WCAP-14519

RV Closure Head Penetration Tube ID Weld Overlay Repair

A Westinghouse Owners Group Program Report

Westinghouse Energy Systems

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RV Closure Head Penetration Tube
ID Weld Overlay Repair

A Westinghouse Owners Group Program Report

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TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS (Continued)

LIST OF TABLES

REVISION RECORD

11-10-95	Proprietary information marked in preparation of Class 3 Report No. 14519	D. Boyle

EXECUTIVE SUMMARY

A technical approach to address the issue of primary water stress corrosion cracking (PWSCC) on the ID surface of reactor vessel closure head penetration tubes has been outlined by the Westinghouse Owners Group (WOG). In addition, the WOG has supported NUMARC at the industry level in taking a proactive role in resolution of this issue. In structuring an approach the WOG has supported root cause evaluations, investigated how WOG plants are impacted, submitted a generic safety evaluation, developed plant inspection criteria, and solicited volunteers to perform plant inspections. Also, via the weld overlay program authorization (MUHP-5017), the subject of this report, the WOG is providing generic guidelines applicable for penetration tube repair and potentially a methodology to mitigate PWSCC in the penetration tube ID.

This part of the program provides a weld design package which can be applied to repair reactor vessel closure head penetration tube ID initiated PWSCC. The weld design package provides the criteria for the repair of the penetration tube ID either through the application of a local weld repair or via the application of a 360° weld overlay. The local weld repair process is targeted at restoring the minimum required design thickness of the penetration tube wall. The 360° weld overlay is intended to provide a remedial measure to mitigate PWSCC in the Alloy 600 penetration tube ID by eliminating exposure of the highly stressed regions of the tube wall to the primary water environment.

If an individual utility decides to perform volumetric inspections of vessel head penetrations indications could possibly be encountered which would require disposition in order to permit plant start-up. Indications detected via penetration tube volumetric inspections need not necessarily immediately be repaired. Each penetration tube indication needs to be evaluated against the established industry acceptance criteria. Dependent on indication position, depth, and orientation it is quite possible no immediate corrective action is required. In fact no corrective measure may be required for the remaining design life of the plant. If however corrective action is required the first course of action would require removal of the defect by excavation. Excavation by itself is an acceptable corrective measure as long as the minimum required design thickness of the penetration tube wall is not violated, approximately 0.3 inch. If the minimum required design thickness is violated the integrity of the penetration tube wall needs to be re-established, i.e. via the local weld repair.

In support of the weld repair processes the following has been investigated; 1) Excavation geometries and various depths as related to flaw geometry, 2) Limitation of the weld repair with respect to crack length, 3) The definition of welding process parameters, 4) The definition of allowable weld filler metals, 5) Weld surface finish, 6) Requirements relative to the surface profile of the penetration inside diameter, 7) Industry suggested parameters for shot peening, and 8) Weld inspection requirements. Shot peening was examined as a post weld surface treatment to mitigate the residual stresses induced by welding. In addition to support the repair process, Westinghouse performed a generic 50.59 Safety Evaluation such that a utility could license such a repair on an as needed basis. The definition of the above items along with the safety evaluation provides a comprehensive package such that the utilities can independently implement and or contract such services, i.e. local weld repair or 360° weld overlay.

Conclusions of the program are:

- An acceptable weld overlay process has been developed and qualified to Section IX of the ASME Code.

- The welding process specification developed as a result of the qualification is applicable for both local weld repairs and 360° weld overlays in the reactor vessel closure head penetration tubes.

- Multiple repair geometries exist, each repair required should be individually specified. An individual utility needs to specify repair requirements based on the technical merits and economic impacts of each repair situation.

  - An excavation only repair is suggested up to a depth of [ ]^{a,c,e}.

  - It is suggested that if excavation to a depth of [ ]^{a,c,e} does not remove the entire defect, excavation should continue until the defect is removed or until [ ]^{a,c,e} inch of the penetration tube wall remains.

  - A weld overlay repair needs to restore the minimum required penetration tube wall design thickness.

- Repair welding provides an overall increase in the surface principle stresses in the penetration tube. Dependent on weld thickness and circumferential extent the principle stresses will vary. These residual principle stresses for any of the geometries considered are comparable in magnitude to the residual plus operating stresses estimated via the elastic/plastic analysis for the outermost penetration tubes.

- Areas of the penetration tube adjacent to the weld may be more susceptible to PWSCC than the alloy 600 base material not impacted by the welding process. However the susceptibility of adjacent material quickly dissipates due to the drop off of residual stresses as you move away from the weld.

- The extent to which a utility wishes to pursue post weld surface treatment(s), such as shot peening needs to be an individual utility decision based on the technical merits and economic impacts. The Westinghouse owner's group may consider such a program in the future.

- The final geometry and surface finish of the repaired area needs to be such to facilitate base and potential future volumetric inspections.

- Weld design depths, geometry, location, and circumferential extent can be varied in an attempt to minimize the impacts of the associated welding residual stresses. These variations are outlined on the associated design drawings provided in Appendix B. The WCAP report which follows is intended to provide the in depth information required to understand these impacts.

1.0 INTRODUCTION

Previously, leakage has been reported from an Alloy 600 reactor vessel closure head penetration tube in a French plant during hydro testing at elevated pressure. Subsequent inspections of the leaking penetration indicate the presence of axial cracks on the inside diameter of the penetration tube. Cracks extend above and below the penetration tube to reactor vessel head attachment weld. The leakage has been determined to result from an axially oriented through-wall crack in the penetration tube wall. The cause of the axially oriented cracks has been attributed to primary water stress corrosion cracking (PWSCC), driven by both steady state operating and residual stress. The residual stresses have been attributed to the ovality in the penetration tube which is a direct result of bending introduced in the penetration tube due to the offset geometry of the attachment weld. Reported data from inspections of head penetrations at additional plants (Both French plants and plants of Westinghouse design) has established the presence of axially oriented cracking in additional penetrations.

The plants of Westinghouse design with reported reactor vessel head penetration tube inside diameter PWSCC are [ ]^{a,c,e}. A review of available inspection data would indicate that flaws have been detected in approximately 2% to 3% of the penetrations inspected. A review of the reported inspection results also indicates that the majority of flaws were detected in penetration tubes located at the periphery of the reactor vessel closure head. This finding is consistent with estimate that residual stresses are greatest in the peripheral penetrations because the offset in the (or angle of) attachment weld is greatest at these locations.

Reactor vessel closure head penetrations on all Westinghouse supplied plants are of similar construction as that of the French plants and Westinghouse designed plants that have experienced cracking. Thus, based on the character of the cracking and the known potential of the Alloy 600 material for susceptibility to PWSCC this phenomenon may be possible on all Westinghouse plants.

Currently the WOG has undertaken an extensive program to examine and manage the phenomena of PWSCC initiated from the inside diameter of the reactor vessel Alloy 600 penetration tubes. The WOG's position has been that U.S. industry should take a proactive but logical approach to addressing the issue. Thus the WOG has initiated various project authorizations, outlined below, which are intended to address the various aspects of this issue such that the issue can be technically and economically managed to a successful resolution.

- Understand the cause and extent of cracking experienced by the French in their plants. From this phase of the work the WOG concluded that the issue could impact selected US plants, however the extent and/or time frame could not be immediately quantified.

- Assess the safety impacts of the issue. Detailed engineering analyses were conducted to understand the extent and safety impacts of cracking. A generic safety evaluation was performed and presented to the NRC. The conclusions were that the issue does not represent an immediate safety issue. The significance of cracking is that it can result in leakage which could result in wastage of the carbon steel vessel head. The WOG estimated wastage corrosion rates based on analysis performed by Westinghouse and experimental data provided by the Combustion Engineering Owners Group. The conclusion was that wastage could alter the reactor vessel head however the ASME Code Allowable stresses would be maintained for a minimum of 6 years.

- The experimental data used to estimate crack propagation for the thick-walled Alloy 600 penetration tubes, which was used in the flaw tolerance evaluation portion of the safety evaluation, was based on thin-walled Alloy 600 tubing. The WOG chose to investigate crack propagation rates in thick-walled Alloy 600 tubing to verify that the crack propagation model for thin-walled tubing was valid for use. Thus the WOG initiated a crack propagation testing program to investigate this phenomenon. This work is scheduled to be completed in the fourth quarter of 1994.

- The WOG had the opportunity to confirm the mechanism of cracking in the penetration tubes. The [ ]^{a,c,e} plant, a Westinghouse supplied plant, has also experienced cracking and has undertaken a program to investigate the cracking. As part of the Ringhals program boat samples were removed from the ID of a penetration which has experienced cracking. The WOG was offered the opportunity to perform a failure evaluation on one of these boat samples. Westinghouse performed this work under authorization [ ]^{a,c,e}. This work further confirmed the French findings that the cause of cracking was PWSCC.

- The WOG has authorized a report outlining a Flaw Evaluation Procedure which is intended to identify the techniques required to estimate the propagation of any flaws detected by an inspection.

- The WOG has supported an industry initiative coordinated by NUMARC to develop acceptance criteria for flaws detected along the inside diameter of reactor vessel closure head penetration tubes. These acceptance standards have been provided as the standard for acceptance of any flaws detected during an in-plant inspection. Additionally, EPRI has applied these acceptance standards in developing a qualification program and standards for utilities to use in the qualification of vendors offering inspection services.

- The WOG has also solicited utility volunteers to perform pilot volumetric inspections of their reactor vessel closure head penetrations. The WOG intends to evaluate inspection results and assess the impact on the pilot and other W plants.

