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TASK B REPORT

Controlled Plasticity Burnishing (CPB) for Developing a Very Deep Layer of Compressive Residual Stresses In Rectangular Specimens of Alloy 22 for Yucca Mountain Nuclear Waste Package Closure Weld

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CONTROLLED PLASTICITY BURNISHING (CPB) FOR DEVELOPING A VERY DEEP LAYER OF COMPRESSIVE RESIDUAL STRESSES IN RECTANGULAR SPECIMENS OF ALLOY 22 FOR YUCCA MOUNTAIN NUCLEAR WASTE PACKAGE CLOSURE WELD

-TASK B REPORT-

Preface

The format of this report will be to list the task from the quote S4901R and the sub-heading will summarize the work preformed as required.

Objective

Successful demonstration of the Low Plasticity Burnishing (LPB) process for controlled plasticity and very deep compression applications have created a new process termed Controlled Plasticity Burnishing (CPB). Surface Enhancement Technologies, LLC (SET) has completed a preliminary effort in determining that CPB can offer an improved method to apply very deep compressive residual stresses to Alloy 22 for use in a containment vessel.

SET Quote No. S4901R outlines the steps required to demonstrate a specific CPB process, which achieves the very deep layer residual compressive stress desired for the Yucca Mountain nuclear waste container cylinder and demonstrates the process on rectangular Alloy 22 specimens (Figure 3). The task is to achieve maximum depth of compression in Alloy 22 plate of thickness 1.0 in (25mm).

Task B2.6 - Technical Final Report

There are three goals to TASK B: Optimized Controlled Plasticity Burnishing:

1. Optimize the CPB processing parameters necessary to produce the deep layer residual compression in Alloy 22 material without causing undesired tensile stresses in other parts of the test specimen.

2. Establish CPB process depth and magnitude of compressive residual stress that can be produced. The target is to achieve greater than 8mm depth of compression in Alloy 22 plate.

3. Recommend closure weld configurations, which are suitable for CPB processing to achieve 8mm depth of compression (or greater).

This report summarizes the work performed.

Results

B1.1 *Definition of the Disposal Container Application*

The material properties, service environment and experience, and other appropriate parameters defining the application were determined initially to provide a basis for understanding the application and for designing the CPB process and tooling. Manufacturing and performance objectives were incorporated at the beginning of the process.

B1.1.1 *Material properties*

The following applicable material properties for Alloy 22 was supplied by Special Metals Corporation:

The Modulus of Elasticity	= 30.3×10^6 psi
Poisson Ratio	= .290
Yield Strength	= 47.9 ksi
UTS	= 106.3 ksi

The source for the Stress Corrosion Cracking initiation point was obtained from a report titled "Stress Corrosion Cracking and Stress Mitigation" provided by Gerald Gordan. SCC initiates at 80% of the Yield Strength of the material, The SCC is a tensile value of 38.32 ksi.

B1.1.2 *Service environment*

The service environment is a radioactive environment. The equipment will need to be designed to guard against this radiation by good accepted practice. There

is a middle, or intermediate, lid on the container before the CPB equipment is in place. This lid will reduce the radiation values but there is not a conscience as to the radiation level that the equipment would be subjected to, although it is clear that it is fairly high. The temperature of the container lid will be between 100°C and 200°C.

B1.1.3 *Container Weld Configuration*

The initial container weld configuration provided is shown in figure 1 and the current configuration is shown in figure 2.

B1.1.4 *CPB Specimen*

The configuration of the specimen for this project is shown in Figure 3.

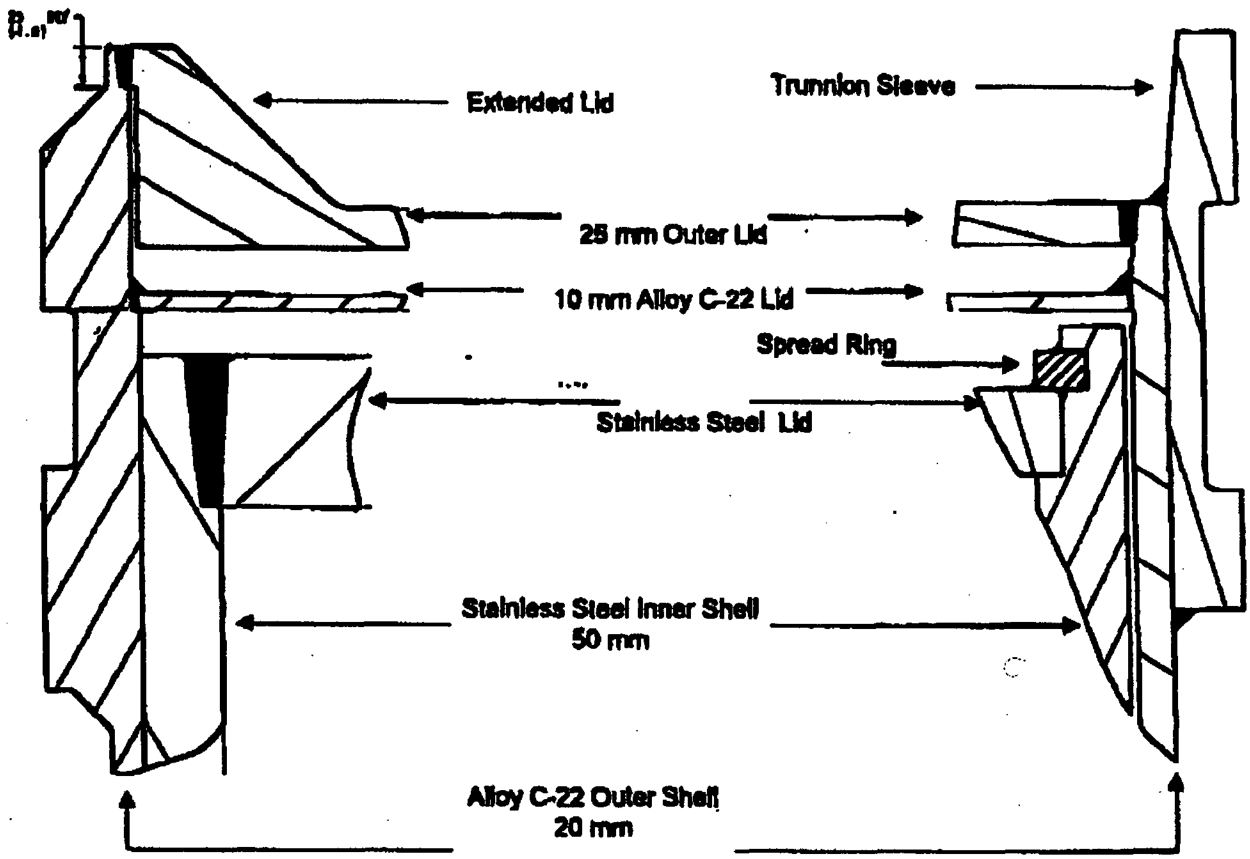

FIGURE 1: Initial Container Weld Configuration

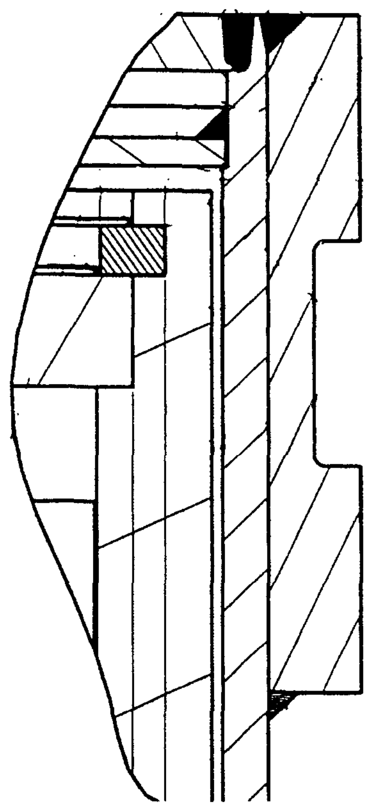

FIGURE 2: Current Container Weld Configuration

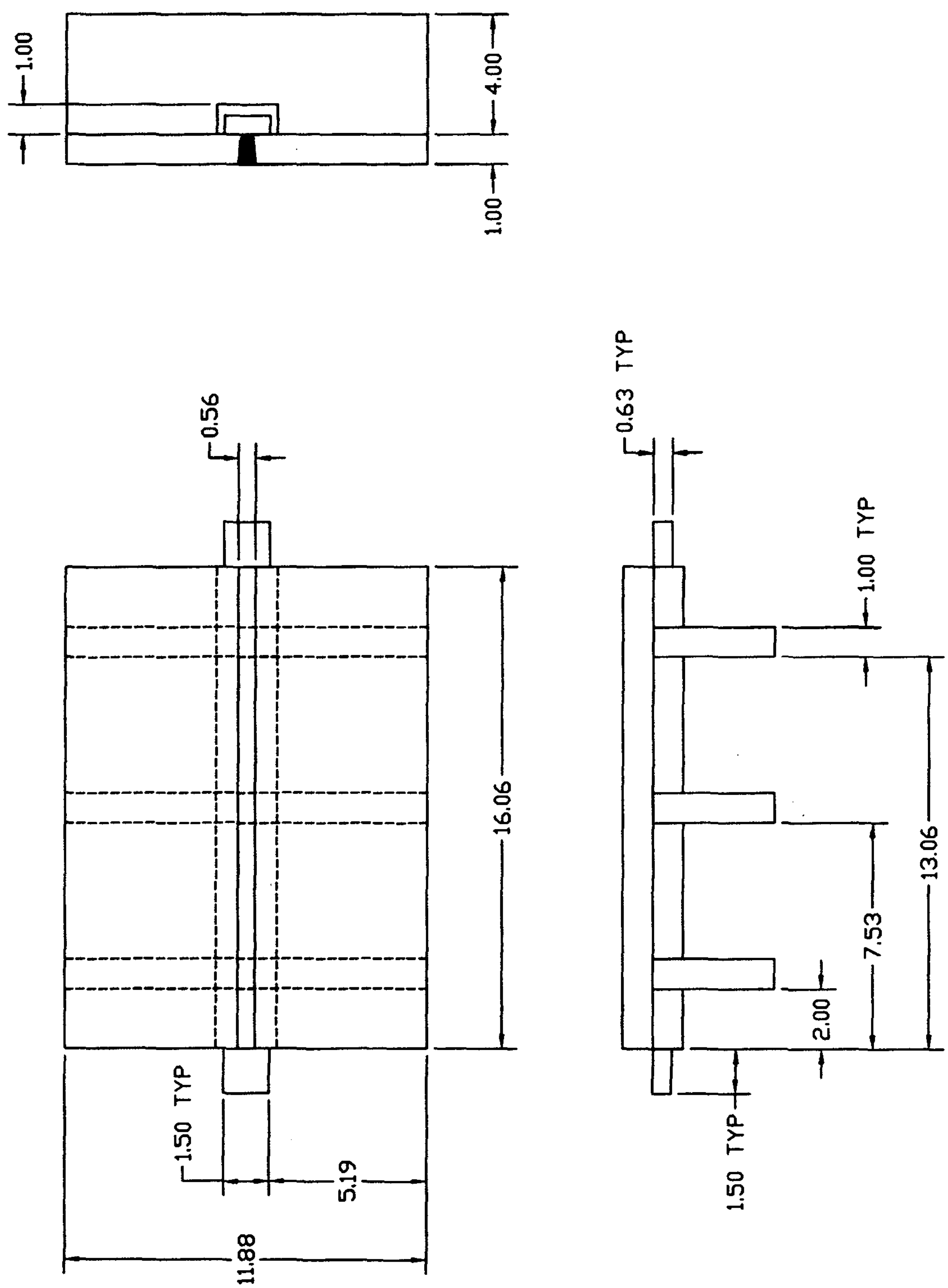

Figure 3: Specimen Configuration

B1.2 *Applied Stress State*

The applied service stresses were estimated to the extent possible. Available design stress analyses and/or mechanics data was reviewed to identify the stress state at the area of interest.

B1.2.1 *Applied Service Stresses*

The weld mock-up does not have any service loads or external loads.

B1.3 *Existing Residual Stress State*

Significant existing residual stress distributions from prior processing and welding existed in the specimens provided to SET. The residual stresses were measured to determine the state of stress as initially manufactured to establish a baseline. The residual stress measurements were performed by Lambda Research utilizing X-ray diffraction and ring-core measurements.

B1.3.1 *Existing Residual Stress State*

The Existing residual stress state measurements have been completed by Lambda Research and provided to SET. Figures 4 thru 6 are the x-ray and ring core residual stress results on the 1-inch As-Welded plate. The results are what would be expected in a fusion weld. The highest tensile stresses are adjacent to the weld. The ring-core measurements shown in Figure 6, taken in the weld, also show tensile stresses with the maximum stress in the parallel direction.

