FINAL REPORT ON
REACTOR CONTAINMENT LINER
OVERLAY PAD FILLET WELD
AT
BEAVER VALLEY POWER STATION - UNIT NO. 2

STONE & WEBSTER ENGINEERING CORPORATION

BOSTON, MASSACHUSETTS

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1.0 SUMMARY

A surface examination of the reactor containment liner plate and associated equipment, following a sandblast operation necessary for prime paint substrate, revealed a one foot long crack along the toe of a bottom horizontal fillet weld which attaches an overlay pad to the reactor containment vertical liner plate. The overlay pad is located at elevation 719'-4", fourteen feet west of the north containment centerline.

As a result of grinding necessary for repair, the crack depth was found to be greater than half the thickness of the liner material. Further investigation has established that the crack did not penetrate the containment boundary and that the crack is unique and restricted to this single overlay pad.

2.0 IMMEDIATE ACTION TAKEN

Since the crack continued beyond the liner contractor's maximum allowed excavation depth, half the thickness of the liner material, the defect was viewed as a possible through-thickness crack, thus a potential breach of the containment vapor boundary. Grinding was stopped and a detailed evaluation initiated. No additional overlay plates have been installed since the discovery of the crack.

Since this problem was considered a possible reportable significant deficiency pursuant to 10CFR50.55(e)(1), the U.S. Nuclear Regulatory Commission (NRC) was notified orally of this situation on December 22, 1978.

3.0 DESCRIPTION OF THE DEFICIENCY

The overlay pad was fit up on December 15, 1977, tacked in place on December 19, 1977, and final welded on December 21, 1977. Visual and magnetic particle examinations were performed on January 16, 1978 and February 15, 1978, respectively, with acceptable results. The sandblast operation and resultant visual observation of the crack was performed on October 23, 1978.

The Contractor's general procedures allow for repair of base metal linear defects which do not exceed 1/2 t (t is base metal thickness) in depth or 1/2 t in width. Linear defects

which exceed the above require the Contractor's Project Engineer to be notified.

Based on this information, Nonconformance and Disposition (N&D) Report No. 9167 was issued by the site personnel. The Engineers reviewed the problems and dispositioned N&D No. 9167. Further grinding invoked by N&D No. 9167 showed the crack to approximate a through-liner crack, thus a potential breach of the containment vapor tight boundary.

Results of the investigation have shown that the crack was not a through crack.

A detailed description of the metallurgical examination of this problem is presented as Enclosure 1. A report by Dr. C.M. Adams, an independent consultant retained to investigate this problem, is presented as Enclosure 2.

It is concluded that the defect is a hydrogen - related delayed crack which initiated at the toe of the fillet weld. Propagation into the base material is explained by observed material properties.

4.0 ANALYSIS OF SAFETY IMPLICATIONS

The safety of offsite personnel and the function of the containment liner to serve as a leak tight boundary are assured for the following reasons:

A. The area of liner plate containing the defect has been removed and will be replaced using controlled repair techniques.

B. The remainder of the overlay plates were reexamined using visual and magnetic particle techniques and found to be free of defects.

C. Between initial acceptance and reexamination of all overlay pads, hydrogen, an essential contributor to delayed cracking, has naturally diffused from the material.

D. Properties of the base material are such that it can readily perform its intended service function (Enclosure 3).

5.0 CORRECTIVE ACTION TO REMEDY DEFICIENCY

The cracked area of the liner plate has been removed and will be replaced using approved repair procedures. All presently installed overlay plates have received additional visual and magnetic particle examinations to assure that welds are free of similar defects.

ENCLOSURE 1

METALLURGICAL EXAMINATION OF REACTOR CONTAINMENT LINER OVERLAY PAD FILLET WELD CRACK AT BEAVER VALLEY POWER STATION - UNIT NO. 2

by

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February 21, 1979

APPROVED BY R.A. Rosenberg
R.A. Rosenberg

PROPRIETARY NOTICE

STONE & WEBSTER ENGINEERING CORPORATION
BOSTON MASSACHUSETTS

DISCLAIMER OF RESPONSIBILITY

ACKNOWLEDGEMENT

The author acknowledges the efforts, advice, and technical support of Mssrs. H. Aznoian, J. Dowicki, C.W. Eriksson, F. Morales, I. Sprung, P.W. Ward, and E.G. Watters during the conduct of this investigation.

SUMMARY

An overlay pad-to-containment liner fillet weld toe crack was subjected to a metallurgical study, which included a review of welding procedures, environmental factors, and evaluative metallurgical tests, i.e., volumetric analysis, magnetic particle testing, macroexamination, metallography, scanning, electron microscopy, chemical analyses, and other destructive tests. Factors contributing to the failure are discussed with initiation attributable to hydrogen delayed cracking. The report concludes that the presence of cracks is not generic, is limited to a local repairable area, and that the A537 Grade B liner material is satisfactory. Finally, special precautions are recommended to minimize the hydrogen problem during repair of affected concrete backed liner plate.

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1.0 INTRODUCTION

Following sand blasting preparatory to painting in October 1978 a crack was visually detected at the toe of a fillet weld attaching a 12 in x 12 in x 1/2 in overlay pad (No. 167A10) onto the 3/8 in thick containment liner. It was probe ground along its entire length, and when further grinding over a 3 in length showed penetration beyond one half thickness of the liner further grinding was stopped. The crack ran continuously along the entire bottom fillet length and became intermittent as it rounded the corner for about one in. An engineering investigation was initiated to determine the cause of cracking and to establish the necessary corrective action. This metallurgical study is part of the investigation.

2.0 CONCLUSIONS

1. The most probable cause of crack initiation was hydrogen embrittlement.

2. The cracking problem is isolated to the local area examined.

3. The A537 Grade B liner plate material is satisfactory.

4. Metallurgically required repair welds for the concrete backed liner replacement can be made successfully.

3.0 RECOMMENDATIONS

1. Repair procedures for the concrete backed liner should include the following precautions to prevent hydrogen embrittlement:

   a. Preheating to a range of 250–350°F for at least thirty minutes after all evidences of moisture have been removed prior to welding and to weld while holding materials within this temperature range. Post weld baking should be in a range of 250–350°F for a minimum of four hours; however, longer periods may be used for added assurance.

   b. Electrode holding ovens be maintained at a mimimum temperature of 250°F and electrode exposure to ambient temperature does not exceed two hours.

4.0 TECHNICAL ANALYSIS

4.1 Review of Procedures and Environment

The technical analysis included a site visitation prior to the removal of the sample for metalluirigical study, a review of the welding procedure used, and a review of the environment data at the time of welding of the overlay pad. Welding procedure required a preheat to 50°F minimum prior to welding. There were no known or apparent deviations from the established welding procedures which included weld rod control. Prior to final welding, there had been periods of rain including light rain on December 20. The day of final welding, December 21, 1977, was cloudy, no rain, and ambient temperature of 30°F.

4.2 In Situ Visual Examination

Examination of the defect in situ disclosed a crack along the lower portion of the overlay pad fillet weld. The jagged appearing crack opening was estimated at approximately .015 to .025 in at a location of minimum probe grinding. The crack appeared to be very tight at the area where probe grinding had proceeded beyond the mid-thickness of the liner. No other defect, such as gross inclusions, laps, seams, etc, were observed. The weld remaining and welds on other overlay pads in the immediate area displayed good workmanship.

4.3 Sample Removal

A section of metal, 6 in x 18 in containing the entire crack was removed from the liner and included approximately a 3 in portion of the pad. Figure 1 shows the location of the pad; Figure 2 shows the segment removed for metallurgical study, and Figure 3 contains a series of photographs taken during the sample removal. The removal procedure required locating the headed concrete anchor studs by ultrasonic techniques, hole-cutting around studs, and removal of the sample section by cutting dry with thin grinding wheels. Views of the sample as received at Stone & Webster, Boston, Massachusetts, are shown in Figures 4 and 5. Figure 4 is from the back side of the liner showing the two studs that were holed out, and Figure 5 is a view of the overlay pad weld area. Due to the geometry of the sample, which impeded ultrasonic detection of the stud, several hole cuts were required in the overlay plate to locate one of the studs precisely. Care was exercised so as not to destroy evidence or aggravate the crack during the sample removal operation.

4.4 Nondestructive Examination

4.4.1 Visual Examination

A minor distortion in the liner on the reverse side of the liner opposite the weld deposit was noted, the depression measuring .006 in (see Figure 6). This deviation is attributable to the plastic deformation caused by the welding shrinkage. At the lower left-hand corner of the pad fillet weld there was a stud attached to the back of the liner, forming stud/liner/weld metal/pad/junction, all in line in the crack path. A cross sectional slice of metal through this junction was used for further evaluative studies which are discussed later in this report. The overlay plate was in direct contact with the liner plate over most of the areas cross sectioned. Various cross sections were polished and etched and showed six weld passes of uniform size and adequate penetration.

4.4.2 Magnetic Particle Examination

All surfaces of the test sample were examined by magnetic particle (MP) testing prior to sectioning for evaluation. MP of the ground surface delineated the crack as a continuous crack along the length of the fillet weld, as previously observed, with some apparent discontinuity as it rounded the corners. MP examination of the back side of the liner disclosed no emergence of the crack through the steel at any location, indicating that the crack has penetrated into the liner but not completely through its thickness. No other defects were uncovered.