Through these programs the WOG has attempted to determine cause, address the safety significance of this issue, develop inspection and acceptance criteria, provide a mechanism to qualify vendors offering inspection services such that interpretation of results across the industry is consistent, and make available pilot inspection results such that the future actions/requirements with respect to this issue relative to the U.S. nuclear industry can be formulated. Lastly, the WOG authorized a program to develop a weld repair methodology for penetrations which have experienced cracking. The following document outlines the program and reports on the results of the weld repair program.

2.0 PROGRAM DESCRIPTION

2.1 Objectives

The objective of the program was to provide a weld design package which can be applied to repair reactor vessel closure head penetration tube ID initiated PWSCC. The weld design study has investigated repair of partial through-wall and full through-wall cracks. The objective was to investigate a local weld repair process and a 360° weld overlay process as part of the weld design package. In addition to the weld repair process, information regarding excavation geometries and post weld surface treatment was investigated. Excavation serves two purposes; 1) It provides access for application of the weld, and 2) It serves to remove any existing defects. For the purposes of this project authorization the post weld surface treatment investigated was shot peening. The objective of a post weld surface treatment such as shot peening is to negate/mitigate residual stresses induced by welding.

In support of the weld repair processes Westinghouse investigated; 1) Excavation geometries and various depths as related to flaw geometry, 2) Limitation of the weld repair with respect to crack length, 3) The definition of welding process parameters, 4) The definition of allowable weld filler metals, 5) Identification of the weld surface finish, 6) Requirements relative to the surface profile of the penetration inside diameter, 7) Industry suggested parameters for shot peening, and 8) Weld inspection requirements. The definition of these items provides a comprehensive definition of the process such that the utilities can independently implement such a repair.

In support of the repair process, Westinghouse performed a generic 50.59 Safety Evaluation such that a utility could license such a repair on an as needed basis. Also, this program provided engineering justification of the process through the preparation of a full size penetration mock-up to provide engineering data to enable evaluation of effects on penetration residual stress and deformation due to the weld overlay. The change in stress was measured using a Hole Drilling Strain Gage Method in accordance with ASTM E837. Mock-up testing was also used to investigate the extent of weld shrinkage associated with the weld overlay process and the extent that the weld overlay process impacts the shrink fit between the penetration tube and reactor vessel head.

2.2 Weld Repair Program Outline

The development of a weld repair design package was structured to investigate specific weld process parameters and provide engineering justification for the various associated technical issues. In order to investigate the weld process parameters and technical issues several major program tasks were defined. Each of these tasks along with a brief description follows:

Task 1 Development of Weld Overlay Repair Process Specification:

The Westinghouse weld repair process specification defines: A weld thickness of [ ]^{a,c,e} to [ ]^{a,c,e} inches, defines critical welding process parameters, defines allowable weld filler metals [ ]^{a,c,e} and identifies weld surface finish requirements and inspection requirements.

Also, shot peening as a post weld surface treatment available for mitigation of post weld residual stresses will be discussed. The documentation also defines target shot peening process parameters. Target shot peen process parameters were provided as a result of recommendations solicited from a commercial shot peen vendor and work performed by Westinghouse, independent of this program authorization.

Task 2 Define Penetration Excavation Geometry:

A drawing is supplied to compliment the penetration repair process to define such items as: the excavation geometry and depths for both an excavation only repair and excavation followed by a weld repair, the required ID profile of the penetration ID after the application of the weld overlay, and any limitations with respect to positioning the weld overlay relative to projected stress profiles in the penetrations.

In addressing excavation of the penetration two aspects were addressed: 1) It was imperative that the structural adequacy of the penetration was not compromised, this was investigated via a review of available ASME code stress reports on the reactor vessel closure head, and 2) The excavation geometry was defined such that adequate

penetration material was removed such that, application of the weld does not restrict the flow area in the penetration or thermal sleeve movement is not impacted.

Task 3 Provide Evaluation of Applying Weld Overlay Over Existing Cracks:

The effect of applying weld material over existing partial through-wall and full through-wall cracks was investigated. The applicable ASME Code paragraphs were investigated which discuss leaving cracks in the pressure boundary were reviewed. Also EDM notches were placed in mock-ups to assess impacts on the welding process.

Task 4 Penetration Mock-up Tests:

A full size penetration mock-up was fabricated. The mock-up was fabricated using an alloy 600 penetration tube welded in a plate of low alloy carbon steel using the partial "J"-groove geometry for the attachment weld. The mock penetration tube was skewed to the surface of the plate to simulate the weld offset of actual penetration tube assembled in the reactor vessel closure head. The mock-up was used to investigate the application of weld material in a similar geometry to the penetration tube, and to quantify the addition of any residual stresses on the ID adjacent to the weld repair.

Several mock penetration tubes were also fabricated to investigate the application of various weld thicknesses and geometries. The various weld thicknesses were evaluated for cladding integrity via a cross-section taken through the weld thickness.

Task 5 Generic Safety Evaluation:

A generic 50.59 safety evaluation was performed to aid WOG members in implementing a weld overlay repair at their specific plant sites. The Safety Evaluation is provided as a stand alone document.

In completing the above tasks the stated goal was to identify engineering justification and appropriate specifications for implementation of a local weld repair and a 360° weld overlay. Both weld repairs involve an appropriate amount of excavation from the penetration inside diameter followed by

application of filler metal in the excavated area. In the case of the local weld repair the repair is targeted at restoring the minimum required penetration tube wall to maintain the pressure boundary. For the 360° weld overlay the intent is to provide a remedial measure for mitigation of PWSCC. The 360° weld overlay would cover the entire inside surface of the penetration tube most susceptible to PWSCC over some given length.

3.0 APPROACH FOR DEVELOPMENT OF PENETRATION TUBE WELD REPAIR AND OVERLAY DESIGNS

In developing the weld application options for the reactor vessel closure head penetration tubes, two basic designs were targeted; 1) A local weld repair process and 2) A 360° weld overlay process. The local weld repair process is targeted to restore the minimum required design thickness of the penetration tube wall. The 360° weld overlay repair is intended to provide a remedial measure to mitigate PWSCC in the Alloy 600 penetration tube ID. Refer to Figure 3.0-1 for an overview of the reactor vessel closure head to penetration tube geometry.

3.1 Local Weld Repair

In designing a local weld repair several considerations were taken into account:

- The weld repair has to restore the minimum required design thickness. The governing design requirement with respect to the penetration tube is design pressure. An examination of a typical 4-loop vessel head indicates that the required penetration tube thickness to meet design pressure requirements is approximately 0.29 inch.

- Slots were examined in [ ]^{a,c,e} Reference 6, as a potential repair for the reduction of residual surface stresses in the penetration tube ID. The maximum slot depth examined was [ ]^{a,c,e} inch.

- The industry flaw acceptance criteria developed for penetration tubes identifies the depth of an allowable flaw to be 75% of the tube wall thickness or [ ]^{a,c,e} = [ ]^{a,c,e} inch. Thus a weld overlay repair in a penetration excavated to a depth of [ ]^{a,c,e} inch may be required.

- In specifying the circumferential extent of the local weld repair designs, the stress analysis results reported in WCAP-13525, Reference 5, were taken into account as well as the slot widths examined in [ ]^{a,c,e} Reference 6. For the purpose of the local weld repair the intent was to position the toe of the weld in an area of the penetration tube ID having relatively low hoop stresses. Thus circumferential extents of 45° and 90° were selected, such

that the toe of the weld could be approximately located on the 45° axis of the penetration tubes where the hoop stresses were estimated to be low.

- Additionally, lengths of 4 and 6 inches were selected to investigate the variations which might occur due to changing the overall weld length.

Based on the above considerations local weld repair design geometries with varying weld thicknesses of [ ]^{a,c,e} inch, overall lengths of 4 to 6 inches, and having circumferential extents of 45° through 90° were considered for investigation.

3.2 360° Weld Overlay

In performing a 360° weld overlay repair the two items taken into consideration were; 1) The weld overlay depth should be thick enough to provide a boundary which prohibits exposure of the Alloy 600 base material to the primary water over the applied length of the repair, and 2) The depth should be minimized such that any associated weld shrinkage minimizes the residual stress in the base material and does not negatively impact the interference fit on the OD of the penetration tube between the reactor vessel closure head and penetration tube.

Based on the above a [ ]^{a,c,e} inch weld thickness was judged as appropriate to meet the above two criteria. A thickness of [ ]^{a,c,e} inch is approximately [ ]^{a,c,e} weld passes. However, an overlay need not be limited to [ ]^{a,c,e} inch. Weld overlay thickness of [ ]^{a,c,e} inch were investigated for lengths varying from 4 to 6 inches.

The perceived advantages of the weld overlay are; 1) Application of the weld overlay can be a continuous process using a spiraling application, and 2) both ends of the weld overlay can be readily positioned in lower stress regions of the penetration tube ID.

3.3 General Program Goal

In order to evaluate the above defined design geometries a series of tests and measurements were identified for investigation of a weld process which could be qualified to the ASME Section IX Code requirements, Reference 2. Additionally, these test and measurements were used to assess technical

impacts such that the specification of weld repair would not negatively impact the penetration tube geometry. These tests and measurements involved the fabrication of penetration tube samples and a full size reactor vessel closure head/penetration tube mock-up as well as the investigation of methodologies for performing weld overlay repairs. The following sections provide the details and results of these investigations.

