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CREVICE CORROSION AND METAL-ION CONCENTRATION CELL-CORROSION RESISTANCE OF CANDIDATE MATERIALS FOR OTEC HEAT EXCHANGERS

Parts I and II

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Parts I and II

by

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PART I

LOCALIZED CORROSION EVALUATIONS OF CANDIDATE MATERIALS IN LOW VELOCITY SEAWATER AT AMBIENT TEMPERATURES

EXECUTIVE SUMMARY

Crevice corrosion and metal-ion concentration cell corrosion evaluations have been conducted for seven materials presently being considered for use in OTEC heat exchangers.

Titanium, stainless alloy AL-6X, Alclad 3003, aluminum alloy 5052, C70600, C72200 and Cu-10Ni-8Sn sheet materials were exposed to ambient temperature, low velocity seawater for 6 months at the LaQue Center for Corrosion Technology site at Wrightsville Beach, N. C.

The combined environmental, metallurgical and geometric elements present during this test were sufficiently critical to initiate crevice attack on control samples of Type 316 stainless steel. While no evidence of corrosion of any form was detected for titanium and AL-6X, the five aluminum and copper base alloys all exhibited varying degrees of general and/or localized attack. For the specimen geometries considered, little, if any, effect of boldly exposed to shielded surface area ratio was found.

Exposure of these candidate materials under other conditions may yield results different to those described by this relatively basic localized corrosion test program.

INTRODUCTION

Crevice corrosion and metal-ion concentration cell corrosion have been identified as corrosion forms which may affect the performance of various candidate materials for OTEC heat exchangers. In the case of some stainless type alloys, accelerated attack is known to occur within crevices where the metal surface is deprived of oxygen and where subsequent concentrations of aggressive chloride ions and lowering of the pH in the confined environment results in the breakdown of passivity. These shielded areas become anodic to the boldly exposed surfaces where cathodic reactions sustain the crevice attack.

For copper alloys, accelerated attack may occur at the surfaces immediately adjacent to the crevice owing to a difference in the concentration of copper ions within and outside of the crevice confines. In this case, the copper ion content within the crevice increases and the shielded area becomes the cathode. The bulk environment, on the other hand, is lower in copper-ion concentration and boldly exposed material at the interface becomes an anode.

The objective of this investigation was to assess the susceptibility of titanium, AL-6X, Alclad and 5052 aluminum, C70600, C72200 and a Cu-10Ni-8Sn alloy to localized corrosion in low velocity, ambient temperature seawater. Type 316 stainless steel crevice corrodes in seawater over a range of environmental, metallurgical and geometric conditions and consequently was selected for comparative baseline purposes. Although other phases of this OTEC program are concerned with the performance of alloy tubing, crevice corrosion and metal ion concentration cell corrosion evaluations were conducted with sheet materials. In the present work, crevices were fabricated by the attachment of grooved nonmetallic washers to the test specimens. The resulting crevice conditions, (i.e., geometries) may or may not be representative of those anticipated from the construction or operation of an OTEC heat exchanger. As will be shown, however, crevice conditions were sufficiently severe to initiate localized attack of Type 316 stainless steel in a relatively short time period.

Results are described by documented observations made throughout the exposure period and by depth of penetration measurements taken at the end of the 6 month test.

EXPERIMENTAL

Materials

Table I gives the chemical composition of the seven candidate materials as well as for AISI Type 316 stainless steel. Except for the experimental Cu-Ni-Sn alloy, all other materials were of commercial origin (see Appendix I). Thermomechanical processing of the Cu-Ni-Sn alloy and C72200 was performed at the Inco Research and Development Center at Sterling Forest, N. Y. (refer to Appendix II for available working and heat treating schedules).

Specimen Preparation

Sheet material was cut and edge ground to the required dimensions, providing duplicate specimens for the two surface areas. Except for the titanium specimens, which measured 7.6 cm x 20.3 cm and 7.6 cm x 40.6 cm, specimens for the remaining 7 alloys measured 10.0 cm x 15.2 cm and 10.0 cm x 30.5 cm. A 1.3 cm diameter hole was drilled in the center of each panel to enable fastening of the crevice assemblies. All specimens were stencil coded for identification.

To remove processing scales, specimens of C72200 and the Cu-Ni-Sn alloy required pickling in 10 wt. % H_2SO_4. All other materials were evaluated in the as received condition. Prior to assembly of the crevice components, each specimen was degreased with acetone, bristle brush scrubbed with pumice, rinsed with water, rinsed in clean acetone and air dried. Except for the drilled hole, all exposed edges of the four Alclad specimens were protected by applying a thermo-setting epoxy resin coating (MORAD®, a product of the Morton Chemical Corporation).

Crevice Assemblies

Multiple crevice assemblies utilized for this program consisted of two grooved Delrin™* washers each having 20 plateaus, secured to the test panel with an insulated titanium fastener (see Figure 1). A total of 40 potential crevice sites were thus present on each specimen. Crevice assemblies were consistently tightened to 8.5 Nm (75 in-lbs) with a torque wrench. Each specimen/crevice assembly was electronically checked to insure against any undesirable galvanic contact.

* Delrin™ is a trademark of E. I. duPont de Nemours and Co.

Test Conditions

Specimens were exposed in once through, unfiltered seawater at a nominal velocity of 0.5 m/sec for six months. The mean seawater temperature for the test period was 24.2°C. The routine seawater hydrology data for the ambient conditions are summarized in Table II. The specimens were exposed vertically on non-metallic supports as shown in Figures 2 and 3.

To minimize the attachment of marine growths and other deposits, a specimen cleaning schedule was established. Initially, specimens were to be wiped with foam type brushes once a week. Because of the attachment of small hard shell fouling on the titanium, alloy 5052, Alclad, AL-6X, and Type 316 specimens, this cleaning scheduled was increased to 3 times per week. Regular cleaning of the copper base alloys was continued on the weekly schedule. As will be discussed, some hard shell fouling attachments were found on the C72200 specimens. Seaweed or other debris trapped by the leading edges and crevice assemblies was periodically removed. All cleaning was performed with the specimens remaining submerged and the crevice assemblies undisturbed.

It was found that wiping of the specimens with the foam brush alone was not effective in removing the hard shell marine attachments which generally measured 1-2 mm in diameter. Wiping with a nylon gloved hand, however, proved to be more effective. It should be noted that in many cases, the base of these already mature species remained firmly affixed to the metal surface.

RESULTS AND OBSERVATIONS

Type 316 Stainless Steel

As determined by the accumulation of corrosion products around the grooved Delrin washers, crevice attack on one of the 10 cm x 15 cm panels of Type 316 was detected within 15 days. By the end of the first 30 days, the remaining control specimens were also corroding.

Figure 4 shows the typical appearance of a cleaned specimen after the 6 month exposure. Note that relatively few of the available crevice sites were attacked. Table III gives the number of attacked sites and range of penetration for each of the four specimens. While these penetrations are within the range of those typically measured for Type 316 stainless steel, recently reported multiple crevice data for Type 316 stainless steel exposed in filtered seawater (<0.05 m/sec) at 12°C and 28°C for only 30 days showed considerably greater depths of penetration.[1] In contrast to a maximum penetration of 0.20 mm in the present work, previous results from the above evaluation showed depths of attack 4 to 5 times greater in only 1/6 of the time. Since crevice initiation in the present evaluation was noted within 30 days, the difference in penetration cannot be attributed to any significant delay in the onset of attack. It is presently not known if the difference in penetration depth can be attributed to differences in seawater velocity (i.e., 0.5 m/sec vs 0.05 m/sec). Increased seawater velocity would, on one hand, tend to increase the supply of available oxygen to the cathode surface and thus alter the reaction rate for propagation. On the other hand, higher seawater velocities would tend to sweep away corrosion products and possibly allow for dilution of the aggressive crevice solution with respect to pH and Cl^- concentration.

Although other investigators[2,3] have described results which indicate that increasing the surface area of the boldly exposed material promotes initiation and intensifies the severity of attack at crevices, little, if any, area effects were found in the present study within the range evaluated.

Titanium and AL-6X

No evidence of crevice attack or other forms of corrosion was found on any of the specimens of these two candidate materials (see Figure 5). However, some crevice attack has been detected on tube specimens of AL-6X exposed in seawater with vinyl tubing acting as a crevice former.[4] These observations have been confirmed by additional studies described in Part II of the present report.

Aluminum Alloy 5052

Figure 6 shows the typical appearance of an exposed crevice test specimen of alloy 5052 after cleaning. No evidence of localized corrosion was detected in the areas shielded by the grooved washers. Under these test conditions, however, alloy 5052 incurred general corrosion of the boldly exposed surfaces. Using the unattacked crevice sites as reference points, approximately 0.01 mm of material was lost during the six month test. As evidenced by the photomacrograph in Figure 7, attack at the specimen edges was somewhat more severe. This first became apparent about two months into the test period. Close examination of specimens after cleaning revealed many small areas in which the general corrosion was less severe. The distribution and size of these areas suggest that some protection was afforded by the remains of marine attachments.