4.4.3 Radiographic Examination

Several radiographs were required before the crack could be clearly delineated. A photograph depicting radiograph results is shown in Figure 7. Other than the crack defect under study, no other defects were observed by the radiographic examination. Radiographic examination was for exploratory purposes and not performed in conformance with any code requirements.

4.4.4 Ultrasonic Testing

Ultrasonic testing (UT), using techiques which exceeded code procedural requirements, was applied for crack evaluation and to determine base metal characteristics:

a. Crack Evaluation

1. Due to partial excavation of the crack along its entire length prior to removal of the samples, meaningful UT could not be performed from the welded side of the section; therefore, all tests were conducted from the opposite surface of the liner plate. An angle beam scan was performed using a miniature size (8 by 9 mm) 4 MHz 70 deg probe, and the ultrasonic instrument calibrated for direct readout of depth of indication. Results show the crack decayed at an approximate depth of .150 in from the probe contact surface, (i.e., the back surface of the liner plate). The response decay point was partially obscured by the initial pulse and probe interface indications, so additional tests were performed using pitch/catch, straight beam techniques to verify the angle beam readings.

2. A 5 MHz, 1/4 in dia dual element probe (pitch and catch) was used to scan the crack. The response indicated that the crack, which had a general through wall direction, was also comprised of steps parallel to the surface and at various depths. The crack tip in many locations appeared to be a laminar type step. The crack generally appeared to stop approximately .120 in to .150 in from the liner plate back surface, confirming the angle beam test results and earlier M.P. test results.

   During the crack evaluation using this technique, a scan was also made to determine the integrity of the fillet weld - heat affected zone along liner plate extending into the weld root. Results showed no deficiencies.

b. Base Material Characteristics

1. The liner plate material of the sample was straight beam examined using a 12 MHz 5 MM dia probe to detect possible laminar conditions and to determine whether base metal surface was consistent throughout. A number of multiple echoes from the plate were displaced on the instrument screen forming an attenuatic curve. When scanning, any deviation from the normal pattern was further investigated to determine whether surface conditions were the contributing cause. Results showed uniformity of the response curve with the exception of two localized areas, away from the crack, each approximately 1 in in diameter. A scan was made of these areas using the dual probe at a very high sensitivity level. Results showed extremely small reflections within the plate at these locations. One area was sectioned, polished, and examined under 10X-30X magnification. This material did show some in-line porosity and/or inclusions. The material would be acceptable if examined by ultrasonic standards invoked by ASME codes.

2. Straight beam pitch and catch examination was performed on the remainder of the liner plate sample as a follow-up of the 12 MHz straight beam tests. Results showed occasional small reflectors and in general verified earlier results.

3. Angle beam testing was performed of the liner plate sample using a 45 deg 4 MHz 8 x 9 MM probe. The sensitivity used far exceeds the three percent notch response required during ASME code examination. Results showed occasional individual reflections with no linear characteristics. The plate would be acceptable if examined to ASME code requirements.

In summary, the UT has shown the crack generally from .120 in to .150 in from

the back side of the liner - again with no penetration at any point. The indications that the crack had lamellar-type propagation associated with it was verified in subsequent metallographic study. Occasionally, line microporosity and inclusions were detected in the material. However, from a steel soundness point view, the liner material would be classified acceptable under existing code requirements.

4.5 Destructive Testing

Following nondestructive examination, the 6 in x 18 in sample cut from the liner plate was sectioned for destructive testing and study. Figure 8 shows the extent and type of tests taken. Except for one chemical analysis and hardness survey in the weld metal area of the overlay pad, all destructive tests involved the liner material as its properties and behavior were considered of prime importance to the study.

4.5.1 Chemical Analysis

Chemical analyses were made of the liner, weld deposit, and overlay pad materials. The elements carbon and sulfur were analyzed by the combustion method using a Leco automatic .70 second carbon analyzer, a Leco indiction furnace, and a Leco automatic titration apparatus. The elements manganese, phosphorus, silicon, chromium, nickel, molybdenum, tin, and vanadium were analyzed by wet chemical methods in accordance with ASTM E30 and E 350. Antimony, bismuth, and lead were analyzed by the atomic absorption method using a Jarell Ash AA Spectrophotometer and manufacturer recommended instrument settings. For nitrogen, the micro Kjeldahl Titration method was used. The results are shown in Table 1.

A comparison is made with the code-acceptable analyses for the materials and the mill certification covering the same materials. In addition, elements not normally specified were determined as these elements, if in sufficient quantity, may affect ductility and impact properties of the steel. All base materials analyzed conformed with the code-required analyses, with the exception of 0.07 percent higher manganese in the weld metal deposit.

4.5.2 Macroetch Examination

At various locations the segmented specimen was examined after lightly etching polished areas perpendicular to the crack. The polished surface showed the weld beads to be of uniform size and having approximately 1/32 in penetration into the base metal. The corresponding heat affected zones showed adequate but not excessive heat input. These were uniform at all sections that were polished and examined. Figure 9 shows one such area, which contained the junction of stud that had been welded to the back of the liner during construction, the liner material containing the crack, the weld metal deposit remaining after probe grinding in the field and the overlay pad material. The crack, as evidenced by the above photographs, progressed in a stepwise fashion into the liner material. The liner material apparently has behaved in a ductile manner thus limiting propogation of the crack. By cutting a number of samples, perpendicular to the crack and fracturing these samples after embrittling the material by immersing in liquid nitrogen, it was possible to examine a considerable length of the crack surface. (see Figure 10) All of the samples opened in this manner displayed the same woody appearance with the cracked surface being heavily corroded, indicating long exposure to the atmosphere, although the length of time of exposure could not be determined quantitatively.

4.5.3 Hardness

Hardness surveys were made using Rockwell "B" scale tests which encompassed the liner, weld metal, and overlay pad shown in Figure 11. In addition, a microhardness survey of weld zones at the junction of the stud/liner/weld metal and overlay pad was made and is also shown in Figure 11.

The Rockwell "B" survey gave hardness readings varying from 94.8 to 99.8 and averaged 96.6 at this level the converted ultimate strength would be about 105 ksi.

Vickers microhardness surveys using a 500 gram load were taken at the stud/liner and metal/overlay pad junction and showed more changes as the indentations proceeded through the weld and heat-affected zones. The liner

base metals directly above the heat-affected zone in the stud area showed lower hardness. Around the crack itself, hardnesses were consistent, averaging about 97.6 RB (converted). At the fillet weld higher hardnesses were observed than in the base metal.

4.5.4 Mechanical Tests

Mechanical tests of the liner material taken transverse to the rolling direction, included tensile specimens, as well as selected bend specimens to ascertain the behavior of the material under extreme loading conditions. Results from tensile testing are shown in Table II. Based on three tensile tests the liner material has an ultimate strength of 97.7 ksi and a yield strength of 86.1 ksi. Elongation averaged 23 percent. Specification required an ultimate strength of 80—100 ksi, a minimum yield strength of 60 ksi and a minimum elongation of 22 percent.

Several tests were made to observe the behavior of the material under conditions of severe plastic deformation. A total of 4 bend specimens were machined and bent over a mandrel having a diameter of 2 t (where t is equal to the specimen thickness).

Figure 12 shows these specimens after bending. Two specimens were taken in the long transverse direction (Figures 12a and 12d) with one specimen having the as received surface (12d) and the other (12a) having the as received surface machined off .010 in prior to bending. This latter specimen was bent 180 deg but displayed fine surface cracks at the bend tension side. Sample 12d failed prematurely after bending approximately 65 deg, with cracks initiating at surface defects (pock marks) on the tension side. Two other specimens (Figure 12c) in the direction of rolling with no surface preparation and the other (Figure 12b) bent parallel to the short transverse axis, were successfully bent 180 deg.

4.6 Scanning Electron Microscopy

Fracture surfaces from (1) the original crack, (2) the failed bend specimen, (3) the tensile test specimen, and (4) laboratory fractured specimens were subject to electron microscopy study.[1] The original crack was heavily oxidized and was cleaned using a phosphoric acid-and-water mixture. It was then cleaned in acetone using an ultrasonic bath, followed by preparation for electron microscopy. All other specimens were examined in the "as-fractured" condition without surface preparation, except that required to enhance the electron microscopy. Specimens used for limited microprobe chemical determination received no preparation. A comparision was made of the phosphoric acid cleaned surfaces against the nonphosphoric acid cleaned surfaces and, essentially, the rust-removal operation did not show any adverse effect on the fracture surface. Figures 13 and 14 show a series of photographs obtained during this examination.

The original cracked surface showed no striations of the type which would indicate fatigue-type failure. The fracture exhibited a fibrous "woody" appearance, suggesting that the base material was heavily banded or contained a large number of stringer inclusions. For comparison purposes, tensile and bend test fracture surfaces were examined, and these exhibited a fibrous appearance containing shear dimples, indicating ductile failures. Inclusions were observed in all fractured surfaces and a microanalytical scan of one of the induced fractures indicated dispersions of inclusions high in manganese content.