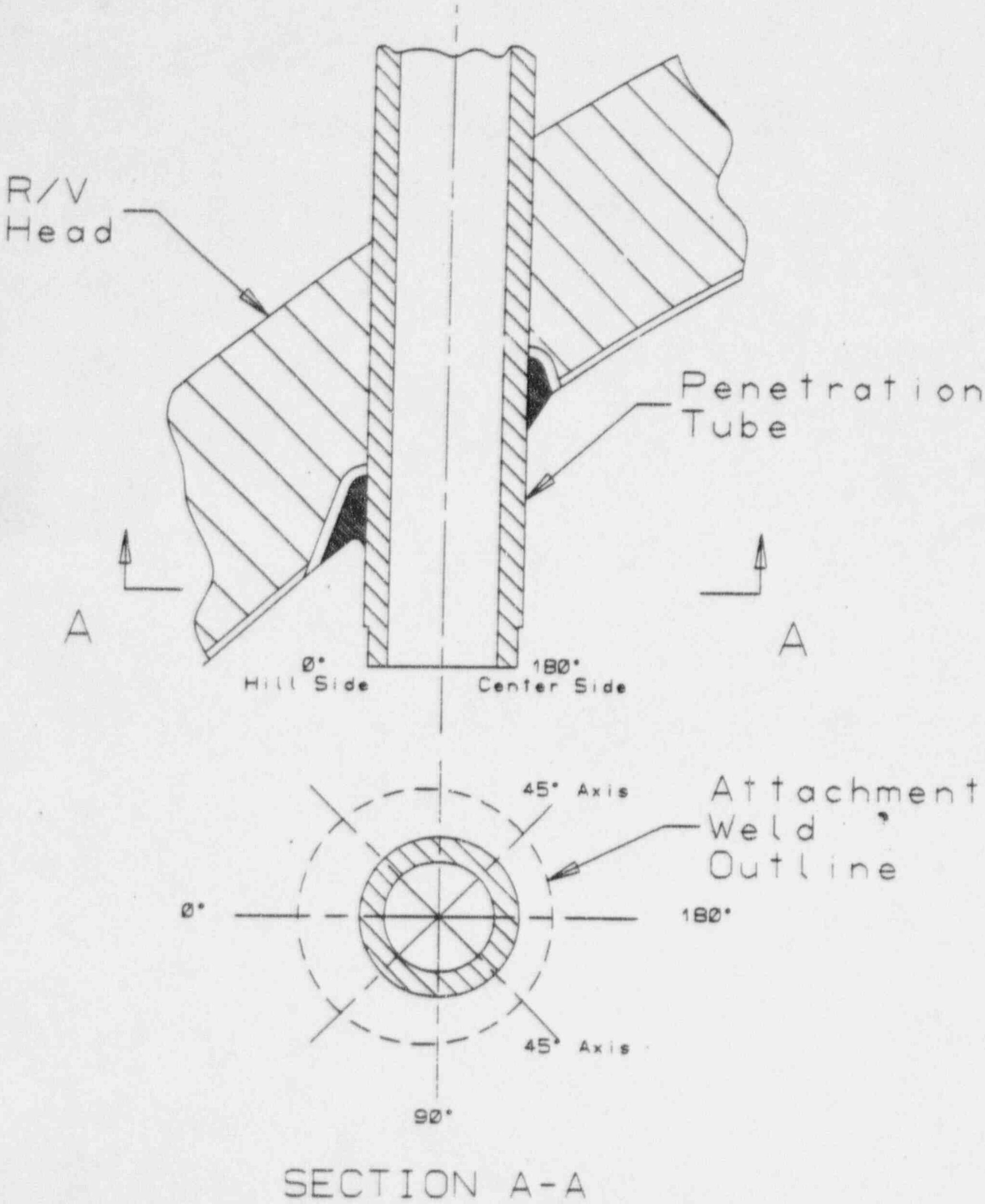

Figure 3.0-1 Reactor Vessel Closure Head to Penetration Tube Geometry

4.0 PENETRATION TUBE SAMPLE & REACTOR VESSEL HEAD/PENETRATION TUBE MOCK-UP FABRICATION

4.1 Preparation of Penetration Tube Samples

Figure 4.1-1 depicts the geometry of the grooves machined in the 10 inch penetration tube samples. The grooves were machined using electric discharge machining (EDM). As shown in Figure 4.1-1 the tube wall was machined to the defined depth and made use of a [ ]^{a,c,e} taper to blend the excavation depth into the original tube inside diameter (2.75 inch). The [ ]^{a,c,e} taper was applied both circumferentially and axially. For the groove depths of [ ]^{a,c,e} inch and [ ]^{a,c,e} inch the [ ]^{a,c,e} taper resulted in an acceptable geometry. However, for those samples with a groove depth of [ ]^{a,c,e} inch the taper was reduced to a ratio of [ ]^{a,c,e}. The taper was reduced because the [ ]^{a,c,e} taper was impractical from the standpoint that it extended two far around the penetration circumference, requiring too much weld filler metal to fill in the taper transition area. After performing weld repairs on the [ ]^{a,c,e} taper geometry process time was still too long and too much weld filler metal was still required, thus an alternative transition design was identified for blending from the excavation depth to the inside surface of the penetration tube. The alternative transition is a typical weld "J" preparation applied in the industry and is depicted in Figure 4.1-2.

4.2 Fabrication of Reactor Vessel Closure Head/Penetration Tube Mock-Up

A full scale mock-up of the reactor vessel closure head and penetration tube was fabricated to depict the most peripheral penetration in a 4-loop reactor vessel head, thus indicative of a penetration tube with the greatest offset in the attachment weld, i.e. therefore the maximum residual stress. Fabrication sketches of the mockup are provided in Appendix C, Fabrication Data Package for the Penetration Mock-Up & Penetration Mock-Up Sketches. The fabrication data package includes as-built dimensional data.

To validate the applicability of the mock-up, measurements were taken of the penetration tube inside diameter to measure the ovality which occurred as a result of performing the mock-up attachment weld. As in the actual reactor vessel head geometry, a "J" groove weld prep was used for the attachment weld between the penetration tube and low carbon steel plate. The maximum ovality

(major diameter less minor diameter) which occurred in the mock-up was [ ]^{a,c,e} mils ([ ]^{a,c,e} inch) as compared to the maximum approximated ovality of [ ]^{a,c,e} mils ([ ]^{a,c,e} inch) estimated from the linear regression equation for ovality which was developed based on actual plant ovality measurements, Reference 1.

a,c,e

Figure 4.1-1 [ ]a,c,e

a,c,e

Figure 4.1-2 Full Size Mock-up Sketch Depicting "J" Preparation Excavation Geometry

5.0 WELD PROCESS SPECIFICATION

A welding process specification, which can be used for either the local repair or application of the 360° weld overlay in the reactor vessel closure head penetration tubes was generated and is attached in Appendix A of this WCAP report. The welding process specification is written to provide guidance for the qualification of welding procedures to be used for the performance of welding in Westinghouse PWR reactor vessel closure head penetration tubes. The parameters recommended in the specification were based on the welding operations performed for this feasibility study. Therefore, the parameters were qualified for the intended applications to the extent as discussed in the following paragraphs.

5.1 Selection of Welding Equipment

An automated pulsed gas tungsten arc welding (GTAW) system designed and manufactured by The [ ][a,c,e] (power supply model 215, Figure 5.1-1, and model 94 ID cladding and welding head, Figure 5.1-2), was selected ... program. The model 94 weld head is designed for spiral cladding and groove welding inside diameters as small as 2 inches. The model 94 provides arc rotation, axial(linear) travel, filler wire feed and arc voltage control (AVC) for arc gap control. The combination of axial travel and arc rotation provides a spiralling effect directly applicable for use in a 360 degree weld metal overlay process.

To demonstrate the capabilities of the selected automated welding system and identify target welding parameters a pipe ID weld overlay was performed on a 2 inch nickel base alloy pipe with inconel 82 filler metal. The current design of the model 94 weld head feeds a 0.030 inch diameter weld wire. The filler metal of choice for this program, [ ][a,c,e] was not available in 0.030 inch diameter at the time of the demonstration. A 20 lb. spool of 0.035 in. diameter [ ][a,c,e] filler metal was obtained and reduced to the required 0.030 inch diameter.

5.2 Qualification of the Welding Parameters

The intent of qualifying the parameters at the beginning of the program was to ensure that the starting parameters were appropriate for use with the [ ][a,c,e] filler metal. The starting parameters were based on the parameters used with the [ ][a,c,e] filler metal during the demonstration of the welding system. This approach was taken due to the limited supply of the [ ][a,c,e] filler

wire at the beginning of the program, and the long lead time required to reduce the diameter of the available weld wire to 0.030 inch. The weld wire situation prevented any practice welding to establish welding parameters in advance with the [ ]a,c,e.

Two alloy 600 pipe assemblies were welded using [ ]a,c,e filler metal to qualify the parameters to the ASME Section IX mechanical test requirements. Four 5-inch long pipe samples were machined with 37.5° grooves as shown in Figure 5.2-1. The 37.5° groove was machined starting from the ID of the pipe and finishing the groove at the OD of the pipe so that the groove could be welded from the pipe ID.

Starting process parameters for welding the pipe assemblies with the [ ]a,c,e filler metal were those process parameters used in the demonstration with [ ]a,c,e. The parameters were adjusted as welding progressed. Some difficulties were experienced in welding the first assembly, during the initial two layers burn-through and stuck wire in the weld puddle occurred. Once the parameters were adjusted based on the difficulties, there was no problem with the subsequent layers of the first assembly or the second assembly. Upon completion of welding the two pipe assemblies, mechanical test coupons, i.e., tensile and bend (face and root) specimens, were machined from each assembly in accordance with ASME Section IX requirements. All bend specimens were free of cracks with the exception of the root bend specimen of the first assembly. The failure of the root bend was attributed to the difficulties experienced as explained above.

