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Repair Weld Induced Residual Stresses in Thick-Walled Steel Pressure Vessels

G. C. Smith
P. P. Holz

MASTER

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CONTENTS

	<u>Page</u>
FOREWORD	v
ACKNOWLEDGMENTS	xi
ABSTRACT	1
1. INTRODUCTION	2
Reference	4
2. DESCRIPTION OF VESSELS AND PROLONGATIONS	5
References	12
3. DESCRIPTION OF REPAIR WELDS	13
V-7A and V-7A Simulation Repair Welds	13
V-7B and V-7B Simulation Repair Welds	19
V-8 and V-8 Simulation Repair Welds	21
References	28
4. RESIDUAL STRESS MEASUREMENT METHODS	29
Direct Strain Gage Method	29
Hole-Drilling Method	30
References	37
5. STRESS RELAXATION RESULTING FROM SECTIONING	39
V-8 Simulation Repair Weld Sectioning Correction	40
V-7A Simulation Repair Weld Sectioning Correction	45
Surface Preparation	51
Reference	51
6. SUMMARY OF EXPERIMENTAL RESULTS	52
Axial and Circumferential Residual Stresses on the Surface of the V-7B Vessel	52
Circumferential Residual Stresses Through the Thickness of the V-7A Simulation Repair Weld	52
Axial Residual Stresses Through the Thickness of the V-7A Simulation Repair Weld	55
Axial and Circumferential Residual Stresses on the Surface of the V-8 Vessel and its Prolongation	56
Circumferential Residual Stresses Through the Thickness of the V-8 Simulation Weld	57
References	59
7. CONCLUSIONS	60

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	<u>Page</u>
APPENDIX A. WELDING PROCEDURE SPECIFICATION	63
APPENDIX B. HOLE-DRILLING MEASUREMENTS MADE ON STRESS-FREE SPECIMENS	79
APPENDIX C. V-7 SERIES REPAIR WELDS - WELDABLE STRAIN GAGE MEASUREMENTS	85
APPENDIX D. V-8 SERIES REPAIR WELDS - WELDABLE STRAIN GAGE MEASUREMENTS	93
APPENDIX E. V-7 SERIES REPAIR WELDS - HOLE-DRILLING MEASUREMENTS	99
APPENDIX F. V-8 SERIES REPAIR WELDS - HOLE-DRILLING MEASUREMENTS	117
APPENDIX G. DISCUSSION OF THE HOLE-DRILLING TYPE SURFACE RESIDUAL STRESS MEASUREMENTS TAKEN FROM THE V-8 VESSEL	123

FOREWORD

The work reported here was performed mostly at Oak Ridge National Laboratory (ORNL) under sponsorship of the U.S. Nuclear Regulatory Commission's (NRC) Heavy-Section Steel Technology (HSST) Program, which is directed by ORNL. The program is conducted as part of the ORNL Pressure Vessel Technology Program, of which G. D. Whitman is manager. The manager for the NRC is E. K. Lynn.

This report is designated Heavy-Section Steel Technology Program Technical Report No. 48. Prior reports in this series are listed below.

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Copies of these reports may be obtained from Laboratory Records Department, Oak Ridge National Laboratory, P.O. Box X, Oak Ridge, Tenn. 37830.

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REPAIR WELD INDUCED RESIDUAL STRESSES IN THICK-WALLED STEEL PRESSURE VESSELS

G. C. Smith
P. P. Holz

ABSTRACT

If a flaw requiring corrective action were to be found in an operating nuclear pressure vessel, there would be considerable safety and economic implications. Should such a flaw be found, one possible corrective action would be an in situ repair weld. A repair of this type would presumably involve grinding away material in a region encompassing the flaw and then filling the resulting cavity with weld metal. Thermal stress relieving under those conditions could lead to serious difficulties associated with thermal expansion and warpage and would therefore most likely be avoided. Such a departure from normal procedure raises questions relating to residual stresses and material toughness levels which would have to be assessed before a repair could be recommended or approved. The residual stress measurements reported here are intended to provide baseline information to aid in an assessment should such a repair ever have to be seriously considered.

Residual stress measurements were made on six large repair welds in two experimental steel pressure vessels and in two cylindrical vessel prolongations made from A533, grade B, class 1 steel with nominal wall thicknesses of 152 mm (6.0 in.). The repair welds were performed in accordance with Section XI of the American Society of Mechanical Engineers Boiler and Pressure Vessel Code. The repair procedure employed, known as the half-bead technique, was devised for repair welds that for practical considerations could not undergo routine high-temperature thermal postweld stress relief. In theory the half- or temper-bead technique is structured so that each weld pass is applied in a manner which results in tempering the preceding weld pass. The residual stresses were determined from pre- and postweld strain gage measurements and from measurements using a semidestructive procedure known as the hole-drilling method. The two cylindrical prolongation specimens were sectioned in order to expose radial planes through each weld. Through-thickness residual stresses based on hole-drilling type measurements, including a correction for sectioning, are reported. It was found that, in general, high tensile residual stresses on the order of the yield stress existed in the base metal surrounding each repair weld, and substantially lower residual stresses existed in the weld metal itself.

1. INTRODUCTION

The structural integrity of steel pressure vessels that could conceivably be flawed has been the subject of extensive research and testing in a number of major industries. This concern has been particularly acute in the nuclear industry, which is characterized by the need to ensure the integrity of thick-walled pressure vessels that contain reactor cores and coolant. The Heavy Section Steel Technology (HSST) Program at the Oak Ridge National Laboratory (ORNL) was instituted to accelerate analytical and experimental investigations of thick-section pressure vessels made from representative nuclear reactor steels. The residual stress measurement work that is reported here was conducted in support of the HSST program intermediate vessel test effort.

The identification of a flaw in an operating nuclear power plant would present the plant owner with a problem requiring immediate attention. For example, if it could be shown by analysis using procedures specified in the Boiler and Pressure Vessel Code¹ that the flaw were sufficiently small compared with the size of a critical flaw, the owner would probably be allowed to continue normal operation of his plant. (This practice of continued operation of equipment with known safe flaws is not unusual in the aircraft industry.) If, on the other hand, an analysis of a flawed vessel indicated a margin of safety that was less than that allowed, the owner would then be faced with the prospect of ceasing operations and making an acceptable repair if possible.

Because there is this possibility of a flawed vessel requiring some form of corrective action, activities have been under way for some time to provide the technical basis for effective and proven corrective measures. A frequently mentioned corrective measure involves the removal of the flawed region of the vessel by grinding. The cavity thus created could then possibly be left alone since the sharp crack tip would have been removed; or if analysis were to show that the remaining wall thickness was less than acceptable, the cavity could then be filled with weld metal, and the vessel could thereby be returned to its original dimensions. A weld repair of this type would, of course, be a very difficult in situ operation. Normally high-temperature thermal stress relief is given to nuclear

vessels after fabrication welding as a means to reduce stresses induced during assembly. A heat treatment under field conditions could, however, result in severe difficulties associated with thermal expansion and warpage. Consequently, the American Society of Mechanical Engineers (ASME) in Section XI of the Boiler and Pressure Vessel Code¹ has provided a procedure for making major repairs without subsequent thermal stress relief. The procedure (paragraph IWB-4420 of the code) employs a technique known as the half-bead technique which operates on the principle that the tempering of each layer of weld bead is accomplished by subsequent weld beads. The work reported here is intended to provide an experimentally based assessment of the magnitudes and distributions of the residual stresses in and around large half-bead weld repairs in thick-section, reactor pressure-vessel steels.

The residual stress measurements reported here were made on three different welds in two different thick-walled test vessel configurations that either have been or will be pressure tested as part of the HSST experimental test program. In addition to the pressure vessel repair welds, three qualification welds were made on two thick-walled cylindrical sections known as prolongations. A summary of the vessels and prolongations that were used for the weld repair studies is given in Table 1.1. Both the vessels and the prolongations, which are described in Chapter 2, were made from A533, grade B, class 1, low-alloy steel plate. A description of each of the weld repairs is contained in Chapter 3. The residual stresses were determined by means of weldable strain gages which had been placed on the vessel and prolongation surfaces and which were read before and after the weld repair and the hole-drilling technique that was used

Table 1.1. Summary of vessels and prolongations
used for the weld repair studies

Test specimen	Repair weld	Prolongation	Qualification weld (simulation)
V-7	V-7A	V-9	V-7A
V-7A	V-7B	V-8	V-7B
V-8	V-8	V-8	V-8

to obtain surface and through-thickness results. Details of the measurement methods are contained in Chapter 4. Chapter 5 describes the sectioning of the prolongations that was done to allow the through-thickness determination of residual stresses. Since sectioning (which in this case was done by sawing) will relieve stresses (at least the Poisson contribution from stresses normal to the cut plane), a correction based on measurements taken during sectioning was determined. The correction is also described in Chapter 5. Chapter 6 contains a summary of the residual stress measurements for all six welds. All of the through-thickness results in Chapter 6 contain the corrections for sectioning described in Chapter 5. Uncorrected results such as radial residual stresses and results not contained in Chapter 6 are contained in Appendices C, D, E, F, and G. Chapter 7 contains the conclusions from this work.

Repair welds and associated residual stress measurements with V-7 in their titles refer to weld repairs penetrating entirely through the 152-mm (6-in.) specimen wall, and V-8 repair welds pertain to repairs made from the exterior surface of the vessel and penetrating slightly over halfway or 89 mm (3.5 in.) through the specimen wall. The repair welds described in this report were the result of cooperative efforts involving ORNL, the Electric Power Research Institute (EPRI), Combustion Engineering, Inc. (CE), the Westinghouse Tampa Division (WTD), and the Advisory Task Group on Weld Repairs of the Pressure Vessel Research Committee (PVRC). In addition, the bulk of the hole-drilling residual stress measurements made on the V-7A simulation repair weld were made at the Westinghouse Research and Development Center (WRDC).

Reference

1. American Society of Mechanical Engineers, *Section XI, Rules for In-Service Inspection of Nuclear Power Plant Components, ASME Boiler and Pressure Vessel Code*, American Society of Mechanical Engineers, New York, July 1, 1974.

2. DESCRIPTION OF VESSELS AND PROLONGATIONS

This chapter describes the two thick-walled pressure vessels and the two qualification pieces which contained six repair welds and were used in the residual stress studies reported here. HSST intermediate test vessel V-7 contained two repair welds made at different times and designated V-7A and V-7B, respectively. HSST intermediate test vessel V-8 contained a single repair weld designated V-8. The configuration and dimensions of the identically shaped V-7 and V-8 vessels are shown in Fig. 2.1. Each of the three repair welds made in an intermediate test vessel

Fig. 2.1. HSST intermediate vessel (1 in. = 25.4 mm).

had an associated qualification repair weld in a prolongation which was a 0.64-m-long (25-in.) right circular cylinder with the same material properties, nominal wall thickness, and nominal radii as those of the intermediate test vessels. The qualification welds are known as the V-7A simulation, the V-7B simulation, and the V-8 simulation. The V-7A repair weld and the V-7A simulation weld in the vessel V-9 prolongation were made by Combustion Engineering in Chattanooga, Tennessee.¹ The V-7B and V-8 repair welds and their corresponding simulation welds made in the vessel V-8 prolongation were fabricated by the Westinghouse Tampa Division.² Figure 2.2 shows vessel V-7 as received at CE prior to beginning the V-7A repair weld, and Fig. 2.3 shows the V-9 prolongation at CE prior to the excavation of the cavity for the V-7A simulation weld. Figure 2.4 shows vessels V-7 and V-8 and the V-8 prolongation prior to their shipment to WTD for the V-7B and V-8 repair and simulation welds. The V-7B and V-8 simulations were located 180° apart in the same prolongation as shown in Fig. 2.5.

The cylindrical shell courses for vessels V-7 and V-8 and the prolongations used for the simulated repair welds were fabricated from ASTM A533, grade B, class 1 steel plate produced by Lukens Steel Company from a single heat identified as B523-2. Chemical analysis reported for this heat is as follows:

<u>Ladle analysis (wt %)</u>						
C	Mn	P	S	Si	Ni	Mo
0.2	1.23	0.015	0.017	0.26	0.49	0.52

After being rolled to their cylindrical shape and prior to making the axial seam welds, the shell courses and prolongations were typically subjected to heat treatments consisting of austenitizing at 899°C (1650°F) for 6 1/2 hr, quenching in agitated water, tempering at 682°C (1260°F) for 6 1/2 hr, air cooling, and stress relieving at 621°C (1150°F) for 30 hr. The cylinders were completed by submerged-arc welding. These weldments were then subjected to an intermediate postweld heat treatment at typically 593°C (1100°F) for 1 1/2 hr. Tensile test data results at 25°C and 93°C (77°F and 200°F) from both tangentially (C) and axially (A) oriented specimens are shown in Fig. 2.6.^{3,4} Further details regarding

Fig. 2.2. Vessel V-7 as received at Combustion Engineering (1 in. = 25.4 mm).

Fig. 2.5. The V-8 prolongation that was used for the V-7B and V-8 simulation repair welds.

Fig. 2.6. Tensile properties of intermediate vessel V-7 using C- and A-oriented subsize tensile specimens from 152-mm-thick (6-in.) ASTM A533, grade B, class 1 carbon steel (1 ksi = 6.895 MPa; 1 in. = 25.4 mm).

fabrication and material properties can be found in Refs. 5 and 6. The V-7 and V-8 vessels were machined to contour after the final stress relief and thereby a skin effect (i.e., shallow compressive residual stresses) was induced. Details of investigations relating to the skin effect are contained in Appendix G.

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3. DESCRIPTION OF REPAIR WELDS

V-7A and V-7A Simulation Repair Welds

Vessel V-7, the eighth HSST thick-walled pressure vessel tested, failed as predicted in a leak mode. A description of the test and results can be found in Ref. 1. Although the failure occurred well above the vessel's design pressure and extensive yielding had occurred, the vessel remained essentially intact and could thus be reused for a subsequent test provided the original flaw, which consisted of the deep, sharpened machined groove shown in Fig. 3.1, was repaired. Figure 3.2 shows the pressure vessel after completion of the first test known as the V-7 test. Since a high-quality repair was required for anticipated additional high-pressure testing and there was considerable interest in repair welds that did not include high-temperature postweld stress relief, it was decided that the weld repair would be performed in general accordance with "Procedure Number 4, Welding Low Alloy Steels," of *Section XI, ASME Boiler and Pressure Vessel Code*.² The weld repair was performed by

Fig. 3.1. Flaw design for HSST program intermediate test vessel V-7 (1 in. = 25.4 mm).

DPM 000 75 10700

Fig. 3.4. Weld repair preparation cavity in vessel V-7. Weld repair for V-7A. Dimensions are approximate and are given in inches (1 in. = 25.4 mm).

schematic of the V-7A qualification weld is shown in Fig. 3.4. The bracing shown in Fig. 3.5 was fillet welded to the ends of the prolongation at the onset to give added stiffness. While the cross sections of the V-7A and V-7A simulation cavities were quite similar, the V-7A simulation weld cavity was shorter than that of the V-7A. This compromise was made so that a significant amount of base metal remained between the ends of the prolongation and the repair weld.

Goins and Butler^{3,4} have published a comprehensive report on the CE V-7A and V-7A simulation repair weld operations. A brief summary of those operations follows. In order to ensure complete removal of the air-arc surface and any heat-affected zone resulting from the air-arc process, a minimum of 6 mm (0.25 in.) of base metal was ground from the surface of the cavity. Resistance heaters were then applied to the V-7 vessel and

Fig. 3.5. V-7A simulation repair weld cavity, V-9 prolongation (1 mm = 0.0394 in.).

the prolongation for a preheat. Approximately 5 hr were required to bring the vessel and prolongation from room temperature up to the required preheat temperature range of 177°C (350°F) to 260°C (500°F). Both cavities were buttered (covered) with a single weld metal layer using 2.38-mm-diam (3/32-in.) electrodes. Approximately one-half of this first layer was then removed by grinding. A second butter deposit layer consisted of 3.18-mm-diam (1/8-in.) electrodes. Subsequent welding was accomplished using 3.18- and 3.97-mm-diam (1/8- and 5/32-in.) electrodes. Upon completion of the weld repair, final crown pass surfaces were ground and the vessel was elevated to and held at a temperature of 232°C (450°F) to 260°C (500°F) for 4 hr. CE welding was performed in the flat position with the vessel and prolongation axes horizontal. A cross section of the V-7A simulation weld is shown in Fig. 3.6. The variation of tensile properties with temperature for the weld metal used in the V-7A and V-7A simulation repair welds is shown in Fig. 3.7.⁵

Fig. 3.6. Cross section of a quarter segment of the V-7A simulation repair weld, V-9 prolongation (1 in. = 25.4 mm).