Alclad

Figure 8 shows the typical appearance of Alclad crevice test specimens after cleaning. As was the case for alloy 5052, no evidence of crevice attack was found in the areas shielded by the grooved Delrin washers. General corrosion occurring on the boldly exposed surfaces appeared to be somewhat less than that for alloy 5052. Measurements of thickness loss taken adjacent to the unattacked crevice sites yielded values <0.01 mm. Areas under previously removed attachments again showed less attack. In addition, no evidence of localized attack was detected at the metal-epoxy interface.

C70600

Metal-ion concentration cell corrosion at the specimen/Delrin washer interface was found to be quite minimal for the C70600. Measurements adjacent to the areas shielded by the crevice assembly plateaus showed attack to be less than 0.01 mm. Figure 9 shows the appearance of one of the more heavily attacked C70600 specimens. In this case, localized attack on the order of 0.01–0.09 mm was measured along the leading edge. First observations regarding this accelerated attack were noted approximately 80 days into the test period. From Figure 9, it can also be seen that general corrosion on the boldly exposed surface reflects some apparent increase in turbulence around the crevice assembly.

C72200

For this chromium containing 85 Cu- 15 Ni alloy, metal-ion concentration cell corrosion adjacent to the crevice assemblies was first observed on day 69 (Figure 10). As evidenced by the photograph in Figure 11, localized attack on the boldly exposed surface also became apparent at that time. Figure 12 shows the appearance of C72200 specimens after approxiamtely 4 months of exposure. (Note the pit-like morphology of the attack).

Figure 13 shows the typical appearance of cleaned C72200 specimens after the six month test. Localized attack adjacent to areas shielded by the crevice assembly ranged from 0.01 to 0.04 mm, while measurements of 0.01 to 0.10 mm were recorded for the pitted areas. It is interesting to note that one of the four C72200 specimens (100 x 300 cm) was virtually free of pit-like attack. Since the four C72200 specimens were exposed next to each other in the test trough, it is doubtful that the difference in corrosion behavior can be attributed to environmental variations. The occurrence of pitting of C72200 in seawater has been found to be strongly dependent on the solubility of Cr and Fe. Earlier investigations indicated that attack could be correlated with the fraction of total Cr and Fe in solution and stressed the importance of achieving maximum solubility of Cr during final heat treatment.[5] The heat treatment indicated in Appendix II follows that recommended for optimum corrosion resistance.

As previously noted, small attachments were found from time to time on this copper base alloy. Figure 14 shows one such incident recorded on day 69.

Cu-10Ni-8Sn Alloy

Typical of the behavior of copper base alloys, localized attack of the Cu-Ni-Sn specimens was located outside the crevice area. Using the unattacked shielded areas as reference points, localized metal-ion concetration cell corrosion in adjacent areas measured 0.01-0.02 mm in depth. Figure 15 shows the typical appearance of the Cu-Ni-Sn crevice specimens after final cleaning.

No evidence of area effects was found for C70600, C72200 or the Cu-Ni-Sn alloy. This behavior is consistent with that for copper alloys in which the cathode is within the crevice.[2,3] Since the crevice area in these tests was held constant and the surrounding boldly-exposed area was varied, no appreciable effect would be expected for the copper alloys.

SUMMARY AND CONCLUSIONS

Crevice corrosion and metal-ion concentration cell evaluations have been conducted for seven materials which have been considered for use in OTEC heat exchangers.

Titanium, stainless alloy AL-6X, Alclad, aluminum alloy 5052, C70600, C72200 and Cu-10Ni-8Sn sheet materials were exposed to ambient temperature, low velocity (0.5 m/sec) seawater for six months. Type 316 stainless steel served at the control material. Potential sites for localized corrosion were provided by grooved, non-metallic washers, commonly referred to as multiple crevice assemblies (MCA). The formation of naturally occurring crevices, i.e., marine attachments and debris, was minimized by routine cleaning.

The combined environmental, metallurgical and geometric elements present during this test were sufficiently critical to initiate localized attack on Type 316 stainless steel. No evidence of corrosion, however, was detected on either titanium or AL-6X.

For Alclad and the 5052 aluminum alloy, no evidence of localized attack was found in the shielded areas. However, both materials incurred general corrosion on the boldly exposed surfaces. In the case of alloy 5052, the attack was somewhat more accelerated on the specimen edges.

While none of the copper base alloys (C70600, C72200 and Cu-Ni-Sn) exhibited attack beneath the crevice assemblies, varying degrees of localized attack, typical of metal-ion concentration cell corrosion, were detected in the immediately adjacent areas. For C70600, this attack was found to be quite minimal. Accelerated corrosion of the boldly exposed surfaces near the leading edges, however, was observed.

In addition to the localized attack found adjacent to the crevice assemblies, C72200 specimens incurred numerous incidences of pit-like attack on the boldly exposed surfaces. No other evidence of localized attack, beyond that adjacent to the crevice assembly, was found on any of the Cu-Ni-Sn specimens.

For the specimen geometries considered, little, if any, effect of boldly exposed to shielded surface area ratio was found.

Exposure of these candidate materials under other conditions may yield results different than those described by this relatively basic test program.

REFERENCES

1. R. M. Kain, "Crevice Corrosion Resistance of Austenitic Stainless Steel in Ambient and Elevated Temperature, Paper No. 230, CORROSION/79, Atlanta, GA, March 1979.

2. F. L. LaQue, Marine Corrosion, Wiley Interscience, John Wiley & Sons, Inc., 1975, p. 106.

3. D. B. Anderson, "Statistical Aspects of Crevice Corrosion in Seawater", Galvanic and Pitting Corrosion - Field and Laboratory Studies, ASTM-STP 576, p. 231.

4. D. G. Tipton, "Effect of Mechanical Abrasion on Corrosion of Candidate OTEC Heat Exchanger Tubing Materials in a Simulated OTEC Environment - Three Month Test Exposures", ANL/OTEC-BCM-013, September 1980.

5. R. D. Schelleng, "Heat Treatment and Corrosion Resistance of Cr-Modified Cu-Ni", Inco publication TP949-OP, 1976.

TABLE I

Identification and Alloy Composition (Wt. %) of Candidate Materials for OTEC Heat Exchangers

Type 316 Stainless Steel (Control Material)
Heat Identification 8642519

C	Mn	Ni	Cr	Mo	Si	P	S	Fe
0.054	1.80	12.75	17.34	2.1	0.45	0.040	0.007	Bal

Allegheny Ludlum AL-6X
Heat Identification 02145

C	Mn	Ni	Cr	Mo	Si	P	S	N	Fe
0.018	1.39	24.64	20.35	6.45	0.41	0.022	0.001	0.01	Bal

Titanium
Heat Identification AT1705
Grade 2 tubing stock, ASTM B338, Specification of maximum contents for

N	C	Fe	O	H
0.03	0.10	0.30	0.25	0.0215

Alclad
3003-H14 (both sides)/7072
Al + 1.3 Mn / Al + 1 Zn   Nominal Composition

Alloy 5052 - H32

Si	Fe	C	Mn	Mg	Cr	Zn	Al
0.45	0.45	0.10	0.10	2.2	0.15	0.10	Bal

C70600
Heat Identification 535

Cr	Fe	Ni	Mn	Zn	Pb
87.87	1.5	10.2	0.26	0.090	0.001

C72200
Heat Identification 7179

Ni	Cr	Fe	Mn	Si	Ti	Al	P	S	Cu
15.6	0.40	0.61	0.53	0.19	0.014	0.009	0.037	0.004	Bal

Cu-Ni-Sn
Heat Identification 82620

Ni	Sn	Cu
10	8	Bal

TABLE II

Summary of Seawater Properties at LCCT for the Period 6/5/79 through 12/12/79

	pH	Salinity (g/L)	Chlorinity[1] (g/L)	Dissolved O_2 (mg/L)
Mean Value	8.0	35.1	19.4	6.1
Maximum	8.2	37.0	20.1	8.3
Minimum	7.8	33.1	18.4	4.7

[1] Salinity = 0.03 + (1.805 x Chlorinity), ref. Corrosion Handbook, Pg. 113.

Seawater Temperature

mean = 24.2°C

standard deviation = ± 8.4°C

number of measurments = 550

High 30.0°C, Low 11.5°C

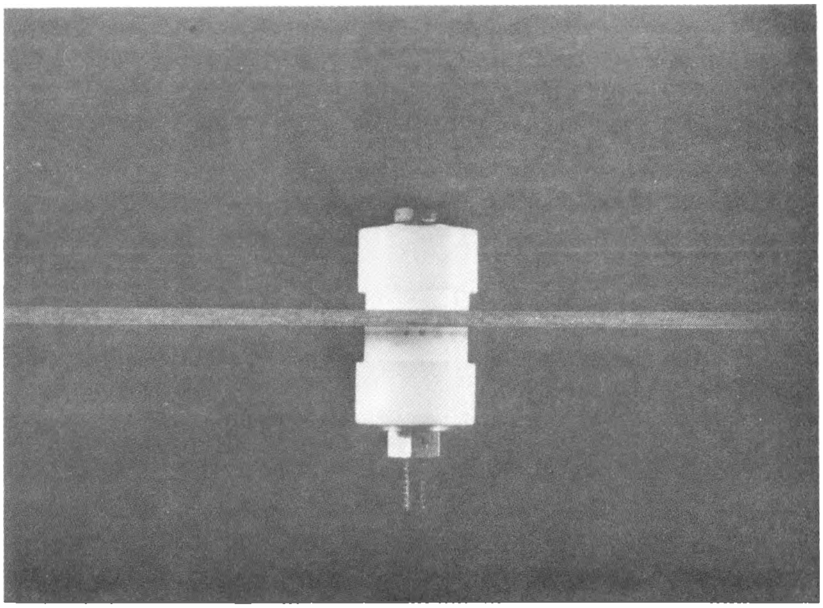
TABLE III

Crevice Corrosion Behavior Exhibited by Type 316 Stainless Steel Control Specimens*