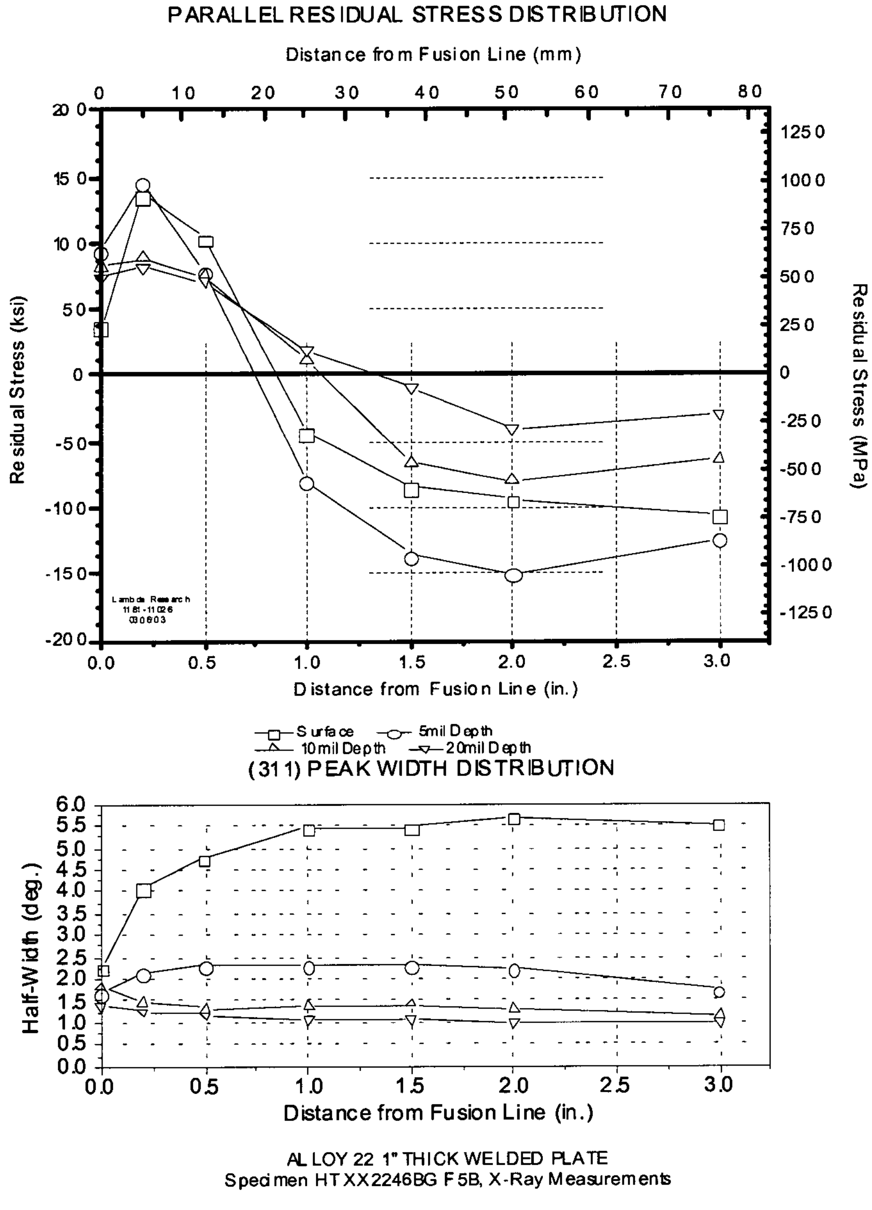

Figure 4: **Alloy 22, 1" Thick As-Welded Plate X-Ray Measurements**

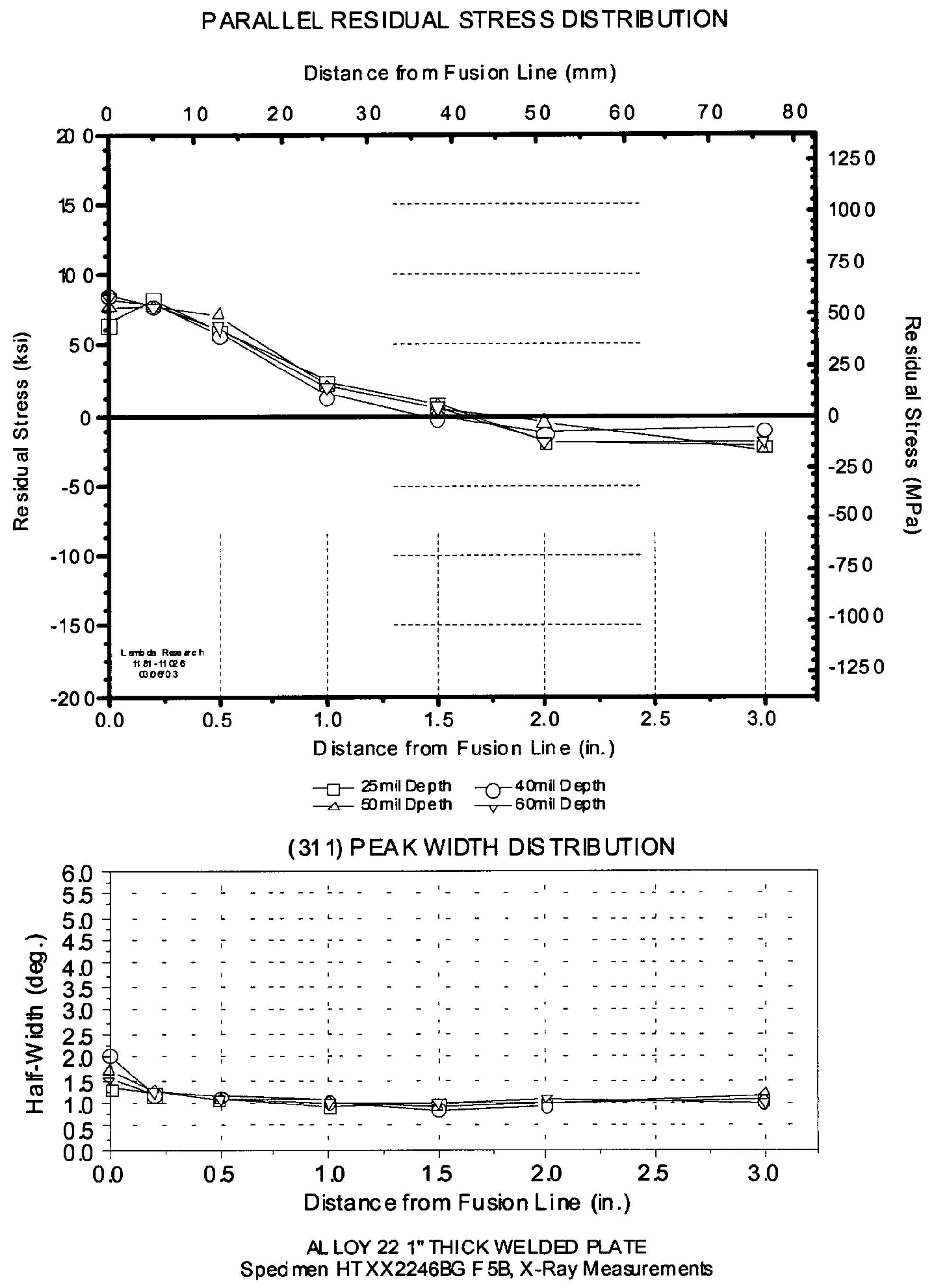

Figure 5: Alloy 22, 1" Thick As-Welded Plate X-Ray Measurements

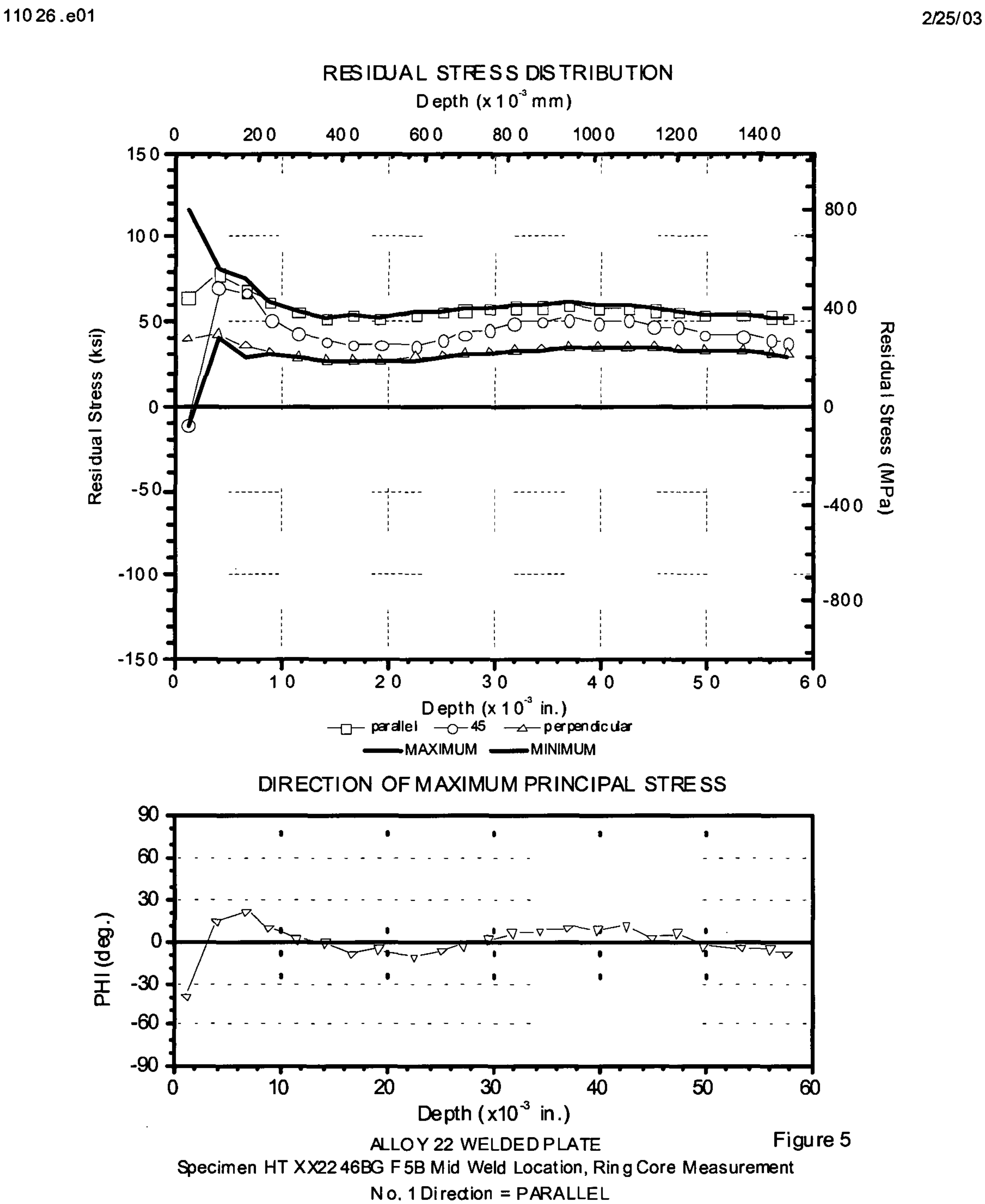

Figure 6: Alloy 22, 1" As-Welded Plate, Ring Core Measurement

B1.4 *Combined Stress State*

The estimated applied and measured residual stress distributions were combined to determine the total stress present in service.

B1.4.1 *Combined Stress State*

The combined stress state would be the same as in section B1.3 (existing residual stress state).

B1.5 CPB Machine

A CPB machine was designed to produce a deep layer of compressive residual stress. A compatible control system and high compliance machine base was integrated into the machine design to minimize design time and costs.

B1.5.1 *Special CPB Machine*

Several concepts were reviewed for designing and building a special machine. A special purpose machine base and a compatible control system have been identified and the design integration completed.

A Supplier Deviation Disposition Request (SDDR) was prepared to record the decision to rent machine time to burnish the specimens and to purchase the machine at a later date.

B1.5.2 *Machine time Supplier*

All of the machine providers that we have found were concerned about the impact that the high loading would have on their machines. For this reason we were able to find only one company that was willing to subject their machine to the required loads. The machine used was a Cincinnati U5 machining center like the one shown in Figure 7.

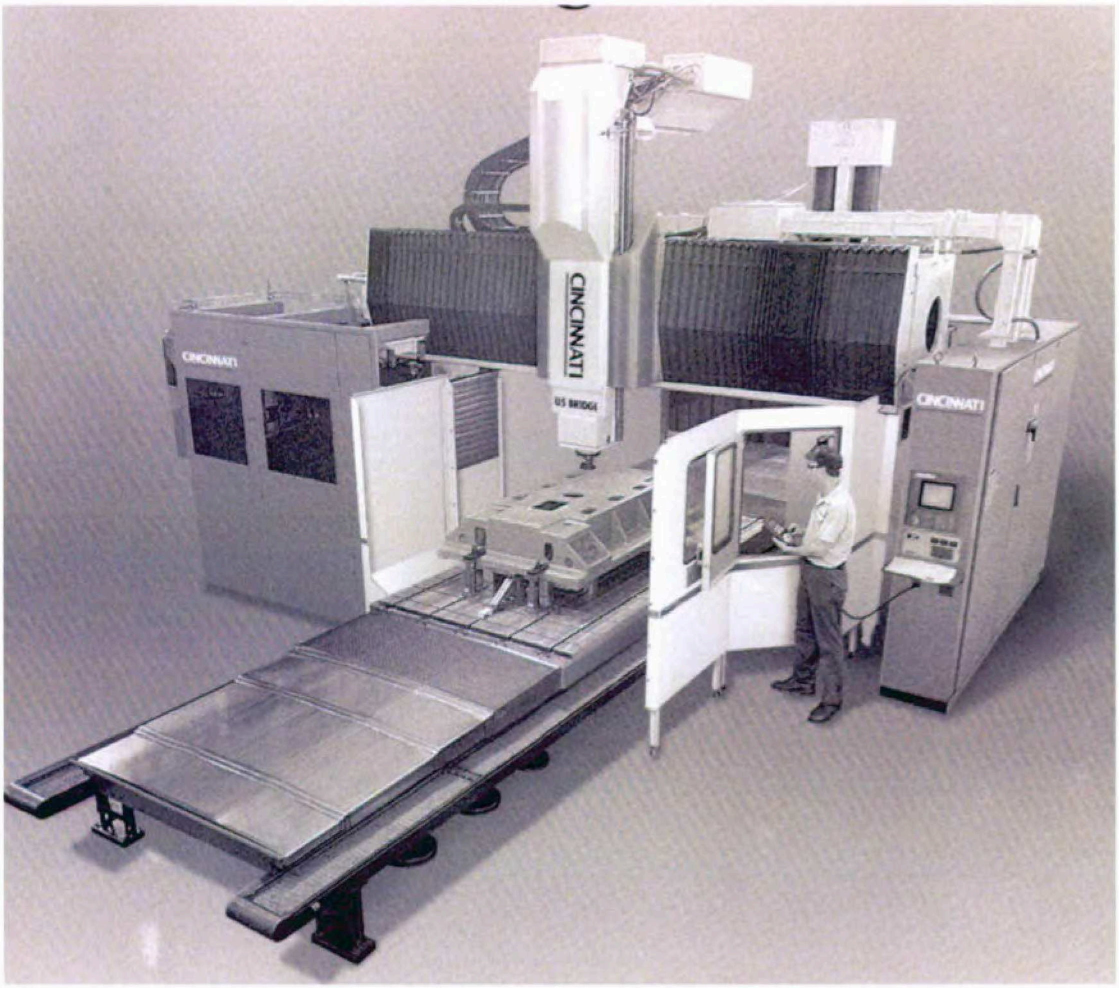

Figure 7: Cincinnati U5 Machining Center

B1.5.3 *Retrofit existing CNC Machine for CPB use*

To complete the task and to be prepared for additional weld/lid configuration tasks expected in the future, several existing large capacity milling machines have been investigated. They include:

1) Monarch VMC 75
2) Cincinnati Milacron 15VC1000
3) Omni Mill
4) Hydratel 6246

Several machine sales companies were utilized. The decision was to retrofit an older CNC machining center, since the older machines were built for strength and stability while the newer machines are built for speed. SET has assessed the needed modifications required to make the machine suitable for applying the very

large normal loads required for achieving the CPB deep compressive residual stress on the waste package. Of the machines identified above, the Monarch machine has been selected. It has a modern control capable of interfacing with our CPB control and enough rigidity in the frame to support the necessary loading.

B1.6 *Initial Performance Evaluation*

Residual stress distributions achieved were documented.

B1.6.1 *Initial Stress Corrosion Fatigue*

This task was clarified during a Design Review meeting held on February 13, 2003 between SET and Bechtel SAIC, LLC. It was decided that SET would propose corrosion studies prior to September 2003 for potential funding in YMP FY04. Initial evaluations of the CPB process for stress corrosion was based upon achieving a stress state below the threshold value for which stress corrosion is possible for Alloy 22 in the environment expected. Based upon publish data (reference section B1.1.1) the threshold stress must stay below 80% of the Yield Strength (38.32 ksi). Results from task B2.5 of actual CPB processed specimen indicates compressive residual stress measured have achieved a stress state below the threshold for corrosion cracking.

B1.7 *Achievable Performance Improvement Evaluation*

This evaluation combined the manufacturing and performance objectives identified in Activities B1.1 through B1.3 to determine CPB effectiveness as a surface enhancement method. It is generally believed that compressive stresses will mitigate stress corrosion behavior of Alloy 22 plate.

B1.7.1 *Performance Evaluation*

A key-manufacturing objective was to verify that the CPB process of developing very deep compressive residual stress is readily adaptable to standard machine tool devices. Successful demonstration of this adaptability in Task 2 confirmed that the CPB process represents a low risk, low cost stress mitigation technology.

The specialized CPB tool (Figure 15) was designed to be compatible with a standard machine tool holder. The tool barrel is mounted directly into a standard CAT 40 machine tool holder. The CPB control interfaces with the machine tool control via a standard RS 232 serial interface connection. The tool pressure cylinder is charged by standard 120 psi shop air and the tool burnishing ball is supported in the tool seat by a fluid bearing charged by a standard water based machine tool cutting fluid. The hydraulic system is assembled from standard industrial grade components.

The demonstration of CPB as a machine tool process was achieved by utilizing a standard Cincinnati Machine U5 milling machine center (Figure 14). The process of connecting the CPB electronic control and hydraulic control was accomplished in less than 60 minutes. The specialized CPB tooling was inserted into the machine tool holder and the charge air pressure and hydraulic lines were connected in less than 30 minutes. The CPB demonstration runs on the Cincinnati Machine U5 were conducted at constant feed rate, normal loads, and various feeds to verify ease of controllability while developing very deep compressive residual stresses and a fine surface finish.

The CPB process is ideally suited for implementation into the closure cell concepts as currently being proposed for the Yucca Mountain Project. The load necessary to produce the required compressive stresses can be accurately and repeatably placed. This load can be specifically tailored and designed to best-offset applied tensile stresses. The CPB application load can be varied and precisely controlled in the CNC software to smoothly blend into untreated areas, avoiding sharp residual stress boundaries. CPB can be performed as rapidly as any conventional machine tool can position the tool. Additionally, the CPB surface finish has improved the original surface finish offering improved NDI detection for weld quality assurance in a remote facility. Table 1 represents a parametric study on feed. We optimized finish verses cycle time and selected the 0.050 inch feed. Table 2 shows the result on the welded mock-up for the selected 0.050 inch feed. Table 1 and Table 2 summarizes the CPB manufacturing process characteristics demonstrated on the U5 Cincinnati Machine in support of Task B1.7.1

Table 1: Parametric Feed Study

FEED (inch)	SPEED (IPM)	SURFACE FINISH WITH PATH (Ra) (10^{-6}in)	SURFACE FINISH CROSS PATH (Ra) (10^{-6}in)
0.025	150	18.3	12.1
0.050	150	17.2	30.9
0.100	150	15.2	186.2

Table 2: 0.050" Feed Result on Welded Mock-Up

	Before CPB (Ra) (10^{-6}in)	After CPB With path (Ra) (10^{-6}in)	After CPB Cross path (Ra) (10^{-6}in)
Near Weld	75	8.8	23.8
At Weld	183.44	15.6	55.33
Stock plate	194.4	8.9	18.5

A major goal of the optimization study was to design a set of CPB parameters that would result in very deep compressive residual stress while achieving the stress mitigation process cycle time target. The diameter of the weld of the container provided was 63.2 inches. This provided a linear weld length of approximately 198.5 inches. With the feed of 0.05 inch and a 2.5 inch patch on both sides of the weld this would require 132.3 minutes or 2.2 hours to mitigate the weld area using the CPB method (see Table 3). Thus, the results of the optimization study have achieved the greater than 6mm deep compression while demonstrating process speeds which achieve the stress mitigation process cycle time target.

Table 3: CPB Process Time

WELD diameter from BSC Sketch Number SK-0237	INCH	63.2
LINEAR WELD LENGTH (calculated)	INCH	198.5487
CPB SPEED	(IPM)	150
FEED	INCH	0.05
WIDTH OF PATH	INCH	5
# OF PASSES		1
TIME	HOUR	2.206096

A key manufacturing and performance objective is to evaluate the cost of the stress mitigation device. As a result of the demonstration of CPB on the Cincinnati Machine U5 and the cost of the CPB control and hydraulic system, the estimated cost of a CPB device suitable for implementation as a stress mitigation system on the Waste Package can be based upon cost of developing and manufacturing of a machine tool. Table 4 represents the CPB system device (see Figure 28) development cost estimate based upon typical machine tool development practice. The CPB system unit costs (Table 5) are also estimated based upon standard machine tool product costing practices. (CPB system device development and unit costs estimated by former Cincinnati Machine Product and Cost Manager acting as a consultant to SET).

Table 4

Controlled Plasticity Burnishing

Prototype I Machine

Development Cost Overview

($ are rounded to the next highest dollar and include a 10% fixed fee)

Task	Senior Engineer		Engineer		Technician		Purchased Materials	Travel Expenses
	Hours	*$*	*Hours*	*$*	*Hours*	*$*		
Preliminary Prototype Design Studies	33	$5,793	312	$42,282				
CPB Processing Development using Special Purpose Machine	3	$446	96	$13,010	96	$8,549		
Prototype Design Schedule/Rev	171	$30,481	136	$18,431				
Detailed Prototype Design			17,000	$2,303,840				
Prototype Module Build and Test			600	$81,312		$53,430	$255,000	
Prototype Build			445	$60,306		$39,627	$255,000	
Travel Expense								$57,000
Prototype Test	20	$3,565	46	$6,234	46	$4,096		
Prototype CPB Process Evaluation			66	$8,944	66	$5,877	$70,000	
Sub-Totals	**226**	**$40,285**	**18701**	**$2,534,360**	**1,253**	**$111,580**	**$580,000**	**$57,000**
GRAND-Totals								***$3,323,224***

Table 5

Controlled Plasticity Burnishing

Prototype I Machine

Unit Cost Overview

Task	Assembly *Hours*	Assembly *$*	Purchased Materials	Totals
CBP Tooling	150	7500	16,000	
CBP Control	50	2500	50,000	
Device Base/Adaptor Plate/Clamp Ring	225	11250	110,000	
Carrier Servo Drive	325	16250	30,000	
Slide Servo Drive	175	8750	22,000	
Carrier	75	3750	10,000	
Drive and Stationary Gears	50	2500	2,000	
TEST, Package, and Ship	25	1250	1,000	
Hydraulic Control	25	1250	40,000	
Sub-Totals	**1100**	**$55,000**	**$281,000**	
GRAND-Totals				***$336,000***

B2 *Component CPB Process Design and Implementation*

CPB was successful in causing compressive stresses to a depth sufficient to prevent stress corrosion cracking; the goal of this activity was to define tooling and process parameters for use by BSC as preliminary input in the design effort.

B2.1 *Estimate Suitable Residual Stress Field*

The development of compression in a component requires tension elsewhere in the body to maintain static equilibrium. Therefore, it is important to identify the residual stress state and minimize distortions by proper positioning of the location and magnitude of both tensile and compressive stresses. The purpose of this scoping and bounding task is to consider the geometry of the disposal container weld region, the applied and residual stresses, and to estimate the residual stress field that would be produced.

B2.1.1 *FEA of Current Waste Container*

An estimate of a suitable residual stress field for the proposed disposal container geometry was made utilizing ANSYS FEA Software. ANSYS is the software tool used for predictive FEA modeling. ANSYS release 7.0 UP20021010 was utilized for this analysis. The following is a Finite Element Analysis report by Mr. Doug Young:

"The objective of this analysis was to determine the reacting tension after the application of a suitable CPB (Controlled Plasticity Burnishing) treatment of the waste container closure weld. Subsequent reviews at SET questioned the model approximation of the Upper Trunnion Collar Sleeve and Outer Shell as an integral unit. The model was updated with those two components connected only at the welds and showed similar results. More importantly the deflections show the two components will contact radially, which justifies the approximation as an integral assembly. This report documents the effort.

A proposed geometry documented in BSC Sketch Number SK-0237 " 44-BWR Waste Package for License Application" was created and an FEA (Finite Element Analysis) model was developed to evaluate CPB configurations. A proposed CPB treatment was simulated by inputting both tangential and radial stress that exceeds measured values spanning across the weld and 1.5 inches on both sides of the fusion line. The depth and magnitude was as measured in weld plate specimen HTXX2246BG F4B. Due to the length of the container results are shown in an area near the Upper Trunnion Collar Sleeve and the closure weld between the Outer Shell and Extended Outer Lid. The resulting stresses (in psi) are shown in" Figures 8 and 9." The radial stress (SX) is shown in" Figure 8" and the tangential or hoop stress (SZ) is shown in" Figure 9." Note that the maximum reacting tension is well below the surface (0.400 inch).

The FEA was updated to remove the connection between the welds joining the Upper Trunnion Collar Sleeve and Outer Shell. The radial deflections (inches) are shown in Figure 10. Note that the Outer Shell deflects radially outward and the Upper Trunnion Collar Sleeve deforms inward radially. Thus the two components will be in contact and the assumption of an integral structure is valid.

The compressive residual stress from CPB does not produce excessive reacting tension anywhere near an exposed surface.

This analysis demonstrated the feasibility of applying a deep residual compressive stress in the container closure weld area without inducing unwanted tension elsewhere. Based on the results of this analysis the proposed CPB treatment for this geometry should be accepted. Updates to the container design may require updates to this analysis. Additionally measurements and analysis of the final geometry and CPB application should be compared for correlation.

The geometry representing the container (per BSC Sketch Number SK-0237 " 44-BWR Waste Package for License Application") was created and is shown in" Figure 9. "Note that only three components from the sketch are required for this analysis. The Upper Trunnion Collar Sleeve and the Outer Shell are welded to make an integral unit, and that weld is stress relieved. The final closure weld joins the Extended Outer Lid to the Outer Shell/Collar assembly. Symmetry was assumed at half the outer shell length so the Lower Trunnion Collar Sleeve was not modeled. A detail of the geometry outline is shown in" Figure 9." The model was meshed using parabolic axisymmetric elements. The mesh in the region of interest is shown in" Figure 11." Since there are no loads to produce stress concentration effects at sharp corners, details such as fillet and chamfers were not required in the model.

Measured residual stresses from HT XX2246BG F5B (figures 8 through 13) showed the closure weld results in tensile stresses almost 1.5 inches from the fusion line. Based on those results a proposed CPB treatment would extend 1.5 inches on both sides of the weld. Measured residual stresses from the weld plate specimen (figure 11) HTXX2246BG F4B showed resulting compression that mitigates the weld induced tension. Since the FEA mesh was not as dense as those measurements an approximate depth profile was input to the FEA model. Table 6 shows the depth and corresponding compressive stress input to the model and is equal or greater compression than measured. Therefore the model should over-estimate any reacting tension. Results shown in figures" 8 and 9" show that the reacting tension is well below the surface (0.400 inch). These results are consistent with analyses and measurements of similar applications."