Fig. 3.7. Variation of tensile properties with temperature for the shielded metal-arc weldment taken from the V-7A simulation repair weld, V-9 prolongation.

V-7B and V-7B Simulation Repair Welds

The vessel designated V-7A (i.e., repaired by CE) was intentionally flawed in base metal remote from the repair weld and tested in June 1976. (For details of the test see Ref. 6). The V-7A test was quite similar to the V-7 test in that the test temperature, flaw location, and flaw size

were nearly identical. The significant differences between the tests were that V-7A had an internal patch in order to hold pressure once the flaw had torn through the wall, and V-7A was pressurized pneumatically while V-7 was pressurized hydraulically. At the completion of the V-7A test, the vessel remained intact as it was after the initial V-7 test. It was therefore possible to repair the vessel again and perform yet a third test with it. Since repair welds were to be the subject of further HSST research and development, it was decided that once again the ASME recommended procedure known as the half-bead technique would be specified to repair the V-7A vessel, which, when repaired for the second time, would be referred to as vessel V-7B. The repair was performed by WTD. The welding procedure⁷ at WTD was similar to that performed at CE except that it was specified that the vessel and prolongation axes be aligned vertically during the welding operation so that weld progression was in vertical passes. The prolongation used for a V-7B simulation repair weld was the V-8 prolongation used by WTD for the V-8 vessel simulation weld discussed in the next section. General dimensions of the vessel V-7B and prolongation V-7B simulation cavities are shown in Figs. 3.8 and 3.9,

Fig. 3.8. Vessel V-7B repair weld cavity, V-7B vessel (1 mm = 0.0394 in.).

Fig. 3.9. V-7B simulation repair weld cavity, V-8 prolongation (1 mm = 0.0394 in.).

and details of the V-7B weld cavity are shown in Fig. 3.10. Both through-wall cavities were of nearly identical width and end slope geometry; the overall length of the prolongation cavity, however, was one-fifth that of the vessel cavity. During welding at WTD, the bolted head end of the vessel and the shell end of the prolongation were oriented downward. An extract of the welding specification describing welding procedures for V-7B and V-8 repairs is contained in Appendix A. A cross section of the V-7B simulation weld is shown in Fig. 3.11.

V-8 and V-8 Simulation Repair Welds

Concurrent with the V-7B repair welds, WTD also made half-head repair welds referred to as the vessel V-8 and the prolongation V-8 simulation.

Fig. 3.10. Intermediate test vessel V-7B repair cavity and flaw preparation details (1 in. = 25.4 mm).

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Fig. 3.11. Cross section of the V-7B simulation repair weld, V-8 prolongation.

The repair welds were located along edge portions of the manufacturer's seam weld with the prolongation weld centered within the cylinder and the vessel weld centered about the midpoint of the vessel's cylindrical portion. The prolongation repair was located 180° from the previously described V-7B simulation repair (Fig. 2.5). Vessel V-8 and prolongation V-8 simulation repair welds had nearly identical dimensions as shown in Fig. 3.12. Unlike previous air-arc gouged and ground cavities, the V-8 and V-8 simulation cavities were machined by Union Carbide shops at Oak Ridge, Tennessee (see Figs. 3.13 and 3.14), in order to permit precision indexing into the original vessel seam-weld radial side planes and to permit uniform depth. The bolted head end of the vessel and the shell end of the prolongation were oriented downward during welding. Welding progression was in vertical passes. A cross section of the V-8 simulation weld is shown in Fig. 3.15.

Fig. 3.12. Vessel V-8 and V-8 simulation repair weld cavity, V-8 vessel and V-8 prolongation (1 mm = 0.0394 in.).

Fig. 3.13. Intermediate test vessel V-8 weld repair cavity machining operations.

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4. RESIDUAL STRESS MEASUREMENT METHODS

This chapter describes the two techniques that were used to measure residual stresses in the vicinity of the V-7A, V-7B, and V-8 repair welds and their respective simulations in prolongations. The first technique that will be described involves direct strain gage readings before and after the weld repair. The second technique that will be described is known as the hole-drilling technique. In order to measure residual stresses at through-thickness locations, it was necessary to section the specimen. This of course can affect subsequent strain readings, and thus a method involving strain gage data taken during sectioning was used to estimate the residual stresses that were relieved during the sectioning process. The method used to account for the relaxation of residual stresses caused by sectioning is discussed in Chapter 5.

Direct Strain Gage Method

The direct strain gage method involved locating gages on the vessels and prolongations after the cavities were machined into the specimens but before welding began. The gages were generally Ailtech SG 425 weldable gages, except for 9 Ailtech SG 125 weldable gages that were placed on the prolongation used for the V-7A simulation repair weld. The SG 425 gages are stable at temperatures below 482°C (900°F) while the SG 125 gages are stable below 316°C (600°F). Both have gage lengths of approximately 25 mm (1.0 in.). For all of the V-7B, V-7B simulation, V-8, and V-8 simulation strain gage sites and for most of the V-7A and V-7A simulation strain gage sites, the gages were configured as T's, and the residual stresses were calculated from the following equations:

$$\sigma_a = \frac{E}{1 - \nu^2} (\epsilon_a + \nu \epsilon_c) , \quad (4.1)$$

and

$$\sigma_c = \frac{E}{1 - \nu^2} (\epsilon_c + \nu \epsilon_a) , \quad (4.2)$$

where the subscripts a and c denote the axial and circumferential directions, respectively. Young's modulus, E, was taken as 200,000 MPa (29×10^6 psi) and Poisson's ratio was taken as 0.29. For single isolated gages, the equation used to calculate stresses was

$$\sigma = E\epsilon \quad (4.3)$$

The gages were zeroed at room temperature. Thermocouples were located around the weld cavity [generally at weldable strain gage sites 38 mm (1.5 in.) from the cavity boundary]. The thermocouples were monitored to ensure that the temperature of the vessels and prolongations did not exceed 316°C (600°F) during the welding operation. If the temperatures indicated by the thermocouples showed a tendency to rise above their nominal 260°C (500°F) value, then the rate of depositing weld metal was decreased. The strain data were examined during hold periods at constant temperatures to determine if drift was occurring. There was no indication of any strain gage drift for the reported data. Upon completion of the weld repair and the return of the specimen to room temperature, a final strain gage reading was made. It was this final value of strain that was used to calculate a change in stress resulting from the weld repair.

Hole-Drilling Method

A commonly used method for measuring residual stresses involves the attachment of a strain rosette to a surface where stresses are to be measured.¹ The rosette gages are initially zeroed and a small hole [e.g., 1.59 mm (1/16 in.) diam] is drilled into the specimen at the center of the rosette pattern. The radial distance from the hole centerline to the gage midpoints for the rosettes used here was 2.54 mm (0.10 in.). The depth of the hole is of the order of the hole diameter. The removal of material, which presumably was stressed, results in relaxation strains being indicated by the rosette gages. By means of calibration coefficients, it is possible to calculate the state of stress that existed at the hole site prior to drilling. Figure 4.1 is a photograph of one of the two sections of the V-7A simulation weld repair which were used for through-thickness measurements. It has four rosettes and associated tabs attached

Fig. 4.1. A section of the V-7A simulation repair weld that has strain gages in place for subsequent hole-drilling measurements. The holes in the specimen are from previous measurements (V-7A, Piece C, Fig. 5.1).

in weld metal. The holes to the right of the rosettes, (i.e., in the base metal and the heat-affected zone) were drilled during prior measurements. The gages for those measurements had been removed, and a mild etch had been used to enhance the weld-metal/base-metal boundary.

A substantial segment of the hole-drilling data for the V-7A simulation weld was generated at WRDC. These data were obtained using Micro-measurement 062RE gages (specially designed gages for the hole-drilling method) and a drilling technique using a stream of air containing fine abrasive particles which chip away the workpiece material. Reference 2 contains a discussion of the approach used at WRDC. The remainder of the hole-drilling data was taken at ORNL and involved the use of Micromasurement 062RF gages and a conventional hand-held drill. Figure 4.2 illustrates how the drill is used with a sighting and stabilizing platform which can be firmly attached to the specimen with an adhesive. Figure 4.3 shows the stabilizing platform and eyepiece that were used to align and measure the actual drilled hole diameter.

The ORNL data were reduced as prescribed in Ref. 3 with one exception. It had been reported² that mechanical drills tended to induce a fictitious apparent strain. Extensive hole drilling on stress-free* bars of A533 steel and on stress-free weld metal taken from the V-8 simulation repair at ORNL confirmed these observations. (See discussion in Appendix B.) It was noted, however, that the fictitious apparent strain applied fairly uniformly to each of the three gages in the rosette when the mechanical drill was used. It was therefore decided to compensate for the average apparent strain ($-78 \mu\epsilon$) induced in the stress-free bars and samples by adding an equivalent amount with the opposite sign to each measurement made on the vessels and prolongations.

The relationships used by ORNL to calculate the principal stresses from the strain changes measured as a result of hole drilling and adjusted to eliminate the spurious drilling effects are given by³

$$\sigma_x = \frac{(A + B \cos 2\theta)\epsilon_2 - (A - B \cos 2\theta)\epsilon_1}{4AF \cos 2\theta}, \quad (4.4)$$

* The bars were heated to 621°C (1150°F) and held at temperature for 72 hr and then furnace cooled over a 24-hr period.

Fig. 4.2. Mechanical drill and stabilizing platform used for hole-drilling measurements at ORNL (V-7B, Piece B, Fig. 5.1).

Fig. 3.6. Schematic of strain gage orientation relative to the principal stress axes, x and y .

ORNL-DWG 78-3982

$$A = - \left(\frac{1+\nu}{2E} \right) \left(\frac{2R_0}{2a} \right)^2$$

$$B = - \left(\frac{1+\nu}{2E} \right) \left[\frac{4}{1+\nu} \left(\frac{2R_0}{2a} \right)^2 - 3 \left(\frac{2R_0}{2a} \right)^4 \right]$$

Fig. 4.5. Coefficients used to determine stresses from hole-drilling measurements (Type 0.062 RE gage on steel).

A schematic of the drills (double-fluted end mills which were specially ground) used for the ORNL hole-drilling measurements is shown in Fig. 4.6. Each drill was used for not more than three holes.

A study of the hole-drilling method is reported in Refs. 4 to 6. Reference 5 concludes that overall measurement accuracy of the hole-drilling method used by the author (air abrasive) is $\pm 8\%$ except when the residual stresses are greater than 50% of yield. Above that level, errors increase due to yielding around the hole; and depending on specific conditions, the error could increase by up to $\pm 16\%$ for a residual stress level near yield. Somewhat lower accuracy would be expected for the mechanical drilling approach.

Fig. 4.6. Double-fluted end mill as modified for hole-drilling operation.

References

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5. STRESS RELAXATION RESULTING FROM SECTIONING

In order to obtain through-thickness residual stress measurements, it was necessary to section each of the two prolongations. Figure 5.1 shows the sectioning plans for both the V-9 and V-8 prolongations. The pieces used for experimental measurement of residual stresses or material properties are labeled with letters, and the cuts in the order that they were

Fig. 5.1. Schematic of the two prolongations used for the simulation (qualification) repair welds. Numbers indicate the order that the vessels were cut to allow through-thickness residual stress measurements. Cut 2 for each prolongation removed the ends of the remaining cross bracing.

made are labeled with numbers. The sectioning of the prolongations would, of course, relax and redistribute the residual stresses. This chapter describes the methods used to determine a correction so that the through-thickness residual stresses in the unsectioned prolongations could be estimated. The estimate is based on subsequent hole-drilling measurements made on the sectioned pieces and the changes in surface strains that were measured during the sawing operation. All of the through-thickness hole-drilling data are contained in the appendices. Chapter 6 of this report is a summary of the most significant findings, and all of the through-thickness measurements contained in that chapter have a correction for sectioning taken directly from either Fig. 5.5, 5.9, or 5.10 (depending on the particular weld repair and orientation of the stresses under consideration). In general, the correction for sectioning consisted of superposing a tensile stress (on the order of one-fifth to one-third of the weld metal or base metal yield stress) on the hole-drilling measurement. The subsequent two sections describe the corrections that were found for the V-8 and the V-7A simulation repair welds, respectively.

V-8 Simulation Repair Weld Sectioning Correction

Figure 5.2 shows the V-8 prolongation with the V-7B and V-8 simulated repair welds being sawed in half. The bundle of wires in the figure connect strain gages on the prolongation to strain gage readout equipment. Since circumferential stress variations through the thickness of the cylinder in the V-8 repair weld were the principal concern for a subsequent HSST vessel test, the single saw cut bisecting the prolongation and shown in Figs. 2.5, 5.1, and 5.2 was all that was made on the V-8 prolongation prior to the hole-drilling measurements.

Twenty equally spaced alternating axial and circumferential strain gages were located on arcs about piece B, parallel to the cut and near the V-8 simulation repair weld. The outside surface gages were located 6 mm (0.25 in.) from the cut line and the inside gages were located 13 mm (0.50 in.) from the cut line. Ten additional strain gages were similarly located near the V-7B simulated repair weld, but the V-7B data were subsequently not considered useful because of the nonsymmetry of the repair

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Fig. 5.2. Sawing the V-8 prolongation into two equal pieces for the purpose of making through-thickness residual stress measurements.

weld with respect to the cut section. The strain gages used were Micro-measurement EA-06-250BG-120. The changes in strains as a result of the bisecting saw cut are given in Table 5.1; the cylindrical coordinate system is defined in Fig. 5.3. The stresses listed in Table 5.1 were calculated using Eqs. (4.1) and (4.2).

The axial stresses listed in Table 5.1 are plotted with their signs reversed in Fig. 5.4. The values in Fig. 5.4 give an indication of the axial residual stress existing along the surfaces of the V-8 prolongation at the center of and on the surface near the V-8 simulated weld repair prior to any sectioning. There would probably be considerable averaging of these stresses as the relaxation of stress at any point would influence every other point in the sectioned prolongation. The circumferential stresses from Table 5.1 with their signs reversed are plotted in Fig. 5.5. The relaxation of the circumferential stresses shown in Fig. 5.5 does not have a straightforward physical interpretation like that of the axial

Fig. 5.3. Cylindrical coordinate system used to define the location of strain gages listed in Table 5.1 which were monitored during the sectioning of the V-8 prolongation.

Table 5.1. Measured strain changes that resulted from the sectioning of the V-8 prolongation

Gage No.	Coordinates ^a			Gage orientation ^b	$\Delta\mu\epsilon$	σ_A^c (MPa)	σ_C^c (MPa)
	r (mm)	θ (deg)	z (mm)				
V-8 repair weld							
1	508	-14.3	6	A	-514	-124	
2	508	-11.5	6	C	-181		-100
3	508	-8.6	6	A	-1390	-313	
4	508	-5.7	6	C	-117		-103
5	508	-2.9	6	A	-1054	-242	
6	508	0	6	C	-270		-126
7	508	2.9	6	A	-1073	-248	
8	508	5.7	6	C	-157		-113
9	508	8.6	6	A	-1398	-306	
10	508	11.5	6	C	144		-24
11	508	14.3	6	A	-367	-71	
12	343	-17.0	6	C	-251		-105
13	343	-12.7	13	A	-787	-195	
14	343	-8.5	13	C	-490		-150
15	343	-4.2	13	A	-580	-165	
16	343	0	13	C	-729		-187
17	343	4.2	13	A	-304	-115	
18	343	8.5	13	C	-813		-188
19	343	12.7	13	A	-30	-40	
20	343	17.0	13	C	-253		57
V-7B repair weld							
21	343	192.7	25	A	-605	-131	
22	343	197.0	25	C	-197		-81
23	343	184.2	25	A	-906	-216	
24	343	188.5	25	C	225		1
25	343	175.8	-25	A	-944	-324	
26	343	180.0	25	C	495		51
27	343	167.3	-25	A	-811	-275	
28	343	171.6	-25	C	-1545		-393
29	343	180.0	-25	C	-2180		-536
30	343	163.0	-25	C			

^aSee Fig. 5.3 for coordinate system definition.