4.7 Metallographic Examination

Metallographic examinations were conducted at several locations to study (a) base material, (b) crack geometric appearance, and (c) selected indications from the ultrasonic test. Photo micrographs are contained in Figure 15. The liner base material displayed a fine-tempered martensitic structure typical for the quench and tempered heat treatment given A537 Grade B steel. A segregated structure of nearly parallel bands aligned in the direction of rolling (banding) was pronounced, and inclusions both stringer-type and globular appeared at a higher frequency than normally encountered in average quality hot-rolled steel of this grade. Banding, a condition normal to such plate

[1] Massachusetts Materials Research Inc. Letter Report No. F153-22 dated February 6, 1979

materials, was aggravated somewhat by the inclusion content. Propagation followed planes of weakness caused by the banding and cut across metal laminates in a ductile fashion, creating the step-like appearance.

Selected indications from the ultrasonic testing were identified as porosity or inclusions.

4.8 Technical Discussion

The palpable offset of the liner opposite the weld indicates that weld shrinkage stress exceeded the yield strength of the material to cause deformation. The liner material displayed the necessary ductility to absorb this stress without cracking, a behavior considered normal for the material.

Various tests and examinations showed that the crack propogated into the liner in a step like fashion. When opened, the crack displayed a "woody" appearance suggesting a lamellar condition and possibily lamellar tearing for cause of defect. However, lamellar tearing is ruled out as the reason for crack initiation because

a. The thickness of the liner material does not make it a prime candidate for lamellar tearing, a condition normally associated with thick plate material.

b. When lamellar tearing is observed in thin plate it occurs under conditions of severe welding restraints, a situation not present during the containment fabrication and.

Extensive ultrasonic examination revealed the character of the crack and extent of its propagation. No evidence of subsurface lamellar tearing was detected in the liner away from the crack in the weld area. Overall, no defects considered rejectable by ASME Code requirements were found, other than the crack.

Chemical analyses disclosed that, for all intents and purposes, all materials, overlay pad, weld metal deposit, and liner met specification requirements. The weld deposit had exceeded the weld rod requirements for manganese by 0.07 percent and this inconsequential increase was due to weld metal dilution during welding. In addition, no trace elements were found in undesirable amounts.

Hardness surveys disclosed good uniformity of the materials with the weld metal slightly higher than the overlay pad or liner, a normal relationship. As might

be expected, variation in hardness was observed in the heat effected zones of the weld area. However, hardness was uniform in the immediate crack area.

Tensile properties were all within code requirements, with elongation being low but within acceptable limits, and yield strength and ultimate strength well above the minimum code requirements. Of the four bend tests taken at different orientations, the transverse tests failed, one bend specimen whose skin was removed achieved a 180 deg bend with slight surface cracks developing during the tests; and the specimen with no surface preparation, achieved a 65 deg bend prior to cracks initiation and premature failure. Specimens taken in the longitudinal direction passed successfully.

Finally, metallographic examination and electron microscopy disclosed the anticipated structure for the heat treatment given, sulphide and silicon inclusion within normal limits, and ductile behavior during failure.

Because of the loss of evidence containing material, removed during the initial repair attempt at the site, it was not possible to establish the exact cause of crack initiation. Base metal properties would not in themselves provide a basis for crack initiation. In fact, the material displayed a level of ductility sufficient to prevent through liner penetration.

Based on the results of the metallurgical investigation:

1. The most probable cause for crack initiation was hydrogen embrittlement because:

   a. The crack was not detected two months after welding during the final MP inspection but was found some eight months later, indicating a delay failure.

   b. Base metal properties do not in themselves provide a basis for crack initiation. In fact, ductile behavior was demonstrated.

   c. Moisture was available during welding in the immediate environment, i.e., moisture being trapped between the tack welded overlay pad and liner. The preheat requirement of 50°F would be insufficient to insure moisture removal prior to and during final welding.

d. The observed crack initiation was located at the toe of the weld.

e. The chemistry of the liner makes it susceptible to hydrogen embrittlement and

f. Stresses imposed by welding were present.

2. The cracking problem is isolated to this local area because.

   a. No similar cracks i.e., hydrogen delayed cracks, or other defects were detected after magnetic particle reexamination of other pads.

   b. Natural hydrogen diffusion has removed the threat of delayed weld cracking

3. The liner plate material is satisfactory for use because:

   a. The base material is of sound quality. Nondestructive examination, such as visual and magnetic particle, radiography, and ultrasonic inspection has disclosed no undesirable plate defects

   b. Strength properties and elongation are within specified limits

   c. Deformation to a degree required for crack initiation in bend testing will not be encountered in service

4. The required repair welds can be made successfully with proper precautions to prevent hydrogen embrittlement as follows:

   1. Preheating to a range of 250–350°F for at least thirty minutes after all evidence of moisture has been removed prior to welding, and to weld while holding materials within this temperature range is suggested. Post weld baking should be in a range of 250–350°F for a minimum of four hours. A 24 hour post bake will absolutely assure hydrogen removal.

   2. Electrode holding oven should be maintained at a minimum temperature of 250°F, and electrode exposure to ambient temperature prior to use is not to exceed two hours.