During welding of the qualification pipe assemblies it was observed that inconel 52 filler metal has a very sluggish characteristic, even worse than [ ]a,c,e. This may be due to higher contents of Cr, Fe and deoxidizers such as Al and Ti in [ ]a,c,e compared to [ ]a,c,e. The [ ]a,c,e filler metal mixed well with the alloy 600 penetration tube producing a relatively smooth surface, as was observed in the first layers of the pipe assemblies. The subsequent layers, however, started showing the sluggish characteristics which produced a relatively rough surface in comparison.

In general the surface condition of a weld is controlled by grinding or machining operations after welding. However, considering the actual field applications of this process it was desirable to improve the surface condition through weld process controls such that no grinding operation would be required after repair welding. As an attempt to improve the surface finish a [ ]a,c,e

mixture of shielding gas was tried during the welding of the second pipe assembly. The [ ]^{a,c,e} mixture gas was tried because it was readily available for a similar application on a nickel base alloy. The change in the shielding gas did not improve the surface finish of the as-welded condition. Thus the shielding gas was changed back to [ ]^{a,c,e} gas. Welding process parameters were adjusted during welding of the subsequent test tube samples to maximize the quality of the final surface finish.

5.3 Welding of Penetration Tube Samples

Table 5.3-1 shows the matrix of the eight [ ]^{a,c,e} penetration tube samples and their respective geometries. Repair welding of the tube samples started with sample number 4, which had a 360 degree groove of [ ]^{a,c,e} inches deep. Although the welding system was capable of welding the groove in one spiral operation the operation was stopped every one (1) inch or so to maintain the interpass temperature below [ ]^{a,c,e} maximum. The [ ]^{a,c,e} interpass temperature was selected because this is typical industry practice for minimizing distortion in stainless and nickel base alloys. Those samples with a partial groove, [ ]^{a,c,e}, required a similar interpass temperature control. It should be pointed out that the samples with a partial groove took a much longer time to weld due to the setup required for every pass. Each weld pass was performed circumferentially for this program. The necessity of a setup for every pass could impose some difficulties on actual field applications for repair welding and special attention should be given in development of field tooling to minimize this impact.

As explained in the previous section during welding of the [ ]^{a,c,e} tube samples the parameters were adjusted to improve the weld surface finish, such that the surface smoothness could be maximized. Although surface finish appeared to be adequate, more improvement would appear to be possible. Welding of additional samples for further adjustment of parameters would be beneficial as well as investigating the use of other shielding gases. Another possible shielding gas would be a helium/argon mixture. Other options, such as a combination of [ ]^{a,c,e} with [ ]^{a,c,e} and/or [ ]^{a,c,e} on the last layer should be considered.

As indicated in the Table 5.3-1 tube sample number 7 and 8 included EDM notches in the repair area. This was to study repair welding over [ ]^{a,c,e}. Figures 5.3-1 through 5.3-5 depict the cross sections of repair welds over the EDM notches. The notches were

approximately [ ]a,c,e inches deep and [ ]a,c,e inch wide. The metallography samples of the notches showed no cracks or indications generated in the surrounding area due to the welding. Considering [

]a,c,e.

5.4 Welding Reactor Vessel Closure Head/Penetration Tube Mock-Up

Two EDM grooves, Figure 4.1-2, were machined in the penetration mockup to simulate weld repairs in the plant. It was learned from the [ ]a,c,e penetration tube samples that a 360° groove would be much easier to weld repair as opposed to the partial groove with the welding system available. Thus, partial grooves were selected for the mockup to investigate the potential difficulties which might be experienced in a field application. The [ ]a,c,e inch groove depth was selected for the partial grooves as the most probable thickness of weld overlay to be used in a field application.

Repair welding the excavation areas in the mockup were performed very much the same as in the penetration tube samples. Since the mockup, Figure 5.4-1, had more mass to transfer the heat during welding it was not necessary to stop the welding operation as often as in the [ ]a,c,e inch penetration tube samples, to meet the [ ]a,c,e interpass temperature requirement. It is estimated that the interpass temperature control may not be a concern with the field application due to the mass of the penetration tube and surrounding reactor vessel closure head.

a,c,e

ARC MACHINES, INC.

Figure 5.1-1 Weld Head Used for Weld Repair Program

a,c,e

ARC MACHINES, INC.

Figure 5.1-2 Weld Power Supply/Controller Used for Weld Repair Program

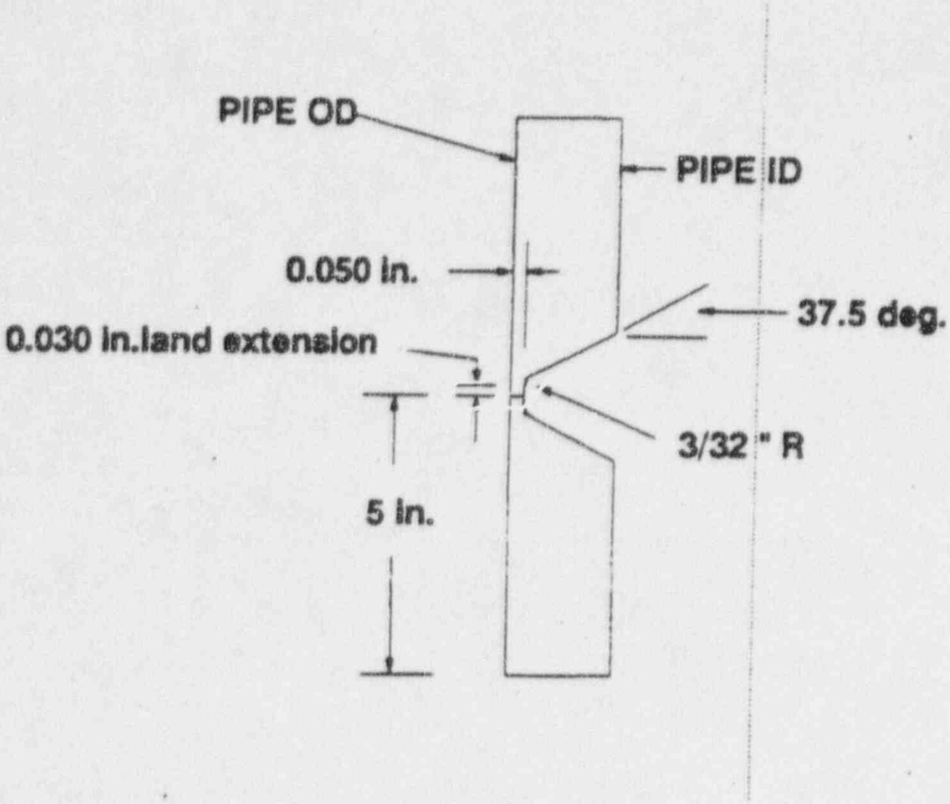

Figure 5.2-1 Joint Geometry for Qualification Samples

Table 5.3-1

TEST MATRIX FOR [ ]^{a,c,e} PENETRATION TUBE SAMPLES

a,c,e

a,c,e

Figure 5.3-1 Penetration Tube Sample No. 8 Cross-Section Showing Weld Repair
[ ]a,c,e

a,c,e

Figure 5.3-2 Penetration Tube Sample No. 8 Cross-Section Showing [
]a,c,e

[ ]a,c,e

Figure 5.3-3 Penetration Tube Sample No. 7 Cross-Section [

]a,c,e.

a,c,e

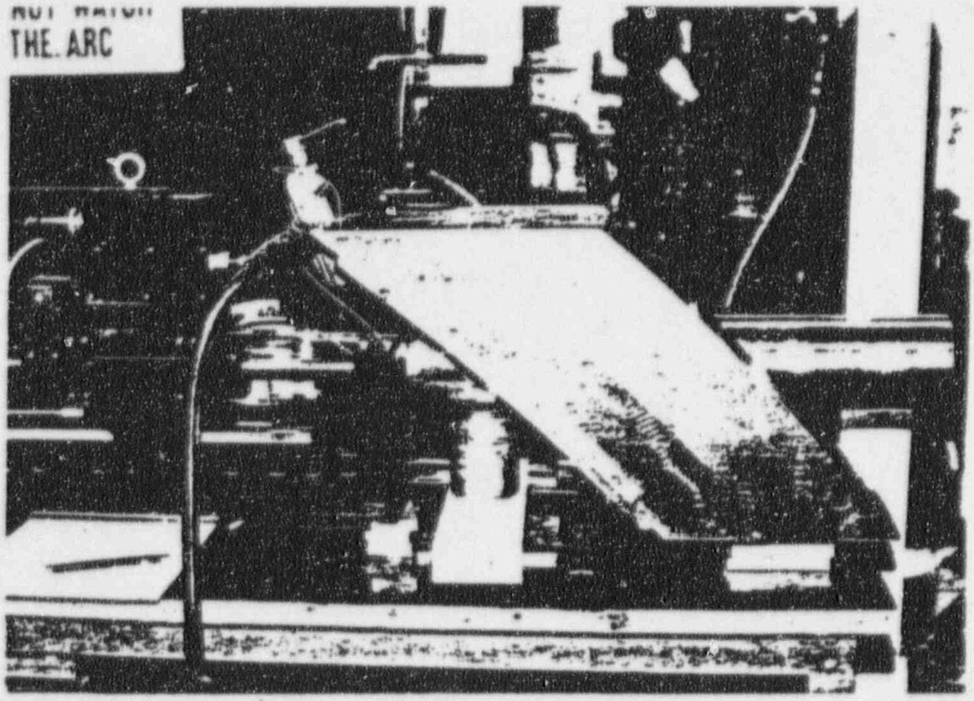

Figure 5.4-1 Photograph Depicting Weld Tooling Set-Up In Full Size Penetration Tube Mock-Up

6.0 EVALUATION OF WELDED PENETRATION TUBE SAMPLES

The penetration tube samples were used to evaluate the feasibility of welding within the 2.75 inch diameter of the penetration tube and to evaluate the impacts of the various selected geometries. As defined in Table 5.3-1, eight penetration tube samples were selected to explore the various weld repair geometries. The overall weld length, circumferential extent and depth were varied.