^bA represents axial and C circumferential.

^cStress calculated according to Eqs. 4.1 and 4.2 where the Poisson component was taken as an average of adjacent gages when possible.

ORNL-DWG 78-3986

Fig. 5.4. Axial stresses (MPa) calculated from the strain relaxation caused by a single bisecting saw cut of the V-8 simulated repair weld (1 MPa = 145 psi; 1 mm = 0.0394 in.).

ORNL-DWG 78-3787

Fig. 5.5. Circumferential stresses (MPa) calculated from the strain relaxation caused by a single bisecting saw cut of the V-8 simulated repair weld (1 MPa = 145 psi; 1 mm = 0.0394 in.).

stresses. The circumferential stresses indicate stress changes due to sectioning but not total residual stresses. However, they are useful for adjusting subsequent through-thickness residual stress measurements so that the stresses in the uncut specimen can be estimated. Fifty-two through-thickness measurements were subsequently made on cut face B-1 (see Fig. 5.1) of the V-8 prolongation. For 31 of those measurements (reported in Chapter 6), the calculated through-thickness circumferential stresses were adjusted by adding a value determined from a linear interpolation of the two surface circumferential stress changes (shown in Fig. 5.5) due to sectioning that were measured along the radial line nearest to the measurement point.

V-7A Simulation Repair Weld Sectioning Correction

The V-7A simulation repair weld was also used for through-thickness residual stress measurements and therefore the V-9 prolongation was also sectioned. Since the V-7A simulated weld was to be used to obtain both the axial and circumferential residual stress distributions, additional cuts on the V-7A prolongation were necessary as shown in Fig. 5.1. Three small sections were thus cut from the V-9 prolongation. One of the sections (section C) is shown in Figs. 4.1 and 4.3. Another section (section A) is shown schematically in Fig. 5.6. The third section (section B) was used only for material property measurements. Ten Micromasurement EA-06-062RG-120 strain rosettes were attached to section A at the locations indicated in Fig. 5.6. These rosettes were monitored during the sectioning of the V-9 prolongation and the resulting strain changes were used to calculate stresses. The gages were zeroed prior to the first saw cut.

Table 5.2 lists the indicated strain from those rosettes after cut 1 was complete, after cut 3 was complete, after the saw had penetrated 76 mm (3.0 in.) into the wall during cut 4, and after cut 4 was completed. One of the strain gage junction boxes failed prior to completion of the fourth cut, and the corresponding data were lost. There was only slight additional relaxation (see Table 5.2) as a result of the fourth cut, and therefore the strain data taken halfway through cut 4 were considered appropriate for describing the relaxation of the completely sectioned

Table 5.2. Strain measurements from rosettes located on piece A of the V-9 prolongation during sectioning

Gage No. ^a	Coordinates ^a			After cut 1 ^b			After cut 3 ^b			Halfway through cut 4			After cut 4 ^b		
	x (mm)	y (mm)	z (mm)	$\mu\epsilon_a$	$\mu\epsilon_c$	$\mu\epsilon_{45}$	$\mu\epsilon_a$	$\mu\epsilon_c$	$\mu\epsilon_{45}$	$\mu\epsilon_a$	$\mu\epsilon_c$	$\mu\epsilon_{45}$	$\mu\epsilon_a$	$\mu\epsilon_c$	$\mu\epsilon_{45}$
1	25	152	165	784	-214	386	878	-473	317	887	-483	315			
2	51	152	165	713	-303	501	813	-572	490	824	-579	491			
3	178	152	165	-322	3	140	-573	34	30	-564	37	39			
4	51	51	165	-861	293	-1073	-520	-405	-1034	-521	-405	-1038	-509		-1032
5	178	51	165	-228	201	179	-407	711	164	-412	708	163	-407	718	170
6	178	25	165	-352	222	28	-594	101	707	-600	100	703	-589	106	709
7	178	105	0	-46	42	-89	-75	153	131	-72	142	121	-73	154	144
8	51	105	0	1	-342	-165	-64	-149	-127	-64	-148	-121	-50	-147	-107
9	178	35	0	-197	215	80	-125	-290	-100	-126	-105	-288	-120	-94	-284
10	51	35	0	-402	-196	-718	-543	45	-730	-543	44	-731	-536	53	-724

^aGage locations and the coordinate system are shown in Fig. 5.6.

^bSubscripts a and c indicate axial and circumferential orientations. The subscript 45 indicates direction of the third leg of the strain rosette.

● ROSETTE LOCATIONS (6) ON EXTERIOR SURFACE

○ ROSETTE LOCATIONS (4) ON INTERIOR SURFACE (ALIGNED WITH EXTERIOR SURFACE ROSETTES ALONG RADIALS)

DIMENSIONS IN MILLIMETERS

Fig. 5.6. V-9 prolongation containing the V-7A simulation repair weld, piece A, Fig. 5.1. Location of strain rosettes used to estimate sectioning effects (100 mm = 3.94 in.).

piece. Table 5.3 contains the axial and circumferential stresses that were calculated from the strains given in Table 5.2. Equations (4.1) and (4.2) were used for these calculations. Figures 5.7 and 5.8 show plots of those calculated stresses as viewed from the outside of the prolongation after the final cut.

Several least-square fits (linear, quadratic, etc.) of the data were examined for the purpose of extending the results shown in Figs. 5.7 and 5.8 to the axial-radial and circumferential-radial faces that were to be used for subsequent through-thickness residual stress measurements by the hole-drilling technique. The final choice of a scheme for fitting and extending the data had the form

$$\sigma_a = a_0 + a_1, x + a_2, z + a_3, xz, \quad (5.1)$$

Table 5.3. Stresses calculated from strain rosettes mounted on piece A of the V-9 prolongation

Gage No.	After cut 1		After cut 3		Halfway through cut 4		After cut 4	
	σ_a (MPa)	σ_c (MPa)	σ_a (MPa)	σ_c (MPa)	σ_a (MPa)	σ_c (MPa)	σ_a (MPa)	σ_c (MPa)
1	151	3	162	-48	163	-49		
2	137	-21	141	-73	143	-74		
3	-71	-21	-123	-29	-121	-28		
4	-169	9	-139	-121	-139	-121		
5	-37	29	-44	129	-45	129	-43	131
6	-63	26	-123	-16	-125	-16	-122	-14
7	-7	6	-7	29	-7	26	-6	29
8	-21	-75	-23	-37	-23	-36	-20	-35
9	-29	34	-46	-71	-34	-31	-32	-28
10	-100	-68	-116	-25	-116	-25	-114	-22

Fig. 5.7. Stresses (MPa) used to determine correction to through-thickness stress measurements, interior surface (1 MPa = 145 psi; 1 mm = 0.0394 in.).

and

$$\sigma_c = b_0 + b_1, y + b_2, z + b_3, yz, \quad (5.2)$$

where the four coefficients in each equation were determined from the four stresses of like orientation that were closest to the radial face

ORNL DWG 76 13570R

Fig. 5.8. Stresses (MPa) used to determine correction to through-thickness stress measurements, exterior surface (1 MPa = 145 psi; 1 mm = 0.0394 in.).

of interest. Contours of the adjustment (sectioning effects with signs reversed) that were determined in this way and which were then added to the axial and circumferential through-thickness measurements are shown in Figs. 5.9 and 5.10, respectively.

Another approach to correct for sectioning would be to make an estimate based on assumed or measured surface stresses and the effect of relaxing those stresses on the values that are actually measured. For example, the measurement of a residual stress by means of the hole-drilling technique on a sectioned piece does not include the effect of the stress that existed normal to the surface prior to cutting. If it were assumed that the normal stress before sectioning was tensile and equal to the base metal yield stress, then the correction needed for the Poisson effect would be tensile and would be approximately 130 MPa (19 ksi). This value is not greatly different from the corrections determined from strain relaxation measured during the sectioning process.

ORNL-DWG 78-3988

Fig. 5.9. Contours of equal axial stress (MPa) that were superposed with through-thickness axial stress measurements (1 mpa = 145 psi; 1 mm = 0.0394 in.).

ORNL-DWG 78-3989

Fig. 5.10. Contours of equal circumferential stress (MPa) that were superposed with through-thickness circumferential measurements (1 MPa = 145 psi; 1 mm = 0.0394 in.).

Surface Preparation

It is well-known¹ that machining or grinding of a metal surface can introduce residual stresses quite close to the surface. Since the hole-drilling technique relies on a very shallow hole being drilled on a surface, it would be particularly susceptible to spurious results caused by machining if special precautions were not observed. For all the through-thickness measurement regions, a gentle grind procedure as suggested in Ref. 1 was employed as the last operation. This typically means taking a large number of grinding passes each of which is on the order of 0.01 mm (0.0003 in.). Based on the results in Ref. 1, it was concluded that the gentle grind procedure precluded the need to make a correction for skin effects due to sawing. (See the discussion in Appendix B.) It was decided not to perform a gentle grind on the interior and exterior surfaces of the vessels except to evaluate machining effects 180° from the repair zone in the V-8 vessel (see Appendix G). Since some cosmetic grinding was performed on the completed weld by the fabricator, some grinding effect may also be present. No compensation was employed for this effect.

Reference

1. L. J. Nowikowski, J. Maranchik, Jr., and M. Field, "Distortion and Residual Surface Stress in Grinding and Milling of High-Strength Steels," *SAE J.* 69(8), 41-45 (August 1961).

6. SUMMARY OF EXPERIMENTAL RESULTS

This chapter selectively summarizes the residual stress determinations made on the V-7 and V-8 series of repair welds and simulation repair welds. All simulation weld through-thickness data in this chapter contain the corrections for sectioning described in Chapter 5 and are thus to be considered best estimates of the stresses that existed in the welds prior to sectioning. Some data, such as the radial stresses in the repair weld or stresses for which a correction for sectioning could not be determined (e.g., V-7B simulation), are omitted from this chapter because they are not of general interest. However, all of the residual stress measurements made on the specimens are contained in the appendices to this report. Residual stress measurements taken at points far removed (90° or more measured from the weld) were typically low. This was as expected since the weld repair specimens had been previously stress relieved. Hole-drilling measurements on the surface of the V-8 vessel were influenced by the prior machining of the vessel during its fabrication. A discussion of those measurements is contained in Appendix G.

Axial and Circumferential Residual Stresses on the Surface of the V-7B Vessel

Figures 6.1 and 6.2 show the surface axial and circumferential residual stresses that were induced by the weld repair of the V-7B vessel. These values were determined from weldable gages and by the method discussed in Chapter 4. While these values pertain strictly to the change in stress, they are close to the absolute residual stresses since the vessel had been stress relieved during fabrication. The gages were placed approximately 51 mm (2 in.) from the weld cavity in order to ensure their temperature limitation.

Circumferential Residual Stresses Through the Thickness of the V-7A Simulation Repair Weld

Figure 6.3 shows through-thickness circumferential stress measurements (in MPa) induced in and near the V-7A simulation repair weld. The

ORNL - DWG 78 - 3991

Fig. 6.1. Axial residual stresses (MPa) measured on base metal 51 mm from the V-7B through-thickness weld repair as determined from gages mounted on the vessel inside and outside surfaces and monitored during welding (1 MPa = 145 psi; 1 mm = 0.0394 in.).

ORNL - DWG 78 - 3991

Fig. 6.2. Circumferential residual stresses (MPa) measured on base metal 51 mm from the V-7B through-thickness weld repair as determined from weldable gages mounted on the vessel inside and outside surfaces and monitored during welding (1 MPa = 145 psi; 1 mm = 0.0394 in.).

Fig. 6.3. Circumferential residual stresses (MPa) through the V-7A simulation repair weld, piece A, Fig. 5.1 (1 MPa = 145 psi; 1 mm = 0.0394 in.).

values denoted with an asterisk are surface measurements that were made on the specimen using the hole-drilling technique prior to any sectioning. The through-thickness values in the figures are the residual stresses existing in the specimen prior to the sectioning which was necessary for access to radial planes. They were determined by superposing the correction for sectioning from Fig. 5.10 on the actual hole drilling results. The data in Fig. 6.3 indicate large circumferential stresses in the base metal adjacent to the weld cavity and much lower residual stresses in the weld metal itself. The base metal data agree with the V-7B circumferential stress data shown in Figs. 6.1 and 6.2. The low stresses in the weld metal were unexpected. These measurements were made at both WRDC and ORNL and exhibit a distribution (i.e., high tensile stress in adjacent base metal and relatively lower stresses in the weld metal) consistent with V-7A axial data and V-8 data which will be described later in this chapter. A probable explanation for the unexpectedly low stresses in the weld metal is that the weld metal was stress relieved by the heat input from subsequent weld passes.

The repair weld to a thick-walled vessel by means of the half-bend technique most likely results in complex three-dimensional effects, heating and cooling cycles, and extensive yielding. Intuitive expectations regarding the net result of these factors could easily be misleading. These results contrast with the work reported in Refs. 1 and 2, which showed both large tensile and large compressive stresses in the weld metal. However, these results were not from a half-bend weld in a thick-walled vessel where restraint to both bending and shrinking exists and where the axial variation of restraint is likely to be very significant.

Axial Residual Stresses Through the Thickness of the V-7A Simulation Repair Weld

Figure 6.4 shows the through-thickness axial stresses (in MPa) indicated in and near the V-7A simulation repair weld. The values denoted

Fig. 6.4. Axial residual stresses (MPa) through the V-7A simulation repair weld, piece A, Fig. 5.1 (1 MPa = 145 psi; 1 mm = 0.0394 in.).

with an asterisk were determined by the hole-drilling method on the surface prior to any cutting. The through-thickness values consist of hole-drilling measurements with a correction for sectioning taken from Fig. 5.9. While the hole-drilling surface measurements seem to be in good agreement with the through-thickness values, the surface measurements were not made after a controlled gentle grind and should therefore not be considered as reliable as the through-thickness measurements.

Axial and Circumferential Residual Stresses on the
Surface of the V-8 Vessel and its Prolongation

Figures 6.5 and 6.6 show the superposition of the weld cavity outlines on the outside surface for the V-8 and the V-8 simulation repair welds (i.e., they were identical) and the axial and circumferential residual stresses that were determined from weldable gage data. The asterisk by a residual stress in the figures is used to indicate that the residual stress value applies to a measurement that was taken from a position centered under the weld and located on the inside surface of the vessel. As in the case of the V-7 series residual stress data, these results indicate high tensile circumferential residual stresses exist in the base metal adjacent to the repair. There is good agreement between the V-8 welds in

Fig. 6.5. Surface axial residual stresses about the V-8 and V-8 simulation repair welds (1 MPa = 145 psi; 1 mm = 0.0394 in.).

Fig. 6.6. Surface circumferential residual stresses (MPa) about the V-8 and V-8 simulation repair welds (1 MPa = 145 psi; 1 mm = 0.0394 in.).

the vessel and the smaller prolongation. The difference in the circumferential residual stresses in the seam welds between the two repairs (the simulation having the lower values) may be the result of variations such as yield strength inherent in seam weld material.

Circumferential Residual Stresses Through the Thickness of the V-8 Simulation Weld

Figure 6.7 shows the circumferential residual stresses that are estimated to have existed in the V-8 simulation prolongation prior to cutting it into two equal halves, which remained complete cylinders (Fig. 5.1). The values marked with an asterisk are based on the weldable type surface measurements shown in Fig. 6.6. The through-thickness values were determined from hole-drilling measurements and a correction for sectioning taken from Fig. 5.5. Reference 3 contains residual stress data from a 15.2-cm-thick (6-in.) flat plate that had been repaired using the half-bead technique. The repairs were made to cavities penetrating approximately halfway through the plate and which had long rectangular

Fig. 6.7. Circumferential residual stresses (MPa) through the V-8 simulation repair weld, piece B, Fig. 5.1 (1 MPa = 145 psi; 1 mm = 0.0394 in.).

shapes with cross sections similar to those of the V-8 simulation repair weld. That work showed high tensile residual stresses in the weld metal. The measurement technique used for the data in Ref. 3 involved shaving material off one side of the specimen while simultaneously monitoring strain gages on the side opposite that being shaved. This measurement technique tends to average results for cases where gradients are significant. The averaging plus the difference in constraint between a flat plate and a cylinder may account for the difference between the results reported in Ref. 3 and those presented here.

