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STRESS CORROSION CRACKING OF CARBON STEEL IN SIMULATED WASTE SOLUTIONS

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ABSTRACT

A laboratory corrosion test program was carried out to determine the cause of cracking failure in carbon steel tanks used for the storage of radioactive waste. Welded test specimens (carbon steel plate, 36 inches square x 1/2-inch thick, ASTM A285 Grade B) suffered stress corrosion cracking in simulated waste solutions containing nitrate. The cracks induced in the laboratory were similar to the cracks observed in the plant. Full stress relief, which prevented stress cracking of the specimens in the test solutions, should be considered for future tanks of this type.

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STRESS CORROSION CRACKING OF CARBON STEEL IN SIMULATED WASTE SOLUTIONS

INTRODUCTION

High level radioactive waste generated by the Savannah River Plant during the past decade has been stored in underground carbon steel tanks of 750,000 and 1,000,000 gallons capacity. The tanks are steel vessels built within concrete outer shells. The carbon steel primary container sets in a 5-foot-high carbon steel saucer, and this assembly is contained within a concrete vault of sufficient diameter to create about a 2-1/2-foot-wide annulus. To date, four of the sixteen tanks of this type in use have developed side-wall leaks. All of the leaks have occurred in one separations location (H Area); none have occurred in the other location (F Area).

Investigations have been carried out both in the field and in the laboratory to determine the cause of tank failure and to find out how to obtain the best service from the present and future tanks.

A companion report, DP-990[1], describes the history of the tanks from the standpoint of construction, tank contents, service conditions, inspection of the tank walls, and the metallographic examination of specimens removed from the areas of the leaks. That report concluded that stress cracking is the most likely cause for the leaks.

The purpose of the experimental work described in this report was twofold:

(1) To demonstrate in the laboratory that the type of cracking observed in the plant tanks was due to stress corrosion. This was to be done with test specimens immersed in simulated waste solutions, i.e., solutions having a chemical composition similar to actual wastes but free of radioactivity.

(2) To investigate the variables that cause carbon steel to crack. Material variables expected to be pertinent were the steel composition, heat treatment, and method of fabrication; environmental variables were the solution compositions (which were slightly different in the two separations areas), temperature, and exposure time.

The tests were devised by W. C. Rion, Jr. of the Du Pont Engineering Department and carried out by the Savannah River Laboratory at the TNX semiworks facilities between April 1961 and December 1962.

SUMMARY

The laboratory tests showed that:

1. Simulated waste (an aqueous solution of about 30% sodium nitrate at pH 11-12) could cause stress corrosion cracking of large carbon steel specimens.

2. The type of cracking induced in the laboratory was similar to that encountered in the plant.

3. The most effective means of preventing cracking of carbon steel test specimens was to give them full stress relief prior to exposure to the simulated waste. This indicates that full stress relief should be considered in the construction of future tanks of this type. Full-scale stress relief can now be accomplished on tanks of this type.

Laboratory tests were performed on a variety of 4- to 36-inch-square welded plate specimens, 1/2-inch thick. Specimens were exposed to three simulated wastes and to the highly aggressive 50% $NaNO_3$ solutions for periods of 100-200 days at temperatures of 90-95°C.

Cracking depended strongly on the residual stress in the test specimens. The large as-welded plates were the most susceptible to stress corrosion, but fully stress-relieved samples were completely immune to cracking. Samples that were partially stress-relieved did not crack as often as the as-welded specimens, but some cracks did occur. Areas that simulated repairs or attachments were more susceptible to stress corrosion than normal weld seams.

The reliability of data was dependent on specimen size. The 4- and 12-inch specimens were far less reliable than the 36-inch square plates. This difference is believed to be due to the fact that the magnitude of residual stresses, which induce cracking, is less in the small specimens than in the large specimens. The residual stresses originate from thermal gradients created by the welding operation and subsequent cooling. In small specimens, the thermal gradient between the weld zone and parent metal is less than in large specimens because the bulk metal temperature is higher in the small specimens.

The composition of the test solution exerted a recognizable effect on the susceptibility to cracking. Cracking in the simulated wastes followed the same pattern as in the actual storage condition, in that failures were limited to H-Area (H-Purex and HM) type wastes; no cracking was noted with F-Area (F-Purex) type wastes. The most severe cracking was produced by the 50% $NaNO_3$ solution.

No correlation between crack susceptibility and carbon content was noted in as-welded material. The 0.26% C steel cracked as readily as the 0.13 and 0.08% C steels. In the partially stress-relieved state the 0.26% steel appeared to be immune; however, the number of samples tested was small so that a definite conclusion cannot be drawn.

DISCUSSION

SIMULATED WASTE TESTS

36-Inch Test Plates

Procedure

"Full-sized" specimens were fabricated in a manner believed to simulate actual tank construction. These specimens, which were 36-inch squares made of 1/2-inch-thick plate, contained the usual weld seams and, in addition, numerous other stress raisers such as small weld attachments, welded attachments which were subsequently removed, repair welds, and clamp marks. The details on the five varieties of 36-inch-square specimens are listed in the Appendix.

Three steels of different carbon contents were investigated, because carbon content is acknowledged to have considerable effect on the susceptibility to stress corrosion. The carbon contents were 0.08, 0.13, and 0.26%; the analyses and the mechanical properties are listed in Table I.

The compositions of the simulated waste solutions are given in Table II. These solutions are primarily alkaline nitrate solutions whose nitrate contents, the ion responsible for stress corrosion, vary from 30 to 37%. The solutions were maintained at 90-95°C by stainless steel steam coils during the runs. A type 304L stainless steel tank contained the solutions, and samples were electrically insulated from the tank by "Teflon"* sheet. No stress corrosion of the stainless steel tank and steam coils was observed.

* E. I. du Pont de Nemours registered trademark for TFE fluorocarbon resin.

TABLE I

Properties and Composition of Steels

Heat Number →	Bethlehem 480 C160	USS 69 U087	Bethlehem 479 C161
ASTM Classification →	Low carbon similar to ASTM A-285, Grade B (aluminum killed)	ASTM A-285, Grade B	ASTM A-212, Grade B
Mechanical Properties			
Yield, psi	38,000	35,780	47,100
Tensile strength, psi	50,300	56,780	74,700
% elong. in 8 in.	31.0	34.0	26.0
Chemical Comp., %			
C	0.08	0.13	0.26
Mn	0.34	0.46	0.65
P	0.010	0.011	0.013
S	0.024	0.027	0.024
Al	0.10	-	-
Si	-	-	0.20

TABLE II

Composition of Simulated Waste Solutions[(a)]

	F Area	H Area	
	F-Purex	H-Purex	HM
$NaNO_3$	29.7	36.6	29.8
$NaAlO_2$	0.0	0.0	7.8
Na_2SO_4	5.8	2.3	0.2
NaOH	1.0	1.1	3.8
MnO_2	0.3	0.6	0.0
$Fe(OH)_3$	2.6	0.5	0.1
$Mn(OH)_2$	0.1	0.1	0.0
KNO_3	0.1	0.3	0.0
$Hg(OH)_2$	0.0	0.0	0.1
H_2O	60.4	58.5	58.2

(a) Weight percent.

Prior to exposure, each specimen was visually inspected for defects so that any cracking subsequently observed could be attributed solely to stress corrosion. In all cases the mill scale on the steel plates was allowed to remain on the surface to simulate the conditions found in tank construction.

In addition to testing materials in the as-welded condition, the effects of two stress-relief heat treatments were investigated. One stress-relief treatment involved passing a wide gas burner over the welded areas. In this manner, the localized stresses immediately adjacent to the weld were modified, but since the entire specimen was not heated and uniformly cooled, there were some residual stresses. This technique should be considered a partial-stress-relief treatment; however, one disadvantage is the considerable warping that occurs. Partial stress relief was investigated because full stress-relief techniques were not considered feasible when this program was performed.