6.1 Discussion of Diametral Measurements

To evaluate the penetration tube samples each sample had pre and post weld dimensional data taken. The measurements were taken across both the inside and outside diameter in 0.5 inch increments over the entire length. The outside diameter measurements were used as the primary mechanism for comparison as opposed to inside diameter measurements in order to avoid variations resulting from the weld surface finish and the weld applied thickness. Figures 6.1-1 through 6.1-8 provide plots of the dimensional data. The dimensional data as-measured pre and post welding is provided in Appendix D, Penetration Tube Dimensional Data.

The penetration tubes were scribed to retain the orientation of the axis, i.e. 0°, 45°, 90°, and 135°. The outside diameter measurements taken across each of these axis were very consistent and on the average were 4.000 +/- 0.001 inch. The pre-weld diametral measurements were averaged and plotted as a single line on Figures 6.1-1 through 6.1-8. Post weld measurements were taken across the same axis and are plotted individually on each of their respective figures.

Based upon a review of Figures 6.1-1 through 6.1-8 the following observations were made:

- Regardless of the weld length (4 or 6 inches) the diametral dimensions are impacted over a length approximately 1 inch greater than the weld repair length. Recall the weld repair lengths do not include the taper length which is also filled with weld material. This would indicate that an approximately 0.5 inch transition zone exists from the end of the repair depth where weld shrinkage impacts the diametral measurements. This transition zone appears to independent of weld depth or taper length.

- A 360° weld repair results in deformation across each axis. The deformation is approximately uniform for each axis, Refer to Figures 6.1-2, 6.1-4, and 6.1-8.

- The deformation associated with a 90° weld repair also impacts each axis, particularly those axis 45° from the weld centerline (i.e. primary axis). The 45° axis experiences deformation approximately 30% to 40% of the primary axis. The axis 90° from the primary axis appears to be the least impacted. See Figure 6.1-3 and 6.1-5.

- In all penetration tube samples the deformation, resulting from weld shrinkage, appeared to result in a decrease of the outside diameter except over a very few number of local positions, See Figures 6.1-1, 6.1-5, and 6.1-7.

- On the average the deformations resulting from the various weld depths are:

Weld Depth (inch)	Average Deformation (inch)	Maximum Deformation (inch)
[ ]a,c,e	[ ]a,c,e	[ ]a,c,e
[ ]a,c,e	[ ]a,c,e	[ ]a,c,e
[ ]a,c,e	[ ]a,c,e	[ ]a,c,e

These deformations are based on the measurements taken in the [ ]a,c,e penetration tube samples. It is judged that deformation in the actual plant penetration tubes would be less because of the available mass to dissipate the welding heat input.

a,c,e

Figure 6.1-1 Deformation in Penetration Tube Sample #1 [ ]^{a,c,e}

a,c,e

Figure 6.1-2 Deformation in Penetration Tube Sample #2 [ ]^{a,c,e}

a,c,e

Figure 6.1-3 Deformation in Penetration Tube Sample #3 [ ]a,c,e

a,c,e

Figure 6.1-4 Deformation in Penetration Tube Sample #4 [ ]^{a,c,e}

a,c,e

Figure 6.1-5 Deformation in Penetration Tube Sample #5 [ ]^{a,c,e}

a,c,e

Figure 6.1-6 Deformation in Penetration Tube Sample #6 [ ]a,c,e

a,c,e

Figure 6.1-7 Deformation in Penetration Tube Sample #7 [ ]a,c,e

a,c,e

Figure 6.1-8 Deformation in Penetration Tube Sample #8 [ ]a,c,e

7.0 RESIDUAL STRESS MEASUREMENTS ON REACTOR VESSEL HEAD/ PENETRATION TUBE MOCK-UP

7.1 Approach to Residual Stress Measurement

To determine the residual stresses buildup from welding the reactor vessel closure head and penetration tube full scale mock-up fabricated for this program was used. The fabrication of the mockup was described in a previous section of this report. The hole drilling met[illegible]od of residual stress measurement was used for these measurements. A s[illegible] f the head penetration model and test fixture is shown in Figure 7.1-1. All of the [illegible] measurements were made on the ID of the tube.

The residual stress measurement program was divided into three steps:

[

]^{a,c,e}

7.2 Hole Drilling Method

This method involves mounting a three strain gage rosette at the location the measurement is required. A small hole is drilled at the center of the rosette and the relieved strain is measured by the three gages of the rosette. The relieved strain and elastic constants of the material and constants for the rosette are used to calculate the residual stress. The rosette constants are obtained by calibration, either by the rosette manufacturer, or using the ASTM standard practices. The rosettes used were procured from Micro Measurements, gage model [ ]^{a,c,e}. This is a special three element 45° rosette in a circular pattern. The hole drilling method measures a near surface residual stress and is described in ASTM standard E-837-92. Stress is assumed to be uniform, or at worst, varying uniformly through the thickness of the object measured. For a uniform stress field the accuracy is estimated within [ ]^{a,c,e}.

7.2.1 Installation of Strain Gage Rosettes

Rosette locations for each step are shown in Figures 7.2-1, 7.2-2, and 7.2-3. These figures depict maps of the inside surface of the penetration tube and show the angular position and distance from the inside end of the penetration tube. The rosette locations are also tabulated in Table 7.2-1. Rosettes were oriented with the number one gage in the axial direction of the tube.

The ID surface of the tube was prepared for installation of the strain gages by first cleaning with a chlorothen degreaser. The surface over which the strain gage rosettes were installed was dusted with micro sand blasters to give a mat finish for better adhesion of the strain gages. For mounting strain gage rosettes in the EDM machined areas, in Step 2, the surface was first smoothed [ ]^{a,c,e}. The welds in the weld repair area, in step 3, were ground to a flat surface suitable for strain gage installation. [ ]^{a,c,e} adhesive was used to bond the gages.

7.2.2 Drilling Holes

The setup for the residual stress measurements on the model is shown in Figures 7.2-4 and 7.2-5. Air abrasive machining was used to machine the holes. A special fixture (shown in Figure 7.1-1) was made to position the drill to target the center of the rosette. The rosettes are masked before drilling to protect them from the abrasive. Strain readings are taken before and after drilling. Hole depth is determined by air pressure, abrasive size, nozzle diameter and time. [ ]^{a,c,e}

7.3 Test Results

The principal stresses and directions were calculated using the relieved strains and equations in ASTM E 837. [ ]^{a,c,e} The relieved strains were corrected for transverse sensitivity and gage factor variations. These factors are provided by the strain gage manufacturer (see Figure 7.3-1). The equations for the calculation of residual stresses are:

[ ]a,c,e

The equation for calculating the angle C from gage 1 of the rosette tc the nearer principal stress is:

[ ]a,c,e

The relationship of principal stress directions to the rosette is shown in Figure 7.3-2.

The results of the residual stress measurement. are given in Table 7.3-1. Residual stress versus distance from the end of the tube is shown in F gures 7.3-3 and 7.3-4.

7.4 Comparison of Test Results to Ar.alysis

Elastic/Plastic analysis of the reactor vr ssel closure head/penetration tube geometry has been performed and documented in WCAP .3525, Reference 5, also several repair geometries have been analyzed and documented in [ ]a,c,e, Reference 6. The elastic/plastic analysis are of particular interest for comparison with residual stress measurements taken in the reactor vessel closure head/penetration tube mock-up, because the measurements serve to validate both the analysis and measurements. Also, the repair geometries examined local grooves (i.e. slots) as measures to reduce penetration tube residual stresses.

While the hole drilling technique is a fairly accurate means for the measurement of residual stresses it should be noted that the measured values represent an average stress over the depth of the hole, [ ]^{a,c,e} inch in this case. Thus the measured stress value is slightly below the actual surface stress on the order of magnitude of 10%. The finite element analysis provides a calculation of the surface stress. Figures 7.4-1 through 7.4-4 provide plots of the penetration tube residual stress as calculated after welding (as-opposed to the residual + operating stress) as compared with the measured stress values. Figures 7.4-1 and 7.4-2 plot hoop stresses while Figures 7.4-3 and 7.4-4 provide plots of the axial stresses. Also, the plots distinguish between the penetration tube center side (180° orientation on Figures 7.2-1, 7.2-2, and 7.2-3) and hill side (0°/360° orientation). The plots depict in general the same trends (peaks and valleys) between the measurements and the finite element calculations, also fairly good quantitative agreement exists, particularly for the hoop stress values.