References

1. D. A. Ferrill, P. B. Juhl, and D. R. Miller, "Measurements of Residual Stresses in a Heavy Weldment," *Weld. Res. Suppl.*, 5045-5135 (November 1966).
2. Y. Ueda et al., "Transient and Residual Stresses from Multipass Weld in Very Thick Plates and Their Reduction from Stress Relief Annealing," *Third International Conference on Pressure Vessel Technology, Part II, Materials and Fabrication, April 19-22, 1977*, American Society of Mechanical Engineers, New York.
3. N. C. Binkley and R. W. Hermann, "An Inservice Reactor Repair Simulation," *Welding in Nuclear Engineering*, Deutscher Verlag Fur Schweisstechnik, Dusseldorf, 1974.

7. CONCLUSIONS

The general conclusions from the residual stress measurements in the vicinity of the half-bead weld repairs made to the HSST intermediate pressure vessel and prolongations are

1. low tensile and compressive circumferential and axial residual stresses existed in the weld metal;
2. the base metal adjacent to the weld repairs had tensile residual stresses close to the yield stress;
3. the highest tensile residual stresses in the base metal tended to be on the order of 25 to 50 mm from the heat-affected zone.

With regard to residual stress measurement techniques, it was concluded that

1. The hole-drilling technique for measuring residual stresses is versatile and effective. A compensation for fictitious stresses that are introduced during drilling should be employed when a mechanical drill is used.

2. Cutting or grinding on surfaces that are to be used as sites for hole-drilling type residual stress measurements can cause misleading results. Controlled gradual removal of surface material is an effective means of reducing or eliminating these spurious skin effects.

APPENDICES

Appendix A

WELDING PROCEDURE SPECIFICATION

Appendix A is extracted from Welding Specification No. W-HB-105, *Low Hydrogen Electrode Manual Shielded Metal-Arc Welding for "Half-Bead" Repair Welding*, which was authored by P. P. Holz, ORNL. The extract from the specification presented here is limited to that section primarily concerned with a description of the procedure that was used in the repair welding of vessels V-7B, V-8, and their companion prolongations. There was a similar specification for the original V-7A vessel and simulation repair welds. The V-7A specification permitted the vessel and prolongation to be welded in a flat position with vessel axes horizontal, while the V-7B and V-8 welds were made in the vertical position with the vessel axes vertical. Figure A.1 contains complete details for the repairs to intermediate test vessels V-7B and V-8, for procedure qualification prolongation V-8, and for miscellaneous practice and specimens fabrication in connection with the vessel repair.

Part I - Welding Procedure1. Welding qualification

All welding in accordance with this procedure shall be done by welders qualified and currently certified under Part II (pages 13-15) or under Section IX Paragraph NB 4300 of the Code for a procedure having the same essential variables for welding performance qualification as this procedure. Welder certification papers shall be available at the job site at all times.

2. Base metal

The base metal will be low-alloy, high-strength carbon steel plate (ASTM A533, grade B, class 1, or equal), P Number 3, Group 3 (Table QW 422, Section IX of the Code).

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Fig. A.1. Repair of
 Welding (Source: Westing
 Division, ETSK Drawing 3)

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ORNL-DWG 78-6373
(PART 1)

GENERAL LAY-OUT
VESSEL V-8

VESSEL V-8
VESSEL V-8
NOTE: LIFTING LUGS
TO BE PROVIDED BY VTO

use Tampa Division Half-Bead
ration, Westinghouse Tampa

NOTES:

- 1) OBTAIN & GROUND ONLY TO WITHIN .25 OF THE SURFACE DIMENSIONS SHOWN; THEN GRIND OUT THE LAST .25 OF MATERIAL. DRAWING DIMENSIONS SHOWN ARE FINISHED DIMENSIONS. NOTE: CARE MUST BE TAKEN NOT TO NICK INTO THE PREMACHINED RADIAL SIDES OF THE CAVITY CENTER PORTION.
- 2) REFER TO UCC-ND FIGURES FOR SCRIBELINE INFORMATION.
- 3) VTD TO SUPPLY SUPPORT STAND FOR VESSELS.
- 4) ALL HALF BEAD TEMPER WELDING TO BE IN ACCORDANCE WITH NPT 17, LATEST REVISION.

ANGULAR TOLERANCE ON WELD JOINT GEOMETRY TO BE $\pm 5^\circ$
MANUFACTURING TOLERANCES UNLESS OTHERWISE SPECIFIED

VTD TO	PERMANENT	TO 1/2" TO 1/4"
1/2"	2.12	2.12

REV. 1	REVISED FOR NEW PROGRAM
REV. 2	REVISED FOR NEW PROGRAM
REV. 3	REVISED FOR NEW PROGRAM
REV. 4	REVISED FOR NEW PROGRAM
WESTINGHOUSE ELECTRIC COMPANY Tampa Division Tampa, Fla.	
VESSEL V-7A & VESSEL V-8 WSET BEAD TEMPER TEST VESSEL PROGRAM	
WTS. DATE BY CHECKED DATE BY	
STG 14-3	

Approved P. P. H. 7/8/78

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QUALIFICATION TEST CM

Y-38 Y-9 THROVAD

(WTD TO ALL HOUSE CANTS
CENTRALIZED FURNISHED
V-TO THROUGHOUT, V-TO)

**NOTE: AFTER WELCOME, LET
THEY TO STABILIZE THEM
WAS. THEN PROCEED AGAIN**

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Fig. A.1 (continued)

Coupon Type	Weld Type	Weld Size	Weld Length	Weld Width
1	B	1/8"	1.000	1.000
2	B	1/8"	1.000	1.000

TYPE 1 & 2 WELD COUPONS

(COUPONS FURNISHED BY UG-NO)
(RESTRAINTS FURNISHED BY VTD)
POSITION VERTICALLY FOR WELDING

H.S.T. PLATE - 57 WELD

(AS RECEIVED FROM UG-NO)
(RESTRAINTS FURNISHED BY VTD)
POSITION VERTICALLY FOR WELDING

Fig. A.1 (continued)

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3. Filler metal

The filler metal shall be covered low-alloy steel electrodes and shall conform to the requirements of Specification SFA-5.5, AWS Classification E8018-C3 of Section II of the Code, or, if the fabricator so elects, shall conform to such other specifications as may be previously approved in writing by UCC-ND. Electrodes shall be clean and dry, and the flux shall not be cracked or spalled. (See Care of Welding Electrodes, Section 8 of Part I of this specification.) Tests of welding materials shall conform to Subarticle NB-2400 of Section III. Evaluation of each lot of weld metal shall be based upon the manufacturer's certification test report (supplied by the fabricator) and approved in writing by UCC-ND.

4. Electrical characteristics

The fabricator shall determine appropriate welding voltage and amperages. As a guide, the following conditions are suggested. Direct current at 20 to 26 V connected for reverse polarity (DCRP) with the base metal on the negative side of the line. Amperages, based upon electrode diameter, are suggested as follows:

<u>Electrode diameter</u> <u>(in.)</u>	<u>Amperages</u>
3/32	85-100
1/8	110-140
5/32	130-185

5. Repair zone

For preheating purposes, each repair zone of the vessel shall consist of the cavity plus a region around the cavity lying beneath the area circumscribed by a line on the outside surface a minimum distance of 3T* from the boundary of the cavity. For inspection purposes the repair zone of the vessel shall consist of the regions specified above for the vessel, except the distance there specified shall be 1T.**

* nT means n times the wall thickness.

** This is a deviation from the Code, which requires an examination of a 3T band.

6. Instrumentation

Thermocouples and recording instruments shall be used to monitor the preheat, gouging, grinding, welding, and final postweld heat treatment operations. Thermocouples may be attached by welding where practicable.

7. Cavity preparation and cleaning

The cavity for the vessel repair, except for the longitudinal boundary for the heat-affected zone flaw, may be partially formed by flame cutting and/or air-arc gouging to rough dimensions and grinding to finished dimensions. Finished dimensions are shown in Fig. A.2 for the vessel. The repair zone shall be preheated and maintained at temperatures in the range of 350°F to 400°F until flame or arc cutting and grinding are finished.* After such cutting is completed, a layer of metal under the cut area a minimum of 1/4 in. deep shall be removed by grinding.

Note: The vessel's longitudinal cavity surfaces have been premilled by UCC-ND to establish final and optimum planes for subsequent postweld repair heat-affected zone flaw preparations. These longitudinal surfaces shall not be ground. The layout for gouging the top and bottom cavity boundaries must allow for 1/4-in. post-gouge grinding and the blending of ground ends to the premachined middle section. Care should be exercised in cavity corners to retain minimum radii as shown in Figs. A.2 and A.3. Care must also be taken to preserve the preground longitudinal sides.

The V-7B cavity for the procedure qualification prolongation shall be formed by the fabricator entirely by air-arc gouging and grinding. The cavity shall be centered about the center lines now scribed to the vessel's outer surface. Cavity end angles must match the angles of the vessel repair cavity ends. Dimensions shown in Fig. A.3 are finished (final ground) dimensions.

The V-8 repair cavity for the same prolongation (shown in Fig. A.4) will be furnished to the fabricator premachined and ready for half-bead technique welding.

* This is a deviation from the Code which does not allow flame (thermal) cutting (with agreement of the Advisory Task Group on Weld Repair for Pressure Vessels; PVRC, Atlanta Meeting 6/6/76).

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NOTES

The vessel is furnished to the fabricator with premachined radial sides for the center portion of the cavity. The fabricator shall air-arc gouge cavity ends to a distance of 1/4 in. of final prerepair weld surfaces; the final 1/4 in. material to be removed by grinding. Care must be taken not to nick into the premachined radial sides of the cavity center portion. (For preheat, etc. refer to UCC-ND Specification W-HB-105.)

The premachined transverse (sectional) weld repair cavity layout was made to have final 5.128 in. chord width for a cavity with radial sides and an included 15° angle. The 5.128 in. reference locates the centerline for the post weld repair flaw slot. The heat-affected zone (from the weld repair) was assumed to be 0.080 in. wide, or 0.040 in. to the center of the heat-affected zone. Accordingly, the machined prerepair weld cavity was offset by 0.040 in. with the cavity sides parallel to the final radial plane sloped surfaces; the resultant prerepair weld cavity chord dimensions, therefore, are 5.058 in. at the vessel exterior and 3.480 in. at the vessel interior. Scribe bench marks have been placed on two flats at 180° from the future flaw slot centers to the 5.128 in. reference dimension. A tape measure should be used to reestablish the 5.128 in. chord reference at the completion of weld repairs. It is intended to use but one flaw slot on either side of the cavity's weld repair. Selection of what side to place slot will be made after weld repair and may depend on fabricator's weld inspection results.

NOTES:

Refer UCC-ND Specification W-HB-105 for fabricator required air-arc gouge/grind preparations, etc.

Gouge only to within 1/4 in. of the surface dimensions shown; then grind out the last 1/4 in. of material. Drawing dimensions shown are finished dimensions.

For required V-8 cavity work on same prolong refer to Fig. A.4. The V-8 cavity (only) will be premachined to final cavity dimensions by UCC-ND.

Provide 4 in. x 4 in. (minimum) cross-brace bars for end restraints on each end of the prolongation. Provide backing plate supports (not shown) to suit.

**ELEVATION
PAIR V7B**

prolongation V-10. Details for V-7B re-

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Fig. A.4. The V-8 repair cavity

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Notes for Layout and Machining V-3 Repair Cavity.

Refer Detail A, PLAN VIEW, Looking Down. Labelled show end to be at bottom. Locate the corners of the cylinder's seam weld, verify an approximate 5 in. outer surface weld width. Measure $2 \frac{9}{16}$ in. cc from the seam weld's centerline to locate the radial centerline, line FF, for the postweld repair flaw. Scribe index line FF over the entire cylinder surface distance.

Measure clockwise from line FF to locate centers for a 1-in.-diam ball mill cutout, line ZZ, which is to be parallel to line FF and 0.040 in. (one half width heat-affected zone of weld repair) plus $\frac{1}{2}$ in. (ball mill radius), or 0.540 in. away. Scribe index line ZZ.

Again measure clockwise, 30° from line FF, along the cylinder's perimeter. (Measure the entire perimeter and divide distance by 12), scribe line WWW onto the cylinder's surface. Also measure clockwise from line FF, a distance of $2 \frac{3}{4}$ in. to locate line VV, centers for a 1-in.-diam ball mill cut for the opposite side of the cavity. Scribe line VV. Set vessel with line FF aligned horizontally and with the horizontal boring mill tool axis.

Lower the tool axis a distance of 0.540 in. and make the trapezoidal cut shown in SECTION BB. Maximum 1-in.-diam ball mill cutting depth = $3 \frac{1}{2}$ in.

Rotate the vessel to align the tool axis to center the 1-in.-diam ball mill on line VV. Machine trapezoidal cutout.

Reset cylinder to remove cylinder surface material for the center portion of the cavity. Hand grind as necessary to blend contours and/or corners.

Note: Postrepair flaw slotting to center about line FF.

Fig. A.4. The V-3 repair cavity.

Detailed procedures for cavity preparation and cleaning as prepared previously shall be kept and adhered to at the job site.

In final preparation for welding, the cavity shall be ground smooth and clean, except as noted above, with beveled sides and edges slightly rounded to provide suitable accessibility for welding. The surfaces within 1T distances of the joint shall be cleaned of all dirt, oil, grease, paint, and excessive amounts of scale and rust. The cavities of the vessel and test pieces shall be examined by magnetic particle inspection in accordance with the requirements of IWA-2221 prior to welding. Additional grinding shall be performed with preheat as necessary to remove indications of flaws. Actual dimensions and location of the cavity shall be documented.

8. Care of welding electrodes

The moisture content in the protective coating of the low-hydrogen electrodes shall not exceed 0.4% by weight. The following steps shall be taken to prevent moisture pickup, except minor deviations may be allowed with prior written approval of JCC-ND.

All coated electrodes shall have been baked before use at temperatures of $800^{\circ}\text{F} \pm 25^{\circ}\text{F}$ for 30 min to 1 hr. The temperature of the oven shall be 300°F or lower when the electrodes are placed in the oven for baking. During the baking cycle, the temperature shall not be raised more than 300°F/hr when oven temperatures are above 500°F , and the total time above 500°F shall not exceed 5 hr. After baking, and before the electrodes are allowed to cool below 150°F , they shall be repackaged in sealed containers. The fabricator shall record and report moisture levels of each batch of electrodes. Electrodes shall not be rebaked more than once.

During the repair, the electrodes shall be removed from their sealed containers and thereafter kept in portable heated ovens which shall be at the work station. These ovens shall be at 225 to 300°F . Electrodes shall not be out of an oven more than 20 min prior to use. Electrodes not used within 20 min after removal from the oven shall be returned to the holding oven and held at 225 to 300°F for at least 8 hr before re-issue. Random moisture contents rechecks should be conducted at least once a day on electrodes of each size in use and on those taken from the

portable heater ovens at the welder work stations. The fabricator shall initiate and maintain records to indicate conformance to the above electrode bakeout and rod issuance regulations.

All electrode end conditions should be inspected carefully before use. The small diameter electrodes are likely to have the flux coating chipped off at the start end. Electrode ends should be examined three times: (1) when the electrode is rebaked, (2) when the vacuum package is opened, and (3) when the electrode is taken from the electrode holding oven by the welder. Electrodes must be rejected whenever there are any signs of cracks in the flux coating.

Detailed fabricator procedures for the care of electrodes must be forwarded to UCC-ND for written approval within one week after contract award. Upon approval, these procedures shall be kept and adhered to at the job site.