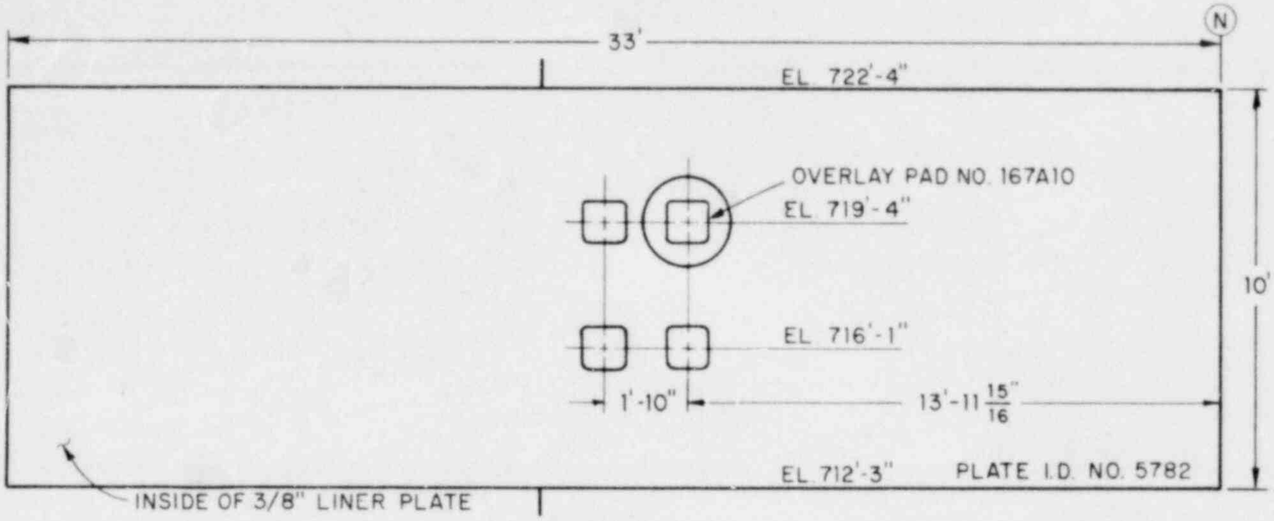


FIGURE 1
OVERLAY PAD LOCATION

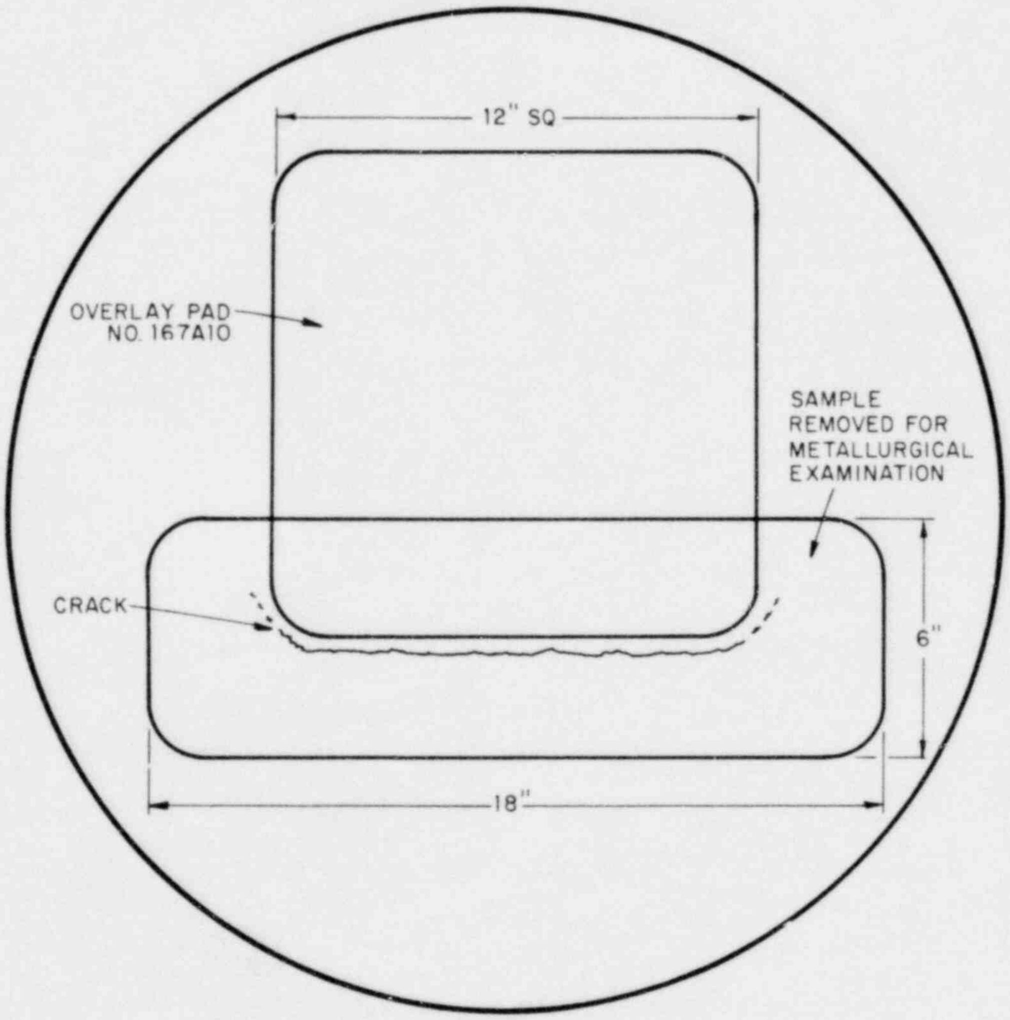
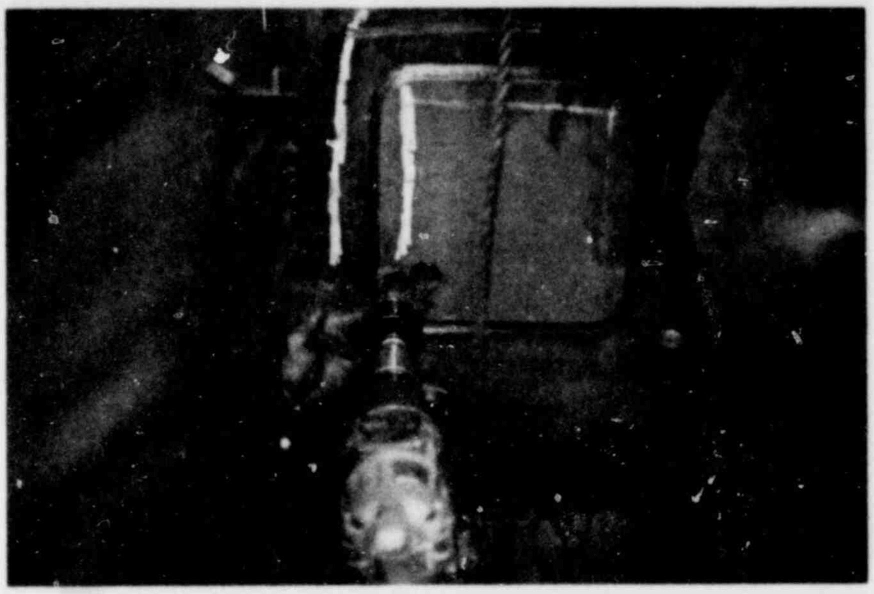
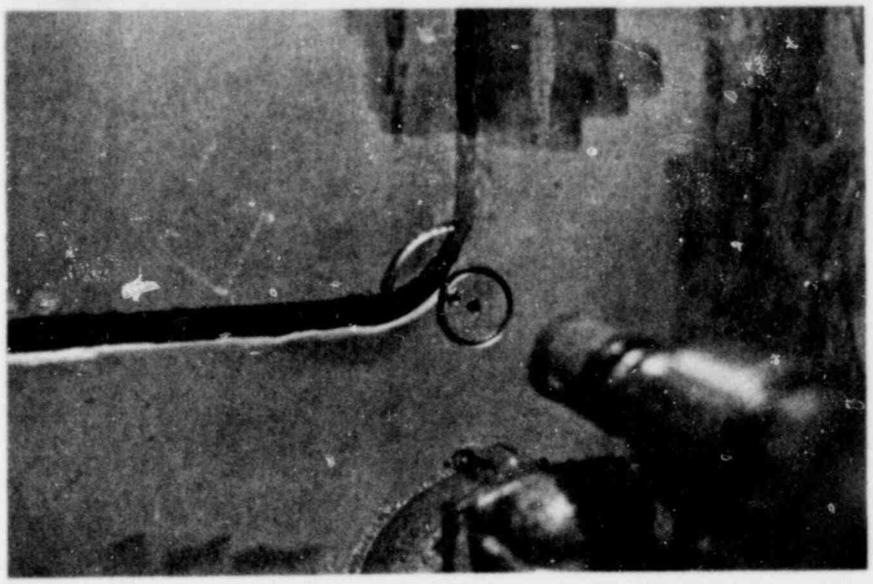


FIGURE 2
LOCATION OF TEST SAMPLE


LOCATING STUD
BY HOLE CUTTING
(LOWER LEFT)


HOLE CUTTING
FOR STUD
DISENGAGEMENT
(LOWER RIGHT)