Boldly Exposed: Shielded Area Ratio

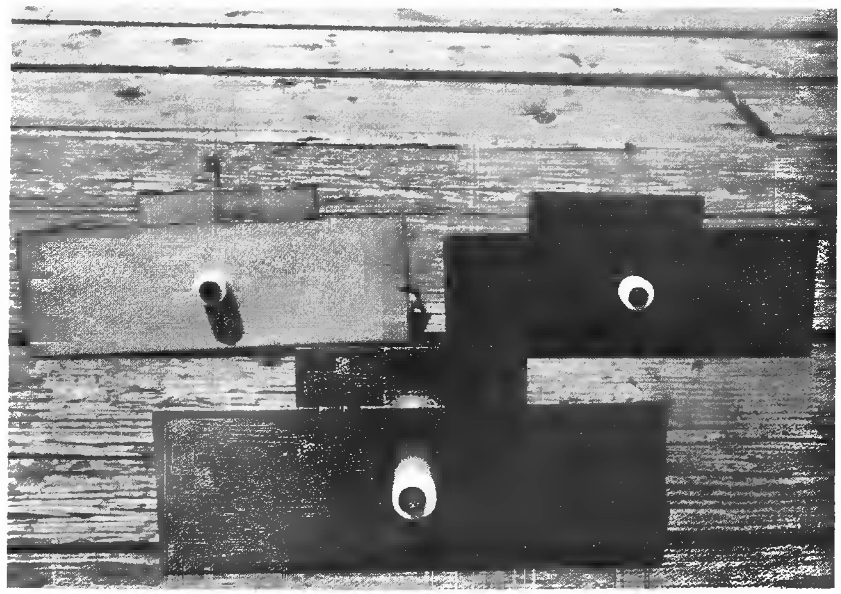
150:1 No. of Attacked Sites	150:1 Penetration Range (mm)	300:1 No. of Attacked Sites	300:1 Penetration Range (mm)
11	0.06 - 0.16	13	0.06 - 0.15
7	0.04 - 0.17	6	0.04 - 0.20

* Duplicate Specimens



79243-4A

Figure 1. Multiple crevice assembly used to evaluate materials for resistance to crevice corrosion and metal-ion concentration cell corrosion.



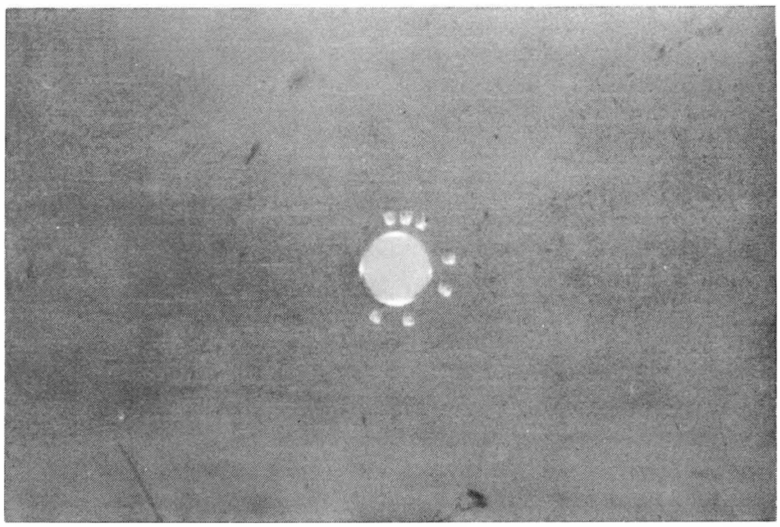
79075-3

Figure 2. Typical appearance of crevice test specimens prior to 6 month exposure. For each alloy, two boldly exposed to shielded surface area ratios were considered (approximately 150:1 and 300:1).

79075-9

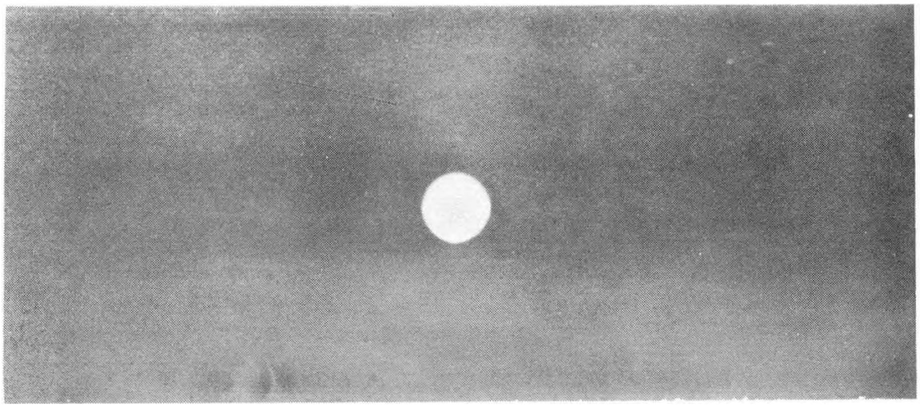
Figure 3. Position of crevice test specimens in 0.5 m/sec. flowing seawater trough. Copper base alloys were located downstream of the titanium, stainless alloy and aluminum alloy specimens.

Marine growths and other deposits were kept to a minimum by periodic underwater cleaning with a nylon gloved hand and foam brushes.

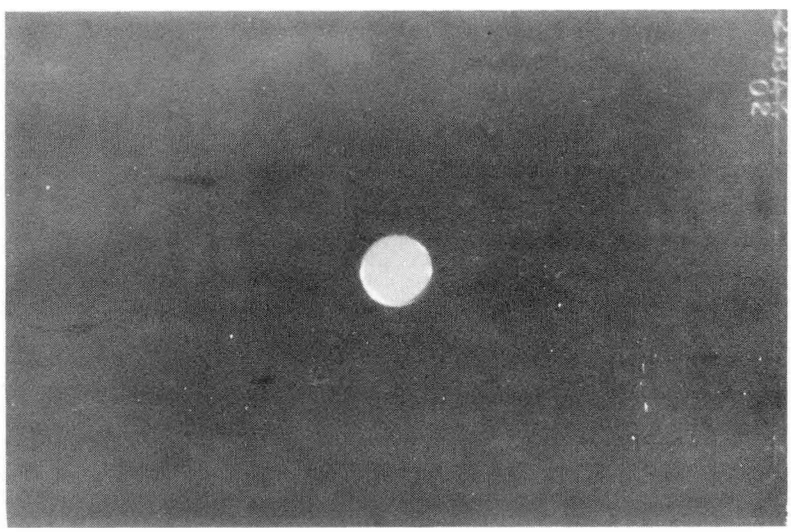


79238-3

Figure 4. Typical appearance of cleaned Type 316 stainless steel (control material) crevice test panel after 6 months exposure to ambient temperature seawater at 0.5 m/sec. For this specimen, crevice attack had initiated at only 7 of the 20 available sites under the Delrin assembly: Penetration range 0.04 - 0.20 mm.