Several other observations/comparisons were drawn from the hole drilling residual stress measurements and finite element calculations (It should be noted that the residual stress measurement locations in Table 7.3-1 identified with the same numerical value are approximately positioned with the same coordinates):

- The machining of the grooves generally appeared to lower stresses at the location measured. Hoop stresses were decreased at locations 4a, 8a, 9a, 12a, 14a and increased only at locations 3a. Axial stresses were decreased at locations 3a, 8a, 9a, 12a, 14 and increased only at location 4a. This generally supports the conclusions made in the analytical study of repair configurations, Reference 6.

- Weld repair areas have fairly high residual stresses, the greatest measured value being a principal stress of [ ]^{a,c,e} ksi, see location 11b on Figure 7.2-3. Although fairly high this value is comparable with the calculated surface stresses.

- Tensile stresses adjacent to the weld as indicated are fairly high but dissipate rather quickly, see locations 11b and 16b on Figure 7.2-3. Adjacent to the weld the axial/hoop stresses are [ ]^{a,c,e} ksi respectively, but drop to [ ]^{a,c,e} ksi less that 1 inch away.

- The penetration tube stresses approaching the 45° axis are expected by analysis to be low approaching compression. A review of these stresses after welding, see location 12B and 14b, in fact have compressive axial stresses of [ ]^{a,c,e} and [ ]^{a,c,e} ksi with low hoop stresses of [ ]^{a,c,e} and [ ]^{a,c,e} ksi.

- Axial and hoop stresses in the alloy 690 weld repair are higher than their corresponding values before welding, hoop stresses increasing by approximately [ ]^{a,c,e} ksi with the largest increase being in the axial stress components [ ]^{a,c,e} ksi to [ ]^{a,c,e} ksi and [ ]^{a,c,e} ksi to [ ]^{a,c,e} ksi, see locations 3/3b and 9/9b.

- A review of measured principal stress in the penetration tube weld region prior to and after welding indicate an overall increase in surface stresses.

- Although the individual measured stress components (axial and hoop) prior to and after welding indicate an overall increase in surface stresses the after welding values are comparable to calculated values. Again, Figures 7.4.1 through 7.4.4 provide the calculated and measured stress component values prior to welding.

a,c,e

Figure 7.1-1 Overall Dimensions of Head Penetration Model and Air Abrasive Drill Positioning Fixture

[ ]a,c,e

Figure 7.2-1 Location Map of Residual Stress Measurements for Step 1 [ ]a,c,e

a,c,e

Figure 7.2-2 Location Map of Residual Stress Measurements for Step 2 [ ]a,c,e

a,c,e

Figure 7.2-3 Location Map of Residual Stress Measurements for Step 3 [ ]a,c,e

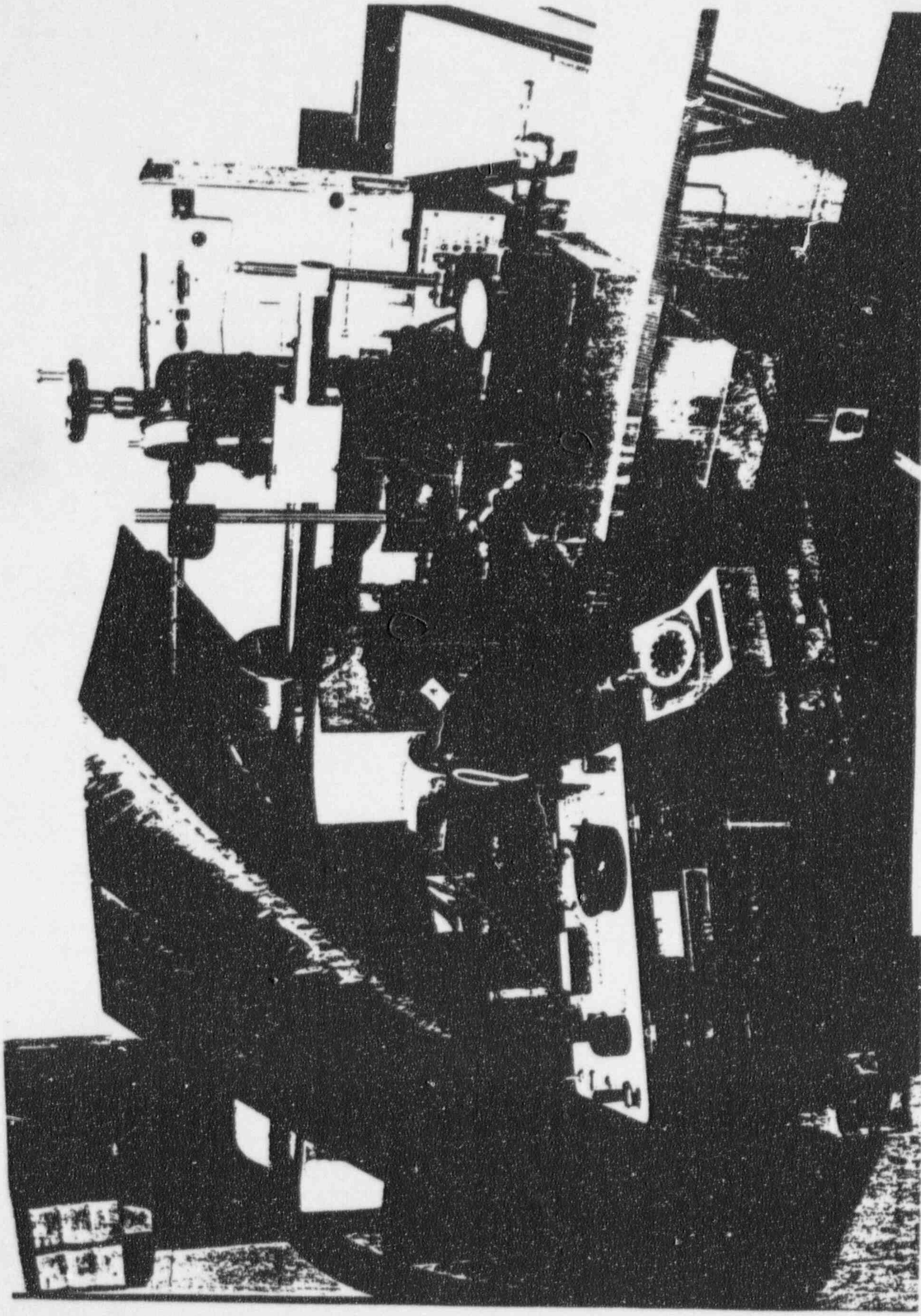

Figure 7.2-4 Test Setup for Residual Stress Measurements

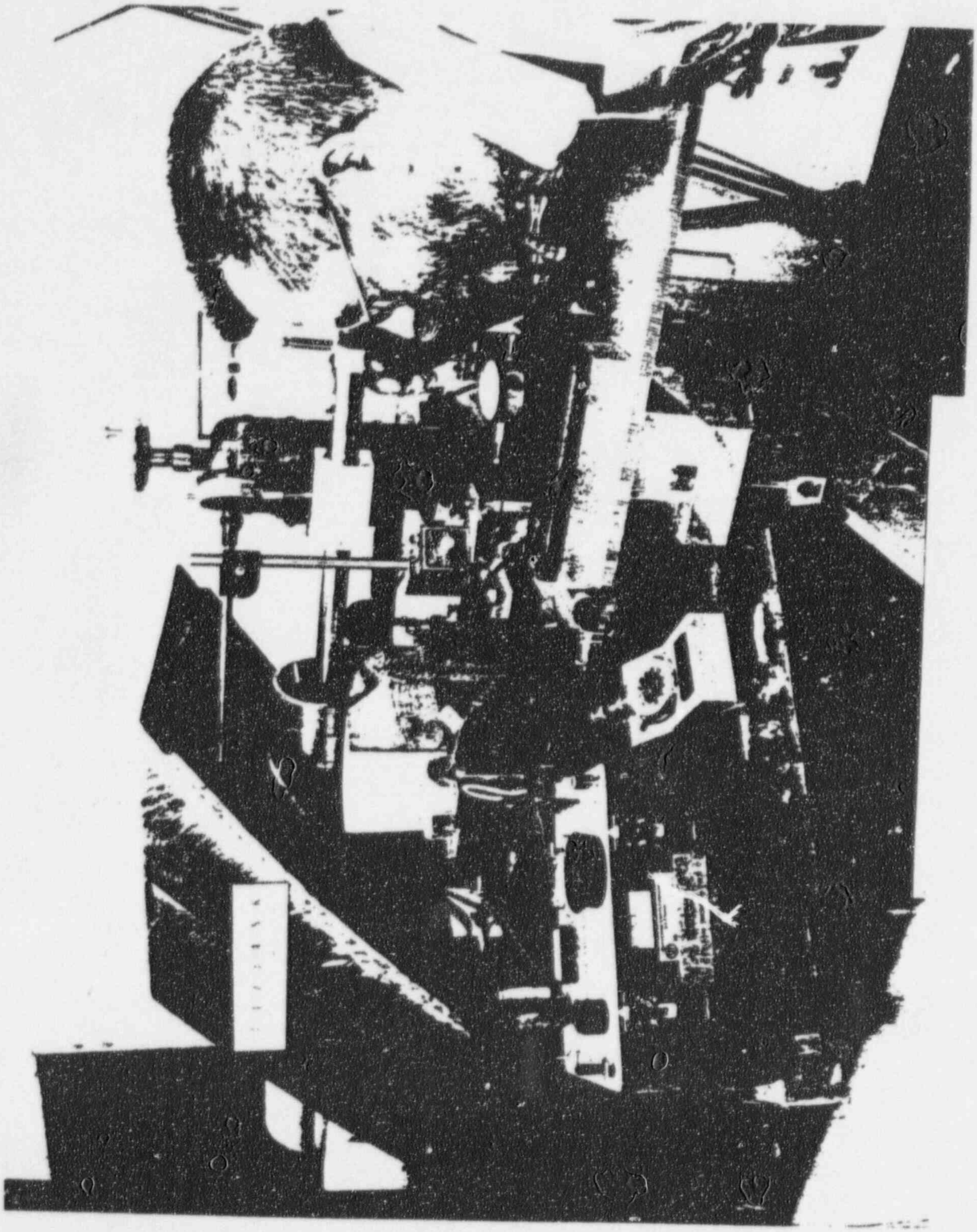

Figure 7.2-5 Adjusting Hole Drilling Fixture

Table 7.3-1
RESIDUAL STRESS MEASUREMENTS IN REACTOR VESSEL HEAD/ PENETRATION TUBE MOCK-UP

a,c,e

a,c,e

Figure 7.3-1 Hole Drilling Rosette Strain Gage Data

a,c,e

Figure 7.3-2 Relationship of Principal Stress Directions to Rosette Gages

a,c,e

Figure 7.3-3 Residual Stress Versus Distance From End of Tube for Step 1 at 180° Location

