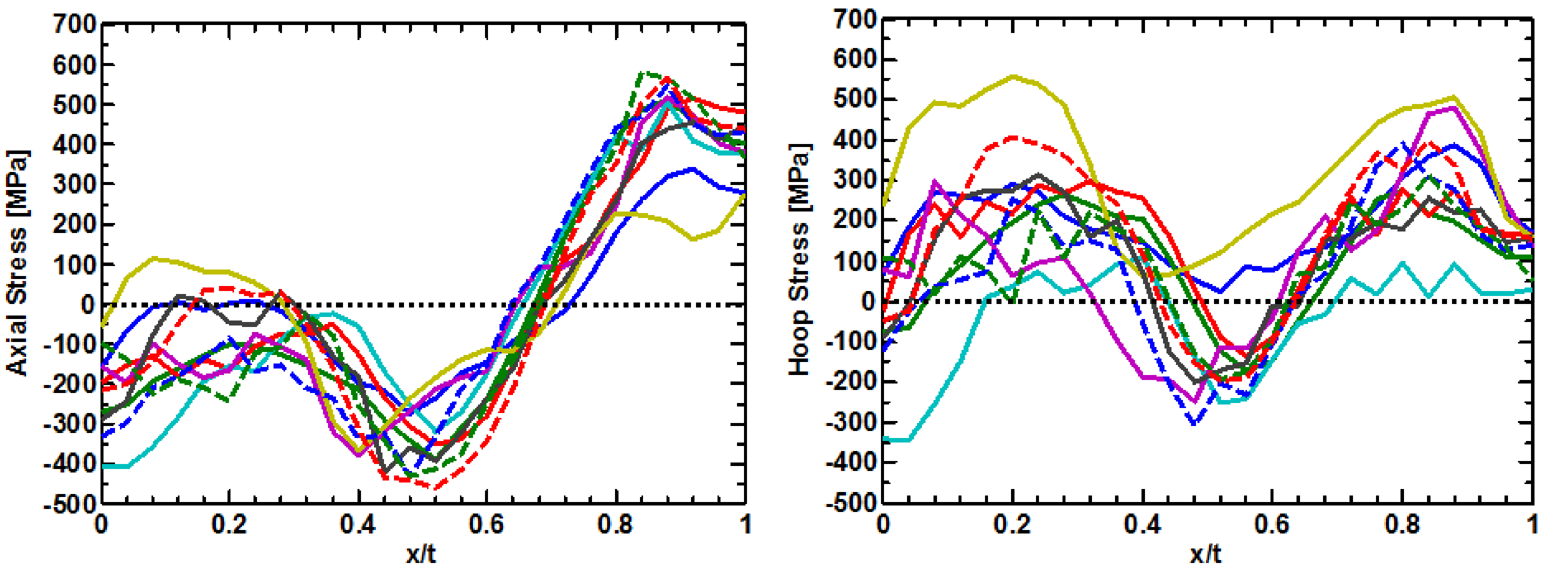
Figure 12: Isotropic Hardening Model Results: a) axial, b) hoop



a) b)

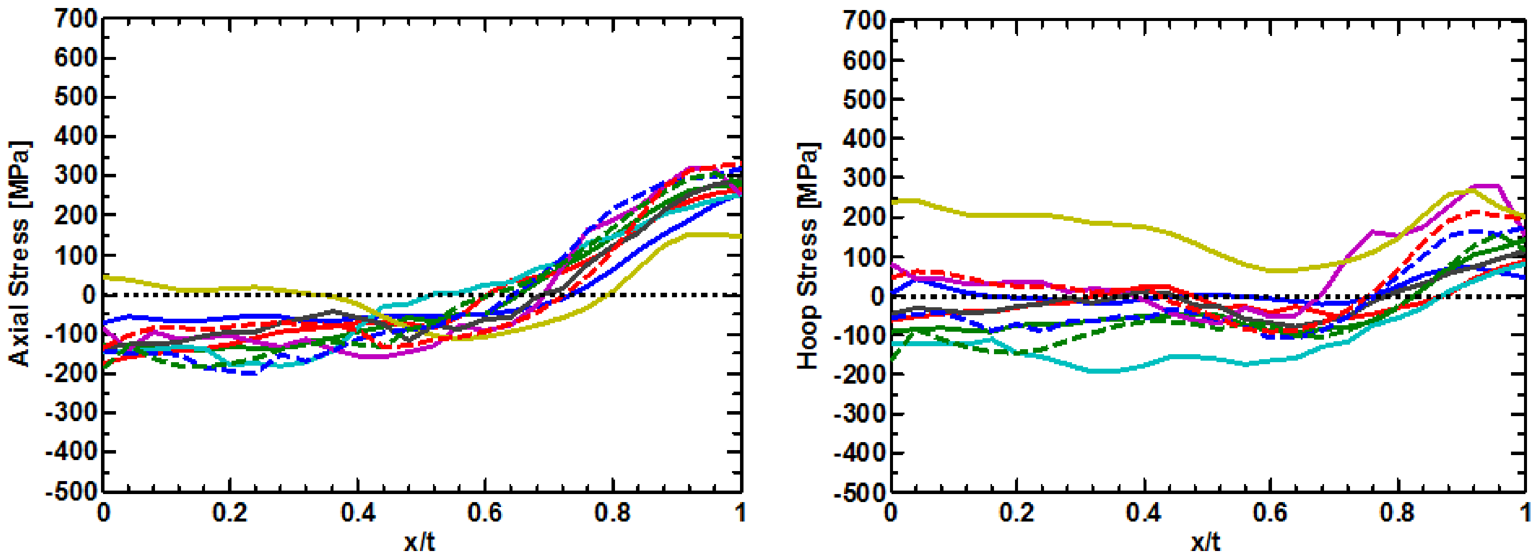
Figure 13: Kinematic Hardening Model Results: a) axial, b) hoop

Figure 14 and Figure 15 show the data after normalization and interpolation. Like the measurements, the individual thicknesses reported by the analysts were used for normalization. The processed data as shown in Figure 14 and Figure 15 is a convenient form for future data analysis. Through interpolation of the measurement and modeling data points, one-to-one comparisons can be made between the two data sets.



a) b)

Figure 14: Normalized Isotropic Hardening Results: a) axial, b) hoop



a) b)

Figure 15: Normalized Kinematic Hardening Results: a) axial, b) hoop

3.3 Flaw Growth Calculations

This section, along with Appendix D, reports results of flaw growth calculations that are based upon reported residual stress profiles in Sections 3.1 and 3.2. The assumed subcritical cracking mechanism for these calculations was stress corrosion cracking. Similar calculations often form the basis for industry requests for temporary regulatory relief from examination and repair/replacement requirements. In the future, these results may be used to inform acceptance criteria for WRS determined by finite element modeling. In addition to the reported WRS, the inputs to the flaw growth calculations are shown in Table 3.

Table 3: Flaw Growth Inputs

OD [mm]	t [mm]	Weld Width [mm]	a_0 [mm]	$2c_0$ [mm]	T [°C]	p [MPa]	σ_m [MPa]	σ_b [MPa]
381	36.07	26.48	3.607	7.214	315.6	15.5	60	100

OD – outer diameter
t – pipe wall thickness
a_0 – initial flaw depth
$2c_0$ – initial flaw length
T – operating temperature
p – operating pressure
σ_m – operating membrane loads
σ_b – operating bending loads

The pipe geometry inputs were chosen to be consistent with the mock-up geometry shown in Figure 1. The weld width input is only relevant for axial crack growth. The loading inputs were based upon typical loads expected in a pressurizer surge line nozzle. Results are also presented for σ_m = 35 MPa, as a sensitivity study. The membrane and bending loads constitute mode I loading for circumferential flaws only. The internal pressure load leads to mode I loading for both axial and circumferential flaws.

The stress intensity factor (SIF) solutions for this work drew upon weight function and influence function methods [5-8]. The total SIF was considered to be the sum of the bending load contribution and contributions from all other load sources. The SIF was calculated for both the deepest point of the flaw (K_{90}) and the surface point (K_0), as demonstrated in Figure 16 for a circumferential semi-elliptical surface flaw in a cylinder. The depth and length of the flaw were grown independently. After calculating SIF, the flaw growth rate due to stress corrosion

cracking was determined according to [10]. The SIF contribution from bending was accounted for by influence coefficients developed for global bending loads [5].

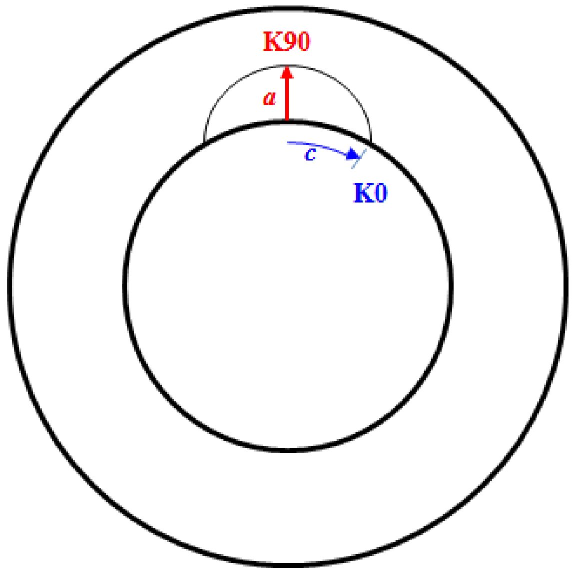


Figure 16: Flaw Geometry

Use of the Universal Weight Function Method (UWFM) to calculate SIF [7] negates the need to fit a polynomial to the assumed through-wall stress profile. Therefore, the stress input for the loads other than global bending was a vector of discrete stress magnitudes, σ_i, corresponding to through-wall radial positions, r_i [6-8]. Past work has shown that obtaining reasonable fits to WRS profiles can be challenging and that use of UWFM can increase accuracy in certain cases [8]. Finally, the methods employed here applied simple mathematical rules to account for axial cracks constrained from growing in the length dimension by the weld width [9], since the base material is not susceptible to primary water stress corrosion cracking (see Section D.2.1 for additional discussion).

This section will focus on depth growth of a circumferential flaw based upon the axial WRS measurements. Appendix D contains comprehensive flaw growth results, including length growth curves and other residual stress cases. The residual stress input for this calculation is shown in Figure 10a. Figure 17 shows K_{90} as a function of time for this case. The resulting flaw growth is shown in Figure 18.

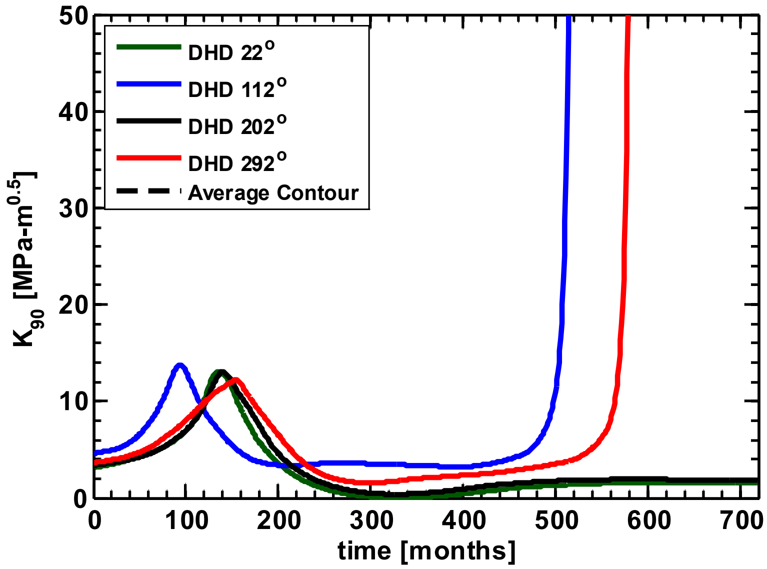


Figure 17: Stress Intensity Factor

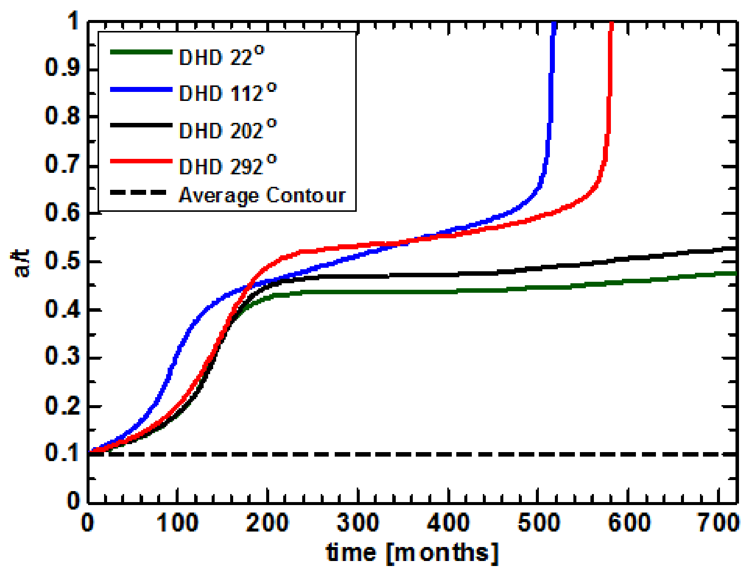


Figure 18: Flaw Growth

Figure 18 shows that variations in residual stress input significantly affect flaw growth calculations. The similar trends in the measurement data lead to similarities in crack growth behavior at early times. Even so, differences in assumed residual stress magnitude can mean the difference between crack arrest and through-wall growth.

The initial K_{90} value depends upon the residual stress magnitude at the assumed initial flaw depth (x/t=0.1, in this case). Figure 10a shows that the DHD 112° measurement is slightly higher than all the others at x/t=0.1. The interpolated values of axial WRS of the respective curves in Figure 10 are -85, -79 (for the DHD 112° case), -89, -88, and -147 MPa. As a result of these differences, the DHD 112° case demonstrated the fastest through-wall growth at approximately 500 months.

The DHD 22°, DHD 202°, and Average Contour curves all demonstrated crack arrest, while the remaining DHD curves showed relatively slow through-wall growth in 40-50 years. In particular, the K_{90} value for DHD 22° and DHD 202° dropped below 2 MPa-m$^{0.5}$ at 300 months and did not rise above this value for 720 months. The DHD 112° and DHD 292° cases, however, did not drop below 2 MPa-m$^{0.5}$ at 300 months (where the crack was under the influence of the large compressive residual stresses around mid-thickness). This behavior allowed for greater crack growth for 200 months < τ < 400 months (where τ is time). Therefore, the crack reached the tensile zone beginning at x/t = 0.65 earlier in time for these two cases and grew through wall rapidly.

The cause for the difference in K_{90} behavior at 300 months, however, may not be readily apparent from inspection of the WRS input (Figure 10a) alone. SIF also depends upon flaw aspect ratio, which may be affected by differences in residual stress near the ID, especially when growing the depth and length of the flaw independently. These issues will be further explored in future work.

As a sensitivity study, the flaw growth calculations were repeated with σ_m = 35 MPa, as shown in Figure 19 and Figure 20. The lower operating loads caused the SIF magnitudes to noticeably decrease throughout the time period analyzed. With the decreased loads, the analyses showed crack arrest for each residual stress case.

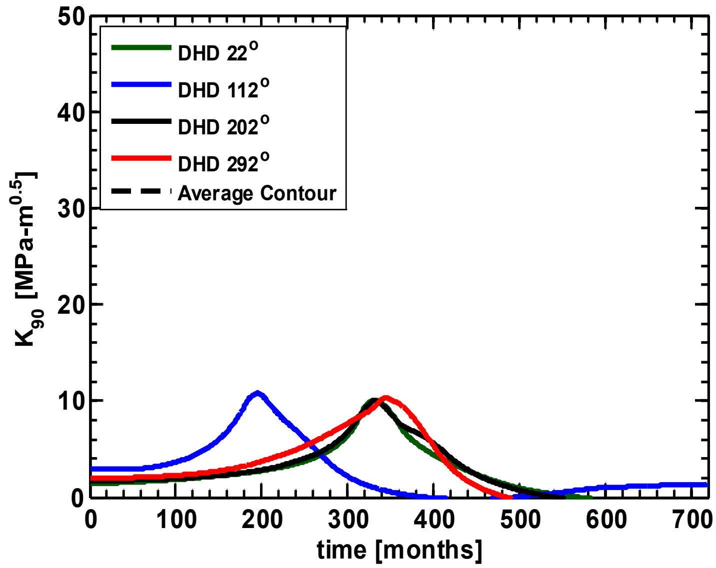


Figure 19: Stress Intensity Factor (Sensitivity Study)

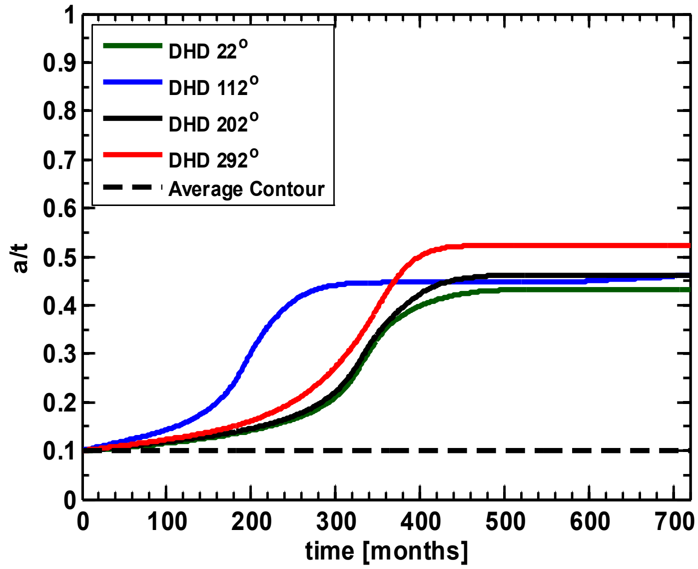


Figure 20: Flaw Growth (Sensitivity Study)

The results in Figure 17 can also be presented as a function of *a*/*t*, rather than as a function of time. This plot is shown in Figure 21. The plots in Figure 21 exhibit similar trends as in Figure 17. A kink in the curves shows up around mid-wall thickness. This kink is a result of the slow growth of the flaw in the compressive region of the WRS curve near *x*/*t*=0.5.

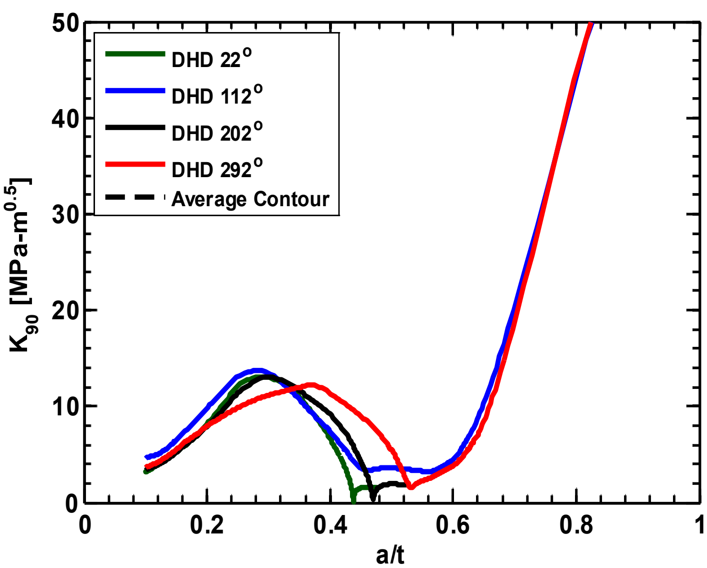


Figure 21: SIF against a/t

For comparison purposes, the flaw growth calculation was repeated with operating loads only. Figure 22 and Figure 23 show K_{90} and a/t, respectively, with the residual stress magnitude set to zero through the wall thickness. In this case, with no compressive residual stresses to counteract the operating loads, K_{90} increased continuously as a result of the increasing flaw size. As a result, the flaw grew through wall in approximately 100 months with a continuously increasing growth rate.

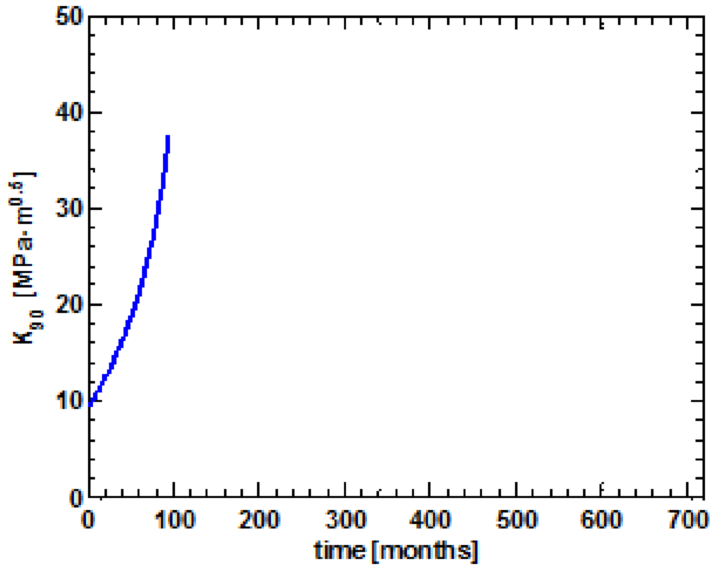


Figure 22: K_{90} for Operating Loads Only

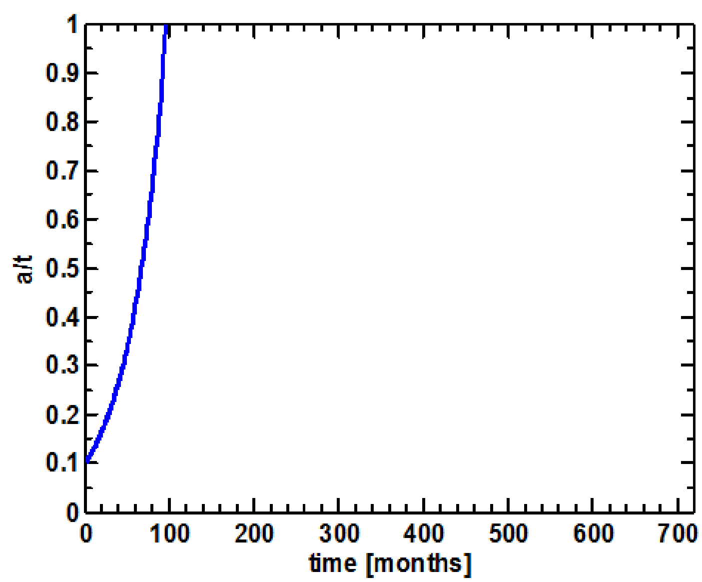


Figure 23: Flaw Growth for Operating Loads Only

In the future, flaw growth calculations based upon the round robin WRS data may inform judgments about acceptance criteria for residual stress predictions. When making those judgments, it is important to consider how these calculations are typically applied in the nuclear industry. For instance, analyzing dispersion in flaw growth may be more appropriate for shorter time frames than the 720 months shown in Figure 18. Future work may also involve developing a more detailed understanding of how small differences in WRS affect flaw growth curves.

4. Summary and Future Work

This document reported the WRS measurement and modeling results of the Phase 2b round robin study. This work is part of a larger NRC/EPRI research program, conducted under a Memorandum of Understanding, assessing current capabilities to numerically predict WRS in safety-related nuclear components. The measurement data included four hole drilling measurements and two contour measurements.

The modeling data was provided by 10 international participants, according to a set of modeling guidelines that was distributed to each analyst. The round robin study was double-blind, such that the modeling data and measurement data were independently developed. The raw measurement and modeling data were sorted, interpolated, and normalized to facilitate future comparisons and analyses.

Section 3.3 and Appendix D of this report presented flaw growth calculations based upon the measured and predicted WRS profiles. These calculations showed that times-to-leakage are significantly affected by subtle differences in the assumed residual stress profile. Flaw shape effects may be causing the observed sensitivity. Future work will explore this topic in more detail.

As of publication of this document, the NRC is developing quantitative tools to assess measurement and modeling uncertainty. This will allow more informed comparisons of measurement and modeling data than what has been reported in the past work [1-2]. NRC staff will then decide upon appropriate WRS guidance and associated acceptance criteria. Furthermore, WRS input guidance will be developed in parallel in the ASME Code process, where NRC staff will be involved alongside industry representatives. NRC will publish a NUREG documenting the final conclusions.

References

1. U.S. Nuclear Regulatory Commission, NUREG-2162, "Weld Residual Stress Finite Element Analysis Validation: Part 1 – Data Development Effort," March 2014 (ML14087A118).
2. Electric Power Research Institute, MRP-316, "Materials Reliability Program: Finite Element Model Validation for Dissimilar Metal Butt Welds," December 2011 (1022861).
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4. Electric Power Research Institute, MRP-317, "Materials Reliability Program: Welding Residual Stress Dissimilar Metal Butt Weld Finite Element Modeling Handbook," December 2011 (1022862).
5. API 579-1/ASME FFS-1, Fitness-for-Service, API Publishing Services, Washington, DC, 2007.
6. R. C. Cipolla and D. R. Lee, "Technical Basis for Equations for Stress Intensity Factor Coefficients in ASME Section XI Appendix A," PVP2004-2708, Proceedings of the 2004 ASME Pressure Vessels and Piping Conference, July 25-29, San Diego, CA, USA.
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8. D.-J. Shim, M. Kerr, and S. Xu, "Effect of Weld Residual Stress Fitting on Stress Intensity Factor for Circumferential Surface Cracks in Pipe," PVP2012-78180, Proceedings of the ASME 2012 Pressure Vessels & Piping Conference, July 15-19, Toronto, Ontario, CANADA.
9. D. Rudland, D. J. Shim, and S. Xu, "Simulating Natural Axial Crack Growth in Dissimilar Metal Welds due to Primary Water Stress Corrosion Cracking," PVP2013-97188, Proceedings of the ASME 2013 Pressure Vessels and Piping Conference, July 14-18, Paris, France.
10. Electric Power Research Institute, MRP-115, "Materials Reliability Program: Crack Growth Rates for Evaluating Primary Water Stress Corrosion Cracking of Alloy 82, 182, and 132 Welds (MRP-115)," November 2004 (1006696).

Appendix A: Phase 2b Mockup Fabrication Report

This Appendix contains an excerpt of the fabrication report for the Phase 2b mockup. The relevant material begins with Section 2.3: WOM Mock-Up. The full report may be found in the NRC ADAMS system under accession number ML16042A325.

The safe end to stainless steel pipe weld was radiographically inspected for quality. The radiographic inspection showed some signs of scattered, small diameter porosity which were not considered rejectable indications. The digital radiographs are not included in this report but will be submitted to PNNL as a separate file upon completion of this program.

After completion of this weld the IWRS mock up was returned for additional stress analysis.

2.3 WOM Mock-Up

The WOM mock-up also consisted of several welds. Each weld is discussed in detail below. During fabrication of the initial WOM mock-up, RT results indicated porosity in the weld greater than would be representative of an ASME Section III component, and it was decided that the safe end to nozzle weld including the nozzle buttering weld needed to be repeated. This report details the fabrication of the mockup per the revised drawings located in Appendix B. The mock-up was sectioned per drawing CG482478-400 by water jet cutting to remove both the buttering passes as well as the actual safe end weld. This mock-up was then re-machined per drawing CG482478-401. Fabrication of the mockup continued at the nozzle buttering stage. These welds will be discussed starting in Section 2.3.2 of this document.

2.3.1 Stiffening Weldment

The stiffening weldment consisted of an external fillet weld and an internal groove weld. The external fillet weld was deposited between the A36 steel flange and the SA182 (chrome moly) forged nozzle. The internal groove weld required three different welding procedures due to the presence of an internal stainless steel liner on the carbon steel nozzle. The welding procedures were a combination of pre-qualified welding procedures from AWS D1.1[(3)] and are provided in Appendix C.

The welds were deposited with the GMAW process using spray transfer. The fillet weld portion of the stiffening weldment was deposited manually with the flange/nozzle assembly in a fixed position. The internal groove welds was deposited by setting the torch in a fixed position and rotating the flange/nozzle assembly in the 1G welding position underneath the welding arc, using a positioner (Figure 22). The flange/nozzle assembly was preheated to 400°F (205°C) prior to welding with the temperature being maintained until the weld was completed.

[3] Structural Welding Code – Steel, AWS D1.1/D1.1M:2008, American Welding Society, Miami, FL, 2008.

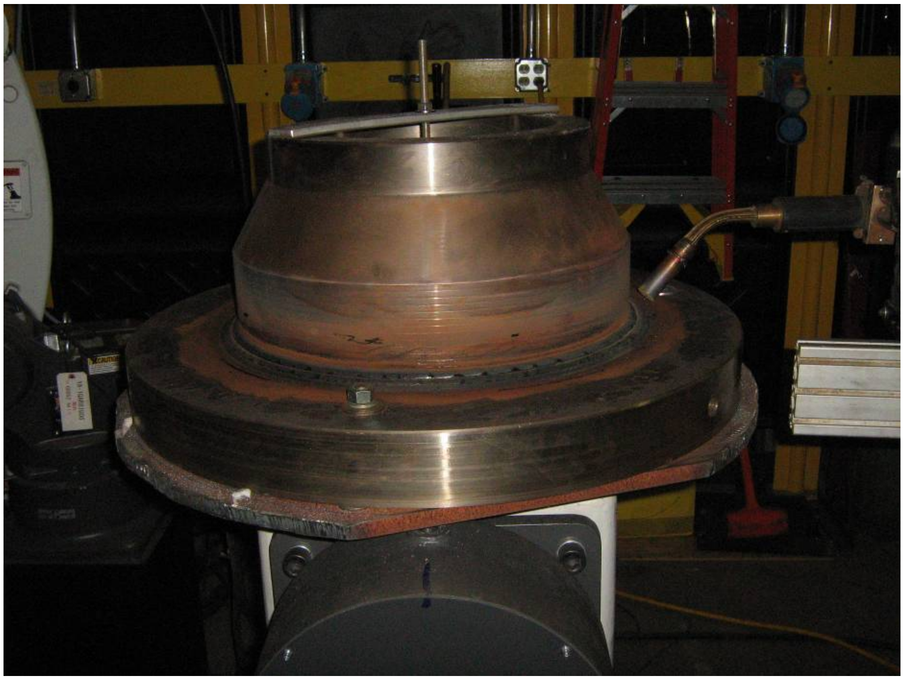


Figure 22. Welding of the Stiffener Plate on the WOM

2.3.2 Nozzle Buttering

The nozzle butter was deposited on the end of the nozzle opposite the flange. The butter was deposited using the GTAW with 0.045-in. (1.2-mm)-diameter Inconel 82 welding wire. The welding torch was set in a fixed position and the flange/nozzle assembly was rotated underneath the welding arc using a positioner (Figure 23). The positioner was tilted so the weld would be deposited in the flat position. The welding procedure that was used to deposit the butter layers was previously developed and is provided in Appendix D. The circumference of the mock-up was divided into eight segments of 45 degrees each labeled A through G. This was done to document the start/stop areas as well as any defects or repairs which might be required. All starts (except one) were done at the 90 degree locations (A, C, E, and G).

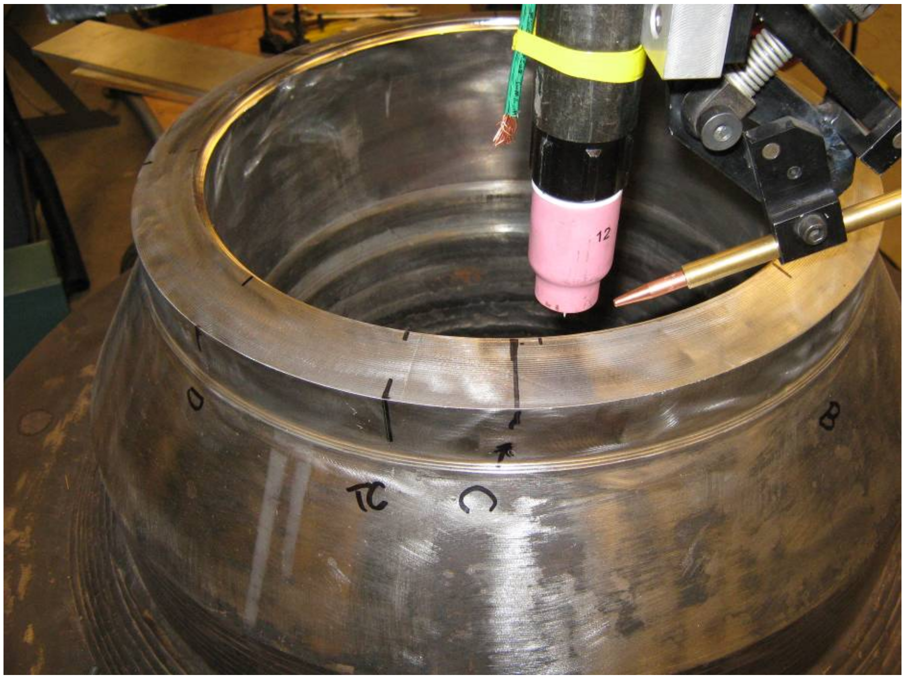


Figure 23. Set-Up for Nozzle Buttering Welds on WOM

The first layer of the butter was preheated to 400°F (205°C), the second layer of the butter was preheated to 200°F (93°C). The remaining layers were deposited with no required minimum preheat.

The first welding pass was placed at the ID sleeve interface such that it would tie the stainless steel sleeve to the carbon steel nozzle. During the welding of this pass several indications of porosity/contamination were noticeable in the weld (Figure 24). It was noted that the most likely cause of the porosity/contamination was due to the years of corrosion and contamination build up at the interface between the stainless steel sleeve and the nozzle ID. There was a concern that the porosity from the first pass would permeate through subsequent butter layer passes if it was not repaired or eliminated. A plan was formulated to grind out the porosity/contaminates (Figure 25) such that no surface porosity was visually apparent and manually repair weld the area using GTAW. The repair was completed and the welding on the WOM mockup continued. Each weld layer was completed using a continuous step over index which would provide one complete layer with only one start and one stop. This weld (layer) would amount to between 3 and 5 complete revolutions of the part. Subsequent layers were started from the WOM mock-up's OD and welded until the last rotation of the torch deposited a weld which overlapped the ID bead by no more than one-quarter of a bead width. This process continued until the minimum thickness of the butter layer had been reached (per drawing CG482478-402) and with minimum overlap of the ID bead.

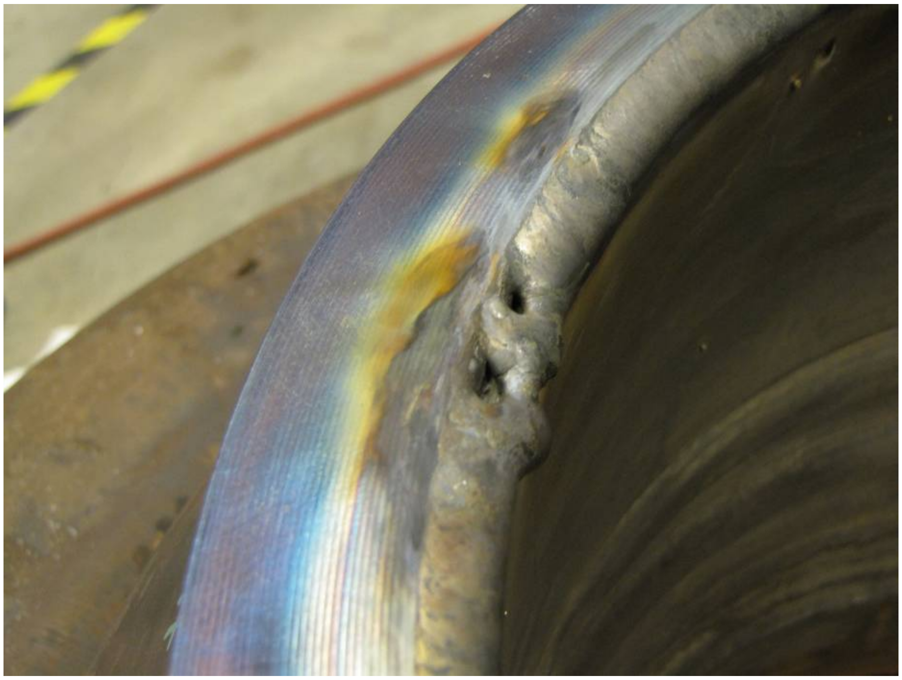


Figure 24. Photo Showing Porosity Indications in WOM Butter Weld

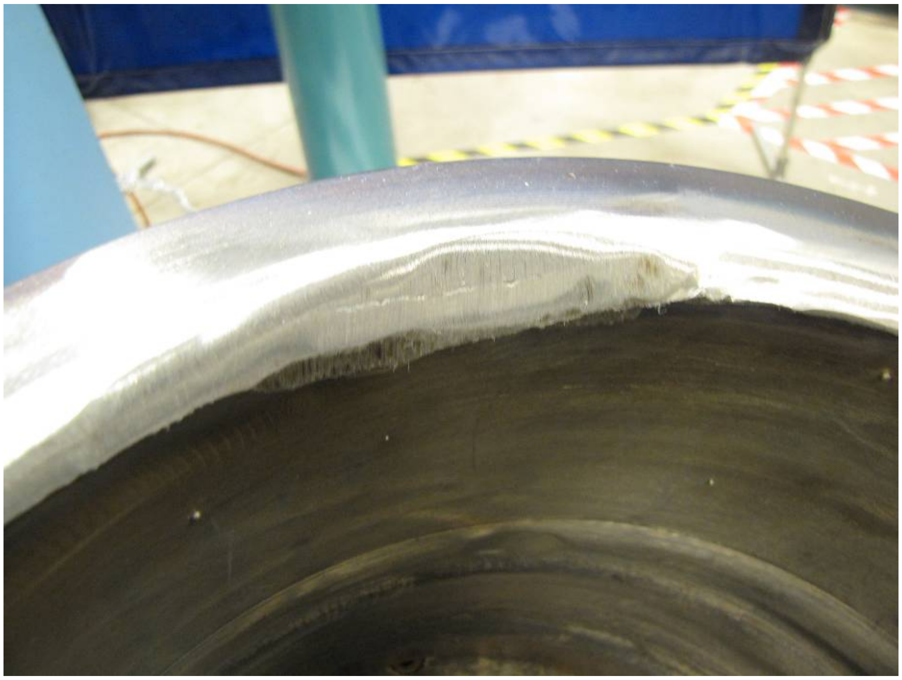


Figure 25. Photo of Rejected Area on WOM Buttering after Grinding

A total of 17 layers were deposited in 29 passes and shown in Figure 26. The welding parameters are listed in Table 8. The completed nozzle butter weld exceeded the final dimension requirements outlined in Battelle Drawing CG482478-204.

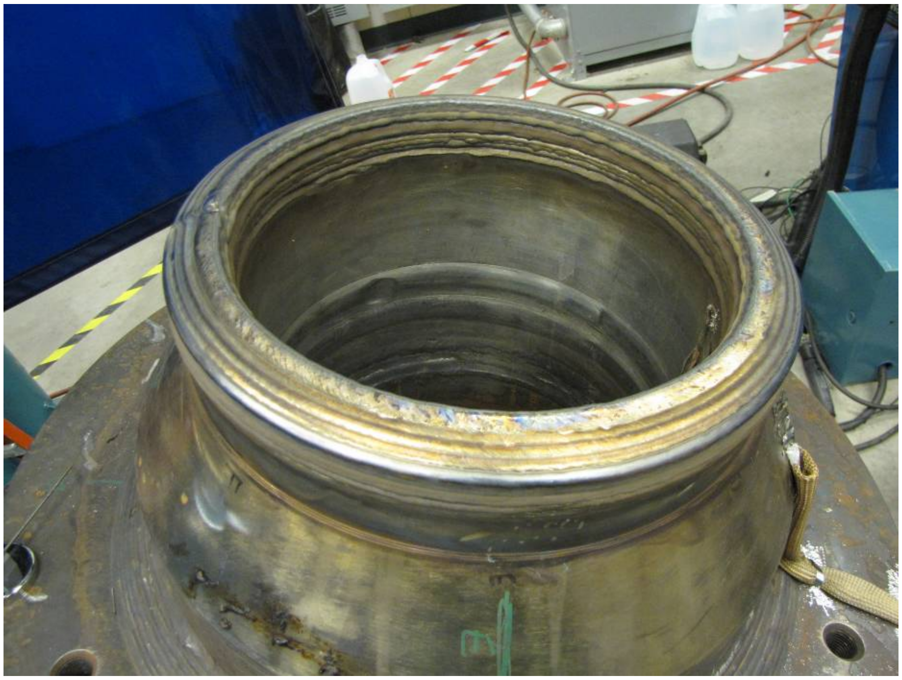


Figure 26. Photo Showing Completed Butter Weld on the WOM Nozzle

Table 8. Welding Parameters for WOM Butter Welds

Parameter	Edge Beads	Standard Beads	ID Weld Beads	ID Groove Welds
Current	220	240	240	240
Voltage	11.5	11.5	11.5	11.5
Wire Feed Speed	60	80	80	80
Travel Speed	5.5 to 6.5 ipm	5.5 to 6.5 ipm	5.5 to 6.5 ipm	5.5 to 6.5 ipm

After completion of the butter layer, the ID bead at the sleeve/nozzle interface and the ID surface of the butter layer were ground clean**Error! Reference source not found.**. A small groove was ground at the location of the sleeve/nozzle interface to help eliminate some of the previously deposited porosity. After the ID grinding had been completed, the surface was dye penetrant inspected to assure no defects remained on the ID surface. If indications were present then these areas were ground again and an additional dye penetrant was performed (Figure 28). After the surface was free from indications it was wiped clean with solvent and prepared for welding. An ID welder (Figure 29) deposited weld metal on the ID of the butter to allow for proper machining of the safe-end weld joint. Welds started to the inboard side and

stepped outward (towards open end of the nozzle) taking care not to weld at the sleeve/nozzle interface. A total of four full or partial layers were completed on the nozzle ID to assure adequate material was present for proper maching. Two short autogenous passes were done to repair two areas of over/under fill, which completed the nozzle buttering operation. Figure 30 shows the completed weld ID.

Figure 27.   Photo Showing ID Grinding and Groove on the WOM Buttering

Figure 28. Photo of Dye Penetrant Test on the WOM Buttering

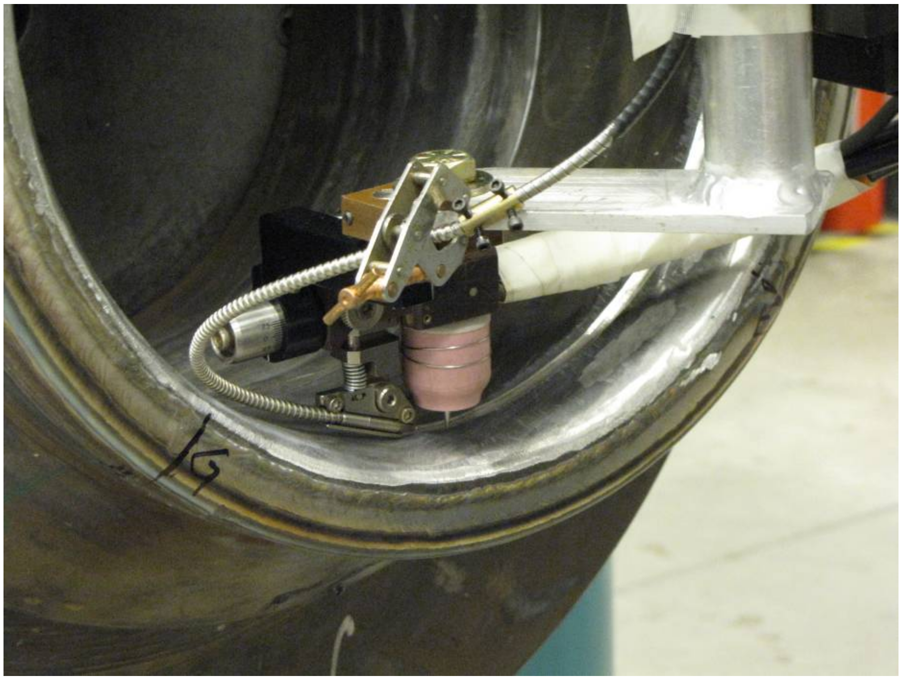


Figure 29. Photo of the ID Welding Torch on the WOM Buttering

Figure 30. Completed WOM ID Butter Weld

An RT of the butter weld was performed. Some small diameter porosity indications were detected; however, the indications were not considered rejectable. The digital radiographs are not included in this report but will be submitted to PNNL as a separate file upon completion of this program.

Temperature profiles were recorded during welding by attaching thermocouples to the ID and OD of the nozzle. There were three thermocouples at each location for a total of six thermocouples (Figure 31 and Figure 32). The thermocouples were located 0.25-in. (6.4-mm) from the edge of the machined bevel with 0.25-in. (6.4-mm) spacing between the thermocouples. The thermocouples were located at 2 inches past the “C” location mark (Figure 33). The thermocouple identification and locations are as follows:

- TC 1 – Located on the OD 0.25-in. (6.4-mm) from the nozzle edge
- TC 2 – Located on the OD 0.25-in. (6.4-mm) from TC1
- TC 3 – Located on the OD 0.25-in. (6.4-mm) from TC2
- TC 4 – Located on the ID 0.25-in. (6.4-mm) from the nozzle edge
- TC 5 – Located on the ID 0.25-in. (6.4-mm) from TC4
- TC 6 – Located on the ID 0.25-in. (6.4-mm) from TC5.

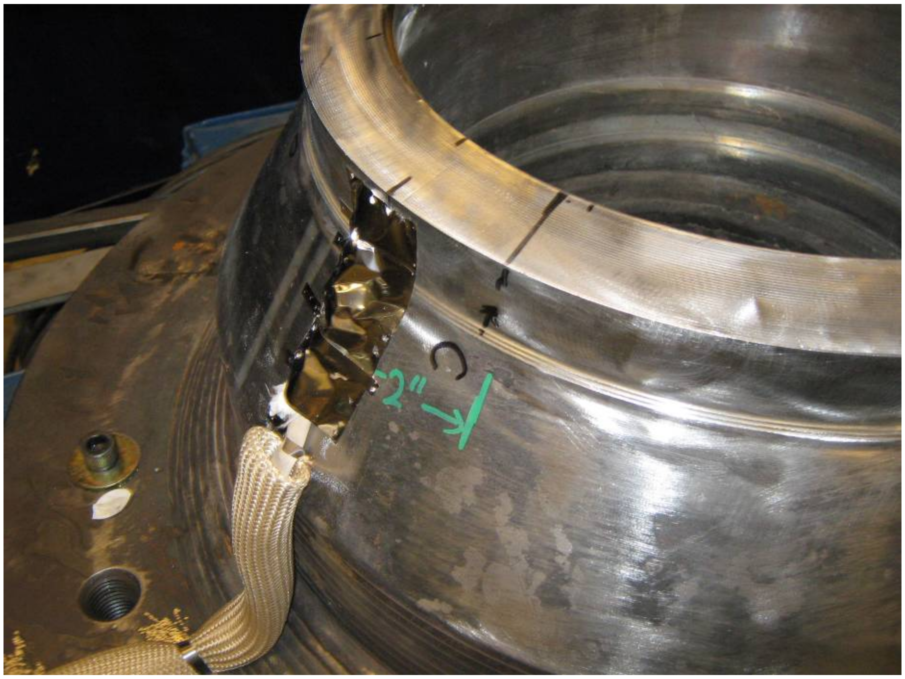


Figure 31. Thermocouple Locations on the OD of WOM Safe End Weld

Figure 32. Thermocouple Locations on the ID of the WOM Safe End for Weld Buttering

Figure 33. Location of Thermocouples relative to Mockup Lettering Grid

The temperature data is not included in this report but will be submitted to PNNL as a separate file entitled “WOM Mock-Up Buttering TC Data.” The recording of the temperature data was stopped after butter pass 26 as a result of welding not significantly increasing the temperature at the thermocouple locations. However, temperature data was again collected for the ID weld passes needed to complete the buttering process since those welds did result in a significant increase in the material temperature.

The nozzle butter weld was videotaped for record. Digital copies of all weld videos will be submitted to PNNL upon completion of this program.

Upon completion of the weld and radiographic inspection, the assembly was delivered to Battelle for post-weld heat treatment. The PWHT was to stress relieve the stiffening weldment as well as the nozzle butter weld prior to the subsequent machining operation and safe end weld.

2.3.3 Safe End Weld

The safe end weld joint was a full penetration V-groove described in Battelle Drawing CG482478-403. The final machined depth of the joint was 1.22-in. (31.2-mm). The safe end weld was deposited with the SMAW process using 1/8-in. and 5/32-in. diameter Inco 182 filler metal. These welds were welded at an approximate linear travel speed of 4 - 6 ipm. The safe end SMAW procedure is located in Appendix H. The safe end weld was made in the 1G

position. A total of 24 passes were required to fill the OD portion of the safe end weld. Typical welding parameters are shown in Table 9. The bead locations are provided in Figure 34.

Table 9. Welding Parameters for Safe End Welds using Inco 182

Diameter	Current	Voltage
1/8"	105 Amps	25 Volts
5/32"	130 Amps	25 Volts

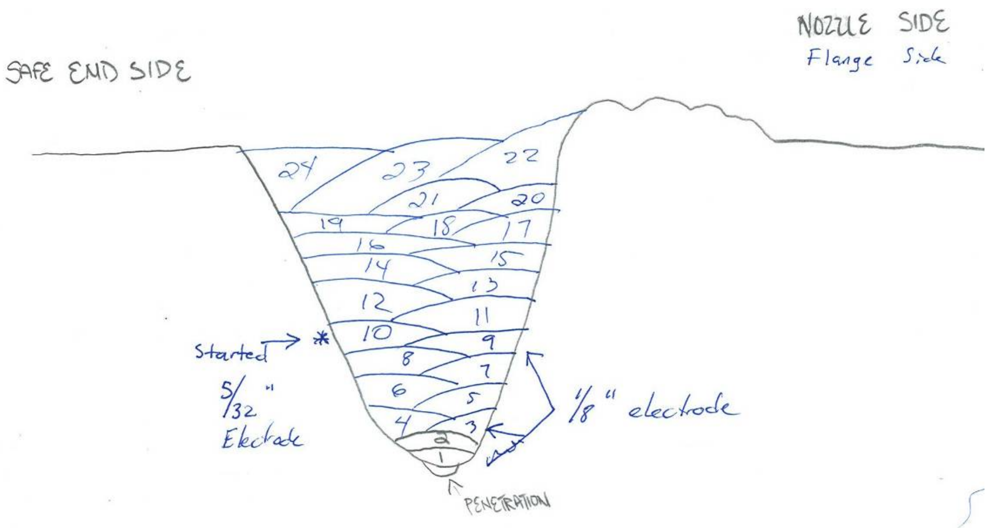


Figure 34. Bead Locations for OD Safe End Welds

Temperature profiles were recorded during welding by attaching thermocouples to the ID and OD of the nozzle. The numbering system for the thermocouples was as follows:

- TC 1 – Located on OD, 0.25-in. (6.4-mm) from the nozzle edge
- TC 2 – Located on OD, 0.25-in. (6.4-mm) from TC1
- TC 3 – Located on OD, 0.25-in. (6.4-mm) from TC2
- TC 4 – Located on OD, 0.25-in. (6.4-mm) from the nozzle edge and 45 deg. from TC1
- TC 5 – Located on OD, 0.25-in. (6.4-mm) from the nozzle edge and 45 deg. from TC4
- TC 6 – Located on ID, 0.25-in. (6.4-mm) from the nozzle edge
- TC 7 – Located on ID, 0.25-in. (6.4-mm) from TC 6
- TC 8 – Located on ID, 0.25-in. (6.4-mm) from TC7
- TC 9 – Located on ID, 0.25-in. (6.4-mm) from the nozzle edge and 45 deg. from TC6
- TC 10 – Located on ID, 0.25-in. (6.4-mm) from the nozzle edge and 45 deg. from TC9

All the temperature data is not included in this report but will be submitted to PNNL as a separate excel file entitled "WOM-2 Mock-Up Safe End TC Data."

Measurements were taken during welding to record the associated welding distortion, as described in the IWRS mock-up section, and are shown in Table 10. Distortion measurements were made after the safe end and nozzle were tacked together, after the root pass was deposited, after the hot pass was deposited, and after pass 3, (the first SMAW weld) and at 25, 50, 75, and 100% joint fill. The temperature of the assembly during the distortion measurements was kept below 150°F (66°C) to assure that most of the thermal shrinkage had occurred.

Table 10. Distortion Measurements for the WOM Safe End Weld

Type	Location	Pass				Distance from Mockup OD			
						0.9705	0.6455	0.3205	0.0000
		0	1 Root	2 HP	3 SMAW	25%	50%	75%	100%
Depth	A	1.2955	1.2920	1.2655	1.1985	0.9405	0.6195	0.2940	n/a
Depth	E +1"	1.3050	1.3010	1.2630	1.2390	0.9895	0.6615	0.3030	n/a
Depth	I	1.3090	1.2995	1.2585	1.1605	0.9295	0.6150	0.2245	n/a
Depth	M	1.3090	1.2890	1.2650	1.1805	0.9445	0.5640	0.2530	n/a
Width	A	2.9435	2.9230	2.9130	2.9350	2.8080	2.7665	2.7380	2.7370
	C	2.9310	2.9020	2.8970	2.8885	2.8070	2.7720	2.7270	2.7290
	E	2.9410	2.9150	2.9110	2.8880	2.8170	2.7510	2.7280	2.7240
	G	2.9450	2.8845	2.8720	2.8870	2.8130	2.7560	2.7430	2.7350
	I	2.9755	2.9440	2.9335	2.9255	2.8435	2.7830	2.7585	2.7555
	K	2.9975	2.9705	2.9685	2.9485	2.8655	2.8110	2.7850	2.7835
	M	2.9810	2.9610	2.9165	2.9320	2.8555	2.8035	2.7820	2.7755
	O	2.9875	2.9710	2.9610	2.9440	2.8660	2.8095	2.7855	2.7760

Laser profilometry was conducted on the safe end weld to map the bead location. An illustration of the laser scanning data is shown in Figure 35. All the laser profilometry data is not included in this report but will be submitted to PNNL as a separate file entitled “WOM-2 Mock-Up Safe End Laser Scans.”

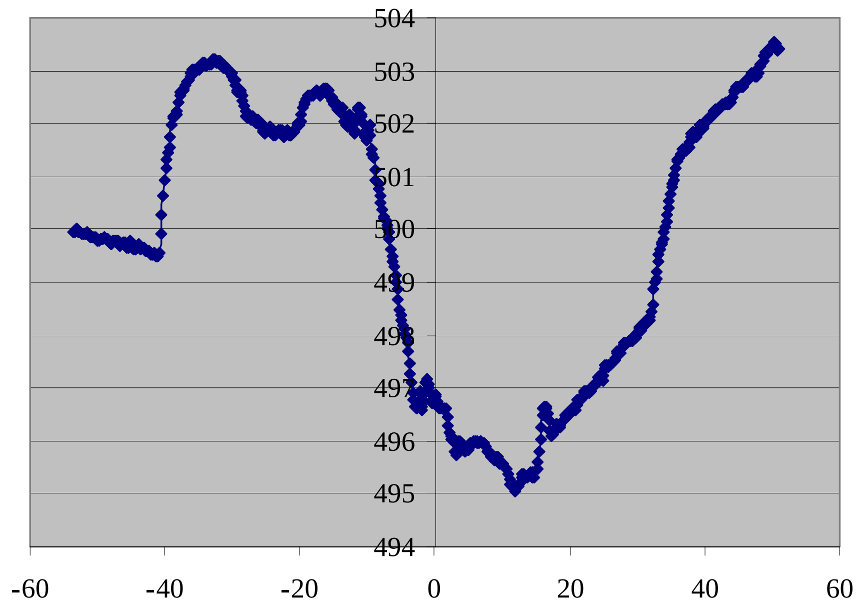


Figure 35. Laser Scan Data from WOM Safe End Weld

The safe end weld was videotaped for record. Digital copies of all weld videos will be submitted to PNNL upon completion of this program.

2.3.4 Back Weld

The back weld joint has a V-preparation which was machined into the previously deposited safe end weld and is described in Battelle Drawing CG482478-406. The back weld was deposited with the SMAW process using 1/8-in. and 5/32-in. diameter Inco 182 filler metal. The back weld groove was rotated using a positioner such that it would be a 1G weld. There was a total of 15 passes needed to complete the back weld. The bead locations are provided in Figure 36. The welding procedure that was used to deposit the safe end weld was also used to deposit the back weld (Appendix H).

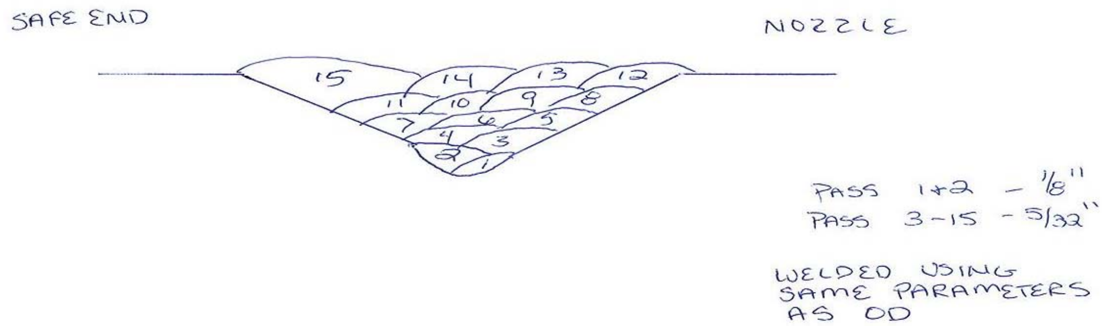


Figure 36. Weld Bead Map of the WOM Safe End Back Weld

Temperature profiles were recorded during the back weld by attaching thermocouples to the ID and OD of the safe end side of the mock up. There were a total of ten thermocouples used to monitor the temperature of the back weld. The thermocouple ID and locations are as follows:

- TC 1 – Located on OD, 0.25-in. (6.4-mm) from the nozzle edge
- TC 2 – Located on OD, 0.25-in. (6.4-mm) from TC1
- TC 3 – Located on OD, 0.25-in. (6.4-mm) from TC2
- TC 4 – Located on OD, 0.25-in. (6.4-mm) from the nozzle edge and 45 deg. from TC1
- TC 5 – Located on OD, 0.25-in. (6.4-mm) from the nozzle edge and 45 deg. from TC4
- TC 6 – Located on ID, 0.25-in. (6.4-mm) from the nozzle edge
- TC 7 – Located on ID, 0.25-in. (6.4-mm) from TC 6
- TC 8 – Located on ID, 0.25-in. (6.4-mm) from TC7
- TC 9 – Located on ID, 0.25-in. (6.4-mm) from the nozzle edge and 45 deg. from TC6
- TC 10 – Located on ID, 0.25-in. (6.4-mm) from the nozzle edge and 45 deg. from TC9

The temperature profile of back weld pass 1 is shown in Figure 37. All the temperature data is not included in this report but will be submitted to PNNL as a separate excel file entitled "WOM-2 Mock-Up Back Weld TC Data."