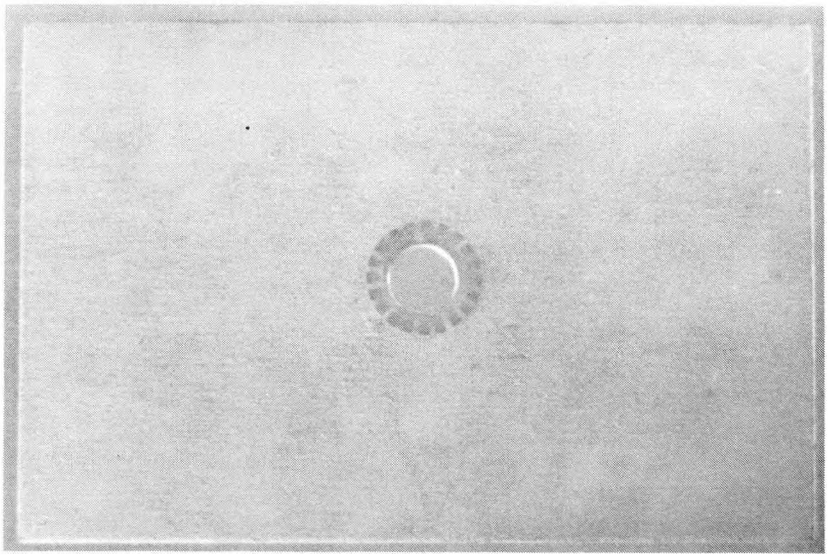


79238-7



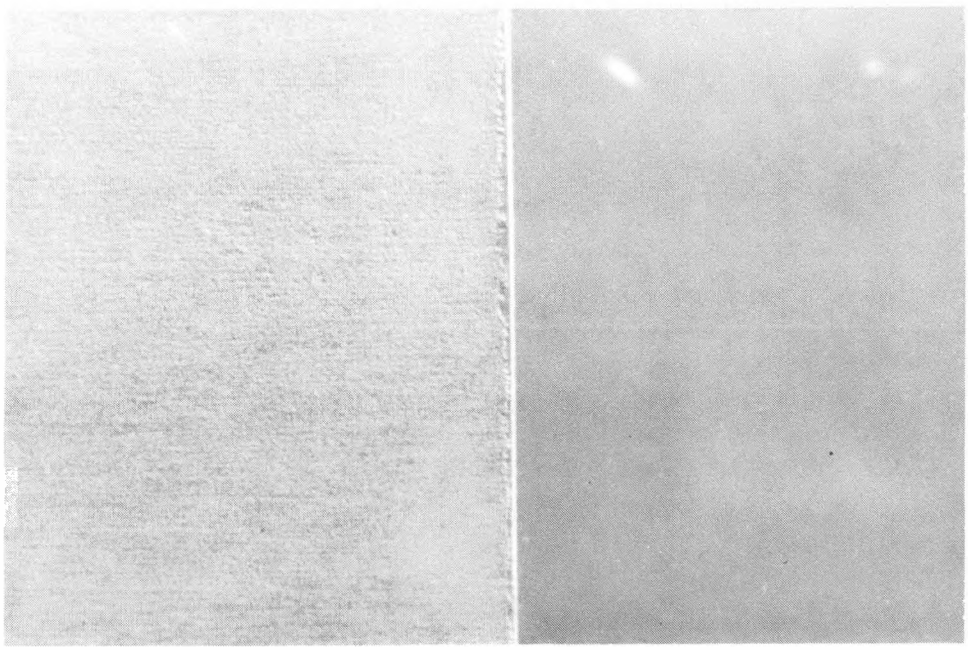
79239-3A

Figure 5. Typical appearance of cleaned titanium (Top) and AL-6X (Bottom) crevice test panels after 6 months exposure to ambient temperature seawater at 0.5 m/sec. For the environmental/metallurgical conditions described herein, neither titanium nor AL-6X exhibited attack at the multiple crevice sites.



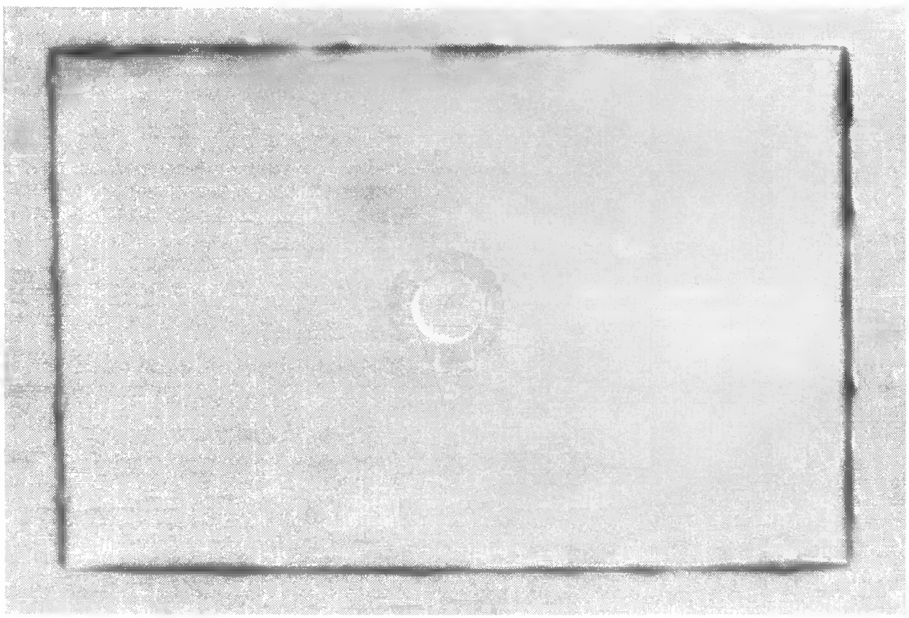
79238-12A

Figure 6. Typical appearance of cleaned aluminum alloy 5052 crevice test panels after 6 months exposure to ambient temperature seawater at 0.5 m/sec. Areas shielded by plateaus of crevice assembly are unattacked. General corrosion and accelerated attack at leading edge is, however, noted.



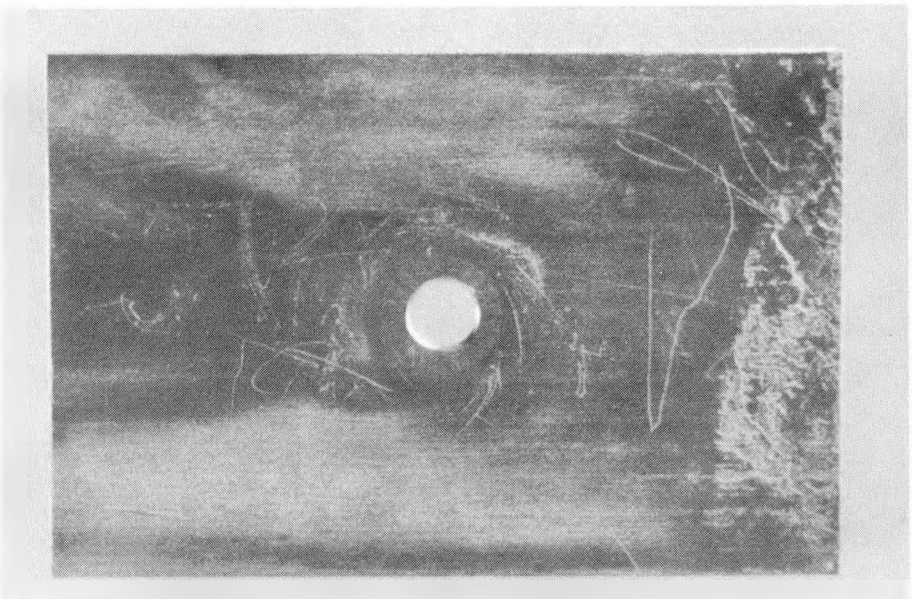
79240-9

Figure 7. Accelerated attack found on the edges of alloy 5052 test specimens.



79238-20

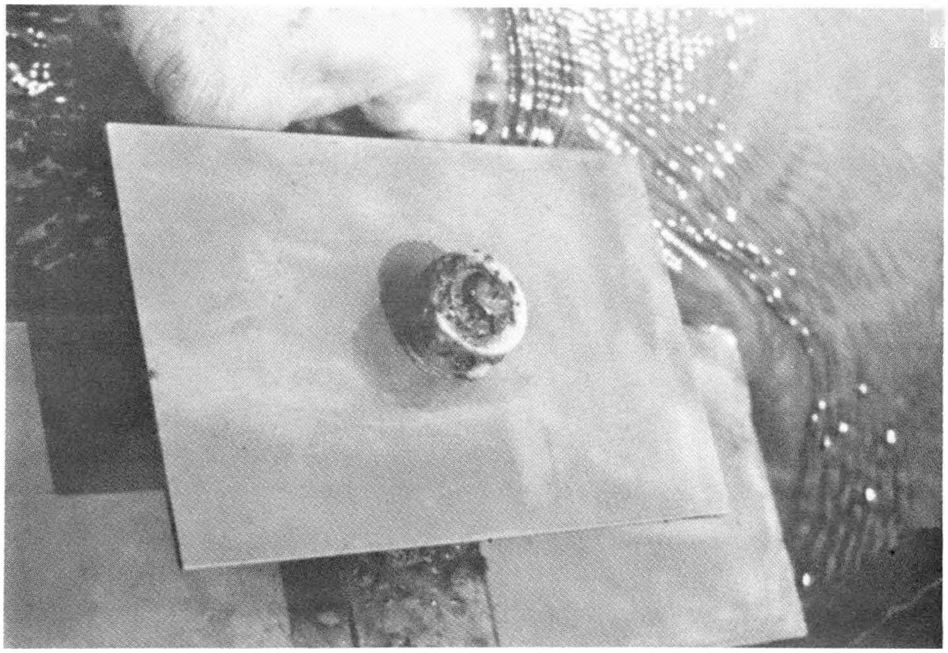
Figure 8. Typical appearance of cleaned Alclad crevice test panel after 6 months exposure to ambient temperature seawater at 0.5 m/sec. Areas shielded by plateaus of crevice assembly are evident. Epoxy sealant was used to protect cut edges of material.