Table 6: Stress verses Depth of Proposed CPB Treatment	
Depth (inches)	Stress (ksi) (radial and tangential direction)
0.05	-85
0.15	-50
0.25	-40

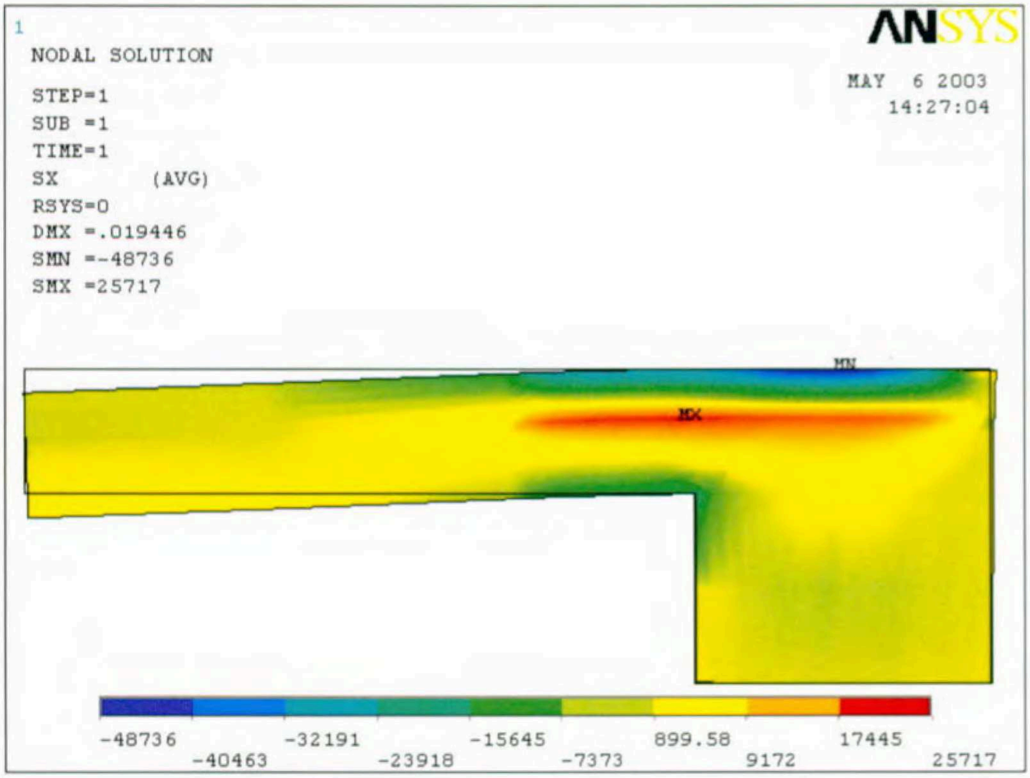

Figure 8: Radial Stresses (PSI) from CPB weld Treatment

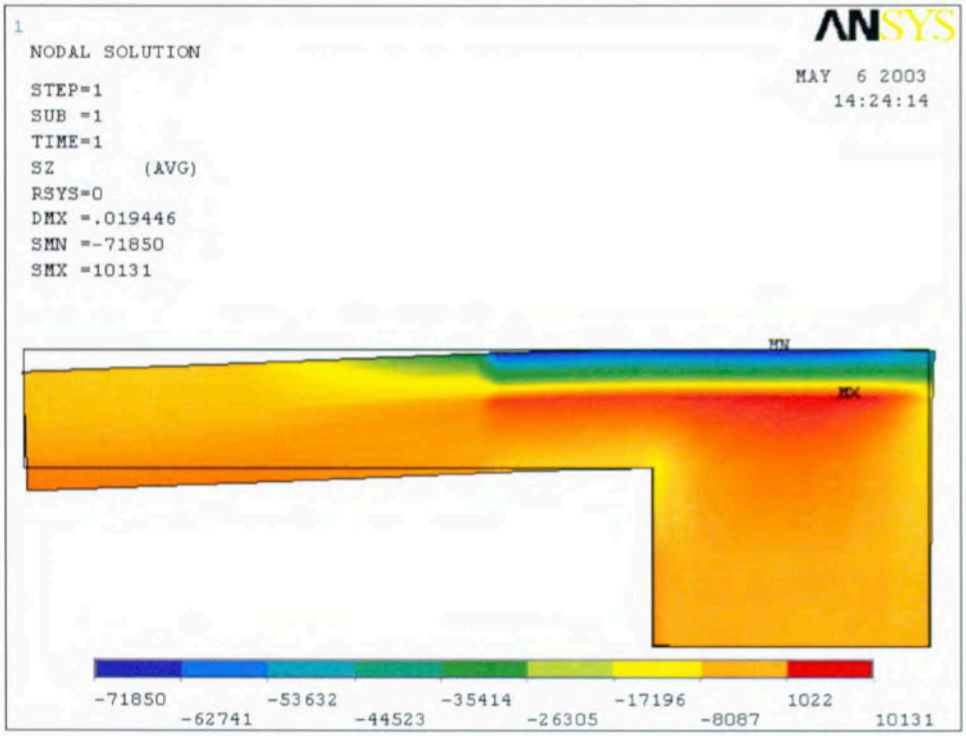

Figure 9: Tangential Stresses (PSI) from CPB Weld Treatment

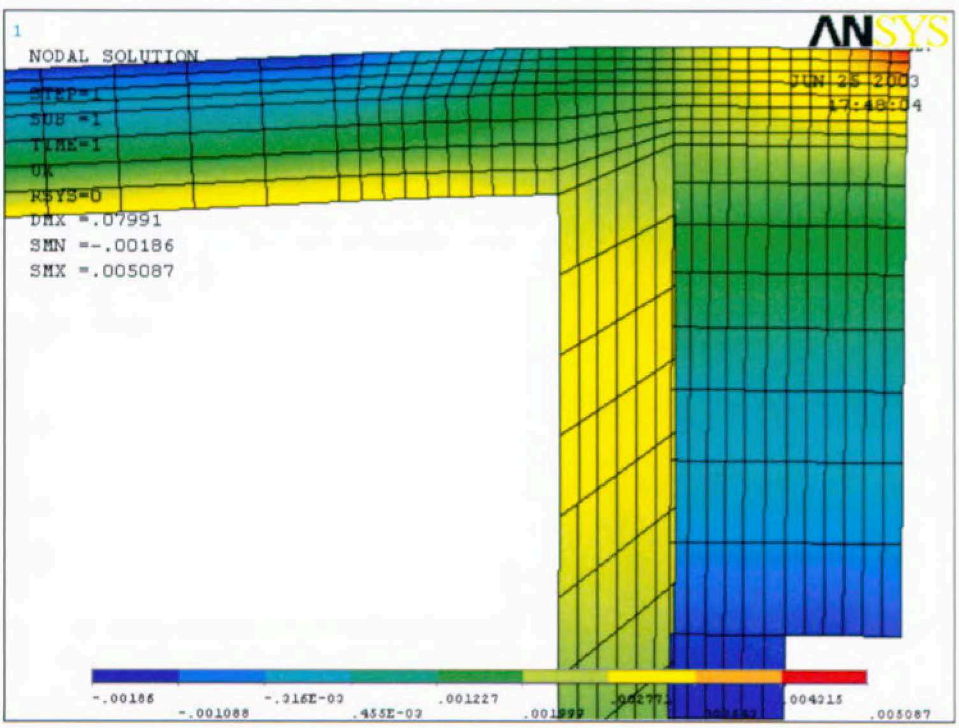

Figure 10: Radial Deflections
Note: Legibility not required

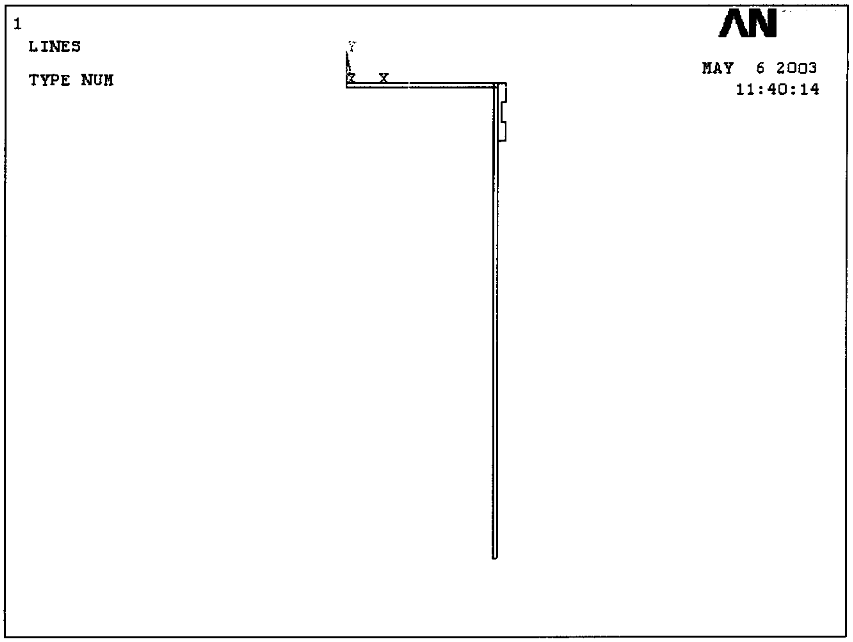

Figure 11: Basic Overall Geometry

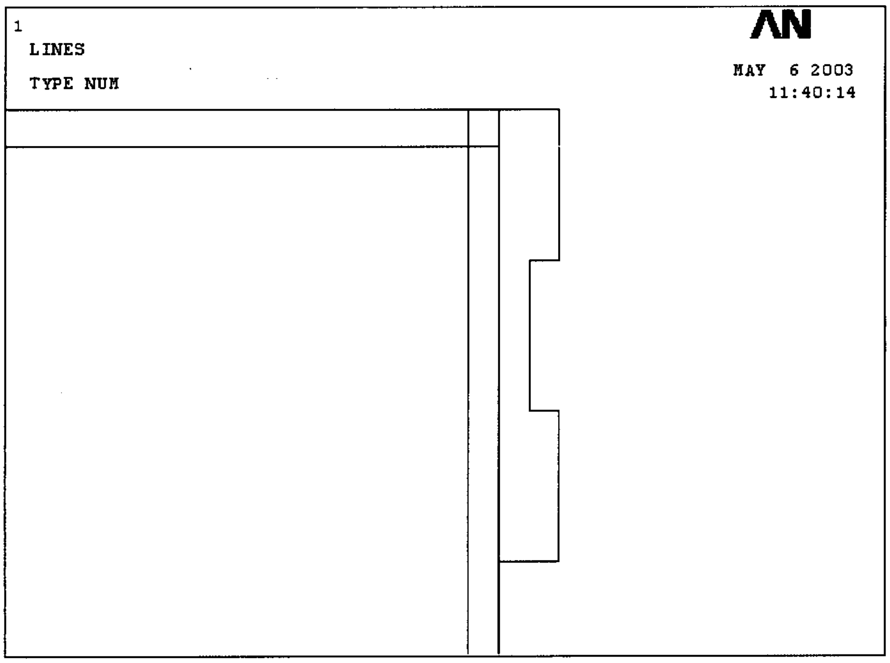

Figure 12: Geometry Near Final Closure Weld

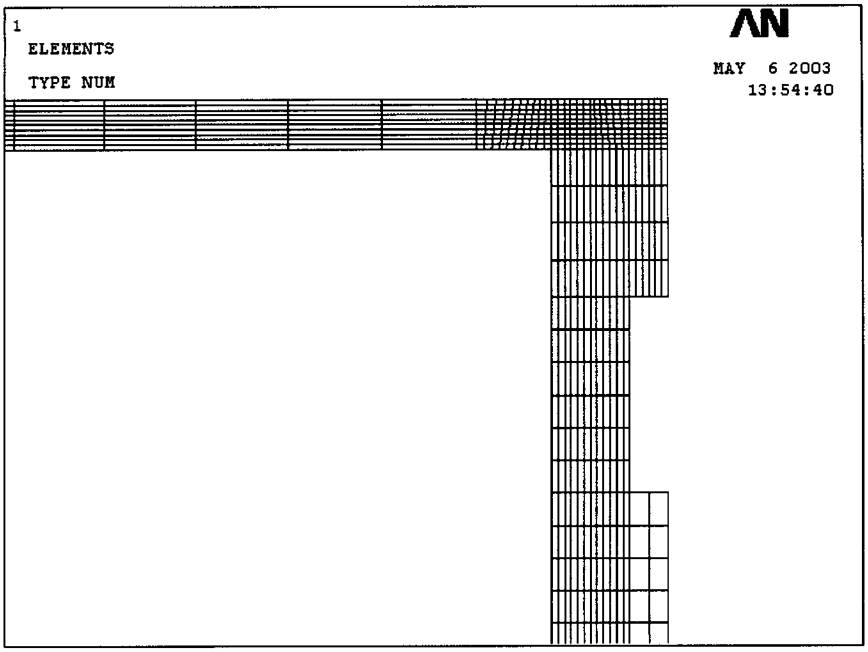

Figure 13: FEA Mesh Near Final Closure Weld

B2.2 *Tooling (General and/or Specific) Design*

General and/or specific CPB tooling was required to burnish the closure weld regions of the Disposal Container. Tooling and fixturing was designed to burnish the contact areas for the specimens provided to SET (Figure 3).