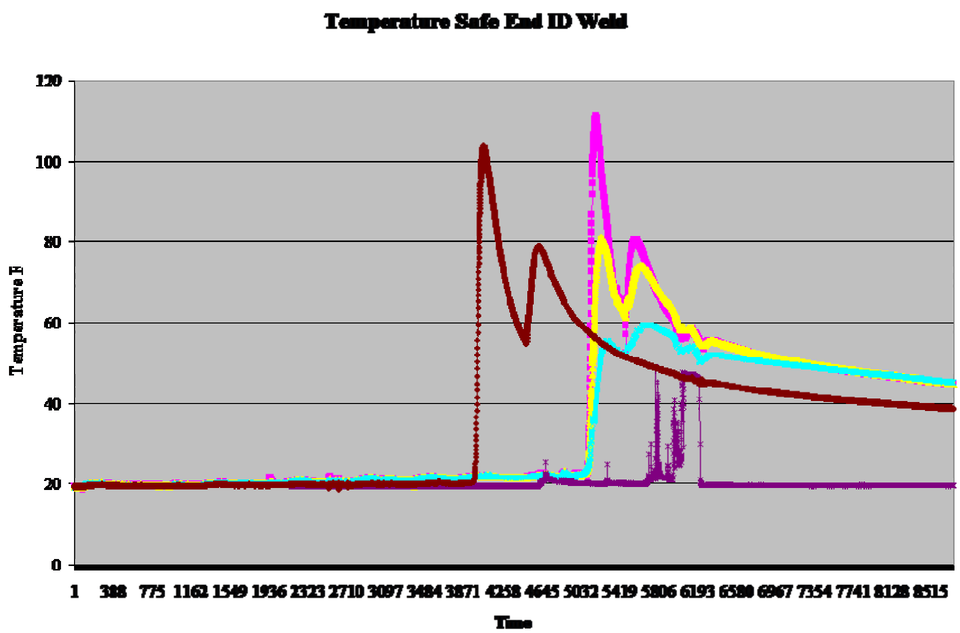


Figure 37. Temperature Profile of the WOM Safe End Back Weld

Measurements were taken before welding began and again after all welding was completed to record the associated welding distortion. The same punch marks that were used to measure distortion during the safe end weld were used to measure distortion caused by the back weld. Note that these measurements were taken on the OD of the mock up. These distortion measurements should be substantially less then on the OD weld in part due to the distance involved from the point of welding to the point of measurement. The temperature of the assembly during the distortion measurements was kept below 150°F (66°C) to assure most of the thermal shrinkage had occurred. The distortion measurements are shown in Table 11.

Table 11. Distortion Measurements for the WOM Safe End Back Weld

Location	Before Welding	After Welding
A	2.7320	2.7435
C	2.7250	2.7390
E	2.7180	2.7275
G	2.7350	2.7315
I	2.7585	2.7620
K	2.7930	2.7905
M	2.7745	2.7730
O	2.7750	2.7865

Laser profilometry was conducted on the back weld to map the bead location using the same equipment that was used during the measuring of the safe end weld. A typical laser scans for pass 2 is shown in Figure 38. It is important to note that when scanning the joint the laser could not intersect the surface perpendicularly due to the mock-up constraints. For this reason Figure 38 appears skewed. All the laser profilometry data is not included in this report but will be submitted to PNNL as a separate file entitled "WOM-2 Mock-Up Safe End Back Weld Laser Scans."

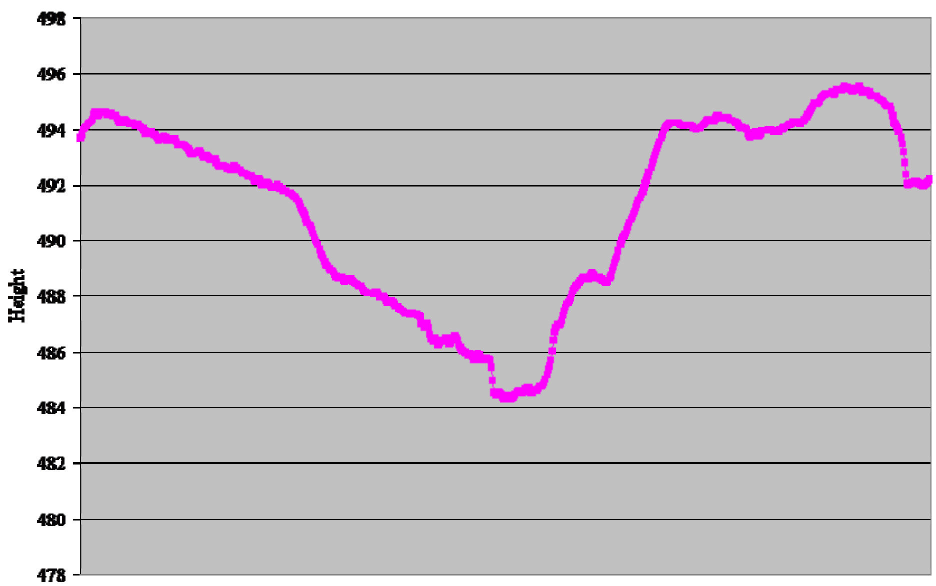


Figure 38. Laser scan of WOM Safe End Back Weld

The safe end back weld was videotaped for record. Digital copies of all weld videos will be submitted to PNNL upon completion of this program.

Both the safe end weld and the back weld were radiographically inspected for quality. The radiographic inspection showed some signs of scattered, small diameter porosity which were not considered rejectable indications. The digital radiographs are not included in this report but will be submitted to PNNL as a separate file upon completion of this program.

2.3.5 Safe End to Stainless Pipe Weld

After machining the safe end back weld the mock-up was returned to EWI for completion of the final weld. This weld was the safe end to stainless steel pipe weld. This weld was performed per Battelle Drawing CG482478-414 which is attached in Appendix B. For this weld the safe end was welded to the stainless steel pipe section by first doing a manual GTAW root weld followed by a manual GTAW hot pass weld. These two passes were done in the 2G position. The balance of the welding was done using the SMAW process in the 1G position. The safe

end to stainless steel pipe welding procedure is located in Appendix G. . The parameters for welding the IWRS mockup were repeated for the WOM and are listed in Table 6.

Distortion measurements, laser scans and temperature data were taken before and during the welding of the safe end to stainless pipe weld Figure 39 shows locations of some of the thermocouples. Figure 40 shows a typical temperature profile from one of the welds. Figure 41 through Figure 43 shows the GTAW root pass, a typical SMAW pass and the completed weld respectively. Figure 44 shows the weld pass map. Measurements for distortion are shown in Table 12.

Figure 39. Location of Thermocouples on the WOM Safe End to Stainless Pipe Weld

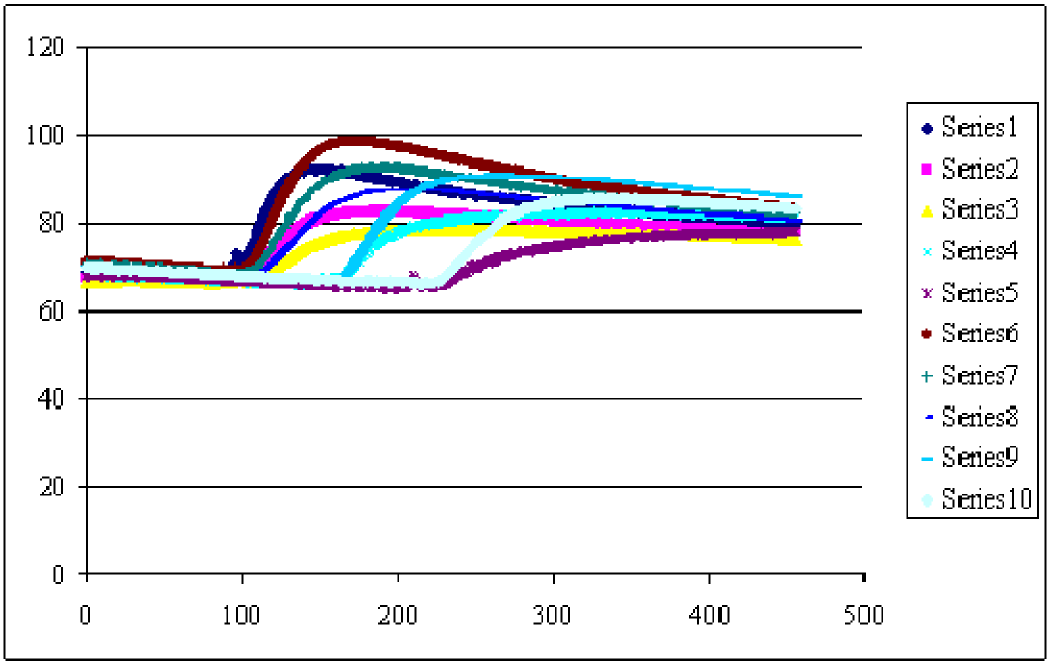


Figure 40. **Typical Temperature Profile for the WOM Safe End to Stainless Pipe Weld**

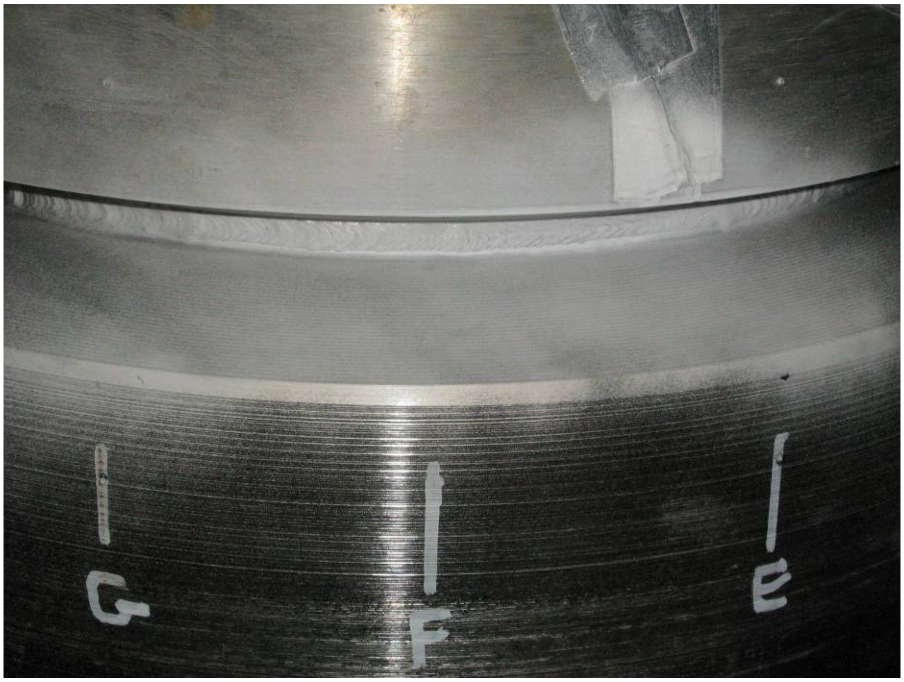


Figure 41. **Photograph of the GTAW Root Pass of the WOM Safe End to Stainless Pipe Weld**

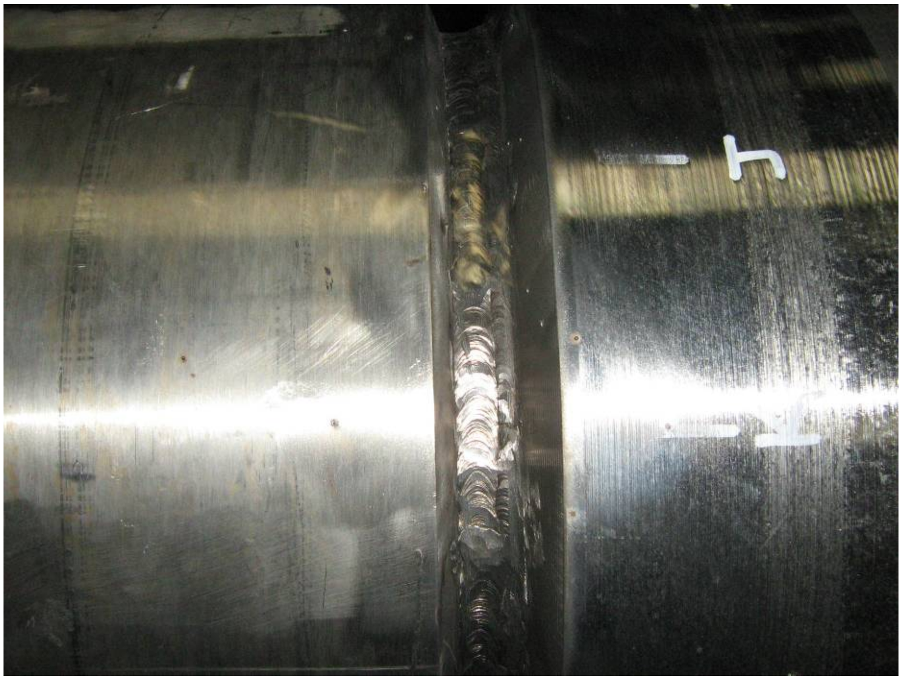


Figure 42. Photograph of a Typical SMAW Weld on the WOM Safe End to Stainless Pipe Weld

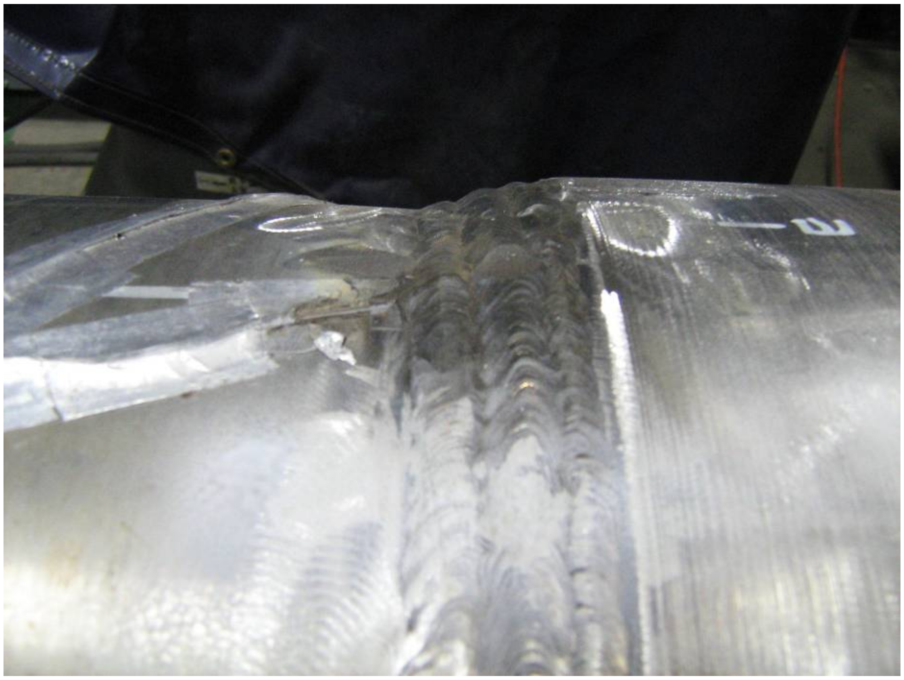


Figure 43. Photograph of the Completed WOM Safe End to Stainless Pipe Weld

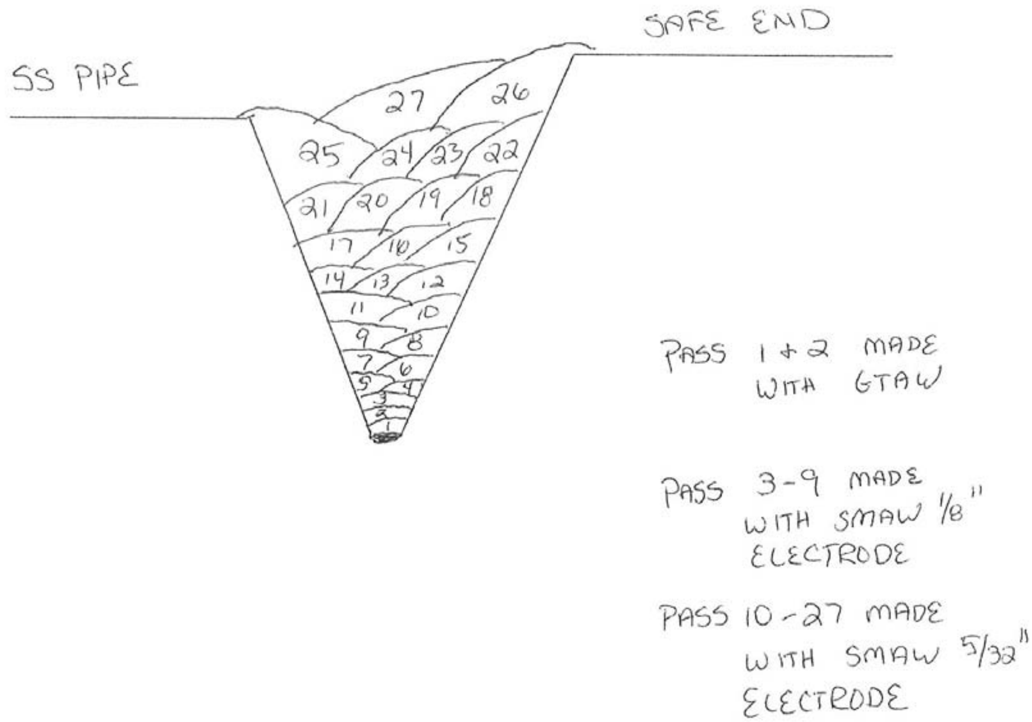


Figure 44. Weld Pass Map for WOM Safe End to Stainless Pipe Weld

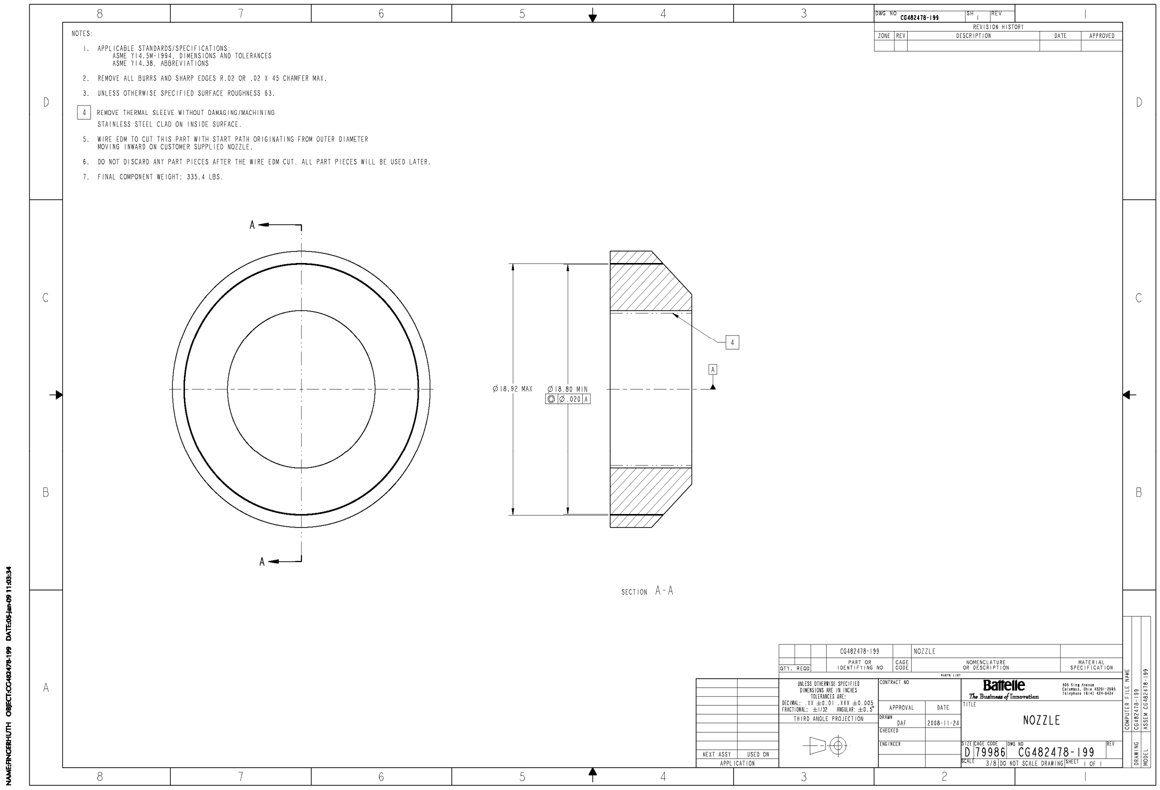
Table 12. Measurements for WOM Safe End to Stainless Steel Pipe Weld

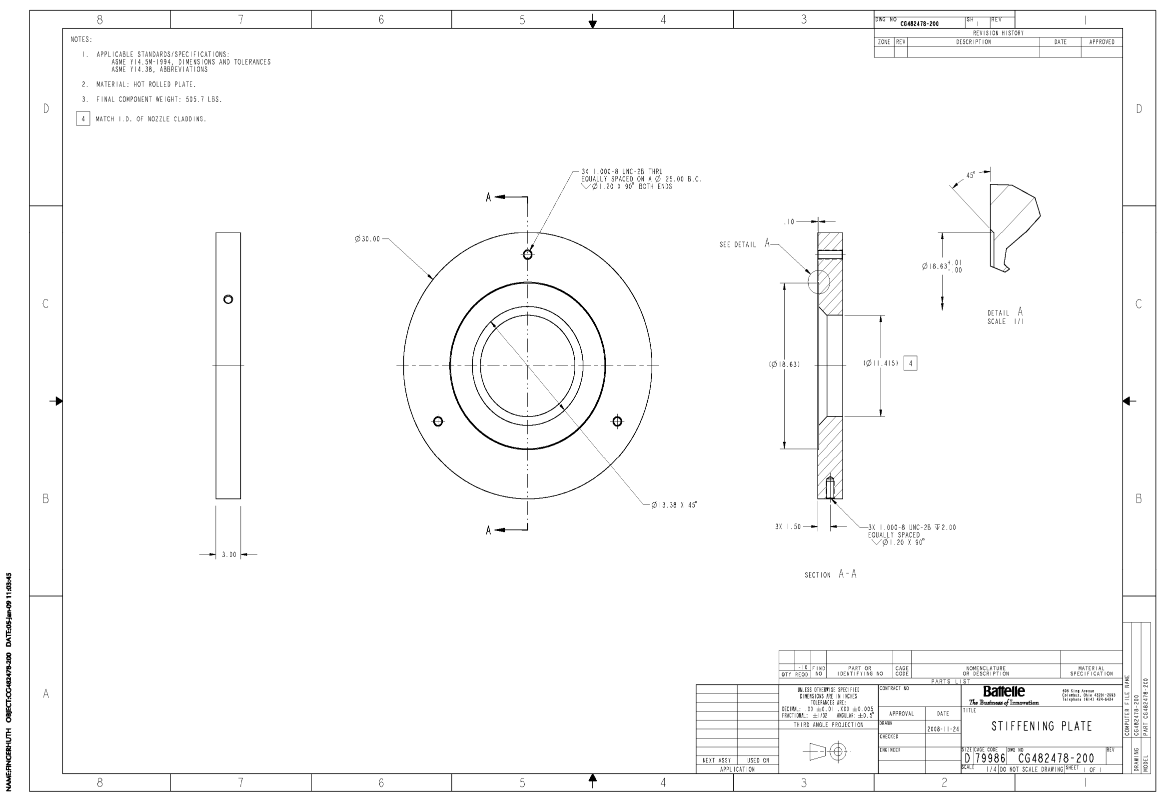
		Pass				Distance from Mock Up OD			
						1.069	.713	.357	0
Type	Loc.	0	1 Root	2 HP	3 SMAW	25%	50%	75%	100%
Depth	A	1.6125	1.5995	1.5730	1.4360	.9965	.6575	.384	
Depth	E	1.5775	1.5730	1.5480	1.4405	1.0265	.7055	.3935	
Depth	I	1.5790	1.5745	1.5540	1.4120	1.0225	.7205	.4430	
Depth	M	1.5880	1.5875	1.5785	1.4350	1.0465	.7120	.4135	
Width	A	3.3330	3.3230	3.3080	3.2730	3.1945	3.1595	3.1525	3.1505
	C	3.3530	3.3380	3.3275	3.2770	3.2085	3.1815	3.1740	3.1525
	E	3.3220	3.3075	3.2960	3.2615	3.1740	3.1460	3.1375	3.1325
	G	3.4090	3.3960	3.3830	3.3470	3.2490	3.2220	3.2155	3.2200
	I	3.3660	3.3595	3.3370	3.3055	3.2220	3.1930	3.1830	3.1755
	K	3.3830	3.3680	3.3590	3.3215	3.2340	3.2050	3.1985	3.1890
	M	3.3630	3.3500	3.3365	3.3020	3.2180	3.1815	3.1730	3.1720
	O	3.3440	3.3310	3.3165	3.2805	3.1945	3.1715	3.1610	3.1530

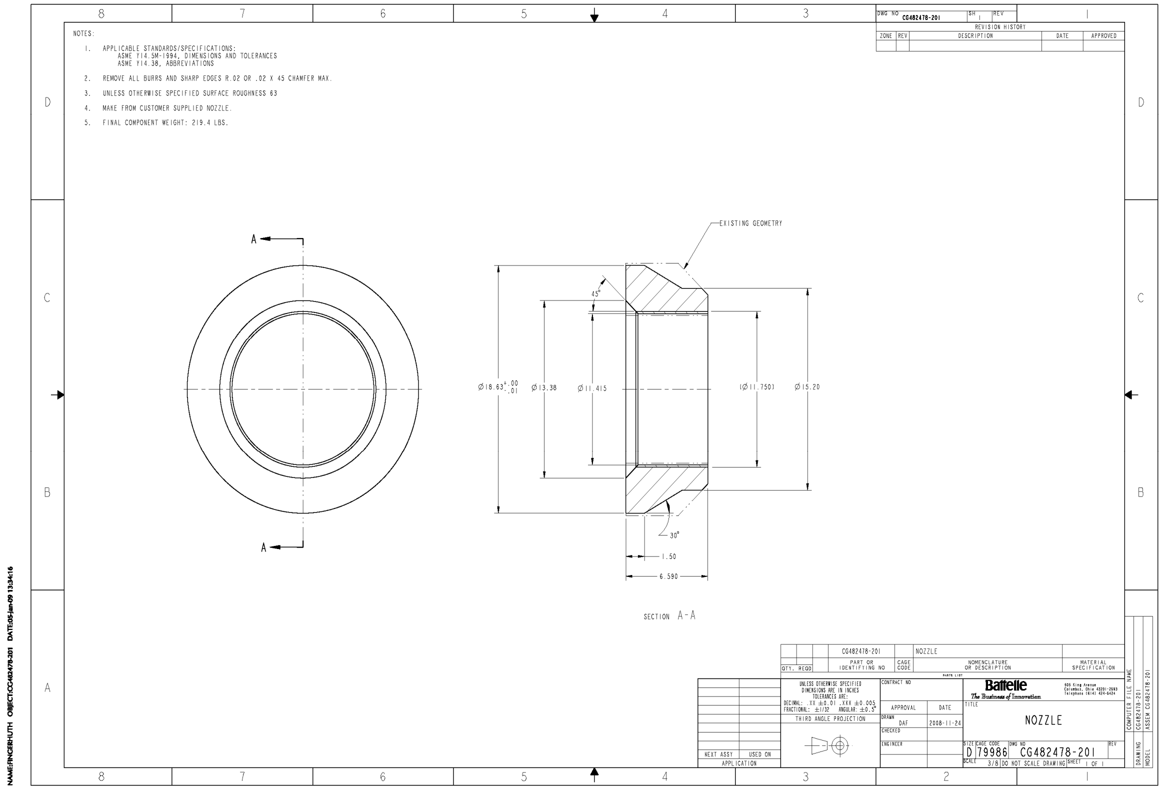
Appendix A

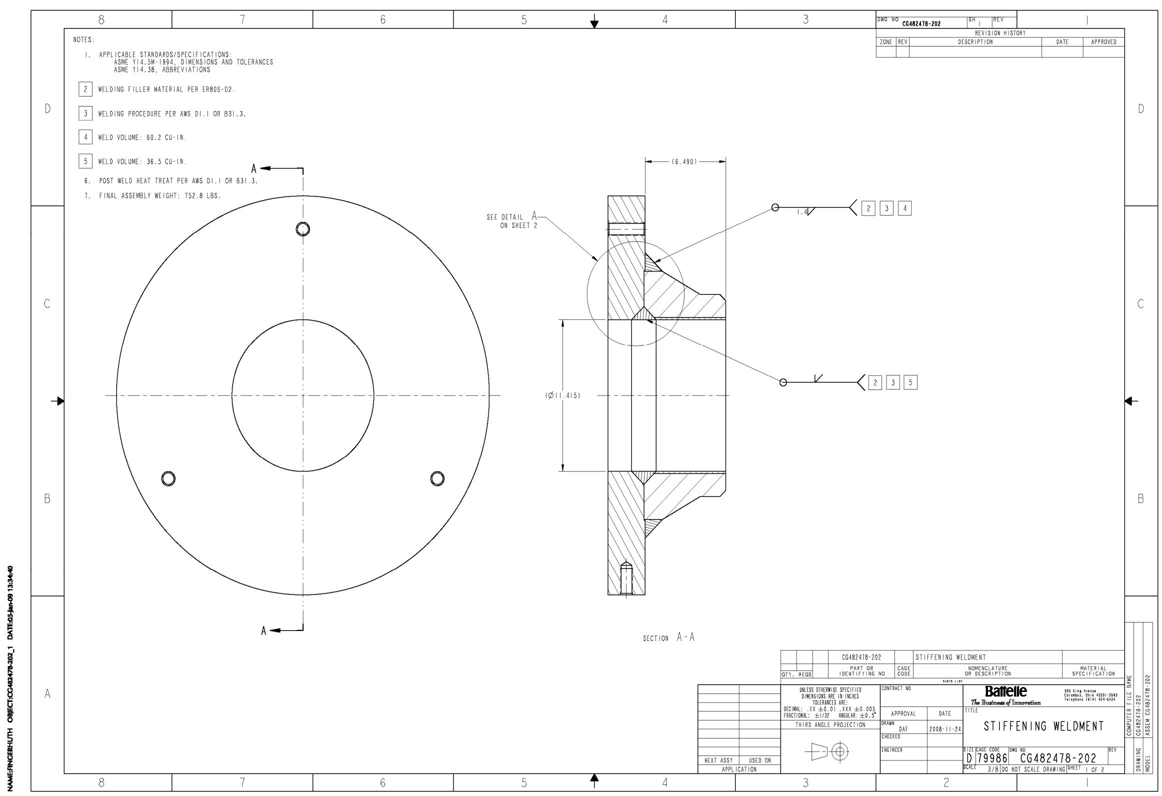
International Weld Residual Stress Mock-Up

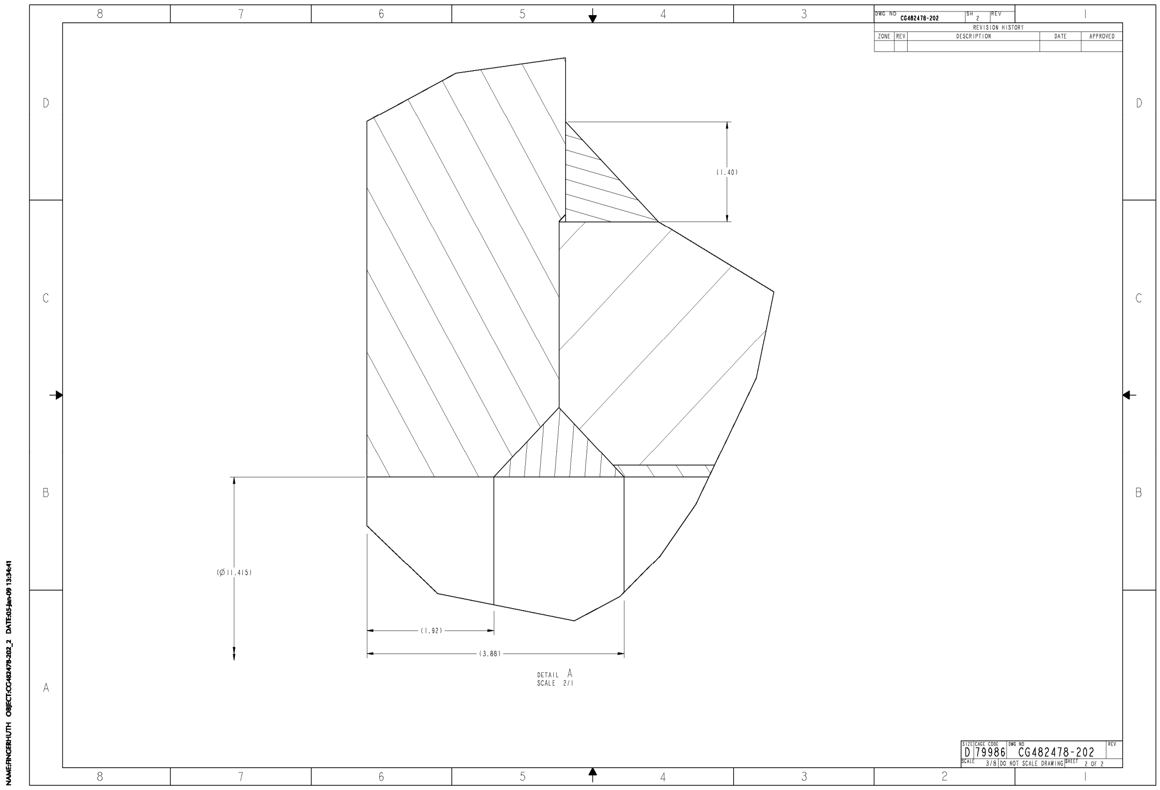
Battelle Drawings CG482478-199 thru CR482478-213

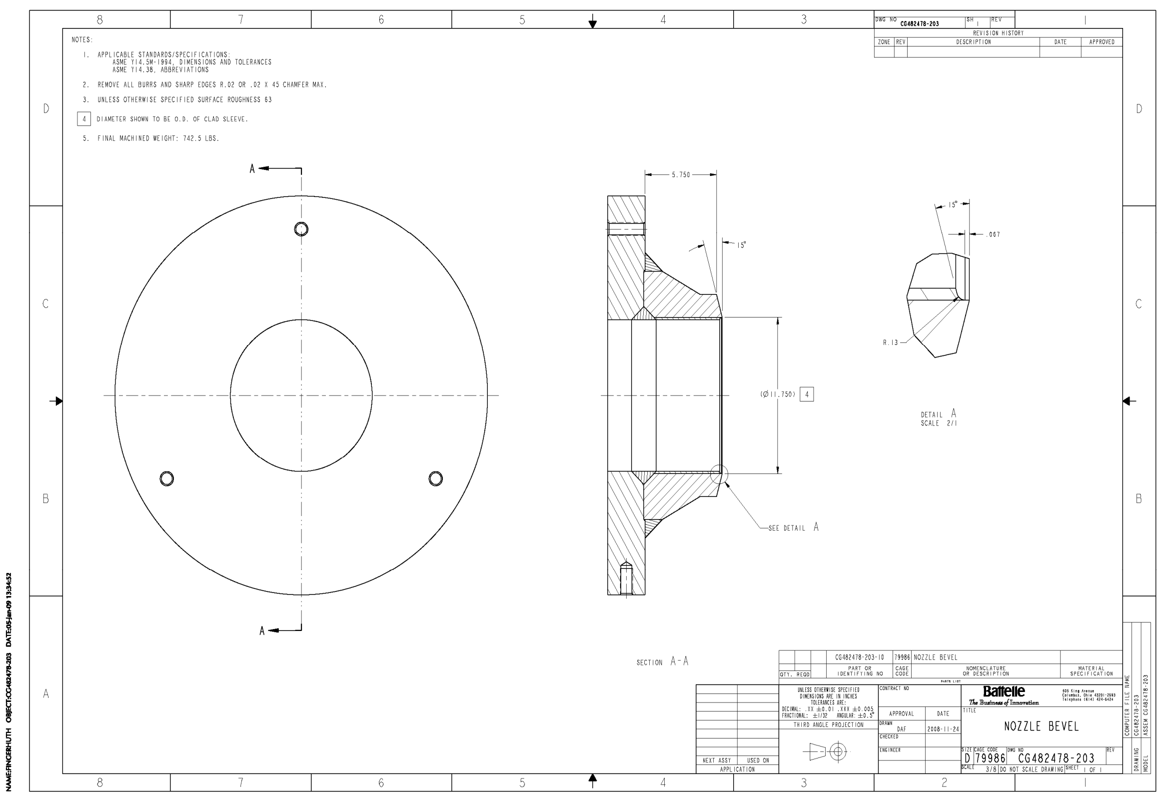

NOTES:
1. APPLICABLE STANDARDS/SPECIFICATIONS:
ASME Y14.5M-1994, DIMENSIONS AND TOLERANCES
ASME Y14.38, ABBREVIATIONS
2. REMOVE ALL BURRS AND SHARP EDGES R.02 OR .02 X 45 CHAMFER MAX.
3. UNLESS OTHERWISE SPECIFIED SURFACE ROUGHNESS 63.
4 REMOVE THERMAL SLEEVE WITHOUT DAMAGING/MACHINING STAINLESS STEEL CLAD ON INSIDE SURFACE.
5. WIRE EDM TO CUT THIS PART WITH START PATH ORIGINATING FROM OUTER DIAMETER MOVING INWARD ON CUSTOMER SUPPLIED NOZZLE.
6. DO NOT DISCARD ANY PART PIECES AFTER THE WIRE EDM CUT. ALL PART PIECES WILL BE USED LATER.
7. FINAL COMPONENT WEIGHT: 335.4 LBS.
SECTION A-A
CG482478-199
NOZZLE
Battelle
The Business of Innovation
NOZZLE
2008-11-24
D 79986 CG482478-199
THIRD ANGLE PROJECTION

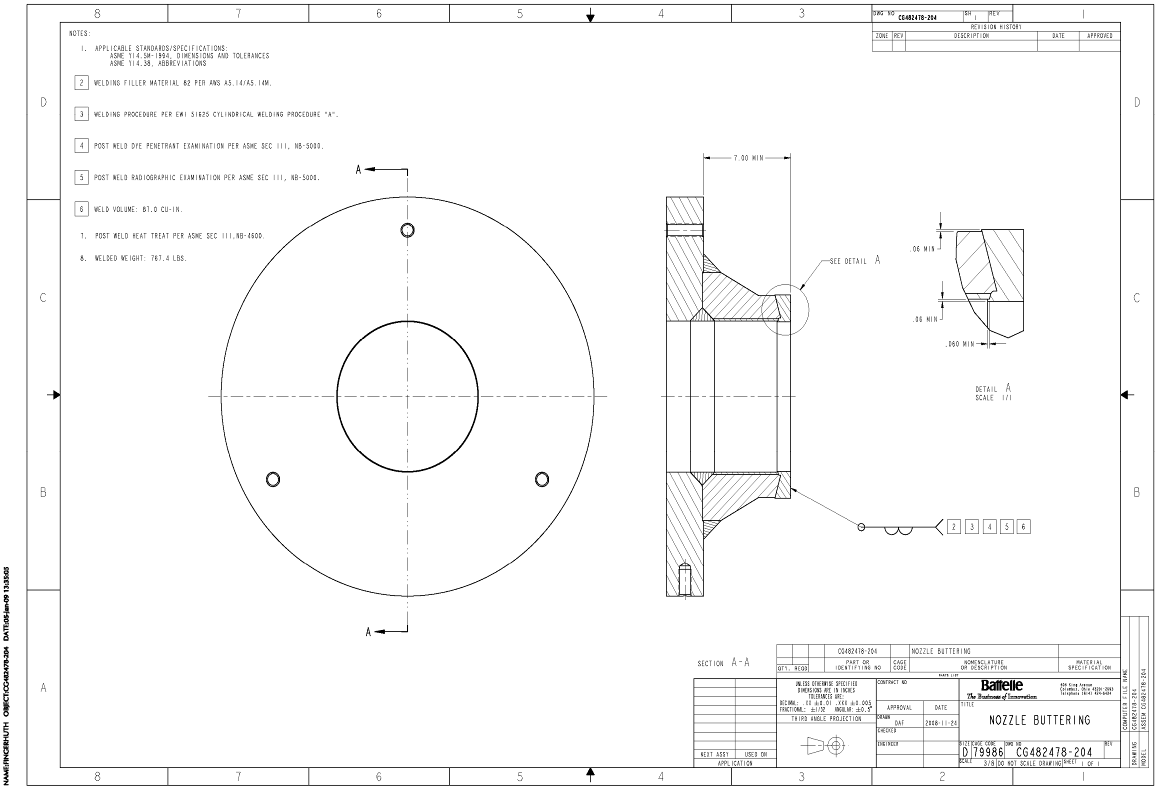

NOTES:
1. APPLICABLE STANDARDS/SPECIFICATIONS:
ASME Y14.5M-1994, DIMENSIONS AND TOLERANCES
ASME Y14.38, ABBREVIATIONS
2. MATERIAL: HOT ROLLED PLATE.
3. FINAL COMPONENT WEIGHT: 505.7 LBS.
4 MATCH I.D. OF NOZZLE CLADDING.
SEE DETAIL A
DETAIL A
SCALE 1/1
SECTION A-A
Battelle
The Business of Innovation
STIFFENING PLATE
2008-11-24
D 79986 CG482478-200
THIRD ANGLE PROJECTION

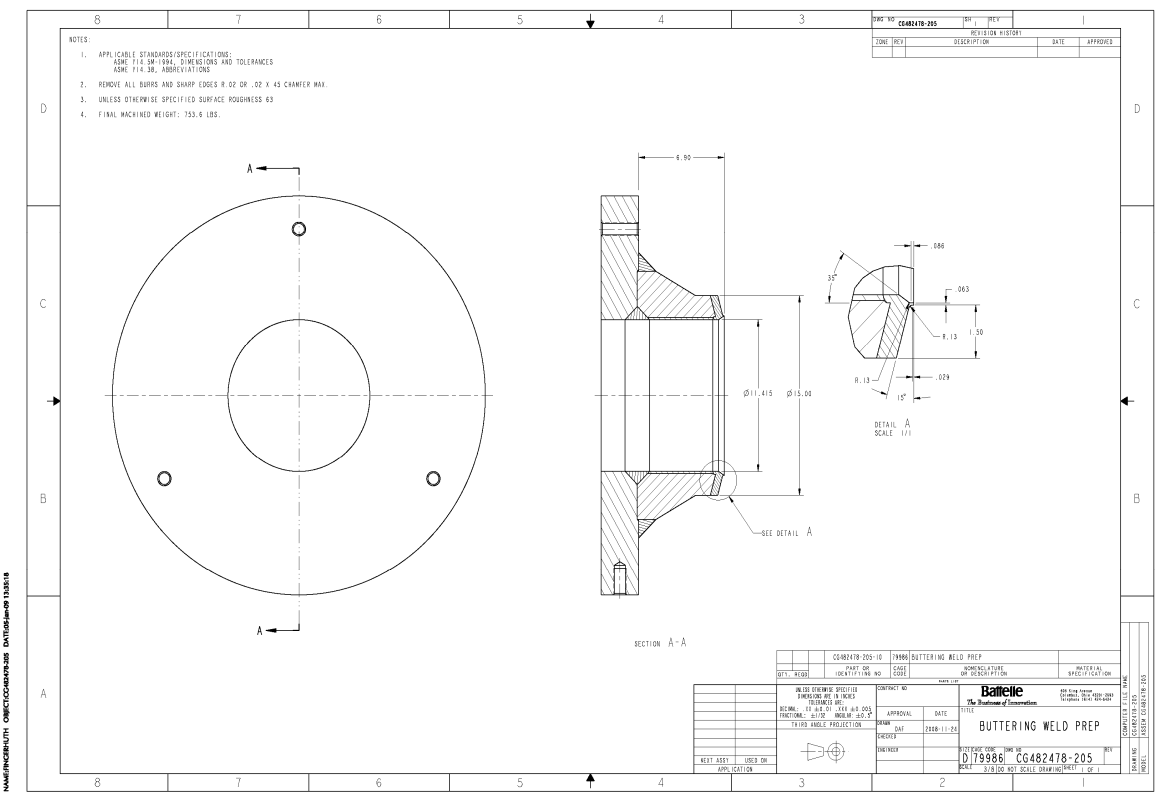

NOTES:
1. APPLICABLE STANDARDS/SPECIFICATIONS:
ASME Y14.5M-1994, DIMENSIONS AND TOLERANCES
ASME Y14.38, ABBREVIATIONS
2. REMOVE ALL BURRS AND SHARP EDGES R.02 OR .02 X 45 CHAMFER MAX.
3. UNLESS OTHERWISE SPECIFIED SURFACE ROUGHNESS 63
4. MAKE FROM CUSTOMER SUPPLIED NOZZLE.
5. FINAL COMPONENT WEIGHT: 219.4 LBS.
EXISTING GEOMETRY
SECTION A-A
CG482478-201
NOZZLE
THIRD ANGLE PROJECTION
Battelle
The Business of Innovation
NOZZLE
D 79986 CG482478-201
DAF 2008-11-24
DO NOT SCALE DRAWING
SHEET 1 OF 1

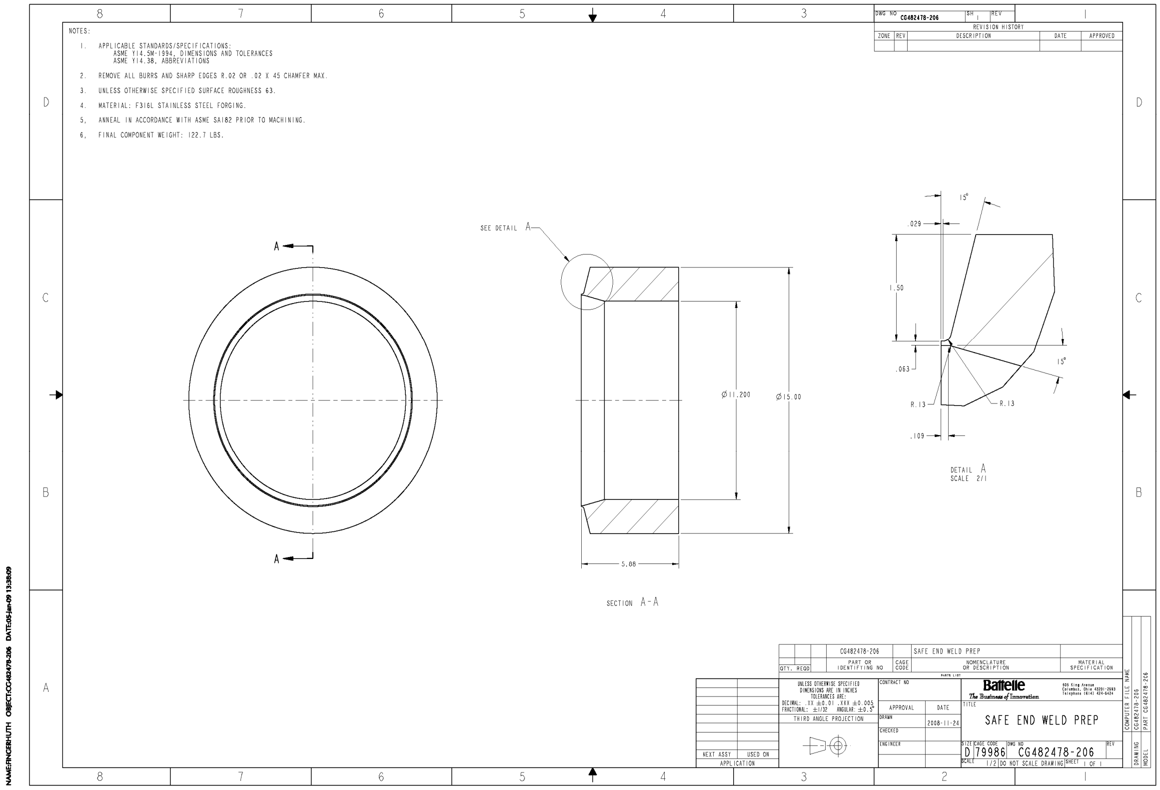

NOTES:
1. APPLICABLE STANDARDS/SPECIFICATIONS:
ASME Y14.5M-1994, DIMENSIONS AND TOLERANCES
ASME Y14.38, ABBREVIATIONS
2 WELDING FILLER MATERIAL PER ER80S-D2.
3 WELDING PROCEDURE PER AWS D1.1 OR B31.3.
4 WELD VOLUME: 60.2 CU-IN.
5 WELD VOLUME: 36.5 CU-IN.
6. POST WELD HEAT TREAT PER AWS D1.1 OR B31.3.
7. FINAL ASSEMBLY WEIGHT: 752.8 LBS.
SEE DETAIL A ON SHEET 2
SECTION A-A
CG482478-202
STIFFENING WELDMENT
THIRD ANGLE PROJECTION
Battelle
The Business of Innovation
STIFFENING WELDMENT
D 79986 CG482478-202
DAF 2008-11-24
DO NOT SCALE DRAWING
SHEET 1 OF 2

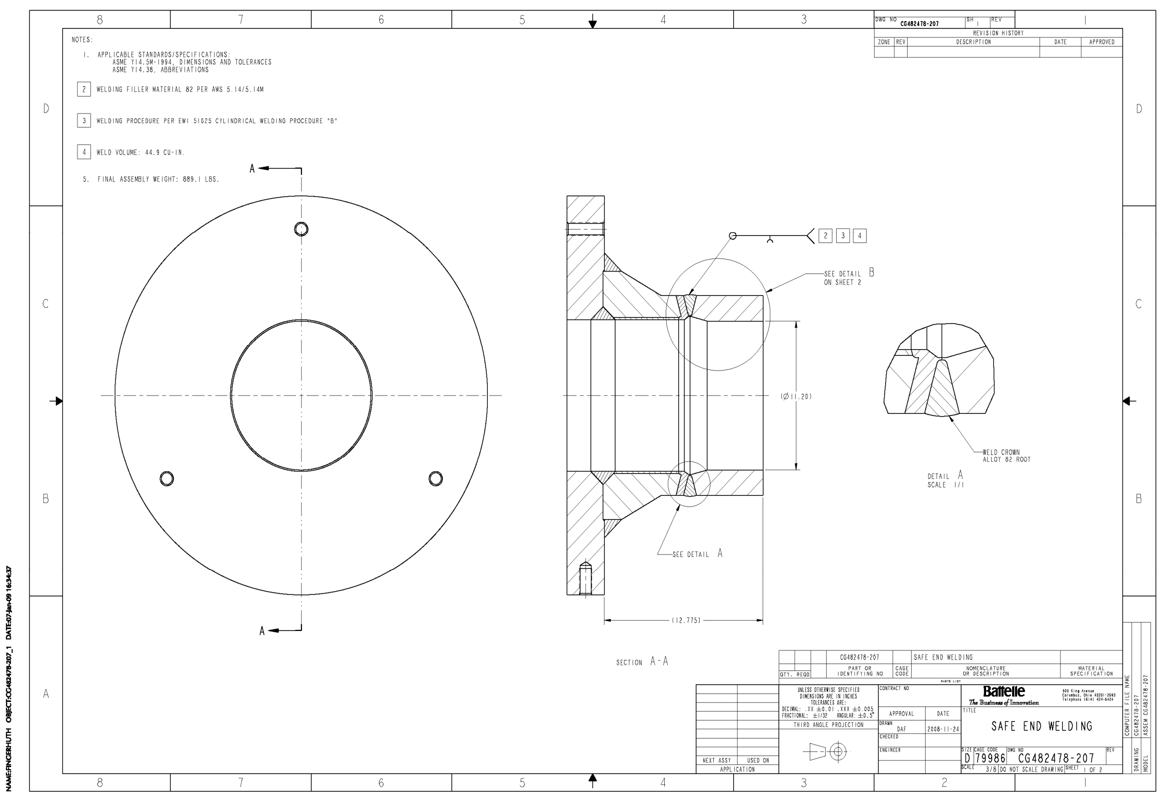

DWG NO CG482478-202
SH 2
REV
REVISION HISTORY
ZONE
REV
DESCRIPTION
DATE
APPROVED
(1.40)
(Ø11.415)
(1.92)
(3.86)
DETAIL A
SCALE 2/1
SIZE D
CAGE CODE 79986
DWG NO CG482478-202
SCALE 3/8
DO NOT SCALE DRAWING
SHEET 2 OF 2

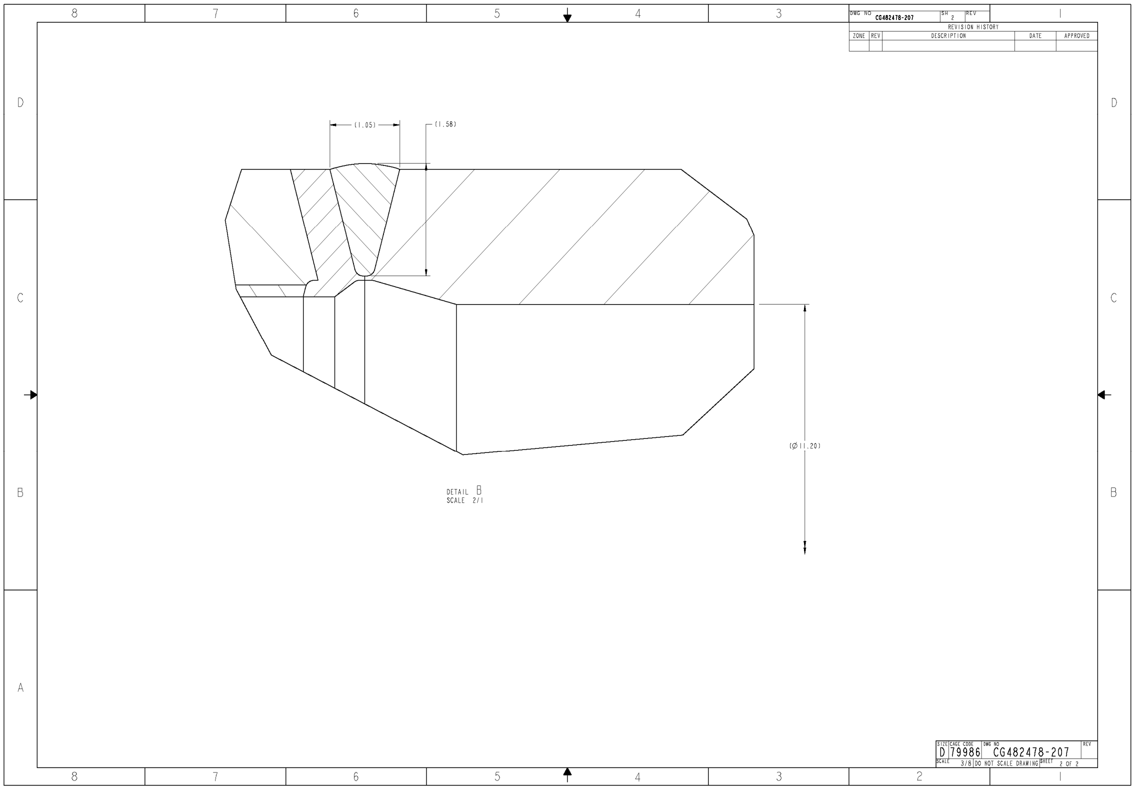

DWG NO CG482478-203
SH 1
REV
REVISION HISTORY
ZONE
REV
DESCRIPTION
DATE
APPROVED
NOTES:
1. APPLICABLE STANDARDS/SPECIFICATIONS:
ASME Y14.5M-1994, DIMENSIONS AND TOLERANCES
ASME Y14.38, ABBREVIATIONS
2. REMOVE ALL BURRS AND SHARP EDGES R.02 OR .02 X 45 CHAMFER MAX.
3. UNLESS OTHERWISE SPECIFIED SURFACE ROUGHNESS 63
4 DIAMETER SHOWN TO BE O.D. OF CLAD SLEEVE.
5. FINAL MACHINED WEIGHT: 742.5 LBS.
A
5.750
15°
(Ø11.750) 4
SEE DETAIL A
15°
.067
R.13
DETAIL A
SCALE 2/1
SECTION A-A
CG482478-203-10
79986
NOZZLE BEVEL
QTY. REQD
PART OR IDENTIFYING NO
CAGE CODE
NOMENCLATURE OR DESCRIPTION
MATERIAL SPECIFICATION
PARTS LIST
UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN INCHES
TOLERANCES ARE:
DECIMAL: .XX ±0.01 .XXX ±0.005
FRACTIONAL: ±1/32 ANGULAR: ±0.5°
THIRD ANGLE PROJECTION
NEXT ASSY
USED ON
APPLICATION
CONTRACT NO
APPROVAL
DATE
DRAWN DAF 2008-11-24
CHECKED
ENGINEER
Battelle
The Business of Innovation
505 King Avenue
Columbus, Ohio 43201-2693
Telephone (614) 424-6424
TITLE
NOZZLE BEVEL
SIZE D
CAGE CODE 79986
DWG NO CG482478-203
REV
SCALE 3/8
DO NOT SCALE DRAWING
SHEET 1 OF 1
COMPUTER FILE NAME
DRAWING CG482478-203
MODEL ASSEM CG482478-203


NOTES:
1. APPLICABLE STANDARDS/SPECIFICATIONS:
ASME Y14.5M-1994, DIMENSIONS AND TOLERANCES
ASME Y14.38, ABBREVIATIONS
2 WELDING FILLER MATERIAL 82 PER AWS A5.14/A5.14M.
3 WELDING PROCEDURE PER EWI 51625 CYLINDRICAL WELDING PROCEDURE "A".
4 POST WELD DYE PENETRANT EXAMINATION PER ASME SEC III, NB-5000.
5 POST WELD RADIOGRAPHIC EXAMINATION PER ASME SEC III, NB-5000.
6 WELD VOLUME: 87.0 CU-IN.
7. POST WELD HEAT TREAT PER ASME SEC III,NB-4600.
8. WELDED WEIGHT: 767.4 LBS.
7.00 MIN
SEE DETAIL A
.06 MIN
.06 MIN
.060 MIN
DETAIL A
SCALE 1/1
SECTION A-A
CG482478-204
NOZZLE BUTTERING
NOZZLE BUTTERING
D 79986 CG482478-204
2008-11-24
NAME:FINGERHUTH OBJECT:CG482478-204 DATE:05-Jan-09 13:35:03