Direction of Flow

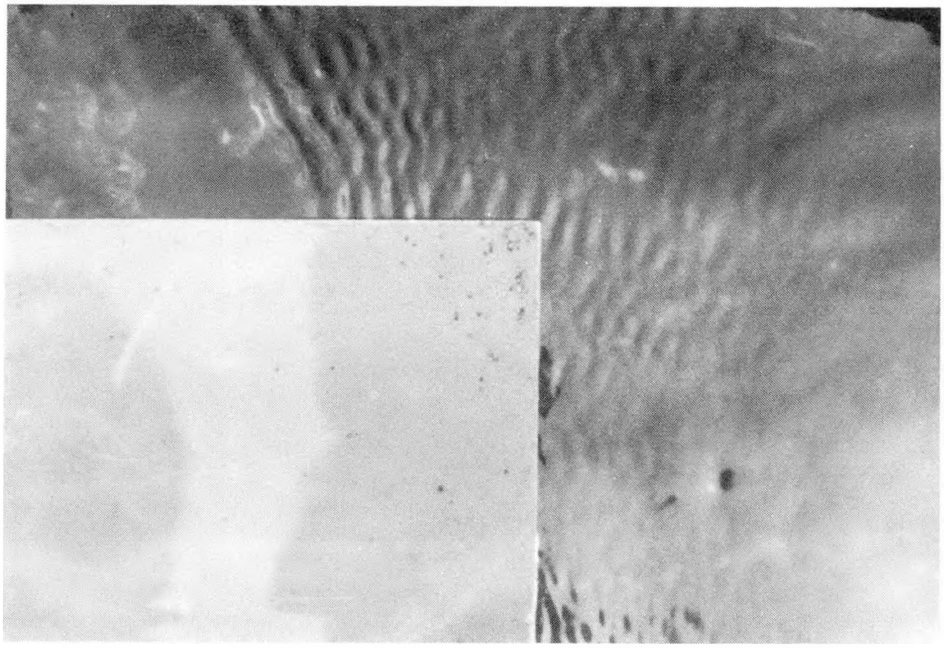
79239-13

Figure 9. Appearance of cleaned C70600 crevice test panel after 6 months exposure to ambient temperature seawater at 0.5 m/sec (note accelerated attack near the leading edge). Relatively little metal-ion concentration cell corrosion is evident at crevice assembly sites.



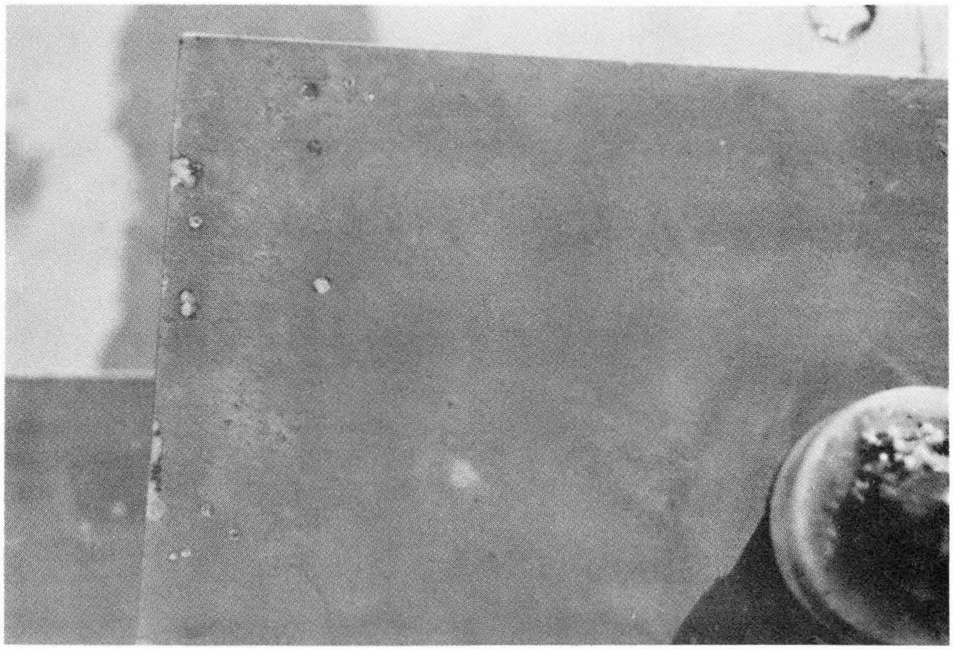
79115-13

Figure 10. Appearance of C72200 specimens on day 69. Green corrosion products, indicative of metal-ion concentration cell corrosion, are visible at the metal/Delrin washer interface.

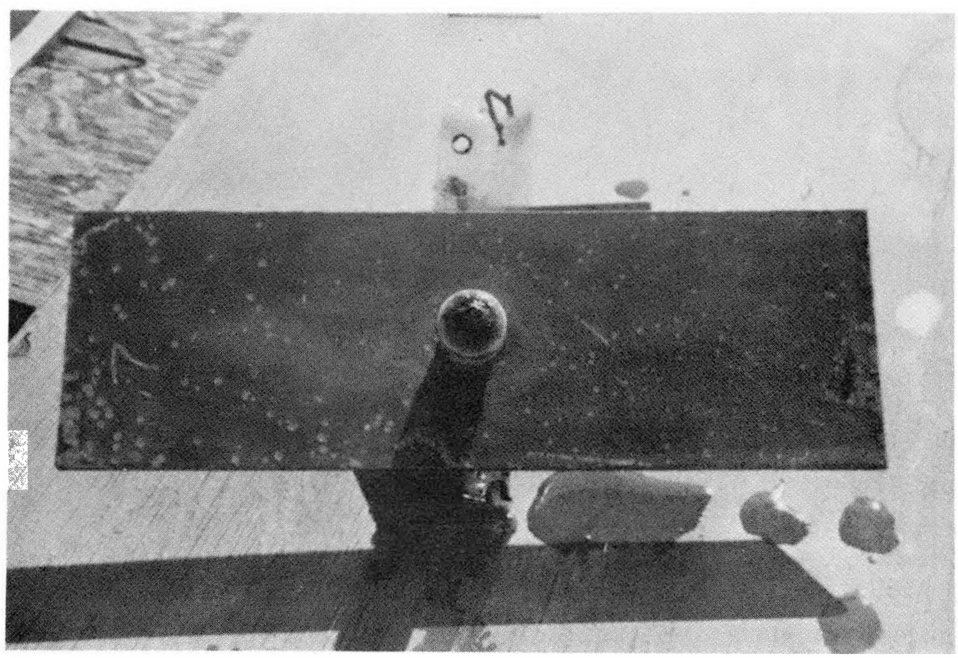


79115-8

Figure 11. Early detection of localized attack on the boldly exposed surfaces of C72200.

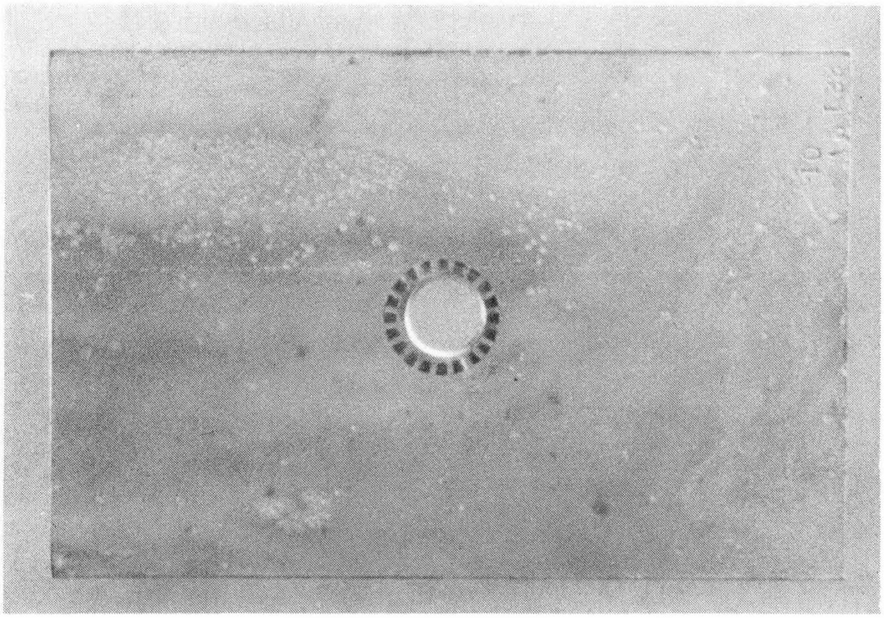


79172-3A



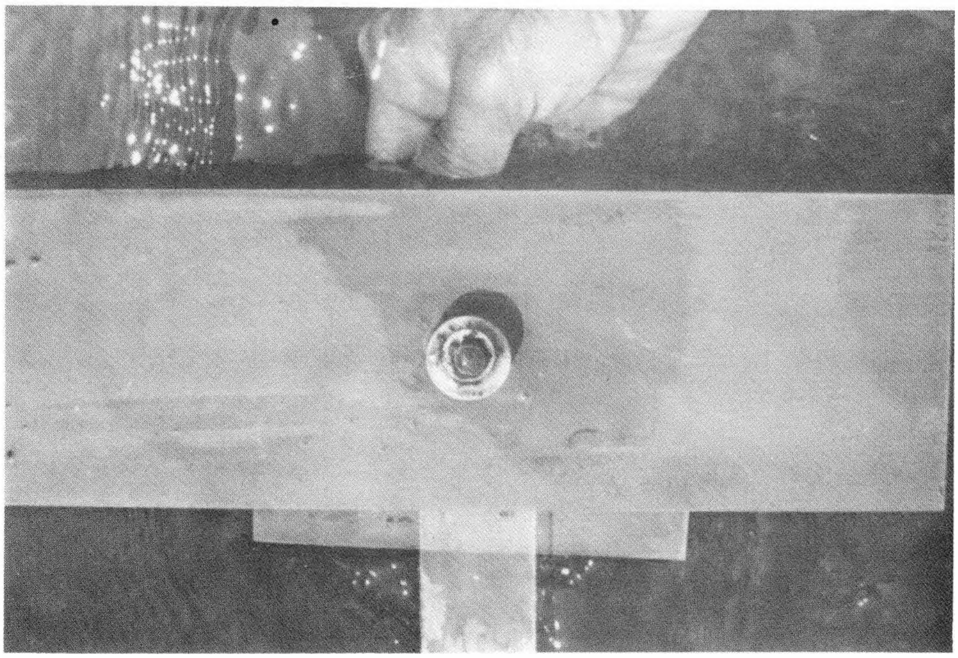
79172-2A

Figure 12. Localized attack detected on surfaces of C72200 test panels.