SET designs general and specific CPB tooling for use in many applications

B2.2.1 *Tool*

The fixturing used to process the weld mock-up samples was standard machining clamps. The end effecter tool used to apply the compressive stress is shown in Figures 14 and 15.

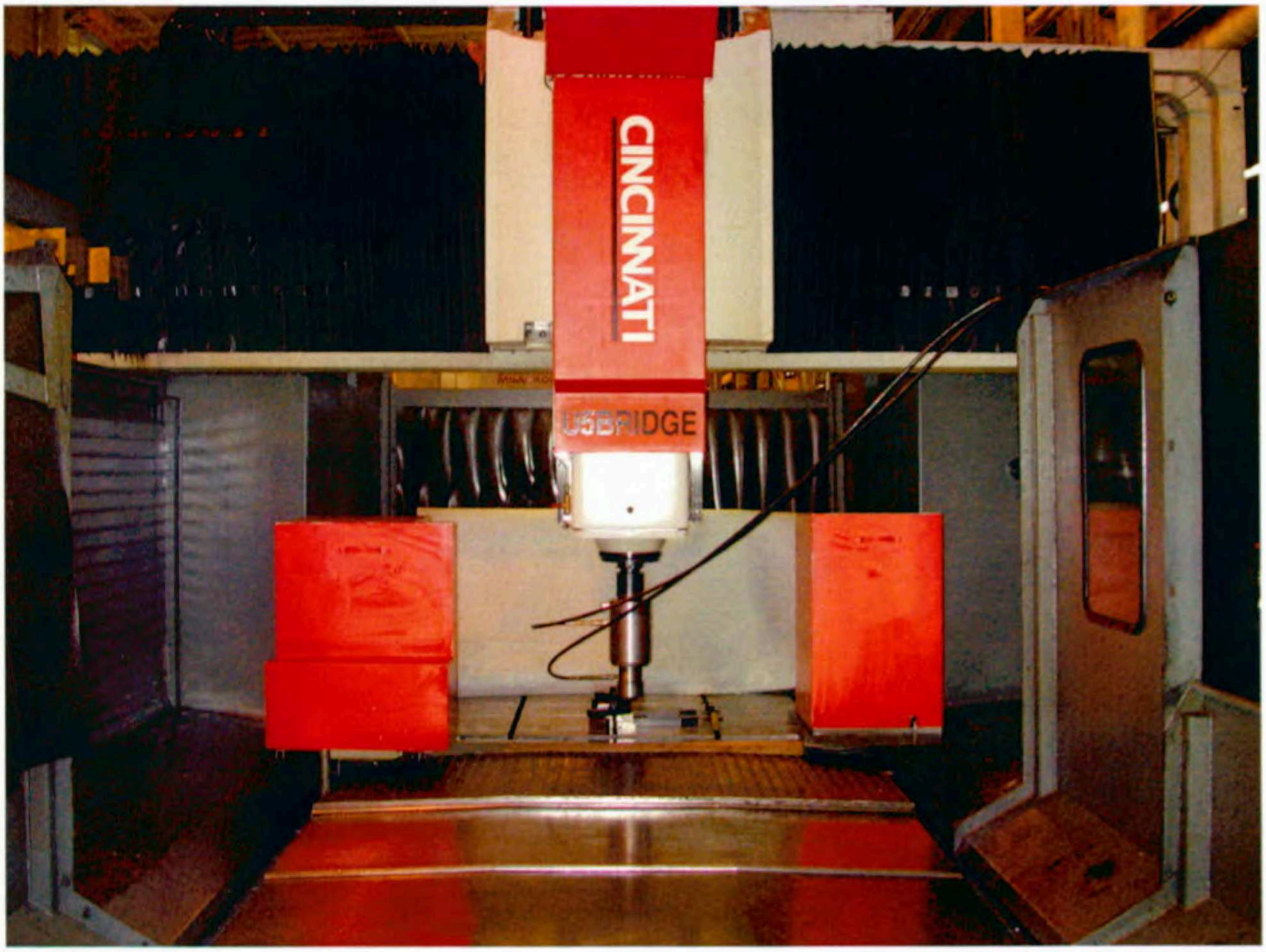

Figure 14: Cincinnati Machine U5 Milling Machine Center

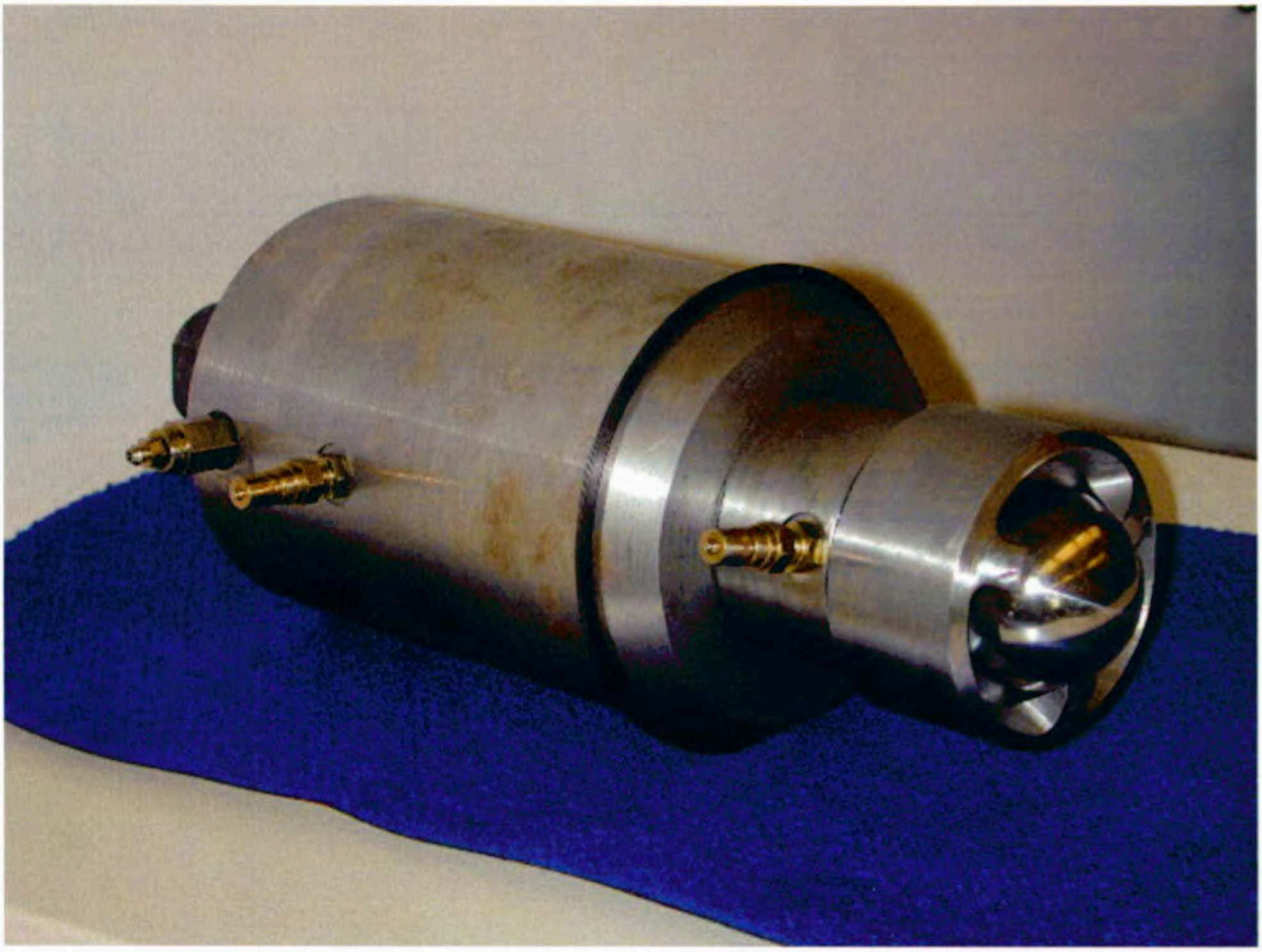

Figure 15: Specialized CPB Tool

B2.3 *CPB Procedure and Tool Control Code to Achieve Suitable Residual Stress Field*

A specific CPB processing sequence and procedure including the positioning of the component and tool, spacing of passes, and pressure variation to achieve feathering necessary to create the suitable residual stress distribution was developed. The target was to achieve greater than 8mm depth of compression. A computer numerical control (CNC) code generated the controlling tool position, component orientation, and pressure to provide a practical manufacturing procedure for the Disposal Container.

B2.3.1 *Tool Control*

The CPB process parameters that were used for the weld mock-up samples are as follows:

Table 7: CPB Process Parameters

	Effective Ball surface area (inch^2)	Effective load/surface area (KSI)	Number of CNC passes	Effective Diameter (inch)
Large Ball	0.0154	779.53	1	0.14
Small Ball	0.00067	820.89	1	0.0294

The initial pass with the large diameter ball will create the required compressive stress to the greater depths. The second pass with the smaller ball will increase the compressive stress near the surface.

B2.4 *Weld Geometry Trade-Off Studies*

Specimens were provided by BSC (see Figure 3). The specimen has been designed to simulate the closure weld region of the Disposal Container. It does not exactly duplicate the configuration of the closure weld region. It is intended to provide a ready test specimen to apply to suitable CNC CPB process. The specimens had residual stress measurements performed to establish a baseline residual stress state by Lambda Research and/or AECL. The later translation of the measured stresses to the actual final closure weld was based on activities not yet taken, however, the final closure weldment design will be provided as an estimate if needed.

B2.4.1 *Weld configuration*

During a Design Review meeting held on February 13, 2003 between SET and Bechtel SAIC, LLC. it was decided that SET would not provide weld geometry recommendations. SET is to provide recommendations of the weld surface profile necessary for the weld to be CPB processed.

B2.4.2 *CPB Weld Profile Recommendations*

Any weld configuration having a maximum of a 1/16-inch convex with a smooth transition gentle sloping from the parent material would be suitable for CPB.

Welds with a 1/16 concave surface would also be acceptable for the CPB process, however it is not a recommended practice since it posses a problem for NDI inspection. The decision from the Design Review was to keep the recommendation for the NDI.

B2.5 *CPB Process Specimens*

The CPB tooling (see Figure 15) was used to process the specimens. The target is to achieve depth of compression greater than 8mm in the specimens. The specimens (see Figure 3) were processed based upon results of Activity B1.7 and prior testing to determine the impact of CPB. The CPB processed specimens had residual stress measurements performed to establish baseline residual stress state.

B2.5.1 *Residual Stress Measurements*

The following is the stress analysis of the CPB processed specimens. The following material in section B2.52 is an excerpt of a report written by Mr. Douglas Hornbach of Lambda Research. The full report contains information other than the CPB processed specimens. Where necessary the statements of Mr. Douglas Hornbach were paraphrased to exclude references to processes other than CPB. Only CPB material will be shown.

Two different methods were utilized to measure the depth and magnitude of the compressive stresses in the weld specimen. Ring core testing method was employed due to coarse grain size of the specimen. The coarse grain limited the resolution of the X-ray diffraction method. Please note that the two methods correlated well.

B2.5.2 *CPB Processed Specimens Residual Stress Report*

INTRODUCTION

A 1 in. thick welded plate was received from Bechtel SAIC Co., LLC for the purpose of determining the subsurface residual stress distributions parallel to the weld line. The welded plate, identified as HTXX2246BG F4B (CPB) was manufactured from Alloy 22 and had maximum nominal dimensions of 16.0 (length) x 12.0 (wide) x 5.0 (high) in.

The technical services for this job were performed in accordance with Bechtel SAIC requirements, as stated in purchase order TAO04667 Rev: 00 and Lambda Research's Quality Assurance program (QA manual1M1000). Testing and calibration were performed per Lambda Research test and calibration procedures 3P1051_3, 2C1021_6, 2C1315_1, 2C1316_1 and 2C1019.02.

<u>Residual Stress</u>

X-Ray Diffraction:

Measurements were made at the surface and at the nominal depths shown in the attached Figure 16 and tables. Measurements were attempted beyond these

depths but were not feasible due to coarse grain size. Measurements were made parallel to the weld line at positions adjacent to the fusion line and at 0.5 and 1.5 in. from the fusion line as shown in Figure 19.

X-ray diffraction residual stress measurements were performed using a multi-angle sine-squared-psi technique, in accordance with SAE J784a, employing the diffraction of Cr K-alpha radiation from the (220) planes of the FCC structure of the Alloy 22.

An AST X2001 portable diffraction system was used to determine the residual stresses. The instrument is a computer controlled x-ray stress analyzer utilizing solid-state linear image sensors as position sensitive detectors.

Details of the diffractometer fixturing are outlined below:

Detector: Dual Position sensitive MOS Linear Image Sensors in symmetrical modified psi geometry.

Psi Rotation:	0 to 42 deg.
Irradiated Area:	0.12 in. diameter

The value of the x-ray elastic constant, E/(1 + v), required to calculate the macroscopic residual stress from the strain measured normal to the (220) planes of Alloy 22 was previously determined empirically [(1)] by employing a simple rectangular beam manufactured from Alloy 22 loaded in four-point bending on the diffractometer to known stress levels and measuring the resulting change in the spacing of the (220) planes in accordance with ASTM E 1426. No attempt was made to determine the x-ray elastic constant of the Alloy 22 employed in the manufacture of the welded plates.

Material was removed electrolytically for subsurface measurement to minimize possible alteration of the subsurface residual stress distribution as a result of material removal.