The second heat treatment involved complete stress relief. The procedure followed is outlined in the ASME code, 1959, paragraph UCS-56; the principal features are listed below.

1. The specimens must be placed in the furnace when the furnace temperature is less than 316°C (600°F).

2. The heating rate from 316°C to 593°C (1100°F) will not exceed 200°C/hour.

3. The 593°C temperature will be maintained for 30 minutes.

4. The maximum cooling rate is not to exceed 260°C/hour on cooling from 593°C to 316°C.

Results

In HM Solution. Nine 36-inch plate specimens were exposed to the simulated HM solution for 171 days, and four of these cracked completely through the 1/2-inch thickness in at least one area. The remaining five plates showed no cracking. Table III summarizes the cracking history.

The cracking tendency was closely related to the heat treatment. The as-welded plates proved to be the most susceptible to cracking; all three specimens failed within 11 days' exposure. The partially stress-relieved specimens were more resistant to cracking; only one of the three failed. No cracks were found in the fully stress-relieved specimens.

TABLE III

History of 36-Inch Plates Exposed
for 171 Days at 90-95°C in HM Solution

Specimen Type	Carbon Content, %	Exposure to the Beginning of Cracking, days	Comments
M-2	0.08	11	Cracked at repair weld
M-2S	0.08	-	No cracks
M-2R	0.08	-	No cracks
O-2	0.13	11	Cracked at repair weld
O-2S	0.13	30	Cracked through vertical weld
O-2R	0.13	-	No cracks
X-2	0.26	11	Cracked at repair weld
X-2S	0.26	-	No cracks
X-2R	0.26	-	No cracks

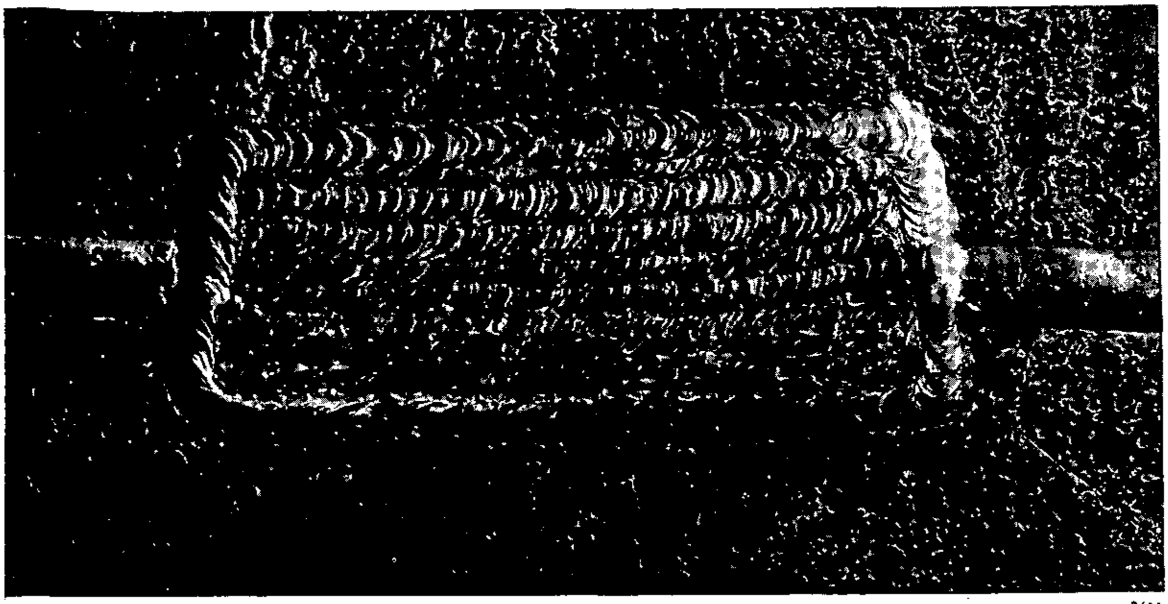
NOTES: See appendix for exact design of specimens. The suffixes S and R designate partial and complete stress relief, respectively. Specimens whose numbers do not end in S or R were tested in the as-welded condition.

Inspections were made every two to three days the first week and weekly thereafter.

In these limited tests, the carbon content of the steel did not have a significant effect on stress corrosion. No difference was seen in the three as-welded specimens that were fabricated from 0.08, 0.13, and 0.26% carbon steel. In the partially stress-relieved specimens only the 0.13% carbon steel failed; specimens of both higher and lower carbon contents did not fail.

The cracks were always associated with welds, particularly with the repair and attachment welds. Figures 1 and 2 show cracks proceeding both through and around the repair weld, although the latter was most often noted. Only with the partially stress-relieved specimens did the failure occur predominantly at the main weld seams, an indication that the residual stresses had been rearranged but not eliminated.

In H-Purex Solution. Eight specimens were exposed for 115 days but only one (as-welded 0.26% carbon steel) cracked, as shown in Table IV. These results suggest that this simulated solution is not as aggressive as the HM solution from the stress-corrosion viewpoint.



NEG. 8341-9 ¾X

This particular area was the only cracked section found on the specimen. This cracking pattern was typical of that noted with the as-welded plates around repair welds; cracking does not penetrate into the welded area but rather traces a path around it and additionally tends to radiate from the corners.

FIG. 1 CRACKED REPAIR WELD IN SPECIMEN M-2 (0.08% C) EXPOSED TO HM SOLUTION

NEG. 8325-28 ¼X

In contrast to specimen M-2 that was shown in Figure 1, this specimen cracked through the repair weld and followed the weld seam for a short distance.

FIG. 2 CRACKED REPAIR WELD IN SPECIMEN O-2 (0.13% C) EXPOSED TO HM SOLUTION

TABLE IV

History of 36-Inch Plates Exposed
for 115 Days at 90-95°C in H-Purex Solution

Specimen Type	Carbon Content, %	Exposure to the Beginning of Cracking, days	Comments
M-F	0.08	-	No cracks
M-FS	0.08	-	No cracks
M-FR	0.08	-	No cracks
O-F	0.13	-	No cracks
O-FS	0.13	-	No cracks
O-FR	0.13	-	No cracks
X-F	0.26	42	Cracked under weld attachment
X-FR	0.26	-	No cracks

NOTES: See appendix for exact design of specimens. The suffixes S and R designate partial and complete stress relief, respectively. Specimens whose numbers do not end in S or or R were tested in the as-welded condition.

Inspections were made every two to three days during the first week and weekly thereafter.

In F-Purex Solution. Seven specimens were immersed in this solution for 190 days but no cracking was observed. This result is in agreement with actual practice in that no leaking tanks have been discovered in F Area where this type of waste is generated and stored. The pertinent data for this test are listed in Table V.

TABLE V

History of 36-Inch Plates Exposed
for 190 Days at 90-95°C in F-Purex Solution

Specimen Type	Carbon Content, %	Comments
M-2	0.08	No cracks
M-F	0.08	No cracks
MF-RR	0.08	No cracks
OF	0.13	No cracks
OF-RR	0.13	No cracks
XF	0.26	No cracks
XF-RR	0.26	No cracks

NOTES: See appendix for exact design of specimens. The suffix R designates a full stress-relief heat treatment; all other specimens were tested in the as-welded condition.

4- and 12-Inch Test Plates

The three simulated waste solutions did not produce stress cracks in a series of smaller welded specimens, which indicated the importance of testing realistic specimens in these simulated solution environments.