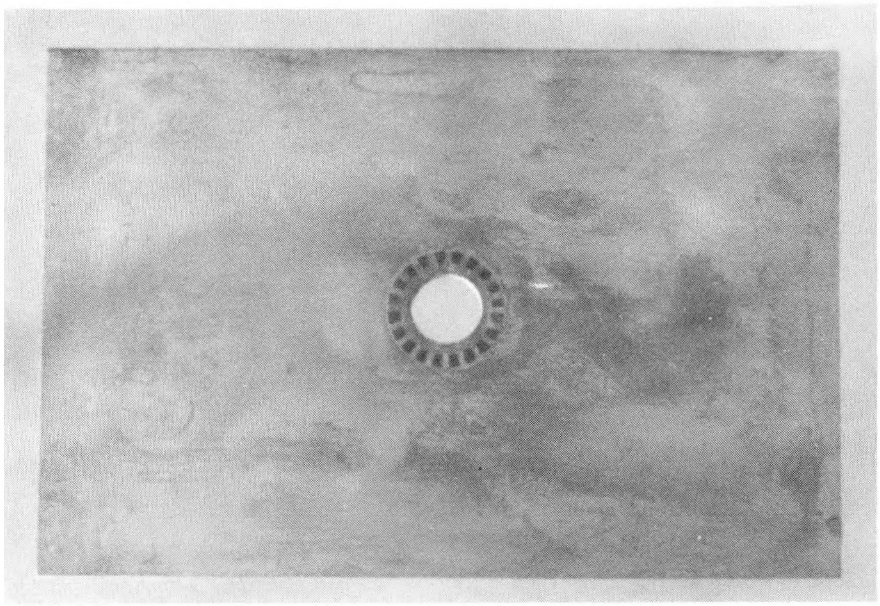
79239-17

Figure 13. Appearance of C72200 crevice test panel after 6 months exposure to ambient temperature seawater (0.5 m/sec). Although areas shielded by plateaus of crevice assembly are not attacked, adjacent regions incurred attack typical of metal-ion concentration cell corrosion. As also shown, considerable pitting occurred on the boldly exposed surface.



79115-6

Figure 14. Appearance of C72200 specimen on day 69 (note small attachments distributed over the surface).



79240-4

Figure 15. Typical appearance of cleaned Cu-Ni-Sn crevice test panel after 6 months exposure to ambient temperature seawater at 0.5 m/sec. Areas shielded by plateaus of crevice assembly are unattacked.

APPENDIX I

Alloy	Supplier/Source
Type 316 Stainless Steel	LCCT, Inc., Stock
AL-6X	Allegheny Ludlum
Titanium	Trent Tube Division of Crucible Inc.
Alclad	American Metals Corporation
Al 5052	J. M. Tull Metals Corporation
C70600	LCCT, Inc., Stock (Hussey)
C72200	Inco Research and Development Center (Revere)
Cu-Ni-Sn	Bell Laboratories

APPENDIX II

Mill Processing for C72200 and Cu-Ni-Sn

C72200: 0.2 inch material was cold rolled to 0.1 inch and given the following heat treatment: 1/2 hour @ 816°C in argon and water quenched. A light rolling pass was used to straighten material.

Cu-Ni-Sn: Processing schedule for this Bell Laboratory experimental alloy is proprietary and currently unavailable.

PART II

CREVICE CORROSION EVALUATIONS OF STAINLESS ALLOYS IN CONTROLLED TEMPERATURE, FILTERED SEAWATER.

EXECUTIVE SUMMARY

Laboratory tests in low velocity, filtered seawater at 30°C resulted in initiation of crevice attack for twelve of the thirteen stainless alloys included in this evaluation. For the most part, evidence of crevice corrosion initiation was detected within the first 30 days of exposure, however, considerable variation in the observed time to initiation of crevice corrosion was noted.

Increasing the test duration from 30 days to 60 days had little effect on the overall performance of these materials. On the other hand, decreasing the level of torque used to tighten the crevice assemblies apparently had a beneficial impact on the resistance of several alloys.

Comparison of OTEC test results with those of other tests suggests that the resistance of some alloys may vary considerably as a function of surface preparation, i.e., mill produced versus surface ground.

Analyses of the present data together with other research indicates that factors such as crevice geometry, i.e., crevice depth and crevice tightness (gap dimension), greatly affect the resistance of stainless alloys. It is presently only a matter of conjecture if the conditions in these tests are representative of those to be encountered in OTEC service.

Additional evaluations for several of the more promising alloys are recommended. Alloys which consistently exhibited little or no attack and those which responded to variation in crevice assembly torque merit further examination. Future assessments could possibly consider other crevice geometries, e.g., wider crevices, and metal to metal components.

INTRODUCTION

These investigations were undertaken to expand the knowledge of the localized corrosion resistance of candidate materials under consideration for OTEC heat exchangers. This report describes the results of seawater crevice corrosion evaluations of thirteen domestic and European stainless type alloys in low velocity filtered seawater at a controlled temperature of 30°C. Crevices were fabricated by the attachment of grooved non-metallic washers to sheet specimens of as-produced material. A test matrix was established to assess effects of test duration and level of crevice tightness on initiation behavior of the candidate materials.

This work follows an earlier investigation (described in Part I) to assess the susceptibility of titanium, AL-6X, Alclad and 5052 aluminum, C70600, C72200 and Cu-10Ni-8Sn alloy sheet materials to localized attack in ambient temperature seawater (0.5 m/sec flow). In those 6 month tests, under similar geometric conditions (crevice application), some evidence of attack was readily determined for control specimens of Type 316 stainless steel. No evidence of crevice attack was found on any specimens of titanium or the stainless alloy 6X.

In another phase of the OTEC corrosion program,[1] crevice corrosion of AL-6X was found on tubular specimens being evaluated for resistance to corrosion accelerated by mechanical abrasion. Localized areas of attack were found at several crevice sites formed by Tygon tubing used to connect a series of specimens in a test loop. The present investigation further examines the resistance of AL-6X tubing and sheet material exposed with Tygon crevice formers.

Most of the alloys considered in the present OTEC program are also being evaluated in a somewhat more extensive U. S. Navy-LCCT crevice test program. A major portion of the two programs were conducted concurrently and, in several cases, common heats of material were utilized. While specimens in the OTEC program were evaluated in the as-produced condition, specimens in the U.S.N.-LCCT program were provided with a 120 grit wet ground surface finish.

EXPERIMENTAL

Materials and Specimens

Table I gives the chemical analyses for the thirteen stainless alloys evaluated in the present study. Samples of sheet stock were obtained from Argonne National Laboratories or directly from the respective alloy producers. With the exception of the Carpenter Technology alloy EX00058, these alloys are also being evaluated in a somewhat more extensive, crevice corrosion program for the U. S. Navy. Those alloys having heats common to both programs are so noted.

A number of materials were provided as 10 X 15 cm test panels. Others were cut from larger sections of stock and machined to those dimensions. A total of nine specimens, with a stenciled identification code number, were prepared for each alloy. The only other machining requirements were the drilling of a 1.3 cm hole in the center of each specimen to facilitate attachment of the crevice formers. In the present study, commercially produced mill surfaces or as-received surfaces were left intact, while materials in the concurrent U.S. Navy program were evaluated in a surface ground condition.

Before crevices were affixed, specimens were degreased with acetone, pumice scrubbed with a bristle brush, rinsed with water, rinsed with fresh acetone and dried.

Crevice Assembly

Crevice formers, utilized for this program, consisted of two grooved Delrin™ washers secured to the test panel with an insulated titanium fastener. Each washer of the multiple crevice assembly (MCA) has 20 plateaus ground to a 600 grit finish (SiC). After tightening with a torque wrench to the desired levels of 8.5 or 2.8 Nm (75 in-lbs or 25 in-lbs, respectively), the assemblies were electronically checked to further insure against any undesirable galvanic interactions. The completed assembly, as shown in Figure 1, is the same as that described for the earlier test program (Part I). Specimens were subsequently mounted on plastic racks (using the crevice fastener to prevent additional crevices) for positioning in the seawater test apparatus.

Apparatus

Tests were conducted in a controlled temperature (30°C) seawater trough equipped with facilities for recirculation and refreshment. Two interconnected, 400L capacity troughs were utilized for these and concurrent tests. Figure 2 shows a sketch of the apparatus and relative positioning of the crevice specimens. The nominal velocity through the test section was <0.1 m/sec. Fresh, filtered seawater was introduced at a rate which provided approximately 6 to 7 complete changes daily.

Environment

During the course of the test program, the mean seawater temperature in the trough was 29.7°C (standard deviation 1.4°C - based on analysis of 9 readings daily). Figure 3 compares the controlled temperature with variations in the ambient seawater temperature for the period 9/8/80 to 12/8/80. Table II gives a summary of the seawater hydrology for weekly sampling of the controlled environment in the troughs and the seawater source.