9. Conditions for welding

The prolongation, vessel, and test coupons shall all be adequately braced to prevent warpage. Test pieces shall be restrained to avoid warpage and to simulate the restraint of the vessel. Backing plates shall be installed before anchoring or bracing. Backing plates shall consist of two layers of precontoured standard fabricator steel backing material. Flat test pieces shall be anchored to heavy support plates or welding tables. All work must be vertically positioned for all welding.

All subsequent repair work shall be performed with preheat applied to the base material. The preheat temperature in the repair zone shall be within the temperature range of 350 to 500°F. The temperature shall not be allowed to fall below 350°F until the completion of either an intermediate postweld heat treatment (PWHT)* of 450 to 550°F for 1/2 hr or after a final PWHT at the same temperatures for 4 hr. If electrical heat is used, standby torches shall be provided to maintain vessel temperature or perform an intermediate PWHT in case of prolonged power outages or unanticipated equipment malfunctions. A magnetic particle test of the weld cavity would be required following any intermediate PWHT.

*PWHT actually infers a postweld tempering treatment only.

10. Position of welding

All welding shall be done with the longitudinal axis of the vessel and/or prolongation or test piece in the vertical position. For the half-bead pass and at least the first pass thereafter, welding shall be in the vertical position for the cavity sides.

11. Weld metal deposition

Welding shall be done in general accordance with the illustrations of Fig. A.5.

The cavity shall be buttered using 3/32-in.-maximum-diam electrodes as shown in Step 1, A.5. Approximately one-half the thickness of this buttering layer shall be removed by grinding before depositing a second layer. Special procedures shall be established as needed to control the grinding of the buttering layer. Such procedures may employ the use of workmanship specimens, dimensional measurements, or other means to demonstrate compliance. The maximum interpass temperature shall be held to 500°F. See Step 2. The second layer shall be deposited with either 1/8-in.- or 5/32-in.-diam electrodes. The maximum bead width shall not exceed four times the electrode core diameter. Bead positioning shall be performed in a manner to temper the prior beads and their heat-affected zones as shown in Step 3 of Fig. A.5. The completed weld shall have at least one layer of weld reinforcement (crown pass) deposited. This final layer should overlap, but shall not extend beyond the buttering deposit of the first pass. This reinforcement shall thereafter be removed by grinding, making the finished surface of the repair substantially flush with the surface of the vessel surrounding the repair. Likewise following all welding and the postheat and cooldown, the backing plate shall be removed, and the interior repair surface shall be contoured evenly to conform to vessel inside diameter dimensions plus or minus 1/8 in. Back welding may be required to satisfy this requirement. UCC-ND will be notified prior to and shall approve any back welding operations. Temper-bead techniques may again be required.

Possible benefits of controlled peening, as permitted by Section XI, shall not be evaluated in this weld repair.

HALF BEAD WELD REPAIR AND TEMPER WELD BEAD REINFORCEMENT FOR HEAVY WALL VESSELS AND/OR THICK PLATES

ALL WELDING SHALL BE DONE WITH THE LONGITUDINAL AXIS OF THE VESSEL OR WORK IN THE VERTICAL POSITION.

Fig. A.5. Half-bead weld repair sequence.

Detailed procedures for grinding and controlling the thickness of the buttering layer and, if elected, controlled peening shall be kept at the job site during this part of the work. Utmost care should be exercised to grind off approximately half of the buttering layer as dimensional verification by measurement is extremely difficult in a cavity at approximately 400°F.

12. Inspection during welding (vessel and both prolongation welds)

A magnetic particle examination (MT) shall be performed on the ground buttered layer, the next 1/8-in. layer, and thereafter on alternate layers and the final ground outside surface.* The final MT shall be completed prior to the start of the 4-hr postweld heat treatment. Layers not inspected by MT shall be visually inspected. Where necessary, weld defects shall be removed and the repaired zone reinspected. If defects occur within 3/16 in. of the base metal, such repairs shall be made using the buttering and half-bead grinding technique. An MT examination shall be performed on the vessel ID after grinding and backwelding (if required). MT indications shall be removed by grinding and blending and a subsequent MT examination shall be made to ensure removal of defects.

13. Postweld nondestructive inspection (vessel and both prolongation welds)

The repair zone as defined above under Repair Zone shall be nondestructively examined after the completed weld has been at ambient temperature for a period of not less than 48 hr. A volumetric examination of the repair zone shall be made by radiography in accordance with IWA-2231 and ultrasonic examination in accordance with IWA-2232, except that calibration block material of the same specification as the base material shall be deemed to meet the requirement of paragraph I-3121. A magnetic particle examination in accordance with IWA-2221 shall be made of the surfaces of the repair zone and of areas representing locations of weld attachments. A visual examination shall be made in accordance with IWA-2210.

Acceptance of the repaired vessel shall be determined in accordance with IWB-3500 and examination category B-A. If necessary, repairs of the repair zone of the vessel shall be made in accordance with the half-bead weld technique as described in the foregoing sections of Part I.

*This deviates from the Code, which calls for examining every layer (with agreement of the Advisory Task Group on Weld Repair for Pressure Vessels, PVRC, Atlanta Meeting, 6/6/75).

A disadvantage of the hole-drilling method of measuring residual stresses is that the removal of material at the center of a stress element by mechanical drilling induces fictitious strains and stresses. This observation has been reported by Bush and Evers.¹ In an effort to further evaluate these fictitious stresses and to establish a basis to compensate for them, measurements were made on stress-free plates. These plates were machined from A533 grade B, class 1 plate stock and were stress relieved at 746°C (1375°F) for 72 hr and furnace cooled for 74 hr. Their dimensions were nominally 152 mm (6 in.) by 104 mm (4.1 in.) by 25 mm (1 in.). A typical specimen was used to WMC for residual stress measurements using an air abrasion hole-drilling technique which induces a minimum of fictitious stresses. These measurements were made under the following conditions.

1. No surface preparation was made to the stress-free plate.
2. Light grinding was used to prepare the surface for gage attachment.
3. A measurement was made on a stress-free plate that was prepared by WMC.

The principal stresses that were found from these measurements are²

Case	σ_{xx}^{max} (MPa (ksi))	σ_{xx}^{min} (MPa (ksi))
1	-7.8 (-0.6)	-6.9 (-1.0)
2	15.2 (5.1)	71.4 (3.1)
3	43.4 (6.3)	10.3 (6.4)

For case 2, the three measured strains were 10×10^{-6} , 6×10^{-6} , and -10×10^{-6} .

The hole-drilling measurements made at WMC using a mechanical drill on the stress-free plates are listed in Table B.1. As had been previously reported, significant negative values of strain were observed when a mechanical drill was used. A representative value of 70 $\mu\epsilon$ was estimated

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Table B.1. Calculated principal stresses from hole-drilling measurements (mechanical drill) on a stress-free plate of A533 grade B, class 1 with no surface preparation³

Date	ϵ_{C1}	ϵ_{C2}	ϵ_{C3}	Hole diam (mm)	σ_{max} [MPa (ksi)]	σ_{min} [MPa (ksi)]
Feb. 19, 1976	-76	-74	-79	1.66	1.3 (0.2)	-2.8 (-0.4)
Feb. 23, 1976	-84	-84	-94	1.66	19.6 (2.8)	12.0 (1.7)
Feb. 23, 1976	-91	-88	-85	1.66	16.0 (2.3)	12.8 (1.8)
Feb. 25, 1976	-78	-74	-83	1.62	7.6 (1.1)	-0.1 (0.0)
Apr. 2, 1976	-95	-106	-92	1.74	26.8 (3.9)	14.4 (2.0)
Apr. 5, 1976	-83	-70	-64	1.82	-1.0 (0.1)	-10.0 (-1.5)
Apr. 5, 1976	-52	-58	-58	1.70	-29.5 (-4.3)	-33.9 (-5.0)
July 9, 1976	-84	-83	-89	1.59	17.4 (2.5)	13.1 (1.7)
Mar. 18, 1977	-92	-96	-85	1.70	18.7 (2.7)	10.2 (1.5)
Apr. 5, 1977	-71	-100	-89	1.58	16.0 (2.3)	-9.7 (-1.4)

³A correction of 78 $\mu\epsilon$ was added to each recorded strain.

from the data listed in Table B.1 and that value of strain with the sign changed was used as a compensation in all hole-drilling type stress calculations reported here. Using the adjusted values, the principal stresses, σ_{max} and σ_{min} , were then calculated using the procedure described in Chapter 4. The principal stresses caused by hole drilling are also listed in Table B.1 and provide an indication of the scatter that can be expected. All of the hole-drilling induced stresses reported in the appendix have been calculated after an adjustment of 78 $\mu\epsilon$. Similar data for weld metal that was cut from the V-7B weld repair simulation and then thermally stress relieved are listed in Table B.2.

In order to make through-thickness residual stress measurements, it was necessary to saw the simulation welds along planes of interest as shown in Fig. 5.1. A typical sawing operation is shown in Fig. 5.2. Sawing, like any other machining operation, induces residual stresses very close to the machined surface. If measurements were taken with no special precautions, misleading through-thickness measurements could result. In order to eliminate the unwanted surface effects resulting from sawing, various surface removal schemes were employed. Results of a study of the gentle grind method of material removal are presented in Ref. 3. The principal conclusion of that work was that if sufficient coolant and slow feed rates are used, then minimal skin effects on residual stress measurements result. A gentle grind procedure, listed in Table B.3, was used to prepare

**Table B.2. Calculated principal stresses from hole-drilling
(mechanical drill) on a stress-free specimen of weld metal^a**

Date	$\mu\epsilon_1$	$\mu\epsilon_2$	$\mu\epsilon_3$	Hole diam (mm)	σ_{max} [MPa (ksi)]	σ_{min} [MPa (ksi)]
May 13, 1977	-63	-59	-53	1.53	-29.8 (-4.3)	-35.9 (-5.2)
May 13, 1977	-43	-54	-48	1.62	-47.3 (-6.9)	-50.1 (-7.3)
Sept. 8, 1977	-50	-54	-41	1.78	-36.3 (-5.3)	-44.2 (-6.4)

^aSpecimen of weld metal was cut from the V-7B simulation repair weld and thermally stress relieved. A correction of 78 $\mu\epsilon$ was added to each recorded strain.

**Table B.3. Procedure used to prepare the
surfaces of the V-7A specimen for
through-thickness measurements**

Grinding wheel selection

Preferred - H, soft grade wheel
Acceptable - K, medium grade wheel
Not acceptable - N, hard grade wheel

Grinding wheel speed

~2000 ft/min

Coolant selection

Acceptable - highly sulphurized oil
Not acceptable - water-based coolants

Grinding wheel downfeed

7 passes at 0.010 in./pass
1 pass at 0.0005 in./pass
2 passes at 0.001 in./pass
2 passes at 0.0005 in./pass
1 pass each at 0.0003, 0.0002, and 0.0001 in./pass

Grinding cross feed

0.030 to 0.060 in./pass

Table speed

60 to 70 ft/min

the surfaces of the V-7A simulation weld sections shown in Figs. 4.1 and 5.6. Since the procedure that was used was very close to the recommended and researched method, no further studies of it were made.

The previously described gentle grind method of preparing a surface was suitable, providing that the specimen to be ground did not exceed the size and weight limitations of the available grinders. For the specimen shown in Fig. 4.2 and the V-8 vessel shown in Fig. F.1, the weight support capability of the available conventional grinders was exceeded and alternative procedures were developed and examined. The entire through-thickness surface of the specimen shown in Fig. 4.2 was given a gentle grind using a Blanchard grinder. The specification used for this operation is presented in Table B.4. Residual stress measurements taken from stress-free plates of A533 grade B, class 1 that had received the grinding described by Table B.4 are given in Table B.5. These data compared favorably with that of the stress-free plate data given in Table B.1.

Table B.4. Specification for grinding the
V-8/V-7B simulation repair weld specimen
used for through-thickness residual
stress measurements^a

Grinding stones

Norton 23A24-F12 VSM

Downfeed

8 mils/min for 100 mils

4 mils/min for 150 mils

Table speed

11.9 rpm

Grinding wheel speed

350 rpm

Maximum coolant flow

^aSee Fig. 4.2.

Table B.5. Calculated principal stresses from hole-drilling measurements (mechanical drill) that were made on a stress-free plate that had been given the surface preparation listed in Table B.4^a

Date	$\mu\epsilon_1$	$\mu\epsilon_2$	$\mu\epsilon_3$	Hole diam (mm)	σ_{max} [MPa (ksi)]	σ_{min} [MPa (ksi)]
Mar. 18, 1977	-83	-75	-77	1.56	6.2 (0.9)	-0.2 (0.0)
Apr. 4, 1977	-60	-80	-66	1.72	-1.6 (-0.2)	-11.1 (-1.6)

^aA correction of 75 $\mu\epsilon$ was added to each recorded strain.

References

1. A. J. Bush and F. J. Kromer, "Simplification of the Hole-Drilling Method of Residual Stress Measurements," *ISA Trans.* 12(3), 249-259 (1973).
2. Telephone communication from A. J. Bush, May 12, 1976.
3. L. J. Nowikowski, J. Maranchik, Jr., and M. Field, "Distortion and Residual Surface Stress in Grinding and Milling of High Strength Steels," 1961 SAE National Aeronautics Meeting, New York, 340L.

Appendix C

V-7 SERIES REPAIR WELDS - WELDABLE STRAIN GAGE MEASUREMENTS

Appendix C contains the weldable strain gage data for the V-7A, V-7A simulation, V-7B, and V-7B simulation repair welds. Chapter 4 contains a discussion relating to the weldable gage measurements.

Figure C.1 shows the coordinate system used to reference centerpoints of the weldable strain gages for the V-7A simulation repair weld (Table C.1) and the centerpoints of the weldable strain gages for the V-7A repair weld (Table C.2). The gages that are listed in each of those tables are identified by a number and are shown to scale relative to the weld cavity outlines as seen from outside the V-9 prolongation and the V-7 vessel in Figs. C.2 and C.3. The total changes in strain, $\Delta\epsilon$ in the tables, were determined by zeroing the gages at room temperature just prior to heatup for the weld repair and then recording the strain upon completion of the weld repair and after the prolongation and vessel had been brought back to the nominal room temperature. In the case of the V-7A repair weld, the total strain measurement was made after the end braces were removed. The amount of strain change that occurred as a result of removing the end braces is listed in Table C.1 as $\Delta\epsilon^*$. For those strain measurement locations where large residual stresses were recorded, (e.g., locations 3A, 4A, 5, 7A, and 8A) the strain change as a result of removing the braces is relatively small. The elapsed time over which the strain $\Delta\epsilon^*$ was measured was nearly 4 1/2 hr, and the nine thermocouples to the prolongation showed an average increase of 5.6 K (10°R). It would therefore appear that the end braces were not a significant factor in the residual stress field that developed in the V-9 prolongation as a result of the V-7A simulation repair weld. The stresses (σ) that are listed in Table C.1 and C.2 are shown in Figs. C.4 and C.5 relative to the weld cavity outline where the weld cavity and the solid lines indicating gages are drawn to scale. The stresses were calculated by the methods described in Chapter 4.

Figure C.6 shows the coordinate system used to reference centerpoints of the weldable gages for the V-7B simulation repair weld (Table C.3) and the centerpoints of the weldable strain gages for the V-7B repair weld (Table C.4). The gages that are listed in each of those tables are

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Fig. C.1. Coordinate system used to define the weldable strain gage locations listed in Tables C.1 and C.2. The rz and r θ planes are planes of symmetry for both the V-7A simulation repair weld and the V-7A repair weld (100 mm = 3.94 in.).

ORNL-DWG 78-3999

Fig. C.2. Weldable strain gage layout about the V-7A simulation repair weld (100 mm = 3.94 in.).