The small specimens were of two sizes, 4-inch and 12-inch squares, made of the same three steels as the larger specimens. Welding was employed to introduce residual stresses. The fabrication details are given in the appendix.

The specimens were tested in 55-gallon stainless steel drums at temperatures between 85 and 90°C, the maximum that could be obtained with the units. The specimens were electrically insulated from the drums.

Six of these small specimens, types M-1, M-11, O-1, O-11, X-6, and X-66, were immersed in each of the three waste solutions. No cracking was detected during a 200-day exposure, and at that point air was bubbled into the solution for 40 more days in an effort to induce cracking. Cracking still did not occur. After 240 days of total exposure, the hydroxide content was increased one weight per cent; cracking did not occur, and finally after 330 days total exposure the tests were terminated.

SCREENING TESTS FOR NITRATE SOLUTIONS

The previous tests with simulated waste solutions clearly showed that some solutions were capable of stress corroding the large plate specimens. The next step was to determine what fabrication variables were most important by conducting tests in highly aggressive solutions.

To select a highly aggressive solution, screening tests were made using the same small-sized (4- and 12-inch square) specimens described previously. Three solutions were evaluated at temperatures of 90-95°C: (1) 50% $NaNO_3$, (2) a mixture of 60% $Ca(NO_3)_2$ and 3% NH_4NO_3, and (3) 20% NH_4NO_3. The data are listed in Table VI, and the results are summarized as follows:

Screening Tests for Nitrate Solutions

Solution	Results
50% $NaNO_3$	Cracked 4 of 4 12-inch specimens and 1 of 3 4-inch specimens
60% $Ca(NO_3)_2$ + 3% NH_4NO_3	Cracked 3 of 4 12-inch specimens and 2 of 3 4-inch specimens
20% NH_4NO_3	Cracked 2 of 4 12-inch specimens and none of 4-inch specimens

TABLE VI

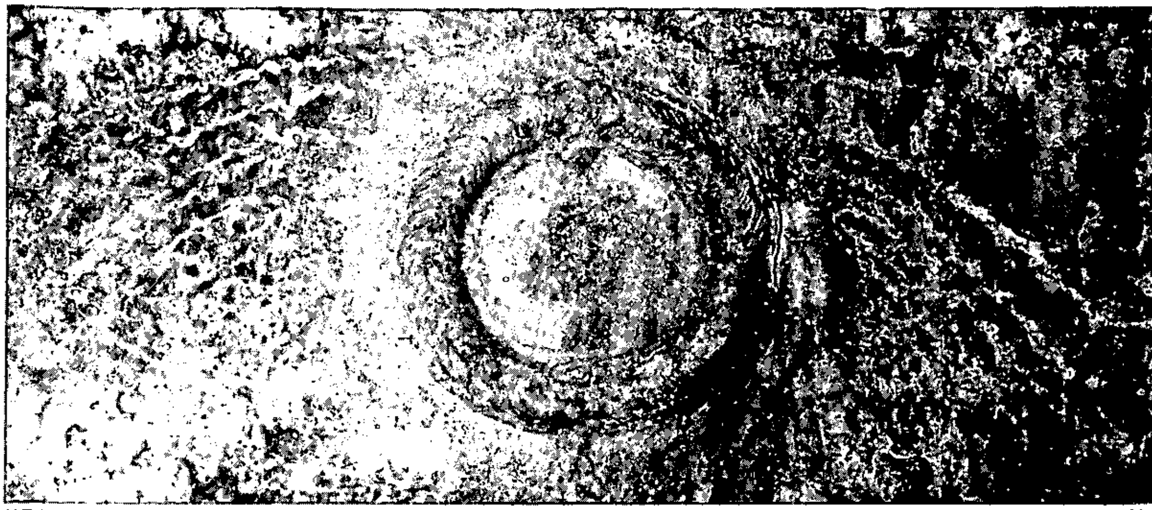
History of Twelve-and Four-Inch Square Specimens Exposed for 24 Days in Nitrate Solutions at 90-95°C (Screening Tests)

Specimen Type,[a]	size	Exposure to the Beginning of Cracking, days	Comments
		In 50% $NaNO_3$	
M-1	12"	8	Cracked around weld
O-1	12"	8	"
X-6	12"	8	"
X-X	12"	22	"
M-11	4"	15	"
O-11	4"	-	No cracks
X-66	4"	-	"
		In 60% $Ca(NO_3)_2$-3% NH_4NO_3	
M-1	12"	6	Cracked around weld
O-1	12"	-	No cracks
X-6	12"	12	Cracked around weld
X-X	12"	7	"
M-11	4"	20	"
X-66	4"	20	"
O-11	4"	-	No cracks
		In 20% NH_4NO_3	
M-1	12"	-	"
O-1	12"	-	Cracked across weld
X-6	12"	15	"
X-X	12"	15	
M-11	4"	-	No cracks
O-11	4"	-	"
X-66	4"	-	"

(a) See appendix for exact design of specimens. The carbon content of the steels was as follows: M = 0.08%, O = 0.13%, X = 0.26%.

Figures 3 and 4 show the appearance of cracks in the 12-inch specimens.

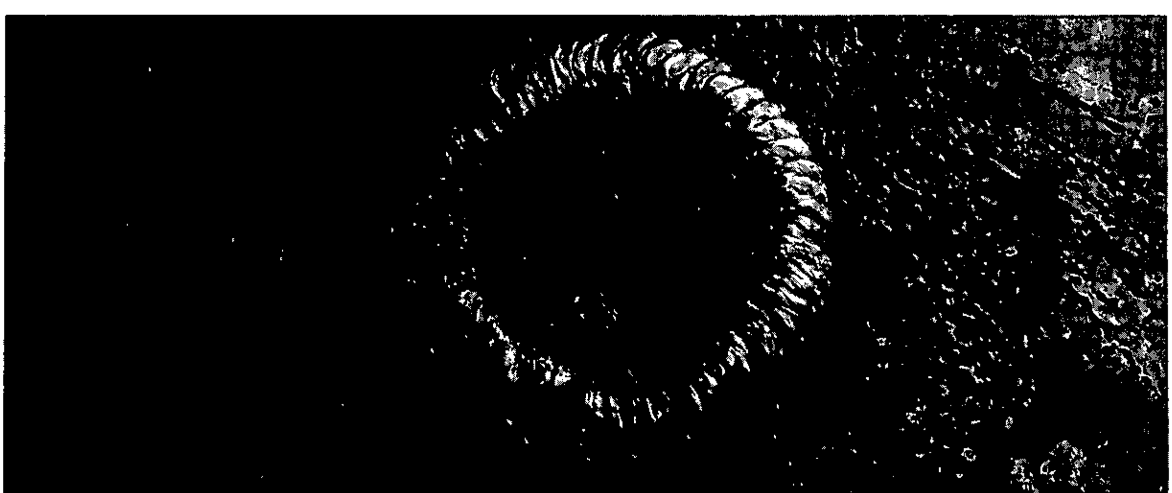
Because the 50% $NaNO_3$ solution cracked all four 12-inch specimens, this solution was used with the 36-inch specimens.



NEG. 34748 ½X

This shows the cracking pattern that was common to all failures in both sodium and calcium nitrate solutions. Cracking was adjacent to but not in the weld metal and was always found on the outside of the circular weld, in contrast to that noted with ammonium nitrate solution. The arcs emanating from the weld are caused by mill scale that flaked off during welding.

FIG. 3 TWELVE-INCH SPECIMEN CRACKED IN $NaNO_3$



NEG. 8340-14 ½X

This sample, XX (0.26% C), shows cracks penetrating the weld metal, as well as extending on both sides. The other specimen that failed in NH_4NO_3 also cracked on the inside of the circular weld.