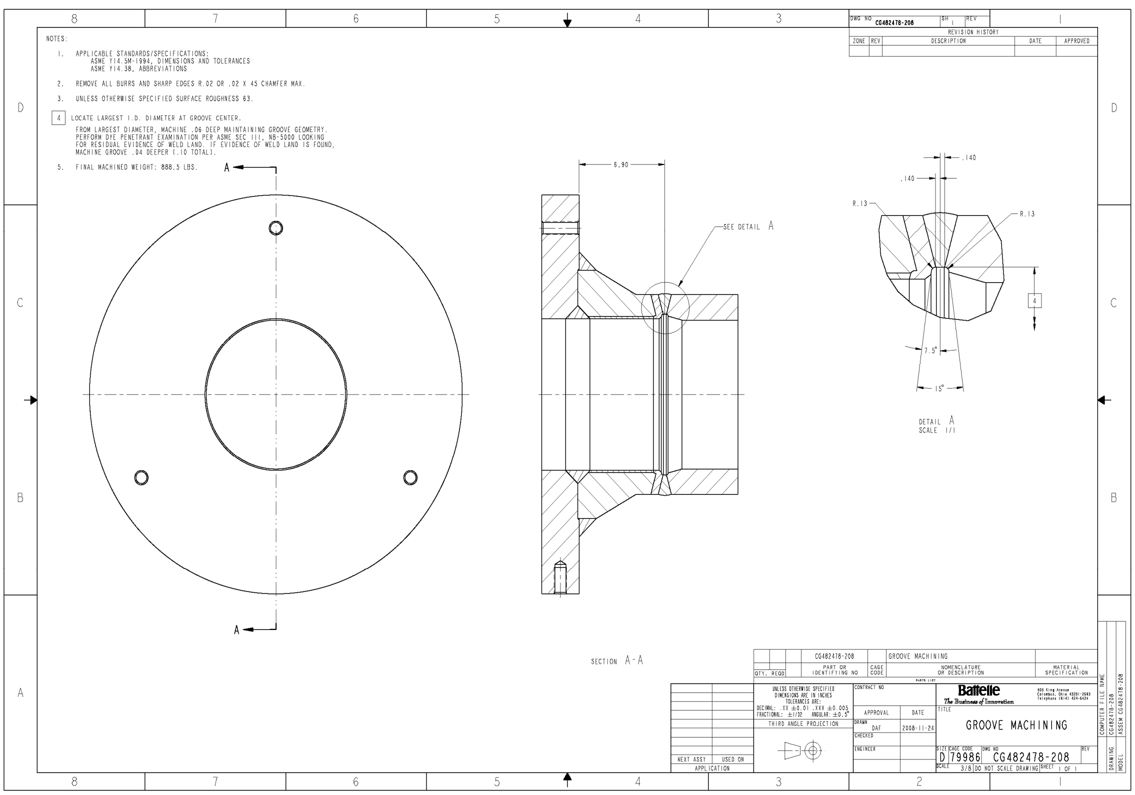

NOTES:
1. APPLICABLE STANDARDS/SPECIFICATIONS:
ASME Y14.5M-1994, DIMENSIONS AND TOLERANCES
ASME Y14.38, ABBREVIATIONS
2. REMOVE ALL BURRS AND SHARP EDGES R.02 OR .02 X 45 CHAMFER MAX.
3. UNLESS OTHERWISE SPECIFIED SURFACE ROUGHNESS 63
4. FINAL MACHINED WEIGHT: 753.6 LBS.
6.90
Ø11.415
Ø15.00
.086
35°
.063
R.13
1.50
R.13
.029
15°
DETAIL A
SCALE 1/1
SEE DETAIL A
SECTION A-A
CG482478-205-10
79986
BUTTERING WELD PREP
BUTTERING WELD PREP
D 79986 CG482478-205
2008-11-24
NAME:FINGERHUTH OBJECT:CG482478-205 DATE:05-Jan-09 13:35:18


NOTES:
1. APPLICABLE STANDARDS/SPECIFICATIONS:
ASME Y14.5M-1994, DIMENSIONS AND TOLERANCES
ASME Y14.38, ABBREVIATIONS
2. REMOVE ALL BURRS AND SHARP EDGES R.02 OR .02 X 45 CHAMFER MAX.
3. UNLESS OTHERWISE SPECIFIED SURFACE ROUGHNESS 63.
4. MATERIAL: F316L STAINLESS STEEL FORGING.
5, ANNEAL IN ACCORDANCE WITH ASME SA182 PRIOR TO MACHINING.
6, FINAL COMPONENT WEIGHT: 122.7 LBS.
SEE DETAIL A
Ø11.200
Ø15.00
5.88
SECTION A-A
.029
15°
1.50
.063
R.13
R.13
.109
DETAIL A
SCALE 2/1
CG482478-206
SAFE END WELD PREP
SAFE END WELD PREP
D 79986 CG482478-206
2008-11-24

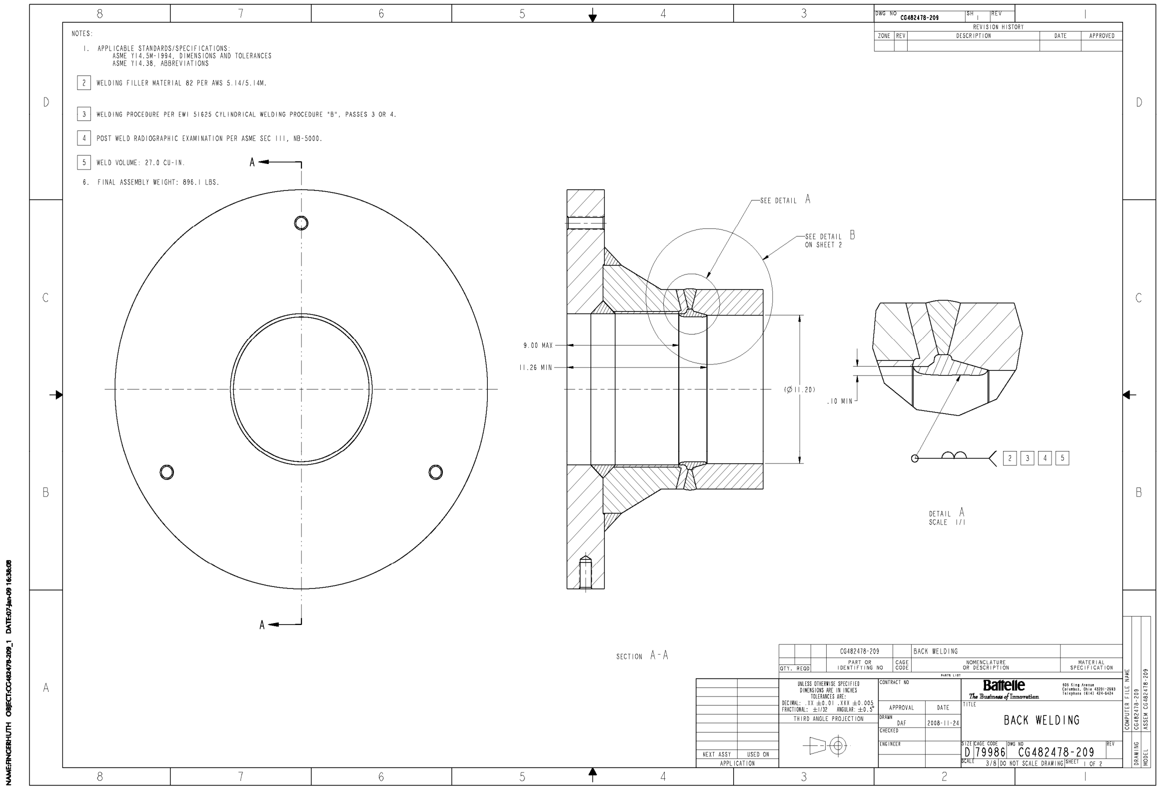

NOTES:
1. APPLICABLE STANDARDS/SPECIFICATIONS:
ASME Y14.5M-1994, DIMENSIONS AND TOLERANCES
ASME Y14.38, ABBREVIATIONS
2 WELDING FILLER MATERIAL 82 PER AWS 5.14/5.14M
3 WELDING PROCEDURE PER EWI 51625 CYLINDRICAL WELDING PROCEDURE "B"
4 WELD VOLUME: 44.9 CU-IN.
5. FINAL ASSEMBLY WEIGHT: 889.1 LBS.
SEE DETAIL B
ON SHEET 2
(Ø11.20)
SEE DETAIL A
(12.775)
SECTION A-A
WELD CROWN
ALLOY 82 ROOT
DETAIL A
SCALE 1/1
CG482478-207
SAFE END WELDING
SAFE END WELDING
D 79986 CG482478-207
2008-11-24

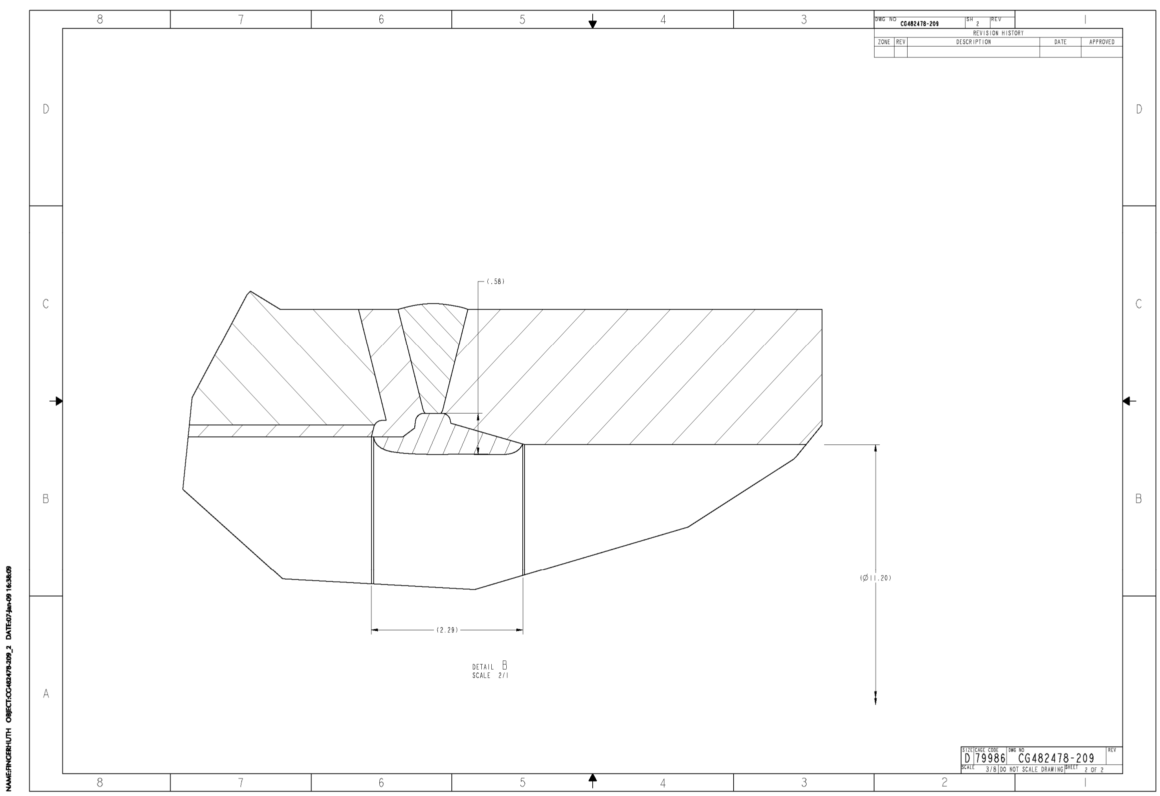


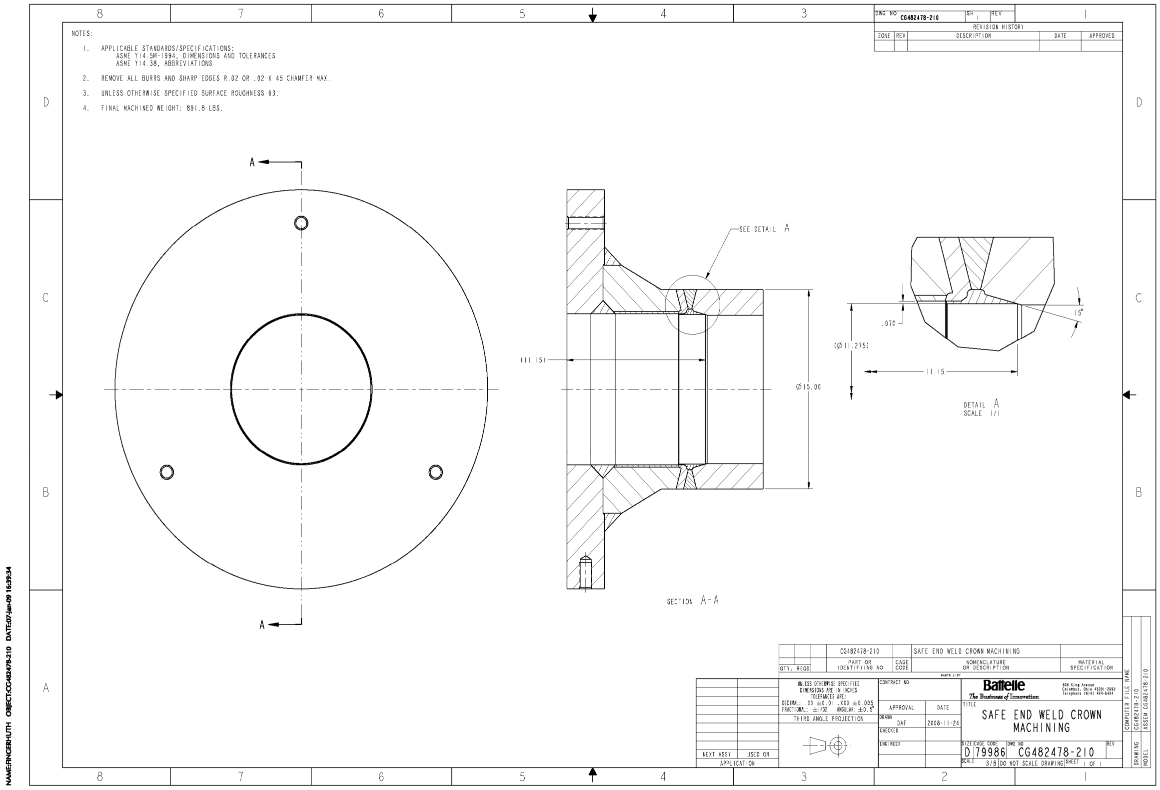
DWG NO CG482478-207 SH 2 REV
REVISION HISTORY
ZONE REV DESCRIPTION DATE APPROVED
(1.05)
(1.58)
(Ø11.20)
DETAIL B
SCALE 2/1
SIZE D CAGE CODE 79986 DWG NO CG482478-207 REV
SCALE 3/8 DO NOT SCALE DRAWING SHEET 2 OF 2

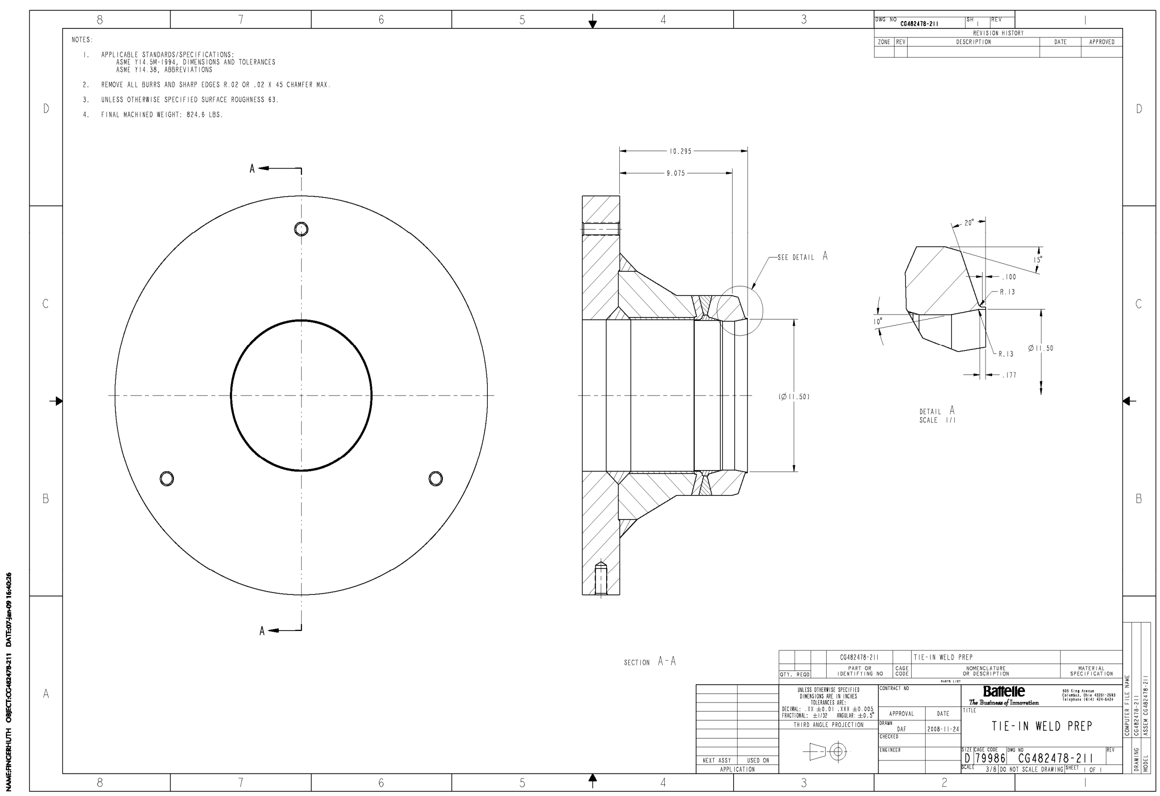


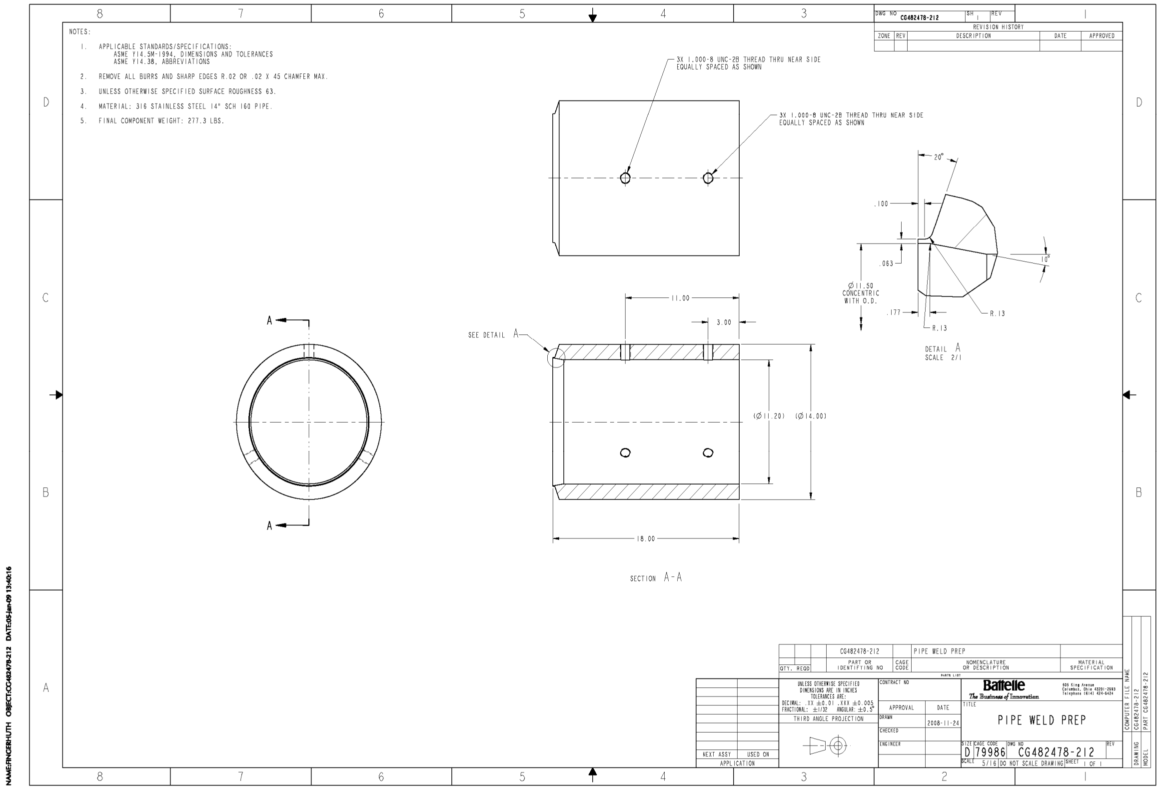
DWG NO CG482478-208 SH 1 REV
REVISION HISTORY
ZONE REV DESCRIPTION DATE APPROVED
NOTES:
1. APPLICABLE STANDARDS/SPECIFICATIONS:
ASME Y14.5M-1994, DIMENSIONS AND TOLERANCES
ASME Y14.38, ABBREVIATIONS
2. REMOVE ALL BURRS AND SHARP EDGES R.02 OR .02 X 45 CHAMFER MAX.
3. UNLESS OTHERWISE SPECIFIED SURFACE ROUGHNESS 63.
4 LOCATE LARGEST I.D. DIAMETER AT GROOVE CENTER.
FROM LARGEST DIAMETER, MACHINE .06 DEEP MAINTAINING GROOVE GEOMETRY.
PERFORM DYE PENETRANT EXAMINATION PER ASME SEC III, NB-5000 LOOKING
FOR RESIDUAL EVIDENCE OF WELD LAND. IF EVIDENCE OF WELD LAND IS FOUND,
MACHINE GROOVE .04 DEEPER (.10 TOTAL).
5. FINAL MACHINED WEIGHT: 888.5 LBS.
A
A
6.90
SEE DETAIL A
SECTION A-A
.140
.140
R.13
R.13
4
7.5°
15°
DETAIL A
SCALE 1/1
CG482478-208 GROOVE MACHINING
QTY. REQD PART OR IDENTIFYING NO CAGE CODE NOMENCLATURE OR DESCRIPTION MATERIAL SPECIFICATION
PARTS LIST
UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN INCHES
TOLERANCES ARE:
DECIMAL: .XX ±0.01 .XXX ±0.005
FRACTIONAL: ±1/32 ANGULAR: ±0.5°
THIRD ANGLE PROJECTION
NEXT ASSY USED ON
APPLICATION
CONTRACT NO
APPROVAL DATE
DRAWN DAF 2008-11-24
CHECKED
ENGINEER
Battelle
The Business of Innovation
505 King Avenue
Columbus, Ohio 43201-2693
Telephone (614) 424-6424
TITLE
GROOVE MACHINING
SIZE D CAGE CODE 79986 DWG NO CG482478-208 REV
SCALE 3/8 DO NOT SCALE DRAWING SHEET 1 OF 1
COMPUTER FILE NAME CG482478-208 ASSEM CG482478-208
DRAWING MODEL

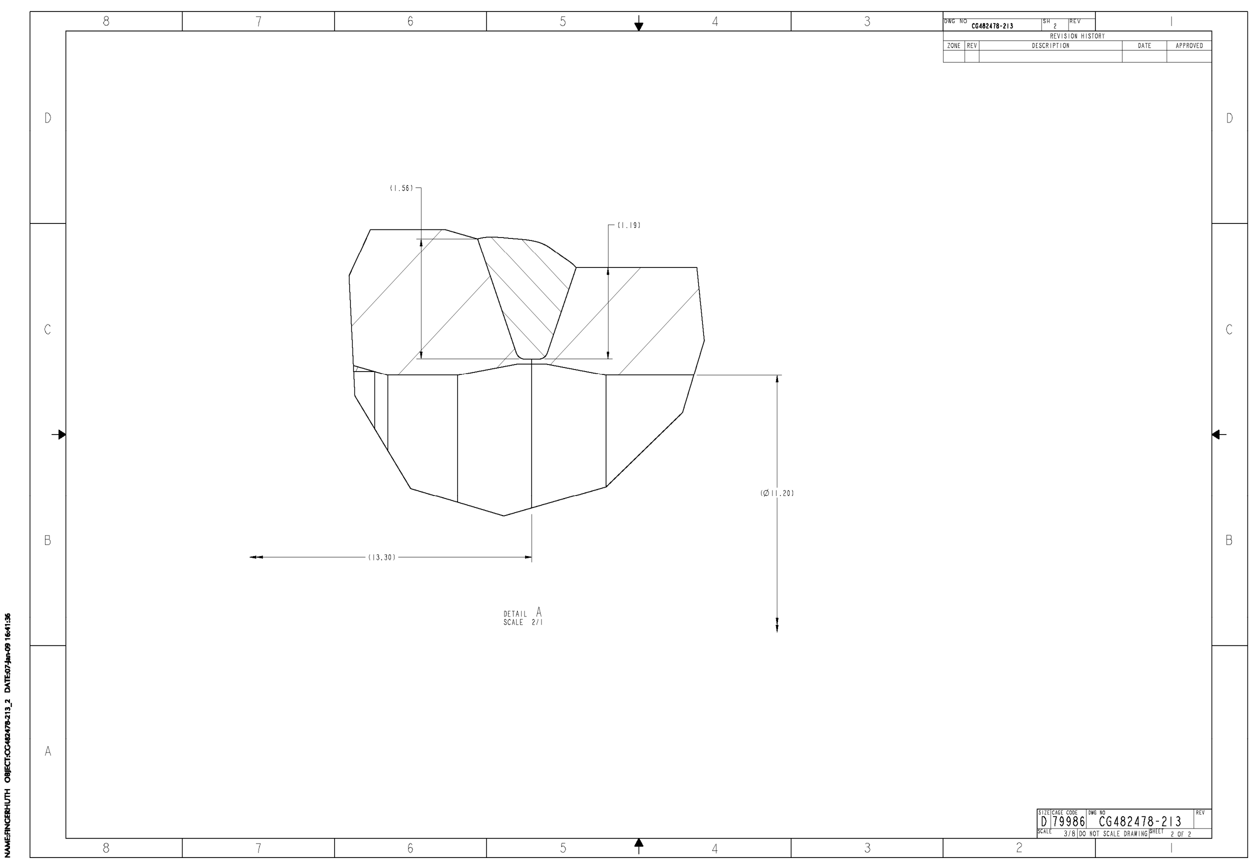

NOTES:
1. APPLICABLE STANDARDS/SPECIFICATIONS:
ASME Y14.5M-1994, DIMENSIONS AND TOLERANCES
ASME Y14.38, ABBREVIATIONS
2 WELDING FILLER MATERIAL 82 PER AWS 5.14/5.14M.
3 WELDING PROCEDURE PER EWI 51625 CYLINDRICAL WELDING PROCEDURE "B", PASSES 3 OR 4.
4 POST WELD RADIOGRAPHIC EXAMINATION PER ASME SEC III, NB-5000.
5 WELD VOLUME: 27.0 CU-IN.
6. FINAL ASSEMBLY WEIGHT: 896.1 LBS.
SEE DETAIL A
SEE DETAIL B ON SHEET 2
9.00 MAX
11.26 MIN
(Ø11.20)
.10 MIN
SECTION A-A
DETAIL A
SCALE 1/1
DWG NO CG482478-209 SH 1 REV
REVISION HISTORY
ZONE REV DESCRIPTION DATE APPROVED
CG482478-209 BACK WELDING
QTY. REQD PART OR IDENTIFYING NO CAGE CODE NOMENCLATURE OR DESCRIPTION MATERIAL SPECIFICATION
PARTS LIST
UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES TOLERANCES ARE:
DECIMAL: .XX ±0.01 .XXX ±0.005
FRACTIONAL: ±1/32 ANGULAR: ±0.5°
THIRD ANGLE PROJECTION
NEXT ASSY USED ON
APPLICATION
CONTRACT NO
APPROVAL DATE
DRAWN DAF 2008-11-24
CHECKED
ENGINEER
Battelle
The Business of Innovation
505 King Avenue
Columbus, Ohio 43201-2693
Telephone (614) 424-6424
TITLE BACK WELDING
SIZE D CAGE CODE 79986 DWG NO CG482478-209 REV
SCALE 3/8 DO NOT SCALE DRAWING SHEET 1 OF 2
COMPUTER FILE NAME CG482478-209 ASSEM CG482478-209
DRAWING MODEL
NAME:FINGERHUTH OBJECT:CG482478-209_1 DATE:07-Jan-09 16:38:08


DWG NO CG482478-209 SH 2 REV
REVISION HISTORY
ZONE REV DESCRIPTION DATE APPROVED
(.58)
(Ø11.20)
(2.29)
DETAIL B
SCALE 2/1
SIZE D CAGE CODE 79986 DWG NO CG482478-209 REV
SCALE 3/8 DO NOT SCALE DRAWING SHEET 2 OF 2
NAME:FINGERHUTH OBJECT:CG482478-209_2 DATE:07-Jan-09 16:38:09


NOTES:
1. APPLICABLE STANDARDS/SPECIFICATIONS: ASME Y14.5M-1994, DIMENSIONS AND TOLERANCES ASME Y14.38, ABBREVIATIONS
2. REMOVE ALL BURRS AND SHARP EDGES R.02 OR .02 X 45 CHAMFER MAX.
3. UNLESS OTHERWISE SPECIFIED SURFACE ROUGHNESS 63.
4. FINAL MACHINED WEIGHT: 891.8 LBS.
SEE DETAIL A
(11.15)
Ø15.00
(Ø11.275)
.070
11.15
15°
DETAIL A
SCALE 1/1
SECTION A-A
CG482478-210
SAFE END WELD CROWN MACHINING
UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES TOLERANCES ARE:
DECIMAL: .XX ±0.01 .XXX ±0.005
FRACTIONAL: ±1/32 ANGULAR: ±0.5°
THIRD ANGLE PROJECTION
DRAWN DAF 2008-11-24
Battelle
The Business of Innovation
505 King Avenue
Columbus, Ohio 43201-2693
Telephone (614) 424-6424
TITLE SAFE END WELD CROWN MACHINING
SIZE D CAGE CODE 79986 DWG NO CG482478-210
SCALE 3/8 DO NOT SCALE DRAWING SHEET 1 OF 1
NAME:FINGERHUTH OBJECT:CG482478-210 DAT:07-Jan-09 16:39:34


NOTES:
1. APPLICABLE STANDARDS/SPECIFICATIONS: ASME Y14.5M-1994, DIMENSIONS AND TOLERANCES ASME Y14.38, ABBREVIATIONS
2. REMOVE ALL BURRS AND SHARP EDGES R.02 OR .02 X 45 CHAMFER MAX.
3. UNLESS OTHERWISE SPECIFIED SURFACE ROUGHNESS 63.
4. FINAL MACHINED WEIGHT: 824.6 LBS.
10.295
9.075
SEE DETAIL A
(Ø11.50)
20°
15°
.100
R.13
10°
R.13
Ø11.50
.177
DETAIL A
SCALE 1/1
SECTION A-A
CG482478-211
TIE-IN WELD PREP
UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES TOLERANCES ARE:
DECIMAL: .XX ±0.01 .XXX ±0.005
FRACTIONAL: ±1/32 ANGULAR: ±0.5°
THIRD ANGLE PROJECTION
DRAWN DAF 2008-11-24
Battelle
The Business of Innovation
TITLE TIE-IN WELD PREP
SIZE D CAGE CODE 79986 DWG NO CG482478-211
SCALE 3/8 DO NOT SCALE DRAWING SHEET 1 OF 1
NAME:FINGERHUTH OBJECT:CG482478-211 DAT:07-Jan-09 16:40:26


DWG NO CG482478-212 SH 1 REV
REVISION HISTORY
ZONE REV DESCRIPTION DATE APPROVED
NOTES:
1. APPLICABLE STANDARDS/SPECIFICATIONS:
ASME Y14.5M-1994, DIMENSIONS AND TOLERANCES
ASME Y14.38, ABBREVIATIONS
2. REMOVE ALL BURRS AND SHARP EDGES R.02 OR .02 X 45 CHAMFER MAX.
3. UNLESS OTHERWISE SPECIFIED SURFACE ROUGHNESS 63.
4. MATERIAL: 316 STAINLESS STEEL 14" SCH 160 PIPE.
5. FINAL COMPONENT WEIGHT: 277.3 LBS.
3X 1.000-8 UNC-2B THREAD THRU NEAR SIDE EQUALLY SPACED AS SHOWN
3X 1.000-8 UNC-2B THREAD THRU NEAR SIDE EQUALLY SPACED AS SHOWN
20°
.100
.063
10°
Ø11.50 CONCENTRIC WITH O.D.
.177
R.13
R.13
DETAIL A SCALE 2/1
11.00
3.00
SEE DETAIL A
A
A
(Ø11.20)
(Ø14.00)
18.00
SECTION A-A
CG482478-212 PIPE WELD PREP
QTY. REQD PART OR IDENTIFYING NO CAGE CODE NOMENCLATURE OR DESCRIPTION MATERIAL SPECIFICATION
PARTS LIST
UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES TOLERANCES ARE:
DECIMAL: .XX ±0.01 .XXX ±0.005
FRACTIONAL: ±1/32 ANGULAR: ±0.5°
THIRD ANGLE PROJECTION
NEXT ASSY USED ON
APPLICATION
CONTRACT NO
APPROVAL DATE
DRAWN 2008-11-24
CHECKED
ENGINEER
Battelle
The Business of Innovation
505 King Avenue
Columbus, Ohio 43201-2693
Telephone (614) 424-6424
TITLE
PIPE WELD PREP
SIZE D CAGE CODE 79986 DWG NO CG482478-212 REV
SCALE 5/16 DO NOT SCALE DRAWING SHEET 1 OF 1
COMPUTER FILE NAME CG482478-212 PART CG482478-212
DRAWING MODEL
NAME:FINGERHUTH OBJECT:CG482478-212 DATE:05-Jan-09 13:40:16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ZONE REV DESCRIPTION DATE APPROVED
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(1.19)
(Ø11.20)
(13.30)
DETAIL A SCALE 2/1
SIZE D CAGE CODE 79986 DWG NO CG482478-213 REV
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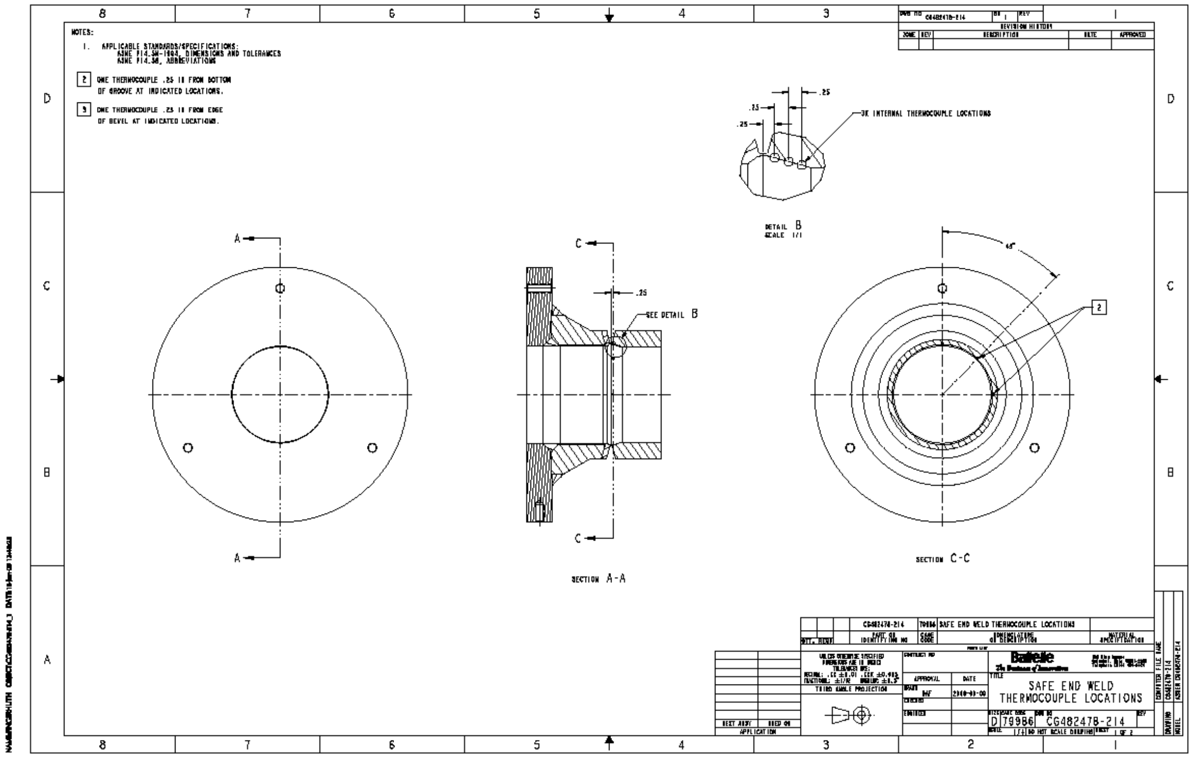
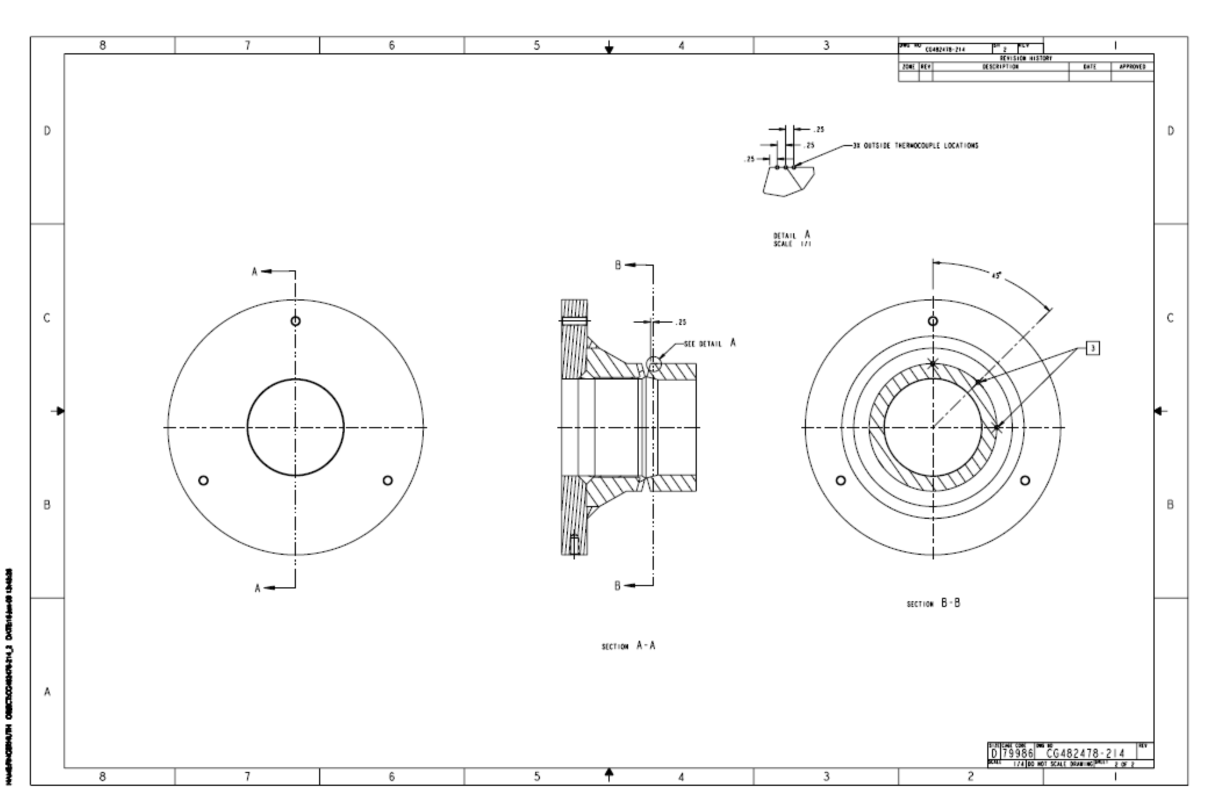
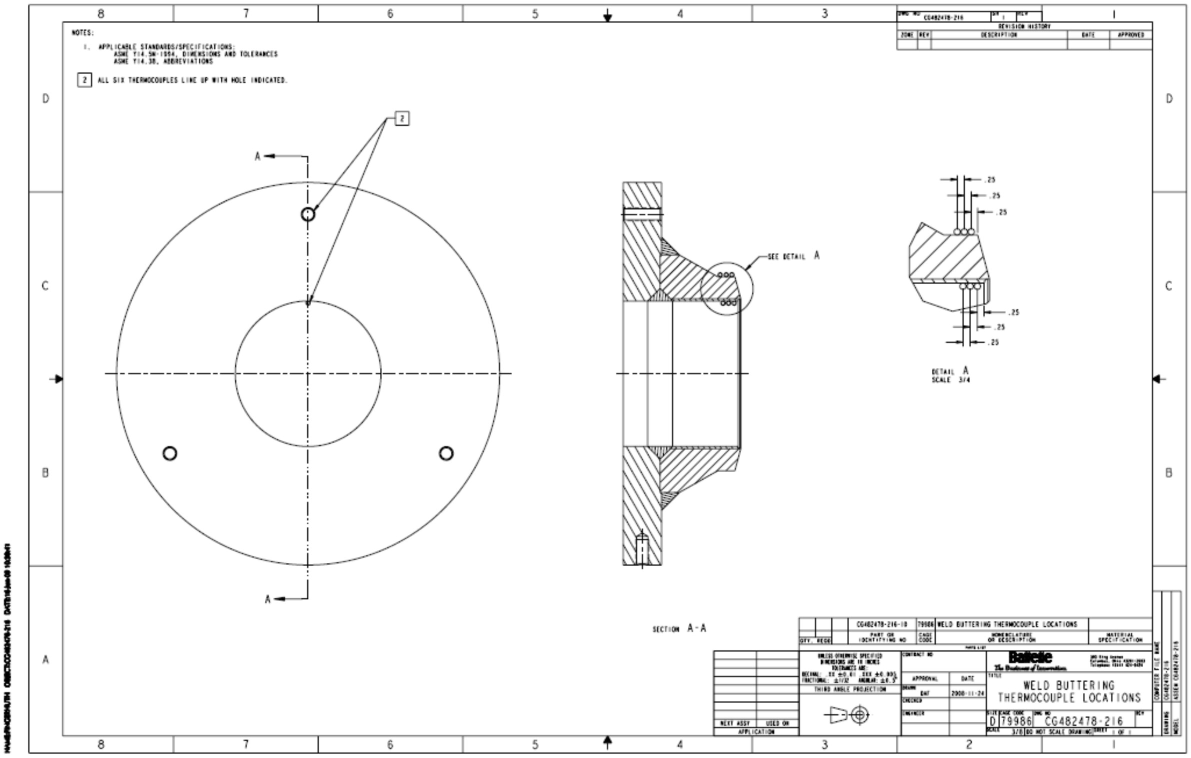
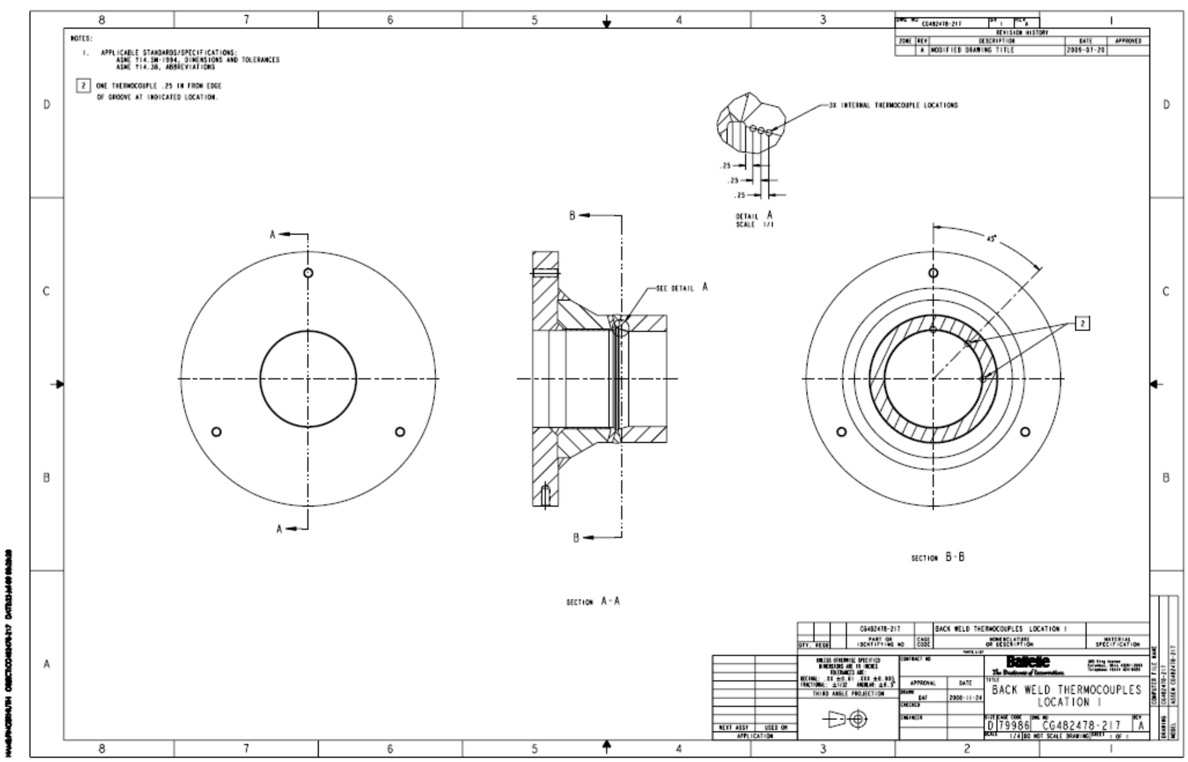
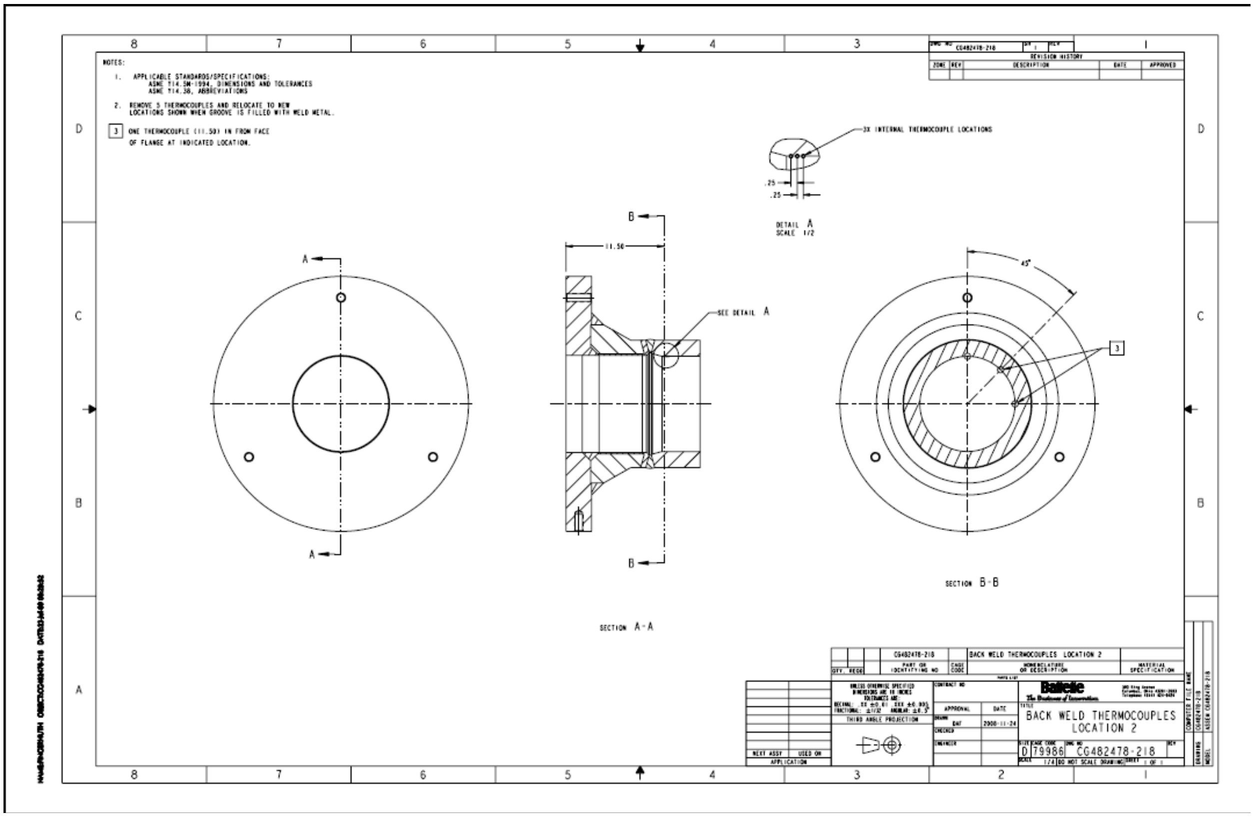

NOTES:
1. APPLICABLE STANDARDS/SPECIFICATIONS:
ASME Y14.5M-1994, DIMENSIONS AND TOLERANCES
ASME Y14.38, ABBREVIATIONS
2 ONE THERMOCOUPLE .25 IN FROM BOTTOM OF GROOVE AT INDICATED LOCATIONS.
3 ONE THERMOCOUPLE .25 IN FROM EDGE OF BEVEL AT INDICATED LOCATIONS.
3X INTERNAL THERMOCOUPLE LOCATIONS
DETAIL B
SCALE 1/1
SEE DETAIL B
SECTION A-A
SECTION C-C
CG482478-214
SAFE END WELD THERMOCOUPLE LOCATIONS
THIRD ANGLE PROJECTION
APPROVAL
DATE
NEXT ASSY
USED ON
APPLICATION
Battelle
SAFE END WELD
THERMOCOUPLE LOCATIONS
D 79986 CG482478-214
DO NOT SCALE DRAWING
1 OF 2


CG482478-214
REVISION HISTORY
ZONE
REV
DESCRIPTION
DATE
APPROVED
3X OUTSIDE THERMOCOUPLE LOCATIONS
DETAIL A
SCALE 1/1
SEE DETAIL A
SECTION A-A
SECTION B-B
D 79986 CG482478-214
DO NOT SCALE DRAWING
2 OF 2


NOTES:
1. APPLICABLE STANDARDS/SPECIFICATIONS:
ASME Y14.5M-1994, DIMENSIONS AND TOLERANCES
ASME Y14.38, ABBREVIATIONS
2 ALL SIX THERMOCOUPLES LINE UP WITH HOLE INDICATED.
SEE DETAIL A
DETAIL A
SCALE 3/4
SECTION A-A
Battelle
WELD BUTTERING THERMOCOUPLE LOCATIONS
D 79986 CG482478-216

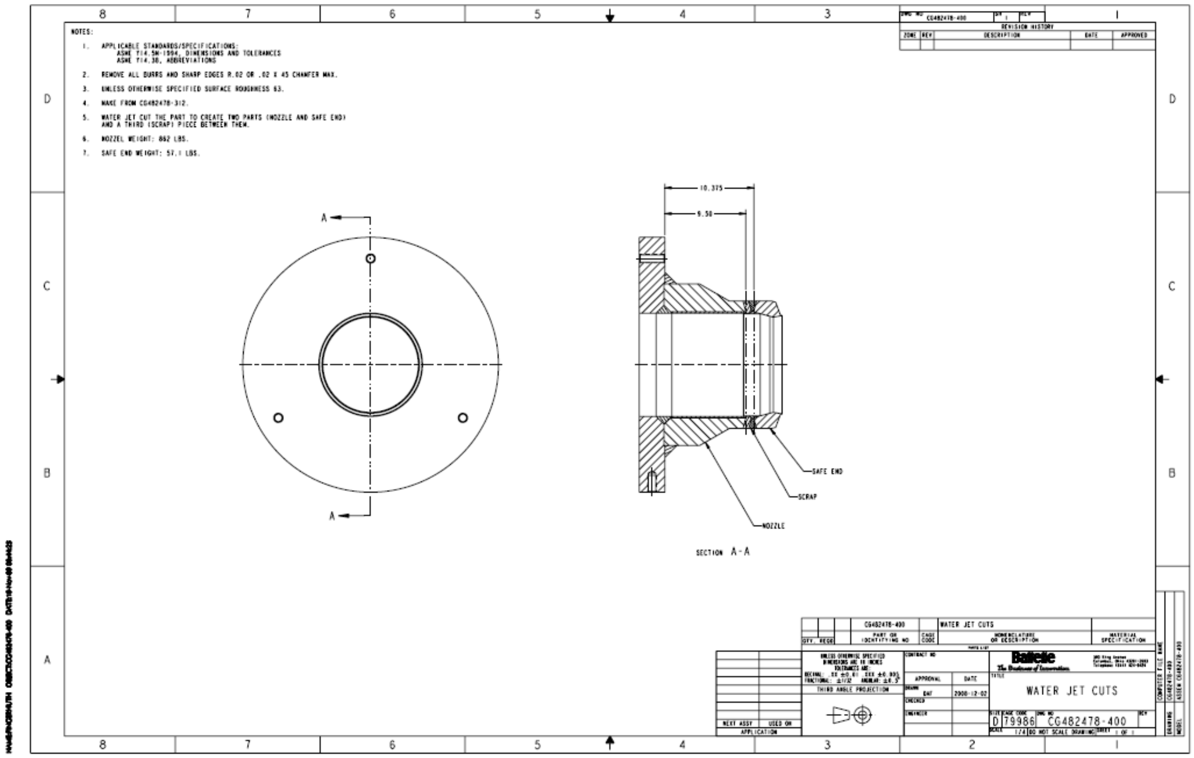

NOTES:
1. APPLICABLE STANDARDS/SPECIFICATIONS:
ASME Y14.5M-1994, DIMENSIONS AND TOLERANCES
ASME Y14.38, ABBREVIATIONS
2 ONE THERMOCOUPLE .25 IN FROM EDGE OF GROOVE AT INDICATED LOCATION.
A MODIFIED DRAWING TITLE
3X INTERNAL THERMOCOUPLE LOCATIONS
DETAIL A
SCALE 1/1
SEE DETAIL A
SECTION A-A
SECTION B-B
Battelle
BACK WELD THERMOCOUPLES LOCATION 1
D 79986 CG482478-217 A

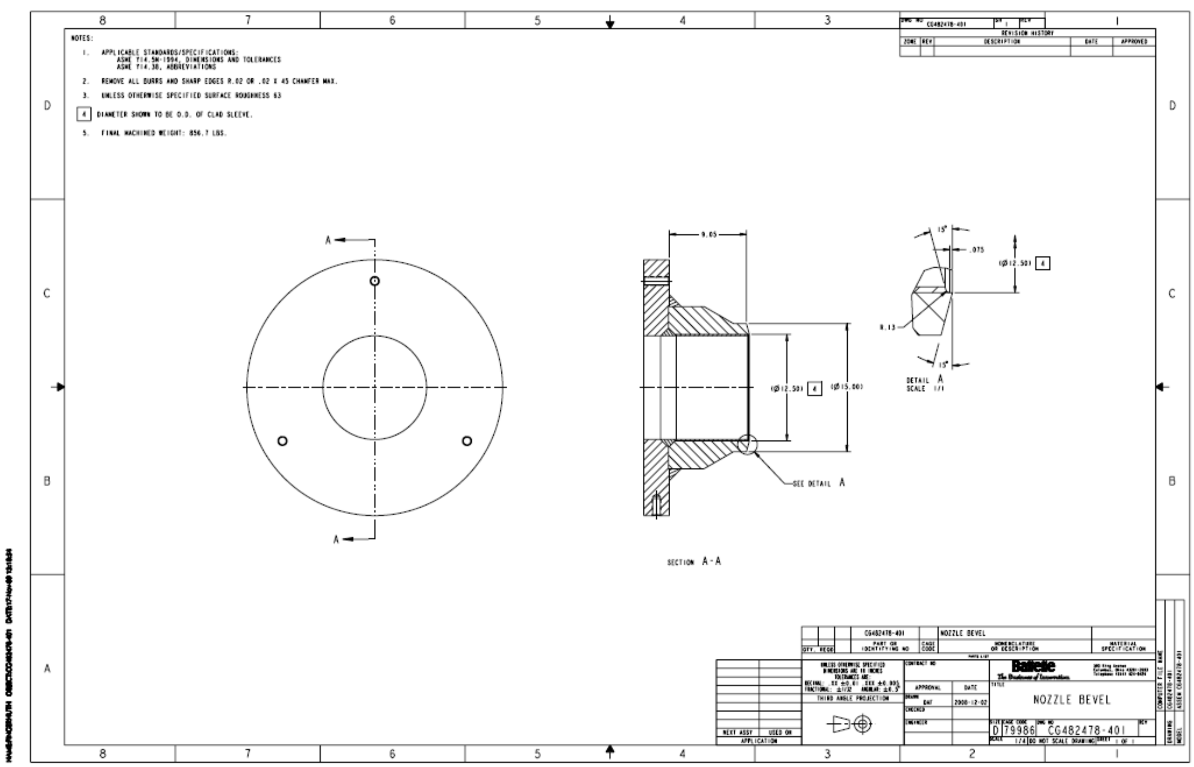

NOTES:
1. APPLICABLE STANDARDS/SPECIFICATIONS:
ASME Y14.5M-1994, DIMENSIONS AND TOLERANCES
ASME Y14.38, ABBREVIATIONS
2. REMOVE 5 THERMOCOUPLES AND RELOCATE TO NEW LOCATIONS SHOWN WHEN GROOVE IS FILLED WITH WELD METAL.
3 ONE THERMOCOUPLE (11.50) IN FROM FACE OF FLANGE AT INDICATED LOCATION.
3X INTERNAL THERMOCOUPLE LOCATIONS
.25
.25
DETAIL A
SCALE 1/2
11.50
SEE DETAIL A
45°
SECTION A-A
SECTION B-B
CG482478-218
BACK WELD THERMOCOUPLES LOCATION 2
THIRD ANGLE PROJECTION
DAT
2008-11-24
Battelle
BACK WELD THERMOCOUPLES
LOCATION 2
D 79986 CG482478-218
DO NOT SCALE DRAWING