Inspections and Assessments

Specimens were inspected during the course of the test for visual signs of accumulated corrosion product. Observations were made without disturbing or removing the specimens from the seawater. Unlike the tests conducted under Part I, exposure to filtered seawater did not promote macrofouling, e.g., barnacles, etc., hence, no in-site cleaning was required. Inspections were conducted on an almost daily basis with an increased frequency during the first week of exposure. The actual times to initiation may differ from those determined during the routine inspection since some finite amount of corrosion has occurred prior to the buildup of corrosion products. The observations, however, provide some indication of approximate times to initiation of crevice corrosion.

Upon completion of the scheduled test period and removal of the crevice assemblies, specimens were immersed in cold 30% HNO_3 for 15 minutes, rinsed and brushed with a pumice-detergent mixture to remove any corrosion products and staining.

Depths of attack at individual crevice sites were measured with a needle point dial gauge to the nearest 0.01 mm. Values reported herein reflect the deepest areas of attack as determined by this method. In several instances, perforations resulting from attack on opposite sites of the specimens were noted. In this case, the depth of attack is considered to be at least one-half of the material thickness.

Additional Crevice Testing of AL-6X

Additional crevice tests were conducted for the sheet material identified in Table I and also on 2.5 cm diameter tubular material (wall thickness = 1 mm) of the same commercial stock utilized in a previous test.[1] Four 15 cm lengths of tubing were fitted with 2 cm long sleeves of Tygon tubing (approximately 2.5 cm ID) forced over each end. These sleeves were constrained with hose clamps (see Figure 4a). In the present tests, positioning and tightening of the clamping devices was held constant. Tube specimens were positioned on non-metallic supports for exposure in the test trough. Contact with the support rack was limited to the Tygon sleeve areas to prevent additional crevice sites on the 6X tubing.

Crevices were formed on the surfaces of two sheet specimens of AL-6X according to Figure 4b. Sections of Tygon tubing were split and cut to form 2.5 cm diameter washers which were compressed on the surfaces. Procedures similar to those of the multiple crevice tests were followed (8.5 Nm torque).

RESULTS AND DISCUSSION

Crevice Corrosion Testing of AL-6X Tubing

Three of the four AL-6X tube specimens exhibited crevice attack at Tygon sleeve sites within 30 days. The fourth specimen apparently initiated sometime after 60 days. The earliest recorded indication of crevice corrosion was at 336 hours. Figure 5 shows the typical appearance of a corroded area after 30 days exposure. Both specimens removed after 30 days exhibited a maximum penetration of approximately 0.60 mm. Examination of the third attacked specimen, after 60 days exposure, revealed that the wall thickness was perforated at one location. The overall extent of attack on the fourth specimen, removed after 90 days, was somewhat less extensive but the maximum depth of attack was comparable, e.g. $\sim$0.50 mm. In each case, attack was limited to only one of the two Tygon sleeve crevice sites. Results of these tests are consistent with the observation of attack for AL-6X tubing in the previous program.[1]

Crevice Corrosion Testing of AL-6X Sheet with Tygon Washers

No evidence of crevice corrosion was found on duplicate specimens of AL-6X exposed for 90 days with crevices formed by washers fabricated from Tygon tubing.

Multiple Crevice Testing

Initially, six specimens of the thirteen alloys were exposed with crevice assemblies tightened to a torque of 8.5 Nm. As evidenced by the accumulation of corrosion products around the crevice washers, ten of the thirteen alloys exhibited some degree of crevice attack within 500 hours. Some trace of ongoing attack was found on one of the SC-1 specimens just prior to completion of the first 30 days (approximately 703 hours). No evidence of crevice corrosion was detected for any of the MONIT or 29-4C alloy specimens at that time.

Upon completion of the first 30 days' exposure, one set of triplicate specimens for all alloys except MONIT, 29-4C and SC-1 were removed from test. The remaining original specimens were left in test for a scheduled termination at 60 days. In the case of the three alloys noted above, one set of triplicate specimens continued for a total exposure of 90 days.

An additional set of triplicate specimens of MONIT, SC-1 and 29-4C, loaded at the 8.5 Nm torque level were exposed for subsequent removal at 30 days. For the other ten alloys, a set of specimens with crevices tightened to 2.8 Nm were exposed at this time with a scheduled termination at 60 days.

At least one specimen of the two Carpenter alloys, JESSOP alloy 700, HAYNES alloy 20MOD and NITRONIC 50, with crevices tighten to 2.8 Nm, exhibited attack within the first 30 days under these conditions. During the second 30 day period slight attack was also noted for one of the AL-6X specimens. No evidence of attack was found on any of the triplicate specimens (2.8 Nm) of AVESTA alloy 254SMO, UDDEHOLM alloy 904L, FERRALIUM and JESSOP alloy 777 during the course of this 60 day test.

Appendicies I - XIII provide a comprehensive description of the crevice corrosion resistance of each of the thirteen alloys. For each specimen, a summary of the test results is presented. Included for each is an indication of the earliest observed time of ongoing attack. The designation ND signifies that while corrosion products were not detected during the course of the test, crevice attack was found upon removal of the crevice assemblies. Data also indicate the number of sites corroding beneath each grooved washer as well as the range of measured penetration depths.

Additional Comments

Crevice geometry is known to affect the initiation resistance of stainless alloys. It has long been recommended, for example, that if crevices are unavoidable, they should be kept as open and as shallow as possible. Current research indicates that in order for initiation to occur, some critical depth-gap dimension combination must exist (see Figure 6). Necessarily, this critical geometry contributes to the conditions that result in the localized environment change (deaeration, acidification and Cl^- concentration) within the crevice and ultimate breakdown of passivity.

Mathematical modelling as described by Oldfield[2] allows for the systematic study of the effects of crevice geometry. Figure 7, for example, shows a schematic representation of the effect of crevice gap on the predicted time to breakdown. Consider, in the first case, two different materials (curve I and curve II, respectively). At a crevice gap described by A, both alloys are predicted to initiate quite rapidly with relatively little difference in the time for each. As the crevice gap becomes wider, e.g., dimension B., the time to breakdown increases with somewhat longer times predicted for Alloy II. Eventually a gap dimension is reached where breakdown is no longer predicted for Alloy I (dimension C). Alloy II, on the other hand, is predicted to initiate until the gap is widened to some dimension between D and E. With all other parameters held constant, the model predicts that a fraction of a micron difference in crevice gap could be the determining factor controlling initiation.

It has been suggested that in the case of the multiple crevice washer, minor variations in the plateau height could affect the width of the gap.[3] Initial contact at one or more crevice sites could control the gap dimension at other sites. Hence, an entire range of gaps may be present beneath a single crevice washer. The possibility for the presence of a range of crevice gaps helps to explain the often observed specimen to specimen variation in time to initiation and incidence of attack.

Figure 7 can also be used to demonstrate the effect of crevice assembly torque as described in the present investigations. If it is assumed that with a torque level of 8.5 Nm, a range of crevice gap dimensions from A to C are present, then initiation is predicted for all materials represented by curves I and II. It follows that lowering the torque level to 2.5 Nm creates somewhat wider crevice gaps, e.g., range C to E. Accordingly, while crevice conditions are no longer severe enough to contribute to breakdown of the alloys described by curve I, materials represented by the curve II will continue to initiate.

Caution must be exercised in relating alloy resistance from one set of conditions to another. For example, deeper crevices would tend to contribute to initiation over a broader range of crevice gaps.[3] In addition, some alloys, as shown in the present report, may be more resistant for one surface condition than another. Alteration of the mill produced surface could in some cases affect the crevice geometry as well as the surface composition.

SUMMARY AND CONCLUSIONS

Crevice corrosion tests were conducted for thirteen stainless alloys in low velocity, filtered seawater at a controlled temperature of 30°C for periods up to 90 days. All materials were evaluated in the as-produced, as-received condition. For the most part, crevices were formed by the application of grooved Delrin washers. Two levels of crevice assembly torque were investigated to assess any effect of crevice tightness on initiation resistance. Additional testing, which was limited to AL-6X, utilized crevice formers prepared from Tygon tubing.

Except for stainless alloy 29-4C which was found to be resistant to initiation under these test conditions, the remaining twelve materials exhibited some degree of susceptibility. For these, attack ranged from only a few shallow penetrations to numerous sites which in some cases resulted in perforation of the specimens.

While several alloys responded favorably to changes in the level of applied torque, others were apparently unaffected. In general, extending the test duration from 30 to 60 days had no pronounced effect on initiation and penetration behavior.

Results describing attack of AL-6X tubing fitted with Tygon sleeves were consistent with earlier observations. No evidence of attack was detected in a 90 day test for AL-6X sheet specimens fitted with Tygon washers.

Results for the OTEC crevice test program are generally consistent with those of a concurrent U.S.N.-LCCT program. In the latter series, however, surface ground samples of several susceptible alloys exhibited somewhat shorter times to initiation and more extensive attack. The greatest effect of surface grinding was noted for two propriety versions of the 25Ni-20Cr-4.5Mo-1.5Cu alloy, i.e., JESSOP alloy 777 and UDDEHOLM alloy 904L. While no evidence of crevice corrosion was detected for as-produced material tested at the 2.8 Nm torque level, surface ground specimens were readily attacked.