Ring Core

Ring-core residual stress measurements were made in accordance with the purchase order TAO04667 Rev: 00 requirements and lambda's QA program. The principal residual stresses were calculated, as a function of depth, at the center of the weld and outside the weld, as shown in Figure 19, on both plates using an incremental ring coring (mechanical dissection) method.

The ring core method consists of applying a strain gage rosette to each area of interest and dissecting a plug containing the strain gages. During the sectioning operation, the residual strain in the part is relieved. The relieved strain is recorded and is used to calculate the residual stress as a function of depth.

Rectangular electrical resistance strain gage rosettes were installed at the measurement location on each specimen. The strain gage rosettes were placed with the No.1 gage reference direction oriented as indicated in the attached tables of data. A plug containing the strain gage was then cut to a total depth of nominally 250 x 10-3 in. at increments of nominally 5 x 10-3 in. The suppliers' strain gage certification for the lot of strain gages used in this investigation is attached.

RESULTS AND DISCUSSION

Residual Stress:

X-Ray Diffraction:

The residual stress distributions measured parallel to the weld line as functions of depth are presented in the Appendix and are shown graphically in Figure 16. Compressive stresses are shown as negative values, tensile as positive, in units of ksi (103 psi) and MPa (106 N/m2).

In the figure, the macroscopic residual stress distribution is plotted in the upper graph.

The error shown for each residual stress measurement is one standard deviation resulting from random error in the determination of the diffraction peak angular positions and in the empirically determined value of E/(1 + v) in the <220> direction. An additional semi-systematic error on the order of =±2 ksi (=±14 MPa) may result from sample positioning and instrument alignment errors. The magnitude of this systematic error was monitored using a powdered metal zero-stress standard in accordance with ASTM Specification E915 and found to be +1.6 ksi during the course of this investigation.

Ring Core:

The residual stress resolved parallel to the 0-deg., 45-deg. and 90-deg. stress values and the principal stress values calculated from the ring core data are presented in the Appendix and are shown graphically in Figures 17 and 18. Compressive stresses are shown as negative values, tensile as positive, in units of ksi (103 psi) and MPa.

In each table the column titled STRESS 1, lists the residual stresses in the reference direction. The columns titled STRESS 2 and STRESS 3 are the residual stresses in the 45 deg. and 90 deg. directions respectively, rotated counterclockwise from the No.1 direction. All three stresses lie in a plane that is parallel to the plane of the surface. The maximum stress, minimum stress and phi are calculated using Mohr's Circle for stress. The maximum stress direction is defined by the angle phi, which is taken to be a positive angle counterclockwise from the No.1 gage reference direction.

In each figure the three residual stresses calculated in the O-deg., 45-deg. and 90-deg. directions are plotted along with the maximum and minimum residual stresses. A plot of phi as a function of depth is also shown.

RS MEASUREMENT CONCLUSIONS

X-Ray Diffraction

X-Ray diffraction results are shown in Figure 16. Data for the CPB plate indicate compression to at least 0.24 in. for all three locations tested. Maximum compression was located below the surface of the CPB sample for all three locations and was on the order of -75 ksi or higher. The location adjacent to the fusion line had the highest compression of the three locations tested at the final depth of the profile.

Ring- Core

The 0.25 and 1.0 in. diameter ring core data for the CPB processed sample are shown in Figure 17. The 0.25 in. diameter ring core results obtained in the weld indicate an increase in compression from relatively low compression to above -150 ksi at the final depth. The 1.0 in. diameter ring core results obtained away from the weld indicate compression to the last depth of nominally 0.3 in.

Any differences between ring core and x-ray results can mostly be attributed to the spatial and depth resolution differences. X-ray measurements are averaged over a 0.12 in. diameter irradiated area and only a few tenths of a thousandth of an inch depth. However, the ring core results are averaged over the diameter of the tool and over a depth of several thousandths of an inch.

Ring Core and X-ray Diffraction

REFERENCES:
[sbastfm.1097]

(1) P.S. Prevey, *Adv. in X-Ray Anal.,* Vol. 20,1977, pp. 345-354.

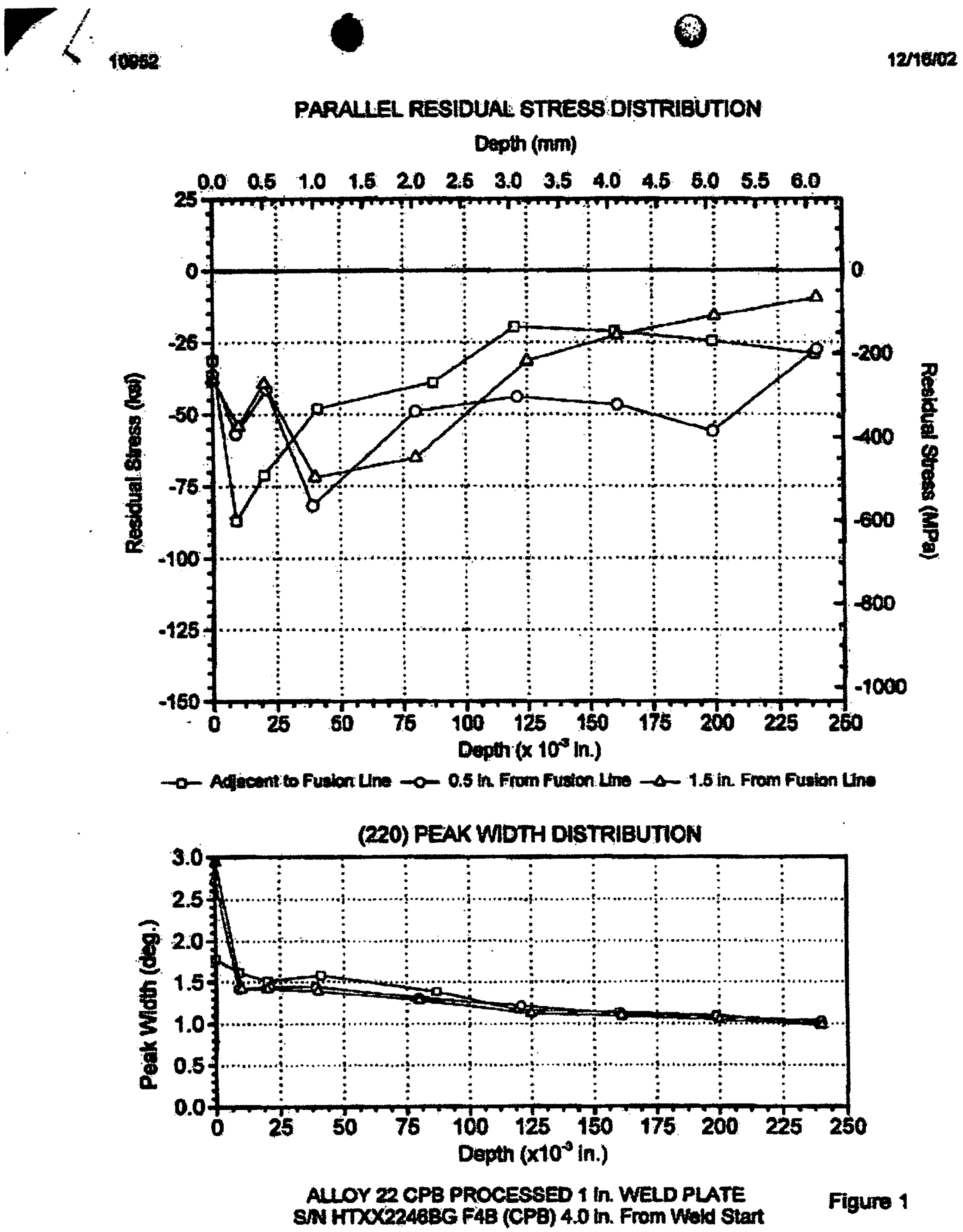

Figure 16: X-Ray Diffraction Measurements on Alloy 22 CPB Processed 1" Weld Plate