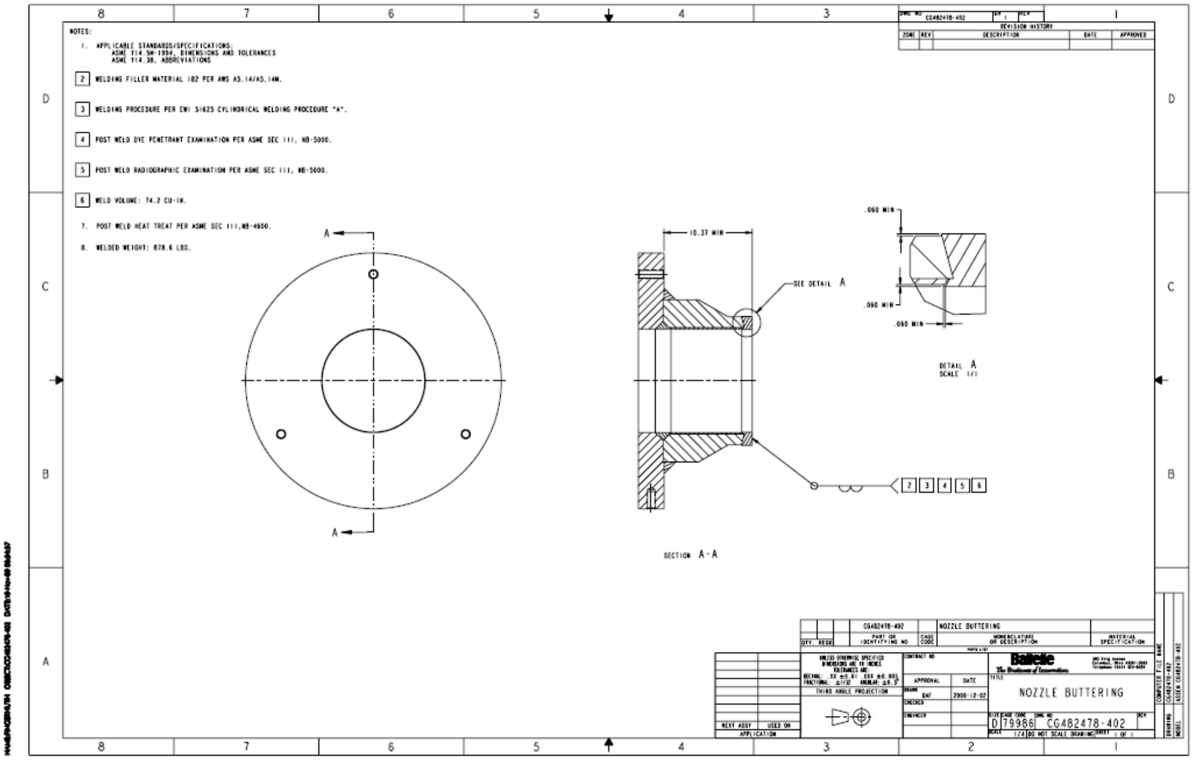
Appendix B

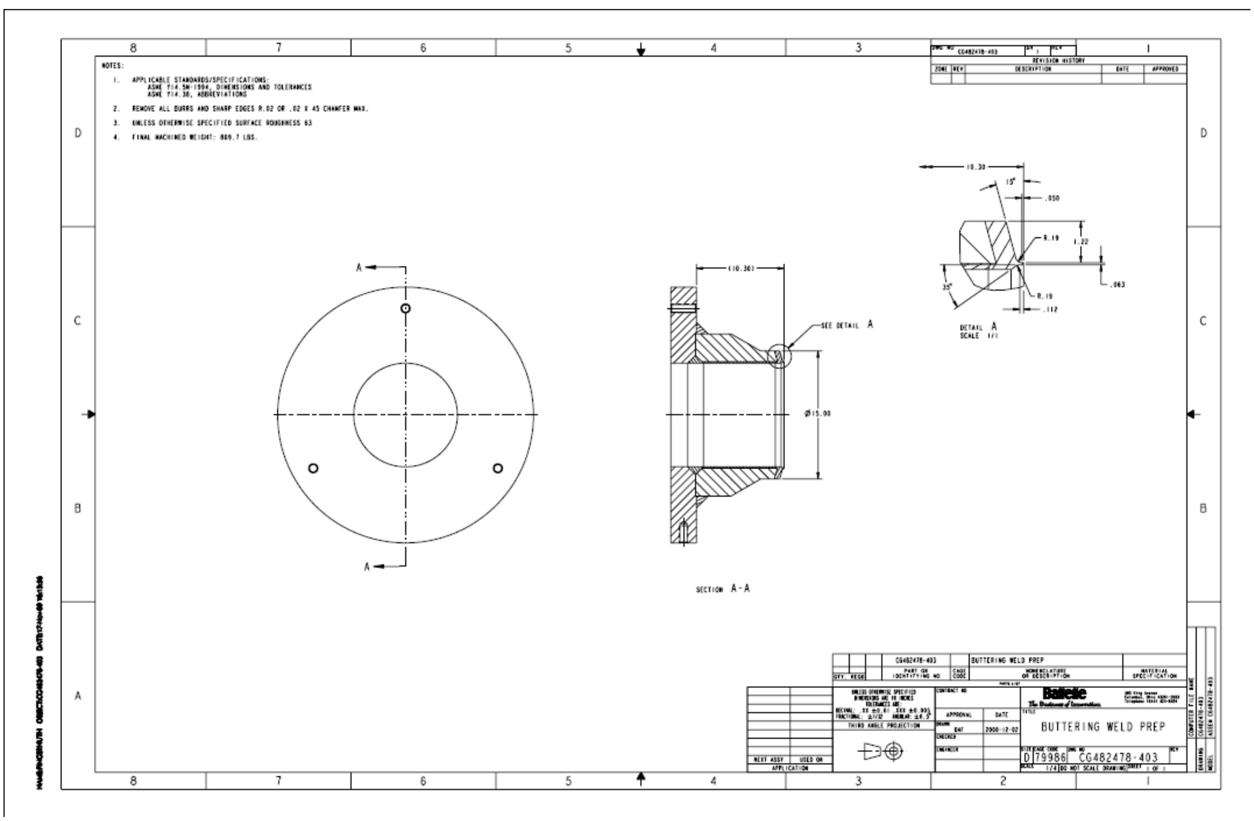
Weld Overlay Residual Stress Mock-Up

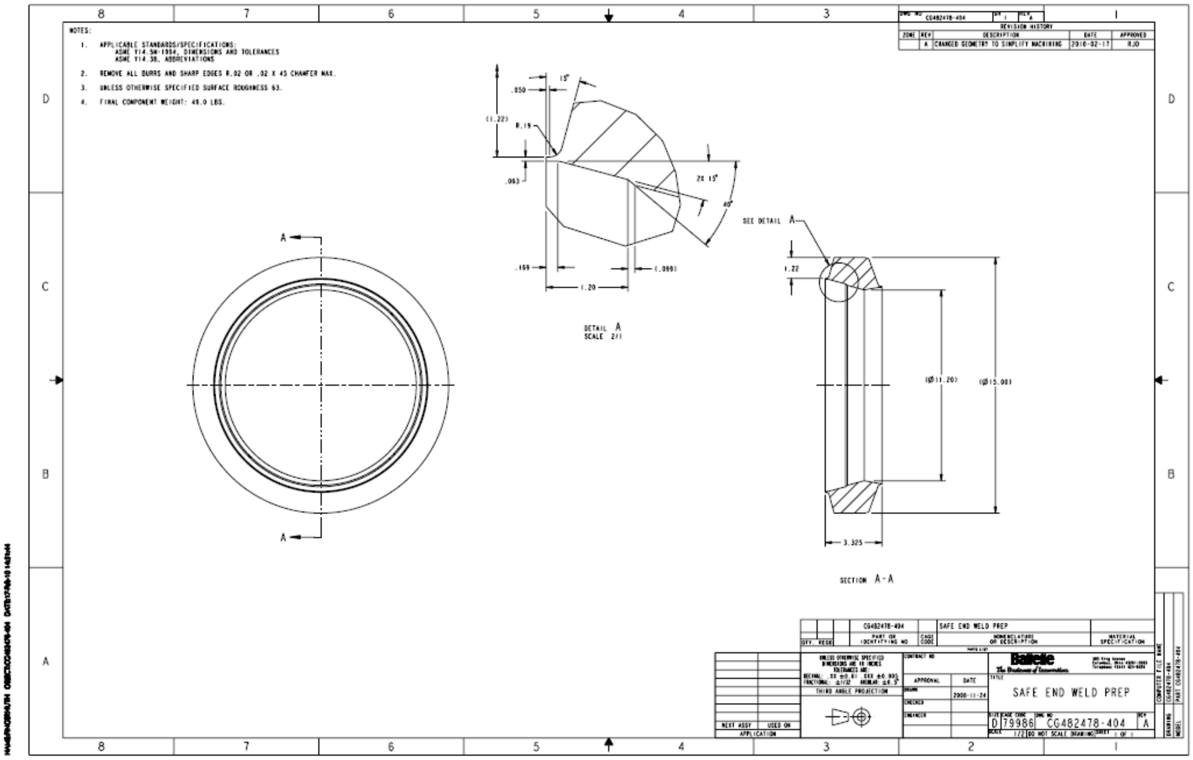
Battelle Drawings CG482478-400 thru CR482478-414

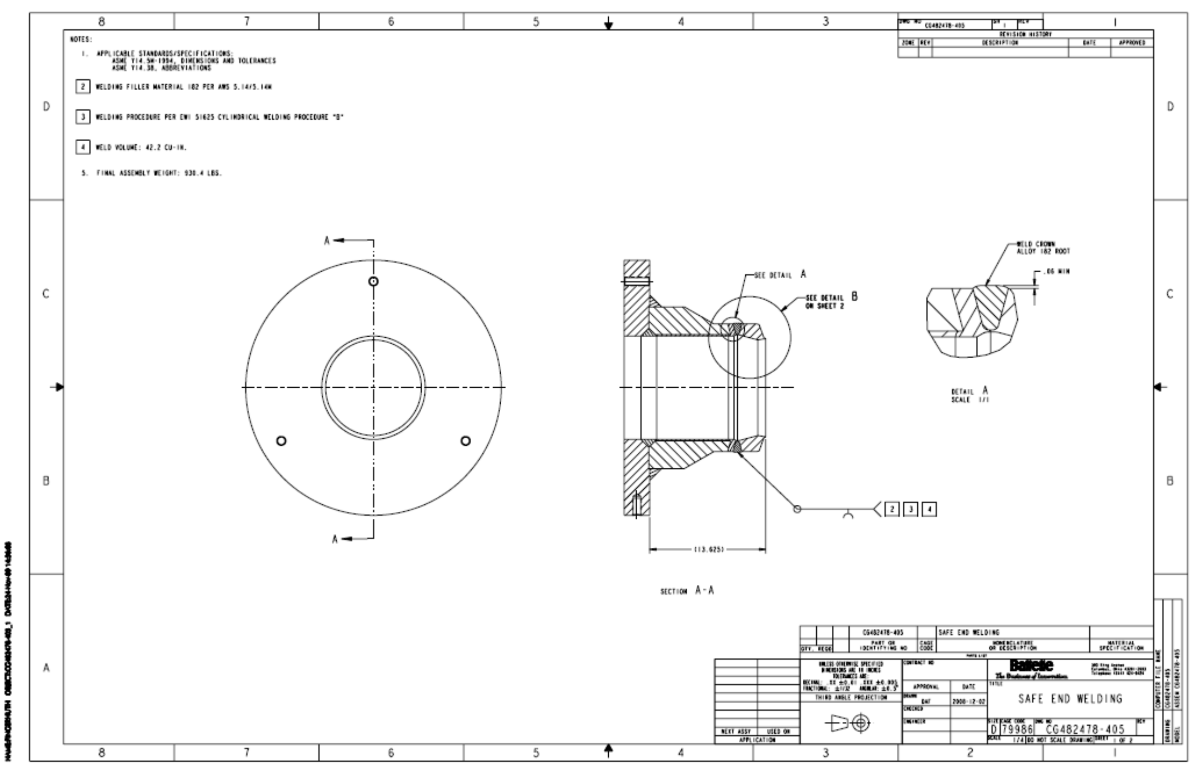

NOTES:
1. APPLICABLE STANDARDS/SPECIFICATIONS:
ASME Y14.5M-1994, DIMENSIONS AND TOLERANCES
ASME Y14.38, ABBREVIATIONS
2. REMOVE ALL BURRS AND SHARP EDGES R.02 OR .02 X 45 CHAMFER MAX.
3. UNLESS OTHERWISE SPECIFIED SURFACE ROUGHNESS 63.
4. MAKE FROM CG482478-312.
5. WATER JET CUT THE PART TO CREATE TWO PARTS (NOZZLE AND SAFE END) AND A THIRD (SCRAP) PIECE BETWEEN THEM.
6. NOZZEL WEIGHT: 862 LBS.
7. SAFE END WEIGHT: 57.1 LBS.
10.375
9.50
SAFE END
SCRAP
NOZZLE
SECTION A-A
CG482478-400
WATER JET CUTS
THIRD ANGLE PROJECTION
2000-12-02
Battelle
WATER JET CUTS
D 79986 CG482478-400
1/4 DO NOT SCALE DRAWING

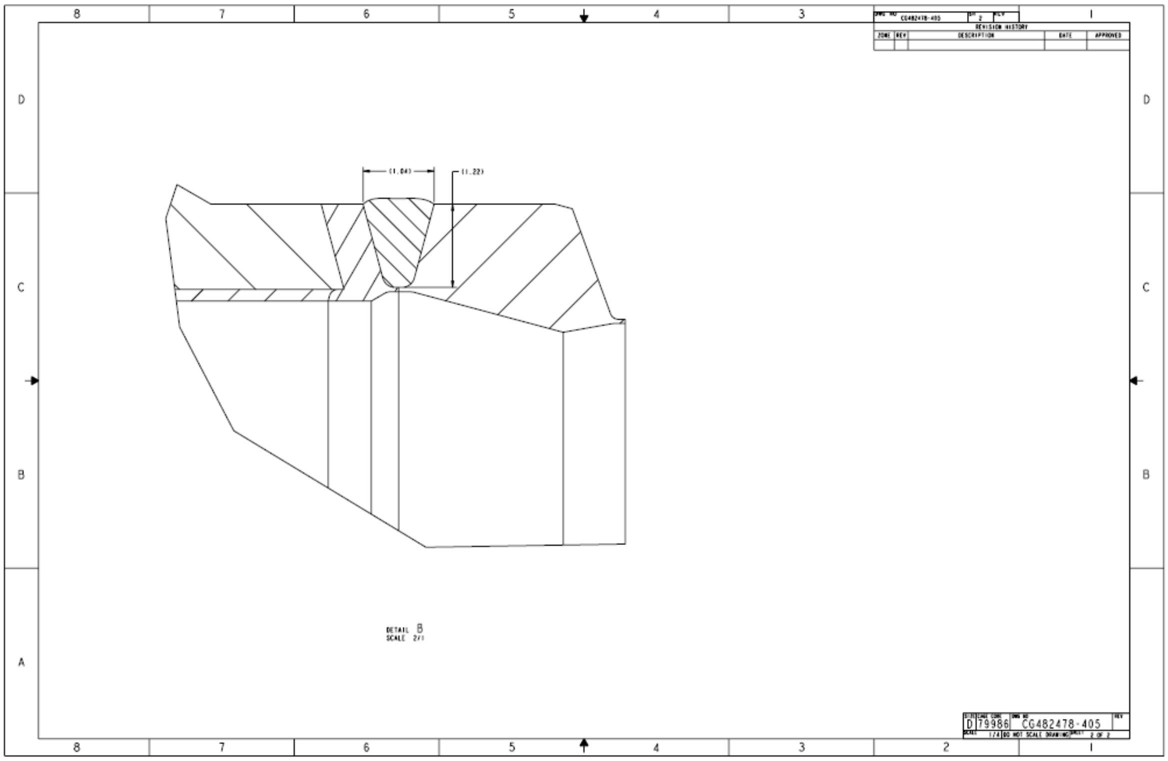

NOTES:
1. APPLICABLE STANDARDS/SPECIFICATIONS:
ASME Y14.5M-1994, DIMENSIONS AND TOLERANCES
ASME Y14.38, ABBREVIATIONS
2. REMOVE ALL BURRS AND SHARP EDGES R.02 OR .02 X 45 CHAMFER MAX.
3. UNLESS OTHERWISE SPECIFIED SURFACE ROUGHNESS 63
4 DIAMETER SHOWN TO BE O.D. OF CLAD SLEEVE.
5. FINAL MACHINED WEIGHT: 856.7 LBS.
9.05
(Ø12.50) 4
(Ø15.00)
SEE DETAIL A
SECTION A-A
15°
.075
R.13
DETAIL A
SCALE 1/1
CG482478-401
NOZZLE BEVEL
THIRD ANGLE PROJECTION
2000-12-02
Battelle
NOZZLE BEVEL
D 79986 CG482478-401
1/4 DO NOT SCALE DRAWING

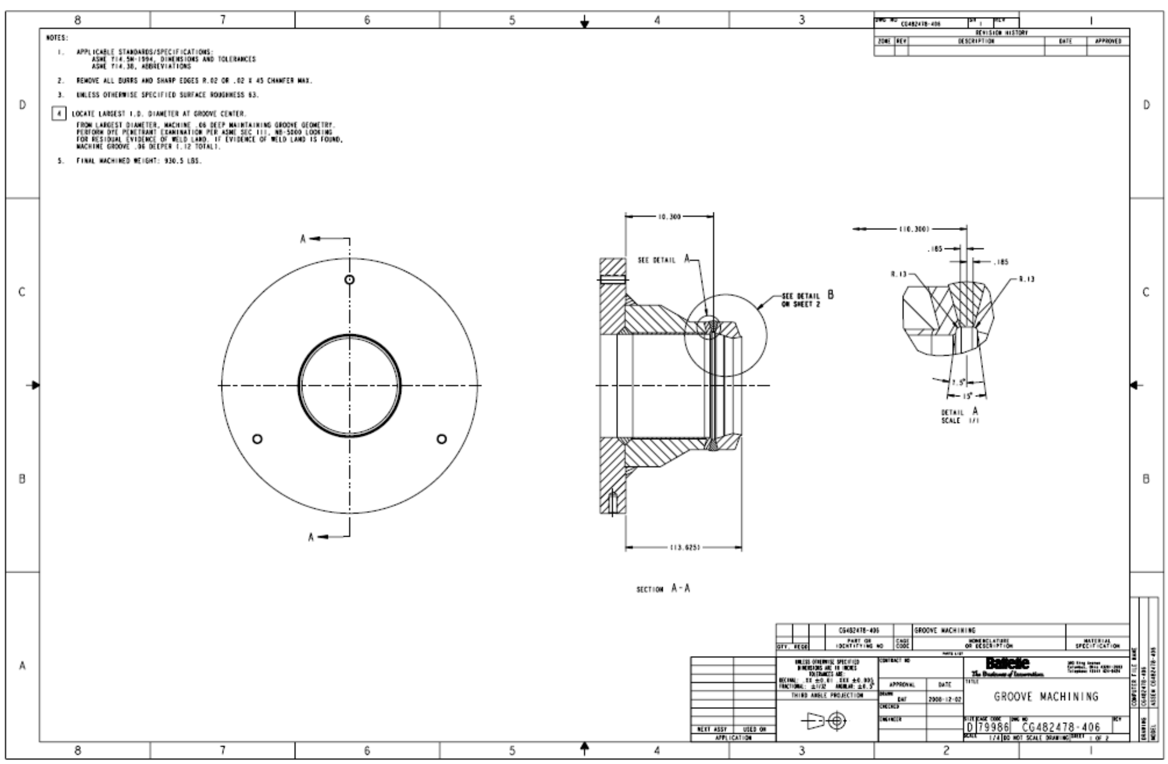

NOTES:
1. APPLICABLE STANDARDS/SPECIFICATIONS: ASME Y14.5M-1994, DIMENSIONS AND TOLERANCES ASME Y14.38, ABBREVIATIONS
2 WELDING FILLER MATERIAL 182 PER AWS A5.14/A5.14M.
3 WELDING PROCEDURE PER EWI 51625 CYLINDRICAL WELDING PROCEDURE "A".
4 POST WELD DYE PENETRANT EXAMINATION PER ASME SEC III, NB-5000.
5 POST WELD RADIOGRAPHIC EXAMINATION PER ASME SEC III, NB-5000.
6 WELD VOLUME: 74.2 CU-IN.
7. POST WELD HEAT TREAT PER ASME SEC III, NB-4600.
8. WELDED WEIGHT: 878.6 LBS.
SEE DETAIL A
DETAIL A SCALE 1/1
SECTION A-A
NOZZLE BUTTERING
THIRD ANGLE PROJECTION
Battelle
NOZZLE BUTTERING
D 79986 CG482478-402

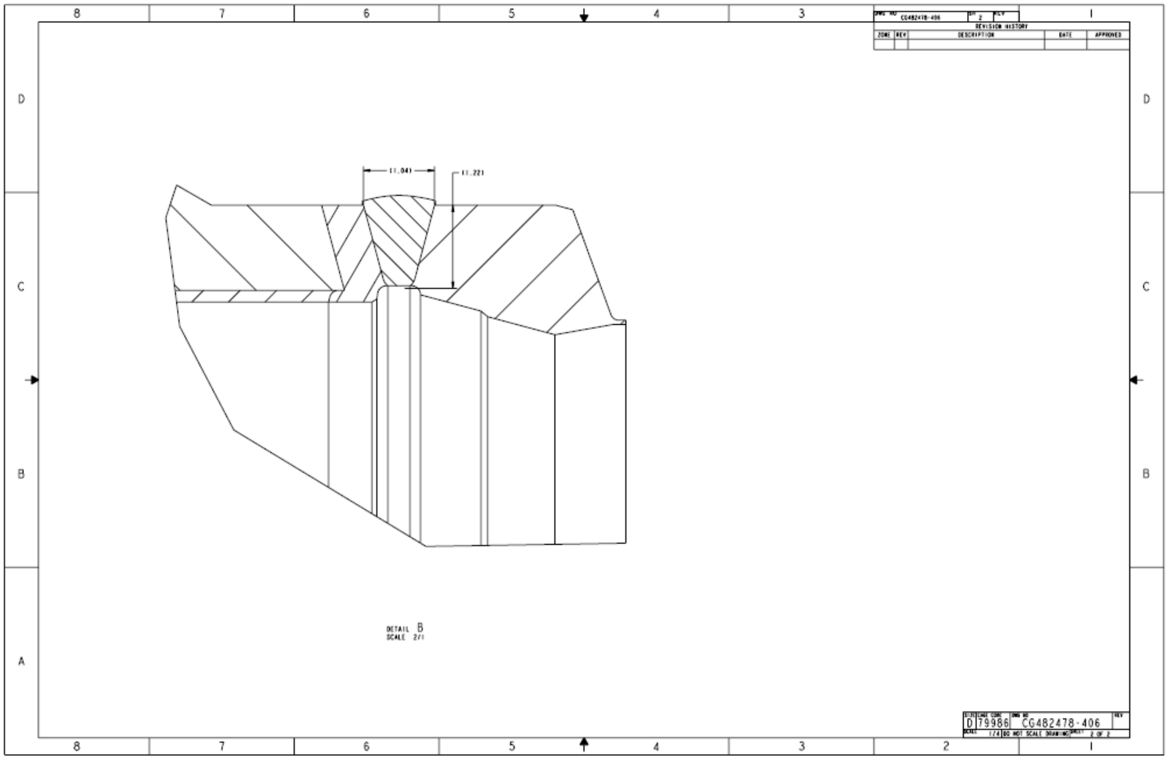

NOTES:
1. APPLICABLE STANDARDS/SPECIFICATIONS: ASME Y14.5M-1994, DIMENSIONS AND TOLERANCES ASME Y14.38, ABBREVIATIONS
2. REMOVE ALL BURRS AND SHARP EDGES R.02 OR .02 X 45 CHAMFER MAX.
3. UNLESS OTHERWISE SPECIFIED SURFACE ROUGHNESS 63
4. FINAL MACHINED WEIGHT: 869.7 LBS.
SEE DETAIL A
Ø15.00
DETAIL A SCALE 1/1
SECTION A-A
BUTTERING WELD PREP
THIRD ANGLE PROJECTION
Battelle
BUTTERING WELD PREP
D 79986 CG482478-403

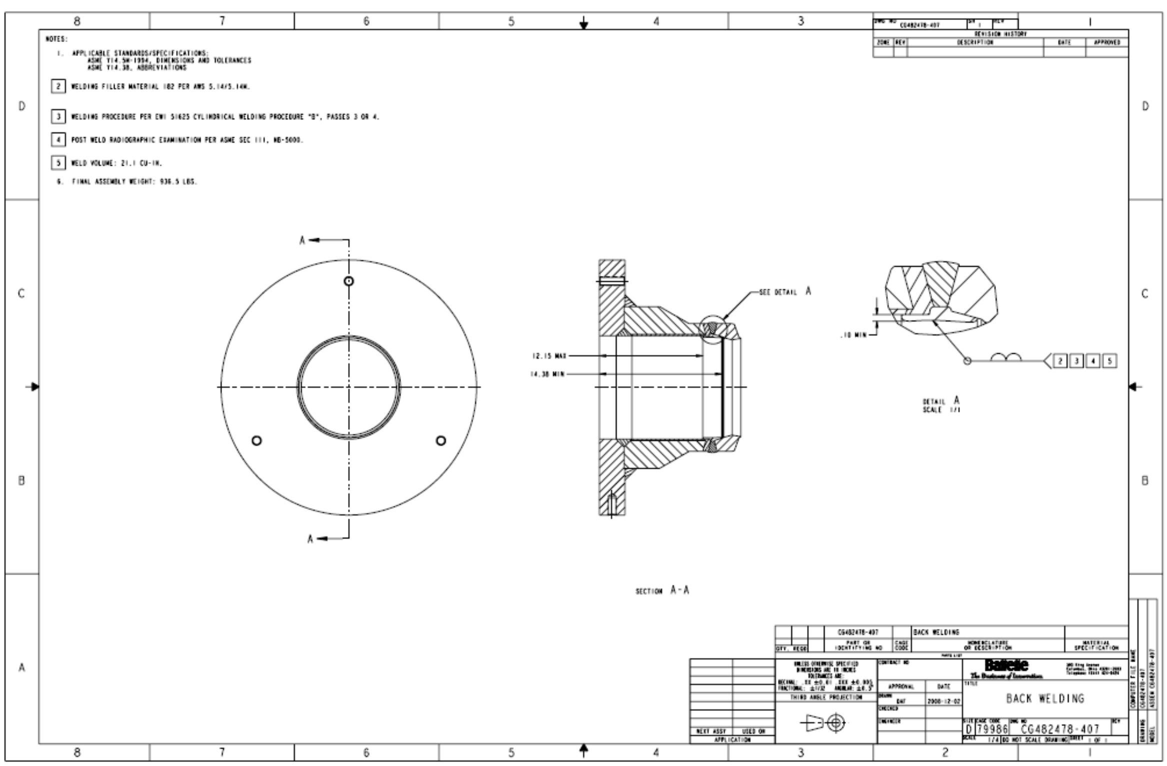


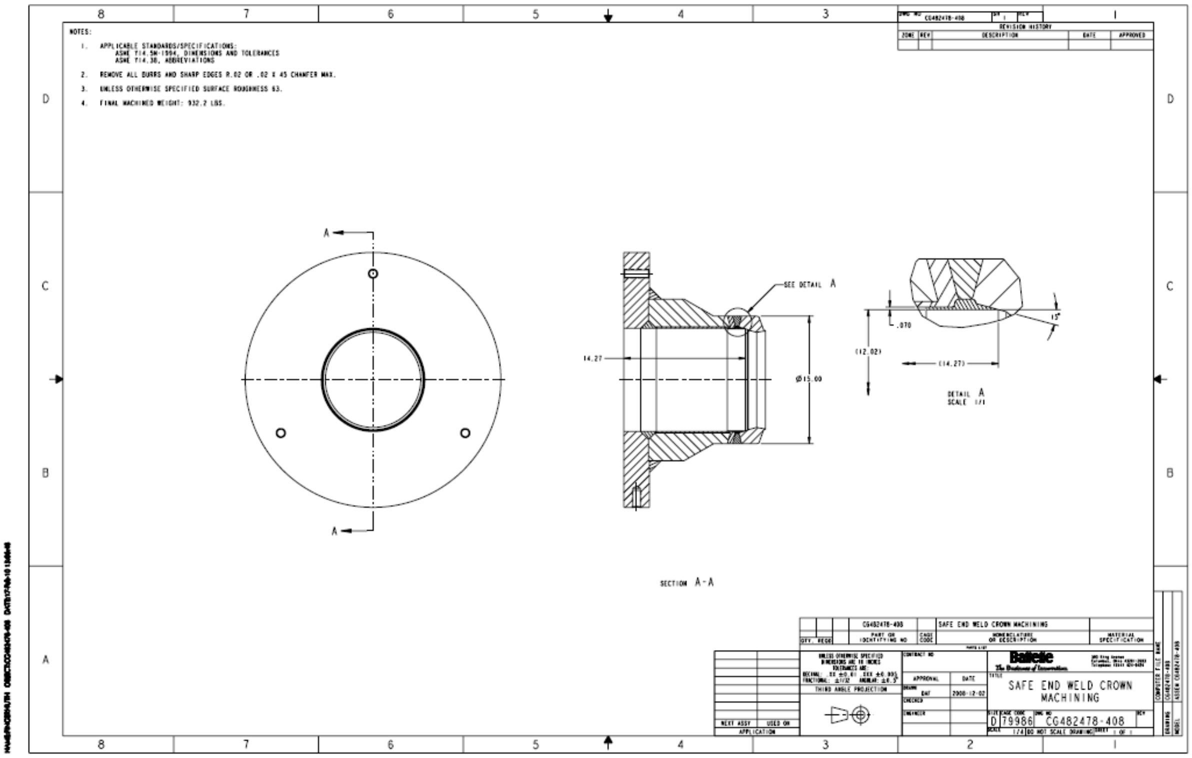


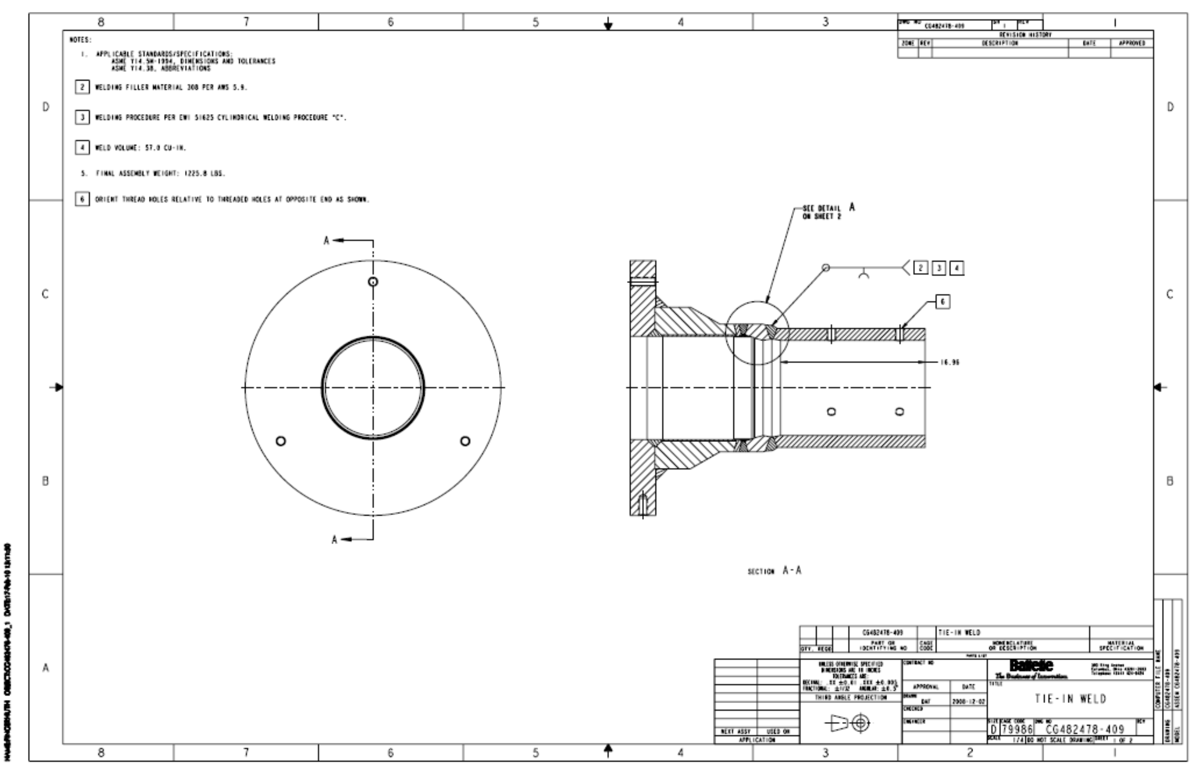

(1.04)
(1.22)
DETAIL B
SCALE 2/1
D79986 CG482478-405
1/4 DO NOT SCALE DRAWING 2 OF 2

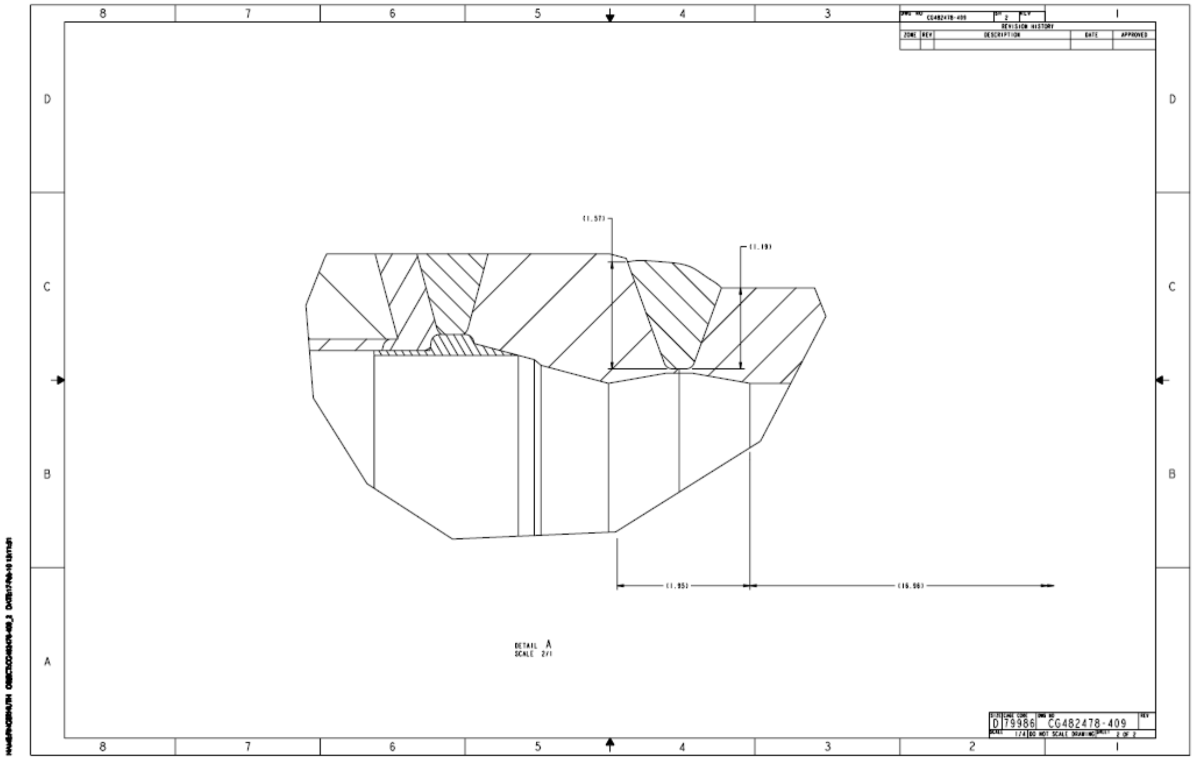

NOTES:
1. APPLICABLE STANDARDS/SPECIFICATIONS:
ASME Y14.5M-1994, DIMENSIONS AND TOLERANCES
ASME Y14.38, ABBREVIATIONS
2. REMOVE ALL BURRS AND SHARP EDGES R.02 OR .02 X 45 CHAMFER MAX.
3. UNLESS OTHERWISE SPECIFIED SURFACE ROUGHNESS 63.
4 LOCATE LARGEST I.D. DIAMETER AT GROOVE CENTER.
FROM LARGEST DIAMETER, MACHINE .06 DEEP MAINTAINING GROOVE GEOMETRY.
PERFORM DYE PENETRANT EXAMINATION PER ASME SEC III, NB-5000 LOOKING
FOR RESIDUAL EVIDENCE OF WELD LAND. IF EVIDENCE OF WELD LAND IS FOUND,
MACHINE GROOVE .06 DEEPER (.12 TOTAL).
5. FINAL MACHINED WEIGHT: 930.5 LBS.
10.300
SEE DETAIL A
SEE DETAIL B ON SHEET 2
(13.625)
SECTION A-A
(10.300)
.185
R.13
7.5°
15°
DETAIL A
SCALE 1/1
CG482478-405
GROOVE MACHINING
THIRD ANGLE PROJECTION
2000-12-02
Battelle
GROOVE MACHINING
D79986 CG482478-406
1/4 DO NOT SCALE DRAWING 1 OF 2


(1.04)
(1.22)
DETAIL B
SCALE 2/1
D 79986 CG482478-406
2 OF 2


NOTES:
1. APPLICABLE STANDARDS/SPECIFICATIONS:
ASME Y14.5M-1994, DIMENSIONS AND TOLERANCES
ASME Y14.38, ABBREVIATIONS
2 WELDING FILLER MATERIAL 182 PER AWS 5.14/5.14M.
3 WELDING PROCEDURE PER EWI 51625 CYLINDRICAL WELDING PROCEDURE "B", PASSES 3 OR 4.
4 POST WELD RADIOGRAPHIC EXAMINATION PER ASME SEC III, NB-5000.
5 WELD VOLUME: 21.1 CU-IN.
6. FINAL ASSEMBLY WEIGHT: 936.5 LBS.
SEE DETAIL A
12.15 MAX
14.38 MIN
.10 MIN
DETAIL A
SCALE 1/1
SECTION A-A
CG482478-407
BACK WELDING
Battelle
THIRD ANGLE PROJECTION
2000-12-02
BACK WELDING
D 79986 CG482478-407


NOTES:
1. APPLICABLE STANDARDS/SPECIFICATIONS:
ASME Y14.5M-1994, DIMENSIONS AND TOLERANCES
ASME Y14.38, ABBREVIATIONS
2. REMOVE ALL BURRS AND SHARP EDGES R.02 OR .02 X 45 CHAMFER MAX.
3. UNLESS OTHERWISE SPECIFIED SURFACE ROUGHNESS 63.
4. FINAL MACHINED WEIGHT: 932.2 LBS.
SEE DETAIL A
14.27
Ø13.00
.070
(12.02)
(14.27)
15°
DETAIL A
SCALE 1/1
SECTION A-A
CG482478-408
SAFE END WELD CROWN MACHINING
THIRD ANGLE PROJECTION
2008-12-02
SAFE END WELD CROWN MACHINING
D 79986 CG482478-408


NOTES:
1. APPLICABLE STANDARDS/SPECIFICATIONS:
ASME Y14.5M-1994, DIMENSIONS AND TOLERANCES
ASME Y14.38, ABBREVIATIONS
2 WELDING FILLER MATERIAL 308 PER AWS 5.9.
3 WELDING PROCEDURE PER EWI 51625 CYLINDRICAL WELDING PROCEDURE "C".
4 WELD VOLUME: 57.0 CU-IN.
5. FINAL ASSEMBLY WEIGHT: 1225.8 LBS.
6 ORIENT THREAD HOLES RELATIVE TO THREADED HOLES AT OPPOSITE END AS SHOWN.
SEE DETAIL A ON SHEET 2
16.95
SECTION A-A
CG482478-409
TIE-IN WELD
THIRD ANGLE PROJECTION
2008-12-02
TIE-IN WELD
D 79986 CG482478-409


(1.57)
(1.19)
(1.95)
(16.56)
DETAIL A
SCALE 2/1
D 79986 CG482478-409
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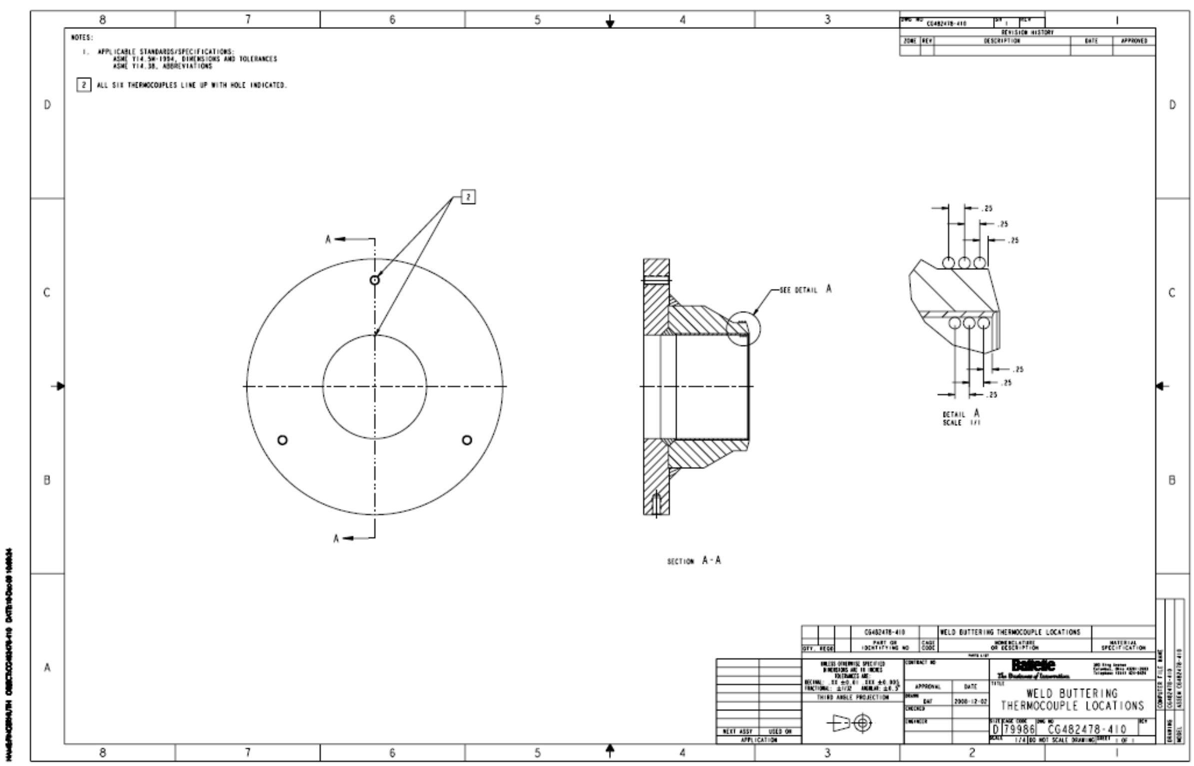
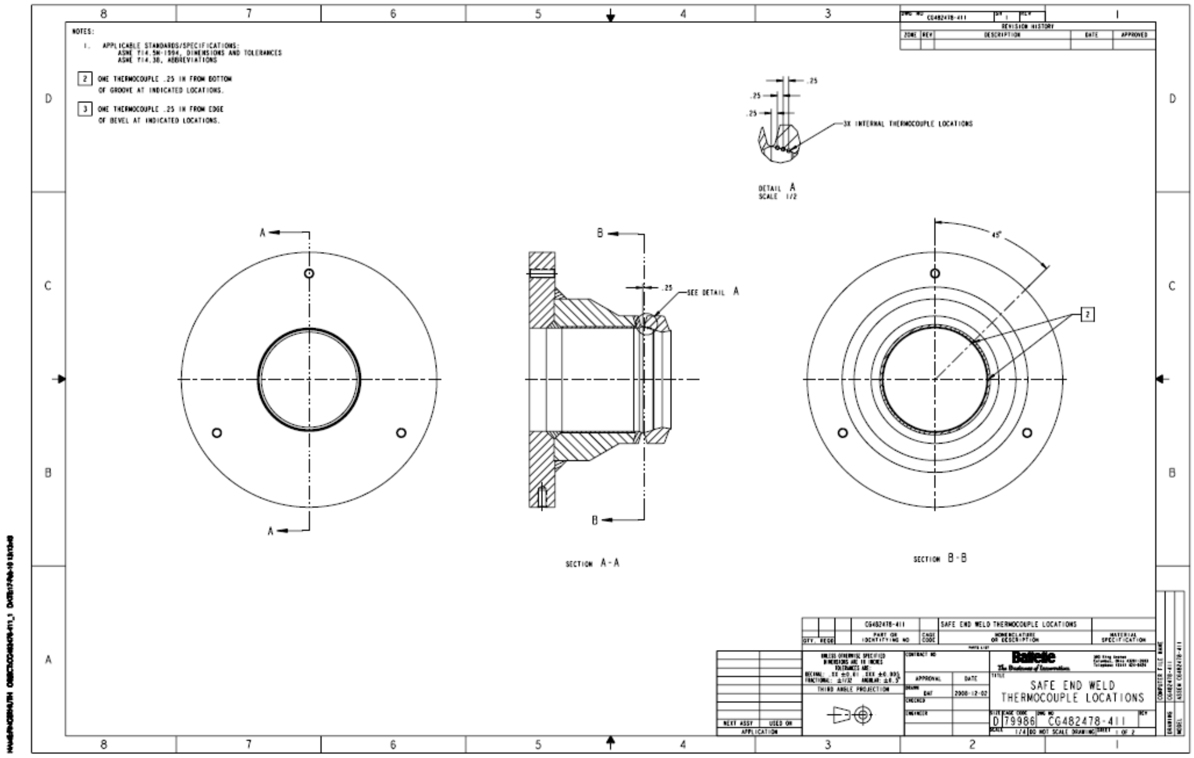
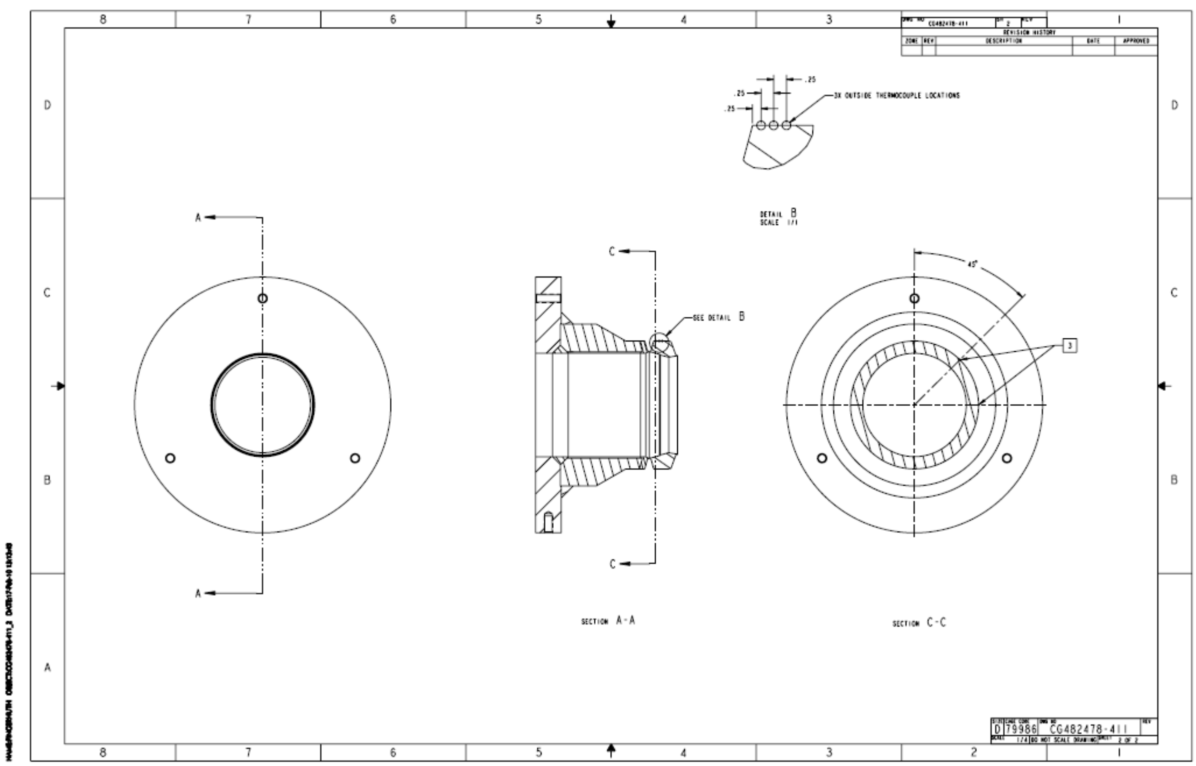
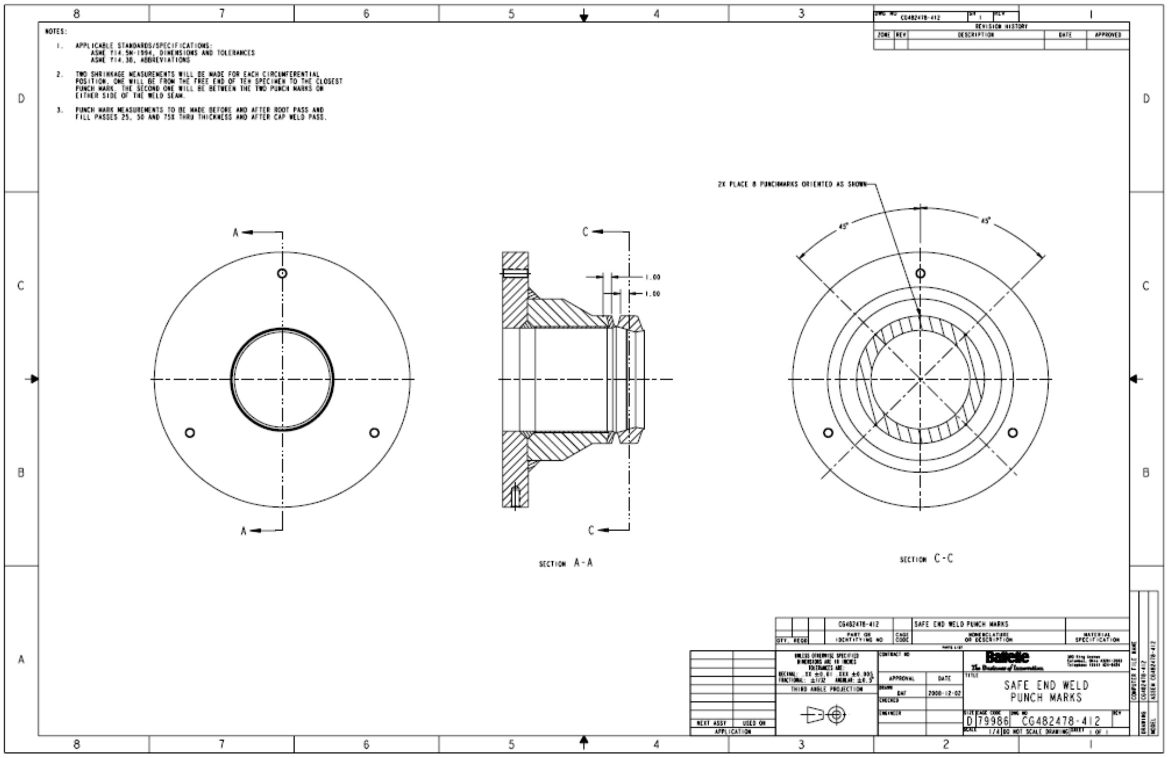
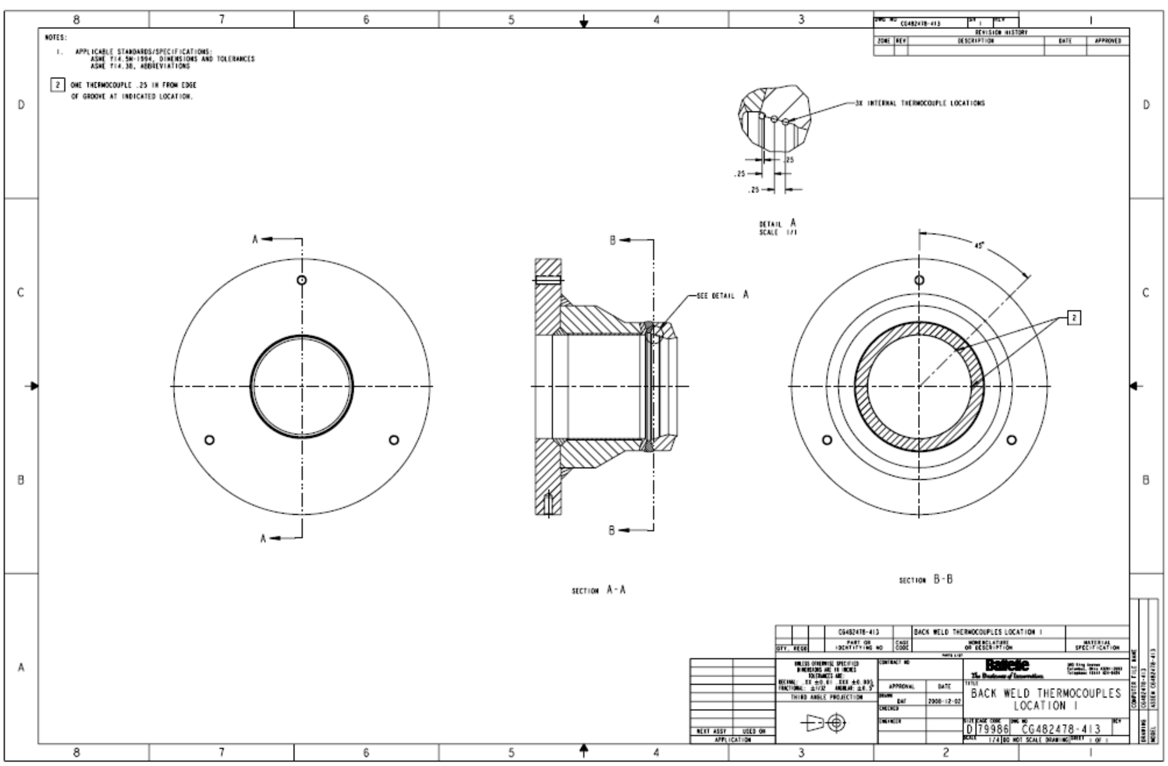
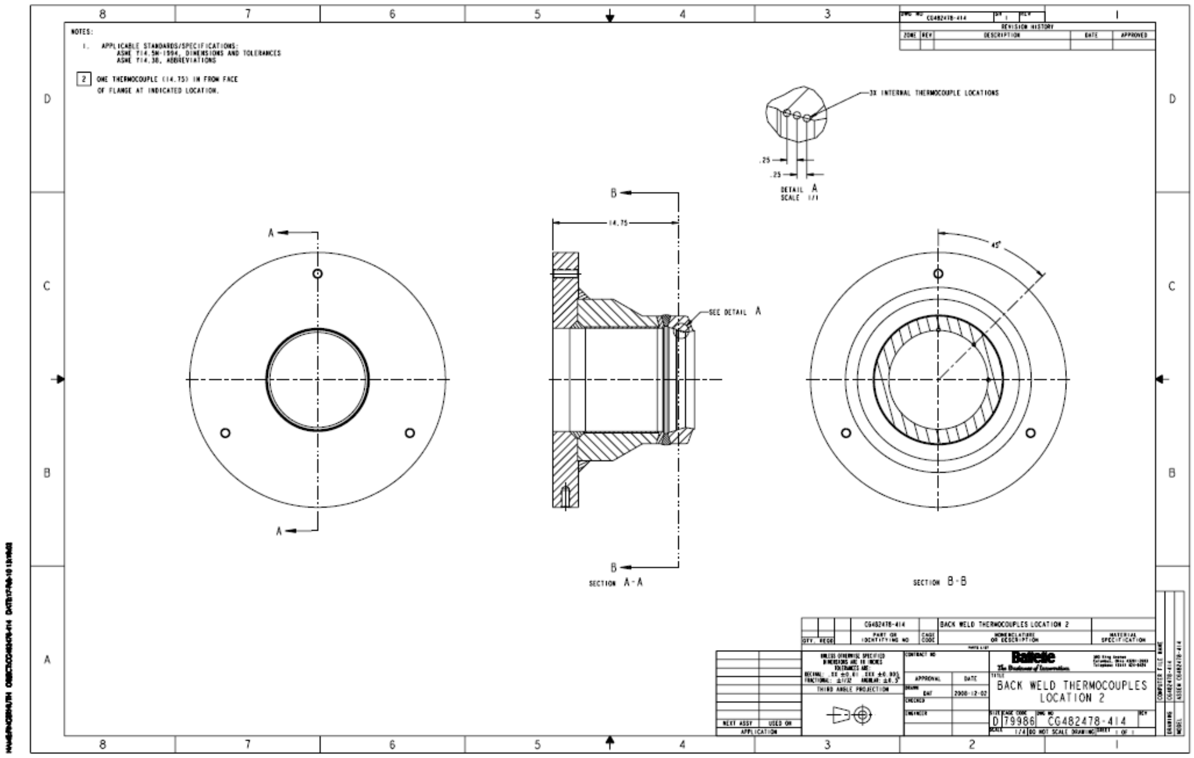

NOTES:
1. APPLICABLE STANDARDS/SPECIFICATIONS:
ASME Y14.5M-1994, DIMENSIONS AND TOLERANCES
ASME Y14.38, ABBREVIATIONS
2 ALL SIX THERMOCOUPLES LINE UP WITH HOLE INDICATED.
SEE DETAIL A
.25
DETAIL A
SCALE 1/1
SECTION A-A
CG482478-410
WELD BUTTERING THERMOCOUPLE LOCATIONS
THIRD ANGLE PROJECTION
DAT 2000-12-02
Battelle
WELD BUTTERING
THERMOCOUPLE LOCATIONS
D 79986 CG482478-410
1/4 DO NOT SCALE DRAWING 1 OF 1


NOTES:
1. APPLICABLE STANDARDS/SPECIFICATIONS: ASME Y14.5M-1994, DIMENSIONS AND TOLERANCES ASME Y14.38, ABBREVIATIONS
2 ONE THERMOCOUPLE .25 IN FROM BOTTOM OF GROOVE AT INDICATED LOCATIONS.
3 ONE THERMOCOUPLE .25 IN FROM EDGE OF BEVEL AT INDICATED LOCATIONS.
3X INTERNAL THERMOCOUPLE LOCATIONS
DETAIL A SCALE 1/2
SEE DETAIL A
SECTION A-A
SECTION B-B
SAFE END WELD THERMOCOUPLE LOCATIONS
THIRD ANGLE PROJECTION
2008-12-02
D 79986 CG482478-411
1/4 DO NOT SCALE DRAWING 1 OF 2


3X OUTSIDE THERMOCOUPLE LOCATIONS
DETAIL B SCALE 1/1
SEE DETAIL B
SECTION A-A
SECTION C-C
D 79986 CG482478-411
1/4 DO NOT SCALE DRAWING 2 OF 2


NOTES:
1. APPLICABLE STANDARDS/SPECIFICATIONS:
ASME Y14.5M-1994, DIMENSIONS AND TOLERANCES
ASME Y14.38, ABBREVIATIONS
2. TWO SHRINKAGE MEASUREMENTS WILL BE MADE FOR EACH CIRCUMFERENTIAL POSITION. ONE WILL BE FROM THE FREE END OF TEH SPECIMEN TO THE CLOSEST PUNCH MARK. THE SECOND ONE WILL BE BETWEEN THE TWO PUNCH MARKS ON EITHER SIDE OF THE WELD SEAM.
3. PUNCH MARK MEASUREMENTS TO BE MADE BEFORE AND AFTER ROOT PASS AND FILL PASSES 25, 50 AND 75% THRU THICKNESS AND AFTER CAP WELD PASS.
2X PLACE 8 PUNCHMARKS ORIENTED AS SHOWN
45°
45°
1.00
1.00
SECTION A-A
SECTION C-C
CG482478-412
SAFE END WELD PUNCH MARKS
THIRD ANGLE PROJECTION
2000-12-02
Battelle
SAFE END WELD PUNCH MARKS
D 79986 CG482478-412
1/4 DO NOT SCALE DRAWING
NEXT ASSY
USED ON
APPLICATION


NOTES:
1. APPLICABLE STANDARDS/SPECIFICATIONS:
ASME Y14.5M-1994, DIMENSIONS AND TOLERANCES
ASME Y14.38, ABBREVIATIONS
2 ONE THERMOCOUPLE .25 IN FROM EDGE OF GROOVE AT INDICATED LOCATION.
3X INTERNAL THERMOCOUPLE LOCATIONS
.25
.25
.25
DETAIL A
SCALE 1/1
SEE DETAIL A
45°
SECTION A-A
SECTION B-B
CG482478-413
BACK WELD THERMOCOUPLES LOCATION 1
THIRD ANGLE PROJECTION
2000-12-02
Battelle
BACK WELD THERMOCOUPLES LOCATION 1
D 79986 CG482478-413
1/4 DO NOT SCALE DRAWING
NEXT ASSY
USED ON
APPLICATION


NOTES:
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ASME Y14.5M-1994, DIMENSIONS AND TOLERANCES
ASME Y14.38, ABBREVIATIONS
2 ONE THERMOCOUPLE (14.75) IN FROM FACE
OF FLANGE AT INDICATED LOCATION.
3X INTERNAL THERMOCOUPLE LOCATIONS
.25
.25
DETAIL A
SCALE 1/1
14.75
SEE DETAIL A
45°
SECTION A-A
SECTION B-B
CG482478-414
BACK WELD THERMOCOUPLES LOCATION 2
THIRD ANGLE PROJECTION
APPROVAL
DATE
DAT
2008-12-02
NEXT ASSY
USED ON
APPLICATION
BACK WELD THERMOCOUPLES
LOCATION 2
D 79986 CG482478-414
1/4 DO NOT SCALE DRAWING
1 OF 1

Appendix C

Stiffening Weldment Welding Procedures

QW-482 SUGGESTED FORMAT FOR WELDING PROCEDURE SPECIFICATIONS (WPS)
(See QW-200.1, Section IX, ASME Boiler and Pressure Vessel Code)

Company Name: Edison Welding Institute — By: David Link

Welding Procedure Specification No.: 51108-WPS1 — Date: 06/15/2009 — Supporting PQR No.(s): N/A

Rev. No.: 0 — Date: 06/15/2009

Welding Process(es): Gas Metal Arc Welding (GMAW) — Type(s): Semi-automatic
(Automatic, Manual, Machine, or Semi-Auto)

Joints (QW-402) — Details

Joint Design: Vee Groove, partial Penetration

Backing (Yes) ______ (No) X

Backing Material (Type) ______
(Refer to both backing and retainers)

☐ Metal ☐ Nonfusing Metal
☐ Nonmetallic ☐ Other

*BASE METALS (QW-403)

P-No. 1 Group No. ______ to P-No. 3 Group No. ______

OR

Specification Type and Grade ______

to Specification Type and Grade ______

OR

Chem. Analysis and Mech. Prop. ______

to Chem. Analysis and Mech. Prop. ______

Thickness Range:

Base Metal: Groove .500” nominal Fillet ______

Other ______

*FILLER METALS (QW-404)			
Spec. No. (SFA)	ER80S-D2		
AWS No. (Class)	A 5.28		
F-No.	6		
A-No.	11		
Size of Filler Metals	.045”		
Weld Metal Thickness Range:			
Groove	.500” nominal		
Fillet	N/A		
Electrode-Flux (Class)	N/A		
Flux Trade Name	N/A		
Consumable Insert	N/A		
Other	N/A		

*Each base metal-filler metal combination should be recorded individually.