a,c,e

Figure 7.3-4 Residual Stress Versus Distance From End of Tube for Step 1 at 0° Location

a,c,
e

Figure 7.4-1 Residual Hoop Stress As-Measured Compared to Analytical Estimates of Hoop Stress for Center Side of Penetration

m:\2506w.wpf:1b-111795

a,c,e

Figure 7.4-2 Residual Hoop Stress As-Measured Compared to Analytical Estimates of Hoop Stress for Hill Side of Penetration

a,c,e

Figure 7.4-3 Residual Axial Stress As-Measured Compared to Analytical Estimates of Hoop Stress for Center Side of

a,c,
e

Figure 7.4-4 Residual Axial Stress As-Measured Compared to Analytical Estimates of Hoop Stress for Hill Side of Penetration

8.0 DISCUSSION OF POST WELD SURFACE TREATMENT

Post weld surface treatment of welds is typically performed to serve one or all of the following functions:

1) Improve the surface finish such that an acceptable surface is provided for performing post-weld inspections and/or future penetration tube inspections.

2) Provide an acceptable geometry such that the function of the component is not negatively impacted. In the case of the penetration tube inside diameter, the inside diameter can not be reduced such that it impacts the thermal sleeve or reduces the flow path in the penetration tube ID to thermal sleeve OD annulus [

]^{a,c,e}.

3) Mitigate the residual stresses in the weld metal and adjacent base material which occur as a result of the welding process.

In developing process requirements for welding, regardless if it is to be used as a mitigative measure for PWSCC (360° overlay) or a repair to restore the penetration tube pressure boundary (local repair), items (1) and (2) above are intended to be addressed via process controls. The post weld surface finish, item 1, and the post weld geometry, item 2, are intended to be controlled via weld process and inspections requirements. In order to address item 3 the WOG requested via the program authorization that shot peening be examined as the remedial measure for the mitigation of residual stresses induced by welding.

8.1 General Discussion of Shot Peening

Shot peening is a cold working process in which the surface of the material is bombarded with small spherical media called shot. Each piece of shot striking the material acts as a tiny peening hammer, imparting to the surface a small indentation or dimple. In order for the dimple to be created, the surface fibers of the material must be yielded. The cold working process results in the application of beneficial compressive stresses being applied at or just below the material surface. Compressive stresses are beneficial in increasing resistance to fatigue failures and stress corrosion cracking. Benefits obtained due to cold working include hardening, intergrannular corrosion resistance and

surface texturing. Westinghouse has investigated shot peening as a mitigative technique for application to the Alloy 600 penetration tube to increase the materials margin against primary water stress corrosion cracking (PWSCC).

The maximum value of the residual compressive stress is often called the magnitude of the residual stress induced. Variations in the shot peening process have little effect on the magnitude of the compressive stress induced as long as the shot used is at least as hard as or harder than the material being peened. The magnitude of the compressive stress is primarily a function of the base material mechanical properties. As a general rule the magnitude of compressive stress induced has a value of at least one half the yield strength to a maximum of approximately 60% of the ultimate tensile strength. For the minimum allowable mechanical properties listed for alloy 600 SB-166 & 167 this relates to a compressive stress range of [ ]^{a,c,e}.

The energy of the shot is a function of the media size, material, hardness, velocity and impingement angle. In order to specify, measure and calibrate peening energy a method utilizing SAE1070 spring steel specimens, called Almen strips, was developed. There are three standard Almen scales currently in use, each based on a different Almen strip thickness. The three scales are the "N", "A", and "C" scale in increasing order of intensity. The depth of the compressive layer is proportional to the Almen intensity. It should be noted that the magnitude of the compressive stress induced is independent of the compressive layer depth. Peening depth needs to be examined from two aspects; 1) The greater the depth the larger the impact on surface or subsurface material imperfections, and 2) The stress distribution through the component has to be balanced, thus for the case of the penetration tube wall an increase of compressive stress on the ID results in an increase in tensile stress on the OD.

The maximum benefit of shot peening is realized when the surface is uniformly peened to a saturation energy level. Saturation is defined as the earliest point where doubling the exposure time produces no more than a 10% increase in Almen intensity.

8.2 Shot Peen Parameters

Westinghouse performed a feasibility study to investigated shot peening for the reactor vessel closure head penetration geometry. The two primary objectives of the feasibility were:

- Show that tensile stresses on the inside diameter of the test chamber (penetration tube mock-up) before shot peening were [ ][a,c,e].

- Confirm that shot peening reduces these inside diameter tensile stresses to [ ][a,c,e].

The intent of these two objectives were to produce stresses in the penetration tube above the estimated threshold to PWSCC such that the penetration tube test chambers were susceptible to PWSCC. The shot peen process investigated did successfully reduce the susceptibility of the test chamber sample material to stress corrosion cracking in a series of laboratory tests.

Through the specification of process control parameters an Almen intensities of [ ][a,c,e] on the "N" scale were developed in the test chambers resulting in a compression layer depth of approximately [ ][a,c,e]. It was estimated that the magnitude of compressive stress induced was [ ][a,c,e], approximately [ ][a,c,e] of the ultimate tensile strength of the material used in the test.

Subsequent discussions with commercial shot peen vendors have indicated that it should be feasible to develop Almen intensities of approximately 8 on the "C" scale resulting in approximate compressive depth layers of [ ][a,c,e]. Although the Almen intensity scales can not be directly related the approximate relationship between the two scales is: N = 0.1C or 10N = C.

8.3 Conclusions Regarding Post Weld Surface Treatment

A properly controlled shot peening process should a reliable remedial measure for the mitigation of residual tensile stresses associated with a weld overlay repair. It appears feasible that a shot peen process can be developed which would apply a compressive stress to the surface of the base material on the order of [ ][a,c,e] ksi or greater dependent on the base material properties to a depth [ ][a,c,e]. Such a process should increase the margin against PWSCC in the alloy 600 base material both in the heat affected zone adjacent to the weld and generally throughout the penetration tube ID.

Much investigation has been given to the development of approaches to provide margin against cracking in the weld toe profile. One common methodology is to grind the weld toe profile such that

the geometric discontinuities are removed from this area. This practice could also prove beneficial to the penetration tube ID, either performed by itself or in combination with shot peening. The extent to which a utility wishes to pursue post weld surface treatment needs to be an individual utility decision based on the technical merits and economic impacts. Clearly all post weld surface treatments add margin to weld life, each having its individual implementation costs and radiological impacts.

9.0 DISCUSSION OF WELD OVERLAY REPAIRS

9.1 Penetration Tube Repair Parameters

Generally, prior to the implementation of a weld overlay repair, any detected flaws will be evaluated against the industry acceptance standard using flaw evaluation techniques to determine if the flaws can be accepted as-is or need to be repaired. If repair is required or the utility chooses to implement a repair, the next appropriate repair would be the removal of the defect. If it is either determined by volumetric inspection or during the course of defect removal that the minimum required penetration tube wall thickness is violated a repair of that penetration location would be required. As investigated via this WCAP report a weld overlay repair is viable option for that repair.

9.1.1 Excavation Depths and Weld Thickness

As defined, the minimum required penetration tube wall thickness is approximately 0.3 inch. Excavation depths which leave a remaining wall ligament of less than the required design thickness, ~0.3 inch, would require a build up of the penetration tube wall. Additionally, another factor should be consider in specifying excavation depths. Excavation of the penetration tube wall and subsequent repair weld . could result in a heat affected zone in the reactor vessel closure head base material. To avoid having to perform a post weld heat treatment of the weld repaired area and adjacent reactor vessel closure head base material it is suggested that some minimum ligament be maintained in the penetration tube wall. [

]^{a,c,e} It is judged that this thickness could be directly applied for use in repair of the penetration tube wall. Thus during excavation it is suggested that a minimum penetration tube wall thickness (ligament) of [ ]^{a,c,e} inch be maintained. Based on the above discussion the following criteria are suggested for repair of reactor vessel closure head penetration tubes:

- Any defects detected in the penetration tube wall surface should first be repaired by excavation. No additional repair is required if the excavation depth does not violate the minimum required design basis thickness, approximately 0.3 inch.

- If excavation to a depth of [ ]^{a,c,e} inch does not remove the entire defect, excavation should continue until the defect is removed or until [ ]^{a,c,e} inch of the penetration tube wall remains.