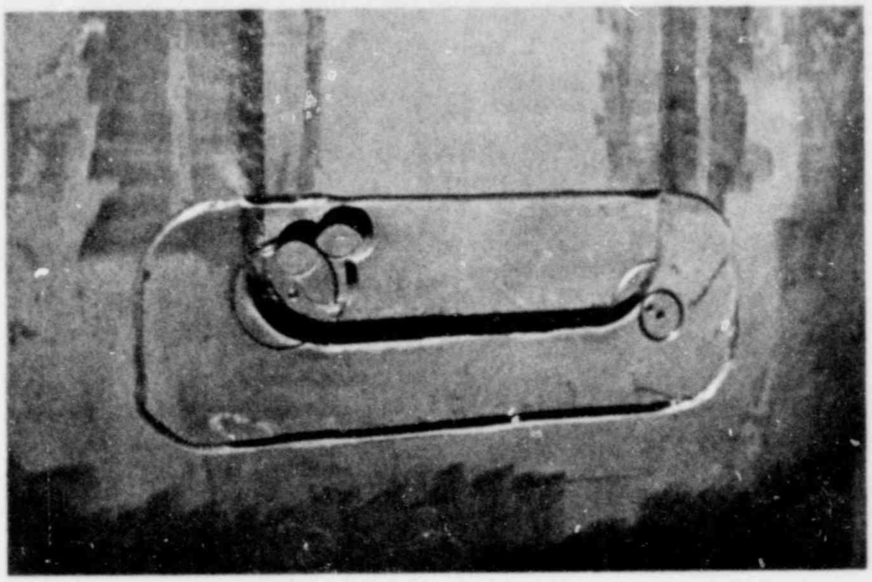

OVERALL CUT
OUT AREA

FIGURE 3
SAMPLE REMOVAL FROM CONTAINMENT

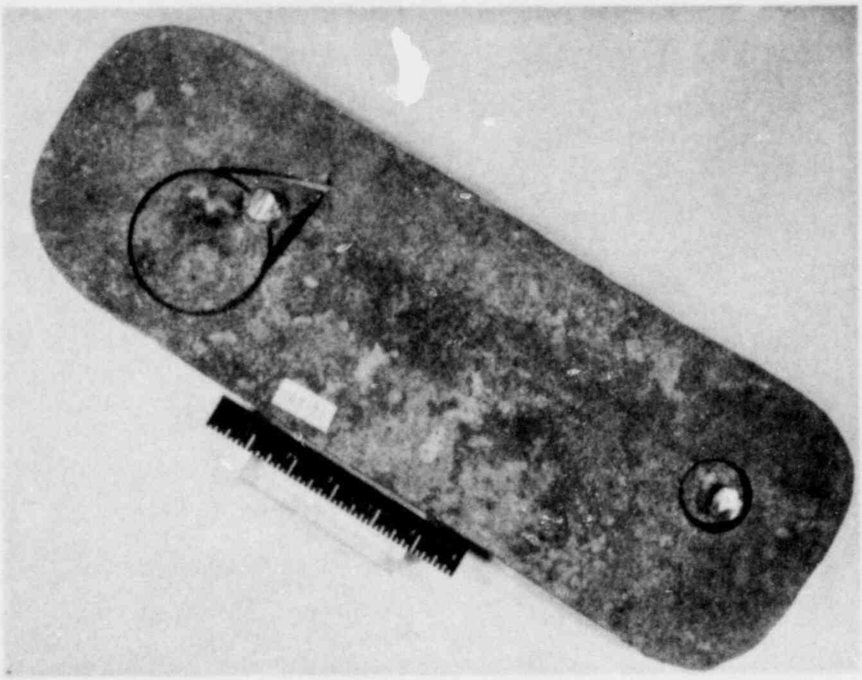


FIGURE 4
VIEW OF SAMPLE FROM BACK SIDE

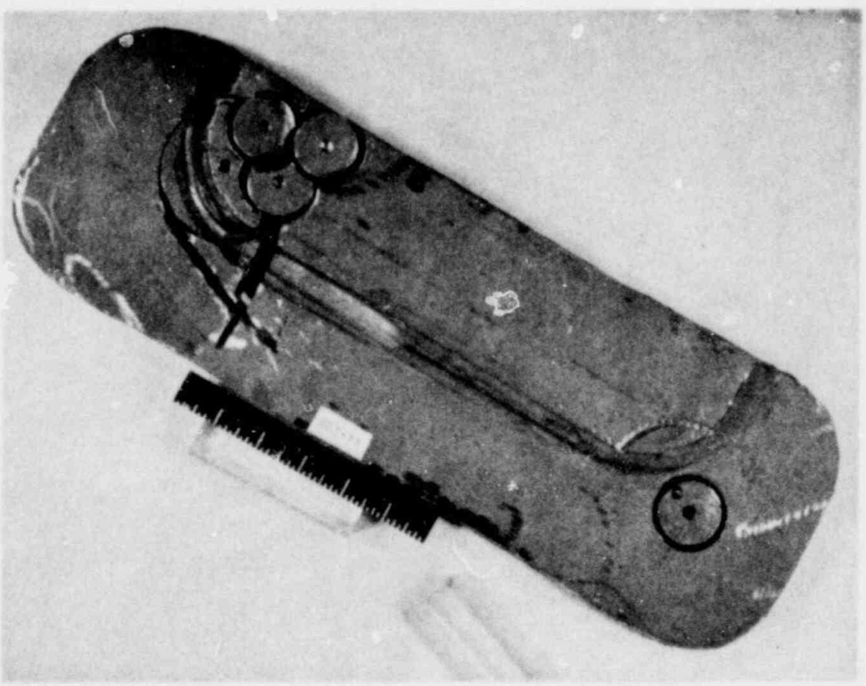


FIGURE 5
VIEW OF SAMPLE FROM WELD SIDE

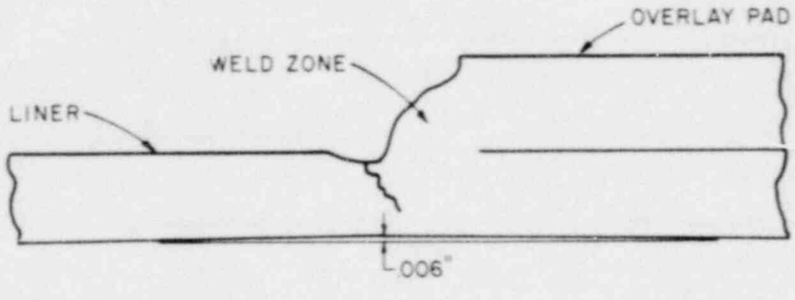
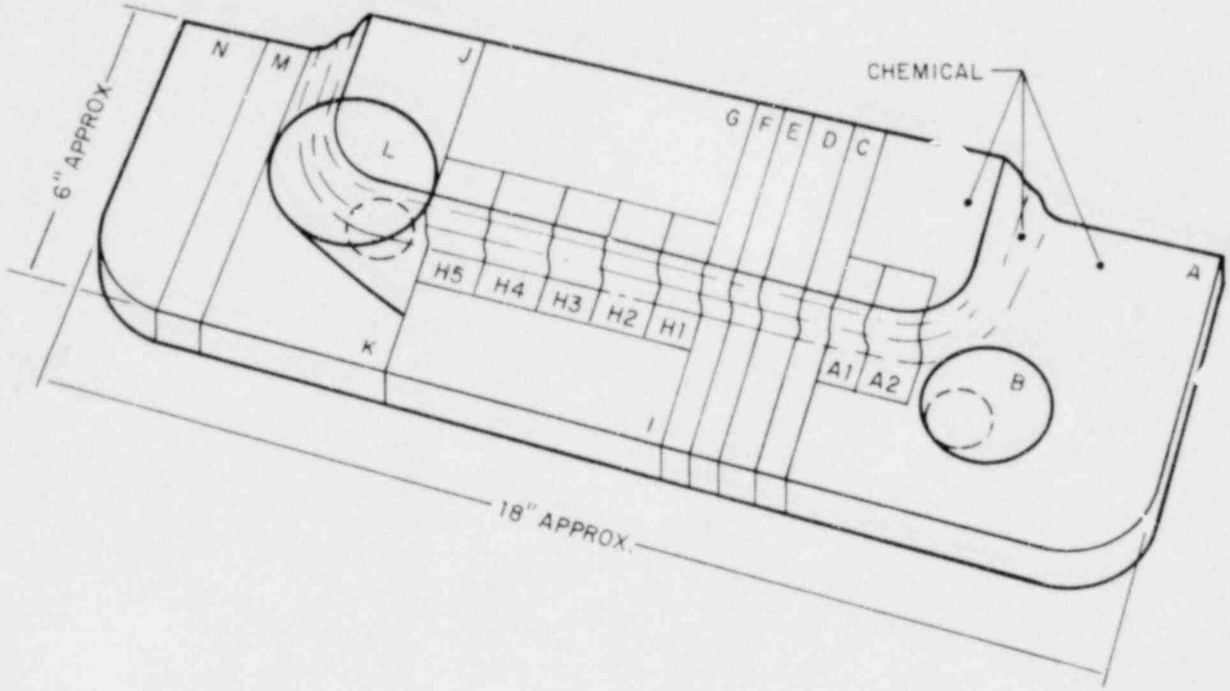


FIGURE 6
PALPABLE DEPRESSION OPPOSITE WELD DEPOSIT
(CROSS SECTIONAL VIEW)

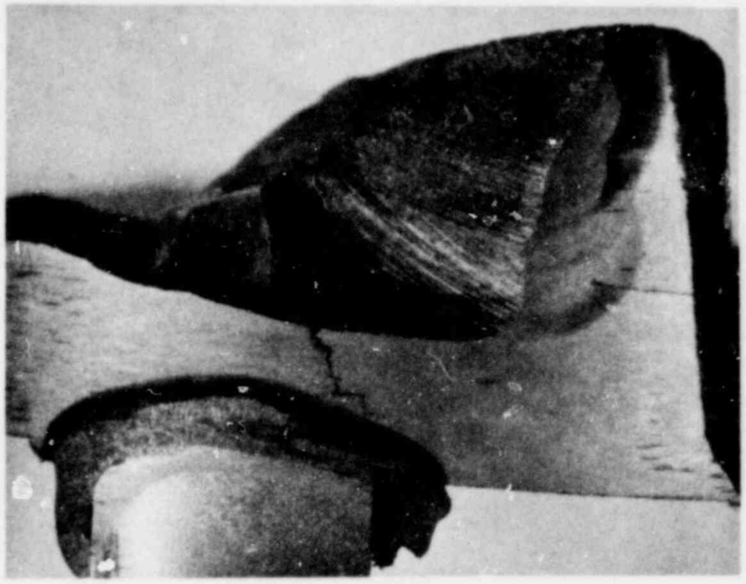
FIGURE 7
PHOTO RADIOGRAPH OF FILLET WELD



TEST	LOCATION
NONDESTRUCTIVE TESTING	
MAGNETIC PARTICLE	ENTIRE SAMPLE
X-RAY	ENTIRE SAMPLE
ULTRASONIC	ENTIRE SAMPLE
CHEMICAL	A (AS INDICATED), LINER ONLY AT J
MACRO	ENTIRE SAMPLE AND ALL CROSS SECTIONS WITH CRACK
METALLOGRAPHIC	C, L
HARDNESS	C
TENSILE	A, N
BEND	M, I, A
FRACTURE SURFACE	A1, A2, D, E, F, H1, H2, H3, H4, H5
SCANNING ELECTRON MICROSCOPE	H1, A1, TENSILE TEST

FIGURE 8

TEST SAMPLE - SECTIONED FOR METALLURGICAL TESTS (LAYOUT)



MAG. 3X

MAG. 12X

FIGURE 9
VIEWS OF CRACK AT STUD/LINER/WELD/PAD JUNCTION

(LOCATION L - FIG.8)