Table C.1. Weldable strain gage results for the
V-7A simulation repair weld

Gage No.	Coordinates ^a			$\Delta\mu\epsilon$ (total)	σ (MPa)	Gage orientation ^b	$\Delta\mu\epsilon^*$ ^c
	r (mm)	θ (deg)	z (mm)				
3A	508	12.2	0	-1063	-151	A	40
4A	508	13.9	0	1278	212	C	-161
5	508	20.8	0	-725	-145	A	39
7A	508	0	-203	-1187	-207	C	-143
8A	508	0	-219	811	102	A	24
9	508	0	-254	270	54	A	101
12	343	11.9	0	95	24	A	63
13	343	14.4	0	43	15	C	-8
19	508	180	0	-66	-13	C	-80
20	343	180	0	215	43	C	144

^aCoordinates are defined in Fig. C.1.

^bA represents axial and C circumferential.

^cStrain change that occurred as a result of removing the end braces.

Table C.2. Weldable strain gage results
for the vessel V-7A repair weld^a

Gage No.	Coordinates ^a			$\Delta\mu\epsilon$	σ (MPa)	Gage orientation ^b
	r (mm)	θ (deg)	z (mm)			
3	496	12.2	0	-642	-67	A
4	496	13.9	0	1151	211	C
8	496	0	-303	817	163	A

^aCoordinates are defined in Fig. C.1.

^bA represents axial and C circumferential.

identified by a number and are shown to scale relative to the weld cavity outline as seen from outside the prolongation and vessel in Figs. C.7 and C.8. The residual stresses (σ) listed in Tables C.3 and C.4 were calculated from the total change in strain, $\Delta\epsilon$, by the method discussed in Chapter 4. These values are shown relative to the weld cavities in Figs. C.9 and C.10.

ORNL-DWG 78-4032

Fig. C.5. V-7A repair weld residual stresses (MPa) determined from weldable strain gage measurements (1 MPa = 145 psi; 100 mm = 3.94 in.).

ORNL-DWG 78-4003

Fig. C.6. Coordinate system used to define the weldable strain gage locations listed in Tables C.3 and C.4. The rz plane is a plane of symmetry for the V-7B simulation repair weld and the V-7B repair weld. The rθ plane bisects the V-8 prolongation and the interior surface outline of the vessel V-7B repair weld (100 mm = 3.94 in.).

Table C.3. Weldable strain gage results for the V-7B simulation repair weld²

Gage No.	Coordinates ^a			$\Delta\mu\epsilon^i$	$\Delta\mu\epsilon^{**c}$	σ (MPa)	Gage orientation ^d
	r (mm)	θ (deg)	z (mm)				
3	343	16.4	-112	-31	-93	3	A
4	343	16.4	-137	155	375	32	C
6	508	19.4	85	-695	-606	-51	A
7	508	19.4	60	1596	1500	305	C
8	508	19.4	-42	1743	1650	318	C
9	508	19.4	-67	-996	-933	-123	A
10	508	19.4	-93	1253	-933	211	C

^aCoordinates are defined in Fig. C.6.

^b $\Delta\mu\epsilon$ is the strain change with the end braces on and is the value that was used to calculate the stresses.

^c $\Delta\mu\epsilon^{**}$ is the strain change measured after the end braces had been removed.

^dA represents axial and C circumferential.

Table C.4. Weldable strain gage results for the V-7B repair weld

Gage No.	Coordinates ^a			$\Delta\mu\epsilon$	J (MPa)	Gage orientation ^b
	r (mm)	θ (deg)	z (mm)			
31	343	15.9	94	-140	6	C
32	343	15.9	68	577	116	A
33	343	15.9	43	-191	-5	C
34	343	15.9	-58	-64	16	C
35	343	15.9	-84	478	102	A
36	343	15.9	-109	-10	28	C
37	495	13.2	224	1741	333	C
38	495	13.2	198	-752	-53	A
39	495	13.2	173	1759	336	C
40	495	13.2	21	1740	343	C
41	495	13.2	-5	-580	-23	A
42	495	13.2	-26	1544	300	C
43	495	13.2	-178	1859	353	C
44	495	13.2	-204	-836	-86	A
45	495	13.2	-229	1201	209	C

^aCoordinates are defined in Fig. C.6.

^bA represents axial and C circumferential.

Fig. C.7. Weldable strain gage layout about the V-7b simulation repair weld (100 mm = 3.94 in.).

Fig. C.8. Weldable strain gage layout about the V-7B repair weld (100 mm = 3.94 in.).

Fig. C.9. V-7B simulation repair weld residual stresses (MPa) determined from weldable strain gage measurements (1 MPa = 145 psi; 100 mm = 3.94 in.).

Fig. C.10. V-7B repair weld residual stresses (MPa) determined from weldable strain gage measurements (1 MPa = 145 psi; 100 mm = 3.94 in.).

Appendix D

V-8 SERIES REPAIR WELDS -- WELDABLE
STRAIN GAGE MEASUREMENTS

Appendix D contains the weldable strain gage data for the V-8 simulation repair weld and the V-8 repair weld. A discussion relating to the weldable gage measurements is contained in Chapter 5.

Figure D.1 shows the coordinate system used to reference centerpoints of the weldable strain gages for the V-8 simulation repair weld (Table D.1) and the centerpoints of the weldable strain gages for the V-8 repair weld (Table D.2). The gages that are listed in each of those tables are

Fig. D.1. Coordinate system used to define the weldable strain gage locations listed in Tables D.1 and D.2. The rz and $r\theta$ planes are planes of symmetry for both the V-8 simulation repair weld and the V-8 repair weld (100 mm = 3.94 in.).

Table D.1. Weldable strain gage results for
the V-8 simulation repair weld

Gage No.	Coordinates ^a			$\epsilon_{w/c}$	σ (MPa)	Gage orientation ^b
	r (mm)	θ (deg)	z (mm)			
11	343	0	51	282	87	C
12	343	0	25	406	105	A
13	343	0	0	222	73	C
14	343	0	-25	380	97	A
15	343	0	-51	233	75	C
16	496	-10.7	127	862	166	C
17	496	-10.7	102	-402	-48	A
18	496	-10.7	76	1780	351	C
19	496	-10.7	25	1920	370	C
20	496	-10.7	0	-773	-50	A
21	496	-10.7	-25	1817	348	C
22	496	-10.7	-76	1502	300	C
23	496	-10.7	-102	-449	-35	A
24	496	-10.7	-127	497	80	C
25	496	10.7	76	1501	280	C
26	496	10.7	51	-754	-47	A
27	496	10.7	25	1548	295	C
28	496	10.7	-25	1616	306	C
29	496	10.7	-51	-773	-71	A
30	496	10.7	-76	1470	272	C

^aCoordinates are defined in Fig. D.1.

^bA represents axial and C circumferential.

Table D.2. Weldable strain gage results
for the V-8 repair weld

Gage No.	Coordinates ^a			$\epsilon_{w/c}$	σ (MPa)	Gage orientation ^b
	r (mm)	θ (deg)	z (mm)			
11	343	0	-51	306	110	C
12	343	0	-25	406	109	A
13	343	0	0	253	81	C
14	343	0	25	300	82	A
15	343	0	51	278	80	C
16	508	10.4	-127	984	166	C
17	508	10.4	-102	-765	-81	A
18	508	10.4	-76	1739	331	C
19	508	10.4	-25	1939	364	C
20	508	10.4	0	-962	-89	A
21	508	10.4	25	1755	326	C
22	508	10.4	76	1685	361	C
23	508	10.4	102	-421	-23	A
24	508	10.4	127	492	81	C
25	508	-10.4	-76	1899	356	C
26	508	-10.4	-51	-926	-72	A
27	508	-10.4	-25	2203	422	C
28	508	-10.4	25	2050	392	C
29	508	-10.4	51	-875	-76	A
30	508	-10.4	76	1584	290	C
31	508	0	-209	-894	-166	C
32	508	0	-235	459	57	A
33	508	0	-261	-474	-79	C
34	508	0	-286	306	62	A
35	508	0	-311	-289	-44	C

^aCoordinates are defined in Fig. D.2.

^bA for axial and C for circumferential.

identified by numbers and are shown to scale relative to the weld cavity outlines as seen from outside the V-8 prolongation and the V-8 vessel in Figs. D.2 and D.3. The total change in strains, $\Delta\epsilon$ in the tables, were determined by zeroing the gages at room temperature just prior to heatup for the weld repair and then recording the strain upon completion of the weld repair and after the prolongation and vessel had been brought back to the nominal room temperature. The total strain measurement for the V-8 simulation repair weld was with the end braces in place; however, for reasons stated in Appendix C, this is not considered significant. The stresses (σ) that are listed in Tables D.1 and D.2 are shown in Figs. D.4 and D.5 relative to the weld cavity outline where the weld cavity and the solid lines indicating gages are drawn to scale. The stresses were calculated by the methods described in Chapter 4.

Fig. D.2. Weldable strain gage layout about the V-8 simulation repair weld. See Table D.1 (100 mm = 3.94 in.).

ORNL-DWG 78-401C

Fig. D.3. Weldable strain gage layout about the V-8 repair weld. See Table D.2 (100 mm = 3.94 in.).

ORNL-DWG 78-401D

* INDICATES INSIDE SURFACE MEASUREMENTS

Fig. D.4. V-8 simulation repair weld residual stresses (MPa) determined from weldable strain gage measurements (1 MPa = 145 psi; 100 mm = 3.94 in.).

*INDICATES INSIDE SURFACE MEASUREMENTS

Fig. D.5. V-8 repair weld residual stresses (MPa) determined from weldable strain gage measurements (1 MPa = 145 psi; 100 mm = 3.94 in.).

Appendix E

V-7 SERIES REPAIR WELDS - HOLE-DRILLING MEASUREMENTS

Appendix E contains the hole-drilling data for the V-7A simulation repair weld and the V-7B simulation repair weld. A discussion relating to the hole-drilling measurement technique is contained in Chapter 4. Table E.1 is a summary of the figures and data contained in this appendix. Figures E.1 and E.16 define cylindrical coordinate systems that are used in locating points where hole-drilling type measurements were made. Figures E.2, E.3, E.6, E.9, E.12, E.13 and E.17 are scale drawings which indicate the location of numbered measurement sites relative to the appropriate weld cavity outline. The remainder of the figures show stresses that were calculated from the strain recorded during the drilling operation. The coordinates of each measurement point and the measured strain as a result of drilling are listed in Tables E.2 through E.7. The orientations of the strain rosettes relative to the angle β or β^* and the principal axes are defined in the figures showing the relative locations of the numbered measurement sites. The principal stresses were resolved into two of the following categories which are listed in the tables: circumferential stress, σ_c , axial stress, σ_a , and/or the radial stress, σ_r . The measured hole diameter is identified as d .

The data presented in this appendix were measured either at ORNL or at WRDC. The original source of the WRDC data is contained in Ref. 1. The ORNL data were obtained by using a mechanical drill and thus the correction of 78 $\mu\epsilon$ discussed in Appendix B was added to each of the recorded strain values. The WRDC data were obtained using an abrasive drilling technique which did not require a correction.

¹ A. J. Bush, *Residual Stresses in Repair Weld of Thick-Walled Pressure Vessel*, Westinghouse Research Report 78-1P6-APMEC-R1 (1968).

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Table E.1. Summary of data presented in Appendix E

Fig. No.	Coordinate system defined	Weld simulation	Section ^a	Measurement locations defined	Circumferential stress	Axial stress	Radial stress	Surface measurements	Through-thickness measurements	Source of data	Table No.
E.1	X	V-7A	Uncut						X		
E.2		V-7A	Uncut	X				Outside			
E.3		V-7A	Uncut	X				Inside			
E.4		V-7A	Uncut		X	X		Outside		ORNL	E.2
E.5		V-7A	Uncut		X	X		Inside		ORNL	E.2
E.6		V-7A	A	X					X		
E.7		V-7A	A			X			X	WRDC	E.3
E.8		V-7A	A				X		X	WRDC	E.3
E.9		V-7A	A	X					X		
E.10		V-7A	A		X				X	WRDC	E.4
E.11		V-7A	A				X		X	WRDC	E.4
E.12		V-7A	C	X					X		
E.13		V-7A	C	X					X		
E.14		V-7A	C		X				X	WRDC/ORNL	E.5, E.6
E.15		V-7A	C				X		X	WRDC/ORNL	E.5, E.6
E.16	X	V-7B	B						X		
E.17		V-7B	B	X					X		
E.18		V-7B	B		X				X	ORNL	E.7
E.19		V-7B	B				X		X	ORNL	E.7

^aSee Fig. 5.1.

Table E.2. Surface hole-drilling type residual stress data from the V-7A simulation repair weld prior to the sectioning of the V-9 prolongation

Location No.	Coordinates ^b			$\mu\epsilon_1$	$\mu\epsilon_2$	$\mu\epsilon_3$	d (mm)	β (deg)	σ_x (MPa)	σ_y (MPa)	σ_z (MPa)	σ_n (MPa)
	r (mm)	θ (deg)	z (mm)									
5	343	+2.1	0	-12	-31	-8	1.56	42.3	-114	-90	-103	-101
6	343	+2.1	-64	-242	-293	9	1.64	27.3	-58	165	-11	118
7	343	-2.1	0	-151	-137	72	1.68	20.6	-124	22	-106	4
8	508	-17.2	-152	77	-188	26	1.53	-42.0	-62	-344	-198	-218
9	343	-17.2	-152	-229	-221	-169	1.60	18.1	154	194	158	190
10	508	0	0	-414	-181	119	1.56	3.6	-45	254	-44	252
11	508	0	-89	-234	-38	118	1.53	-3.2	-135	72	-134	72
12	508	0	-162	-267	-288	-119	1.53	26.0	110	251	137	224
13	508	0	-186	-360	-274	145	1.53	5.3	-7	413	-3	409
14	508	0	-213	-496	-218	44	1.53	-1.9	74	390	74	390
15	508	-3.6	0	-243	-61	-99	1.53	-28.4	69	223	104	188
16	508	-5.7	0	-259	-236	-138	1.53	15.9	147	230	154	224
17	508	-6.6	0	-97	-113	-383	1.56	20.8	349	137	322	163
18	508	-11.5	0	279	-195	-525	1.56	-5.1	297	-160	291	-156
19	343	+2.1	64	-42	274	-92	1.56	42.9	174	-206	-3	-30
20	343	+6.3	0	-16	-241	-265	1.60	-19.5	176	4	157	23

^a Numbered locations are shown in Figs. E.2 and E.3.

^b Coordinates are defined in Fig. E.1.

Table 2.3. Axial through-thickness hole-drilling type residual stress data (MINC) from Section A (see Fig. 5.1) which contains part of V-7A repair weld

Location No.	Coordinates			z (mm)	UC ₁	UC ₂	UC ₃	d (mm)	δ^* (deg)	σ_{max} (MPa)	σ_{min} (MPa)	σ_a (MPa)	σ_f (MPa)	Correction ^b (%)	σ_d
	r (mm)	θ (deg)	ϕ (deg)												
1	465	0	174		-45.5	72.8	-147.5	1.62	36.6	255	52	143	125	102	285
2	465	0	150		-84.0	141.3	-393.0	1.59	33.9	637	151	436	103	109	595
3	465	0	141		50.7	86.9	-169.3	1.59	24.9	456	70	303	139	115	503
4	465	0	131		111.3	48.3	-133.0	1.55	12.9	104	-66	95	-57	115	210
5	465	0	121		29.7	18.4	-72.3	1.58	18.9	74	-3	66	3	116	162
6	465	0	111		16.5	11.3	-47.1	1.63	20.0	48	1	42	6	116	158
7	465	0	90		-93.2	-27.5	20.9	1.50	85.7	106	29	30	105	125	155
8	465	0	49		-62.4	-36.0	44.6	1.56	103.4	52	-21	-17	48	131	114
9	465	0	17		-12.0	-70.1	-3.9	1.66	132.5	45	-26	7	11	139	146
11	364	0	53		-47.0	59.4	-94.5	1.55	39.9	217	37	143	111	117	260
12	364	0	41		69.7	-77.2	-8.7	1.53	155.9	65	-67	43	-45	119	162
13	364	0	33		-49.8	-25.4	83.5	1.56	106.2	19	-77	-70	12	125	155
31	498	0	180		140.1	-41.8	-415.2	1.61	13.1	402	43	383	61	118	501
32	498	0	168		126.6	81.0	-466.0	1.58	20.1	517	51	461	106	120	581
33	498	0	144		95.1	13.2	-110.9	1.57	5.8	77	-50	76	-49	135	211
34	498	0	25		11.9	-28.2	5.9	1.57	137.3	8	-36	-13	-17	156	143
35	424	0	173		-60.0	33.7	7.8	1.57	61.1	111	11	34	88	81	115
36	424	0	107		-202.8	109.9	-108.9	1.61	50.0	410	95	226	260	107	328
37	424	0	93		-50.0	49.5	-98.4	1.55	40.3	232	26	144	114	108	252
38	424	0	69		39.3	47.3	66.6	1.61	102.2	-79	-67	-67	-79	118	21
40	351	0	39		-39.3	195.6	-27.4	1.63	44.6	247	-48	102	97	118	220
41	351	0	27		-30.6	65.6	-140.6	1.61	35.0	231	46	171	107	124	295
42	493	0	51		65.0	-25.7	-47.6	1.75	164.3	21	-45	17	-40	131	151

^a Numbered locations are shown in Fig. E.6.