This form (E00006) may be obtained from the Order Dept., ASME, 22 Law Drive, Box 2300, Fairfield, NJ 07007-2300

QW-482 (Back)

WPS No. 51108-WPS1 Rev. 0

POSITIONS (QW-405)
Position(s) of Groove 1G
Welding Progression: Up N/A Down N/A
Position(s) of Fillet N/A

POSTWELD HEAT TREATMENT (QW-407)
Temperature Range N/A
Time Range N/A

PREHEAT (QW-406)
Preheat Temp. Min. 400 F
Interpass Temp. Max. 500 F
Preheat Maintenance N/A
(Continuous or special heating where applicable should be recorded)

GAS (QW-408)

	Gases	Percent Composition (Mixture)	Flow Rate
Shielding	Ar/Co2	90%/10%	30-40 CFH
Trailing	N/A		
Backing	N/A		

ELECTRICAL CHARACTERISTICS (QW-409)
Current AC or DC DC Polarity EP
Amps (Range) 250-325 Volts (Range) 29-31
(Amps and volts range should be recorded for each electrode size, position, and thickness, etc. This information may be listed in a tabular form similar to that shown below.)

Tungsten Electrode Size and Type N/A
(Pure tungsten, 2% thoriated, etc.)
Mode of Metal Transfer for GMAW Spray
(Spray arc, short circuiting arc, etc.)
Electrode Wire Feed Speed Range 400-450

TECHNIQUE (QW-410)
Sting or Weave Bead Stringer
Orifice or Gas Cup Size .750”
Initial and Interpass Cleaning (brushing, grinding, etc.) SS wire brush and acetone
Method of Back Gouging N/A
Oscillation N/A
Contact Tube to Work Distance .500” - .750”
Multiple or Single Pass (per side) Multiple
Multiple or Single Electrodes Single
Travel Speed (range) 12 - 15 IPM
Peening N/A
Other Part Rotated under fixed torch

Weld Layer(s)	Process	Filler Metal		Current		Volt Range	Travel Speed Range	Other (e.g., Remarks, Comments, Hot Wire Addition, Technique, Torch Angle, etc.)
		Class	Dia.	Type Polar.	Amp Range			
All	GMAW	ER80S-D2	.045”	DCEP	250-325	29-31	12-15 IPM	WFS 400-450

QW-482 SUGGESTED FORMAT FOR WELDING PROCEDURE SPECIFICATIONS (WPS)
(See QW-200.1, Section IX, ASME Boiler and Pressure Vessel Code)

Company Name: Edison Welding Institute   By: David Link

Welding Procedure Specification No.: 51108-WPS2   Date: 06/15/2009   Supporting PQR No.(s): N/A

Revision No.: 0   Date: 06/15/2009

Welding Process(es): Gas Metal Arc Welding (GMAW)   Type(s): Semi-automatic
(Automatic, Manual, Machine, or Semi-Auto)

Joints (QW-402)   Details

Joint Design: Fillet, Partial Penetration

Backing (Yes) ______   (No) X

Backing Material (Type) ______
(Refer to both backing and retainers)

- ☐ Metal   ☐ Nonfusing Metal
- ☐ Nonmetallic   ☐ Other

*BASE METALS (QW-403)

P-No. 1   Group No. ______   to P-No. 3   Group No. ______

OR

Specification Type and Grade ______

to Specification Type and Grade ______

OR

Chem. Analysis and Mech. Prop. ______

to Chem. Analysis and Mech. Prop. ______

Thickness Range:

Base Metal: Groove ______   Fillet 1.000”

Other ______

*FILLER METALS (QW-404)			
Spec. No. (SFA)	ER80S-D2		
AWS No. (Class)	A 5.28		
F-No.	6		
A-No.	11		
Size of Filler Metals	.045”		
Weld Metal Thickness Range:			
Groove	N/A		
Fillet	1.000”		
Electrode-Flux (Class)	N/A		
Flux Trade Name	N/A		
Consumable Insert	N/A		
Other	N/A		

*Each base metal-filler metal combination should be recorded individually.

QW-482 (Back)

WPS No. 51108-WPS2 Rev. 0

POSITIONS (QW-405)
Position(s) of Groove 2F
Welding Progression: Up N/A Down N/A
Position(s) of Fillet Horizontal

POSTWELD HEAT TREATMENT (QW-407)
Temperature Range N/A
Time Range N/A

PREHEAT (QW-406)
Preheat Temp. Min. 400 F
Interpass Temp. Max. 500 F
Preheat Maintenance N/A
(Continuous or special heating where applicable should be recorded)

GAS (QW-408)

	Gases	Percent Composition (Mixture)	Flow Rate
Shielding	Ar/Co2	90%/10%	30-40 CFH
Trailing	N/A		
Backing	N/A		

ELECTRICAL CHARACTERISTICS (QW-409)
Current AC or DC DC Polarity EP
Amps (Range) 250-325 Volts (Range) 29-31
(Amps and volts range should be recorded for each electrode size, position, and thickness, etc. This information may be listed in a tabular form similar to that shown below.)

Tungsten Electrode Size and Type N/A
(Pure tungsten, 2% thoriated, etc.)
Mode of Metal Transfer for GMAW Spray
(Spray arc, short circuiting arc, etc.)
Electrode Wire Feed Speed Range 400-450

TECHNIQUE (QW-410)
Sting or Weave Bead Stringer
Orifice or Gas Cup Size .750"
Initial and Interpass Cleaning (brushing, grinding, etc.) SS wire brush and acetone
Method of Back Gouging N/A
Oscillation N/A
Contact Tube to Work Distance .500" - .750"
Multiple or Single Pass (per side) Multiple
Multiple or Single Electrodes Single
Travel Speed (range) 12 - 15 IPM
Peening N/A
Other Part Rotated under fixed torch

Weld Layer(s)	Process	Filler Metal		Current		Volt Range	Travel Speed Range	Other (e.g., Remarks, Comments, Hot Wire Addition, Technique, Torch Angle, etc.)
		Class	Dia.	Type Polar.	Amp Range			
All	GMAW	ER80S-D2	.045"	DCEP	250-325	29-31	12-15 IPM	WFS 400-450

QW-482 SUGGESTED FORMAT FOR WELDING PROCEDURE SPECIFICATIONS (WPS)
(See QW-200.1, Section IX, ASME Boiler and Pressure Vessel Code)

Company Name: Edison Welding Institute By: Steve Manring

Welding Procedure Specification No.: 51108-WPS-3 Date: 6-15-2009 Supporting PQR No.(s): N/A

Revision No.: 0 Date: 6-15-2009

Welding Process(es): Gas Metal Arc Welding (GMAW) Type(s): Semi-automatic
(Automatic, Manual, Machine, or Semi-Auto)

Joints (QW-402) Details

Joint Design: Vee Groove Partial Penetration

Backing (Yes) ____ (No) X

Backing Material (Type) ____________
(Refer to both backing and retainers)

☐ Metal ☐ Nonfusing Metal
☐ Nonmetallic ☐ Other

*BASE METALS (QW-403)

P-No. 1 Group No. ____ to P-No. 1 Group No. ____

OR

Specification Type and Grade: A-36

to Specification Type and Grade: A105

OR

Chem. Analysis and Mech. Prop. ____________

to Chem. Analysis and Mech. Prop. ____________

Thickness Range:

Base Metal: Groove .500” nominal Fillet N/A

Other ____________

*FILLER METALS (QW-404)			
Spec. No. (SFA)	ER70S-6		
AWS No. (Class)	A 5.18		
F-No.	6		
A-No.	1		
Size of Filler Metals	0.045”		
Weld Metal Thickness Range:			
Groove	0.500” nominal		
Fillet	N/A		
Electrode-Flux (Class)	N/A		
Flux Trade Name	N/A		
Consumable Insert	N/A		
Other	N/A		

*Each base metal-filler metal combination should be recorded individually.

This form (E00006) may be obtained from the Order Dept., ASME, 22 Law Drive, Box 2300, Fairfield, NJ 07007-2300

QW-482 (Back)

WPS No. 51108-WPS-3 Rev. 0

POSITIONS (QW-405)
Position(s) of Groove 1G
Welding Progression: Up N/A Down N/A
Position(s) of Fillet N/A

POSTWELD HEAT TREATMENT (QW-407)
Temperature Range N/A
Time Range N/A

PREHEAT (QW-406)
Preheat Temp. Min. 225 F for Pass 1, 200 F for Pass 2 & 3, RT remainder
Interpass Temp. Max. 500F
Preheat Maintenance N/A
(Continuous or special heating where applicable should be recorded)

GAS (QW-408)

	Gases	Percent Composition (Mixture)	Flow Rate
Shielding	Ar/CO2	90/10	30-40 CFH
Trailing	N/A		
Backing	N/A		

ELECTRICAL CHARACTERISTICS (QW-409)
Current AC or DC DC Polarity EP
Amps (Range) 250 - 325 Volts (Range) 29 - 31
(Amps and volts range should be recorded for each electrode size, position, and thickness, etc. This information may be listed in a tabular form similar to that shown below.)

Tungsten Electrode Size and Type N/A
(Pure tungsten, 2% thoriated, etc.)

Mode of Metal Transfer for GMAW Spray
(Spray arc, short circuiting arc, etc.)

Electrode Wire Feed Speed Range 400 – 500 ipm

TECHNIQUE (QW-410)
Sting or Weave Bead Stringer
Orifice or Gas Cup Size 0.750”
Initial and Interpass Cleaning (brushing, grinding, etc.) SS wire Brush
Method of Back Gouging N/A
Oscillation N/A
Contact Tube to Work Distance 0.500 – 0.750 inches
Multiple or Single Pass (per side) Multiple
Multiple or Single Electrodes Single
Travel Speed (range) 12 – 15 ipm
Peening N/A
Other Part rotated under fixed torch

Weld Layer(s)	Process	Filler Metal Class	Filler Metal Dia.	Current Type Polar.	Current Amp Range	Volt Range	Travel Speed Range	Other (e.g., Remarks, Comments, Hot Wire Addition, Technique, Torch Angle, etc.)
All	GMAW	ER70S-6	0.045”	DCEP	250 – 325	29 - 31	12 – 15 IPM	WFS 400 - 450

QW-482 SUGGESTED FORMAT FOR WELDING PROCEDURE SPECIFICATIONS (WPS)
(See QW-200.1, Section IX, ASME Boiler and Pressure Vessel Code)

Company Name: Edison Welding Institute By: Steve Manring

Welding Procedure Specification No.: 51108-WPS-4 Date: 6-15-2009 Supporting PQR No.(s): N/A

Revision No.: 0 Date: 6-15-2009

Welding Process(es): Gas Metal Arc Welding (GMAW) Type(s): Semi-automatic
(Automatic, Manual, Machine, or Semi-Auto)

Joints (QW-402) Details

Joint Design: Fillet

Backing (Yes) ____ (No) X

Backing Material (Type): N/A
(Refer to both backing and retainers)

☐ Metal ☐ Nonfusing Metal
☐ Nonmetallic ☐ Other

*BASE METALS (QW-403)

P-No. 1 Group No. ____ to P-No. 1 Group No. ____

OR

Specification Type and Grade ____

to Specification Type and Grade ____

OR

Chem. Analysis and Mech. Prop. ____

to Chem. Analysis and Mech. Prop. ____

Thickness Range:

Base Metal: Groove N/A Fillet 1.000”

Other ____

*FILLER METALS (QW-404)			
Spec. No. (SFA)	ER70S-6		
AWS No. (Class)	A 5.18		
F-No.	6		
A-No.	1		
Size of Filler Metals	0.045”		
Weld Metal Thickness Range:			
Groove	N/A		
Fillet	1.000”		
Electrode-Flux (Class)	N/A		
Flux Trade Name	N/A		
Consumable Insert	N/A		
Other	N/A		

*Each base metal-filler metal combination should be recorded individually.

This form (E00006) may be obtained from the Order Dept., ASME, 22 Law Drive, Box 2300, Fairfield, NJ 07007-2300

QW-482 (Back)

WPS No. 51108-WPS-4 Rev. 0

POSITIONS (QW-405)

Position(s) of Groove: 2F

Welding Progression: Up N/A Down N/A

Position(s) of Fillet: Horizontal

POSTWELD HEAT TREATMENT (QW-407)

Temperature Range: N/A

Time Range: N/A

PREHEAT (QW-406)

Preheat Temp. Min.: 225 F for Pass 1, 200 F for Pass 2 & 3, RT remainder

Interpass Temp Max.: 500F

Preheat Maintenance: N/A

(Continuous or special heating where applicable should be recorded)

GAS (QW-408)

	Gases	Percent Composition (Mixture)	Flow Rate
Shielding	Ar/CO2	90/10	30-40 CFH
Trailing	N/A		
Backing	N/A		

ELECTRICAL CHARACTERISTICS (QW-409)

Current AC or DC: DC Polarity: EP

Amps (Range): 250 - 325 Volts (Range): 29 - 31

(Amps and volts range should be recorded for each electrode size, position, and thickness, etc. This information may be listed in a tabular form similar to that shown below.)

Tungsten Electrode Size and Type: N/A
(Pure tungsten, 2% thoriated, etc.)

Mode of Metal Transfer for GMAW: Spray
(Spray arc, short circuiting arc, etc.)

Electrode Wire Feed Speed Range: 400 – 500 ipm

TECHNIQUE (QW-410)

Sting or Weave Bead: Stringer

Orifice or Gas Cup Size: 0.750"

Initial and Interpass Cleaning (brushing, grinding, etc.): SS wire Brush

Method of Back Gouging: N/A

Oscillation: N/A

Contact Tube to Work Distance: 0.500 – 0.750 inch

Multiple or Single Pass (per side): Multiple

Multiple or Single Electrodes: Single

Travel Speed (range): 12 – 15 ipm

Peening: N/A

Other: Part Rotated under fixed torch

Weld Layer(s)	Process	Filler Metal Class	Filler Metal Dia.	Current Type Polar.	Current Amp Range	Volt Range	Travel Speed Range	Other (e.g., Remarks, Comments, Hot Wire Addition, Technique, Torch Angle, etc.)
All	GMAW	ER70S-6	0.045"	DCEP	250 – 325	29 - 31	12 – 15 IPM	WFS 400 - 450

QW-482 SUGGESTED FORMAT FOR WELDING PROCEDURE SPECIFICATIONS (WPS)
(See QW-200.1, Section IX, ASME Boiler and Pressure Vessel Code)

Company Name: Edison Welding Institute   By: Steve Manring

Welding Procedure Specification No.: 51108-WPS-5   Date: 6-15-2009   Supporting PQR No.(s): N/A

Revision No.: 0   Date: 6-15-2009

Welding Process(es): Gas Metal Arc Welding (GMAW)   Type(s): Semi-Automatic
(Automatic, Manual, Machine, or Semi-Auto)

Joints (QW-402)   Details

Joint Design: Vee Groove

Backing (Yes) ______ (No) X

Backing Material (Type) ______
(Refer to both backing and retainers)

☐ Metal ☐ Nonfusing Metal
☐ Nonmetallic ☐ Other

*BASE METALS (QW-403)

P-No. 1   Group No. ______   to P-No. 8   Group No. ______

OR

Specification Type and Grade ______

to Specification Type and Grade ______

OR

Chem. Analysis and Mech. Prop. ______

to Chem. Analysis and Mech. Prop. ______

Thickness Range:

Base Metal: Groove 0.250”   Fillet N/A

Other: Welded 1 entire layer in groove of 309L to completely cover the Carbon Steel base metals. Balance will use ER308L

*FILLER METALS (QW-404)			
Spec. No. (SFA)	ER309L		
AWS No. (Class)	A 5.9		
F-No.	6		
A-No.			
Size of Filler Metals	0.045”		
Weld Metal Thickness Range:			
Groove	0.250”		
Fillet	N/A		
Electrode-Flux (Class)	N/A		
Flux Trade Name	N/A		
Consumable Insert	N/A		
Other	N/A		

*Each base metal-filler metal combination should be recorded individually.

This form (E00006) may be obtained from the Order Dept., ASME, 22 Law Drive, Box 2300, Fairfield, NJ 07007-2300

QW-482 (Back)

WPS No. 51108-WPS-5 Rev. 0

POSITIONS (QW-405)

Position(s) of Groove: 1G

Welding Progression: Up: N/A Down: N/A

Position(s) of Fillet: N/A

POSTWELD HEAT TREATMENT (QW-407)

Temperature Range: N/A

Time Range: N/A

PREHEAT (QW-406)

Preheat Temp. Min.: 225 F

Interpass Temp. Max.: 500F

Preheat Maintenance: N/A

(Continuous or special heating where applicable should be recorded)

GAS (QW-408)

	Gases	Percent Composition (Mixture)	Flow Rate
Shielding	Ar	100	30-40 CFH
Trailing	N/A		
Backing	N/A		

ELECTRICAL CHARACTERISTICS (QW-409)

Current AC or DC: DC Polarity: EP

Amps (Range): 250 - 325 Volts (Range): 29 - 31

(Amps and volts range should be recorded for each electrode size, position, and thickness, etc. This information may be listed in a tabular form similar to that shown below.)

Tungsten Electrode Size and Type: N/A
(Pure tungsten, 2% thoriated, etc.)

Mode of Metal Transfer for GMAW: Spray
(Spray arc, short circuiting arc, etc.)

Electrode Wire Feed Speed Range: 400 – 500 ipm

TECHNIQUE (QW-410)

Sting or Weave Bead: Stringer

Orifice or Gas Cup Size: 0.750”

Initial and Interpass Cleaning (brushing, grinding, etc.): SS wire Brush

Method of Back Gouging: N/A

Oscillation: N/A

Contact Tube to Work Distance: 0.500 – 0.750 inch

Multiple or Single Pass (per side): Multiple

Multiple or Single Electrodes: Single

Travel Speed (range): 12 – 15 ipm

Peening: N/A

Other: Part Rotated under fixed torch

Weld Layer(s)	Process	Filler Metal		Current		Volt Range	Travel Speed Range	Other (e.g., Remarks, Comments, Hot Wire Addition, Technique, Torch Angle, etc.)
		Class	Dia.	Type Polar.	Amp Range			
All	GMAW	ER309L	0.045”	DCEP	250 – 325	29 - 31	12 – 15 IPM	WFS 400 - 450

QW-482 SUGGESTED FORMAT FOR WELDING PROCEDURE SPECIFICATIONS (WPS)
(See QW-200.1, Section IX, ASME Boiler and Pressure Vessel Code)

Company Name: Edison Welding Institute   By: Steve Manring

Welding Procedure Specification No.: 51108-WPS-6   Date: 6-15-2009   Supporting PQR No.(s): N/A

Revision No.: 0   Date: 6-15-2009

Welding Process(es): Gas Metal Arc Welding (GMAW)   Type(s): Semi-Automatic
(Automatic, Manual, Machine, or Semi-Auto)

Joints (QW-402)   Details

Joint Design: Vee Groove

Backing (Yes) ______ (No) X

Backing Material (Type) ______
(Refer to both backing and retainers)

☐ Metal   ☐ Nonfusing Metal
☐ Nonmetallic   ☐ Other

*BASE METALS (QW-403)

P-No. 3   Group No. ______   to P-No. 8   Group No. ______

OR

Specification Type and Grade ______

to Specification Type and Grade ______

OR

Chem. Analysis and Mech. Prop. ______

to Chem. Analysis and Mech. Prop. ______

Thickness Range:

Base Metal: Groove 0.250”   Fillet N/A

Other: Welded 1 entire layer in groove of 309L to completely cover the Carbon Steel base metals (WPS-5). Balance will use ER308L (WPS-6)

*FILLER METALS (QW-404)			
Spec. No. (SFA)	ER309L		
AWS No. (Class)	A 5.9		
F-No.	6		
A-No.			
Size of Filler Metals	0.045”		
Weld Metal Thickness Range:			
Groove	0.250”		
Fillet	N/A		
Electrode-Flux (Class)	N/A		
Flux Trade Name	N/A		
Consumable Insert	N/A		
Other	N/A		

*Each base metal-filler metal combination should be recorded individually.

This form (E00006) may be obtained from the Order Dept., ASME, 22 Law Drive, Box 2300, Fairfield, NJ 07007-2300

QW-482 (Back)

WPS No. 51108-WPS-6 Rev. 0

POSITIONS (QW-405)	POSTWELD HEAT TREATMENT (QW-407)
Position(s) of Groove 1G	Temperature Range N/A
Welding Progression: Up N/A Down N/A	Time Range N/A
Position(s) of Fillet N/A	

PREHEAT (QW-406)

Preheat Temp. Min. 400 F

Interpass Temp. Max. 500F

Preheat Maintenance N/A

(Continuous or special heating where applicable should be recorded)

GAS (QW-408)

	Gases	Percent Composition (Mixture)	Flow Rate
Shielding	Ar	100	30-40 CFH
Trailing	N/A		
Backing	N/A		

ELECTRICAL CHARACTERISTICS (QW-409)

Current AC or DC DC Polarity EP

Amps (Range) 250 - 325 Volts (Range) 29 - 31

(Amps and volts range should be recorded for each electrode size, position, and thickness, etc. This information may be listed in a tabular form similar to that shown below.)

Tungsten Electrode Size and Type N/A

(Pure tungsten, 2% thoriated, etc.)

Mode of Metal Transfer for GMAW Spray

(Spray arc, short circuiting arc, etc.)

Electrode Wire Feed Speed Range 400 – 500 ipm

TECHNIQUE (QW-410)

Sting or Weave Bead Stringer

Orifice or Gas Cup Size 0.750”

Initial and Interpass Cleaning (brushing, grinding, etc.) SS wire Brush

Method of Back Gouging N/A

Oscillation N/A

Contact Tube to Work Distance 0.500 – 0.750 inch

Multiple or Single Pass (per side) Multiple

Multiple or Single Electrodes Single

Travel Speed (range) 12 – 15 ipm

Peening N/A

Other Part Rotated under fixed torch

Weld Layer(s)	Process	Filler Metal Class	Filler Metal Dia.	Current Type Polar.	Current Amp Range	Volt Range	Travel Speed Range	Other (e.g., Remarks, Comments, Hot Wire Addition, Technique, Torch Angle, etc.)
All	GMAW	ER309L	0.045”	DCEP	250 – 325	29 – 31	12 – 15 IPM	WFS 400 - 450

QW-482 SUGGESTED FORMAT FOR WELDING PROCEDURE SPECIFICATIONS (WPS)
(See QW-200.1, Section IX, ASME Boiler and Pressure Vessel Code)

Company Name: Edison Welding Institute   By: Steve Manring

Welding Procedure Specification No.: 51108-WPS-7   Date: 6-15-2009   Supporting PQR No.(s): N/A

Revision No.: 0   Date: 6-15-2009

Welding Process(es): Gas Metal Arc Welding (GMAW)   Type(s): Semi-Automatic
(Automatic, Manual, Machine, or Semi-Auto)

Joints (QW-402)   Details

Joint Design: Vee Groove, Partial Penetration

Backing Yes) ________ (No) No

Backing Material (Type) ________
(Refer to both backing and retainers)

☐ Metal   ☐ Nonfusing Metal
☐ Nonmetallic   ☐ Other

*BASE METALS (QW-403)

P-No. 8   Group No. ________   to P-No. 8   Group No. ________

OR

Specification Type and Grade ________

to Specification Type and Grade ________

OR

Chem. Analysis and Mech. Prop. ________

to Chem. Analysis and Mech. Prop. ________

Thickness Range:

Base Metal: Groove 0.250”   Fillet N/A

Other: Welded balance with ER308L

*FILLER METALS (QW-404)			
Spec. No. (SFA)	ER308L		
AWS No. (Class)	A 5.9		
F-No.	6		
A-No.			
Size of Filler Metals	0.045”		
Weld Metal Thickness Range:			
Groove	0.250”		
Fillet	N/A		
Electrode-Flux (Class)	N/A		
Flux Trade Name	N/A		
Consumable Insert	N/A		
Other	N/A		

*Each base metal-filler metal combination should be recorded individually.

This form (E00006) may be obtained from the Order Dept., ASME, 22 Law Drive, Box 2300, Fairfield, NJ 07007-2300

QW-482 (Back)

WPS No. 51108-WPS-7 Rev. 0

POSITIONS (QW-405)
Position(s) of Groove 1G
Welding Progression: Up N/A Down N/A
Position(s) of Fillet N/A

POSTWELD HEAT TREATMENT (QW-407)
Temperature Range N/A
Time Range N/A

PREHEAT (QW-406)
Preheat Temp. Min. RT
Interpass Temp. Max. 500F
Preheat Maintenance N/A
(Continuous or special heating where applicable should be recorded)

GAS (QW-408)

	Gases	Percent Composition (Mixture)	Flow Rate
Shielding	Ar	100	30-40 CFH
Trailing	N/A		
Backing	N/A		

ELECTRICAL CHARACTERISTICS (QW-409)
Current AC or DC DC Polarity EP
Amps (Range) 250 - 325 Volts (Range) 29 - 31
(Amps and volts range should be recorded for each electrode size, position, and thickness, etc. This information may be listed in a tabular form similar to that shown below.)

Tungsten Electrode Size and Type N/A
(Pure tungsten, 2% thoriated, etc.)
Mode of Metal Transfer for GMAW Spray
(Spray arc, short circuiting arc, etc.)
Electrode Wire Feed Speed Range 400 – 500 ipm

TECHNIQUE (QW-410)
Sting or Weave Bead Stringer
Orifice or Gas Cup Size 0.750”
Initial and Interpass Cleaning (brushing, grinding, etc.) SS wire Brush
Method of Back Gouging N/A
Oscillation N/A
Contact Tube to Work Distance 0.500 – 0.750 inch
Multiple or Single Pass (per side) Multiple
Multiple or Single Electrodes Single
Travel Speed (range) 12 – 15 ipm
Peening N/A
Other Part Rotated under fixed torch

Weld Layer(s)	Process	Filler Metal Class	Filler Metal Dia.	Current Type Polar.	Current Amp Range	Volt Range	Travel Speed Range	Other (e.g., Remarks, Comments, Hot Wire Addition, Technique, Torch Angle, etc.)
All	GMAW	ER308L	0.045”	DCEP	250 – 325	29 - 31	12 – 15 IPM	WFS 400 - 450

Appendix D

Nozzle Buttering Welding Procedure

QW-482 SUGGESTED FORMAT FOR WELDING PROCEDURE SPECIFICATIONS (WPS)
(See QW-200.1, Section IX, ASME Boiler and Pressure Vessel Code)

Company Name Edison Welding Institute By Steve Manring

Welding Procedure Specification No. 51108-WPS-8 Date 6-15-2009 Supporting PQR No.(s) N/A

Revision No. 0 Date 6-15-2009

Welding Process(es) Gas Tungsten Arc Welding (GTAW) Type(s) Machine
(Automatic, Manual, Machine, or Semi-Auto)

Joints (QW-402) Details

Joint Design Bead on Pipe

Backing (Yes) Yes (No) No

Backing Material (Type) SA105
(Refer to both backing and retainers)

☐ Metal ☐ Nonfusing Metal
☐ Nonmetallic ☐ Other

*BASE METALS (QW-403)

P-No. 1 Group No. ______ to P-No. N/A Group No. ______

OR

Specification Type and Grade ______

to Specification Type and Grade ______

OR

Chem. Analysis and Mech. Prop. ______

to Chem. Analysis and Mech. Prop. ______

Thickness Range:

Base Metal: Groove N/A Fillet N/A

Other Butter Thickness 1 ¼ " minimum

*FILLER METALS (QW-404)			
Spec. No. (SFA)	ERNiCr-3		
AWS No. (Class)	A 5.9		
F-No.	43		
A-No.			
Size of Filler Metals	0.045"		
Weld Metal Thickness Range:			
	1 ¼" minimum Butter layer		
Groove	N/A		
Fillet	N/A		
Electrode-Flux (Class)	N/A		
Flux Trade Name	N/A		
Consumable Insert	N/A		
Other	N/A		

*Each base metal-filler metal combination should be recorded individually.

QW-482 (Back)

WPS No. 51108-WPS-8 Rev. 0

POSITIONS (QW-405)
Position(s) of Groove N/A, Flat
Welding Progression: Up N/A Down N/A
Position(s) of Fillet

POSTWELD HEAT TREATMENT (QW-407)
Temperature Range N/A
Time Range N/A

PREHEAT (QW-406)
Preheat Temp. Min. 225 F for Pass 1, 200F for Pass 2 & 3, RT remainder
Interpass Temp. Max. 500F
Preheat Maintenance N/A
(Continuous or special heating where applicable should be recorded)

GAS (QW-408)

	Gases	Percent Composition (Mixture)	Flow Rate
Shielding	Argon	100%	30-40 CFH
Trailing	N/A		
Backing	N/A		

ELECTRICAL CHARACTERISTICS (QW-409)
Current AC or DC DC Polarity En
Amps (Range) 175 - 225 Volts (Range) 9.2 – 11.2
(Amps and volts range should be recorded for each electrode size, position, and thickness, etc. This information may be listed in a tabular form similar to that shown below.)

Tungsten Electrode Size and Type 1/8” dia 2% Ce with a 22 deg included angle and a .02 - .03” flat
(Pure tungsten, 2% thoriated, etc.)
Mode of Metal Transfer for GMAW N/A
(Spray arc, short circuiting arc, etc.)
Electrode Wire Feed Speed Range 70 - 90 ipm

TECHNIQUE (QW-410)
Sting or Weave Bead Stringer
Orifice or Gas Cup Size #12 (0.750”)
Initial and Interpass Cleaning (brushing, grinding, etc.) SS wire Brush
Method of Back Gouging N/A
Oscillation N/A
Contact Tube to Work Distance N/A
Multiple or Single Pass (per side) Multiple
Multiple or Single Electrodes Single
Travel Speed (range) 5.8 – 6.8 ipm
Peening N/A
Other Part Rotated under fixed torch

Weld Layer(s)	Process	Filler Metal Class	Filler Metal Dia.	Current Type Polar.	Current Amp Range	Volt Range	Travel Speed Range	Other (e.g., Remarks, Comments, Hot Wire Addition, Technique, Torch Angle, etc.)
All	GTAW	ERNiCr-3	0.045”	DCEN	175 - 225	9.2 – 11.2	5.8 – 6.8 IPM	WFS 70 – 90 ipm

QW-482 SUGGESTED FORMAT FOR WELDING PROCEDURE SPECIFICATIONS (WPS)
(See QW-200.1, Section IX, ASME Boiler and Pressure Vessel Code)

Company Name Edison Welding Institute By Steve Manring

Welding Procedure Specification No. 51108-WPS-9 Date 6-15-2009 Supporting PQR No.(s) N/A

Revision No. 0 Date 6-15-2009

Welding Process(es) Gas Tungsten Arc Welding (GTAW) Type(s) Machine
(Automatic, Manual, Machine, or Semi-Auto)

Joints (QW-402) Details

Joint Design Bead on Pipe

Backing (Yes) ______ (No) No

Backing Material (Type) ______
(Refer to both backing and retainers)

☐ Metal ☐ Nonfusing Metal
☐ Nonmetallic ☐ Other

*BASE METALS (QW-403)

P-No. 3 Group No. ______ to P-No. N/A Group No. ______

OR

Specification Type and Grade ______

to Specification Type and Grade ______

OR

Chem. Analysis and Mech. Prop. ______

to Chem. Analysis and Mech. Prop. ______

Thickness Range:

Base Metal: Groove N/A Fillet N/A

Other Butter Thickness 1 ¼ " minimum

*FILLER METALS (QW-404)			
Spec. No. (SFA)	ERNiCr-3		
AWS No. (Class)	A 5.14		
F-No.	43		
A-No.			
Size of Filler Metals	0.045"		
Weld Metal Thickness Range:	1 ¼" minimum Butter layer		
Groove	N/A		
Fillet	N/A		
Electrode-Flux (Class)	N/A		
Flux Trade Name	N/A		
Consumable Insert	N/A		
Other	N/A		

*Each base metal-filler metal combination should be recorded individually.

This form (E00006) may be obtained from the Order Dept., ASME, 22 Law Drive, Box 2300, Fairfield, NJ 07007-2300

QW-482 (Back)

WPS No. 51108-WPS-9 Rev. 0

POSITIONS (QW-405)

Position(s) of Groove: N/A, Flat

Welding Progression: Up N/A Down N/A

Position(s) of Fillet:

POSTWELD HEAT TREATMENT (QW-407)

Temperature Range: N/A

Time Range: N/A

PREHEAT (QW-406)

Preheat Temp. Min.: 400 F Pass 1, 400F Pass 2 & 3, RT Balance

Interpass Temp. Max.: 500F

Preheat Maintenance: N/A

(Continuous or special heating where applicable should be recorded)

GAS (QW-408)

	Gases	Percent Composition (Mixture)	Flow Rate
Shielding	Argon	100%	3o-40 CFH
Trailing	N/A		
Backing	N/A		

ELECTRICAL CHARACTERISTICS (QW-409)

Current AC or DC: DC Polarity: En

Amps (Range): 175 - 225 Volts (Range): 9.2 – 11.2

(Amps and volts range should be recorded for each electrode size, position, and thickness, etc. This information may be listed in a tabular form similar to that shown below.)

Tungsten Electrode Size and Type: 1/8" dia 2% Ce with a 22 deg included angle and a .02 - .03" flat
(Pure tungsten, 2% thoriated, etc.)

Mode of Metal Transfer for GMAW: N/A
(Spray arc, short circuiting arc, etc.)

Electrode Wire Feed Speed Range: 70 - 90 ipm

TECHNIQUE (QW-410)

Sting or Weave Bead: Stringer

Orifice or Gas Cup Size: #12 (0.750")

Initial and Interpass Cleaning (brushing, grinding, etc.): SS wire Brush

Method of Back Gouging: N/A

Oscillation: N/A

Contact Tube to Work Distance: N/A

Multiple or Single Pass (per side): Multiple

Multiple or Single Electrodes: Single

Travel Speed (range): 5.8 – 6.8 ipm

Peening: N/A

Other: Part Rotated under fixed torch

Weld Layer(s)	Process	Filler Metal		Current		Volt Range	Travel Speed Range	Other (e.g., Remarks, Comments, Hot Wire Addition, Technique, Torch Angle, etc.)
		Class	Dia.	Type Polar.	Amp Range			
All	GTAW	ERNiCr-3	0.045"	DCEN	175 - 225	9.2 – 11.2	5.8 – 6.8 IPM	WFS 70 – 90 IPM

Appendix E

Butter Weld Penetrant Inspection Report

LIQUID PENETRANT EXAMINATION REPORT

ENGINEER			JOB NUMBER		DATE	
Matt Boring			51108GTH		June 24, 2009	
ITEM DESCRIPTION / DRAWING NO.			PROCEDURE NO.		REPORT NO.	
Weld Neck Flange (Weld Build Up)			REF: ASTM E 1417-05		51108GTH / LPT-1	
PEN TYPE SKL-SP1	BATCH NO. 04G019	DEV. TYPE SKD-S2	BATCH NO. 05J06K 05708	CLEAN TYPE SKC-S	BATCH NO. 05H06K 035199	ACCEPTANCE CRITERIA REF: ASTM E 1417-05 Paragraph 7.6.2
DWELL TIME 20 MINUTES		DEVELOPING TIME 10 MINUTES		DRYING TIME 5 MINUTES		POST CLEANING Yes

IDENTIFICATION/ LOCATION	ACCEPT	REJECT	DEFECT	REMARKS
Weld build up on Weld Neck Flange	Accept			OD area between section P & M had rounded indications that were determined to be non relevant. This was due to surface irregularities preventing proper removal of excess penetrant at the toe of a weld pass.

SKETCH - SHOW LOCATION (USE ADDITIONAL SHEETS AS REQUIRED)

No accept / reject criteria was provided so evaluation was done

per ASTM Standard Practice E 1417-05, Paragraph 7.6.2.

LIQUID PENETRANT EXAMINATION REPORT

LIQUID PENETRANT EXAMINATION REPORT

☐ SEE ADDITIONAL SHEETS

DEFECT CODE			
LA = LAMINATION	IF = INCOMPLETE FUSION	S = SLAG	P = POROSITY
RI = ROUNDED INDICATION	LI = LINEAR INDICATION	C = CRACKS	OTHER = SPECIFY

EXAMINATION PERFORMED BY:	EVALUATOR:	
PERRY WHITE	PERRY WHITE (ASNT NDT LEVEL III CERT. # 139980)	Perry White 6/24/09

Appendix F

Safe End and Back Weld Welding Procedure

QW-482 SUGGESTED FORMAT FOR WELDING PROCEDURE SPECIFICATIONS (WPS)
(See QW-200.1, Section IX, ASME Boiler and Pressure Vessel Code)

Company Name: Edison Welding Institute — By: Steve Manring

Welding Procedure Specification No.: 51108-WPS-10 — Date: 6-15-2009 — Supporting PQR No.(s): N/A

Revision No.: 0 — Date: 6-15-2009

Welding Process(es): Gas Tungsten Arc Welding (GTAW) — Type(s): Machine
(Automatic, Manual, Machine, or Semi-Auto)

Joints (QW-402) — Details

Joint Design: Double Sided Groove Weld

Backing (Yes): x — (No):

Backing Material (Type): P8 and P43
(Refer to both backing and retainers)

☐ Metal ☐ Nonfusing Metal
☐ Nonmetallic ☐ Other

*BASE METALS (QW-403)

P-No.: 8 — Group No.: — to P-No.: 43 — Group No.:

OR

Specification Type and Grade:

to Specification Type and Grade:

OR

Chem. Analysis and Mech. Prop.:

to Chem. Analysis and Mech. Prop.:

Thickness Range:

Base Metal: Groove: 1” — Fillet: N/A

Other:

*FILLER METALS (QW-404)			
Spec. No. (SFA)	ERNiCr-3		
AWS No. (Class)	A 5.14		
F-No.	43		
A-No.			
Size of Filler Metals	0.045”		
Weld Metal Thickness Range:			
Groove	1”		
Fillet	N/A		
Electrode-Flux (Class)	N/A		
Flux Trade Name	N/A		
Consumable Insert	N/A		
Other	N/A		

*Each base metal-filler metal combination should be recorded individually.

QW-482 (Back)

WPS No. 51108-WPS-10 Rev. 0

POSITIONS (QW-405)	POSTWELD HEAT TREATMENT (QW-407)
Position(s) of Groove 1G	Temperature Range
Welding Progression: Up N/A Down N/A	Time Range
Position(s) of Fillet N/A	

PREHEAT (QW-406)

Preheat Temp. Min. RT

Interpass Temp. Max. 500F

Preheat Maintenance N/A

(Continuous or special heating where applicable should be recorded)

GAS (QW-408)

	Gases	Percent Composition (Mixture)	Flow Rate
Shielding	Ar/He	75/25	30-40 CFH
Trailing	N/A		
Backing	Ar	100	10-30 CFH

ELECTRICAL CHARACTERISTICS (QW-409)

Current AC or DC DC Polarity En

Amps (Range) 75 – 260 * Volts (Range) 9.5 – 10.3

(Amps and volts range should be recorded for each electrode size, position, and thickness, etc. This information may be listed in a tabular form similar to that shown below.)

Tungsten Electrode Size and Type 1/8" dia 2% Ce with a 22 deg included angle and a .02 - .03" flat
(Pure tungsten, 2% thoriated, etc.)

Mode of Metal Transfer for GMAW N/A
(Spray arc, short circuiting arc, etc.)

Electrode Wire Feed Speed Range 20 - 90 ipm

TECHNIQUE (QW-410)

Sting or Weave Bead Stringer

Orifice or Gas Cup Size #12 (0.750")

Initial and Interpass Cleaning (brushing, grinding, etc.) SS wire Brush

Method of Back Gouging Machined back side groove

Oscillation N/A

Contact Tube to Work Distance N/A

Multiple or Single Pass (per side) Multiple

Multiple or Single Electrodes Single

Travel Speed (range) 5.8 – 6.8 ipm

Peening N/A

Other Part Rotated under fixed torch

Weld Layer(s)	Process	Filler Metal Class	Filler Metal Dia.	Current Type Polar.	Current Amp Range	Volt Range	Travel Speed Range	Other (e.g., Remarks, Comments, Hot Wire Addition, Technique, Torch Angle, etc.)
1	GTAW	ERNiCr-3	0.045"	DCEN	125 – 175	9.5 – 10	5 – 7 IPM	WFS 15 – 25 IPM
2	GTAW	ERNiCr-3	0.045"	DCEN	150 – 100	9.5 – 10	5 – 7 IPM	WFS 25 – 35 IPM
3-4	GTAW	ERNiCr-3	0.045"	DCEN	210 – 230	9.5 – 11	5 – 7 IPM	WFS 60 – 85 IPM
Balance	GTAW	ERNiCr-3	0.045"	DCEN	160 – 220	9.5 – 10.5	5.5 – 6.5 IPM	WFS 85 – 95 IPM
Cap	GTAW	ERNiCr-3	0.045"	DCEN	210 – 230	9.5 – 10	6 – 6.5 IPM	WFS 80 – 90 IPM

Appendix G

Safe End to Stainless Steel Pipe Weld Procedure

QW-482 SUGGESTED FORMAT FOR WELDING PROCEDURE SPECIFICATIONS (WPS)
(See QW-200.1, Section IX, ASME Boiler and Pressure Vessel Code)

Company Name Edison Welding Institute By Steve Manring

Welding Procedure Specification No. 51108-WPS-12 Date 6-15-2009 Supporting PQR No.(s) N/A

Revision No. 0 Date 6-15-2009

Welding Process(es) Shielded Metal Arc Welding (SMAW) Type(s) Manual
(Automatic, Manual, Machine, or Semi-Auto)

Joints (QW-402) Details

Joint Design Vee Groove, 15 degree extended land

Backing (Yes) X (No) ____

Backing Material (Type) 308L
(Refer to both backing and retainers)

☐ Metal ☐ Nonfusing Metal
☐ Nonmetallic ☐ Other

*BASE METALS (QW-403)

P-No. 8 Group No. ____ to P-No. 8 Group No. ____

OR

Specification Type and Grade ____

to Specification Type and Grade ____

OR

Chem. Analysis and Mech. Prop. ____

to Chem. Analysis and Mech. Prop. ____

Thickness Range:

Base Metal: Groove 1" nominal Fillet N/A

Other ____

*FILLER METALS (QW-404)

Spec. No. (SFA)	E308L		
AWS No. (Class)	A 5.4		
F-No.	6		
A-No.			
Size of Filler Metals	1/8 – 5/32"		
Weld Metal Thickness Range:			
Groove	1" minimum		
Fillet	N/A		
Electrode-Flux (Class)	N/A		
Flux Trade Name	N/A		
Consumable Insert	N/A		
Other	N/A		

*Each base metal-filler metal combination should be recorded individually.

QW-482 (Back)

WPS No. 51108-WPS-12 Rev. 0

POSITIONS (QW-405)
Position(s) of Groove 1G
Welding Progression: Up N/A Down N/A
Position(s) of Fillet

POSTWELD HEAT TREATMENT (QW-407)
Temperature Range
Time Range

PREHEAT (QW-406)
Preheat Temp. Min. RT
Interpass Temp. Max. 500F
Preheat Maintenance N/A
(Continuous or special heating where applicable should be recorded)

GAS (QW-408)

	Gases	Percent Composition (Mixture)	Flow Rate
Shielding	Ar	100	30 – 40 CFH
Trailing	N/A		
Backing	N/A		

ELECTRICAL CHARACTERISTICS (QW-409)
Current AC or DC DC Polarity EP
Amps (Range) 110-150 Volts (Range) 23-27

(Amps and volts range should be recorded for each electrode size, position, and thickness, etc. This information may be listed in a tabular form similar to that shown below.)

Tungsten Electrode Size and Type
(Pure tungsten, 2% thoriated, etc.)
Mode of Metal Transfer for GMAW N/A
(Spray arc, short circuiting arc, etc.)
Electrode Wire Feed Speed Range

TECHNIQUE (QW-410)
Sting or Weave Bead Stringer
Orifice or Gas Cup Size
Initial and Interpass Cleaning (brushing, grinding, etc.) SS wire Brush
Method of Back Gouging N/A
Oscillation N/A
Contact Tube to Work Distance N/A
Multiple or Single Pass (per side) Multiple
Multiple or Single Electrodes Single
Travel Speed (range) 4-6 IPM
Peening N/A
Other Part Rotated

Weld Layer(s)	Process	Filler Metal Class	Filler Metal Diameter	Current Type Polar.	Current Amp Range	Volt Range	Travel Speed Range	Other (e.g., Remarks, Comments, Hot Wire Addition, Technique, Torch Angle, etc.)
Any	SMAW	E308L	1/8”	DCEP	110-120	23-27	4-6 IPM	
Any	SMAW	E308L	5/32”	DCEP	140-150	23-27	4-6 IPM	

QW-482 SUGGESTED FORMAT FOR WELDING PROCEDURE SPECIFICATIONS (WPS)
(See QW-200.1, Section IX, ASME Boiler and Pressure Vessel Code)

Company Name: Edison Welding Institute   By: Steve Manring

Welding Procedure Specification No.: 51108-WPS-13   Date: 6-15-2009   Supporting PQR No.(s): N/A

Revision No.: 0   Date: 6-15-2009

Welding Process(es): Gas Tungsten Arc Welding (GTAW)   Type(s): Machine
(Automatic, Manual, Machine, or Semi-Auto)

Joints (QW-402)   Details

Joint Design: Vee Groove, 15 degree extended land

Backing (Yes): ______   (No): X

Backing Material (Type): ______
(Refer to both backing and retainers)

☐ Metal   ☐ Nonfusing Metal
☐ Nonmetallic   ☐ Other

*BASE METALS (QW-403)

P-No.: 8   Group No.: ______   to P-No.: 8   Group No.: ______

OR

Specification Type and Grade: ______

to Specification Type and Grade: ______

OR

Chem. Analysis and Mech. Prop.: ______

to Chem. Analysis and Mech. Prop.: ______

Thickness Range:

Base Metal: Groove: 1” nonimal   Fillet: N/A

Other: ______

*FILLER METALS (QW-404)			
Spec. No. (SFA)	ER308L		
AWS No. (Class)	A5.9		
F-No.	6		
A-No.			
Size of Filler Metals	0.045”		
Weld Metal Thickness Range:			
Groove	¼”		
Fillet	N/A		
Electrode-Flux (Class)	N/A		
Flux Trade Name	N/A		
Consumable Insert	N/A		
Other	N/A		

*Each base metal-filler metal combination should be recorded individually.

This form (E00006) may be obtained from the Order Dept., ASME, 22 Law Drive, Box 2300, Fairfield, NJ 07007-2300

QW-482 (Back)

WPS No. 51108-WPS-13 Rev. 0

POSITIONS (QW-405)
Position(s) of Groove 1G
Welding Progression: Up N/A Down N/A
Position(s) of Fillet

POSTWELD HEAT TREATMENT (QW-407)
Temperature Range
Time Range

PREHEAT (QW-406)
Preheat Temp. Min.
Interpass Temp. Max. 500F
Preheat Maintenance N/A
(Continuous or special heating where applicable should be recorded)

GAS (QW-408)

	Gases	Percent Composition (Mixture)	Flow Rate
Shielding	Ar/He	75/25	30 – 40 CFH
Trailing	N/A		
Backing	Ar	100	10 – 20 CFH

ELECTRICAL CHARACTERISTICS (QW-409)
Current AC or DC DC Polarity EN
Amps (Range) 75 – 260 * Volts (Range) 9.5 – 10.3

(Amps and volts range should be recorded for each electrode size, position, and thickness, etc. This information may be listed in a tabular form similar to that shown below.)

Pulsed and Non Pulsed Current, See information below.

Tungsten Electrode Size and Type 1/8" dia 2% Ce with a 22 deg included angle and a .02 - .03" flat
(Pure tungsten, 2% thoriated, etc.)

Mode of Metal Transfer for GMAW N/A
(Spray arc, short circuiting arc, etc.)

Electrode Wire Feed Speed Range 20 - 90 ipm

TECHNIQUE (QW-410)
Sting or Weave Bead Stringer
Orifice or Gas Cup Size #12 (0.750")
Initial and Interpass Cleaning (brushing, grinding, etc.) SS wire Brush
Method of Back Gouging N/A
Oscillation N/A
Contact Tube to Work Distance N/A
Multiple or Single Pass (per side) Multiple
Multiple or Single Electrodes Single
Travel Speed (range) 5.8 – 6.8 ipm
Peening N/A
Other Part Rotated under fixed torch

Weld Layer(s)	Process	Filler Metal Class	Filler Metal Dia.	Current Type Polar.	Current Amp Range	Volt Range	Travel Speed Range	Other (e.g., Remarks, Comments, Hot Wire Addition, Technique, Torch Angle, etc.)
1	GTAW	ERNiCr-3	0.045"	DCEN	125 – 175	9.5 – 10	5 - 7 IPM	WFS 15 – 25 IPM
2	GTAW	ERNiCr-3	0.045"	DCEN	150 – 100	9.5 – 10	5 – 7 IPM	WFS 25 – 35 IPM
3-4	GTAW	ERNiCr-3	0.045"	DCEN	210 – 230	9.5 – 11	5 – 7 IPM	WFS 60 – 85 IPM
Balance	GTAW	ERNiCr-3	0.045"	DCEN	260 – 220	9.5 – 10.5	5.5 – 6.5 IPM	WFS 85 – 95 IPM
Cap	GTAW	ERNiCr-3	0.045"	DCEN	210 – 230	9.5 - 10	6 – 6.5 IPM	WFS 80 – 90 IPM

Appendix H

Safe End Inco 182 SMAW Groove Weld Procedure

QW-482 SUGGESTED FORMAT FOR WELDING PROCEDURE SPECIFICATIONS (WPS)
(See QW-200.1, Section IX, ASME Boiler and Pressure Vessel Code)

Company Name: Edison Welding Institute — By: Steve Manring

Welding Procedure Specification No.: 51108-WPS-11 — Date: 6-15-2009 — Supporting PQR No.(s): N/A

Revision No.: 0 — Date: 6-15-2009

Welding Process(es): Shielded Metal Arc Welding (SMAW) — Type(s): Manual
(Automatic, Manual, Machine, or Semi-Auto)

Joints (QW-402) — Details

Joint Design: Double Sided Groove Weld

Backing (Yes): Yes (No):

Backing Material (Type): P-No and P-No 43
(Refer to both backing and retainers)

☐ Metal ☐ Nonfusing Metal
☐ Nonmetallic ☐ Other

*BASE METALS (QW-403)

P-No.: 8 Group No.: to P-No.: 43 Group No.:

OR

Specification Type and Grade:

to Specification Type and Grade:

OR

Chem. Analysis and Mech. Prop.:

to Chem. Analysis and Mech. Prop.:

Thickness Range:

Base Metal: Groove: 1" nonimal Fillet: N/A

Other:

*FILLER METALS (QW-404)			
Spec. No. (SFA)	ENiCrFe-3		
AWS No. (Class)	A 5.11		
F-No.	43		
A-No.			
Size of Filler Metals	1/8 – 5/32"		
Weld Metal Thickness Range			
Groove	1" minimum		
Fillet	N/A		
Electrode-Flux (Class)	N/A		
Flux Trade Name	N/A		
Consumable Insert	N/A		
Other	N/A		

*Each base metal-filler metal combination should be recorded individually.

QW-482 (Back)

WPS No. 51108-WPS-11 Rev. 0

POSITIONS (QW-405)

Position(s) of Groove 1G

Welding Progression: Up N/A Down N/A

Position(s) of Fillet

PREHEAT (QW-406)

Preheat Temp. Min. RT

Interpass Temp. Max. 500F

Preheat Maintenance N/A

(Continuous or special heating where applicable should be recorded)

POSTWELD HEAT TREATMENT (QW-407)

Temperature Range

Time Range

GAS (QW-408)

	Gases	Percent Composition (Mixture)	Flow Rate
Shielding	N/A		
Trailing	N/A		
Backing	N/A		

ELECTRICAL CHARACTERISTICS (QW-409)

Current AC or DC DC Polarity EP

Amps (Range) 100-140 Volts (Range) 23-27

(Amps and volts range should be recorded for each electrode size, position, and thickness, etc. This information may be listed in a tabular form similar to that shown below.)

Tungsten Electrode Size and Type N/A

(Pure tungsten, 2% thoriated, etc.)

Mode of Metal Transfer for GMAW N/A

(Spray arc, short circuiting arc, etc.)

Electrode Wire Feed Speed Range N/A

TECHNIQUE (QW-410)

Sting or Weave Bead Stringer

Orifice or Gas Cup Size N/A

Initial and Interpass Cleaning (brushing, grinding, etc.) SS wire Brush

Method of Back Gouging The back groove was machined

Oscillation N/A

Contact Tube to Work Distance N/A

Multiple or Single Pass (per side) Multiple

Multiple or Single Electrodes Single

Travel Speed (range) 2 – 4 IPM

Peening N/A

Other Part Rotated

Weld Layer(s)	Process	Filler Metal Class	Filler Metal Dia.	Current Type Polar.	Current Amp Range	Volt Range	Travel Speed Range	Other (e.g., Remarks, Comments, Hot Wire Addition, Technique, Torch Angle, etc.)
Any	SMAW	ENiCrFe-3	1/8”	DCEP	100-110	23-27	2 – 4 IPM	
Any	SMAW	ENiCrFe-3	5/32”	DCEP	125-125	23-27	2 – 4 IPM	

Appendix B: Round Robin Problem Statement

This guidance was provided to the analysts with the intent of reducing previously-observed scatter in WRS predictions.

Weld Residual Stress Round Robin Problem Statement:

Phase 2b of the NRC/EPRI WRS Validation Program

Version 3.0
October 25, 2013

US Nuclear Regulatory Commission
Office of Nuclear Regulatory Research
Division of Engineering
Component Integrity Branch

Note to participants: please read the entire problem statement, including the participant questionnaire, before beginning.

1 Introduction

Weld residual stress (WRS) has been identified as an important driver for primary water stress corrosion cracking, which is observed in nuclear power plant safety-related components. As a result, the U.S. Nuclear Regulatory Commission (NRC) and the Electric Power Research Institute (EPRI) initiated the WRS Validation Program. This research effort, performed under an addendum to the ongoing Memorandum of Understanding between NRC and EPRI, was aimed at validating 2-D axisymmetric finite element (FE) models for WRS prediction and quantifying associated modeling uncertainty.

Four phases of the program have been completed, including measurement and modeling of WRS in prototype nozzle-to-pipe dissimilar metal welds. These studies were double-blind, in that the modelers and measurement personnel did not have access to each other's results. Phase 2a, in particular, consisted of an international round robin modeling study with 19 participants. That study showed that significant analyst-to-analyst scatter exists in the results. The observed scatter was driven by choice of hardening law to some degree, indicating that guidance on hardening law use is necessary to develop reliable numerical procedures for WRS prediction.

The aim of the present study is to determine if the previously-observed scatter can be reduced by providing analysts with additional guidance on model development. Guidance was developed as a part of the previous phases of the WRS Program. EPRI published MRP-317 that discusses various model attributes and best practices for reliable, consistent results. Additional WRS FE work was performed as part of development of the Extremely Low Probability of Rupture (xLPR) version 2.0 code. Three independent modelers were able to obtain much more consistent results than was observed in the Phase 2a work. The modeling recommendations developed from this previous work will be applied here.