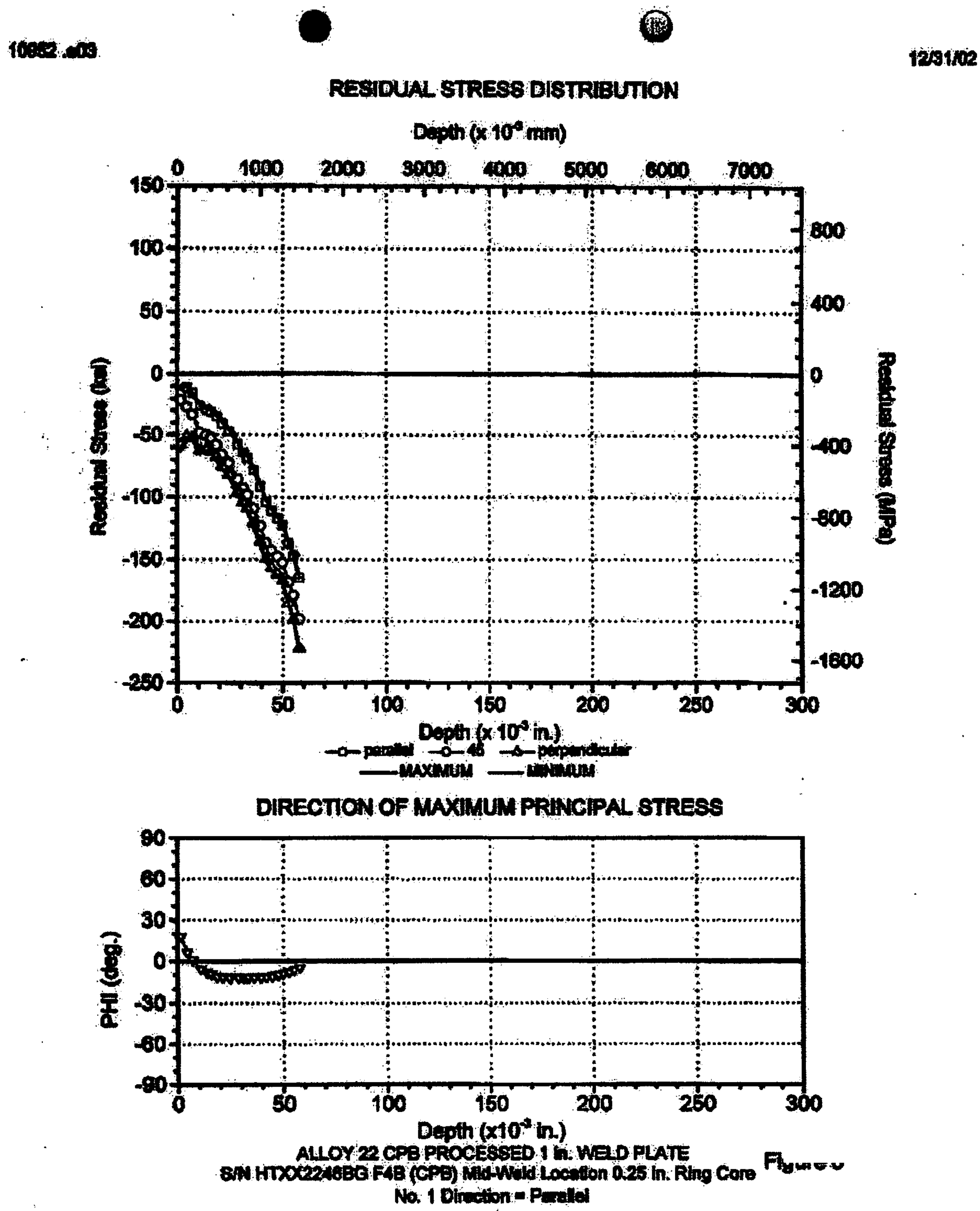

Figure 17: Ring Core Measurements on Alloy 22 CPB Processed 1" Weld Plate

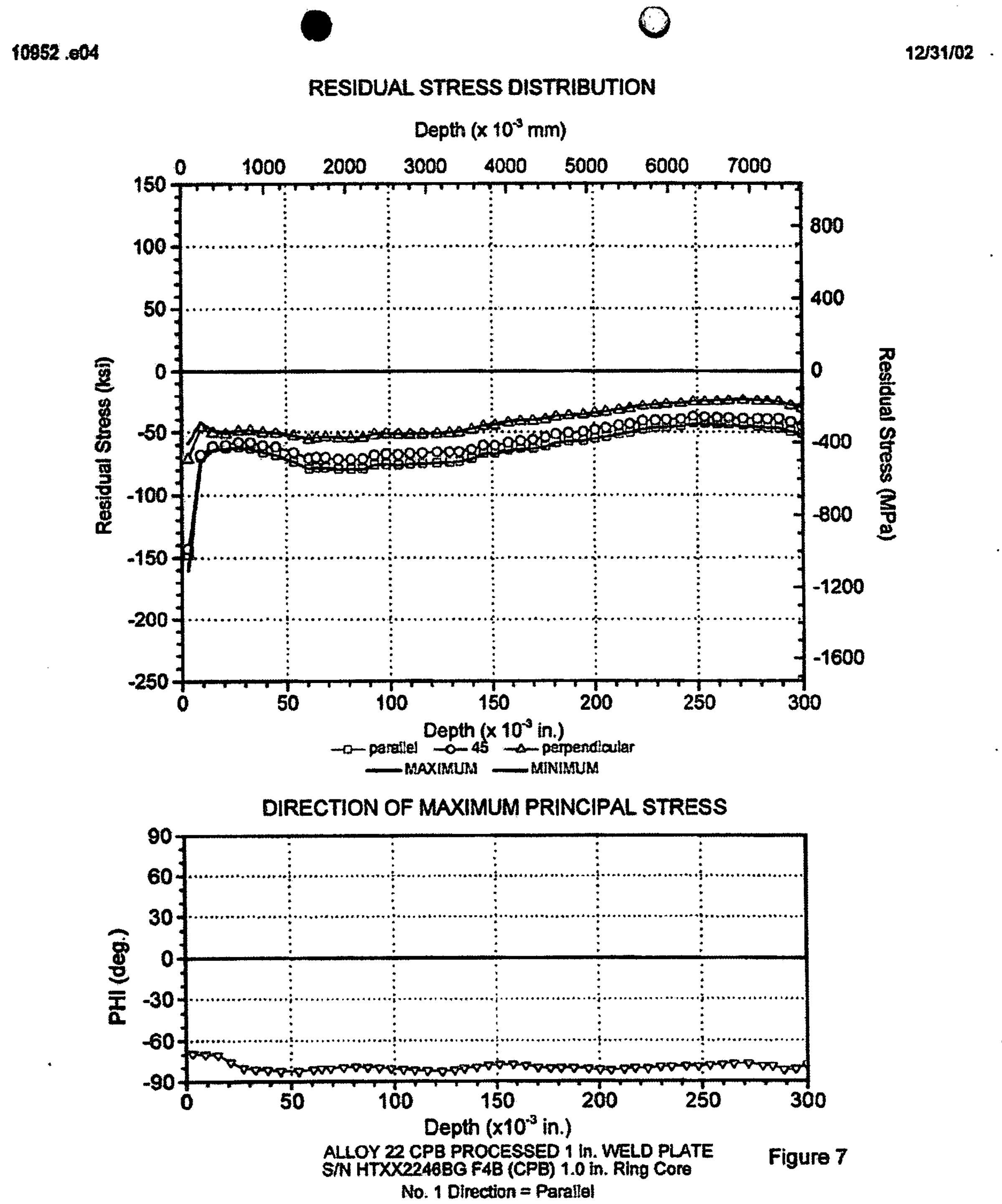

Figure 18: Ring Core Measurements on Alloy 22 CPB Processed 1" Weld Plate

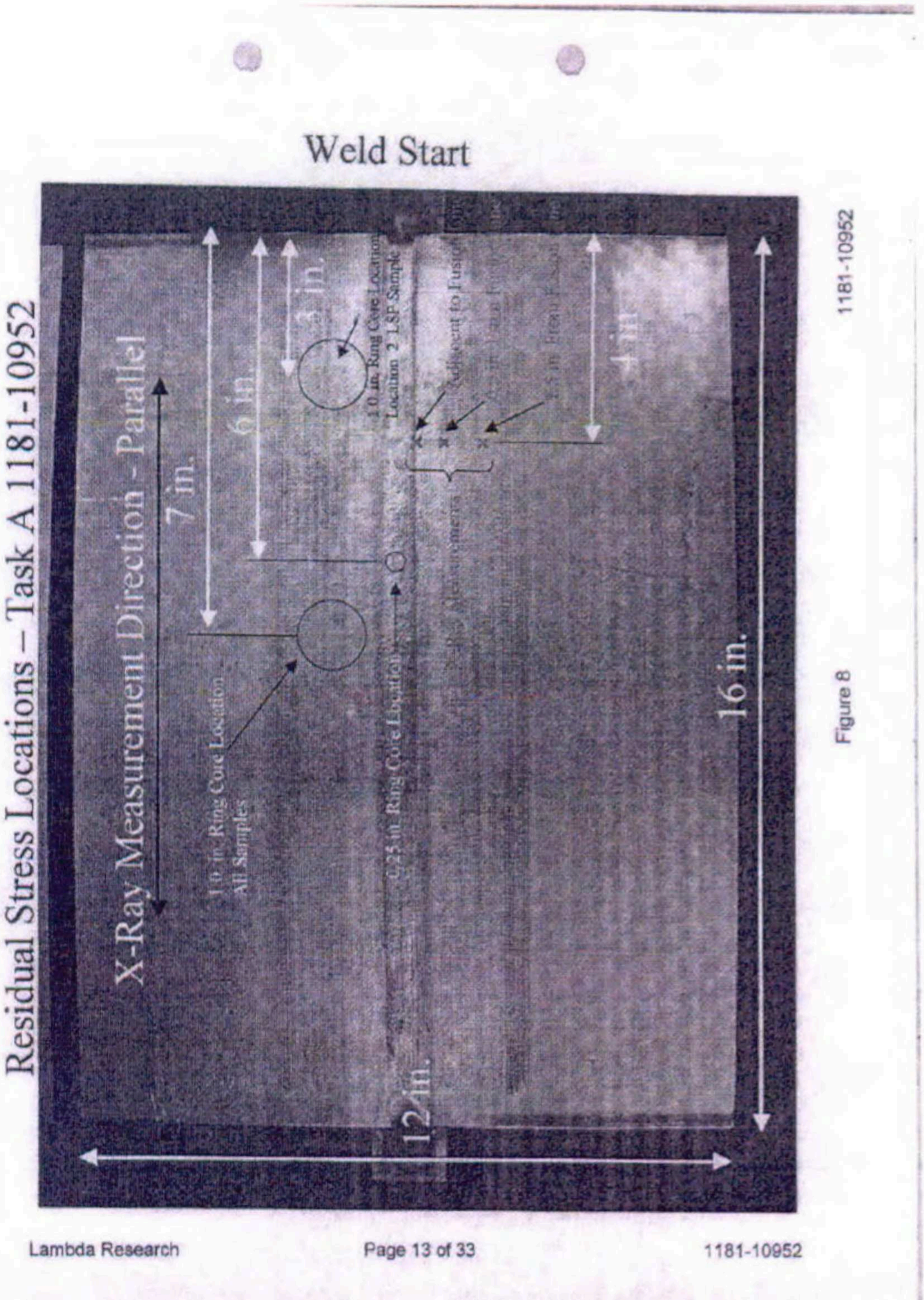

Figure 19: Measurements Parallel to the Weld Line on Alloy 22 CPB Processed 1" Weld Plate

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STRESS RESOLVED ALONG GAGE AXES. 2

MODULUS OF ELASTICITY = 30.3 (X10^6 PSI) POISSON RATIO = .290

ALLOY 22 WELD PLATE #1 = PARALLEL DIRECTION
Specimen CPB Mid Weld Location 0.25" Ring Core

	DEPTH		STRESS 1		STRESS 2		STRESS 3	
	in.	(mm)	ksi	(MPa)	ksi	(MPa)	ksi	(MPa)
1	.0017	(.044)	-15.6	(-107.)	-21.0	(-144.)	-57.7	(-398.)
2	.0046	(.118)	-11.2	(-77.)	-26.8	(-185.)	-51.9	(-358.)
3	.0072	(.183)	-15.3	(-106.)	-33.4	(-230.)	-52.6	(-362.)
4	.0109	(.277)	-26.2	(-180.)	-48.1	(-332.)	-62.7	(-432.)
5	.0139	(.352)	-28.8	(-199.)	-50.3	(-347.)	-61.9	(-427.)
6	.0159	(.404)	-30.8	(-213.)	-52.6	(-363.)	-63.3	(-437.)
7	.0186	(.472)	-35.0	(-241.)	-58.2	(-402.)	-68.1	(-469.)
8	.0213	(.542)	-41.0	(-282.)	-65.7	(-453.)	-75.4	(-520.)
9	.0246	(.625)	-47.1	(-325.)	-72.5	(-500.)	-82.1	(-566.)
10	.0287	(.728)	-57.6	(-397.)	-85.6	(-590.)	-96.3	(-664.)
11	.0313	(.795)	-64.2	(-443.)	-93.1	(-642.)	-104.2	(-719.)
12	.0333	(.847)	-68.8	(-474.)	-98.1	(-676.)	-109.4	(-754.)
13	.0361	(.916)	-78.5	(-542.)	-109.1	(-752.)	-121.2	(-835.)
14	.0394	(1.001)	-91.7	(-632.)	-123.2	(-849.)	-135.6	(-935.)
15	.0421	(1.068)	-104.1	(-718.)	-136.8	(-943.)	-149.8	(-1033.)
16	.0448	(1.138)	-111.2	(-766.)	-142.9	(-985.)	-156.5	(-1079.)
17	.0477	(1.211)	-117.2	(-808.)	-147.9	(-1020.)	-162.0	(-1117.)
18	.0501	(1.272)	-122.7	(-846.)	-152.5	(-1051.)	-167.4	(-1154.)
19	.0529	(1.343)	-137.1	(-946.)	-168.1	(-1159.)	-183.3	(-1278.)
20	.0552	(1.403)	-147.3	(-1015.)	-178.8	(-1233.)	-198.6	(-1369.)
21	.0580	(1.474)	-164.9	(-1137.)	-198.3	(-1367.)	-222.4	(-1533.)

Figure 20: Alloy 22 1" Weld Plate – CPB Processed Mid-Weld Location 0.25" Ring Core Stress Resolved Along Gage Axes

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PRINCIPAL STRESSES AND PRINCIPAL DIRECTION. 3

MODULUS OF ELASTICITY = 30.3 (X10^6 PSI) POISSON RATIO = .290

ALLOY 22 WELD PLATE #1 = PARALLEL DIRECTION
Specimen CPB Mid Weld Location 0.25" Ring Core

	DEPTH in.	(mm)	MAXIMUM STRESS ksi	(MPa)	MINIMUM STRESS ksi	(MPa)	PHI (Deg.)
1	.0017	(.044)	-10.4	(-71.)	-62.9	(-434.)	18.3
2	.0046	(.118)	-10.6	(-73.)	-52.5	(-362.)	6.6
3	.0072	(.183)	-15.3	(-106.)	-52.6	(-362.)	.8
4	.0109	(.277)	-25.8	(-178.)	-63.0	(-435.)	-5.7
5	.0139	(.352)	-28.1	(-194.)	-62.6	(-432.)	-8.3
6	.0159	(.404)	-29.9	(-206.)	-64.2	(-443.)	-9.4
7	.0186	(.472)	-33.7	(-232.)	-69.4	(-478.)	-11.1
8	.0213	(.542)	-39.4	(-272.)	-76.9	(-530.)	-11.8
9	.0246	(.625)	-45.4	(-313.)	-83.8	(-578.)	-12.1
10	.0287	(.728)	-55.7	(-384.)	-98.1	(-677.)	-12.0
11	.0313	(.795)	-62.3	(-429.)	-106.1	(-732.)	-12.0
12	.0333	(.847)	-66.9	(-461.)	-111.3	(-767.)	-12.0
13	.0361	(.916)	-76.6	(-528.)	-123.1	(-849.)	-11.8
14	.0394	(1.001)	-89.7	(-618.)	-137.6	(-948.)	-11.8
15	.0421	(1.068)	-102.1	(-704.)	-151.8	(-1047.)	-11.6
16	.0448	(1.138)	-109.4	(-754.)	-158.3	(-1091.)	-10.9
17	.0477	(1.211)	-115.7	(-798.)	-163.5	(-1127.)	-10.2
18	.0501	(1.272)	-121.4	(-837.)	-168.6	(-1162.)	-9.2
19	.0529	(1.343)	-136.2	(-939.)	-186.3	(-1285.)	-7.9
20	.0552	(1.403)	-146.6	(-1011.)	-199.2	(-1374.)	-6.4
21	.0580	(1.474)	-164.5	(-1134.)	-222.8	(-1536.)	-4.6

Figure 21: Alloy 22 1" Weld Plate – CPB Processed Mid-Weld Location 0.25" Ring Core Principal Stresses and Principal Direction

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STRESS RESOLVED ALONG GAGE AXES. 3

MODULUS OF ELASTICITY = 30.3 (X10^6 PSI) POISSON RATIO = .290

ALLOY 22 WELD PLATE #1 = PARALLEL DIRECTION
Specimen CPB 1.00" Ring Core Location