FIG. 4 TWELVE-INCH SPECIMEN CRACKED IN 20% NH_4NO_3

TESTS OF 36-INCH PLATES IN 50% SODIUM NITRATE

Twenty of the large plates were exposed to 50% $NaNO_3$ at 90-95°C for as long as 167 days to determine which fabrication variables were most important in promoting stress corrosion. The specimens and heat treatments were identical to those used in the simulated waste tests. Table VII lists the results of the tests.

TABLE VII

History of 36-Inch Plates Exposed for 167 Days at 90-95°C in 50% $NaNO_3$

Speciman Type	Carbon Content, %	Exposure to the Beginning of Cracking, days	Comments
M-2	0.08	3	Cracked around repair weld
M-2S	0.08	27	Cracked near repair weld
M-2R	0.08	-	No cracks
M-22	0.08	3	Cracked around clamp and weld
M-22R	0.08	-	No cracks
MF	0.08	3	Cracked at attachment
MF-S	0.08	3	Cracked at attachment
MF-R	0.08	-	No cracks
O-2	0.13	3	Cracked around repair weld
O-2S	0.13	14	Cracked near repair weld
O-2R	0.13	-	No cracks
O-F	0.13	7	Cracked at attachment
O-FS	0.13	83	Cracked along horizontal weld
O-FR	0.13	-	No cracks
X-2	0.26	3	Cracked around repair weld
X-2S	0.26	-	No cracks
X-2R	0.26	-	No cracks
X-F	0.26	3	Cracked at attachment
X-FS	0.26	-	No cracks
X-FR	0.26	-	No cracks

NOTES: See appendix for exact design of specimens. The suffixes S and R designate partial and complete stress-relief heat treatments, respectively. Specimens whose numbers do not end in S or R were tested in the as-welded condition.

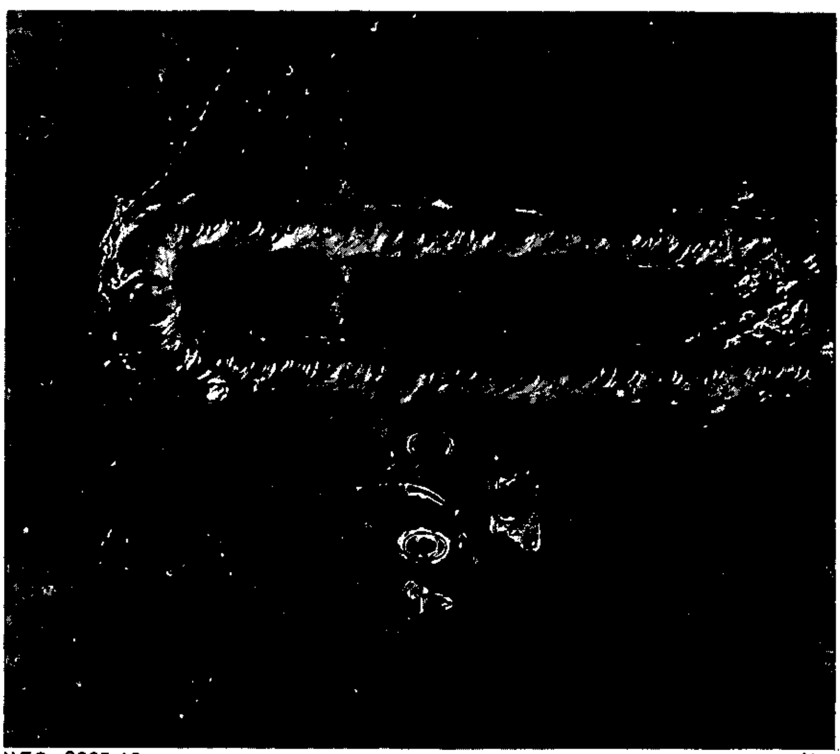
Inspections were made every two to three days the first week and weekly thereafter.

The findings were virtually identical with those of simulated waste solutions. All six as-welded plates, which included two of each steel, failed after relatively short exposures; for example, five failed within 3 days and the sixth failed within 7 days.

In the partially stress-relieved condition, one specimen failed in 3 days, one in 14 days, one in 27 days, one in 83 days, and the remaining two did not fail. Hence, partial stress relief is beneficial but it does not guarantee freedom from stress corrosion. It may be important to note that in no case, in either simulated wastes or in 50% $NaNO_3$, did the 0.26% carbon steel crack after being partially stress relieved. Because of the relatively small number of samples tested, however, it is difficult to assess the value of this observation.

None of the seven fully stress-relieved specimens showed any indication of failure.

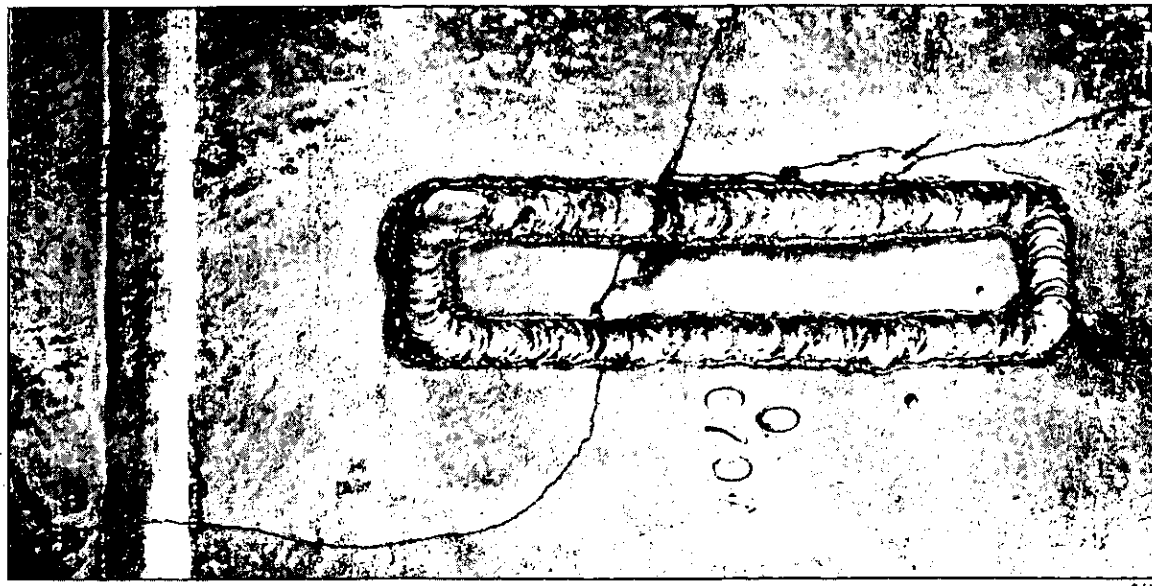
Typical failures from these tests are shown in Figures 5 through 10.



NEG. 8325-18 ½X

This crack pattern was observed frequently near weld attachments, although the type shown in Figure 6 was also seen. The numbers shown in photographs were stamped on the specimen after test, and have no relation to the failure.