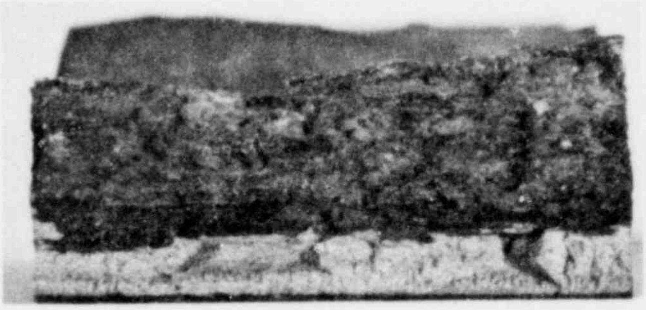
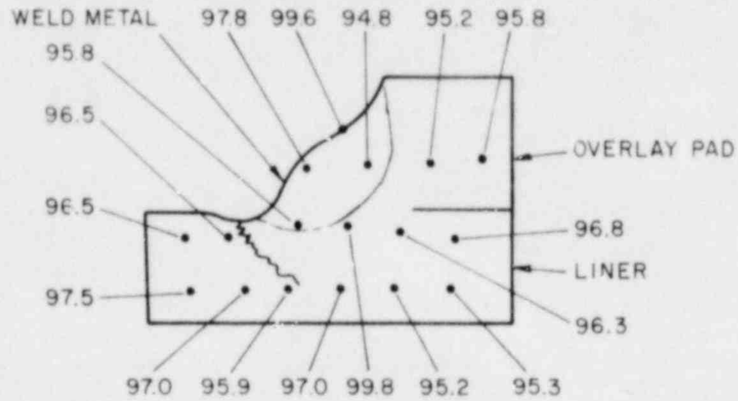
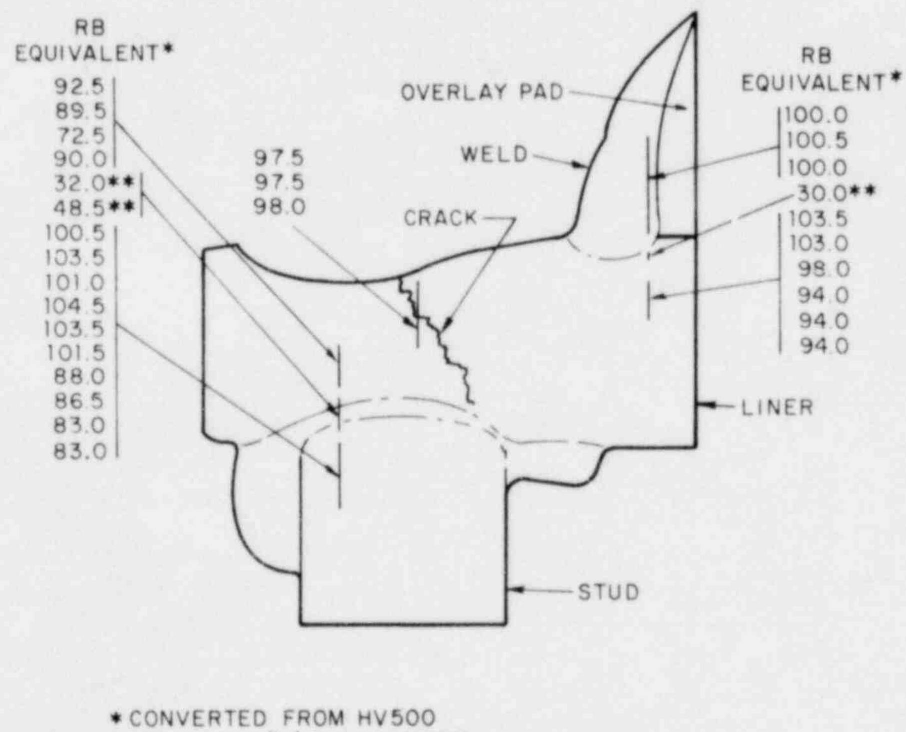


FIGURE 10
CRACK SURFACE
(LOCATION D - FIG. 8)



ROCKWELL "B" SURVEY
(LOCATION C - FIGURE 8)



* CONVERTED FROM HV500
** ROCKWELL "C" (CONVERTED)

MICROHARDNESS SURVEY
(LOCATION L - FIGURE 8)