	DEPTH		STRESS 1		STRESS 2		STRESS 3	
	in.	(mm)	ksi	(MPa)	ksi	(MPa)	ksi	(MPa)
1	.0031	(.078)	-147.6	(-1017.)	-143.0	(-986.)	-71.6	(-494.)
2	.0092	(.232)	-69.9	(-482.)	-68.0	(-469.)	-46.3	(-320.)
3	.0150	(.381)	-62.4	(-430.)	-61.3	(-422.)	-50.6	(-349.)
4	.0211	(.536)	-62.6	(-432.)	-60.1	(-415.)	-51.6	(-356.)
5	.0272	(.690)	-61.7	(-426.)	-57.8	(-398.)	-49.4	(-340.)
6	.0329	(.836)	-63.0	(-435.)	-58.2	(-402.)	-49.0	(-338.)
7	.0388	(.985)	-66.0	(-455.)	-60.7	(-419.)	-50.7	(-349.)
8	.0449	(1.142)	-68.0	(-469.)	-61.9	(-427.)	-51.2	(-353.)
9	.0536	(1.360)	-73.5	(-507.)	-66.2	(-456.)	-53.2	(-367.)
10	.0608	(1.544)	-78.9	(-544.)	-71.0	(-490.)	-56.0	(-386.)
11	.0644	(1.637)	-77.8	(-536.)	-70.2	(-484.)	-54.9	(-379.)
12	.0689	(1.750)	-77.9	(-537.)	-70.3	(-485.)	-54.4	(-375.)
13	.0751	(1.908)	-79.1	(-545.)	-71.7	(-494.)	-55.1	(-380.)
14	.0812	(2.063)	-79.0	(-544.)	-71.8	(-495.)	-55.1	(-380.)
15	.0869	(2.208)	-78.8	(-543.)	-71.4	(-492.)	-54.8	(-378.)
16	.0926	(2.352)	-75.7	(-522.)	-68.3	(-471.)	-52.3	(-360.)
17	.0983	(2.497)	-75.1	(-518.)	-67.3	(-464.)	-51.7	(-356.)
18	.1043	(2.648)	-75.9	(-524.)	-67.8	(-468.)	-52.2	(-360.)
19	.1099	(2.792)	-75.0	(-517.)	-66.9	(-461.)	-52.0	(-358.)
20	.1160	(2.946)	-74.8	(-516.)	-66.5	(-459.)	-51.8	(-357.)
21	.1232	(3.130)	-74.3	(-513.)	-65.9	(-455.)	-51.5	(-355.)
22	.1293	(3.284)	-73.6	(-507.)	-65.6	(-452.)	-50.9	(-351.)
23	.1340	(3.404)	-73.0	(-504.)	-65.6	(-452.)	-50.3	(-347.)
24	.1400	(3.555)	-70.8	(-488.)	-63.9	(-440.)	-48.4	(-334.)
25	.1458	(3.704)	-66.7	(-460.)	-60.7	(-419.)	-45.6	(-314.)
26	.1515	(3.849)	-66.4	(-458.)	-60.8	(-419.)	-45.1	(-311.)
27	.1582	(4.018)	-64.0	(-441.)	-58.3	(-402.)	-42.9	(-296.)
28	.1642	(4.169)	-62.9	(-434.)	-56.8	(-392.)	-41.7	(-288.)
29	.1702	(4.323)	-62.8	(-433.)	-56.0	(-386.)	-41.4	(-285.)
30	.1763	(4.477)	-60.9	(-420.)	-54.2	(-374.)	-40.3	(-278.)
31	.1814	(4.608)	-58.1	(-401.)	-51.7	(-356.)	-38.1	(-263.)
32	.1876	(4.766)	-56.9	(-392.)	-50.6	(-349.)	-37.2	(-256.)
33	.1947	(4.946)	-56.5	(-390.)	-49.8	(-344.)	-36.5	(-252.)
34	.2003	(5.087)	-55.0	(-379.)	-48.1	(-332.)	-35.3	(-243.)
35	.2056	(5.223)	-53.5	(-369.)	-46.6	(-322.)	-34.1	(-235.)
36	.2120	(5.384)	-51.2	(-353.)	-44.9	(-309.)	-32.5	(-224.)
37	.2173	(5.518)	-49.8	(-344.)	-43.8	(-302.)	-31.3	(-216.)
38	.2235	(5.678)	-47.5	(-327.)	-41.4	(-286.)	-29.4	(-203.)
39	.2296	(5.832)	-46.3	(-319.)	-40.9	(-282.)	-28.7	(-198.)
40	.2349	(5.966)	-45.8	(-316.)	-40.3	(-278.)	-27.9	(-192.)
41	.2420	(6.146)	-45.0	(-310.)	-39.8	(-274.)	-27.4	(-189.)
42	.2481	(6.301)	-42.8	(-295.)	-37.7	(-260.)	-25.7	(-177.)
43	.2536	(6.441)	-43.1	(-297.)	-38.1	(-262.)	-25.6	(-176.)
44	.2596	(6.595)	-43.7	(-301.)	-38.7	(-267.)	-25.3	(-174.)
45	.2650	(6.732)	-43.8	(-302.)	-38.9	(-268.)	-24.9	(-171.)
46	.2720	(6.909)	-44.5	(-307.)	-39.3	(-271.)	-24.5	(-169.)
47	.2788	(7.082)	-45.5	(-314.)	-39.5	(-272.)	-25.0	(-172.)
48	.2835	(7.201)	-46.1	(-318.)	-39.9	(-275.)	-25.3	(-175.)
49	.2889	(7.338)	-46.7	(-322.)	-39.3	(-271.)	-25.7	(-177.)

Figure 22: Alloy 22 1" Weld Plate – CPB Processed 1.00" Ring Core Location
Stress Resolved Along Gage Axes

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STRESS RESOLVED ALONG GAGE AXES. 4

MODULUS OF ELASTICITY = 30.3 (X10^6 PSI) POISSON RATIO = .290

ALLOY 22 WELD PLATE #1 = PARALLEL DIRECTION
Specimen CPB 1.00" Ring Core Location

	DEPTH in.	(mm)	STRESS 1 ksi	(MPa)	STRESS 2 ksi	(MPa)	STRESS 3 ksi	(MPa)
50	.2945	(7.481)	-49.1	(-339.)	-42.2	(-291.)	-28.8	(-198.)

Figure 23: Alloy 22 1" Weld Plate – CPB Processed 1.00" Ring Core Location
Stress Resolved Along Gage Axes

Lambda Research, Inc.

10952.e04 TRECAL.17 01/16/03

PRINCIPAL STRESSES AND PRINCIPAL DIRECTION. 6

MODULUS OF ELASTICITY = 30.3 (X10^6 PSI) POISSON RATIO = .290

ALLOY 22 WELD PLATE #1 = PARALLEL DIRECTION
Specimen CPB 1.00" Ring Core Location

	DEPTH in.	(mm)	MAXIMUM STRESS ksi	(MPa)	MINIMUM STRESS ksi	(MPa)	PHI (Deg.)
50	.2945	(7.481)	-28.3	(-195.)	-49.6	(-342.)	-81.1

Figure 24: Alloy 22 1" Weld Plate – CPB Processed 1.00" Ring Core Location
Principal Stresses and Principal Direction

Lambda Research 1181-10952

PARALLEL RESIDUAL STRESS
1.0 in. CPB Processed Welded Plate
4.0 in. From Weld Start
Adjacent to Fusion Line

Depth (in.)	Residual Stress (ksi)	Peak Width (deg.)
Surface	-31.2 ± 3.3	1.78
0.009	-87.0 ± 11.4	1.62
0.020	-71.1 ± 7.4	1.51
0.041	-48.1 ± 8.2	1.58
0.087	-38.9 ± 9.7	1.38
0.120	-19.8 ± 7.4	1.16
0.160	-21.4 ± 10.6	1.13
0.199	-24.6 ± 12.3	1.09
0.239	-29.0 ± 14.1	1.00

Figure 25: Alloy 22 1" Weld Plate – CPB Processed, 4.0" from Weld Start
Adjacent to Fusion Line

Lambda Research 1181-10952

PARALLEL RESIDUAL STRESS
1.0 in. CPB Processed Welded Plate
4.0 in. From Weld Start
0.5 in. From Fusion Line

Depth (in.)	Residual Stress (ksi)
Surface	-36.1 ± 3.0
0.009	-56.7 ± 2.4
0.021	-41.4 ± 4.2
0.039	-81.6 ± 5.2
0.080	-48.9 ± 3.6
0.121	-44.1 ± 3.0
0.161	-46.8 ± 15.5
0.199	-55.9 ± 20.4
0.240	-27.5 ± 19.9

Figure 26: Alloy 22 1" Weld Plate – CPB Processed, 4.0" from Weld Start
0.5" from Fusion Line

Lambda Research 1181-10952

PARALLEL RESIDUAL STRESS
1.0 in. CPB Processed Welded Plate
4.0 in. From Weld Start
1.5 in. From Fusion Line

Depth (in.)	Residual Stress (ksi)
Surface	-37.9 ± 3.6
0.010	-54.1 ± 7.5
0.020	-39.4 ± 4.5
0.040	-71.8 ± 5.6
0.080	-64.9 ± 21.0
0.125	-31.6 ± 9.8
0.161	-22.7 ± 13.5
0.200	-16.0 ± 17.5
0.240	-9.6 ± 13.4

Figure 27: Alloy 22 1" Weld Plate – CPB Processed, 4.0" from Weld Start
1.5" from Fusion Line

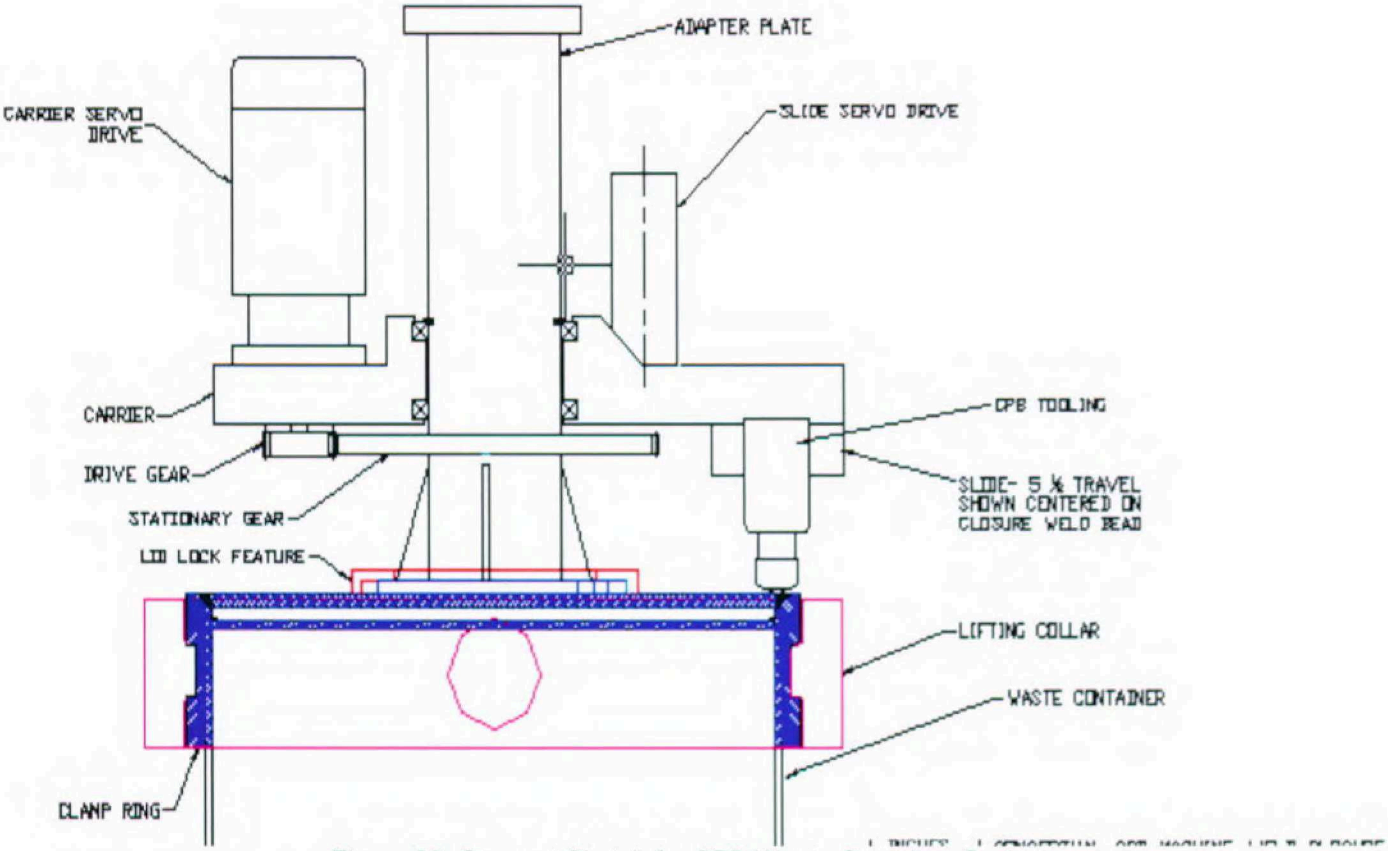

Figure 28: Concept Sketch for CPB Waste Container System

Conclusion

Several discussions with the Yucca Mountain project team indicated that a depth of compression greater than 6 mm would be more than ample for this application. The depth of compression target for this task was to obtain 8mm or greater. Our maximum measured depth (see figure 19) with XRD was 6.2 mm. There was a problem in measuring to greater depths with this method due to coarse grain size. Another method was used to measure to greater depths. This was the ring core method. With this method we were able to measure a depth of approximately 7.6 mm of compression. This was 1.6mm above the verbal goal. Unfortunately the ring core equipment was not able to measure to greater depths so, it is unknown if compressive stress depths were greater than the measured 7.6 MM. No undesired tensile stresses were detected.

Any weld configuration having a maximum of a 1/16-inch convex with a smooth transition gentle slope from the parent material would be suitable for CPB. This required weld profile was the same as the required weld profile for other processing tasks for the waste container. The CPB process would fit in well with the other waste container processes.

To develop CPB parameters necessary to achieve deep layer of compression without causing undesired tensile stresses in the test specimen was the main objective of Task B. This main objective is a combination of the first two goals of SET Quote No. S4901R. The third goal of the SET Quote, which was to recommend CPB acceptable weld profile, was mere reassurance of realistic feasibility of the CPB process. In several discussions with the Yucca Mountain project team, the achievement of the depth of compression and the required weld profile was deemed a success.

The manufacturing and performance results demonstrated in this study are as follows:

- Demonstrated 7.6 mm depth of compression in Alloy 22
- Low risk controllable machine tool process
- Relatively high speed process (approximately 2 hour cycle for each WP)
- Minimal processing materials required (water based solution) during CPB stress mitigation process. Volume of water-based solution required can be readily designed for evacuation and recirculation resulting in no residual materials in the closure cell.
- The CPB surface finish (8.8 – 55.3 Ra)has improved the original surface finish (75- 194 Ra), offering improved NDI detection for weld quality assurance in a remote facility.
- Machine implementation readily designed for irradiated environment
- Demonstrated analytical design methods for developing process parameters and tooling that predict process results as measured
- Capability to design sufficient depth of compression to resist Stress Corrosion Cracking (SCC)
- CPB application via machine tool supports relatively low cost application device development and low cost unit cost