FIG. 5 CRACK IN XF SPECIMEN (0.26% C) BELOW A REMOVED ATTACHMENT



NEG. 8325-24 ¾X

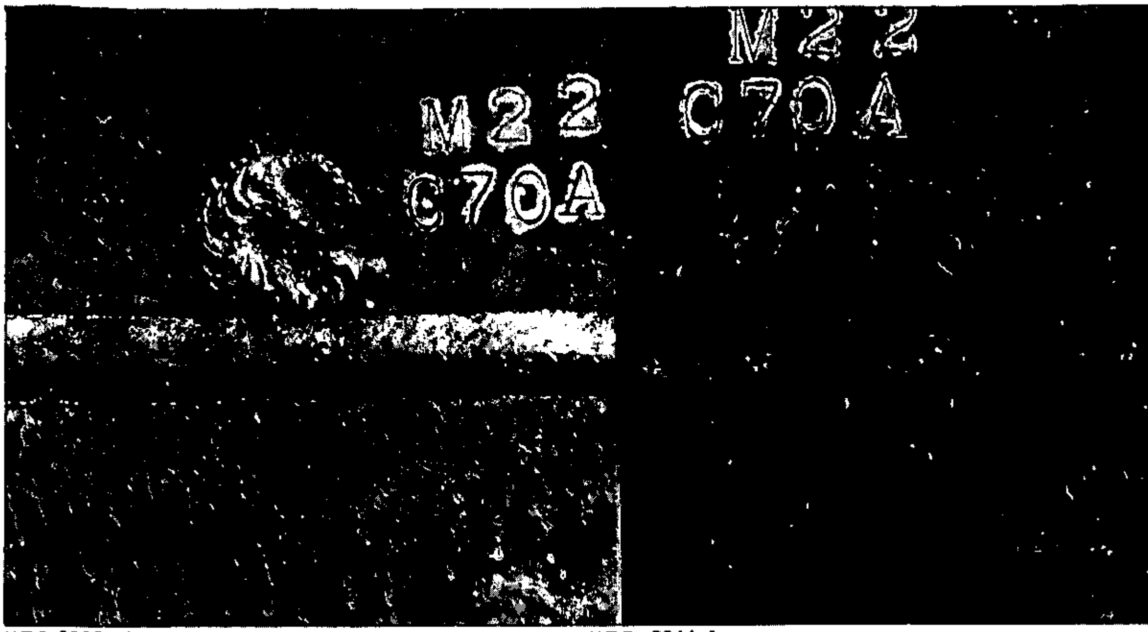
FIG. 6 CRACKING OF AREA WHERE ATTACHMENT WAS REMOVED (0.13% C)

Specimen Backup Strip Specimen

NEG. 8341-10 1½X

The backup strip was welded to the specimen only at a few points but enough tensile stress was imparted to cause failure.

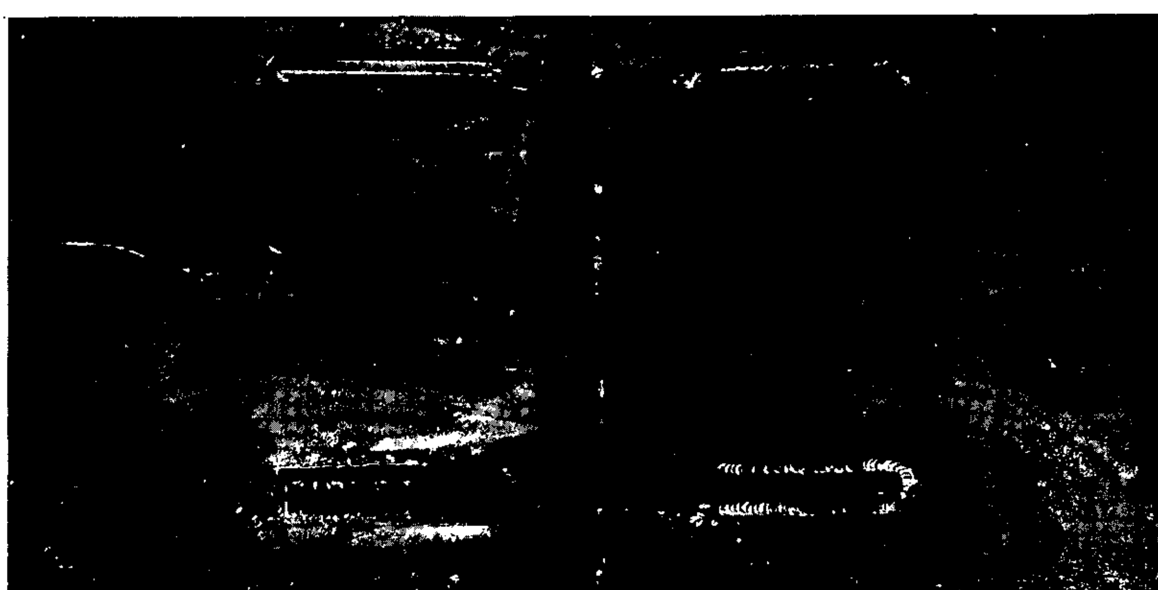
FIG. 7 CRACKING OF BACKUP STRIP ON "OF" SPECIMENS (0.13% C)



NEG 8326-16 NEG. 8341-4

FRONT SIDE (½X) *REVERSE SIDE (½X)*

FIG. 8 CRACKING NEAR A CLAMP IN AN M-22 SPECIMEN (0.08% C)
The crack generally follows the weld and not the clamp marks.



NEG. 8325-15 ¼X

The length of the crack on the top covers nearly 80% of the distance from left to right. This extent of cracking indicates that the partial stress relief introduces stresses in areas not normally affected by the attachments.

FIG. 9 CRACK PATTERN IN PARTIALLY STRESS-RELIEVED MF-S SPECIMEN (0.08% C)

NEG. 8380-4 1X

The specimen was deformed on a press to accentuate cracks. The radial cracks at the corners are typical of repair welds when the cracking process was limited to the area adjacent to the welds.

FIG. 10 CRACK PATTERN NEAR REPAIR WELD IN SPECIMEN M-2 (0.08% C)

TWELVE-INCH SPECIMENS IN 50% SODIUM NITRATE

The seven specimens listed in Table VIII were exposed in the same solution at the same time as the 36-inch plates described above. The 12-inch specimens were identical to those used in the 55-gallon tanks for solution screening purposes. In these tests only one of three as-welded specimens failed, in contrast to the cracks that developed in all four samples exposed in the 55-gallon drums previously, Table VI.

Table VIII

History of Twelve-Inch Specimens Exposed for 167 Days at 90-95°C in 50% $NaNO_3$

Specimen Type	Carbon Content, %	Exposure to the Beginning of Cracking, days	Comments
M-1	0.08	3	Cracked around weld
M-1R	0.08	-	No cracks
O-1	0.13	-	No cracks
O-1R	0.13	-	No cracks
X-6	0.26	-	No cracks
X-6R	0.26	-	No cracks
XX-R	0.26	-	No cracks

NOTES: See appendix for exact design of specimens. The suffix R designates complete stress relief; all others tested in the as-welded condition.

Inspections were made every two to three days during the first week and weekly thereafter.

TESTS IN SODIUM NITRATE WITH RESTRESSED SPECIMENS OF INITIALLY STRESS-RELIEVED MATERIAL

Seven specially designed large specimens were fabricated to determine whether stress-relieved specimens would crack if stress were reapplied. See the Appendix for specimen detail. The stress-relieving procedure is described on page 5.

Unfortunately, during the first 90 days of testing some of the samples were grounded to the tank from time to time, and the number of samples so affected undoubtedly changed after each inspection. The influence that this deviation might have exerted on the test results is unknown, although probably it was small.

Cracking Tests[a] with Restressed Specimens

Number of Plates	Condition During Test	Results
1	Stressed to 70% of yield	No cracks after 183 days
1	Stressed to 100% of yield	No cracks after 183 days
2	Stressed to 150% of yield	No cracks after 183 days
1	Fully stress relieved	No cracks after 183 days
2	As-welded control	One sample cracked at flame-cut edge after 22 days

(a) 50% $NaNO_3$ at 90-95°C

The only cracks observed were in the flame-cut edge of one of the as-welded control samples. These cracks did not propagate across the specimen but remained in the vicinity of the edge. It is surprising that no cracking was noted near the repair welds in view of the high susceptibility found in these areas in the 36-inch test plates; the possible influence of the periodic grounding was not resolved.