2 Geometry

2.1 Overall

The overall geometry for the Phase 2b mock-up is shown in Figure 1. All fabrication drawings for this mock-up are found in Appendix A. *Note that the drawing dimensions in Appendix A are provided in English units*, but can be easily converted to SI units (1 inch = 25.4 mm). Figure A-1 provides relevant mockup dimensions. The nozzle was attached to a steel plate to represent the stiffness of the nozzle in service. The welds between the stiffening plate and the nozzle are detailed in the Appendix A drawings, but will not be analyzed in this effort. The mockup consists of a carbon steel nozzle, Alloy 182 butter layer on the nozzle, an Alloy 182 dissimilar metal (DM) weld between the butter and the stainless steel safe end, and a stainless steel weld between the safe end and the stainless steel pipe. A groove was machined at the ID surface of the DM weld, followed by a back weld to mimic a 360° repair. The exact process is described in chronological sequence in the following paragraphs. Further details on the welding process are found in the report named "EWI Report.pdf," beginning with Section 2.3, "WOM Mock-Up."

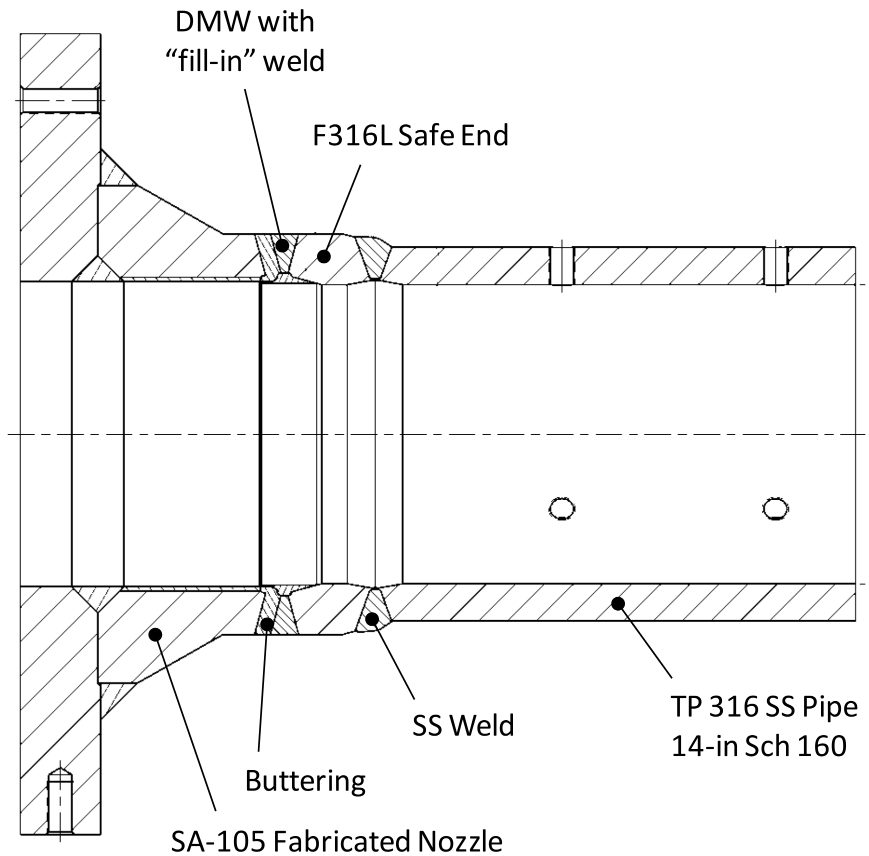

Figure 1 Overall mock-up geometry

2.2 Nozzle

The A36 steel stiffening plate and SA105 low alloy steel nozzle may be treated as one piece for the purposes of this study. The geometry of the stiffening plate is shown in Figure A-2. The dimensions needed to completely define the nozzle geometry, including the bevel for the butter surface, are shown in Figures A-1 and A-3. There is a layer of cladding present on the nozzle inner surface. The cladding process is not to be modeled for this work. Participants instead are requested to include the cladding layer with assigned stainless steel material properties.

2.3 Nozzle Buttering

The schematic bead map for the butter, which is based upon consultation with the mockup fabricator, is shown in Figure 2. The geometry is shown in Figure A-4. Laser profilometry is not available for the butter operation. Participants are requested to model trapezoidal weld beads of approximately equal area, consistent with Figures A-4 and 2. After deposition, the butter was postweld heat treated at 890 K for 10 800 s. Then, the butter was machined according to the geometry detailed in Figure A-5, before performing the DM weld to the safe end. The weld parameters used for the buttering are listed in Table 1.

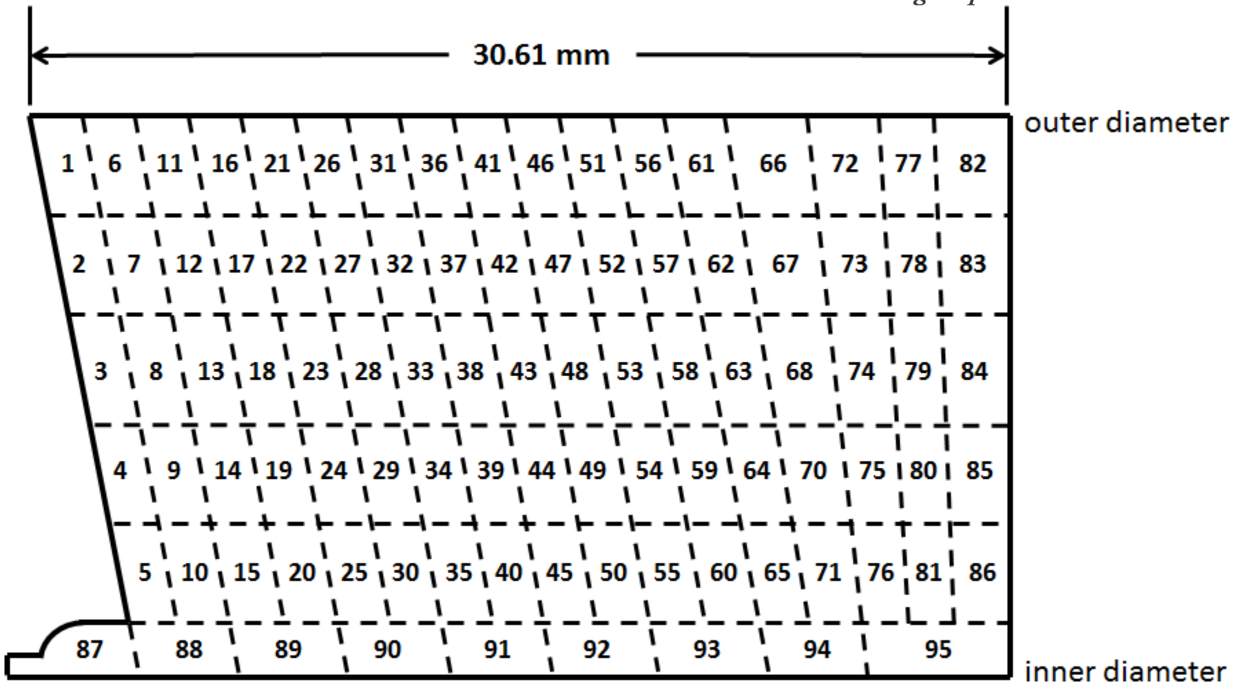

Figure 2 Bead map of butter (not to scale)

Table 1 Weld parameters for butter

Current	240 A
Voltage	11.5 V
Travel Speed	2.3 mm/s

2.4 Nozzle to Safe End DM Weld

The relevant dimensions for the safe end are defined in Figures A-1 and A-6. The DM weld was formed with 24 passes of Alloy 182 filler metal deposited in the order shown in Figure 3.

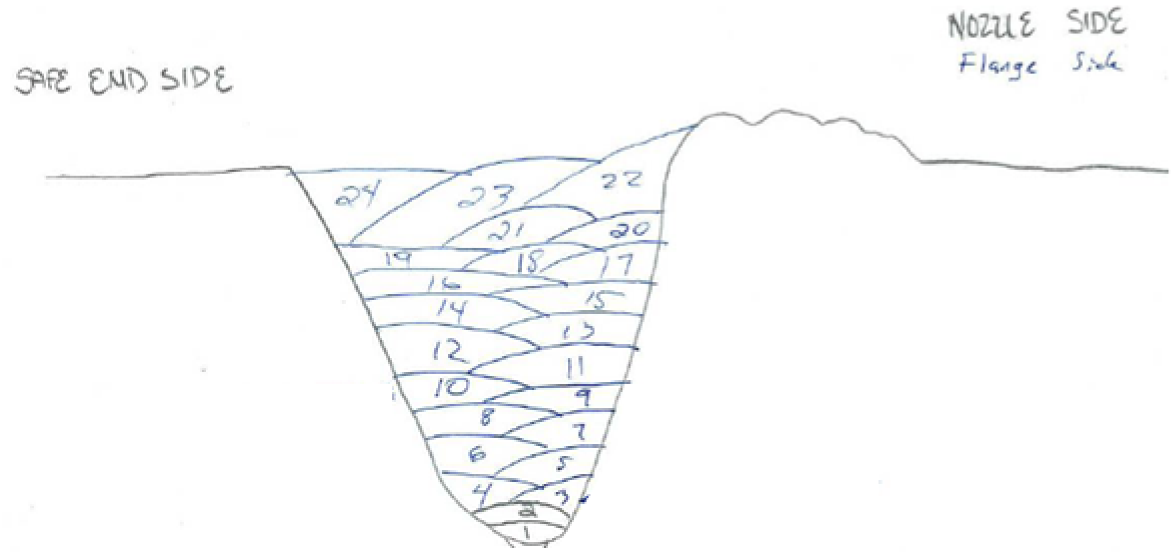

Figure 3 Bead map of DM weld

Laser profilometry of the DM weld is contained in the file "DM Weld Laser Profile.xlsx." Table 2 shows the weld parameters for the DM weld.

Table 2 Weld parameters for DM Weld and back weld

Current	130 A
Voltage	25 V
Travel Speed	2.3 mm/s

2.5 Groove Machining and Back Weld/Weld Crown Machining

To approximate a 360º repair operation, a groove was machined at the inner diameter location according to the geometry in Figure A-7. The back weld was performed in the sequence shown in Figure 4 with Alloy 182 filler metal.

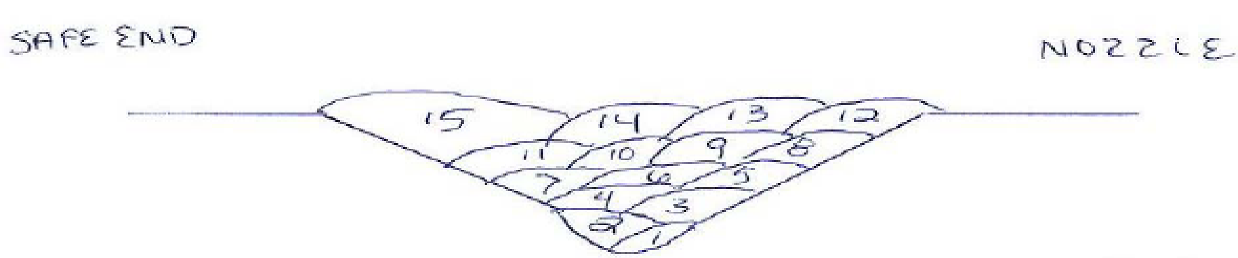

Figure 4 Bead map of back weld

The weld parameters for the back weld are the same as those used for the DM weld (Table 2). Geometry for the back weld is defined in Figure A-8. After the back weld was complete, it was machined to the dimensions shown in Figure A-9. Figure A-9 also indicates machining of the weld crown. Profilometry for the back weld is found in "Back Weld Laser Profile.xlsx."

2.6 Pipe and Closure Weld

The stainless steel weld consisted of SFA 5.4 weld metal. The geometry of the stainless steel pipe is shown in Figure A-10. The weld bead map of the closure weld is shown in Figure 5.

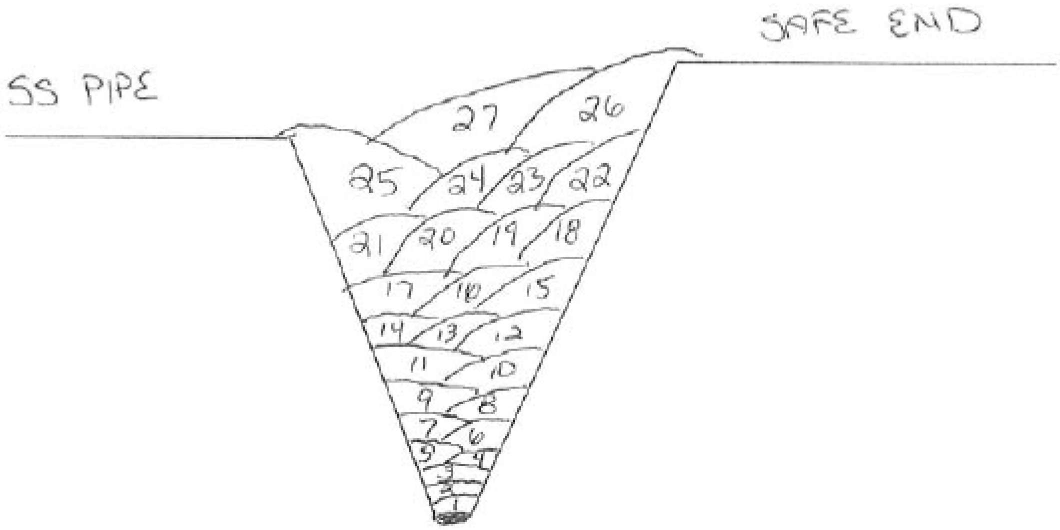

Figure 5 Bead map of closure weld

Table 3 lists the weld current, voltage, and travel speed for the closure weld.

Table 3 Weld Parameters for closure weld

Current	125 A
Voltage	26 V
Travel Speed	1.7 mm/s

3 Model Guidance

MRP-317 offers guidance on a number of WRS FE modeling issues, including weld bead geometry definition, element selection, and structural boundary conditions. Some of the guidance in MRP-317 is adopted here. Since the purpose of the round robin study is to determine if modeling uncertainty is reduced by following certain procedures, the participants are requested to follow these guidelines.

3.1 Hardening Law

Choice of hardening law is known to be a significant driver of uncertainty in WRS predictions. Models with the isotropic hardening assumption tend to predict larger stress magnitudes than models with the kinematic hardening assumption. While the mixed hardening law provides the most physically accurate description of material behavior, the testing required to develop the material parameters is resource-intensive. For the purposes of this study, participants are requested to provide two sets of results: one with the isotropic hardening assumption and one with the nonlinear kinematic hardening assumption. Participants are to use the provided Abaqus material input files, named “materials_ISO.inp” and “materials_nlinKIN.inp.”

Comparable ANSYS input files are also provided: “ANSYS_materials_ISO.inp” and “ANSYS_materials_NLKN.inp.”

3.2 Weld Bead Geometry Definition

Participants should endeavor to model the number of passes shown in Figures 2-5. Studies in MRP-317 demonstrated that modeling the precise bead shape, as provided by laser profilometry, may not add greatly to the solution accuracy. Trapezoidal beads of approximately the same area are sufficient to obtain reasonable results for welds of this size. Laser profilometry data for the DM weld, the back weld, and the stainless steel closure weld are provided to the participants for reference, as discussed in Section 2. These data are provided to help inform the participants’ choice of bead geometry.

The schematic in Figure 2 is less certain than Figures 3-5 (and the associated laser profilometry), so analysts may use judgment when sketching the butter geometry. The sequence for each layer should, however, start at the outer diameter and work toward the inner diameter with 17 total layers. The postweld heat treatment should be modeled prior to the butter machining operation.

3.3 Thermal Model Tuning

Material properties for the thermal model are provided in “materials_heat.inp” and “ANSYS_materials_heat.inp.” Participants are free to choose the heat input model, but some method to tune the model should be prescribed. In the Phase 2a study, participants completed three models: one without thermocouple or material property data, one with provided thermocouple data but no material property data, and one with prescribed thermocouple and material property data. Surprisingly, providing the participants with measured transient temperatures did not reduce modeling uncertainty (note: nor did providing a consistent set of material properties). This result suggests that, provided that the thermal model is calibrated to reasonably approximate the expected melt zone, the results are only weakly sensitive to heat input. Sensitivity studies on heat input support this conclusion, as well. While tuning of the thermal model to match thermocouple data is not required, the transient temperature data will be made available upon request. Analysts should ensure that a reasonable area around the weld bead reaches the annealing temperature, 1500 K. An example of a reasonable melt zone around a highlighted weld pass is provided in Figure 6.

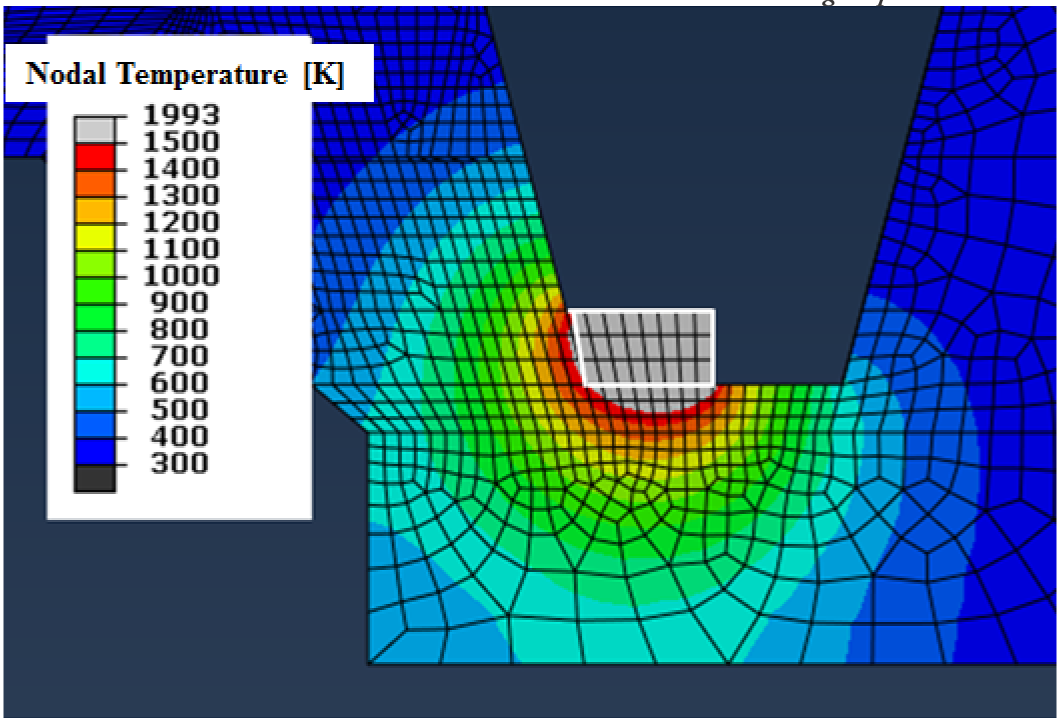

Figure 6 Simulated melt zone around a weld pass

3.4 Structural Boundary Conditions

Boundary conditions should always represent the physical situation being modeled. MRP-317 indicates that nuclear piping welds are typically not constrained to prevent displacement during welding. The mockup being modeled in this study was not constrained during fabrication. Therefore, minimal boundary conditions are appropriate for this model. Participants are requested to fix one single node against displacement along the axial direction of the pipe, as shown in Figure 7. Axisymmetric finite element models are the primary focus of this study, but participants may submit a 3-D analysis if desired (note: one participant in the Phase 2a round robin submitted a 3-D analysis).

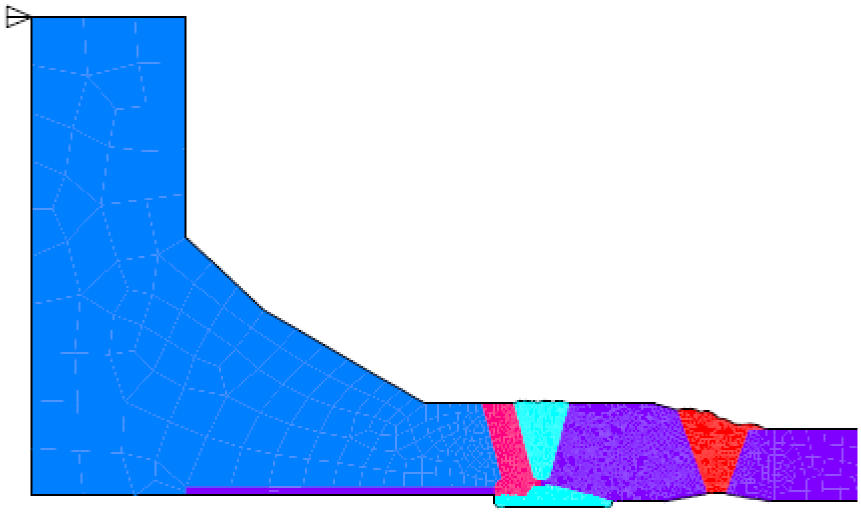

Figure 7 Structural boundary condition

3.5 Material Properties

All material properties are provided to the participants in the form of input decks, as described in Sections 3.1 and 3.3. The files contain density, latent heat, conductivity, and specific heat of Alloy 82, stainless steel, and carbon steel. These properties are appropriate for the thermal analysis. The mechanical properties for the structural analyses are provided for both hardening law cases.

3.6 Post Processing

During work on xLPR v2.0, NRC and EPRI determined that a consistent method for extracting results from the FE output database is important for minimizing uncertainty. A prescribed extraction method will also minimize data massaging performed on participant results for comparison purposes. Therefore, participants are requested to define one path through the thickness, such that the starting point is on the inner diameter (inner diameter of fill-in weld after machining), the final point is on the as-machined outer diameter (note: the weld crown should be machined as indicated in Figure A-9), and there are 24 equally-spaced points along the path in between. Axial and hoop stresses are requested both prior to the stainless steel closure weld and after the stainless steel closure weld. All data should be extracted at room temperature, since all residual stress measurements were performed at room temperature.

3.7 Pass Lumping and Bead Sequence

Combining multiple passes into one is a common practice to facilitate computational efficiency. Results from an MRP-317 study on bead lumping are shown in Figure 8. The results without bead lumping are shown with maroon square and blue diamond points for axial and hoop stresses, respectively. Two cases of bead lumping are shown as dotted and dashed lines. The study shows that significant differences can result from different bead lumping assumptions, even to the extent of one case predicting tensile stresses and the other predicting compressive stresses. Each participant performing bead lumping under diverse assumptions will likely lead to unnecessary uncertainty in the results. Therefore, participants are requested to refrain from bead lumping. The sequencing should follow Figures 3-5 exactly. Given the uncertainty in the

fabrication of the butter, participants should follow Figure 2 as closely as possible (see Section 3.2).

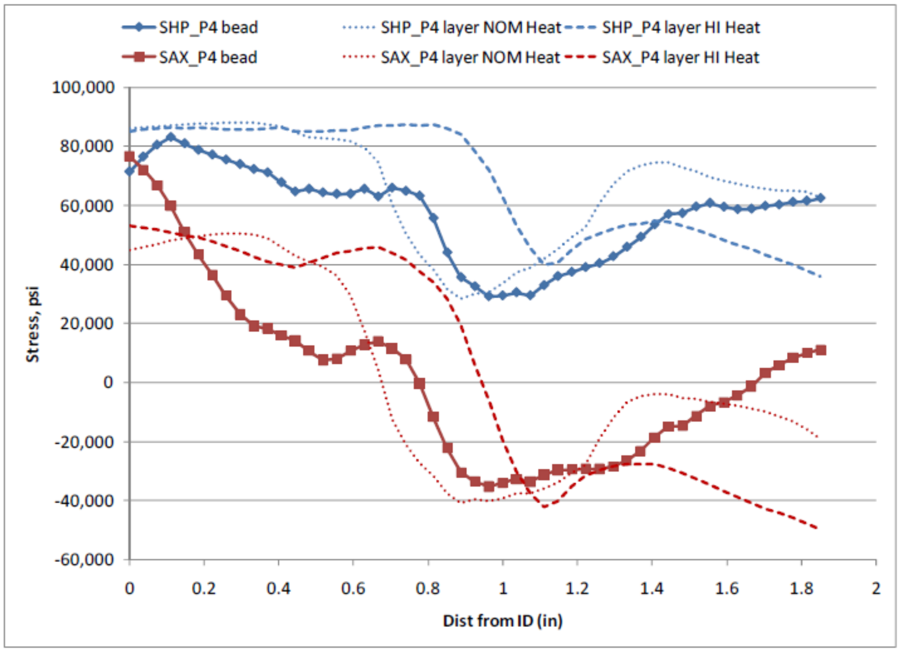

Figure 8 Effect of bead lumping assumptions

3.8 Miscellaneous

According to MRP-317, a fine mesh of linear elements is recommended for these analyses over quadratic elements. Approximate mesh size for the weld passes should be 1.25 mm square, with no triangular elements included in the mesh. This mesh size corresponds to roughly 20-25 elements per weld pass. The mesh should be allowed to coarsen away from the weld passes for computational efficiency.

4 Reporting

Participants should provide the extracted hoop and axial stresses (see Section 3.6), along with screenshots of associated contour plots in the vicinity of the DM and closure welds. These data are requested both before and after completion of the closure weld. Participants should fill out and submit the attached questionnaire, “Participant Questionnaire.docx.” The questionnaire is designed to document the extent to which the model guidance was followed for each participant. Any deviations from this guidance should be explained in 2-3 sentences in the questionnaire. Participants should also include a spreadsheet or text file of all node locations and associated nodally-averaged stresses (all six components of the stress tensor). The extracted data may be provided in an Excel spreadsheet or a text file, with data columns labeled for proper interpretation of the data.

5 Measurement Description

This section provides the participants with a brief description of the measurement activities on the Phase 2b mockup. This discussion is not intended as a comprehensive treatment of the techniques applied. Three sets of measurements were performed: hole drilling, contour, and

slitting measurements. Each of these residual stress measurement techniques rely upon mechanical strain relief.

5.1 Hole Drilling Measurements

The hole drilling measurements consisted of a combination of incremental center hole drilling near the outer diameter surface and deep hole drilling/incremental deep hole drilling through the thickness. The incremental deep hole drilling technique was considered more appropriate in areas were the WRS was expected to approach the material yield strength. Four hole drilling measurements were made, roughly 90° apart from one another. The measurement locations were carefully chosen to avoid weld start/stop locations. Figures 9 and 10 show the experimental setup. Hoop and axial stresses along the linear drilling path through the center of the DM weld were measured with this experiment.

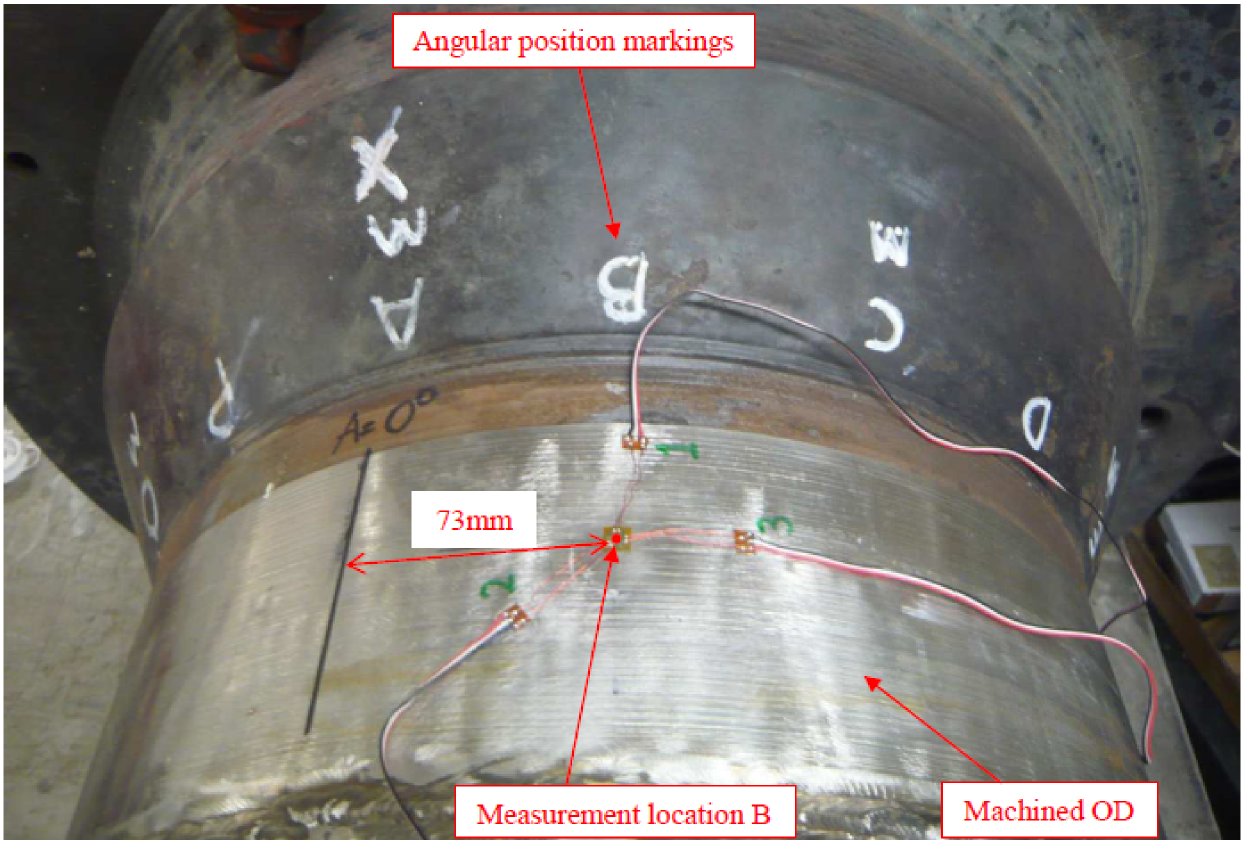

Figure 9 Incremental center hole drilling setup with strain gauges

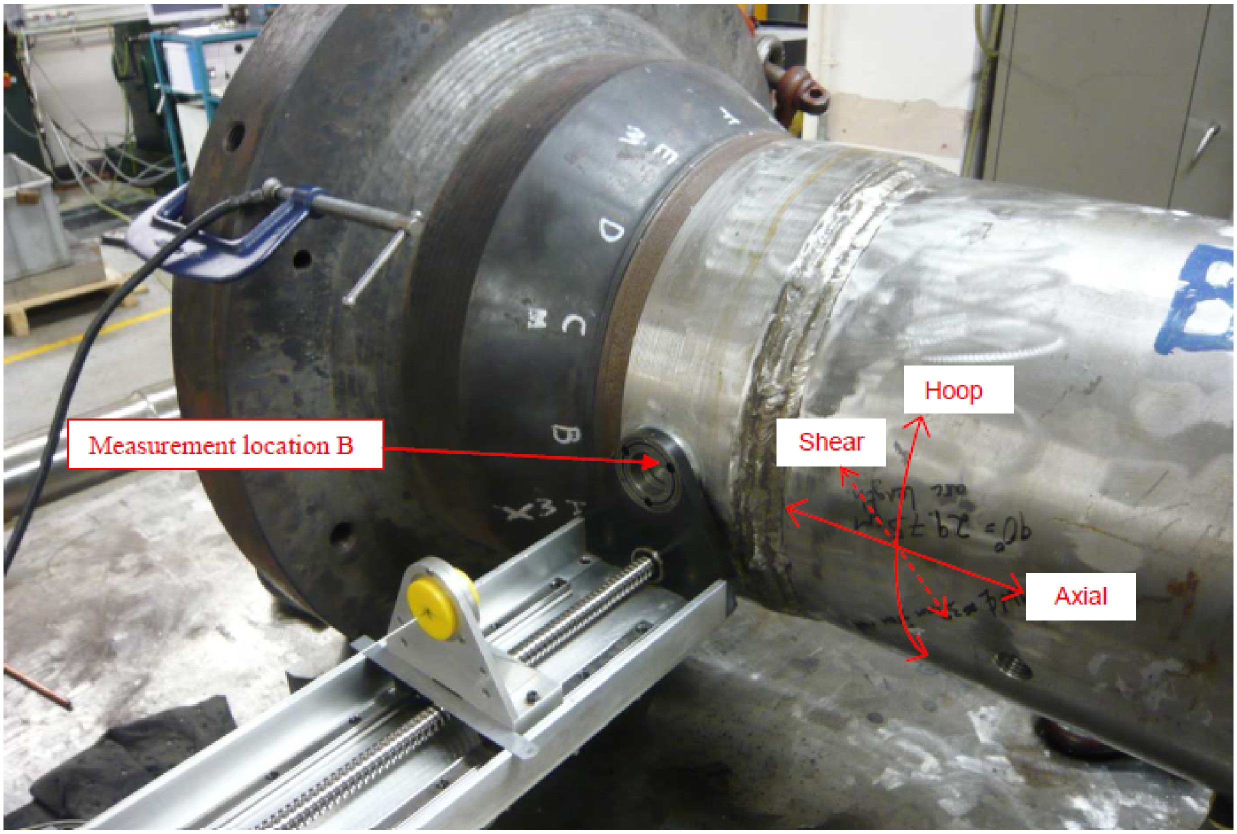

Figure 10 Deep hole drilling setup

5.2 Contour and Slitting Measurements

These measurements were performed after the hole drilling measurements. They involve a series of sectioning cuts. Figure 11 illustrates the first three cuts:

1. Removal of the thick nozzle section and the stainless steel pipe.
2. A radial cut to relieve the through-wall bending moment.
3. Radial cuts to remove the 90^{o} section that forms the measurement piece.

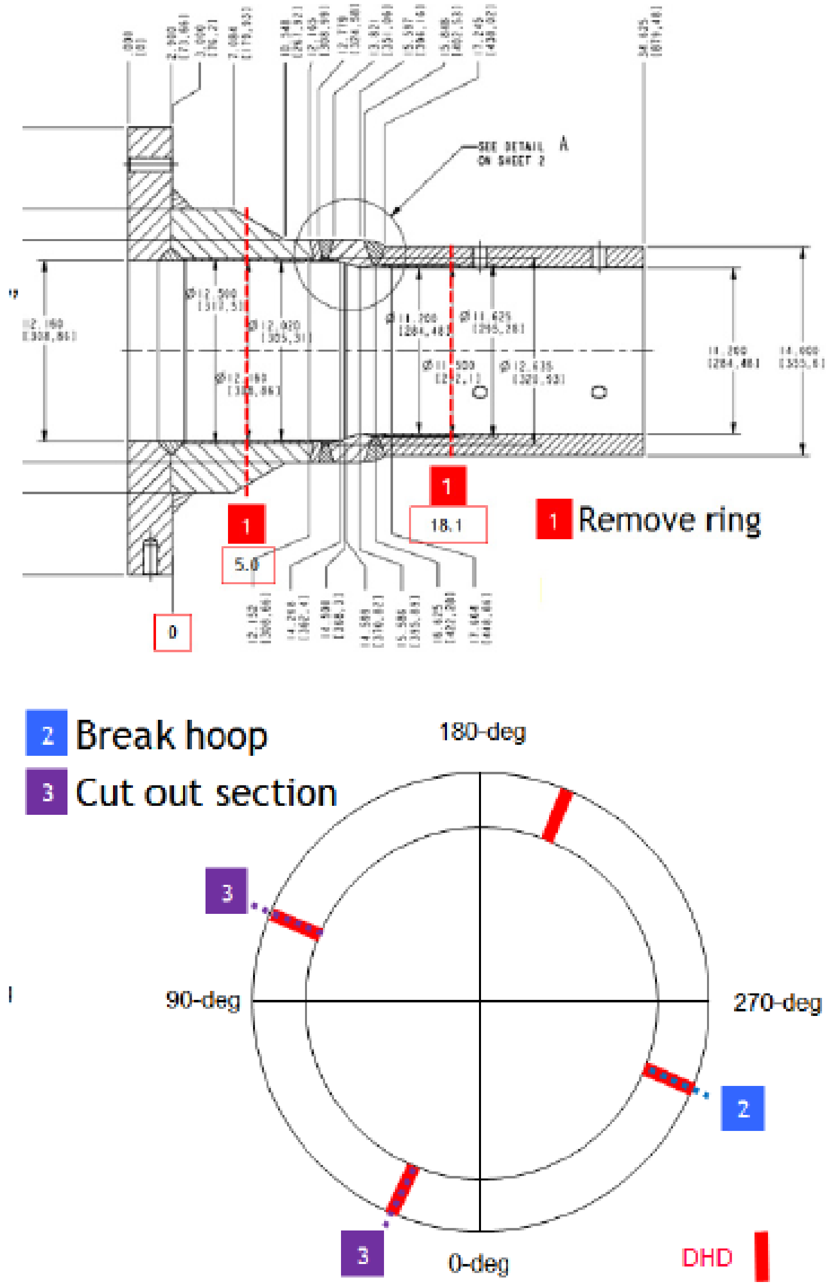

Figure 11 Three cuts prior to the contour and slitting measurements

Two cut surfaces were required for the contour measurements: one for measuring hoop stress, one for measuring axial stress. The contour measurements provided stress data distributed over an area. The slitting method measured axial stress along a linear path through the center of the DM weld. These cuts are illustrated in Figure 12.

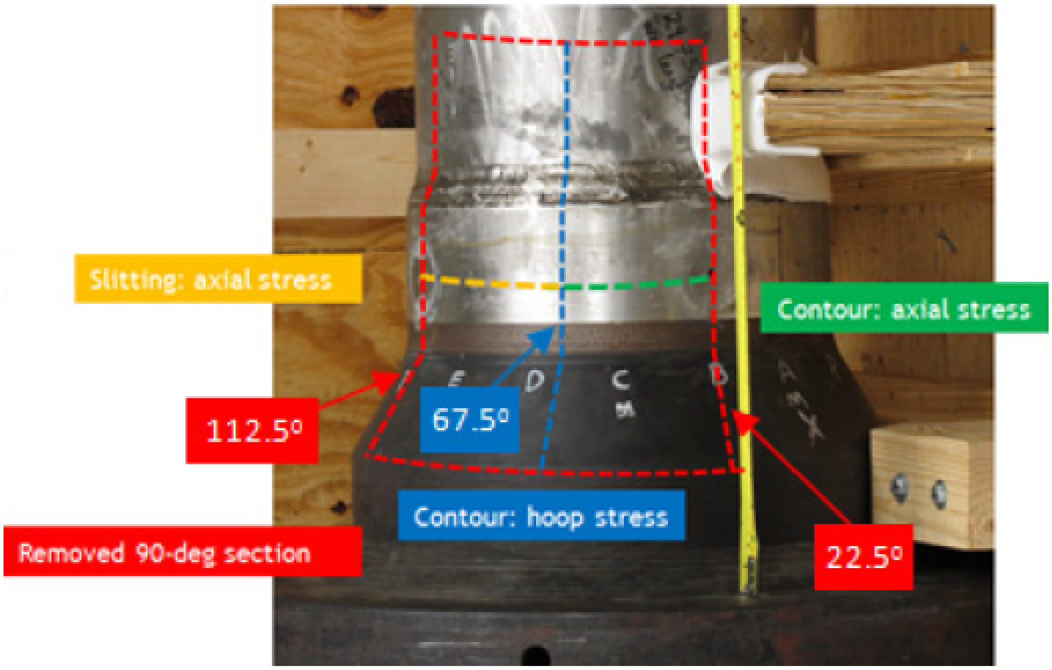

Figure 12 Measurement cutting planes

Appendix C: Raw Measurement and Modeling Tabular Data

This appendix shows raw tabular data of all measurement and modeling activities presented in this report.

Table C-1: Hole Drilling Data, 22° Location

Depth from OD [mm]	Axial [MPa]	Hoop [MPa]	Shear [MPa]
1	297.6	205.5	10.8
1.2	307	213	10.2
1.4	311.3	219.8	10.6
3.8	370.8	271.9	14.4
6.2	379.6	296.1	-7.2
9.2	391.4	348.4	2.2
13	49.7	162.8	-24.3
14.6	-140.8	10.6	-13.4
14.8	-154.3	-24.2	-20.1
15	-177.9	-25.7	-12.5
15.2	-189.6	-30.7	-15.2
15.4	-190.2	-32.5	-18.4
15.6	-205.5	-54.2	-8.6
15.8	-211.2	-64.9	-12.9
16	-224.8	-74	-10.7
16.2	-222.1	-82.7	-8.3
16.4	-228.7	-81.1	-7.4
16.6	-236.3	-90.9	-7.5
16.8	-236.2	-95.7	-11
17	-257.8	-97.6	-7.7
17.2	-253.3	-95.3	-11.3
17.4	-264.4	-100.7	-11.3
17.6	-265.5	-101.1	-7.5
17.8	-265.5	-107.4	-8.7
18	-266.5	-116.3	-9.5
18.2	-274.8	-112.3	-8.5
18.4	-270.3	-118.3	-5.4
18.6	-271.7	-107.2	-9.3
18.8	-272.5	-109	-10.5
19	-271.4	-110.7	-10.6
19.2	-272.8	-107.2	-11.4
19.4	-275.4	-105.7	-13
19.6	-268.2	-104.4	-17.3
19.8	-290.6	-97.9	-23.8
20	-315.4	-86	-12
20.2	-289.6	-93.2	-3.6
20.4	-283.7	-87.6	-9.5
20.6	-279.1	-86.9	-14.6
20.8	-256.8	-75.7	-17.5
21	-273	-69.7	-7
21.2	-273	-58.7	-7.9

21.4	-256.1	-49.7	0.5
21.6	-252.4	-32.3	-8.8
21.8	-257.5	-33.5	-7.7
22	-251.7	-16.2	-6.3
22.2	-254.2	-5.6	-6.6
22.4	-245	-4.4	-10.3
22.6	-266.6	-7.7	-4.7
22.8	-228.6	33.1	-0.1
23	-213.4	32.6	-9
23.2	-218.9	49.2	-4.9
23.4	-231.7	47.6	0.2
23.6	-206.7	94.1	-4.8
23.8	-199.8	99.7	-0.2
24	-182.1	113.4	0.1
24.2	-177.1	124	-2.8
24.4	-167.3	139.9	-3.7
24.6	-148.7	165.7	-7.1
24.8	-145.1	162.3	-5.5
25	-134.5	174.5	-6
25.2	-108.2	204.6	-5.2
25.4	-93.7	220	-5.2
25.6	-86.3	225.3	-2.8
25.8	-70.8	208.1	-1
26	-57.9	230.4	-8.5
26.2	-44.4	241.2	-7.9
26.4	-34.1	240.6	-10
26.6	-21.9	244.1	-11.4
26.8	-24.8	245.9	-12.9
27	-27	264.2	-12.6
27.2	2.2	261.4	-12.2
27.4	17.1	258.9	-13.9
27.6	31	251.4	-4
27.8	28.6	253.3	-14.6
28	24.9	240.4	-9.7
28.2	30.5	222.5	-17
28.4	21.5	208.4	-21.2
28.6	25.6	201.1	-21.6
28.8	25.1	202.1	-20.5
29	24	184.1	-19.5
29.2	16.7	174.6	-26.2
29.4	6.1	171.4	-26.8
29.6	0.2	164.5	-30.5
29.8	-10.4	135	-23.7
30	-0.1	145.3	-20
30.2	-2.1	125.6	-19.9
30.4	-31.1	102.1	-28
30.6	-26.4	98.1	-30.6
30.8	-41.2	93.9	-28.3
31	-33.4	90.5	-26.1

31.2	-39.1	83.4	-31.6
31.4	-46.2	82.5	-28.6
31.6	-36.8	78.2	-22.9
31.8	-45.9	63.8	-23.1
32	-51.3	73.2	-26.3
32.2	-56.4	67.5	-33.9
32.4	-64.3	61	-35
32.6	-63.5	54.9	-33.9
32.8	-66.7	45.8	-33.2
33	-78.3	38.1	-34.7
33.2	-84.5	35.7	-33.3
33.4	-92.4	31	-35
33.6	-99.4	24.9	-36.7
33.8	-104.3	19.2	-35.9
34	-107.6	21.2	-37.2
34.2	-103.9	25.3	-34
34.4	-111.1	18.9	-31.6
34.6	-111.7	15	-36.8
34.8	-115.5	10.7	-33.8
35	-103.3	17.8	-32.5
35.2	-136.2	-11	-30.1
35.4	-137.4	-11.1	-30.9
35.6	-138.5	-15	-28.4
35.8	-162.3	-28.7	-24.1
36	-149.7	-23.8	-26.2
36.2	-172.8	-38.6	-22.3
36.4	-168.9	-51	-25.9
36.6	-186.1	-64.9	-20.2
36.8	-179.1	-53.7	-12

Table C-2: Hole Drilling Data, 112° Location

Depth from OD [mm]	Axial [MPa]	Hoop [MPa]	Shear [MPa]
1	308.5	161.3	5.6
1.2	323.4	185.4	6.7
1.4	332.9	203.5	7.6
1.6	336.4	216.1	8
4	359.5	264.7	11.9
6.8	395.7	330.9	14.8
9.6	291.8	284.3	2.4
12.6	55.7	122.8	-7.7
14.6	-136.7	-46.7	-4.9
14.8	-157.1	-55.2	-4.2
15	-155	-60.9	-4.5
15.2	-184.4	-84.5	-6.8
15.4	-195.4	-90.8	-8
15.6	-198.7	-94.2	-8.9
15.8	-214.3	-101.7	-9.5
16	-227.7	-104.7	-8.6
16.2	-225.9	-109.5	-10.8
16.4	-224	-116.4	-10.5
16.6	-245.8	-115	-12.2
16.8	-250.1	-125.2	-20
17	-250.5	-120.4	-16
17.2	-253.1	-117.5	-16.8
17.4	-251.7	-124.8	-11.5
17.6	-251.6	-128.8	-13.1
17.8	-251.3	-128.2	-11.9
18	-243.1	-120.6	-12.1
18.2	-245.8	-120.9	-12.5
18.4	-241.1	-119.6	-11.3
18.6	-235.3	-115.7	-9
18.8	-235.7	-116.5	-8.1
19	-237.2	-111.6	-9.3
19.2	-236.6	-109.9	-9.2
19.4	-235	-109.1	-7.5
19.6	-233.2	-104.9	-6.6
19.8	-228.2	-103.7	-8
20	-223.8	-94.1	-4.7
20.2	-227.2	-91.1	-6
20.4	-229.6	-87.7	-4.9
20.6	-233.7	-91.1	-13.4
20.8	-230.4	-73.1	-4.9
21	-212.3	-55.8	7.6
21.2	-229.9	-60.4	-6.8
21.4	-227.3	-51.5	-6.5
21.6	-227.5	-46	-6.8
21.8	-225.6	-36.5	-6.7
22	-222	-31.3	-5

22.2	-212.1	-15.8	-4.9
22.4	-202.4	-2.5	-2.5
22.6	-198.1	7.9	-0.3
22.8	-185.4	21.3	-0.4
23	-173.9	36.1	0
23.2	-173.9	44.8	1.4
23.4	-175.7	51.5	1.2
23.6	-168.3	63.8	1.8
23.8	-161.4	78.9	3.6
24	-158	93.6	2.7
24.2	-157.7	93.9	2.9
24.4	-140.1	111.2	0.9
24.6	-137.1	124.4	-0.2
24.8	-122.2	141.9	-0.4
25	-118.4	147.9	-0.4
25.2	-108.5	163.8	-0.7
25.4	-103.8	170.2	-2.3
25.6	-97.4	172.7	-4.2
25.8	-98	172.6	-6.3
26	-82.3	181.4	-5
26.2	-70.7	193.2	-10.2
26.4	-49	205.6	-9.2
26.6	-32.7	218.3	-10.7
26.8	-26	220.8	-11.5
27	-21.1	212.5	-13.2
27.2	-17.4	209.7	-14.1
27.4	-4.2	213.3	-16.4
27.6	4.6	212.6	-17
27.8	11.7	209.5	-18.7
28	15.6	203.3	-19.4
28.2	17.1	200.6	-23.4
28.4	23.7	194.1	-27.2
28.6	22.1	204.7	-38
28.8	19.6	177.4	-26.7
29	24.5	171.6	-28.4
29.2	21.6	162.8	-31.6
29.4	15.2	151	-28.8
29.6	9.9	143.4	-28.7
29.8	10.7	140.9	-32.4
30	5.5	128.7	-31.1
30.2	-17.3	125	-38.4
30.4	-3.2	116.2	-32.3
30.6	-22.4	102.5	-35.9
30.8	-23.3	102.3	-39.4
31	-23.4	102.3	-41.6
31.2	-9.2	106.5	-45.7
31.4	-23.3	87.7	-38.2
31.6	-36.2	73.7	-41
31.8	-38.9	65.5	-41.1

32	-41.3	59.1	-44.3
32.2	-48.3	60.1	-44.4
32.4	-54.6	52.6	-41.3
32.6	-64.8	51.9	-43.8
32.8	-72.8	45.7	-48.6
33	-76.5	33	-51.1
33.2	-74.8	36.2	-50.4
33.4	-82.3	30.7	-48.1
33.6	-92	18.4	-47.3
33.8	-84.3	12.7	-57
34	-84	13.7	-40.5
34.2	-82.4	13.9	-39.2
34.4	-87.3	12.7	-33.4
34.6	-89.2	13.1	-35.6
34.8	-90.4	15.3	-32.8
35	-93.9	12	-34.5
35.2	-88.5	20	-31
35.4	-89	22.4	-27.4
35.6	-82.1	22.7	-30.3
35.8	-100.9	-2.4	-27.1
36	-96.7	-6.6	-23.6
36.2	-96.8	-1.1	-24.4
36.4	-112.8	-14.9	-21.2
36.6	-105.9	-14.3	-23.2
36.8	-124.8	-50.6	-18.4
37	-140.5	-60.1	-22
37.2	-155.5	-84.7	-33.6

Table C-3: Hole Drilling Data, 202° Location

Depth from OD [mm]	Axial [MPa]	Hoop [MPa]	Shear [MPa]
0.004	-82.7	87.3	-417.1
0.012	77.1	-25.7	-170.8
0.02	297.4	-3.1	-40.9
0.028	433.2	25.8	35.5
0.036	506.3	49.1	76.8
0.044	534.6	62.8	92.5
0.056	528.6	66	90.7
0.072	500.3	57.4	82
0.088	441.5	43.4	54.6
0.104	382.7	25	27.5
0.12	312.4	6.5	-7.1
0.144	245.6	-10.1	-44.3
0.176	196.9	-20.9	-71.1
0.224	162.8	-24.4	-82.1
0.256	160	-17.5	-81.3
0.288	185	-2.3	-63.4
0.32	234.5	22.3	-35.4
0.384	317	50.7	17.4
0.448	371.4	76.9	44.5
0.512	405.8	93.2	53.4
1	337.9	235.2	26.4
1.2	347.8	253.2	29.9
1.4	350.5	264.5	29.9
3.6	355.8	259.7	7.3
6.4	394.6	345.4	4.1
9.4	296.8	299.8	9.7
12.8	18	129.5	-1.9
14.6	-167.3	-14.7	-3.1
14.8	-179.8	-28.8	-4.7
15	-182.5	-46.1	-7.5
15.2	-183.1	-57.8	-8.6
15.4	-192.6	-46.5	-7.4
15.6	-210.5	-52.4	5
15.8	-207.6	-64.7	-7.6
16	-205.5	-70.6	-8.4
16.2	-209.4	-73.3	-6.6
16.4	-225.2	-86.4	0.2
16.6	-243.8	-108.6	-8.5
16.8	-251.4	-115.4	-4.7
17	-257.6	-119.3	-5.8
17.2	-236.3	-103	-6.2
17.4	-239.7	-99.7	-3.7
17.6	-259.1	-114.4	-12.2
17.8	-254.7	-111.3	-2.1
18	-256.8	-109.5	-2.3
18.2	-260.9	-107.9	-0.3

18.4	-254.8	-98.4	2.2
18.6	-258.1	-101.4	2
18.8	-257.8	-79	2
19	-254.7	-78.7	3.6
19.2	-252.7	-70.5	-0.7
19.4	-249.8	-67.4	0.2
19.6	-258.7	-49.4	-9.2
19.8	-237.9	-44.4	-3.3
20	-236.3	-40.9	1.1
20.2	-242.5	-43	-1.5
20.4	-256.3	-44.1	-1.4
20.6	-249.7	-37.7	-0.2
20.8	-253.3	-43.8	-3
21	-243.9	-29.7	-1.9
21.2	-254.7	-15.5	2.3
21.4	-253.2	-11	3.1
21.6	-247.6	-5.9	3.2
21.8	-239.1	7.6	3.5
22	-227.1	20.7	2.9
22.2	-221.8	27.1	4.2
22.4	-208.2	40.6	1.8
22.6	-208.3	47.4	1.3
22.8	-205.6	55	2.4
23	-204.7	57.5	4.4
23.2	-201.1	59.7	5
23.4	-193	73.9	5.5
23.6	-185	73.9	2.2
23.8	-175.2	86.2	4.7
24	-167.1	95.8	7.5
24.2	-159.7	104.1	4.9
24.4	-148.9	110.8	5.5
24.6	-139.7	122.5	6.8
24.8	-132.4	124.8	3.5
25	-111	138	1.3
25.2	-102.1	147.8	-4
25.4	-92.7	152.4	-4.3
25.6	-83.2	161	-5.7
25.8	-71.9	158.7	-10.8
26	-63.8	163.6	-12.9
26.2	-45.5	178.8	-11.2
26.4	-37.5	179.2	-10.8
26.6	-32.6	178.8	-14.2
26.8	-21	181.3	-14.1
27	-7.4	193.8	-11.7
27.2	-3.9	185.6	-16.4
27.4	-5.3	184.7	-15.9
27.6	-0.1	180.6	-19.2
27.8	-4.4	177.1	-21.5
28	8.2	179	-18.9

28.2	13	180.8	-21.7
28.4	11.5	171.3	-23.8
28.6	-2.8	159.4	-24.3
28.8	-4.9	153	-27.3
29	-7.9	149.3	-31.1
29.2	-4.4	152.5	-27.7
29.4	1.6	153.3	-31.3
29.6	-17.1	148.6	-26
29.8	-10.9	137.3	-29.6
30	-11.8	138.4	-28.6
30.2	-10.4	137.7	-28.1
30.4	-25.7	121	-28.1
30.6	-22.6	113.6	-27
30.8	-33.5	107.8	-30.3
31	-31.1	107	-26.4
31.2	-34.1	104.7	-28.2
31.4	-36.9	96.3	-27.4
31.6	-45.6	82.7	-26.6
31.8	-50	81.5	-29.7
32	-55.7	76.1	-28
32.2	-68.8	61.3	-23.6
32.4	-85	60.7	-26.3
32.6	-70.6	52.9	-29.3
32.8	-79.2	46.1	-29.5
33	-85.6	41	-28.8
33.2	-91.8	34.8	-27.8
33.4	-94.3	29.6	-30.1
33.6	-96	25.2	-28.4
33.8	-100	21.3	-34.4
34	-102.2	22.9	-27.8
34.2	-104.6	23.2	-27.2
34.4	-104.4	18.9	-25.9
34.6	-104.7	11	-32.9
34.8	-106.2	-2.1	-41.6
35	-99.8	8.5	-31.8
35.2	-109	0.9	-30.2
35.4	-114.5	-3.7	-32
35.6	-117.9	-8.2	-32.1
35.8	-127.7	-18.1	-31.8
36	-128.7	-23.2	-30.4
36.2	-138.1	-29.9	-30.8
36.4	-153.9	-44.9	-29.5
36.6	-169.3	-61.8	-31.1
36.8	-195.7	-65	-29.5
37	-189.5	-73.5	-32.3

Table C-4: Hole Drilling Data, 292° Location

Depth from OD [mm]	Axial [MPa]	Hoop [MPa]	Shear [MPa]
0.004	298.1	-225.6	256
0.012	151.7	-121.6	58.5
0.02	125.1	-107.4	-13.9
0.028	113.4	-91.1	-24.2
0.036	113.6	-75	-12.8
0.044	123.8	-62	3.7
0.056	139.5	-51	17.6
0.072	152.5	-39.9	22.3
0.088	164.6	-32.6	27.4
0.104	174.1	-26.3	30.7
0.12	172.2	-22.3	34.6
0.144	166.7	-20.8	42.1
0.176	154.1	-21.4	53.4
0.224	132	-20	66.4
0.256	112.3	-21.6	84.5
0.288	92	-22.8	101.7
0.32	79.5	-23.8	119.6
0.384	84.5	-17.5	135.9
0.448	105.3	-3.7	145.6
0.512	157.7	28.6	152.2
1	354.7	185.6	3.8
1.2	378.4	209.6	6.1
1.4	389.3	219.5	8.1
3.4	388.4	254.4	7.8
5.4	386.6	303.9	2.4
7.2	404.3	334	12.8
9.6	339.4	300	6.6
12.8	28.9	30.7	14.6
14.4	-171.1	-50.4	-9.5
14.6	-179.5	-58	-8.8
14.8	-182.9	-62.3	-5.7
15	-186.7	-56.5	-6.7
15.2	-186.6	-56.3	-4.6
15.4	-204.4	-76.4	-5.4
15.6	-209.6	-85.9	-5.9
15.8	-221.5	-94.1	-6.3
16	-220.7	-91.7	-10.8
16.2	-233.8	-101.7	-9.3
16.4	-237.5	-95.4	-6.3
16.6	-229.6	-102.5	-6
16.8	-239.9	-117	-4.7
17	-245.7	-116.3	-6.5
17.2	-247.9	-118.3	-2.8
17.4	-241.7	-105.5	-4.4
17.6	-235.2	-96.2	-1.7
17.8	-236.8	-92.5	-1.8

18	-236.5	-91	-0.4
18.2	-238.9	-88.4	1.8
18.4	-239.9	-90.7	2.5
18.6	-229	-80.1	4.4
18.8	-239.4	-82.5	4.8
19	-229.1	-72.1	10
19.2	-226.4	-63.2	9.2
19.4	-210.7	-58.6	13.9
19.6	-203.4	-37.7	13.8
19.8	-207	-35.6	13.5
20	-211.4	-43.4	12.9
20.2	-205.4	-35.4	11.8
20.4	-193	-18.1	18.4
20.6	-199.1	-9.1	15.3
20.8	-195.8	-3.5	14
21	-190.1	15.4	12.6
21.2	-185.6	12.2	12.5
21.4	-192.1	18.7	12.7
21.6	-192.5	25.9	10.1
21.8	-206.2	21.8	10.8
22	-216.4	27.7	11.8
22.2	-168.8	62.5	9.5
22.4	-152.2	86	11.1
22.6	-151.6	96.7	7
22.8	-149.2	109.2	5.4
23	-149.1	105.1	4.3
23.2	-135.7	115.9	10.1
23.4	-122	136.8	2.2
23.6	-120.9	145.3	4.8
23.8	-109.5	158.7	2
24	-89.7	172.2	3.8
24.2	-75	181.9	-0.7
24.4	-77.8	194	4
24.6	-87.6	190	-2
24.8	-68.9	210.4	-1
25	-58.7	213.5	-4.7
25.2	-63.9	205.9	-5.5
25.4	-64.3	189.8	-5.4
25.6	-71.2	192.2	-6
25.8	-64.5	198.6	-10.3
26	-56.3	205.5	-9
26.2	-52	209.6	-10.8
26.4	-48.3	210.2	-11.6
26.6	-45.9	200.2	-12.2
26.8	-39.9	199.7	-12.8
27	-41.9	185.6	-16.6
27.2	-30.1	191.3	-15.9
27.4	-27.4	186	-19.6
27.6	-14.5	192.1	-22.4