^bCoordinates are defined in Figs. 2.1.

See FIG. 3.9.

2300 FIG. 6-4.

Table E.6. Circumferential through-thickness hole-drilling type residual stress data (WRDC) from Section A (See Fig. 5.1) which contains part of the V-7A repair weld

Location No.	Coordinates ^b			$\mu\epsilon_1$	$\mu\epsilon_2$	$\mu\epsilon_3$	d (mm)	θ^* (deg)	σ_{max} (MPa)	σ_{min} (MPa)	σ_A (MPa)	σ_T (MPa)	Correction ^c (MPa)	
	r (mm)	θ (deg)	z (mm)											
14	465	-2.3	0	-249.3	-88.6	45.5	1.58	87.4	259	81	82	258	118	200
15	465	-3.7	0	-227.6	-31.9	71.2	1.58	81.7	223	37	41	220	111	152
16	465	-4.9	0	-216.6	43.3	75.1	1.60	71.0	226	7	10	201	105	135
17	465	-6.2	0	-130.1	90.4	118.2	1.55	71.1	108	47	-67	87	97	10
18	465	-7.4	0	81.8	-141.6	-179.7	1.59	162.3	177	-14	159	3	90	249
19	384	-2.9	0	-366.5	-69.8	120.5	1.65	83.8	328	50	54	324	13	67
20	384	-4.4	0	-265.4	-75.4	81.9	1.63	87.3	245	-46	-46	245	57	103
21	384	-5.8	0	59.1	-223.7	-356.3	1.66	160.8	261	39	237	63	57	294
22	498	-5.0	0	-66.9	39.9	91.6	1.67	80.4	27	-65	-62	25	125	63
23	498	-7.8	0	89.7	-190.1	-273.8	1.66	165.8	253	26	239	40	108	147
24	498	-9.3	0	159.5	-305.5	-457.4	1.69	166.5	403	34	383	54	94	477
25	424	-3.2	0	-311.4	-76.2	59.1	1.67	82.5	292	85	88	289	82	170
26	424	-6.5	0	66.2	-216.4	-220.5	1.67	157.9	223	7	193	38	75	268
27	424	-8.1	0	32.9	-166.3	-188.2	1.48	160.6	243	52	222	73	70	292
28	424	-9.8	0	0.5	-177.3	-150.9	1.66	153.3	184	44	156	72	68	224
29	351	-5.1	0	-43.8	-190.3	-120.5	1.67	144.8	186	61	144	102	40	184
30	351	-7.2	0	-75.7	-43.3	-22.2	1.67	84.1	89	59	59	88	40	99
43	498	-2.0	0	-44.7	21.4	64.0	1.68	83.9	16	-44	-43	15	150	107

^aNumbered locations are shown in Fig. E.9.

^bCoordinates are defined in Fig. E.1.

^cSee Fig. 5.10.

^dSee Fig. 6.3.

Location No.	Coordinates				lat	lon	d (cm)	θ (deg)	θ_{min} (mils)	θ_{max} (mils)	θ_{avg} (mils)	θ_{std} (mils)
	r (cm)	ϕ (deg)	λ	μ								
1	488	-10.0	0	70.9	-1.5	-362.0	1.33	13.9	39	278	34	33
2	488	-8.4	0	36.8	12.4	-220.1	1.31	18.5	39	271	34	31
3	488	-7.7	0	-126.8	-37.6	112.3	1.37	97.1	-83	88	-60	59
4	488	-4.9	0	-149.4	-39.3	189.4	1.36	99.6	-133	70	-144	66
5	488	0.4	0	-134.3	1.3	187.4	1.36	93.8	-143	66	-143	53
6	488	1.8	0	-57.0	99.5	164.9	1.38	76.2	-155	56	-149	43
7	488	7.6	0	75.4	-103.7	-20.3	1.60	144.8	-131	39	-131	33
8	488	9.4	0	74.5	-105.9	-20.3	1.61	158.8	359	63	319	26
9	481	-3.6	0	-217.4	116.8	270.4	1.63	79.8	-163	106	-163	97
10	483	-18.3	0	10.2	13.0	-26.8	1.33	24.6	31	32	36	3
11	483	-11.6	0	7.0	27.0	-110.9	1.60	26.7	44	144	119	30
12	483	-9.3	0	-3.7	18.9	-138.9	1.62	26.7	44	141	141	66
13	483	-7.3	0	30.2	0.0	-150.7	1.36	18.8	34	134	103	49
14	483	-3.4	0	-227.9	13.9	210.9	1.61	54.7	-114	131	-134	131
15	483	-3.6	0	-283.3	-3.7	240.3	1.50	88.7	-142	208	-142	209
16	483	-0.3	0	-363.9	2.7	170.9	1.67	83.6	-163	263	-163	260
17	483	1.4	0	-191.4	44.1	137.5	1.38	78.1	-78	195	-77	164
18	483	3.4	0	-193.2	140.8	225.6	1.63	74.6	-163	114	-163	89
19	483	7.2	0	41.0	-69.1	56.0	1.61	135.5	-164	8	-164	74
20	483	9.3	0	9.3	-167.8	-139.4	1.63	159.6	36	181	180	79
21	483	11.0	0	3.2	-140.1	-117.8	1.61	153.1	33	132	139	57
22	424	-10.9	0	-3.3	-7.3	-72.3	1.60	20.7	34	88	81	41
23	424	-8.7	0	10.1	-12.8	-130.8	1.66	9.3	46	122	120	43
24	424	-6.7	0	16.3	-13.6	-148.6	1.61	7.4	37	134	133	36
25	424	-4.7	0	-259.6	-23.3	238.3	1.61	92.3	-117	146	-117	147
26	424	-2.4	0	-302.6	-48.4	273.2	1.58	93.4	-148	199	-148	198
27	366	-0.4	0	39.9	-50.0	-134.0	1.39	5.3	26	130	130	36
28	366	-1.2	0	27.5	-56.6	-124.4	1.39	5.3	61	181	181	43
29	366	-3.9	0	-390.1	-8.4	216.7	1.58	66.8	-93	215	-93	214
30	366	-1.6	0	-293.6	-5.7	264.3	1.61	89.6	-117	187	-117	187
31	331	-8.8	0	-20.5	-20.3	-134.5	1.61	15.8	61	132	131	127
32	331	-6.3	0	-56.7	54.7	-71.7	1.61	43.2	34	109	109	87
33	331	-3.7	0	-35.3	137.6	32.6	1.59	35.6	-53	139	-53	99
34	331	-1.7	0	-31.9	-27.7	33.3	1.63	34.0	-13	69	-13	80
35	308	-13.9	38	18.3	-49.7	-89.7	1.67	9.0	3	47	3	68
36	308	-9.8	38	66.7	101.9	-140.2	1.62	26.8	-41	139	-41	139
37	308	-8.3	38	-10.6	248.6	-20.6	1.61	44.0	-76	185	-76	185
38	308	-6.4	38	-120.6	216.4	16.1	1.63	32.3	-99	231	-99	231
39	308	-4.7	38	178.0	180.2	14.1	1.17	32.8	-308	-400	-308	308
40	308	0.6	38	211.8	183.7	107.8	1.67	42.4	-350	-265	-350	355

^a Cluster locations are shown in Fig. E.13.

^b Coordinates are defined in Fig. E.1.

Table E.6. Through-thickness hole-drilling type residual stress data (ORNL)
from section C (see Fig. 5.1) which contains part of the V-7A repair weld

Location No.	Coordinates ^b					$\mu\epsilon_1$	$\mu\epsilon_2$	$\mu\epsilon_3$	d (mm)	β (deg)	σ_x (MPa)	σ_y (MPa)	σ_c (MPa)	σ_r (MPa)
	r (mm)	θ (deg)	z (mm)											
22	337	6.4	0	-36	134	55	1.56	-35.1	-208	-25	-147	-85		
24	383	6.4	0	-459	60	244	1.53	-12.7	-181	274	-159	252		
25	395	6.4	0	-356	-126	131	1.53	2.6	-110	187	-110	187		
26	408	6.4	0	-299	14	239	1.60	-4.6	-216	78	-214	76		
27	421	6.4	0	-304	0	229	1.60	-4.0	-203	87	-202	85		
28	433	6.4	0	-400	5	192	1.60	-10.1	-133	207	-122	197		
29	446	6.4	0	-216	21	214	1.60	-2.9	-227	6	-226	5		
30	459	6.4	0	-233	-16	268	1.45	3.8	-323	-6	-322	-8		
31	471	6.4	0	-257	-76	250	1.45	8.0	-294	37	-287	30		
32	484	6.4	0	-183	31	253	1.45	1.0	-332	-58	-332	-58		
33	497	6.4	0	-102	7	501	1.45	16.3	-703	-254	-667	-289		
34	374	10.3	0	-45	-192	-237	1.60	-4.7	202	65	202	66		
35	411	9.9	0	-7	-143	-314	1.60	3.3	202	35	201	36		
36	452	9.6	0	-54	-137	-255	1.56	4.9	171	58	171	59		
37	490	9.4	0	-34	-60	-334	1.56	19.8	267	51	242	75		
38	368	2.5	0	-282	-54	35	1.60	-11.8	-28	159	-20	151		
39	404	2.8	0	-385	-91	158	1.60	-2.4	-98	205	-98	204		
40	444	3.1	0	-426	-110	127	1.60	-4.1	-48	263	-47	261		

^aNumbered locations are shown in Fig. E.13.

^bCoordinates are defined in Fig. E.1.

Table E.7. Through-thickness hole-drilling type residual stress data from section B (see Fig. 5.1) which contains part of the V-7B repair weld

Location No. ^a	Coordinates ^b			UC ₁	UC ₂	UC ₃	d (mm)	β (deg)	σ_x (MPa)	σ_y (MPa)	σ_c (MPa)	σ_r (MPa)
	r (mm)	θ (deg)	z (mm)									
1	470	-7.4	0	58	-494	-565	1.56	-18.8	482	44	436	90
2	470	-4.3	0	-90	-73	-72	1.53	-20.8	-2	12	-1	10
3	470	0	0	-291	-79	40	1.64	-7.8	-23	154	-20	151
4	470	4.3	0	-102	-24	-52	1.53	7.8	-17	14	-16	13
5	470	7.4	0	131	-187	-514	1.53	0.4	366	-11	366	-11

^a Numbered locations are shown in Fig. E.17.

^b Coordinates are shown in Fig. E.16.

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Fig. E.1. Coordinate system used to define the hole-drilling residual stress measurement locations about the V-7A simulation repair weld, V-9 prolongation. The yz and xz planes are planes of symmetry for the V-7A simulation repair weld.

SHELL-000 70-0000

SHELL END

Fig. E.2. Hole-drilling measurement layout for outside surface measurements about the V-7A simulation repair weld. See Table E.2 (100 mm = 3.94 in.).

ORNL-DWG 78-4005

SHELL END
←

BASE METAL

AXIS 3 IS ALIGNED
IN THE CIRCUMFERENTIAL
DIRECTION

Fig. E.3. Hole-drilling measurement layout for inside surface measurements about the V-7A simulation repair weld. See Table E.2 (100 mm = 3.94 in.).

ORNL-DWG 78-4005

SHELL END
←-108
+218

Fig. E.4. Simulation repair weld residual stresses (MPa) on the exterior surface determined with the hole-drilling method (1 MPa = 145 psi).

ORNL-DWG 78-4017

Fig. E.5. V-7A simulation repair weld residual stresses (MPa) on the interior surface determined with the hole-drilling method (1 MPa = 145 psi.).

ORNL-DWG 78-4018

Fig. E.6. Hole-drilling measurement layout for measurements on an axial plane of the V-7A simulation repair weld. See Table E.3 (100 mm = 3.94 in.).

Fig. E.7. V-7A simulation repair weld axial stresses (MPa) determined with the hole-drilling method. WRDC data with no correction for cutting (1 MPa = 145 psi; 100 mm = 3.94 in.).

Fig. E.8. V-7A simulation repair weld radial stresses (MPa) determined with the hole-drilling method. WRDC data with no correction for sectioning (1 MPa = 145 psi; 100 mm = 3.94 in.; 1 mm = 0.039 in.).

NBS 806 70-0020

Fig. E.9. Hole-drilling measurement layout for measurements on a circumferential plane of the V-ZA simulation repair weld. See Table E.4 (100 mm = 3.94 in.).

NBS 806 70-0022

Fig. E.10. V-ZA simulation repair weld circumferential stresses (MPa) determined with the hole-drilling method. WRDC data with no correction for sectioning (1 MPa = 145 psi; 100 mm = 3.94 in.).

Fig. E.11. V-7A simulation repair weld radial stresses (MPa) determined with the hole-drilling method. WRDC data with no correction for sectioning (1 MPa = 145 psi; 100 mm = 3.94 in.).

Fig. E.12. Hole-drilling measurement layout for measurements on a circumferential plane of the V-7A simulation repair weld. WRDC measurement locations on piece C of Fig. 5.1. See Table E.5 (100 mm = 3.94 in.).

Fig. E.13. Hole-drilling measurement layout for measurements on a circumferential plane of the V-7A simulation repair weld. ORNL measurement locations on piece C of Fig. 5.1. See Table E.6 (100 mm = 3.94 in.).

Fig. E.14. V-7A simulation repair weld circumferential residual stresses (MPa) determined with the hole-drilling method, no correction for sectioning (1 MPa = 145 psi; 100 mm = 3.94 in.).

Fig. E.15. V-7A simulation repair weld radial residual stresses (MPa) determined with the hole-drilling method, no correction for sectioning (1 MPa = 145 psi; 100 mm = 3.94 in.).

Fig. E.16. Coordinate system used to define the hole-drilling residual stress measurement locations about the V-7B simulation repair weld. The rz plane is a plane of symmetry for the V-7B simulation repair weld, and the rθ plane divides the V-8 prolongation into two equal pieces.

Fig. E.17. Hole-drilling measurement layout for measurements on a circumferential plane of the V-7B simulation repair weld. See Table E.7 (100 mm = 3.94 in.).

Fig. E.18. Circumferential residual stresses (MPa) in the V-7B simulation repair weld, no correction for sectioning. A full penetration is not shown because the saw cut bisecting the V-8 prolongation cut the V-7B weld repair as it transitioned from the inside to outside contours (see Fig. 2.5), no correction for sectioning (1 MPa = 145 psi; 100 mm = 3.94 in.).

Fig. E.19. Radial residual stresses (MPa) in the V-7B simulation repair weld, no correction for sectioning (1 MPa = 145 psi; 100 mm = 3.94 in.).

Appendix F

V-8 SERIES REPAIR WELDS - HOLE-DRILLING MEASUREMENTS

Appendix F contains the hole-drilling data for the V-8 simulation repair weld. A discussion relating to hole-drilling type measurements is contained in Chapter 4.

Figure F.1 shows the coordinate system used to reference centerpoints of the hole-drilling type rosettes used for through-thickness measurements on the V-8 prolongation (Tables F.1 and F.2). Each measurement location listed in the tables is identified by a number and is shown to scale relative to the weld cavity outlines in Figs. F.2 and F.3. The strains listed

ORNL-DWG 78-4032

Fig. F.1. Coordinate system used to define the hole-drilling residual stress measurement locations about the V-8 simulation repair weld. The r_z and r_θ planes are planes of symmetry for the V-8 simulation repair weld (100 mm = 3.94 in.).