EVALUATION OF TESTING TECHNIQUES

Size of Test Specimen

The most important observation was the difference in stress-corrosion behavior shown by the various sizes of welded test specimens. The 4-inch samples were so unpredictable that they were virtually useless. The 12-inch samples showed a more pronounced trend but discrepancies presisted; for example, the 12-inch specimens exhibited a high incidence of cracking in $NaNO_3$ screening Tests, Table VI, but indicated a low susceptibility to cracking when immersed with the 36-inch plates, Table VIII. Only the 36-inch test plates showed any real reproducibility.

The explanation for the wide difference in susceptiblity to stress corrosion of the various specimen sizes is probably related to fabrication variables and particularly to the manner in which the specimens were welded. The residual stresses responsible for stress corrosion originate from temperature differences created by the welding operation. In small specimens, the bulk metal temperature increased significantly during welding, thereby (1) decreasing the temperature difference between welded zones and the surrounding metal, and (2) decreasing the strength of the metal and hence the residual stresses which could arise. In large specimens, the bulk metal temperature was virtually unchanged, with the result that maximum residual stresses arose.

Previous work with large specimens has been reported by Pearson and Parkins[2] with good reproducibility, and by DeGarmo and Cornet[3] with somewhat less reproducibility, although the latter tests were not extensive.

Because of the inconsistent performance of the 4- and 12-inch specimens, the principal reliance was placed on results obtained with the 36-inch test plates.

Solution Composition

Nitrate and hydroxyl ions are the only two reagents known to cause stress corrosion of carbon steel in aqueous solutions. The susceptibility to stress corrosion is increased with increasing temperature and nitrate content.[4]

Thus, of the fabrication and material variables involved in waste tank construction, a full stress-relieving anneal appears to be the most valuable factor in reducing the susceptibility of the structure to stress-corrosion cracking.

SIGNIFICANCE OF TEST RESULTS TO WASTE TANK CONSTRUCTION

Effect of Heat Treatment

The most pronounced effect noted in all tests was the difference in susceptiblity to stress corrosion between the as-welded and fully stress-relieved specimens. All the as-welded specimens developed cracks in the 50% $NaNO_3$ and HM solutions; additionally, the only specimen to crack in the H-Purex waste was an as-welded plate. In contrast, no fully stress-relieved specimen cracked in any solution. The behavior of the partially stress-relieved specimens was intermediate in that the cracking did occur, but not to the extent shown by the as-welded condition.

These results indicate that stress relief is highly desirable in fabricated tanks. Not only does the heat treatment reduce the residual stresses, but as Rädeker[4] and Uhlig and Sava[5] point out, the inherent susceptibility to stress corrosion is also reduced. In fact, this is one explanation for the absence of cracking in the tests with restressed specimens of initially stress-relieved steel.

Effect of Carbon Content

One of the more interesting results of these tests was the indication that for as-welded specimens, increased carbon content did not confer stress corrosion resistance to cracking. Most investigators have found that the cracking tendency of hot-rolled carbon steels is greatly reduced when the carbon content reaches 0.15-0.20%. The present results parallel those of Pearson and Parkins who cracked as-welded samples of 0.18-0.22% carbon steels, but differ from the results of DeGarmo and Cornet who could not crack as-welded plates of a 0.24% carbon steel.

Effect of Aluminum Content

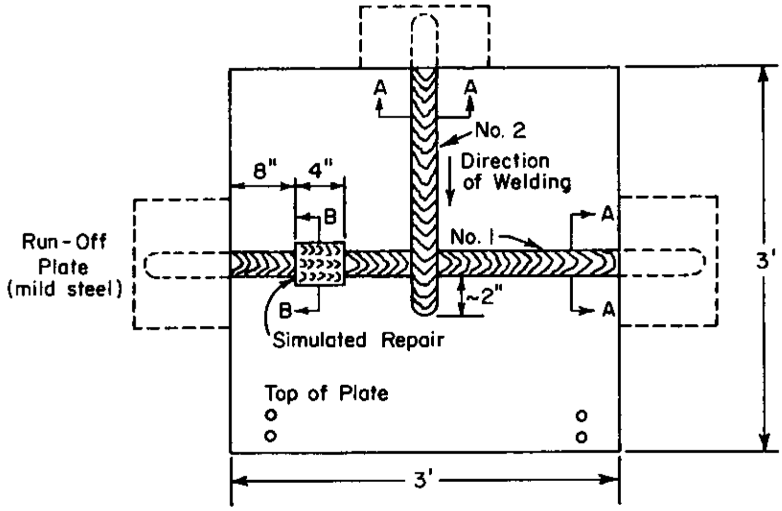
Aluminum-killed steels reputedly possess superior resistance to stress corrosion; however, the one aluminum-killed steel used in this work (0.08% carbon) showed no superior resistance. The reason for the apparent discrepancy is that to attain maximum resistance to cracking, the aluminum-killed steels require an intermediate heat treatment at approximately 700°C, a condition most closely related to the fully stress-relieved state than to any other.

Thus, of the fabrication and material variables involved in waste tank construction, a full stress-relieving anneal appears to be the most valuable factor in reducing the susceptibility of the structure to stress-corrosion cracking.

— APPENDIX —
FABRICATION DETAILS OF SPECIMENS

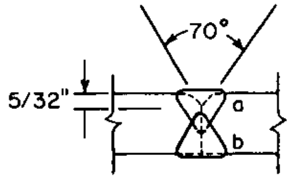
SPECIMEN DESIGNATION	M-2	X-2
PLATE MATERIAL	A-285 Grade B, 0.07-0.09% C	A-212 Grade B, 0.22-0.28% C
Section A-A	L60 Wire + Lincoln No. 760 Flux (Both passes)	L70 Wire + Lincoln No. 781 Flux (Both passes)
Section B-B	E 6010 rod	E 7010 rod

SPECIMEN PLAN



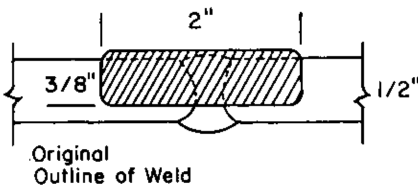
PROCEDURE

1. Weld in sequence (steps 1 and 2) and in direction noted on plan.
   a. First pass: 3/16" wire; 600 amp; 33v; 27 ipm.)submerged
   b. Second pass: 3/16" wire; 800 amp; 33v; 27 ipm.)arc)welding



Section A-A

2. Complete butt welds per section A-A prior to making repairs.
3. Remove metal for simulated repairs by machining or by flame gouging, per section B-B. Method shall be identical for all specimens.
4. Repairs on all specimens shall be deposited in identical manner.