27.8	-21	175.4	-23.6
28	-25.8	169.5	-30
28.2	-20.8	149.8	-32.8
28.4	-26.4	137.8	-30
28.6	-37.3	117.7	-33.4
28.8	-35.8	119	-32.8
29	-31.1	113.3	-32.4
29.2	-20.8	123.9	-33.1
29.4	-22.5	139	-37.4
29.6	-29.4	109.4	-33.4
29.8	-22.6	108.2	-32.6
30	-33.5	102	-33
30.2	-26.1	100.1	-32.8
30.4	-26.2	95.7	-30.6
30.6	-43	81.9	-31.2
30.8	-37	87.3	-27.7
31	-24.8	94.3	-27.7
31.2	-31.1	82.6	-30.5
31.4	-47.3	67.7	-28.1
31.6	-47.2	59.7	-30.8
31.8	-55.9	51.5	-30.9
32	-65.7	42.9	-33
32.2	-67.9	40	-32.6
32.4	-71.7	36.1	-30.3
32.6	-70.6	38.3	-31.1
32.8	-79.2	32.5	-31.3
33	-82.1	37.1	-27.8
33.2	-81.4	36.9	-27.9
33.4	-85.8	32.4	-34
33.6	-97.7	25.4	-31
33.8	-100.2	20.4	-30.2
34	-101.1	17.1	-29.9
34.2	-102.5	14	-30.7
34.4	-104	13.3	-28.2
34.6	-91.6	28.6	-30.9
34.8	-84.2	38.8	-28
35	-77.4	29.1	-23.5
35.2	-100.3	13.8	-26
35.4	-103.5	5.1	-24.9
35.6	-116.6	-3.3	-21.1
35.8	-114.3	0.1	-22.2
36	-117.5	-7.3	-23
36.2	-126.7	-17.8	-21.8
36.4	-131.9	-25.4	-19.4
36.6	-131.4	-33.1	-19.8
36.8	-150.3	-47	-19.5
37	-166.1	-59.8	-18.2

Table C-5: Contour Data, Hoop Stress

	mid weld -10 mm	mid weld -5 mm	mid weld	mid weld +5 mm	mid weld +10 mm
Depth from ID [mm]	**Stress [MPa]**	**Stress [MPa]**	**Stress [MPa]**	**Stress [MPa]**	**Stress [MPa]**
0.0					
1.0	-198.6	-220.5	-221.0	-192.8	-136.4
2.0	-98.9	-98.8	-90.1	-68.9	-39.8
3.0	-46.9	-26.6	-3.2	21.0	39.9
4.0	-16.3	19.6	56.1	86.7	103.4
5.0	1.3	49.8	100.4	135.2	149.6
6.0	12.0	69.2	125.6	167.9	182.2
7.0	19.1	80.2	141.5	186.9	200.0
8.0	20.3	90.1	147.6	192.4	205.2
9.0	17.9	94.3	146.5	189.2	198.8
10.0	14.2	89.4	139.6	178.8	183.3
11.0	9.1	81.6	128.3	161.9	162.5
12.0	3.4	71.6	114.1	141.6	137.4
13.0	-3.7	60.2	98.2	119.0	110.2
14.0	-10.9	47.5	81.9	96.6	82.0
15.0	-18.6	34.2	65.4	75.3	57.8
16.0	-26.3	21.4	50.4	57.3	36.8
17.0	-34.4	9.6	37.7	42.8	21.1
18.0	-42.0	-0.4	27.9	32.9	11.5
19.0	-49.1	-8.1	20.9	27.9	8.3
20.0	-55.3	-13.7	18.5	29.9	14.3
21.0	-60.2	-16.9	19.9	36.7	25.6
22.0	-63.4	-17.3	25.2	49.1	43.2
23.0	-63.8	-15.2	34.0	66.2	65.2
24.0	-62.5	-10.2	46.1	86.7	93.2
25.0	-57.8	-2.5	61.3	110.4	122.8
26.0	-49.9	9.2	78.9	135.3	152.5
27.0	-38.4	22.9	98.4	159.5	181.9
28.0	-23.4	39.3	118.1	183.7	208.0
29.0	-5.0	57.5	137.7	205.2	229.6
30.0	16.6	76.8	155.7	221.5	244.6
31.0	39.4	95.8	171.4	232.9	252.5
32.0	62.0	113.9	182.6	235.9	252.3
33.0	82.2	128.9	188.1	232.1	242.7
34.0	95.9	136.2	185.6	220.7	226.1
35.0	99.2	131.0	172.6	200.3	205.5
36.0	79.3	105.7	141.7	173.3	187.8
37.0	7.5	28.5	78.6	141.2	194.7

Table C-6: Contour Data, Axial Stress

	mid weld -10 mm	mid weld -5 mm	mid weld	mid weld +5 mm	mid weld +10 mm
Depth from ID [mm]	**Stress [MPa]**	**Stress [MPa]**	**Stress [MPa]**	**Stress [MPa]**	**Stress [MPa]**
0.0					
1.0	-293.5	-275.6	-249.1	-216.2	-281.9
2.0	-250.7	-236.0	-177.8	-189.0	-245.6
3.0	-206.3	-200.0	-138.3	-166.7	-216.0
4.0	-166.4	-168.7	-115.9	-148.9	-192.0
5.0	-130.7	-142.2	-103.6	-134.9	-172.4
6.0	-103.8	-122.2	-99.1	-125.1	-159.8
7.0	-85.7	-108.5	-99.8	-120.2	-152.0
8.0	-75.7	-101.4	-104.3	-118.8	-150.2
9.0	-74.1	-101.6	-111.7	-121.7	-152.8
10.0	-78.2	-106.5	-120.8	-128.0	-156.4
11.0	-92.9	-116.9	-130.2	-136.2	-170.0
12.0	-113.0	-131.0	-140.4	-146.8	-182.9
13.0	-137.9	-147.3	-149.8	-158.1	-199.4
14.0	-163.6	-164.3	-158.1	-168.8	-214.1
15.0	-187.4	-180.3	-164.0	-178.0	-224.9
16.0	-211.3	-193.2	-166.8	-184.5	-235.1
17.0	-227.6	-201.7	-166.1	-186.9	-239.0
18.0	-237.9	-204.7	-161.3	-184.8	-236.4
19.0	-241.9	-200.7	-151.8	-177.2	-230.1
20.0	-235.1	-189.1	-137.6	-163.9	-214.5
21.0	-218.7	-169.3	-117.7	-144.1	-191.8
22.0	-193.2	-141.3	-92.8	-118.2	-163.4
23.0	-157.2	-105.6	-62.1	-86.2	-127.2
24.0	-113.2	-62.6	-25.9	-49.2	-85.4
25.0	-61.6	-13.9	15.1	-6.9	-38.0
26.0	-5.2	39.2	60.5	39.0	12.4
27.0	54.5	95.1	109.4	87.6	65.7
28.0	115.1	152.2	161.0	138.1	119.8
29.0	171.6	207.7	214.2	188.6	171.1
30.0	223.4	259.5	266.6	237.5	219.7
31.0	265.6	306.0	316.5	284.0	264.0
32.0	296.5	345.0	361.3	325.6	301.9
33.0	316.4	374.8	397.9	362.3	332.7
34.0	321.8	393.8	422.8	392.3	355.2
35.0	316.3	398.3	427.8	412.8	369.7
36.0	305.9	385.8	401.5	420.3	377.6
37.0	307.8	344.0	311.4	406.1	382.1

Table C-7: Participant Modeling Data (1 of 10)

Depth from ID [mm]	Axial ISO [MPa]	Hoop ISO [MPa]	Axial KIN [MPa]	Hoop KIN [MPa]
0.00	-330	-124	-143	-54
1.51	-297	-28	-148	-47
3.03	-211	38	-149	-42
4.54	-180	53	-153	-63
6.05	-137	73	-184	-86
7.57	-84	254	-195	-72
9.08	-166	219	-201	-90
10.59	-153	136	-152	-64
12.11	-210	149	-169	-64
13.62	-235	126	-142	-54
15.13	-340	-55	-113	-60
16.65	-326	-203	-96	-34
18.16	-430	-310	-87	-42
19.67	-330	-202	-81	-63
21.18	-213	-232	-52	-78
22.70	-151	-106	-49	-107
24.21	6	16	-4	-107
25.72	93	68	40	-89
27.24	212	190	92	-54
28.75	332	335	159	-3
30.26	442	390	216	51
31.78	471	308	249	102
33.29	548	279	280	153
34.80	451	167	296	167

Table C-8: Participant Modeling Data (2 of 10)

Depth from ID [mm]	Axial ISO [MPa]	Hoop ISO [MPa]	Axial KIN [MPa]	Hoop KIN [MPa]
0.00	-157	65	-71	6
1.65	-58	195	-53	47
3.29	3	285	-65	21
4.94	8	255	-68	4
6.58	-25	249	-64	-4
8.23	19	318	-53	-7
9.87	-3	231	-51	-10
11.52	-36	185	-65	-18
13.16	-120	164	-71	-20
14.81	-193	160	-61	-11
16.45	-208	96	-55	-2
18.10	-277	53	-54	3
19.75	-232	22	-55	3
21.39	-162	94	-54	-1
23.04	-142	72	-50	-9
24.68	-75	136	-40	-17
26.33	-49	133	-25	-21
27.97	11	189	2	-12
29.62	135	285	42	11
31.26	241	343	94	44
32.91	309	395	144	70
34.55	349	365	183	73
36.20	295	228	224	61
37.85	277	169	260	47

Table C-9: Participant Modeling Data (3 of 10)

Depth from ID [mm]	Axial ISO [MPa]	Hoop ISO [MPa]	Axial KIN [MPa]	Hoop KIN [MPa]
0.00	-270	-75	-131	-90
1.63	-250	-66	-127	-82
3.25	-181	54	-138	-81
4.88	-155	98	-138	-90
6.51	-116	181	-144	-89
8.13	-92	206	-124	-67
9.76	-115	272	-147	-78
11.39	-139	259	-120	-64
13.02	-178	203	-117	-61
14.64	-195	225	-96	-49
16.27	-282	125	-85	-48
17.90	-338	-6	-60	-47
19.52	-391	-127	-68	-50
21.15	-299	-178	-47	-79
22.78	-223	-141	-51	-90
24.40	-77	-15	-1	-94
26.03	82	80	49	-81
27.66	239	196	87	-76
29.29	385	312	125	-50
30.91	467	222	178	0
32.54	525	209	221	56
34.17	473	162	260	103
35.79	418	111	276	119
37.42	402	111	276	144

Table C-10: Participant Modeling Data (4 of 10)

Depth from ID [mm]	Axial ISO [MPa]	Hoop ISO [MPa]	Axial KIN [MPa]	Hoop KIN [MPa]
0.00	-196	-25	-174	-62
1.51	-151	166	-159	-51
3.03	-128	241	-148	-44
4.54	-180	159	-141	-41
6.06	-138	246	-135	-39
7.57	-161	218	-127	-30
9.08	-108	288	-112	-16
10.60	-76	269	-93	-16
12.11	-75	299	-87	-2
13.63	-48	273	-82	12
15.14	-126	256	-72	24
16.65	-231	163	-71	20
18.17	-307	32	-76	0
19.68	-349	-87	-85	-30
21.19	-337	-134	-55	-26
22.71	-281	-91	-5	-44
24.22	-154	27	35	-25
25.74	-2	154	45	-42
27.25	110	258	58	-54
28.76	157	166	84	-46
30.28	274	277	118	-31
31.79	354	210	163	-16
33.30	488	277	207	7
34.82	515	181	236	42
36.33	494	170	255	71
37.85	479	166	265	88

Table C-11: Participant Modeling Data (5 of 10)

Depth from ID [mm]	Axial ISO [MPa]	Hoop ISO [MPa]	Axial KIN [MPa]	Hoop KIN [MPa]
0.00	-409	-340	-146	-123
1.51	-409	-345	-147	-122
3.03	-358	-256	-140	-120
4.54	-282	-150	-134	-124
6.06	-192	7	-136	-109
7.57	-154	39	-179	-147
9.09	-167	74	-175	-154
10.60	-91	22	-179	-173
12.12	-34	41	-171	-194
13.63	-22	93	-142	-191
15.15	-55	108	-84	-178
16.66	-169	-5	-31	-154
18.18	-251	-141	-24	-156
19.69	-318	-252	2	-163
21.20	-271	-242	5	-173
22.72	-174	-147	23	-163
24.23	-46	-56	31	-157
25.75	71	-33	66	-131
27.26	195	56	84	-116
28.78	306	19	130	-73
30.29	421	96	147	-56
31.81	388	12	171	-29
33.32	505	93	205	10
34.84	409	20	221	38
36.35	382	17	239	64
37.87	378	31	251	84

Table C-12: Participant Modeling Data (6 of 10)

Depth from ID [mm]	Axial ISO [MPa]	Hoop ISO [MPa]	Axial KIN [MPa]	Hoop KIN [MPa]
0.00	-154	81	-86	82
1.71	-206	33	-144	44
3.58	-91	308	-93	46
5.23	-146	227	-114	33
6.80	-158	185	-108	28
8.36	-213	138	-105	33
9.90	-144	31	-103	40
11.47	-70	102	-120	35
13.03	-107	122	-135	10
14.52	-112	24	-114	14
15.78	-170	21	-115	25
17.00	-317	-95	-140	14
17.38	-340	-122	-145	8
18.42	-390	-187	-154	-3
19.81	-358	-186	-156	-24
21.19	-305	-197	-158	-51
21.27	-303	-200	-158	-52
22.66	-269	-254	-146	-62
23.95	-215	-129	-151	-84
25.27	-211	-97	-105	-51
26.57	-183	-119	-77	-29
27.28	-192	-109	-84	-39
27.88	-198	-86	-91	-47
29.27	-116	32	-92	-58
29.82	-64	81	-85	-54
30.54	14	148	-74	-45
31.70	104	232	-47	-20
32.67	83	190	-5	31
33.59	90	129	42	75
34.69	103	129	109	127
35.85	123	169	162	165
35.90	126	173	162	165
37.02	168	257	175	151
38.23	280	348	195	155
39.45	442	457	214	168
40.69	498	483	243	198
41.95	526	477	284	238
43.24	489	396	313	269
44.56	420	292	340	308
45.92	394	215	306	263
47.31	380	135	253	152

Table C-13: Participant Modeling Data (7 of 10)

Depth from ID [mm]	Axial ISO [MPa]	Hoop ISO [MPa]	Axial KIN [MPa]	Hoop KIN [MPa]
0.0	-59	238	43	240
1.6	78	447	37	242
3.3	120	501	21	219
4.9	99	480	9	206
6.6	74	546	13	201
8.2	81	563	16	206
9.9	26	513	18	207
11.5	-4	451	5	188
13.2	-258	151	-1	181
14.8	-380	64	-15	179
16.5	-320	63	-51	162
18.1	-239	88	-85	133
19.7	-183	122	-106	105
21.4	-133	178	-115	76
23.0	-110	227	-106	62
24.7	-118	254	-89	68
26.3	-44	341	-72	79
28.0	96	404	-49	97
29.6	228	483	-15	125
31.3	224	471	44	179
32.9	224	522	117	255
34.6	161	459	152	277
36.2	177	211	154	229
37.8	279	157	148	200

Table C-14: Participant Modeling Data (8 of 10)

Depth from ID [mm]	Axial ISO [MPa]	Hoop ISO [MPa]	Axial KIN [MPa]	Hoop KIN [MPa]
0.00	-289	-90	-137	-47
1.50	-243	-6	-125	-29
3.01	-79	156	-126	-36
4.51	21	255	-121	-43
6.01	7	276	-103	-39
7.52	-45	276	-95	-26
9.02	-52	312	-94	-19
10.52	32	273	-72	-4
12.03	-28	160	-58	-17
13.53	-129	202	-43	0
15.04	-180	74	-59	12
16.54	-422	-123	-76	7
18.04	-360	-201	-116	-23
19.55	-394	-173	-79	-26
21.05	-320	-152	-88	-58
22.55	-234	-9	-61	-68
24.06	-163	-10	-57	-79
25.56	-6	152	-5	-66
27.06	59	157	16	-51
28.57	162	193	75	-15
30.07	260	179	124	13
31.57	403	257	156	30
33.08	438	221	213	56
34.58	455	226	254	74
36.08	412	147	278	96
37.59	443	161	290	113

Table C-15: Participant Modeling Data (9 of 10)

Depth from ID [mm]	Axial ISO [MPa]	Hoop ISO [MPa]	Axial KIN [MPa]	Hoop KIN [MPa]
0.00	-99	107	-186	-165
0.38	-73	147	-136	-110
0.76	-76	153	-113	-81
1.14	-105	125	-117	-79
1.51	-140	99	-129	-86
1.89	-166	86	-138	-91
2.27	-187	65	-147	-98
2.65	-202	45	-154	-104
3.03	-226	18	-162	-109
3.41	-245	-12	-168	-114
3.78	-252	-23	-172	-118
4.16	-233	22	-176	-122
4.54	-188	113	-179	-129
4.92	-173	145	-181	-133
5.30	-189	114	-181	-137
5.68	-203	90	-182	-140
6.06	-208	80	-183	-142
6.43	-219	59	-181	-144
6.81	-219	65	-179	-145
7.19	-216	65	-177	-145
7.57	-240	-7	-175	-145
7.95	-203	24	-173	-144
8.33	-117	181	-170	-142
8.71	-100	244	-166	-140
9.08	-122	223	-161	-136
9.46	-99	190	-156	-131
9.84	-107	146	-151	-126
10.22	-123	106	-145	-120
10.60	-106	108	-140	-115
10.98	-64	143	-135	-109
11.35	-40	171	-131	-104
11.73	-28	194	-128	-99
12.11	-25	219	-126	-93
12.49	-25	242	-124	-88
12.87	-41	231	-122	-83
13.25	-63	204	-120	-79
13.63	-77	178	-119	-75
14.00	-93	154	-119	-72
14.38	-133	149	-120	-70
14.76	-184	145	-122	-67
15.14	-255	150	-127	-65
15.52	-276	120	-132	-65
15.90	-297	84	-138	-65
16.27	-319	45	-142	-65
16.65	-340	5	-134	-67
17.03	-357	-40	-123	-69
17.41	-377	-85	-108	-70

17.79	-399	-117	-96	-71
18.17	-430	-129	-88	-72
18.55	-457	-133	-84	-76
18.92	-453	-150	-82	-81
19.30	-426	-176	-81	-87
19.68	-412	-192	-72	-84
20.06	-403	-208	-60	-79
20.44	-394	-224	-46	-71
20.82	-391	-205	-36	-69
21.19	-378	-174	-28	-68
21.57	-359	-130	-23	-69
21.95	-322	-118	-18	-72
22.33	-285	-112	-11	-74
22.71	-250	-96	-5	-76
23.09	-222	-54	1	-80
23.47	-197	-4	6	-85
23.84	-171	45	10	-93
24.22	-142	66	14	-99
24.60	-117	62	19	-104
24.98	-95	52	24	-107
25.36	-55	60	32	-106
25.74	-6	87	41	-104
26.12	42	135	49	-101
26.49	91	197	59	-97
26.87	133	245	68	-92
27.25	169	244	78	-87
27.63	209	252	88	-81
28.01	248	275	98	-75
28.39	276	262	109	-68
28.76	280	191	120	-61
29.14	275	145	131	-53
29.52	303	175	142	-46
29.90	345	205	155	-37
30.28	393	230	168	-27
30.66	446	265	181	-17
31.04	519	321	197	-5
31.41	564	341	207	5
31.79	580	312	219	18
32.17	543	235	230	33
32.55	519	197	239	47
32.93	531	205	249	61
33.31	566	237	258	75
33.68	597	261	267	89
34.06	626	282	278	104
34.44	590	244	286	116
34.82	516	184	293	128
35.20	458	140	297	136
35.58	448	135	300	142
35.96	445	139	305	150

36.33	444	135	308	157
36.71	447	140	309	161
37.09	463	162	320	180
37.47	444	141	316	175
37.85	367	50	281	119

Table C-16: Participant Modeling Data (10 of 10)

Depth from ID [mm]	Axial ISO [MPa]	Hoop ISO [MPa]	Axial KIN [MPa]	Hoop KIN [MPa]
0.00	-217	-50	-137	47
1.19	-199	-39	-117	57
1.77	-202	-10	-93	69
2.33	-182	104	-85	70
2.89	-150	177	-85	62
3.74	-123	187	-84	54
4.59	-45	256	-85	45
5.26	-6	322	-85	39
5.68	16	367	-85	35
6.10	35	379	-87	31
6.86	43	391	-84	27
7.80	38	410	-79	24
8.38	26	410	-77	23
8.97	22	393	-75	22
9.56	23	382	-74	22
10.46	35	365	-73	21
11.36	1	336	-75	15
12.26	-58	295	-74	9
13.16	-115	262	-75	11
14.06	-201	221	-79	19
14.96	-295	141	-87	25
15.86	-378	25	-107	12
16.76	-440	-66	-136	-19
17.66	-435	-121	-144	-32
18.56	-443	-173	-119	-34
19.46	-463	-197	-114	-53
20.36	-444	-200	-113	-75
21.26	-413	-189	-108	-85
22.16	-379	-130	-99	-90
23.06	-321	-80	-91	-93
23.96	-245	-21	-80	-90
24.86	-146	81	-65	-81
25.76	-35	169	-46	-68
26.66	70	237	-23	-51
27.56	163	298	4	-28
28.46	245	353	34	-1
29.13	311	387	61	23
29.81	331	345	90	47
30.48	359	317	122	77
31.16	438	379	160	111
32.06	528	405	206	147
32.96	584	390	254	181
33.86	539	260	298	206
34.76	469	178	312	213
35.66	454	168	316	209
36.56	447	163	323	202
37.20	443	159	329	198

37.85	440	155	332	196

Appendix D: Comprehensive Flaw Growth Calculations

This appendix provides all of the results of flaw growth calculations associated with the Phase 2b study. Table 3 shows all inputs to these calculations, save the WRS inputs (which vary). The WRS inputs for each set of calculations are shown in this appendix. Section D.1 shows circumferential crack growth, while Section D.2 shows axial crack growth. Section 3.3 provides a discussion of this work for one example case. With the exception of Section D.2.1, no further technical discussion is offered here. Regarding the modeling WRS data, flaw growth calculations are presented for WRS calculated from isotropic hardening models, kinematic hardening models, and the average WRS of the two hardening models.

D.1 Circumferential Crack Growth

D.1.1 Operating Loads Only

The residual stress magnitude was set to zero through the wall thickness for this calculation. Figures D-1 and D-2 show K_{90} and the depth growth normalized to the wall thickness, respectively. Figures D-3 and D-4 show K_0 and the length growth normalized to the circumference, respectively.

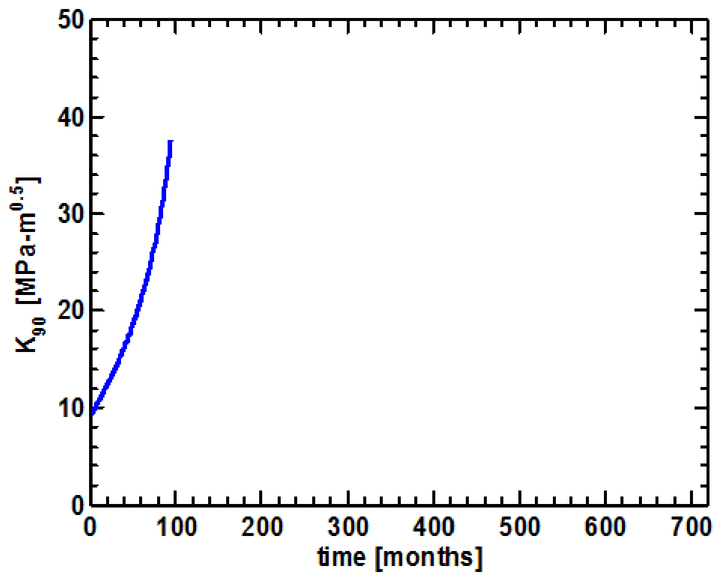

Figure D-1: K_{90} for No Residual Stress

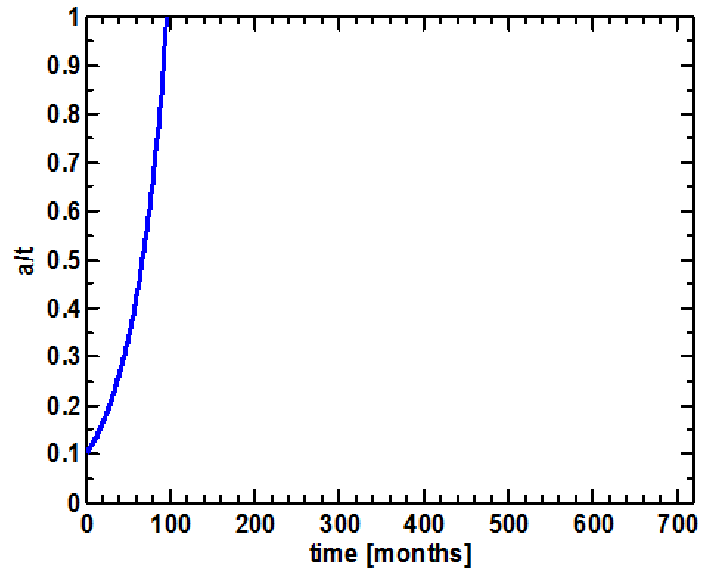

Figure D-2: Depth Growth for No Residual Stress

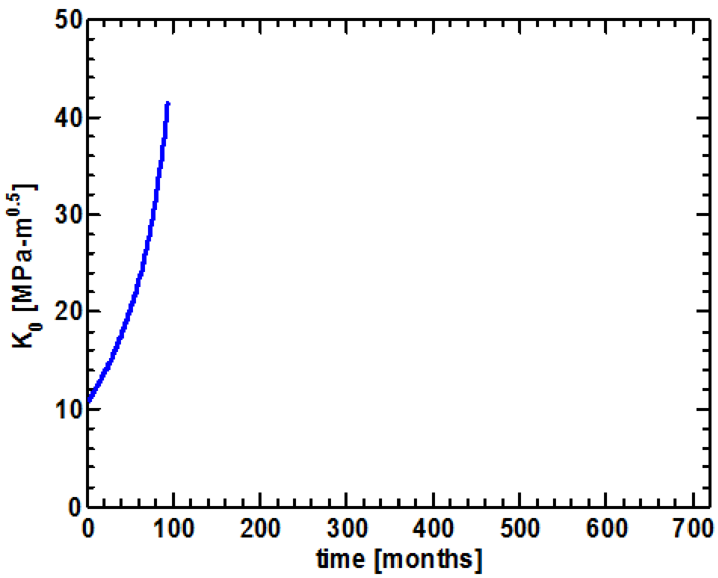

Figure D-3: K_0 for No Residual Stress

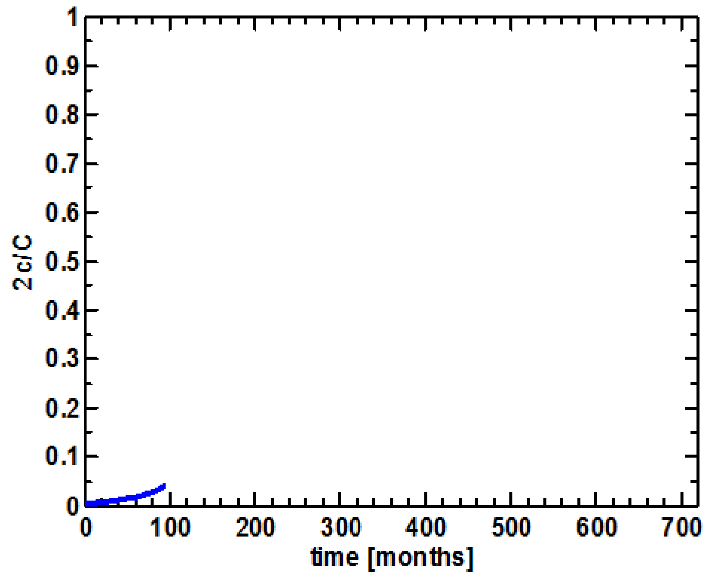

Figure D-4: Length Growth for No Residual Stress

D.1.2 Measurement WRS

Figure D-5 shows the residual stress input for this set of calculations. Figures D-6 and D-7 show K_{90} and the depth growth normalized to the wall thickness, respectively. Figures D-8 and D-9 show K_0 and the length growth normalized to the circumference, respectively.

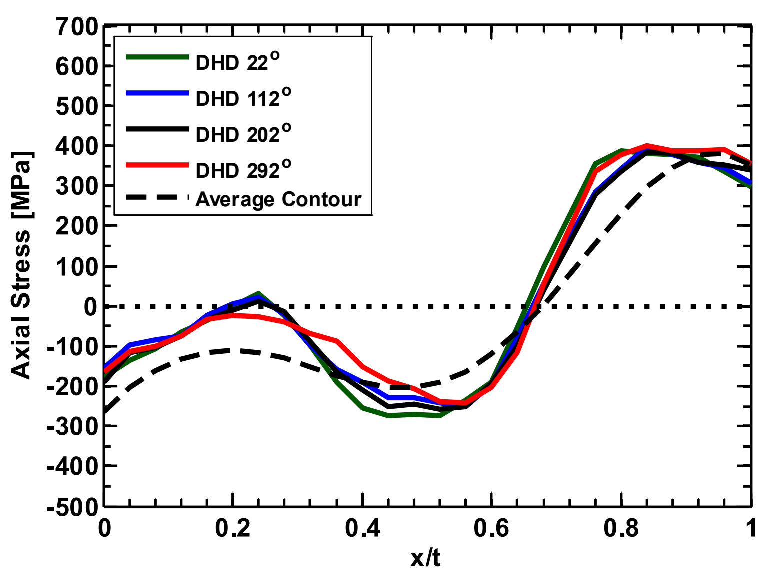

Figure D-5: Residual Stress Input

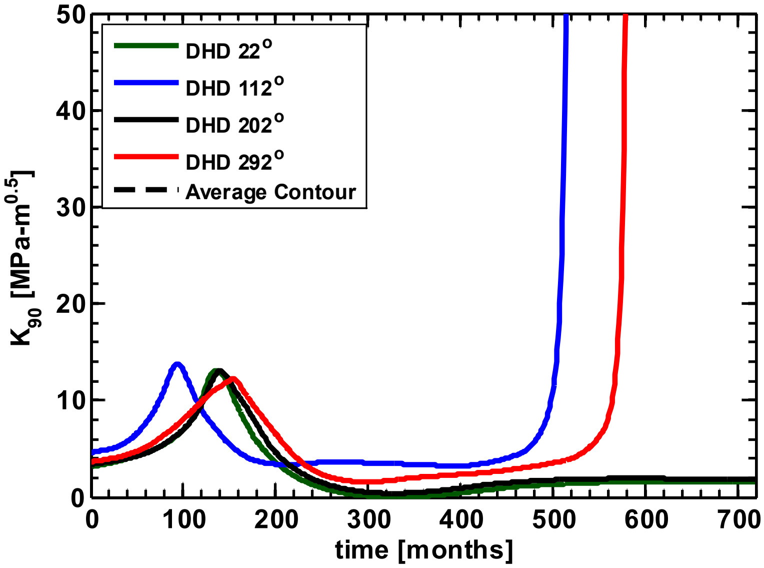

Figure D-6: Stress Intensity Factor at the Deepest Point

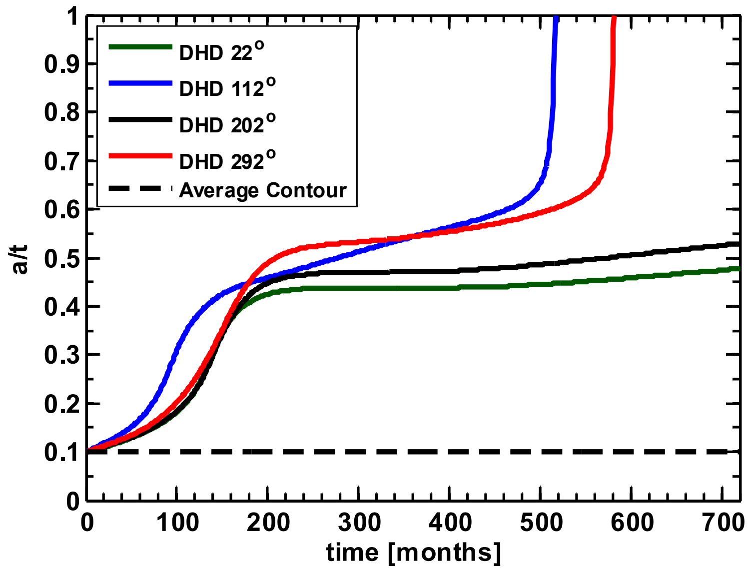

Figure D-7: Depth Growth

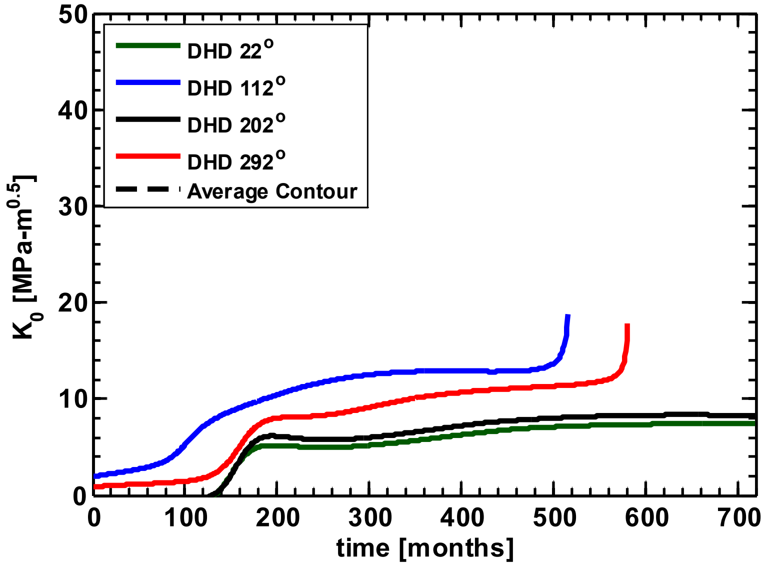

Figure D-8: Stress Intensity Factor at the Surface Point

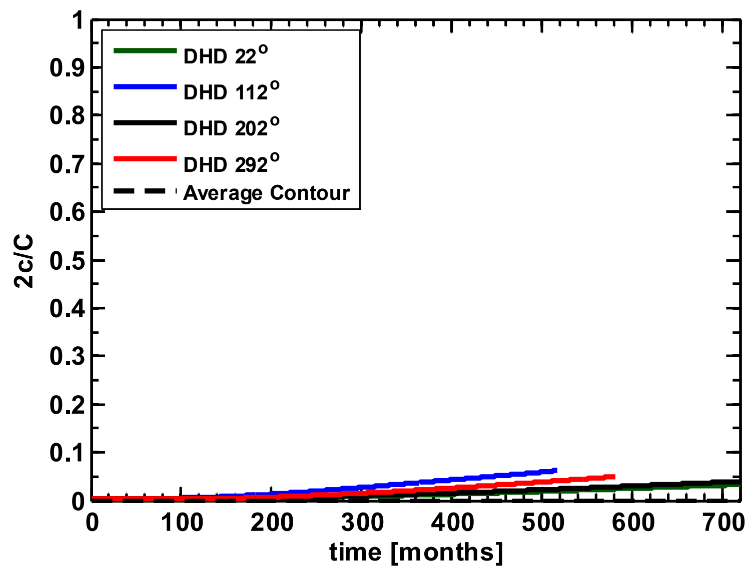

Figure D-9: Length Growth

Figures D-10 and D-11 replot Figures D-6 and D-8 as a function of a/t, respectively.

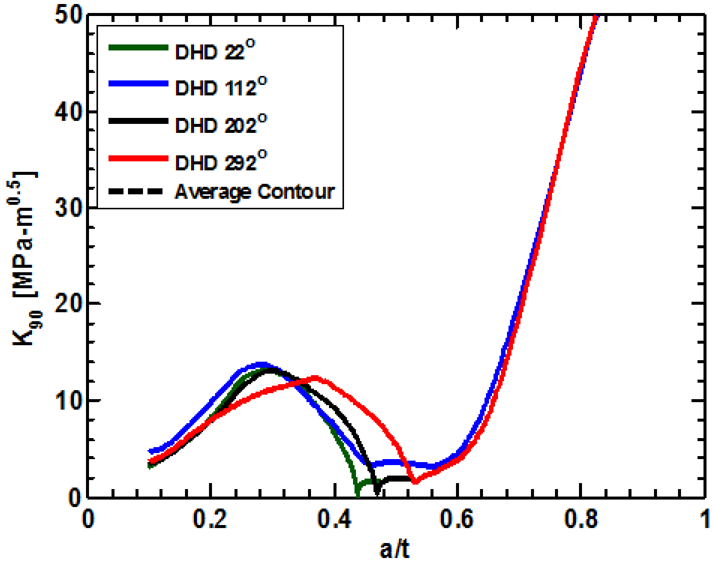

Figure D-10: Stress Intensity Factor at the Deepest Point

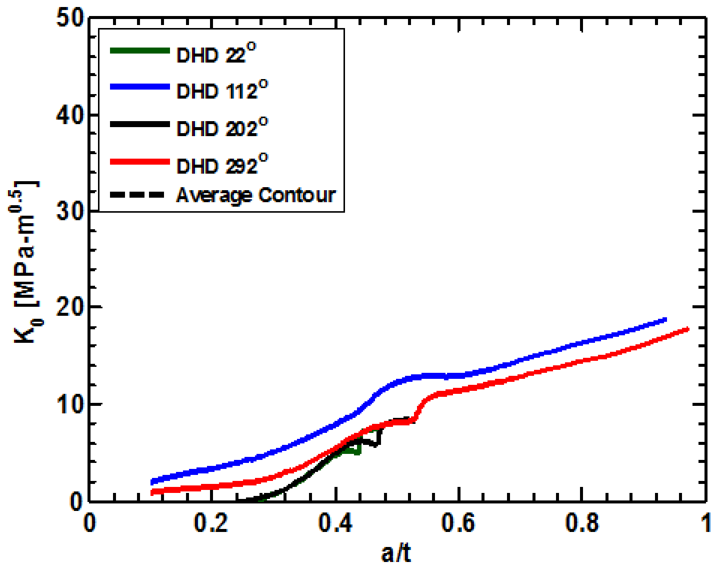

Figure D-11: Stress Intensity Factor at the Surface Point

D.1.3 Modeling WRS: Isotropic Hardening

Figure D-12 shows the residual stress input for this set of calculations. Figures D-13 and D-14 show K_{90} and the depth growth normalized to the wall thickness, respectively. Figures D-15 and D-16 show K_0 and the length growth normalized to the circumference, respectively.

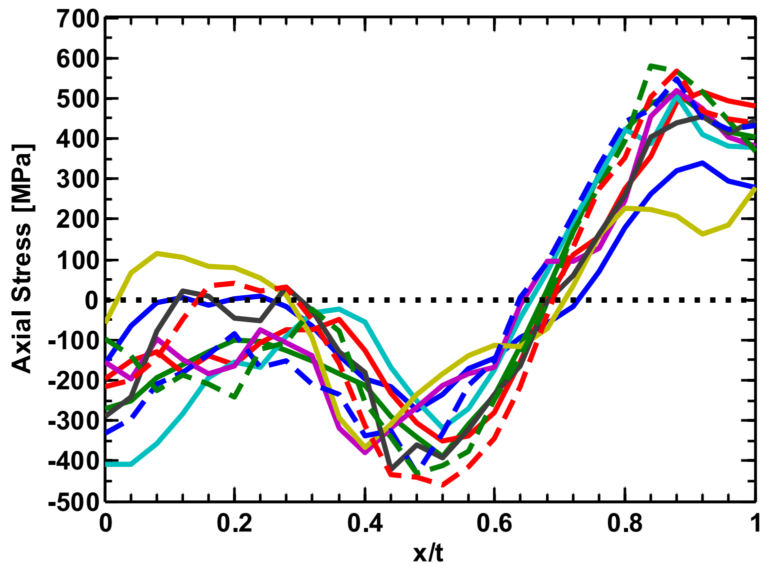

Figure D-12: Residual Stress Input

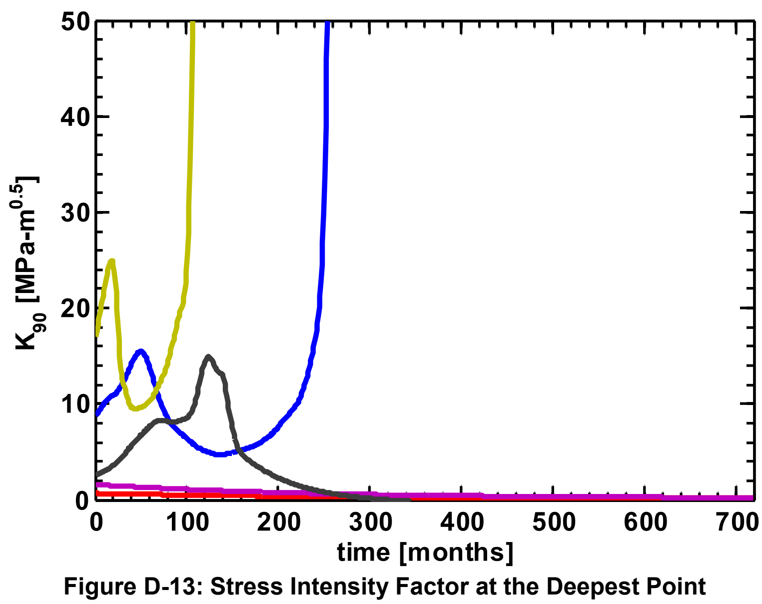

Figure D-13: Stress Intensity Factor at the Deepest Point

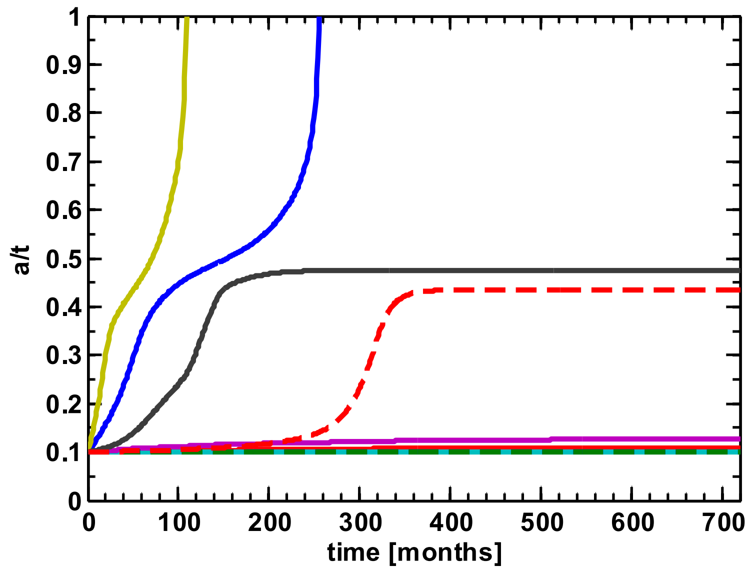

Figure D-14: Depth Growth

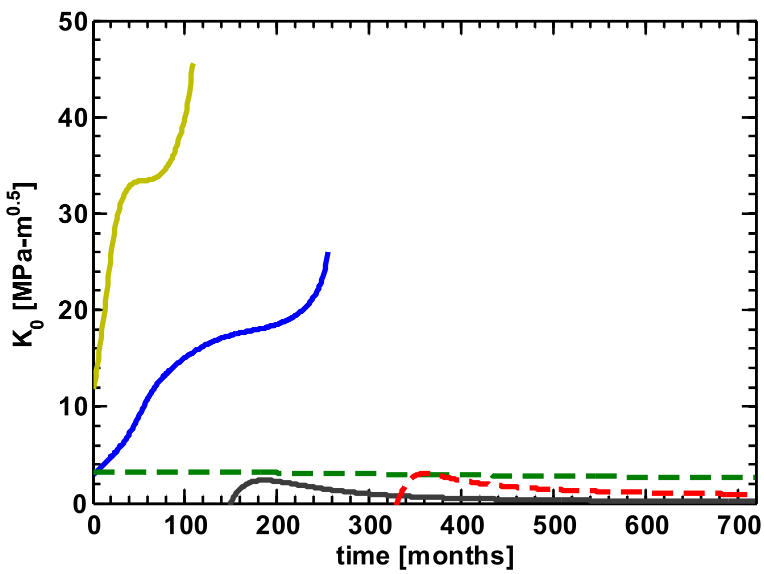

Figure D-15: Stress Intensity Factor at the Surface Point

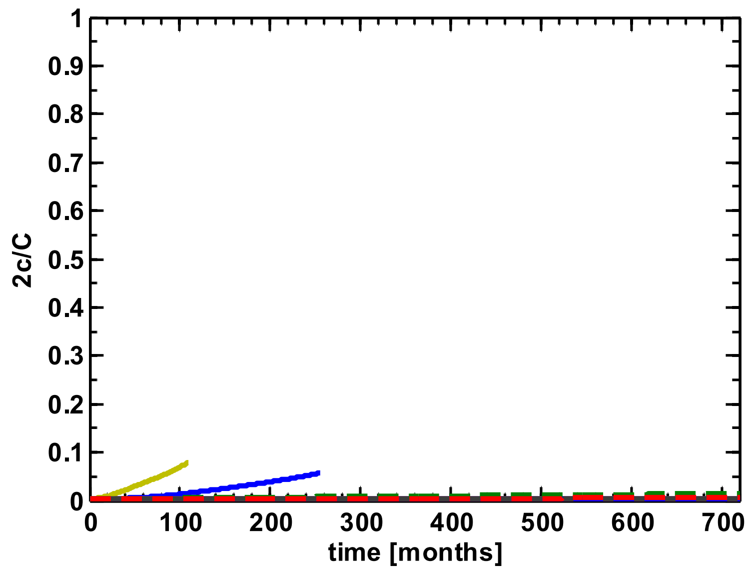

Figure D-16: Length Growth

Figures D-17 and D-18 replot Figures D-13 and D-15 as a function of *a*/*t*, respectively.

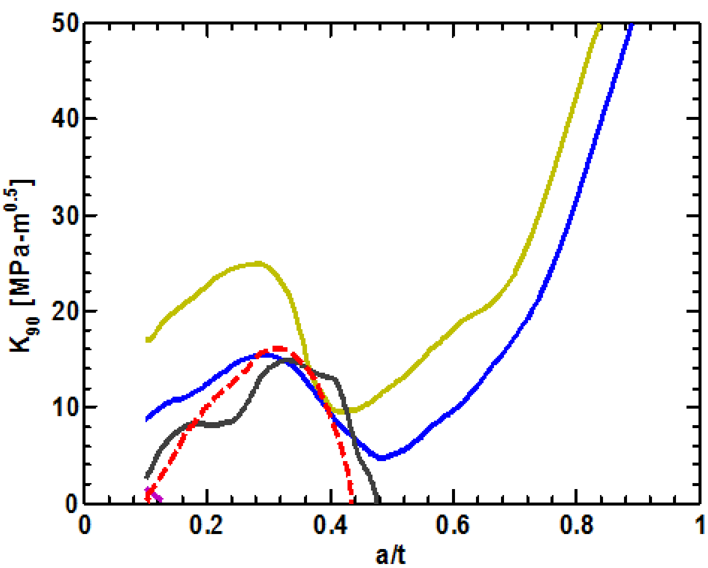

Figure D-17: Stress Intensity Factor at the Surface Point

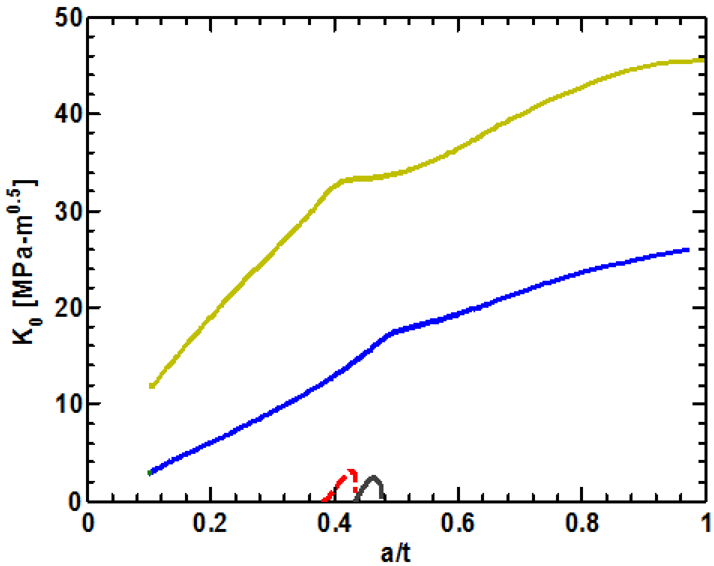

Figure D-18: Stress Intensity Factor at the Deepest Point

D.1.4 Modeling WRS: Kinematic Hardening

Figure D-19 shows the residual stress input for this set of calculations. Figures D-20 and D-21 show K_{90} and the depth growth normalized to the wall thickness, respectively. Figures D-22 and D-23 show K_0 and the length growth normalized to the circumference, respectively.

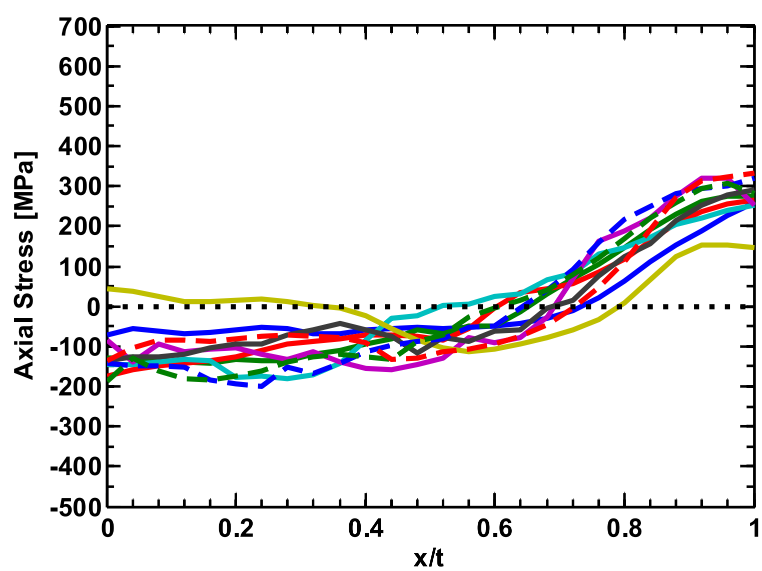

Figure D-19: Residual Stress Input

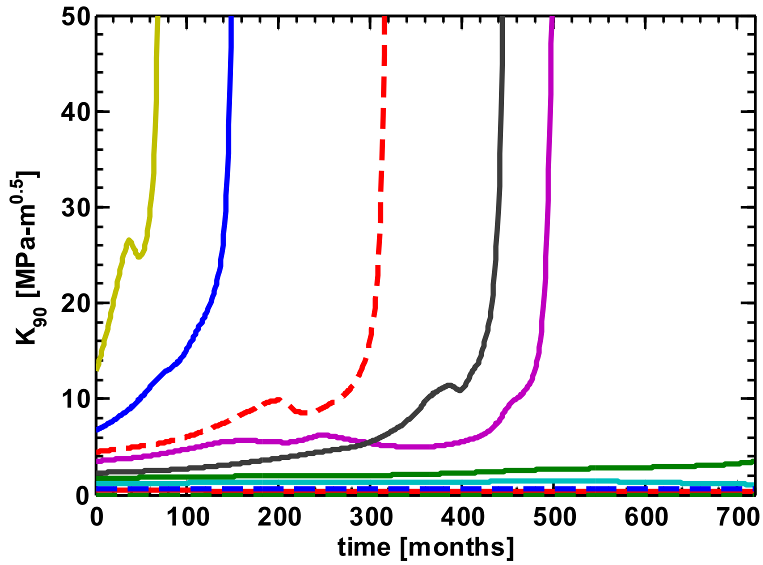

Figure D-20: Stress Intensity Factor at the Deepest Point

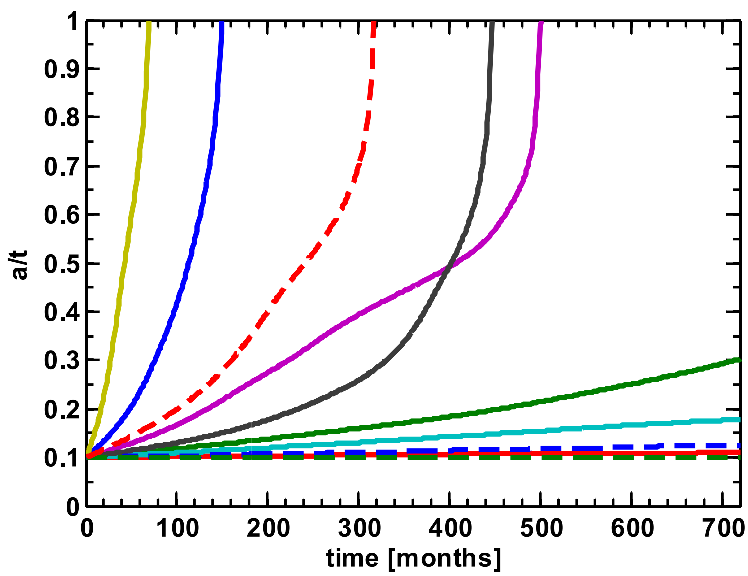

Figure D-21: Depth Growth

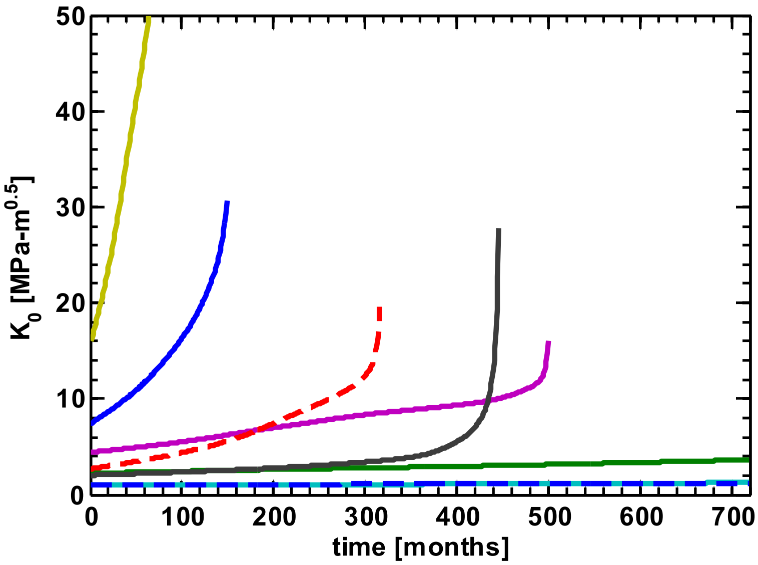

Figure D-22: Stress Intensity Factor at the Surface Point

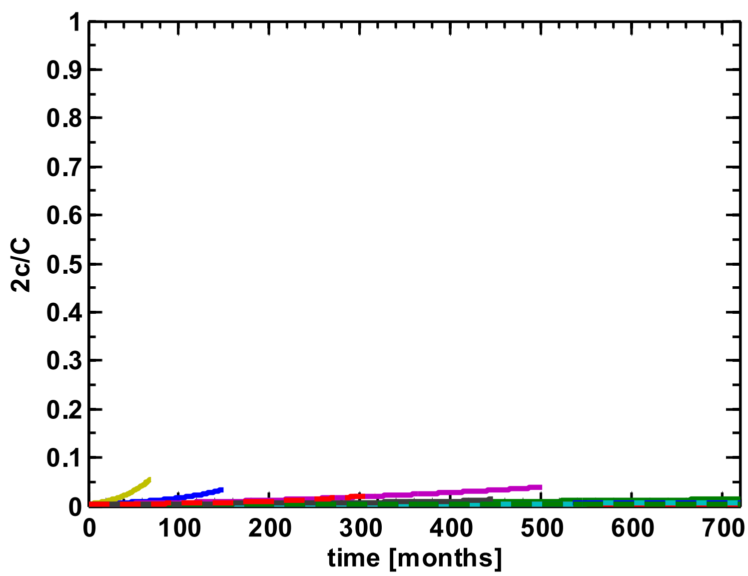

Figure D-23: Length Growth

Figures D-24 and D-25 replot Figures D-20 and D-22 as a function of a/t, respectively.

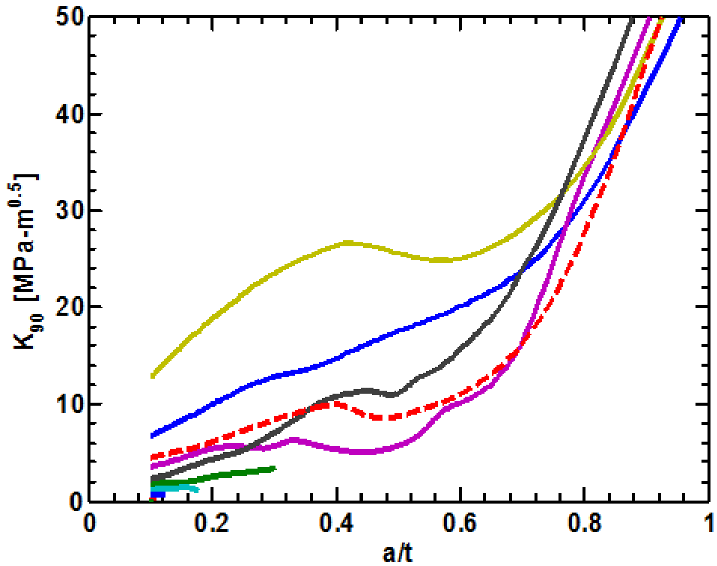

Figure D-24: Stress Intensity Factor at the Surface Point

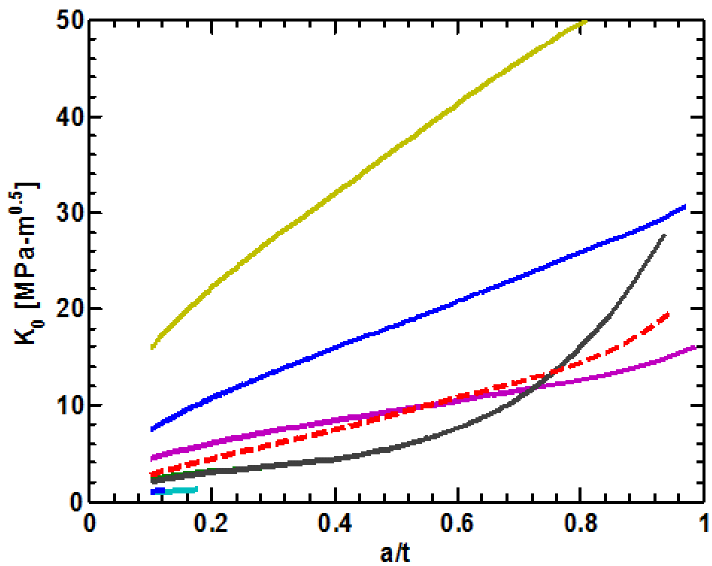

Figure D-25: Stress Intensity Factor at the Deepest Point

D.1.5 Modeling WRS: Average Hardening

Figure D-26 shows the residual stress input for this set of calculations. Figures D-27 and D-28 show K_{90} and the depth growth normalized to the wall thickness, respectively. Figures D-29 and D-30 show K_0 and the length growth normalized to the circumference, respectively.