FIGURE 11

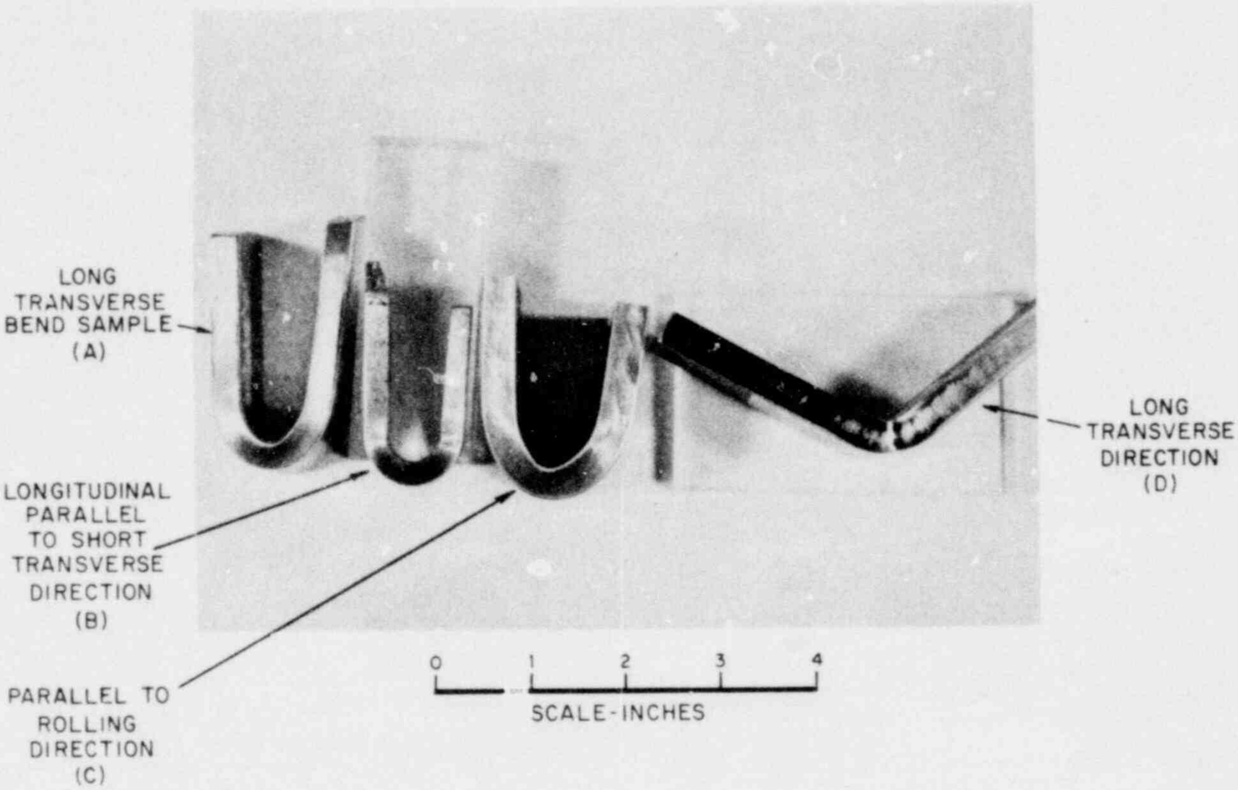


FIGURE 12

SERIES OF SPECIMENS PLASTICALLY DEFORMED BY BENDING OVER A 2-THICKNESS RADIUS MANDREL

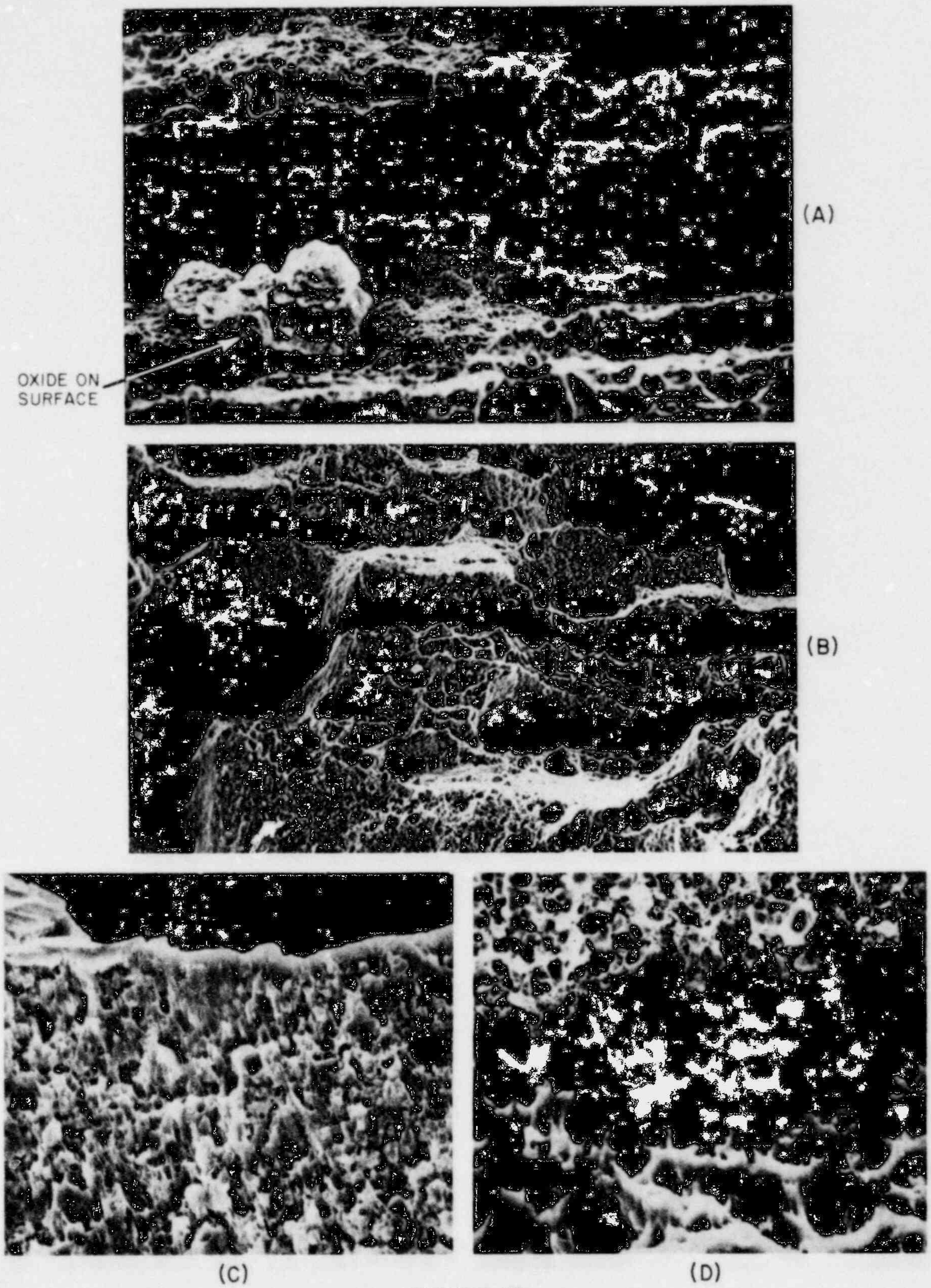
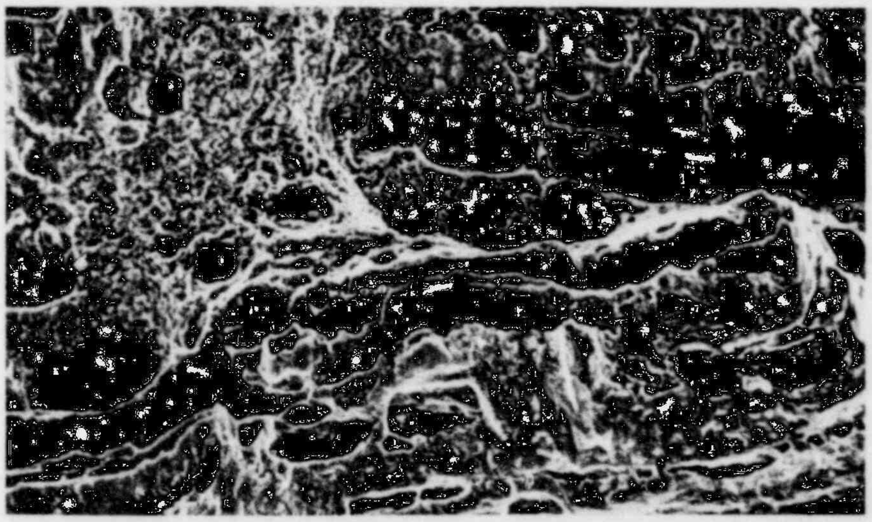
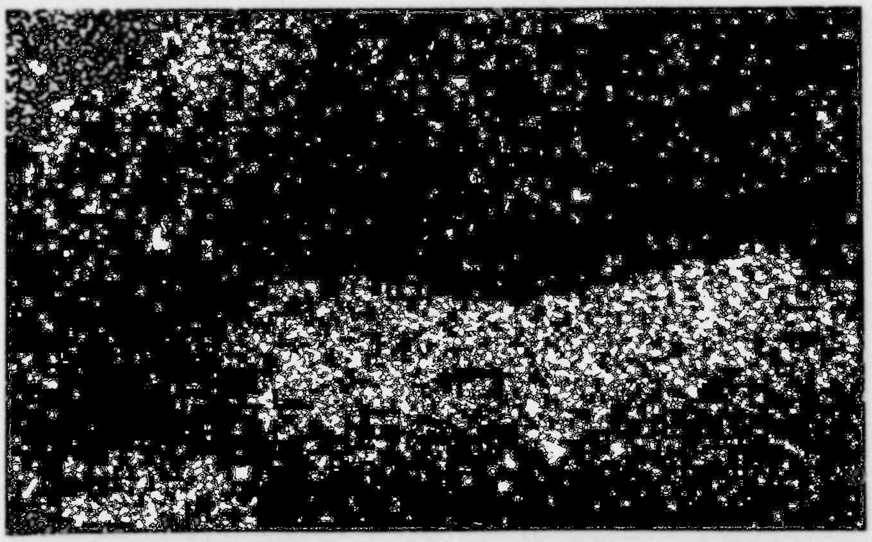


FIGURE 13

(A) FRACTURE OF CRACK SURFACE (PHOSPHORIC ACID CLEANED) MAG. 200X
(B) FRACTURE OF TENSILE SPECIMEN (NO CLEANING) MAG. 200X
(C) BEND TEST FRACTURE (TENSION SIDE) MAG. 1700X
(D) BEND TEST FRACTURE (COMPRESSION SIDE) MAG. 2100X



(A)



(B)

(C)

FIGURE 14

(A) FRACTURE DETAIL OF BEND TEST FRACTURE - TENSION SIDE MAG 425X

(B) MANGANESE X-RAY MAPPING OF AREA SHOWN IN FIGURE 14(A) WHITE DOTS DENOTE MANGANESE RICH AREAS MAG 425X

(C) A NONMETALLIC INCLUSION (MANGANESE RICH) OBSERVED IN TENSILE TEST FRACTURE SHOWN IN FIGURE 13(B) MAG 5000X

PORTION OF CRACK AND INCLUSIONS
UNETCHED MAG. 50X

CARBIDES IN A TEMPERED MARTENSITIC MATRIX
NITAL ETCH MAG. 500X

FIGURE 15
PHOTOMICROGRAPHS

(LOCATION C - FIG.8)

ELEMENT	LINER				OVERLAY PAD			WELD ROD		
	ASTM	MILL[1]	1[2]	2[3]	ASTM	MILL	S&W	ASME II	MILL	S&W**
C	.24 MAX.	.18	.17	.19	24 MAX.	.20		.12 MAX.	.05	.10
Mn	.65-1.40	1.33	1.28	1.29	.65-1.40	1.23	1.15	.40-1.25	1.07	1.32
Si	.13-.55	.34	.34	.33	.13-.55	.36	.32	.80 MAX.	.40	.58
S	.040 MAX.	.022	.020	.021	.040 MAX	.021	.020	.030 MAX.	.012	.019
P	.035 MAX.	.008	.024	.023	.035 MAX.	.008	.021	.030 MAX.	.011	<.005
Ni	.25 MAX.	*	.21	.19	.25 MAX.	.17	.14	.80-1.10	1.06	1.00
Cr	.25 MAX.	*	.19	.20	.25 MAX.	.13	.10	.15 MAX.	.01	.08
Mo	.08 MAX.	*	.04	.06	.08 MAX.	.05	.03	.35 MAX.	.10	.10
V	—	—	.001	.005	—	—	.001	.05 MAX.	.02	.015
Cu	.35 MAX.	*	.12	.17	.35 MAX.	.30	.07	—	.03	.07
Pb	—	—	<.001	<.005	—	—	<.001	—	—	<.001
Sn	—	—	<.005	<.01	—	—	<.005	—	—	<.005
Sb	—	—	<.005	<.005	—	—	<.005	—	—	<.005
Bi	—	—	<.005	<.005	--	—	<.005	—	—	<.005
O_2	—	—	.0027	.0023	—	—	.0022	—	—	.080
N_2	—	—	.014	.023	—	—	.019	—	—	.012

LEGEND:

1 LADLE ANALYSIS

2 SAMPLES FROM SECTION A (SEE FIGURE 8)

3 SAMPLES FROM SECTION J (SEE FIGURE 8)

* LACKING FROM MILL CERTIFICATION REPORT

** ACTUAL WELD DEPOSIT

TABLE I

CHEMICAL ANALYSIS

(PER CENT)

	ASTM	MILL	S & W LOCATION N*	A*
ULTIMATE STRENGTH (KSI)	80.-100.	86.2, 89.1	97.3, 98.6	97.3
YIELD POINT OFFSET (KSI)	60 MIN.	77.5, 74.5	86.0, 86.3	85.9
ELONGATION (%)	22 MIN.	23.0, 30.0	24,24	22

LEGEND:

* ROUND .250 DIA. TENSILE SPECIMENS WERE USED IN ACCORDANCE WITH ASTM-A-370

TABLE II

TENSILE TESTS
OF LINER STEEL (A537B)

Enclosure 2

Enclosure 2

REACTOR CONTAINMENT LINER
OVERLAY PAD FILLET WELD CRACK
AT
BEAVER VALLEY POWER STATION - UNIT NO. 2

Prepared By Mel Adams

Dr. C. M. Adams

The following paragraphs summarize my conclusions in connection with the causes and implications of the subject failure:

1. The location and orientation of the crack leave little doubt that the fracture initiated at the toe of the fillet weld joining the pad to the liner plate, and that the crack was hydrogen-induced. This conclusion would be supportable even in the absence of evidence that crack initiation took place several weeks after welding. The delay reinforces this finding.