Section B-B

FIG. A-1 DETAIL OF M-2 AND X-2 PLATES

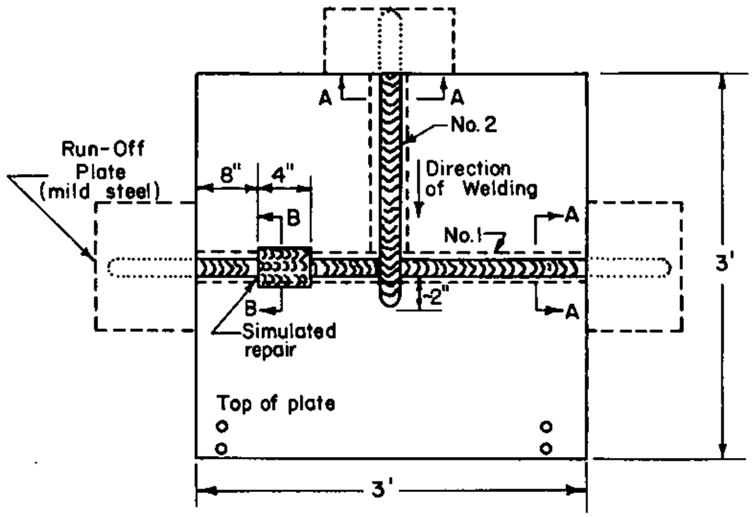
SPECIMEN DESIGNATION — O-2

PLATE MATERIAL — A-285 Grade B
0.12-0.15% C

Section A-A
a. Manual — E 6010 rod
b. and c. Submerged arc — L60 wire and Lincoln No. 760 Flux

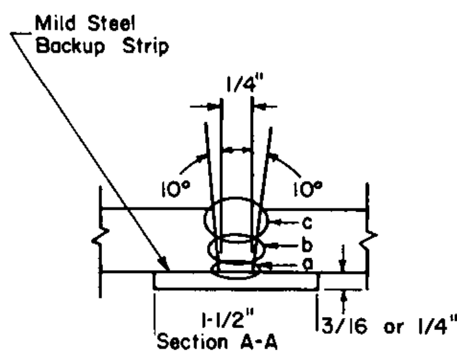
Section B-B — E 6010 rod

SPECIMEN PLAN



PROCEDURE

1. Weld in sequence (steps 1 and 2) and in direction noted on plan.
   a. First pass: Manual - 3/16" electrode
   b. and c. Submerged arc
   c. Second pass: 3/16" wire; 700 amp; 33v; 19 ipm
   d. Third pass: 3/16" wire; 790 amp; 32v; 15 ipm



2. Complete butt welds per section A-A prior to making repairs.
3. Remove metal for simulated repairs by machining or by flame gouging. Method shall be identical for all specimens.
4. Repairs on all specimens shall be deposited in identical manner.

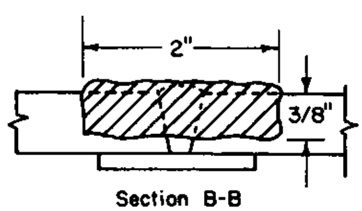
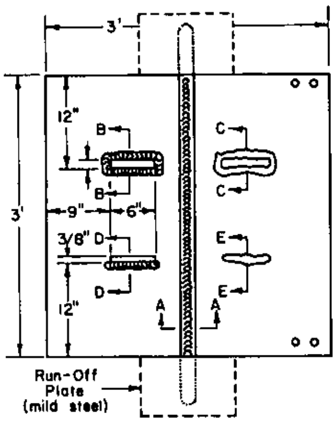


FIG. A-2 DETAIL OF O-2 PLATES

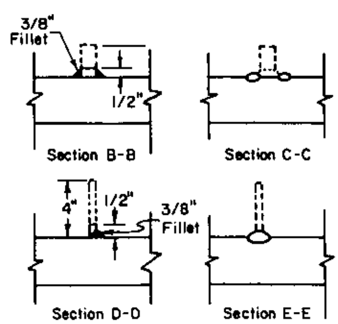
SPECIMEN DESIGNATION	MF	XF
PLATE MATERIAL	A-285 Grade B, 0.07-0.09% C	A-212 Grade B, 0.22-0.38% C
Section B-B, 3/8" Fillet. Cut to 1/2" after butt weld.	E 6010 rod	E 7018 rod
Section C-C, 3/8" Fillet. Remove welds with Arc-Air after butt weld.	E 6010 rod	E 7018 rod
Fill grooves	E 6010 rod	E 7018 rod
Section D-D, 3/8" Fillet. Cut to 1/2" after butt weld.	E 6010 rod	E 7018 rod
Section E-E, 3/8" Fillet. Remove weld with Arc-Air after butt weld.	E 6010 rod	E 7018 rod
Fill groove	E 6010 rod	E 7018 rod
Section A-A	L-60 wire + Lincoln No. 760 Flux (both passes)	L-70 wire + Lincoln No. 781 Flux (both passes)

SPECIMEN PLAN

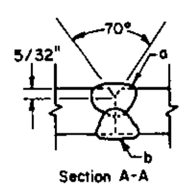


PROCEDURE

1. Attach two 6" x 1" x 2" bars located per sections B-B and C-C and two 6" x 4" x 3/8" plates located per sections D-D and E-E BEFORE depositing butt weld, Section A-A.



2. Deposit butt weld, Section A-A.
   a. First pass: 3/16" wire; 600 amp; 33v; 27 ipm.
   b. Second pass: 3/16" wire; 800 amp; 33v; 27 ipm. Submerged-arc welding.



3. Trim attachments or remove attachments and repair per sections AFTER depositing butt weld.

FIG. A-3 DETAIL OF MF AND XF PLATES

SPECIMEN DESIGNATION OF

PLATE MATERIAL A-285 Grade B, 0.12-0.15% C

Section B-B, 3/8" Fillet E 6010 rod
Cut to 1/2" after butt weld

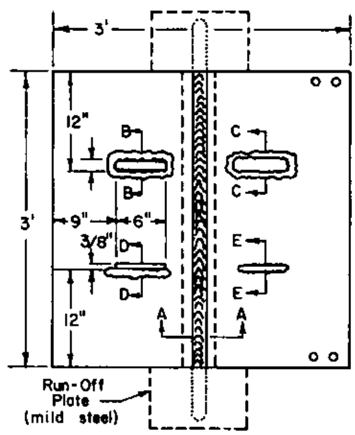
Section C-C, 3/8" Fillet E 6010 rod
Remove welds with Arc-Air after butt weld
Fill grooves E 6010 rod

Section D-D, 3/8" Fillet E 6010 rod
Cut to 1/2" after butt weld

Section E-E, 3/8" Fillet E 6010 rod
Remove weld with Arc-Air after butt weld
Fill groove E 6010 rod

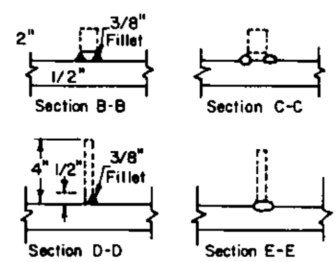
Section A-A
a. Manual E 6010 rod
b. and c. Submerged arc L-60 wire + Lincoln No. 760 flux

SPECIMEN PLAN

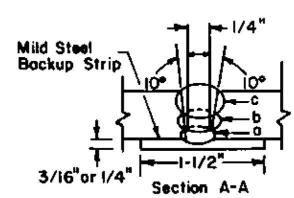


PROCEDURE

1. Attach two 6" x 1" x 2" bars located per sections B-B and C-C and two 6" x 4" x 3/8" plates located per sections D-D and E-E BEFORE depositing butt weld, Section A-A.



2. Deposit butt weld, Section A-A.
   a. First pass: Manual 3/16" electrode
   b. Second pass submerged arc: 3/16" wire; 700 amp; 33v; 19 ipm.
   c. Third pass submerged arc: 3/16" wire 790 amp; 32v; 15 imp.



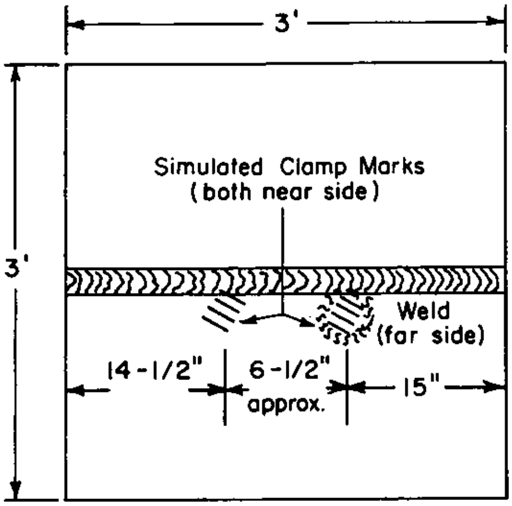
3. Trim attachments or remove attachments and repair per sections AFTER depositing butt weld.