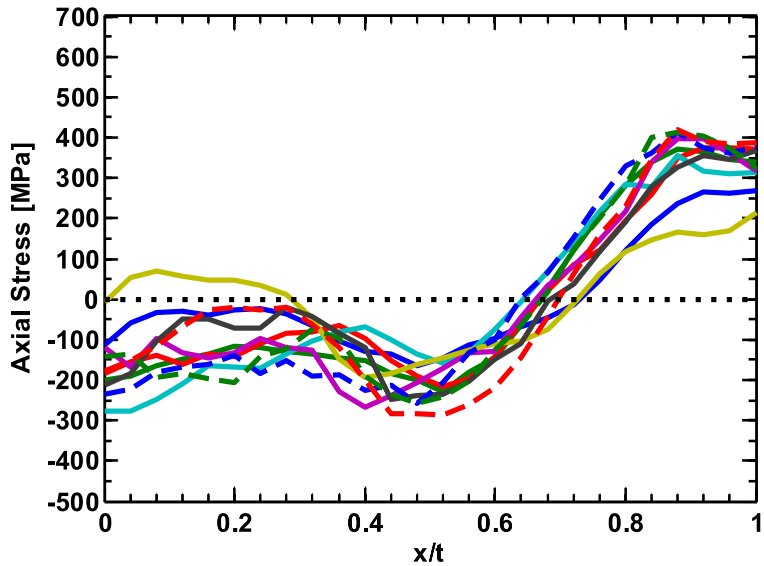

Figure D-26: Residual Stress Input

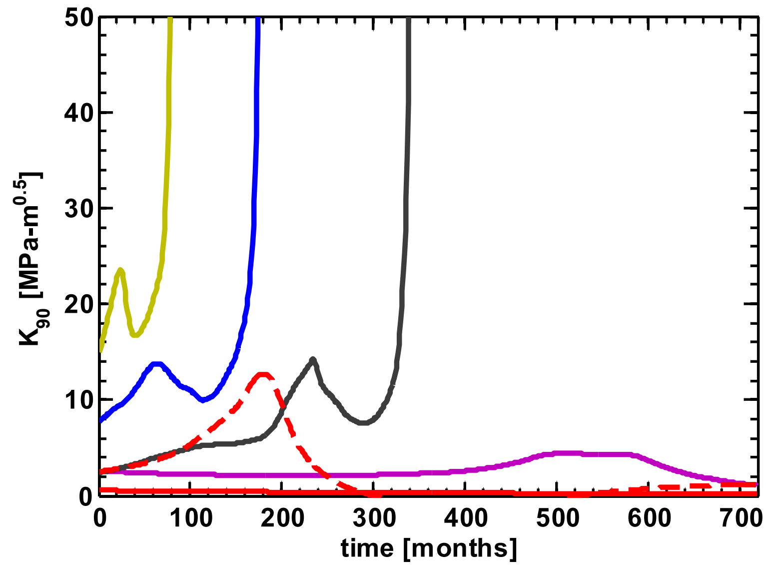

Figure D-27: Stress Intensity Factor at the Deepest Point

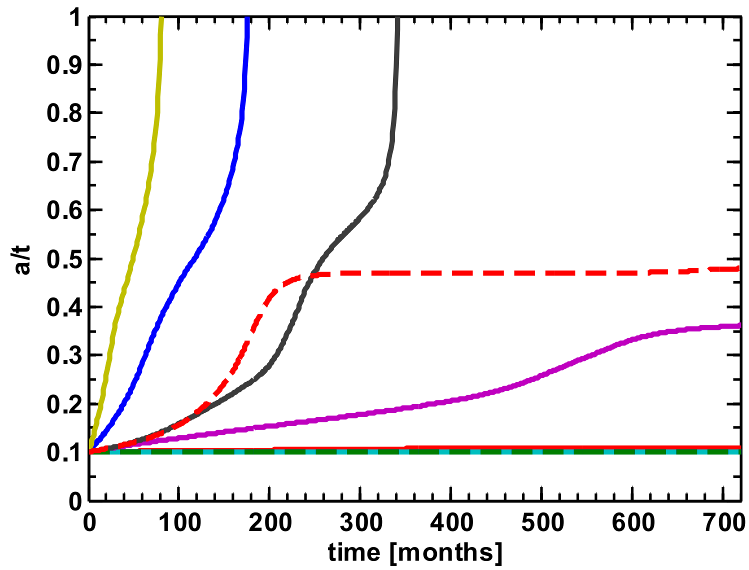

Figure D-28: Depth Growth

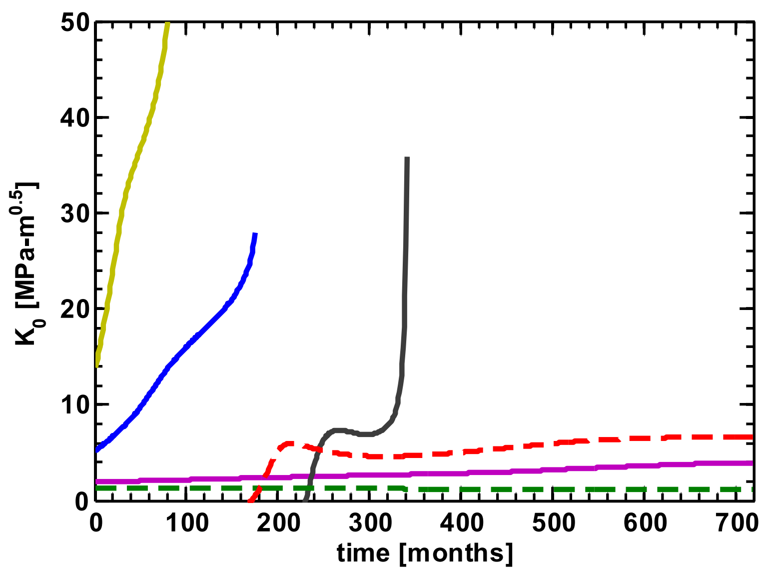

Figure D-29: Stress Intensity Factor at the Surface Point

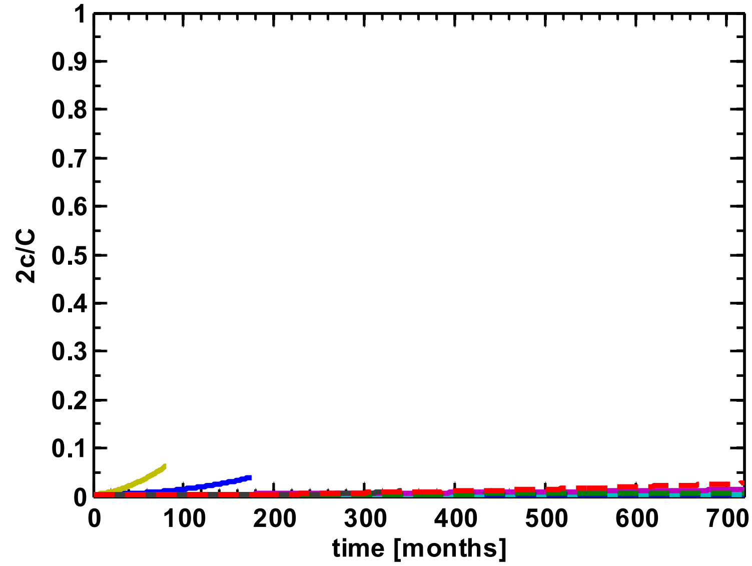

Figure D-30: Length Growth

Figures D-31 and D-32 replot Figures D-27 and D-29 as a function of *a*/*t*, respectively.

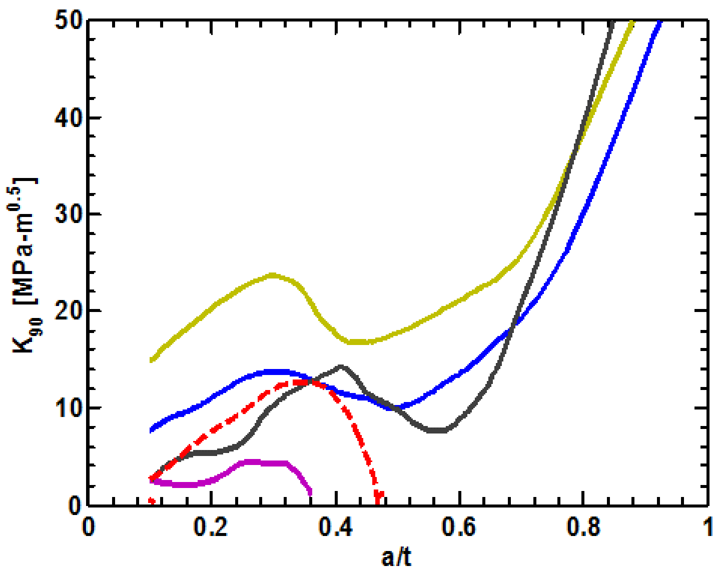

Figure D-31: Stress Intensity Factor at the Surface Point

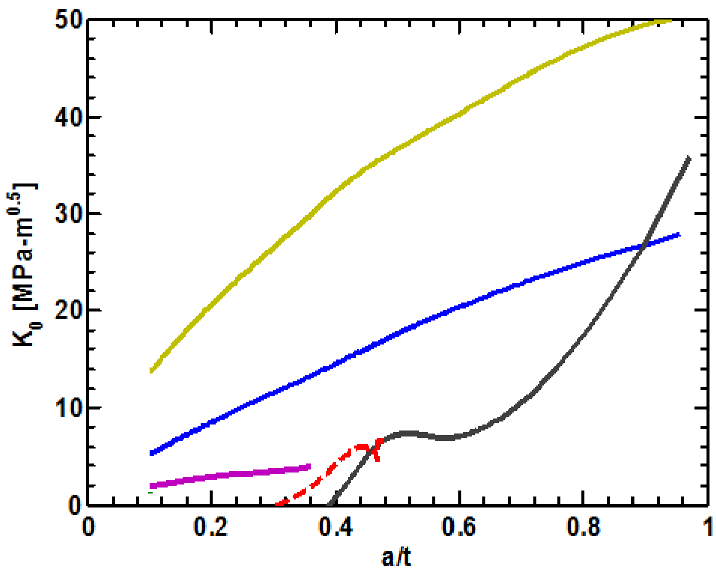

Figure D-32: Stress Intensity Factor at the Surface Point

D.2 Axial Crack Growth

D.2.1 Operating Loads Only

The residual stress magnitude was set to zero through the wall thickness for this calculation. Figures D-33 and D-34 show K_{90} and the depth growth normalized to the wall thickness, respectively. Figures D-35 and D-36 show K_0 and the length growth normalized to the weld width, respectively.

This case demonstrates the methodology for treating axial cracks, as first mentioned in Section 3.3. When the length of an axial crack becomes equal to the weld width (at approximately 100 months in Figure D-36), the crack length can no longer increase since the material outside the weld is not susceptible to stress corrosion cracking. If the crack continues to grow in the depth direction after this point (as is the case here, see Figure D-34), the aspect ratio of the flaw may become a/c < 1. This situation can lead to unrealistic predictions of stress intensity factor, as is discussed in [9]. To correct for this potential error, Reference [9] recommends to adjust a/c inputs to influence coefficient and shape factor calculations. The recommended rules lead to closer prediction of Advanced Finite Element natural flaw growth simulations. As demonstrated in Figure D-33, this methodology caused K_{90} to slightly decrease at 100 months. The near constant K_{90} between 100-200 months led to a roughly linear increase in crack depth (Figure D-34), before K_{90} began to increase again after 200 months.

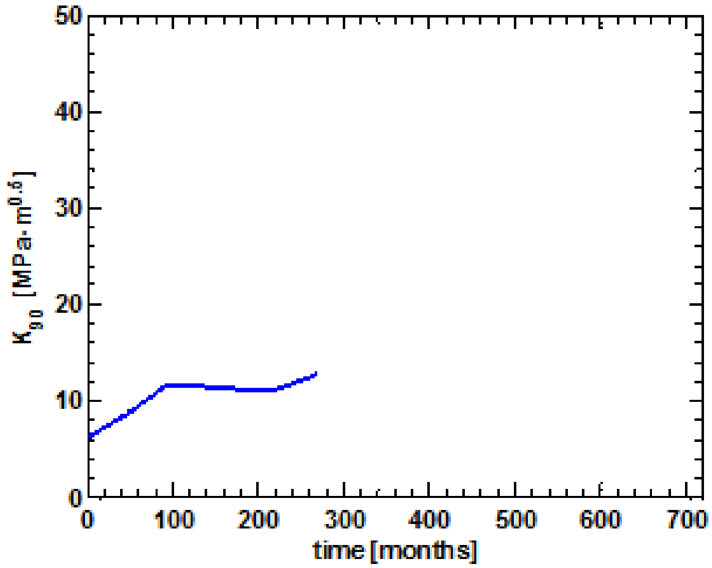

Figure D-33: K_{90} for No Residual Stress

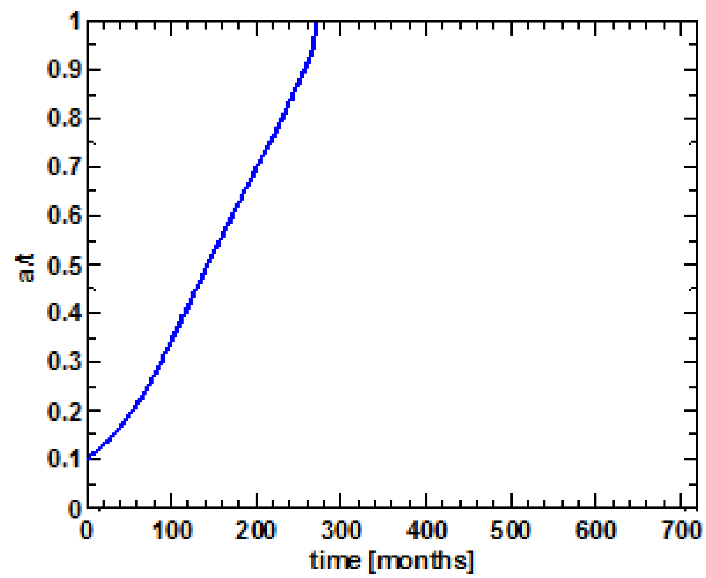

Figure D-34: Depth Growth for No Residual Stress

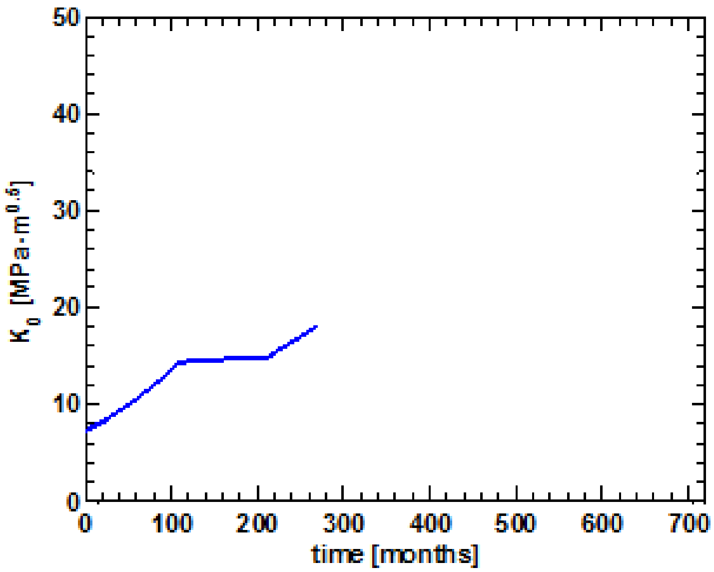

Figure D-35: K_0 for No Residual Stress

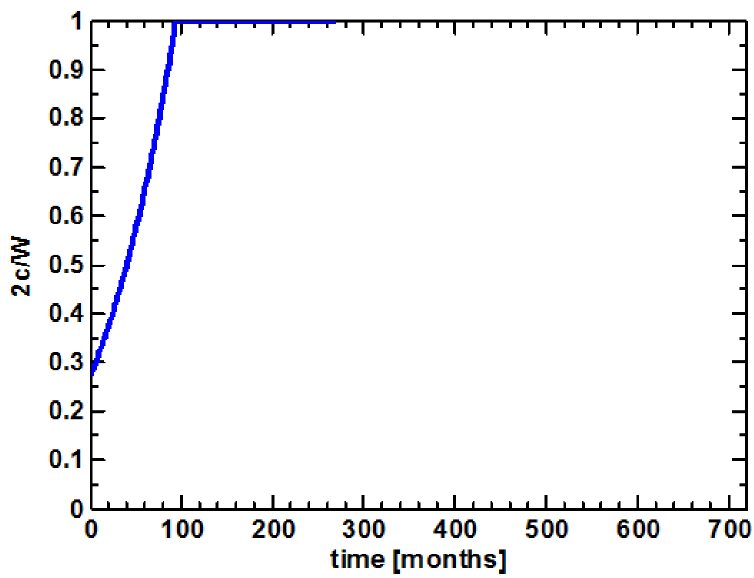

Figure D-36: Length Growth for No Residual Stress

D.2.2 Measurement WRS

Figure D-37 shows the residual stress input for this set of calculations. Figures D-38 and D-39 show K_{90} and the depth growth normalized to the wall thickness, respectively. Figures D-40 and D-41 show K_0 and the length growth normalized to the weld width, respectively.

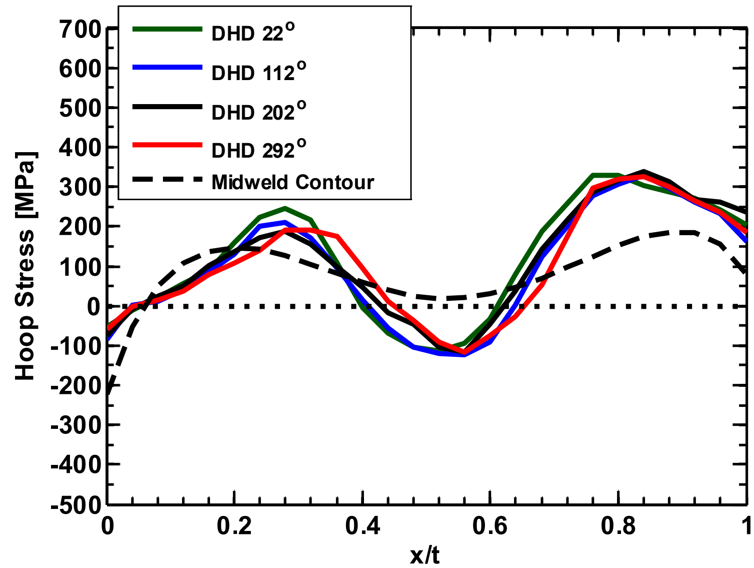

Figure D-37: Residual Stress Input

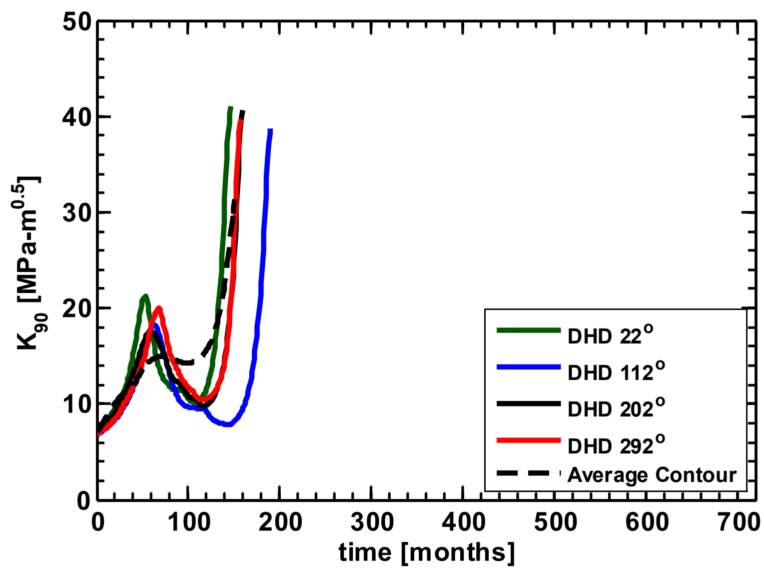

Figure D-38: Stress Intensity Factor at the Deepest Point

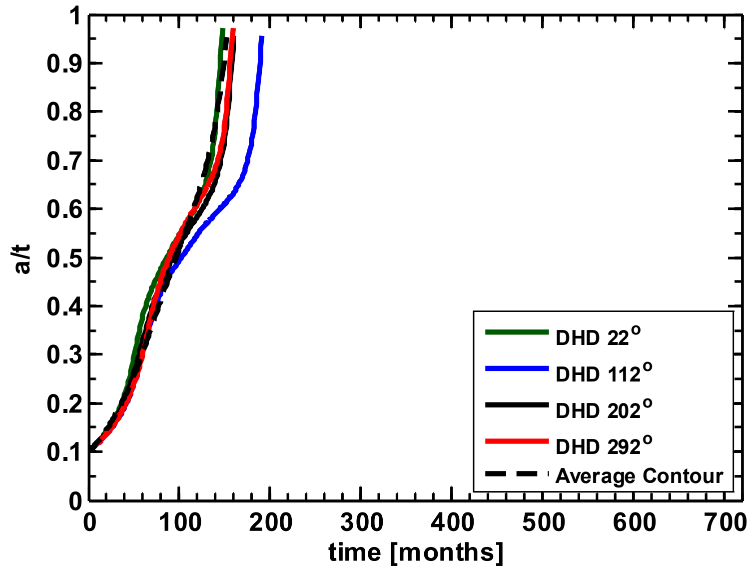

Figure D-39: Depth Growth

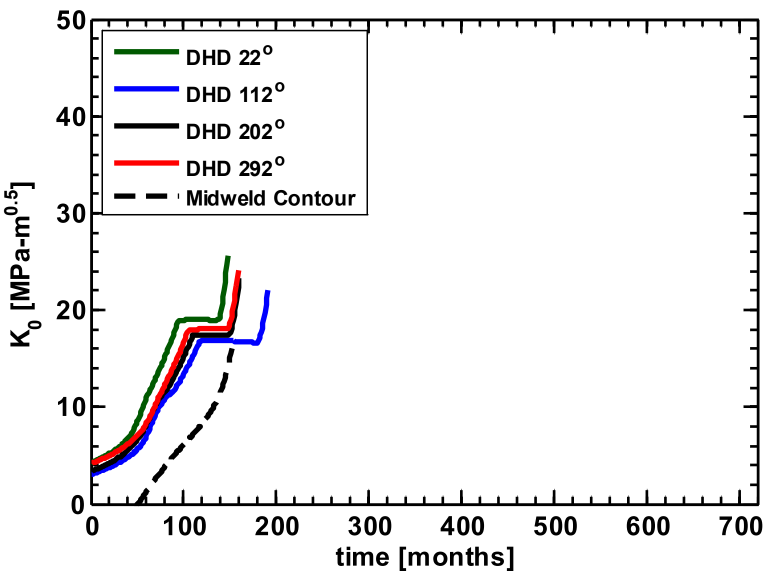

Figure D-40: Stress Intensity Factor at the Surface Point

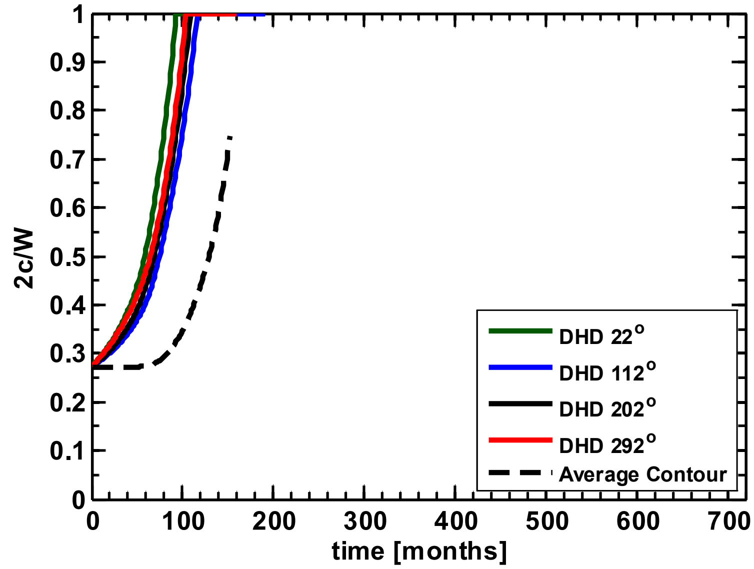

Figure D-41: Length Growth

Figures D-42 and D-43 replot Figures D-38 and D-40 as a function of *a*/*t*, respectively.

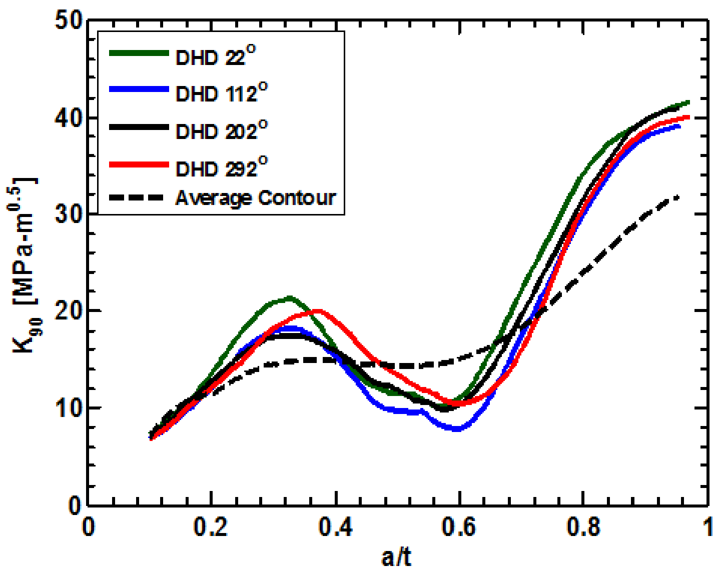

Figure D-42: Stress Intensity Factor at the Deepest Point

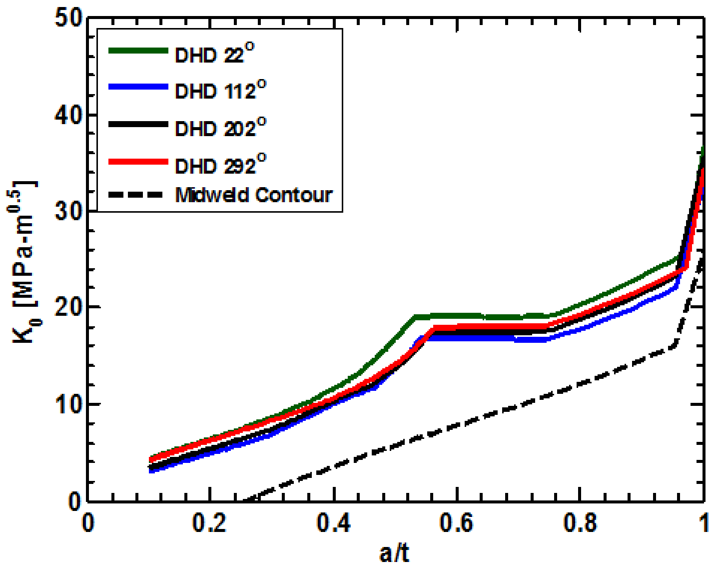

Figure D-43: Stress Intensity Factor at the Surface Point

D.2.3 Modeling WRS: Isotropic Hardening

Figure D-44 shows the residual stress input for this set of calculations. Figures D-45 and D-46 show K_{90} and the depth growth normalized to the wall thickness, respectively. Figures D-47 and D-48 show K_0 and the length growth normalized to the weld width, respectively.

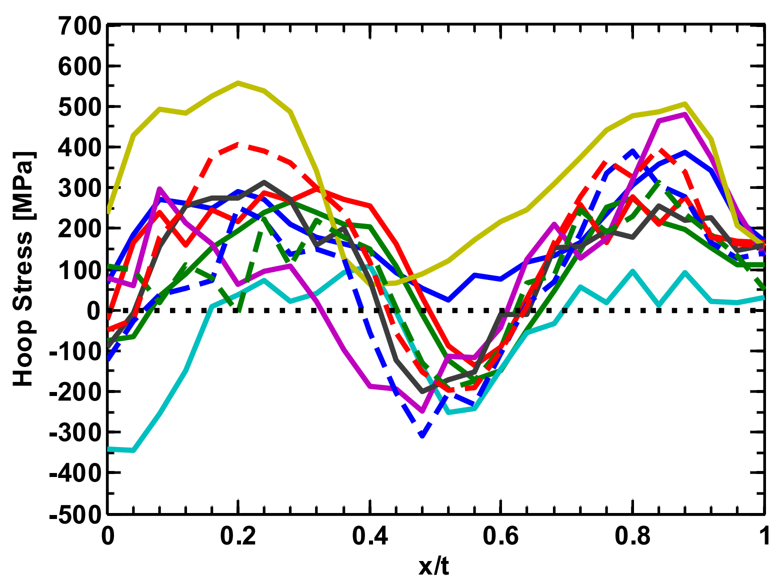

Figure D-44: Residual Stress Input

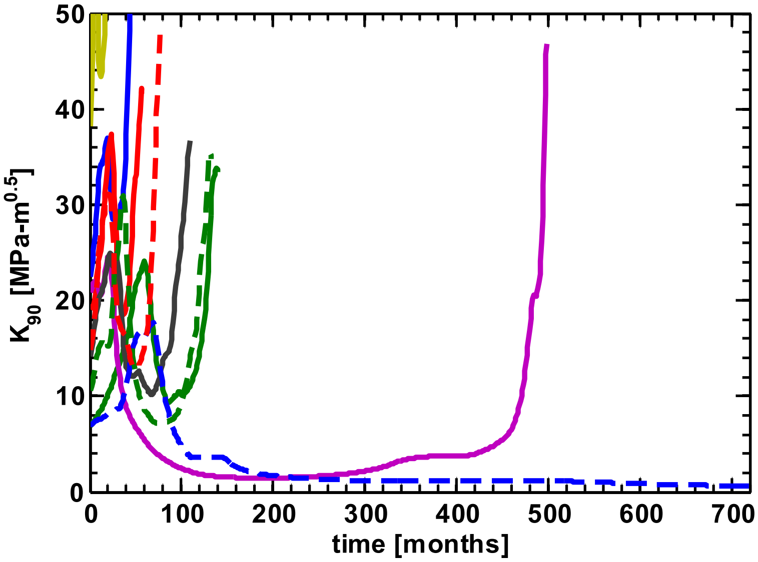

Figure D-45: Stress Intensity Factor at the Deepest Point

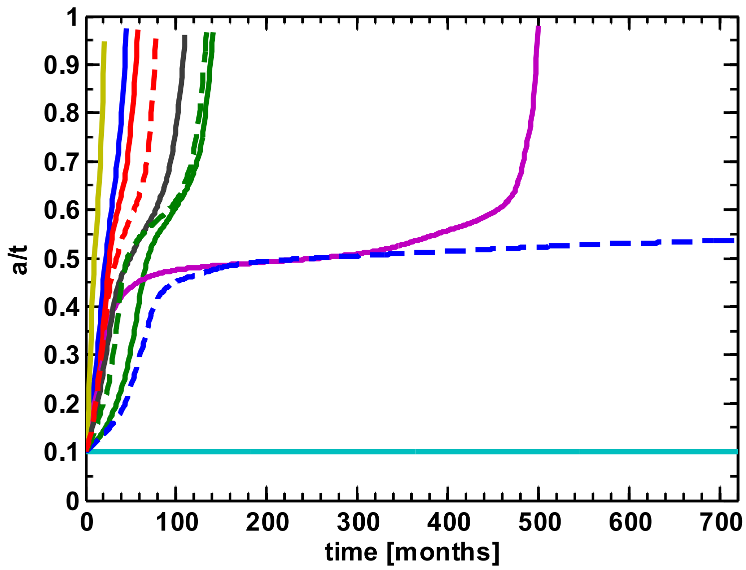

Figure D-46: Depth Growth

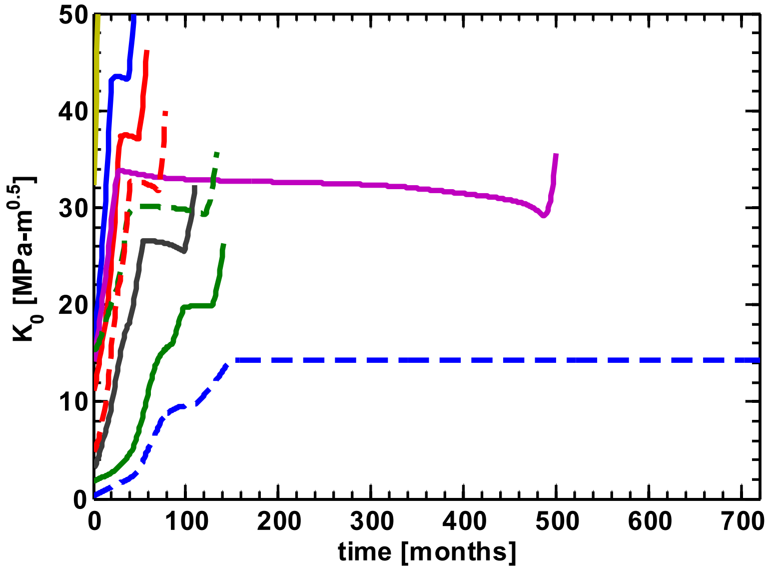

Figure D-47: Stress Intensity Factor at the Surface Point

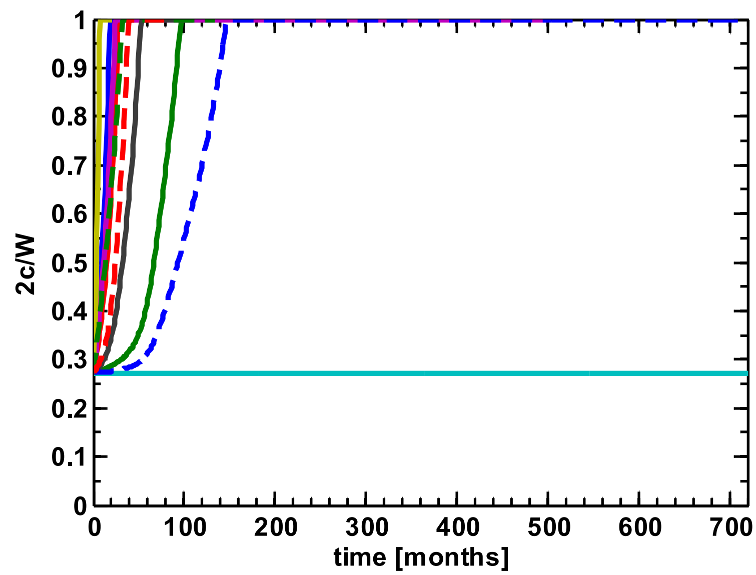

Figure D-48: Length Growth

Figures D-49 and D-50 replot Figures D-45 and D-47 as a function of a/t, respectively.

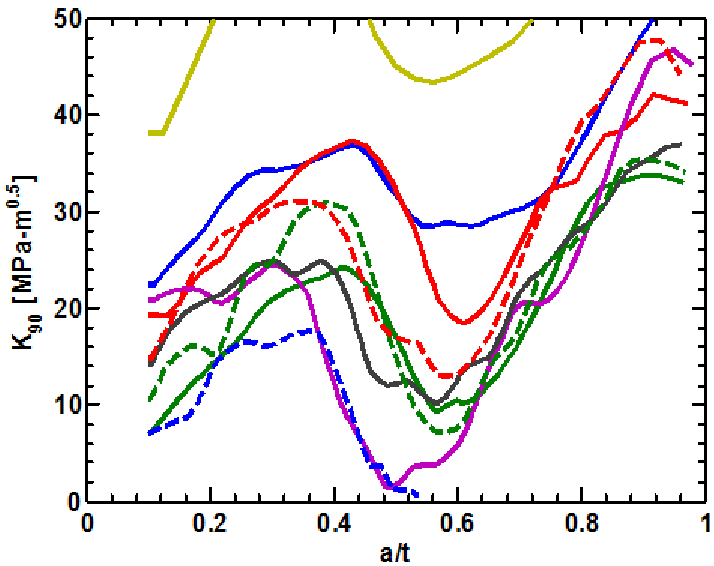

Figure D-49: Stress Intensity Factor at the Surface Point

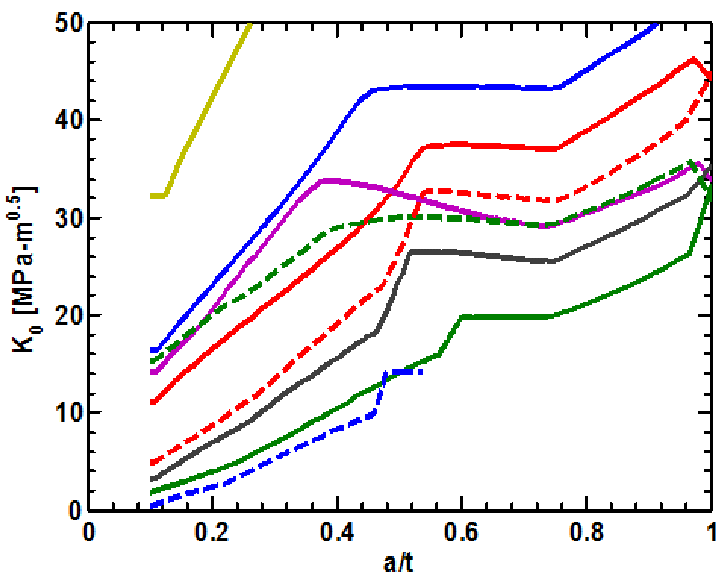

Figure D-50: Stress Intensity Factor at the Deepest Point

D.2.4 Modeling WRS: Kinematic Hardening

Figure D-51 shows the residual stress input for this set of calculations. Figures D-52 and D-53 show K_{90} and the depth growth normalized to the wall thickness, respectively. Figures D-54 and D-55 show K_0 and the length growth normalized to the weld width, respectively.

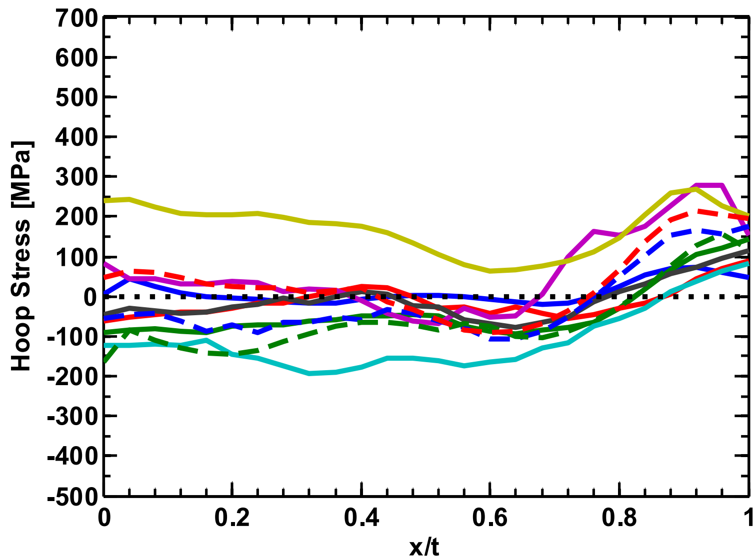

Figure D-51: Residual Stress Input

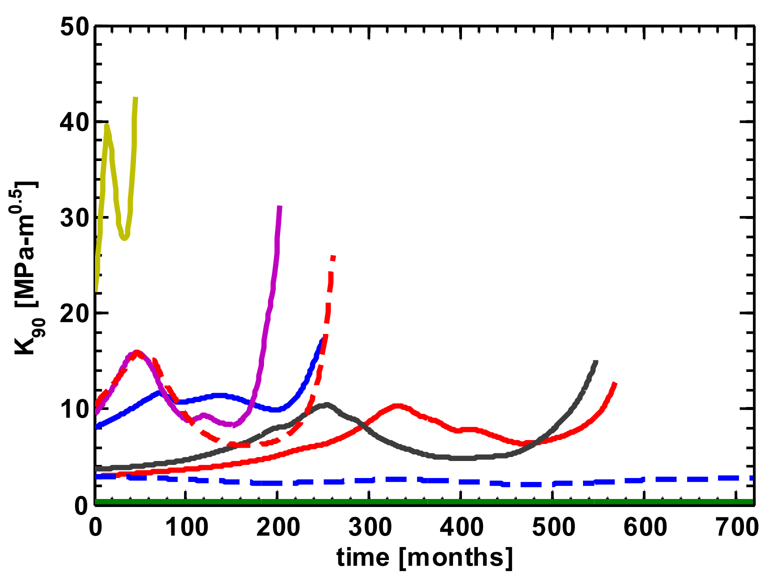

Figure D-52: Stress Intensity Factor at the Deepest Point

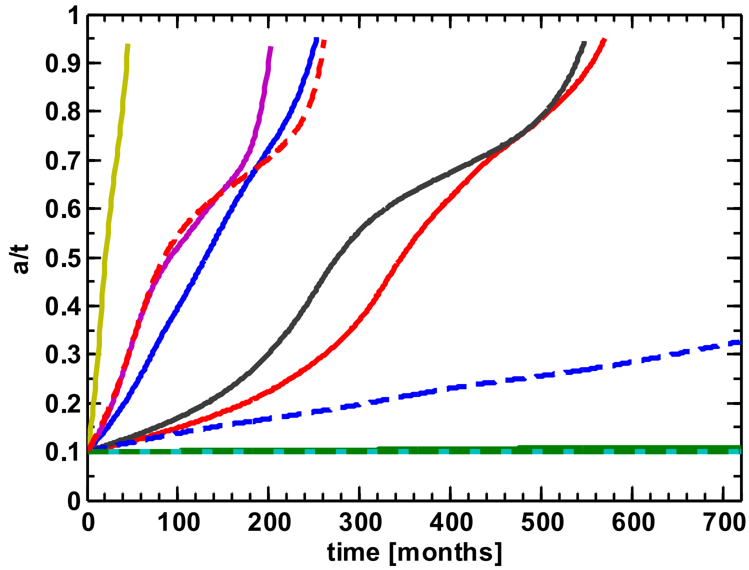

Figure D-53: Depth Growth

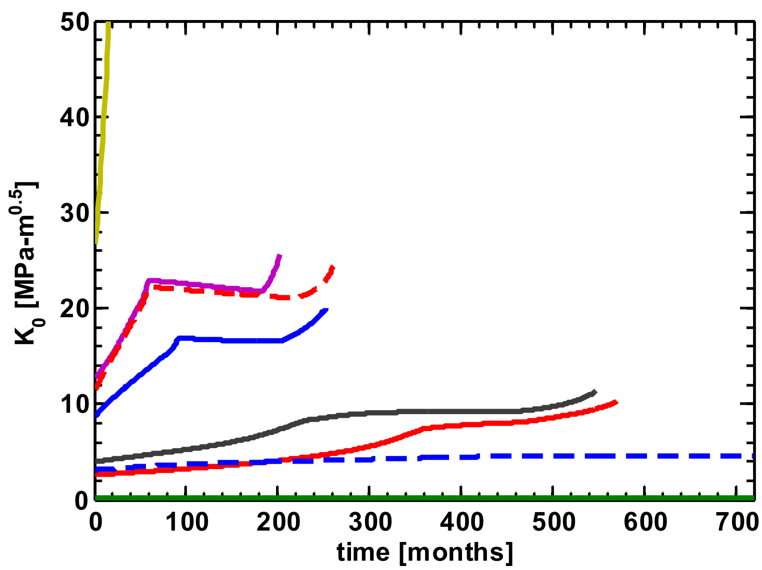

Figure D-54: Stress Intensity Factor at the Surface Point

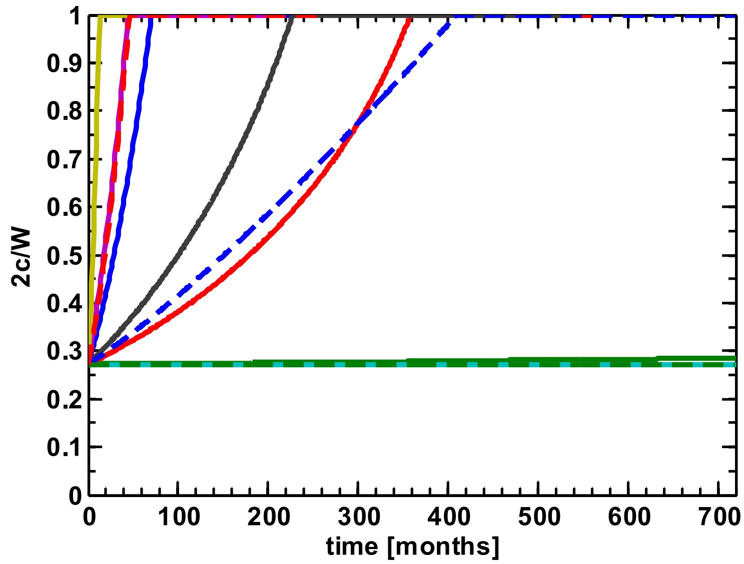

Figure D-55: Length Growth

Figures D-56 and D-57 replot Figures D-52 and D-54 as a function of a/t, respectively.

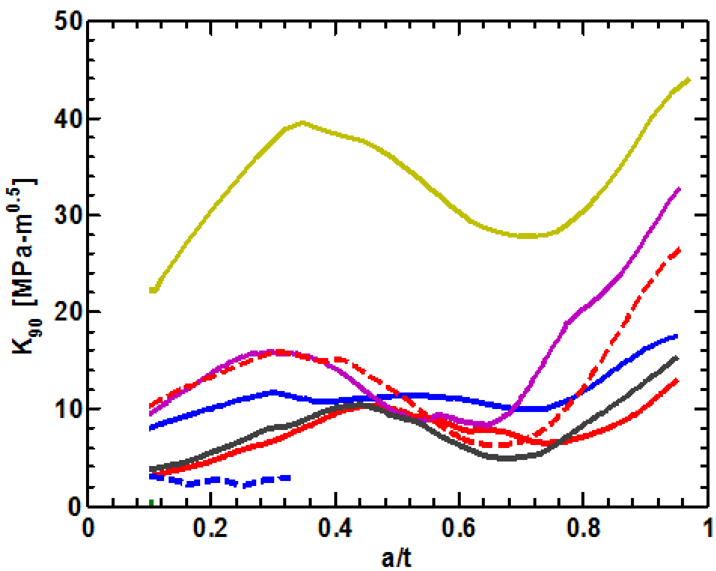

Figure D-56: Stress Intensity Factor at the Deepest Point

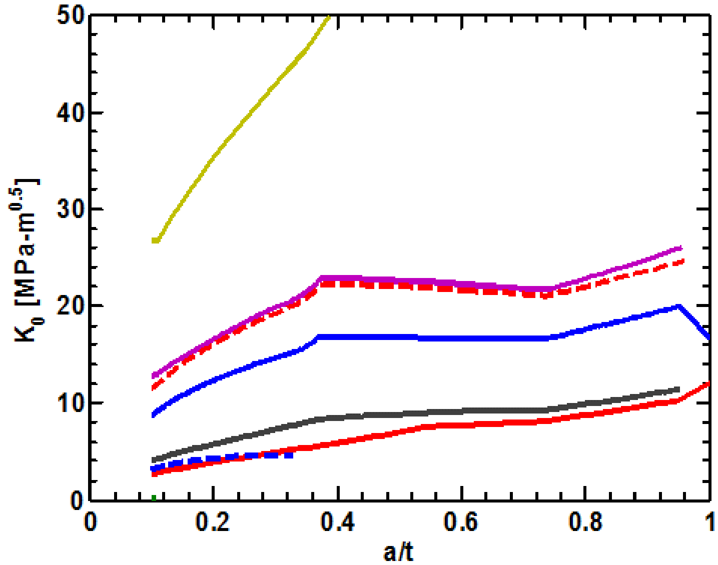

Figure D-57: Stress Intensity Factor at the Surface Point

D.2.5 Modeling WRS: Average Hardening

Figure D-58 shows the residual stress input for this set of calculations. Figures D-59 and D-60 show K_{90} and the depth growth normalized to the wall thickness, respectively. Figures D-61 and D-62 show K_0 and the length growth normalized to the weld width, respectively.

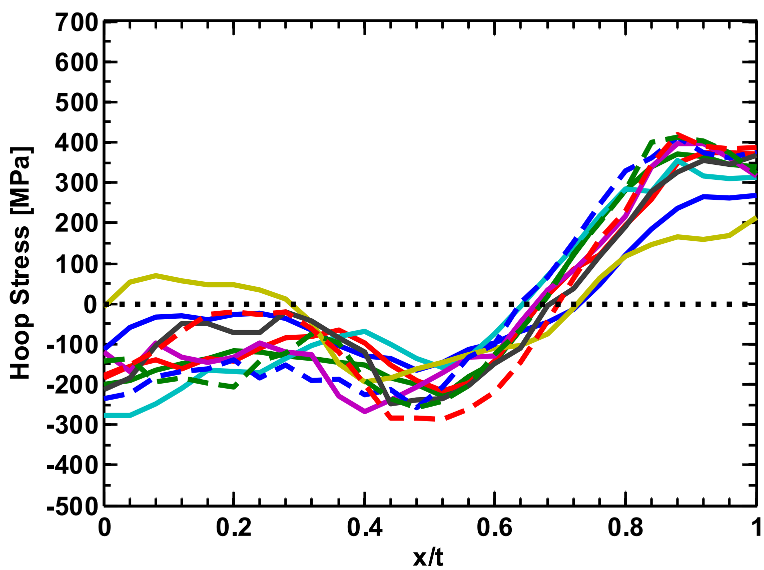

Figure D-58: Residual Stress Input

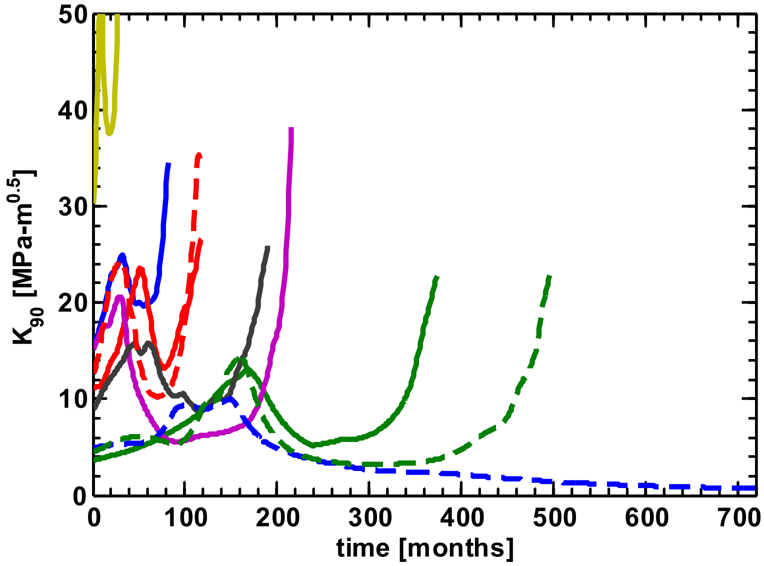

Figure D-59: Stress Intensity Factor at the Deepest Point

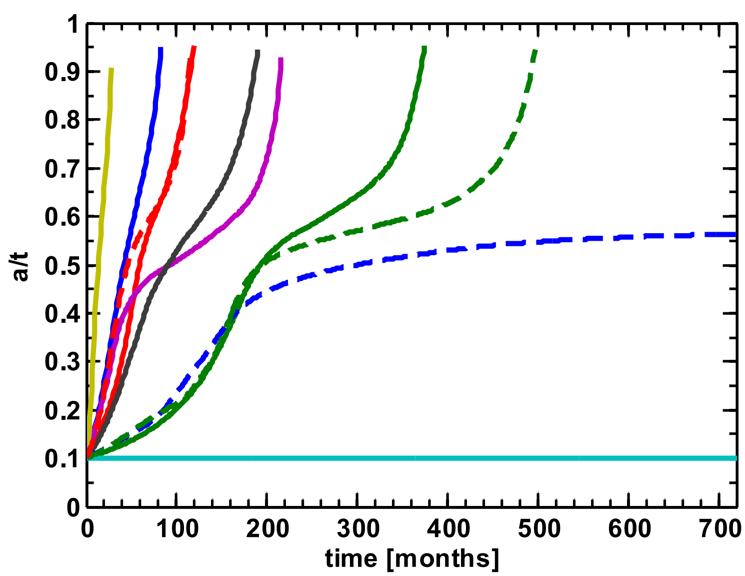

Figure D-60: Depth Growth

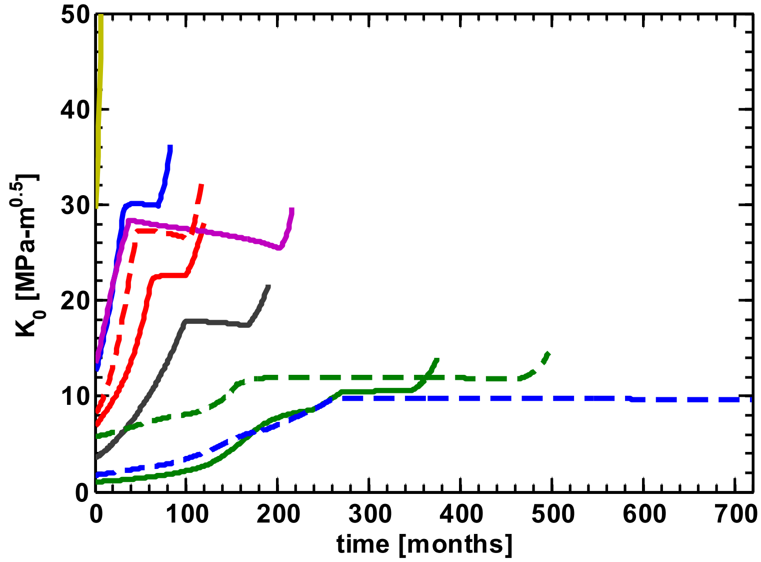

Figure D-61: Stress Intensity Factor at the Surface Point

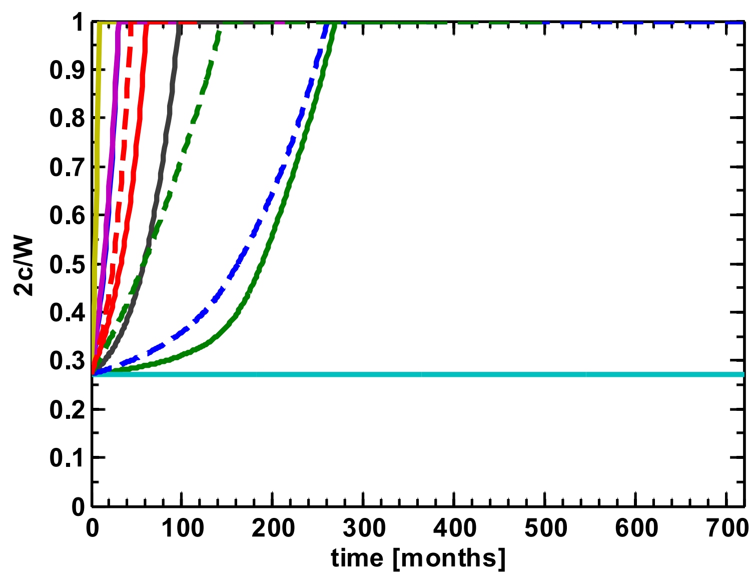

Figure D-62: Length Growth

Figures D-63 and D-64 replot Figures D-59 and D-61 as a function of a/t, respectively.

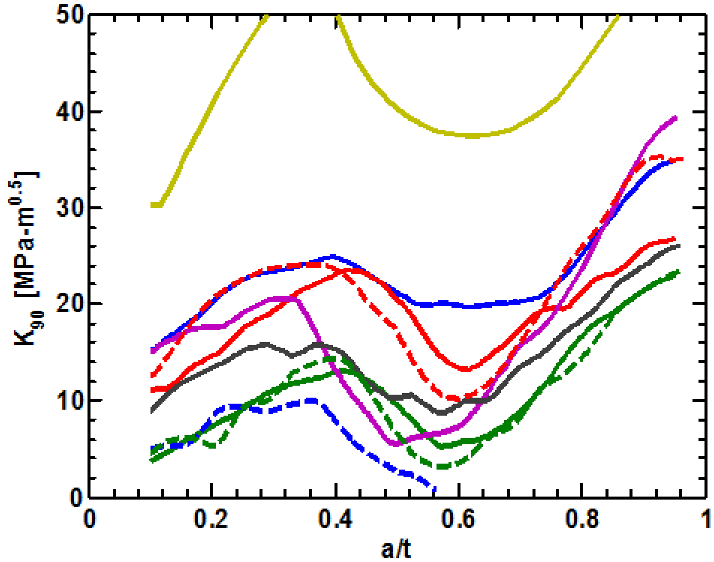

Figure D-63: Stress Intensity Factor at the Surface Point

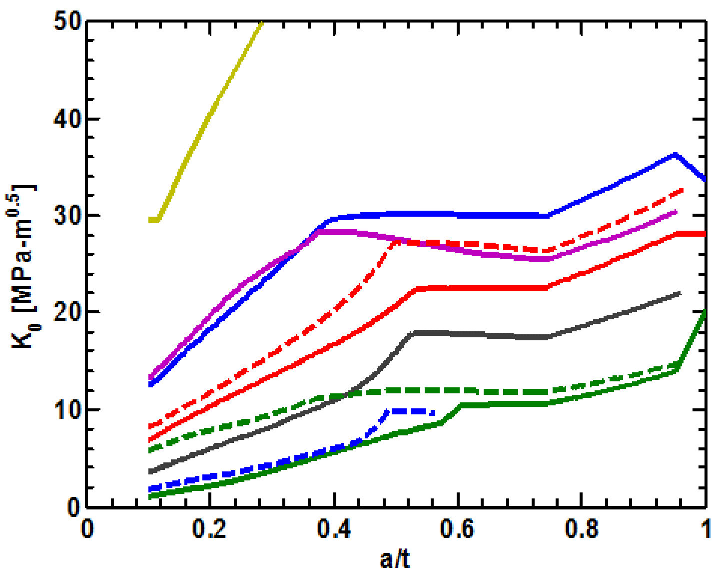

Figure D-64: Stress Intensity Factor at the Surface Point