Table F.1. Through-thickness hole-drilling type residual stress data near the V-b simulation repair weld

Location No.	Coordinates ^a			UC1	UC2	UC3	d (mm)	β (deg)	σ_x (MPa)	σ_y (MPa)	σ_z (MPa)	σ_r (MPa)	Correction ^b (MPa)	σ_c (MPa)
	r (mm)	θ (deg)	z (mm)											
1	499	6.6	0	42	-197	-523	1.56	4.1	403	85	401	87	27	428
2	473	6.8	0	63	-23	-349	1.60	15.1	222	-35	204	-18	27	234
3	448	7.0	0	126	14	-154	1.60	14.0	198	-95	181	-78	40	221
4	496	3.7	0	-13	-29	-69	1.53	11.6	-40	-76	-42	-74	118	76
5	469	3.7	0	-113	41	104	1.56	-11.4	-176	-45	-171	-50	130	-41
6	445	3.8	0	-161	62	126	1.64	-14.5	-168	1	-137	-10	143	-14
7	496	-3.7	0	-23	-44	-21	1.60	43.7	-92	-99	-81	-80	109	26
8	469	-3.7	0	-103	31	120	1.60	-5.7	-186	-63	-184	-64	115	-49
9	445	-3.8	0	-221	-26	206	1.68	2.5	-199	12	-199	12	123	-76
10	499	-6.6	0	108	-94	-229	1.60	-5.6	67	-118	66	-116	99	102
11	473	-6.8	0	136	-93	-250	1.64	-5.3	72	-130	70	-128	102	172
12	448	-7.0	0	205	-104	-250	1.76	-9.9	41	-176	35	-172	103	138
16	495	0	0	33	41	-34	1.72	24.9	-54	-118	-61	-107	134	69
17	470	0	0	-100	-6	65	1.56	-4.0	-137	-44	-137	-45	144	7
18	444	0	0	-165	-9	76	1.53	-8.2	-126	21	-123	13	151	28
19	495	8.9	0	154	-97	-541	1.49	7.8	407	-29	400	-71	28	426
20	470	8.9	0	30	-402	-450	1.49	19.9	347	7.2	308	47	17	345
21	444	8.9	0	19	19	-336	1.60	22.5	251	-20	211	20	37	248
22	495	-8.9	0	68	-317	-450	1.56	-13.0	330	9	313	25	101	414
23	470	-8.9	0	28	-152	-184	1.60	-17.5	70	-70	57	-57	102	159
24	444	-8.9	0	19	-208	-136	1.56	-31.3	64	-123	14	-72	103	117
25	432	0	0	-118	-26	43	1.72	-4.1	-91	-13	-90	-13	139	69
26	406	0	0	-384	-176	169	1.60	7.0	-111	196	-107	191	169	62
27	381	0	0	-419	-161	65	1.60	-1.9	12	273	12	273	176	186
28	412	9.3	0	-164	-104	144	1.56	15.7	-202	-2	-138	-16	105	-81
29	387	9.9	0	-248	-107	237	1.60	11.4	-246	37	-235	76	104	-111
30	496	5.9	0	-51	-295	-114	1.56	-40.8	126	-113	24	-11	50	74
31	473	6.0	0	35	27	-228	1.53	21.6	134	-76	106	-40	56	162
32	447	6.2	0	-25	52	-126	1.53	34.2	76	-64	25	-13	65	90
44	500	-8.0	0	88	-233	-341	1.56	-13.2	206	-60	192	-47	100	242
45	486	-8.7	0	109	-65	-250	1.64	0.9	82	-102	82	-102	100	182
46	475	-8.3	0	73	-106	-196	1.56	-9.2	54	-103	50	-104	100	150
47	461	-8.9	0	104	-44	-163	1.56	-3.1	2	-147	2	-147	102	104

^aCoordinates are defined in Fig. F.1.

^bSee Fig. 5.5.

^cSee Fig. 6.7.

Table P.2. Through-thickness hole-drilling type residual stress data remote from the V-8 simulation repair weld

Location No.	Coordinates ^a			$\mu\epsilon_1$	$\mu\epsilon_2$	$\mu\epsilon_3$	d (mm)	β (deg)	σ_x (MPa)	σ_y (MPa)	σ_c (MPa)	σ_r (MPa)
	r (mm)	θ (deg)	z (mm)									
13	495	-94.8	0	-65	-66	-89	1.53	21.3	8	-11	5	-9
14	470	-94.8	0	-55	-72	-85	1.56	-3.8	-4	-20	-4	-20
15	444	-94.8	0	-47	-76	-68	1.68	-30.2	-17	-38	-22	-32
33	448	-12.2	0	-53	-286	-215	1.64	-31.0	166	-11	119	36
34	448	-15.5	0	-65	-164	-101	1.56	-38.7	54	-39	18	-1
35	448	-18.7	0	-58	-236	-221	1.56	-24.9	167	22	138	47
36	448	-22.0	0	3	-129	-135	1.64	-11.2	32	-65	19	-52
37	448	-25.3	0	-3	-112	-125	1.56	-19.1	22	-64	13	-55
38	499	-25.3	0	15	-141	-211	1.68	-10.4	86	-33	82	-29
39	448	-31.8	0	-27	-95	-128	1.68	-9.6	26	-27	24	-26
40	448	-38.4	0	-13	-58	-150	1.56	9.5	46	-35	43	-33
41	448	-44.9	0	-15	-31	-52	1.53	3.8	-59	-81	-59	-81
42	448	-58.0	0	-2	-28	-40	1.56	-10.1	-74	-97	-75	-96

^aCoordinates are defined in Fig. P.1.

ORNL-DWG 78-4033

Fig. F.2. Hole-drilling measurement layout about the V-8 simulation repair weld. See Table F.1 (100 mm = 3.94 in.).

ORNL-DWG 78-4034

Fig. F.3. Hole-drilling measurement layout about the V-8 simulation repair weld. See Table F.2 (100 mm = 3.94 in.).

in the tables are the values that were measured when the drilled hole depth was 1.91 mm (0.075 in.). The measured hole diameter is indicated as d . A value of 78 $\mu\epsilon$ was added to each measured strain value (for reasons discussed in Appendix B) to calculate the angle β and principal stresses σ_x and σ_y by the method described in Chapter 4. The angle β is defined in Fig. 4.4, and the direction 3 shown in that figure is always aligned in the circumferential direction. The stresses σ_c and σ_r are the stress components resolved in the circumferential and radial directions and are shown relative to the weld cavity and seam weld outlines in Figs. F.4, F.5, and F.6. An estimate of a correction for sectioning is discussed in Chapter 5. The column titled "Correction" in Table F.1 lists corrections taken from Fig. 5.5, which when added to σ_c give the estimated circumferential stress, σ , that existed in the prolongation prior to sectioning. These presectioned estimates of the circumferential stresses are plotted in Fig. 6.7.

Fig. F.4. V-8 simulation repair weld circumferential residual stresses (MPa) determined by the hole-drilling method, no correction for sectioning (1 MPa = 145 psi; 100 mm = 3.94 in.).

ORNL-DWG 78-4036

Fig. F.5. V-8 simulation repair weld radial residual stresses (MPa) determined by the hole-drilling method in close proximity to the repair weld, no correction for sectioning (1 MPa = 145 psi; 100 mm = 3.94 in., 1 mm = 0.039 in.).

ORNL-DWG 78-4037

Fig. F.6. V-8 simulation repair weld circumferential residual stresses (MPa) determined by the hole-drilling method remote from the repair weld, no correction for sectioning (1 MPa = 145 psi; 100 mm = 3.94 in.).

Appendix G

DISCUSSION OF THE HOLE-DRILLING TYPE SURFACE RESIDUAL
STRESS MEASUREMENTS TAKEN FROM THE V-8 VESSEL

Appendix C contains a discussion of 42 residual stress measurements made on or near the surface of the V-8 vessel using the hole-drilling method. Twenty-four of those measurements were made at surface locations that were in or near the V-8 half-bead repair weld. The other 18 measurements were made at sites that were located 180° from the repair weld. The purpose of these latter 18 measurements was to allow an assessment of skin effects that might have resulted from the final machining to contour received by the V-8 vessel during its original fabrication and assembly.

The skin effect assessment was made by taking 3 sets of 6 measurements at different depths relative to the exterior surface. The first set of 6 hole-drilling measurements was made on the as received surface of the vessel 180° from the repair weld. A gentle mill operation was used to remove 3 mm (0.115 in.) of surface material at the same locations that had been used for the as received measurements. The second set of hole-drilling measurements was then made on the recessed surface that had resulted from the gentle mill operation. After this second set of measurements, 3 mm (0.115 in.) of material was again removed and the final set of residual stress measurements was made. The gentle milling used for this assessment involved 42 passes with a 63-mm-diam (2.5-in.) carbide-tipped end mill. First, 2 passes of 0.254-mm (0.01-in.) material removal were made. This was followed by 6 passes of 0.127 mm (0.005 in.) and 24 passes of 0.0635 mm (0.0025 in.) respectively. The last 10 passes involved the removal of 0.0254 mm (0.001 in.) of material on each pass. Speed selections for the dry milling operations were 1020 rpm for the tool and 132 cm/min (52 in./min) for the table. The purpose of the gradual removal of material was to minimize residual stresses that would result from the milling process.

Table G.1 contains a list of 6 residual stress measurements (hole-drilling type) made on a stress-free bar [i.e., stress relieved at 746°C (1375°F) for 72 hr and furnace cooled for 24 hr] in a location that had received the same gradual material removal process that was given to the

Table G.1. Hole-drilling type residual stress measurements on a stress free plate that had received the same milling process used to gradually remove surface material from the V-8 vessel

Residual stresses	
σ_m^a [MPa (ksi)]	σ_p^b [MPa (ksi)]
-41 (-6)	-29 (-4)
-80 (-12)	-64 (-9)
-75 (-11)	-40 (-6)
-90 (-13)	-72 (-10)
-74 (-11)	-67 (-10)
-88 (-13)	-78 (-11)

^a Measured parallel to the milling direction.

^b Measured perpendicular to the milling direction.

selected locations on the V-8 vessel. Table G.2 contains a list of 18 residual stress measurements made 180° from the V-8 repair weld. From the data in Table G.1, it would appear that the gradual milling process itself induced some compressive residual stresses which were of the order of 75 MPa (11 ksi). That level of stress is not significantly different from the measurements made at depths of 3 mm (0.115 in.) and 6 mm (0.230 in.) from the surface (Table G.2). These data thus confirm other measurements which have indicated that low residual stresses exist at locations remote from the half-bead repair weld. There is, however, a large difference between the residual stresses measured on the as received V-8 vessel surface and those made at shallow depths and on the stress free bar. These results suggest that very large and very shallow compressive stresses were put into the V-8 vessel when it received its final machining during assembly.

The study of the skin effects described above was performed to evaluate the residual stresses existing in the vessel at points removed from the repair weld and to interpret surface residual stress measurements made

Table G.2. Hole-drilling type residual stress measurements made on the V-8 vessel at various depths relative to the vessel outside surface and at locations 180° from the half-bead repair weld

Circumferential stress ^a	Axial stress
σ_c [MPa (ksi)]	σ_a [MPa (ksi)]
As received V-8 surface	
-275 (-40)	-264 (-38)
-286 (-42)	-265 (-38)
-269 (-39)	-228 (-33)
-261 (-38)	-256 (-37)
-322 (-47)	-303 (-44)
-279 (-40)	-277 (-40)
3 mm (0.115 in.) below the V-8 surface	
-83 (-12)	-40 (-6)
-85 (-12)	-45 (-7)
-64 (-9)	-14 (-2)
-68 (-10)	-56 (-8)
-69 (-10)	-52 (-8)
-91 (-13)	-70 (-10)
6 mm (0.230 in.) below the V-8 surface	
-46 (-7)	9 (1)
-27 (-4)	21 (3)
-16 (-2)	44 (6)
-91 (-13)	-77 (-11)
-93 (-13)	-73 (-11)
-98 (-14)	-72 (-10)

^aThe gentle milling was aligned with the vessel's circumferential direction.

in and near the repair weld. Figure G.1 shows a residual stress measurement being made on the surface of the V-8 vessel. The smoothness of the vessel's surface and the absence of any evidence of the fabrication welds indicate the postassembly machining that was done to remove approximately 12 mm (0.5 in.) of material from the surface of the vessel. The surface

Coordinate system used to determine the location of the weld, the location of symmetry for the repair weld (100 mm) and the location of the weld.

Table G.3. Hole-drilling type residual stress data for
the surface of the V-8 vessel near the repair weld

Location No.	Coordinates ^a				$\mu\epsilon_1$	$\mu\epsilon_2$	$\mu\epsilon_3$	d (mm)	β	σ_x (MPa)	σ_y (MPa)	σ_c (MPa)	σ_r (MPa)
	r (mm)	θ (deg)	z (mm)										
1	496	0	25		-46	33	-59	1.56	42.8	9	-86	-35	-42
2	496	2.9	25		-20	-10	-19	1.56	-43.5	-93	-82	-88	-87
3	496	5.9	25		-259	-122	-128	1.56	-23.8	119	227	138	210
4	496	8.8	25		111	-209	-425	1.56	-5.5	270	-33	268	-31
5	496	-2.9	25		-14	-91	-36	1.56	-40.3	-42	-117	-73	-86
6	496	-5.9	25		-130	-108	-5	1.53	16.5	-60	27	-53	20
7	496	-8.8	25		98	81	-296	1.60	21.2	174	-114	136	-76
8	496	-11.7	25		109	-62	-310	1.53	5.2	160	-89	158	-87
9	496	-14.7	25		29	-74	-323	1.56	11.3	209	-3	201	6
10	496	-23.5	25		228	128	-49	1.56	7.8	-171	-331	-174	-328
11	496	11.7	25		196	-151	-383	1.60	-5.6	181	-137	178	-134
12	496	14.7	25		153	-80	-250	1.53	-4.0	79	-162	78	-161
13	496	23.5	25		252	84	-28	1.49	-5.7	-226	-398	-227	-397
14	496	0	51		72	-61	-172	1.60	-2.6	26	-106	26	-106
15	496	0	76		-10	-51	-65	1.60	-13.1	-42	-73	-43	-73
16	496	0	102		-78	-53	-146	1.60	30.0	86	12	67	31
17	496	0	127		35	24	-92	1.60	19.8	-27	-116	-37	-105
18	496	0	152		-42	12	-129	1.49	33.0	77	-52	39	-14
19	496	0	203		-127	5	234	1.56	7.5	-301	-93	-298	-97
20	496	0	0		-27	10	-59	1.60	36.6	-20	-80	-42	-59
21	496	0	254		30	50	147	1.56	16.7	-289	-211	-282	-217
22	496	-17.6	25		141	-54	-172	1.49	-6.9	-5	-200	-8	-197
23	496	-45	25		180	113	26	1.56	3.7	-228	-315	-228	-314
24	496	-90	25		78	80	64	1.56	26.1	-217	-230	-219	-227

^aCoordinates are defined in Fig. G.2.

ORNL-DWG 78-4039

Fig. G.3. Hole-drilling measurement layout about the V-8 repair weld. See Table G.3 (100 mm = 3.94 in.).

Fig. G.4. Surface circumferential residual stresses (MPa) about the V-8 repair weld (1 MPa = 145 psi; 100 mm = 3.94 in.).

Fig. G.5. Surface axial residual stresses (MPa) about the V-8 repair weld (1 MPa = 145 psi; 100 mm = 3.94 in.).

could be expected when the compressive stress induced by the skin effect is considered. There is the additional complication however, that the surface near the repair weld was ground after the weld was completed. Grinding which is not an intentional gentle grind can induce yet another skin effect, which generally creates a tensile stress in material close to the surface. In the case of the V-8 vessel the surface grind that was used to clean up the weld region would tend to cancel the machining skin effect discussed previously in this section. The skin effects thus have the effect of obscuring the true surface residual stress, and primary emphasis should be placed on weldable gage data and through-thickness residual stress measurements which were made after the surface had been prepared according to a defined and controlled procedure.