FIG. A-4 DETAIL OF OF PLATES

SPECIMEN DESIGNATION M-22

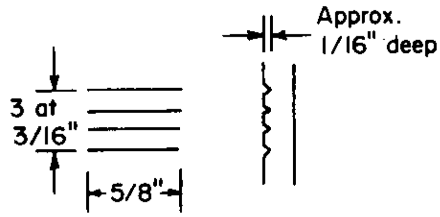
PLATE MATERIAL A-285 Grade B, 0.07-0.09% C

SPECIMEN PLAN



PROCEDURE

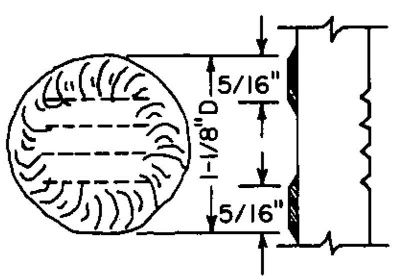
1. Prepare specimen for butt weld per section A-A, Figure A-3
2. BEFORE welding (and after 1 above) produce simulated clamp marks on plate.



Detail of Simulated Clamp Marks

3. Deposit butt weld with submerged-arc welding per section A-A, Figure A-3.

4. AFTER depositing butt weld, make simulated manual repair weld per detail on opposite side of ONE clamp mark.



Detail of Repair Weld Opposite Clamp Marks

FIG. A-5 DETAIL OF M-22 PLATES

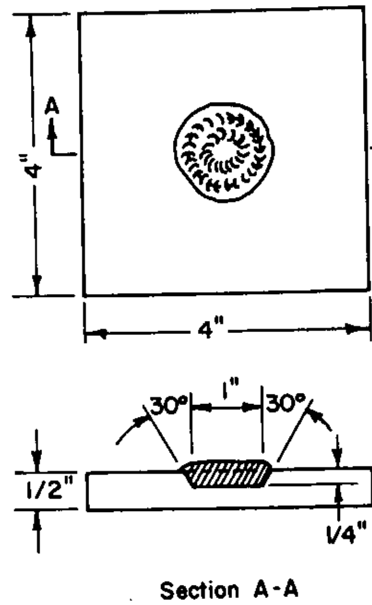


FIG. A-6 DETAIL OF 4-INCH PLATE

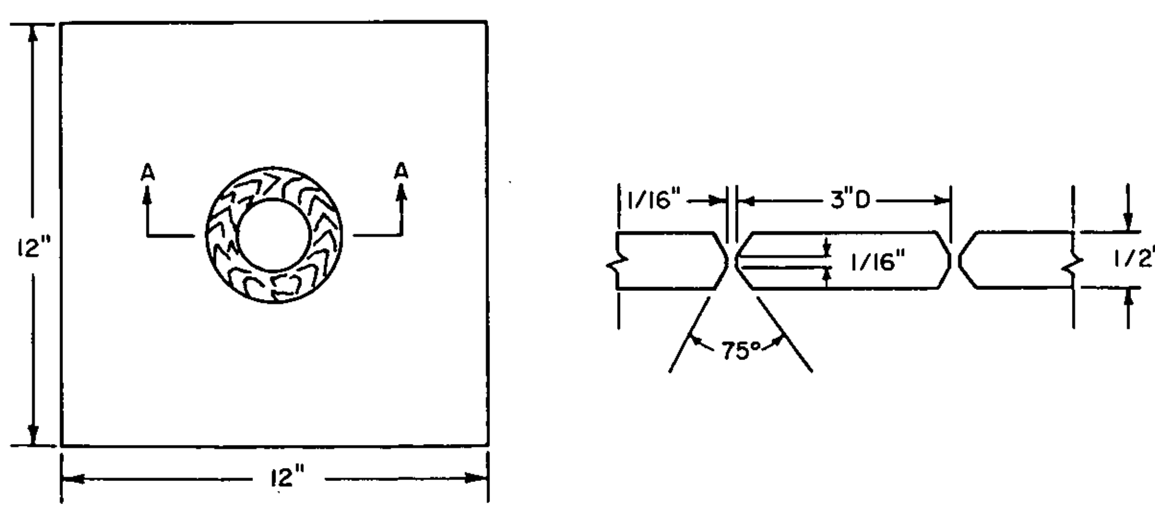
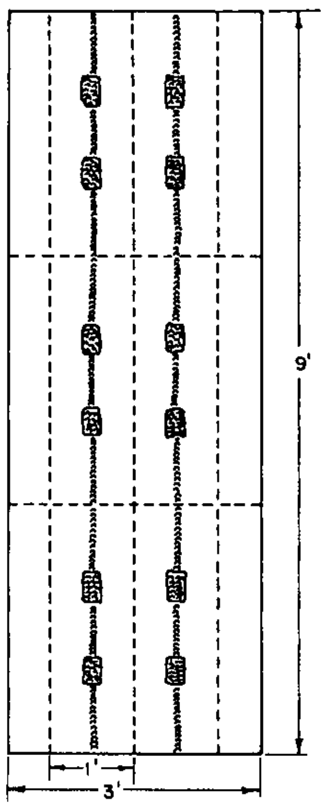


FIG. A-7 DETAIL OF 12-INCH PLATE



1. Plate is 3' x 9' x 1/2" thick; carbon content is 0.13% (Heat USS 69 U087)

2. Seam and repair welds are identical to those shown in Figure A-1.

3. Dotted lines indicate path of flame cutting after all welding had been completed.

4. Final sample size was 1' x 3'.

FIG. A-8 FABRICATION OF SPECIMEN FOR RESTRESSING TESTS

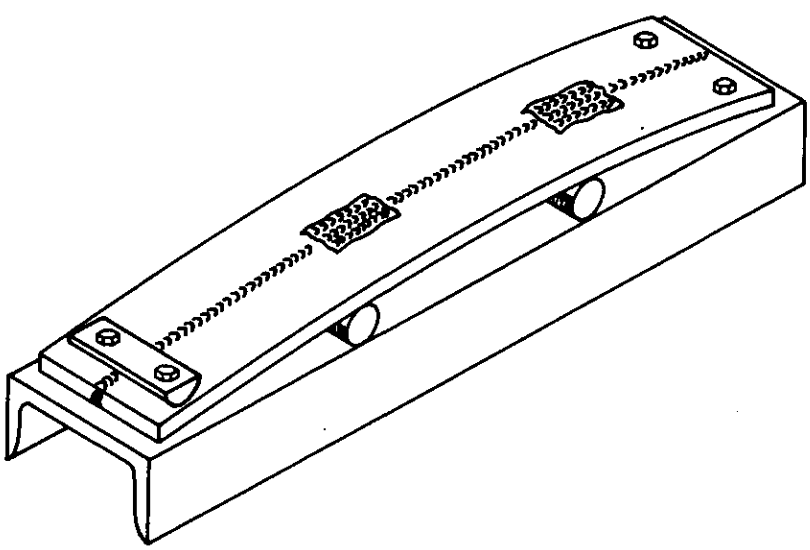


FIG. A-9 STRESS-RELIEVED SPECIMEN RESTRESSED ON CHANNEL BEAM SPECIMEN HOLDER

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3. E. P. DeGarmo and I. Cornet. Welding Journal. 34, 472s-475s, (October 1955).

4. W. Rädeker. Stahl und Eisen. 73, 8, 485-92 (April 1953).

5. H. H. Uhlig and J. Sava. ASM Trans. Quarterly. 56, 3, 361-76 (September 1963).