- A weld repair to restore the minimum required design thickness needs to take into consideration the remaining acceptable penetration tube wall thickness such that the acceptable tube wall after repair welding is 0.3 inch or greater. For example;

  If the flaw were through wall, no remaining acceptable penetration tube wall thickness would exist and the minimum required weld overlay thickness would be 0.3 inch.

  Conversely, If the remaining acceptable tube wall thickness were [ ]^{a,c,e} inch, the minimum required weld overlay thickness would be [ ]^{a,c,e} inch, such that the total thickness was 0.3 inch.

9.1.2 Repair Geometry

As reported welding does provide an overall increase in the surface principle stresses of the penetration tube. These residual stresses are comparable in magnitude to the maximum residual plus operating stresses estimated via the elastic/plastic analysis for the outermost penetration tubes. It is difficult to quantify the impacts this increase in stress would have on the susceptibility of the alloy 600 base material to PWSCC. However, it would seem appropriate to estimate that the areas of the penetration tube adjacent to the weld would be more susceptible to PWSCC than the alloy 600 base material not impacted by the welding process. Of course, the alloy 690 weld filler metal should not be susceptible to PWSCC as compared with the base material.

As discussed previously, the toe of the weld could potentially be positioned, by design, in areas of the penetration tube estimated to initially have relatively low stresses by comparison. The intent being that the increase in stress due to welding will result in final stresses of lower magnitude than if the toe of the weld were positioned in a high stress region initially.

These considerations directly impact the selection of weld repair circumferential extent.

As investigated in this WCAP, if it is desirable to locate the toe of the weld outside the comparably high stress zones in the penetration tube ID, the circumferential extent of the weld should be selected such that it falls along the [ ].[a,c,e] Or as discussed in Section 8.0, post weld surface treatment(s) could be used as a means to possibly mitigate the residual stresses induced by welding.

The specific local weld repair geometry a utility wishes to pursue needs to be an individual utility decision based on the technical merits and economic impacts. Westinghouse drawing [ ],[a,c,e] attached in Appendix B, depicts the various weld repair geometry requirements and suggested repair profiles.

Drawing [ ][a,c,e] also depicts the geometries associated with a 360° weld overlay. As stated earlier a 360° weld overlay repair was investigated to offer a remedial repair which could generally be implemented to mitigate PWSCC in the highly susceptible region of the penetration tube ID.

9.1.3 Weld Surface Finish

The surface finish achieved in the application of a local weld repair or 360° weld overlay in the reactor vessel closure head penetration tubes is important from two aspects; 1) An acceptable weld surface finish is desirable to permit inspection of the weld and penetration tube base material, and 2) The smoother the weld surface finish the less susceptible the weld filler metal is to the initiation of surface cracks.

The intent as discussed in development of the weld process parameters was to refine the parameters such that the best possible surface finish could be achieved. The goal was to achieve a surface finish that would permit the volumetric inspection (ECT and/or UT) of the weld filler metal and base metal without having to rework the weld surface finish by some post weld machining operation. While rework of the surface is permissible the intent was to avoid the time and cost associated with rework of the surface. A realistic target surface finish judged to be achievable via the weld process and yet permissible for volumetric inspection was [ ].[a,c,e] In the development work performed a [ ][a,c,e] was achieved over limited lengths of applied weld, but over the full 6 inch length weld applied in the penetration tube samples the [ ][a,c,e] surface finish was not maintained.

It is suggested that the final check/qualification of the applied welding process should be verification that the final weld geometry/surface finish could be volumetrically inspected, using ECT as a minimum.

9.1.4 ASME Code Approach to Weld Repair

Repair welding is intended to be performed to the guidelines established in Section XI of the ASME Code. However, Section XI does not specifically define guidelines for what depth of flaws must be repaired in the reactor vessel closure head penetration tube ID. In applying weld repair to re-establish the minimum required design thickness of the penetration tube wall no code ambiguities seem to exist for the case where the defects have been totally removed. [

]a,c,e

[

] a,c,e

9.1.5 Post Weld Inspection Requirements

ASME Code Section XI Subsection IWA-4500 outlines the guidelines for inspections of repair welds made to pressure boundary components. The code requires that a baseline volumetric inspection be performed of the weld repair for future reference, this is also consistent with the general guidelines

outlined for repair welds made to base metal by the component fabricator, ASME Section III Subsection NB-4130.

9.2 Conclusions

In summary the following conclusions are made:

[ ]a,c,e

a,c,e

10.0 REFERENCES

[ ] a,c,e

2. ASME Boiler and Pressure Vessel Code, Section IX, "Welding and Brazing Qualifications," 1989 Edition, ASME, New York, New York, July 1, 1989

3. ASME Boiler and Pressure Vessel Code, Section XI, "Rules for Inservice Inspection of Nuclear Power Plant Components," 1989 Edition, ASME, New York, New York, July 1, 1989

[ ] a,c,e

APPENDIX A

WELDING PROCESS SPECIFICATION

REPAIR WELDING OF REACTOR VESSEL CLOSURE HEAD PENETRATIONS

[ ]a,c,e

SAFETY REQUIREMENTS: Personnel responsible for welding application shall have a safety and industrial hygiene program for handling hazardous materials and arc welding equipment (ANSI B7.1, Z43 and Z49.1)

1.0 SCOPE

[ ] a,c,e

1.2 This process specification is applicable to the Safety related ASME Code items. The applicable code issue and/or other requirements will be specified in the equipment specification or procurement document.

1.3 This process specification is intended as a guide for the qualification of welding procedures and for the performance of welding on Westinghouse Nuclear Steam Supply System Components. Any exceptions to or deviations from the requirements of this specification must be documented in writing and submitted to WNTD (Westinghouse Nuclear Technology Division), Materials and Engineering Mechanics, at the time the welding procedure is submitted for approval.

2.0 REFERENCE DOCUMENTS

2.1 ASME Boiler and Pressure Vessel Code Section IX "Welding and Brazing Qualifications".

2.2 ASME Code Case 2142.

[ ]a,c,e

2.4 Additional documents that may be referenced in design specification, drawings and/or procurement documents.

3.0 MATERIALS

3.1 Base Materials

3.1.1 Nickel-Chromium-Iron Alloy base material in the solution annealed condition, ASME Section IX classification P-43.

3.2 Filler Materials

[ ]a,c,e

3.3 Electrode

[ ]a,c,e

3.4 Shielding Gas

3.4.1 The shielding gas shall be welding grade [ ]a,c,e.

4.0 PROCEDURE REQUIREMENTS

4.1 Qualification

All weld procedure specifications and welding personnel shall be qualified to the requirements of Section XI of the ASME Code. Exceptions to this requirement will only be permitted by written approval of W NTD, prior to any welding being performed on components.

4.2 Equipment

[ ] a,c,e

4.3 Joint Geometry & Preparation

4.3.1 Weld joint geometry shall be in accordance with the drawing number [ ]a,c,e attached in Appendix C.

4.3.2 The joint geometry shall be prepared by [ ]a,c,e.

[ ] a,c,e

4.4 Electrical Characteristics

[ ]a,c,e

4.5 Welding Position

All welding shall be done in the horizontal (2G) position where possible.

4.6 Preheat and Interpass Temperature

[ ]a,c,e

4.7 Postweld Heat Treatment

Postweld Heat Treatment (PWHT) is not required, nor permitted, unless specified in design specification, design drawings or other contractual documents.

4.8 Technique

4.8.1 Filler metal diameter shall be suitable for the base material thickness and weld joint configuration used in the component. [ ]a,c,e diameter is required for the parameters in table 1.

[ ]a,c,e

4.8.2 Deposition Method

4.8.2.1 All welds must be deposited with stringer beads.

4.8.3 Interpass Cleaning

[ ] a,c,e

[ ] a,c,e

4.9 Tooling & Fixturing

4.9.1 Discretion shall be used in the selection of material for tooling and fixturing for parts being welded such that there will be no detrimental effects to the weldment due to contamination as a result of heating, rubbing, smearing or excessive clamping pressure.

[ ] a,c,e

5.0 QUALITY ASSURANCE

5.1 Fabricators Quality System, Quality Release Requirements, Data Packages, and witness and notification points, when required, shall be as specified in the procurement documents.

5.1.1 Weld procedures shall be submitted to W NTD, or its designee, for review and approval. Any deviation from the requirements of this specification shall be

resolved by W NTD, Materials and Engineering Mechanics, as specified in Paragraph 1.3 of this specification.

5.1.2 All nondestructive examination procedures shall be submitted to W NTD, or its designee, for review and approval. Any procedure requirements not in compliance with Code or procurement document requirements shall be resolved by W NTD, as specified in paragraph 1.3 of this specification.

5.2 All welding inspections shall be in accordance with applicable code requirements and/or design specifications and drawings.

Table 1

MACHINE WELDING PARAMETERS

Function

Time--

a,c,e

APPENDIX B

WELD REPAIR DRAWING

a,c,e

a,c,e

APPENDIX C

DATA PACKAGE FOR THE PENETRATION MOCK-UP
&
PENETRATION MOCK-UP SKETCHES

All of this section is proprietary [a,c,f]

This Appendix C, pages C-1 thru C-31, contains detail dimensional data on the penetration mock-up test piece and material certifications that apply to the components within the mock-ups. Also contained are proprietary Westinghouse sub vendor information.

APPENDIX D

PENETRATION TUBE DIMENSIONAL DATA

All of this section is proprietary [a,b,c,g]

This Appendix D, pages D-1 thru D-33, contains detail diametrical measurement data on the penetration mock-up tube samples before and after weld repair. Also contained are proprietary Westinghouse sub vendor information