2. This failure is considered unique, in no way symptomatic of some generic defectiveness, and no problem is foreseen with the other pad welds or with implementing a completely secure repair.

DISCUSSION

Some two (cold) months after welding, the pad welds passed visual and magnetic particle inspection. The crack either had not initiated or was small enough to escape detection; surely, it had not become of such dimensions as were later observed during preparation for painting. Studs were welded to the outside of the liner within a few days before or after execution of the pad fillet weld. Concrete was poured roughly six months after welding.

The fracture itself is distinguished in several ways:

a. Orientation suggests initiation as a typical toe crack, as does the original report of the crack. The exact point of initiation has been removed by grinding.

b. The transverse profile of the crack indicated substantial displacement, with the maximum crack opening, in excess of 0.020 in, prevailing nearest the toe of the weld. The crack opening decreases with distance into the plate, away from the toe of the weld.

c. The fracture surfaces, as well as metallographic cross sections, revealed some propensity for lamellar tearing as a mechanism for crack propogation. However, it is most unlikely this crack initiated as a lamellar tear, especially in light of the aforementioned displacement, the geometry of which forces the conclusion the crack propagated from the toe inward. Moreover, lamellar tearing is very rarely encountered near single fillet lap welds in plate less than one inch thick. Finally, exhaustive ultrasonic testing of the plate

material beneath the fillet weld revealed no indications of isolated lamellar tears. All tearing was closely associated with and functioned to extend initial toe cracking. Weld areas adjacent to each end of the crack had no lamellar tears.

d. The fracture surface indicated transverse bend ductility was low.

e. There was no fractrographic evidence of fatigue.

f. The fracture was not of the brittle cleavage type associated with fast propagation below the transition temperature.

The mechanical properties of the liner plate, at least in the region of the crack, were marginal, and differed from the certified mill test report, indicating these marginal properties were localized (i.e., did not prevail throughout the plate). In the region of the crack, the ultimate tensile and yield strengths were about 10 ksi higher than the mill test report values (the U.T.S. close to the ASTM maximum, 100 ksi, for A537B), and the elongation right at the minimum, 22 percent, all values determined by testing in the long transverse direction. The transverse bend tests failed in the marginal region, but passed in the mill test.

The steel is quite clear, exhibiting normal microstructure. Local property variations are considered due to microsegregation of alloying elements, principally manganese, together with some variation in mill heat treatment, in that some portions of the plate were rendered harder and stronger than would have been preferred, although within specified ranges. In view of the generally high metallurgical quality of the material studied, it is considered most unlikely local variations would include regions which fall outside specifications in any mechanical property except bend ductility.

The slightly low local transverse ductility is not considered to have played a significant part in crack initiation. The relatively high local strength did increase the susceptibility to hydrogen embrittlement. Once initiated as a hydrogen-induced crack, subsequent crack growth was doubtless exacerbated by the limited transverse ductility.

Although fixing the blame positively on hydrogen as an initiating cause may seem unduly speculative, since the locus of crack initiation was destroyed by grinding, field experience with A537B supports this conclusion. Much of the support is indirect: even with low bend ductility, this material is so tough and plastic that a classic toe crack almost defies any explanation other than hydrogen. And, where toe cracking has been a problem in other

instances, with steels like A537B, instituting programs which positively eliminate hydrogen, notably a post-weld bake, has constituted an absolute fix. Thus, although hydrogen is difficult positively to detect or measure, the circumstantial evidence is compelling. The delay in cracking, if real, would, in and of itself, leave no doubt. Absent fatigue loading, there is no probable way to initiate a delayed toe crack, except by hydrogen induction.

In the context of the stresses and strains expected in service, the mechanical properties of this liner plate are entirely satisfactory. Only if severe plastic bending or other deformation were contemplated would the limited short transverse ductility be grounds for concern. By now any hydrogen has diffused from the steel, and a post weld bake will ensure this also for the repair; therefore, the hazard of toe cracking has been eliminated. By the same argument, the other pad welds and other liner plates can be given a clean bill of health.

The conclusion is this pad weld was unique in that three adverse circumstances prevailed simultaneously:

a. Hydrogen in the form of moisture entered the arc atmosphere, either from the electrode coating, which would permit an inference of improper electrode handling, for which there is no evidence, or from the interface between the pad plate and the liner, which seems more likely, since substantial preheat was not required, the ambient temperature was quite low, and rain had occurred the day before welding.

b. Location of the studs on the outside of the liner offered somewhat more than normal restraint to loads in the case of this particular weld.

c. Transverse ductility in the immediate region of the weld was low.

REPAIR OF CONTAINMENT

There is no reason to doubt that repair welds against the concrete can be successfully and permanently executed, provided that all steps are taken to prevent hydrogen embrittlement of the heat-affected zones of the repair welds.

Specifically:

1. Preheat in the range 250°F to 350°F should be sustained for at least 30 minutes prior to and during welding.

2. Postweld baking at 250°F to 350°F for 24 hours will absolutely ensure removal of any hydrogen.

3. Electrodes should be transferred directly from their hermetically sealed containers to a holding oven at 250°F, and should suffer no more than two hours total exposure to the ambient atmosphere between removal from the oven and welding.

Dr. C. M. Adams

ENCLOSURE 3

Enclosure 3

REACTOR CONTAINMENT LINER

OVERLAY PAD FILLET WELD

AT

BEAVER VALLEY POWER STATION - UNIT NO. 2

LINER PLATE SERVICEABILITY REVIEW

Prepared By P.W. Ward
P.W. Ward

Liner Plate Serviceability Review

The metallurgical investigation of the overlay pad fillet weld crack has found the local liner base material to exhibit a transverse ductility lower than mill certified. The material is satisfactory for use as required by the ASME II, Part A, SA-537 CL-2 requirements; i.e., minimum elongation of 22% in 2 in. The following will show that this local area of the liner base material is acceptable for meeting the intended service for the life of the power plant.

Stresses are calculated in the containment liner in a very conservative manner. A liner finite element model was developed by representing the composite reinforcing steel and liner steel as an equivalent orthotropic shell, neglecting any strength contribution by the concrete. This model was subjected to the combined axisymmetric loadings of deadweight, DBA pressure, and DBA temperature in order to establish the membrane and bending stresses in the liner. The total seismic shear force in the reinforced concrete containment wall (neglecting the strength of the concrete) was then assumed to be applied to the liner and rebar in order to establish a conservative estimate of liner shear stress. The shear stress was combined with the liner finite element model membrane and bending stresses to determine the maximum stress intensity range. This stress range was compared to and found to be less than the established allowables.

Stone & Webster Engineering Corporation calculation 12241-SM-EA-3 "Stress Analysis of Containment Liner" demonstrates the adequacy of the containment liner design for the pressure, temperature, and seismic loads associated with the conditions specified in the Beaver Valley Power Station - Unit No. 2 Preliminary Safety Analysis Report. The conservatism of the above analysis is also shown by the stresses and strains recorded by strain gage readings during the Reinforced Concrete Containment structural acceptance tests of Beaver Valley Power Station - Unit No. 1. The geometry and test pressures for Unit No. 1 and Unit No. 2 of the Beaver Valley Power Station are the same. A Comparison of the stresses resulting from metallurgical tests, analysis and the BVPS No. 1 structural acceptance test is shown in Table 1.

The current industry code applicable to the design of containment liners is ASME Section III, Division 2. This code recognizes that liner forces are displacement limited and provides liner allowables in units of in./in. of strain. In order to compare stress results with current code strain limits, the membrane and bending stresses calculated by elastic theory have been converted to strain (by dividing stresses by the Modulus of Elasticity) and are listed in Table 2. Since these strains are mostly membrane strain, they are conservatively compared in the table to the lower code allowable for membrane strain of 5×10^{-3} in/in. (The code allowable for membrane plus bending is 14×10^{-3} in/in.)

The above discussion and the tables clearly show that the local liner material is adequate for the intended service.

Table 1 Stress Comparisons

Case	Stresses			
	Principal		Max Intensity (psi)	ASME III Allowable Intensity Stress (psi)
	Circ (psi)	Long (psi)		
Analysis				
Emergency	-18000	-32000	32000	60000
Severe Operational	-8000	-11500	11500	20000
Normal Operation	-18000	-23000	23000	60000
Structural Acceptance Test	25000	13000	25000	54000
Metallurgical Test Results	Yield (psi) 86100	Tensile (psi) 97700		
BV#1 Structural Acceptance Test Results	Maximum (psi) 12000	Minimum (psi) 8000		

Table 2 Strain Comparisons

Case	Strains		
	Circ (in/in)*	Long (in/in)*	ASME III Allowable (in/in)
Analysis			
Emergency	.00065	.00115	.005**
Severe Operational	.00029	.00054	.005**
Normal Operation	.00065	.00082	.002***
Structural Acceptance Test	.00090	.00047	.003****
Metalluriqical Test Results	Yield* .0031	Tensile .220	
BV#1 Structural Acceptance Test Results	Maximum* .0004	Minimum* .00027	

*E = 27.9 x 10^6 psi

** Factored Compression
*** Service
**** Factored Tension

} Table CC-3720-1