Resistance or susceptibility to attack in these or other tests are highly dependent on a number of inter-related metallurgical, geometric and environmental factors. It is presently only a matter of conjecture if conditions described herein are representative of those to be encountered in an OTEC facility. Additional tests are deemed necessary to further characterize the resistance of candidate materials. Obvious difficulties arise in devising a single test that is appropriate to simulate any or all crevices encountered in service. Future research could be directed at investigating behavior for a variety of crevice formers including metal to metal crevice components.

REFERENCES

1. D. G. Tipton, "Effect of Mechanical Abrasion on Corrosion of Candidate OTEC Heat Exchanger Tubing Materials in a Simulated OTEC Environment - Three Month Test Exposures", ANL/OTEC-BCM-013, September 1980.

2. J. W. Oldfield and W. H. Sutton, "Crevice Corrosion of Stainless Steels I. A Mathematical Model", British Corrosion Journal, Vol. 13, 1970.

3. R. M. Kain, "Crevice Corrosion of Stainless Steels in Seawater and Related Environments", Paper No. 200 presented at CORROSION/81, Toronto, Canada, April 5-6, 1981.

TABLE I

Identification and Chemical Analyses of Stainless Alloys

Alloy Designation	Heat No.*	LCCT Code	Cr	Ni	Mo	Cu	Si	Mn	C	S	P	Other
JESSOP alloy 700	25092	270AC	20.70	24.80	4.45	0.29	0.37	1.68	0.025	0.015	0.025	Cb 0.30 Co 0.16
JESSOP alloy 777 (N)	None	274AB	21.0	25.0	4.5	2.0			0.04			
HAYNES alloy 20MOD	5320.6.6013*	128AG	21.58	25.52	4.95	<0.05	0.49	0.90	<0.01			Co 0.49
FERRALIUM 255	8537.8.7443*	449AC	26.15	5.64	3.20	1.75	0.37	0.77	0.02			N 0.19
29-4C	740966	271AC	28.54	0.49	3.78		0.53	0.23	0.023	0.001	0.021	N 0.035
AL-6X	02145*	258AL	20.35	24.64	6.45		0.41	1.39	0.018	0.001	0.022	
UDDEHOLM alloy 904L	01152*	276AF	20.5	24.7	4.7	1.57	0.46	1.46	0.014	0.005	0.028	
MONIT	1-0840*	280AC	25.3	4.1	3.8	0.37	0.31	0.43	0.012	0.006	0.031	
Type 325 Stainless Steel	X30559	500AA	26.68	4.23	1.37		0.28	0.32	0.06			
CARPENTER Exp. 58	X00058	501AA			-----NOT AVAILABLE-----							
CRUCIBLE alloy SC-1	162097	279AA	25.34	2.25	3.10		0.20	0.20	0.010	0.007	0.025	
NITRONIC 50	326236*	275AB	21.08	13.70	2.28		0.47	4.81	0.045	0.012	0.025	
AVESTA 254SMO	174827*	278AB	20.0	17.9	6.10	0.78	0.41	0.49	0.013	0.008	0.023	N 0.203

* Heats common with U.S.N./LCCT crevice test program.

(N) Nominal composition

TABLE II

Seawater Hydrology[1]

	Sample Location	
	Test Trough	Source
pH	7.7 to 8.2	7.8 to 8.1
Salinity (mg/L)	34.4 to 39.1	32.8 to 38.5
Chloride (mg/L)	19.2 to 21.7	18.2 to 21.3
Dissolved Oxygen (mg/L)	5.3 to 6.7*	4.7 to 7.9*
*Percent saturation at sample temperature	84.7 to 100.0	77.3 to 99.7

[1]Based on routine weekly analyses for the test period 9/8/80 to 12/8/80.

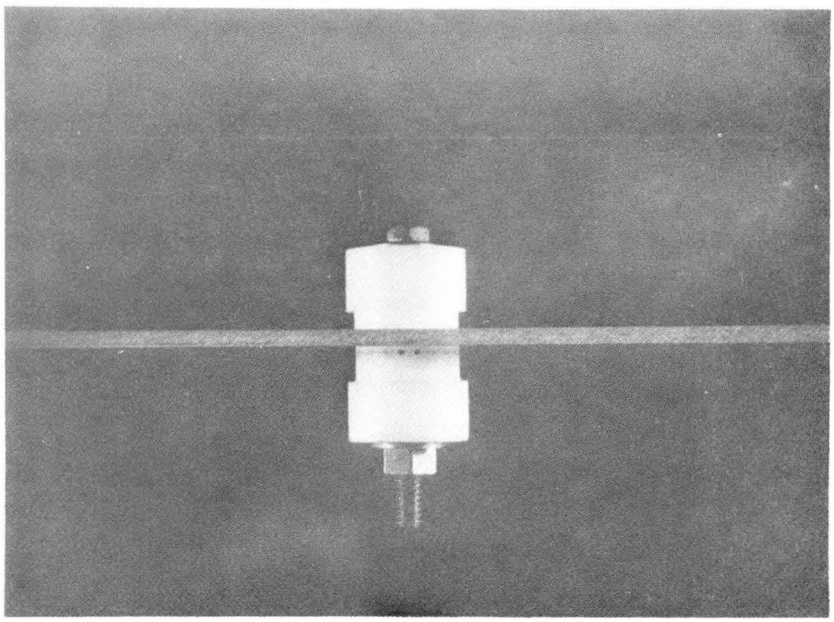
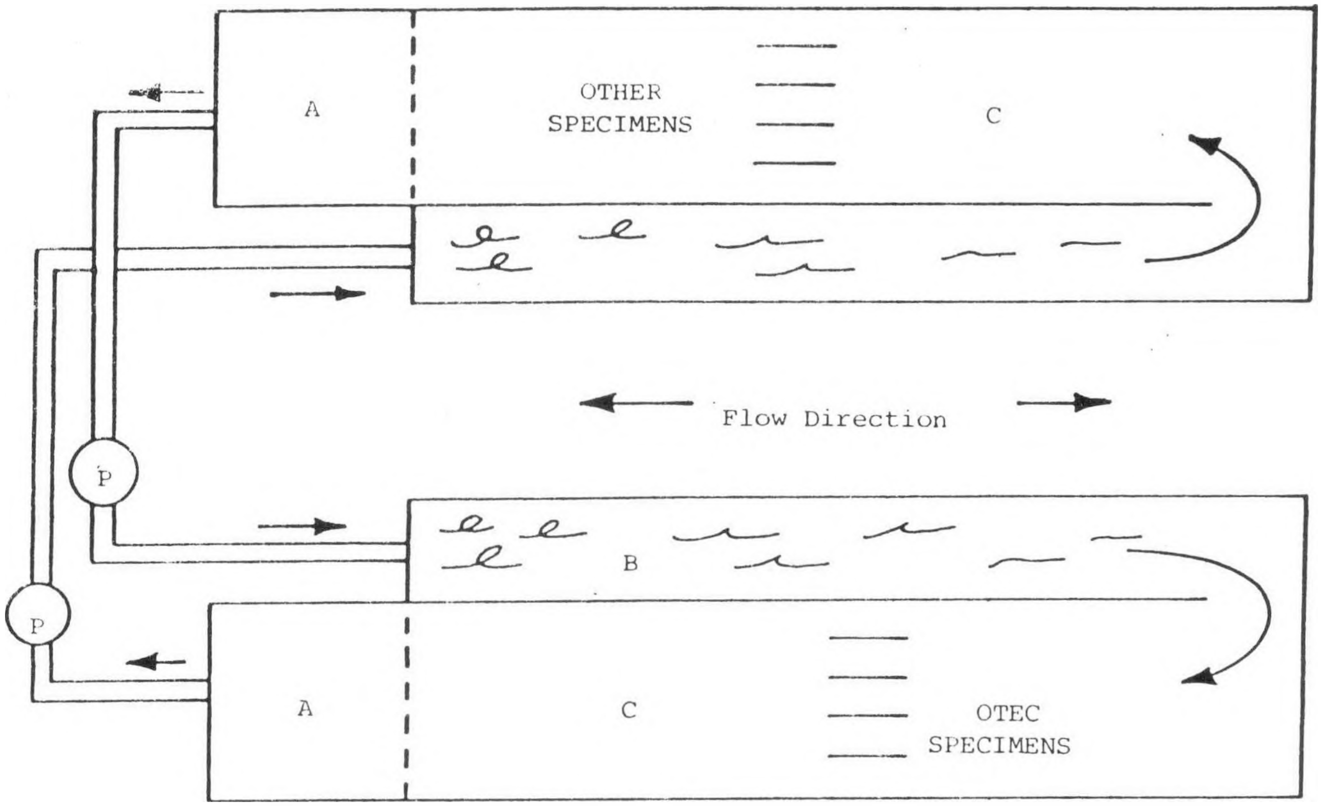


Figure 1. Completed multiple crevice assembly: overhead view - approximately 80% of actual size.



A) Deep Well Compartment - Temperature Controls- Heaters - Refreshment and Overflow

P) Recirculation Pump

B) Baffle Section

C) Smooth Flow Test Section with Specimens

Figure 2. Schematic of overhead view of interconnected seawater troughs for crevice corrosion testing.

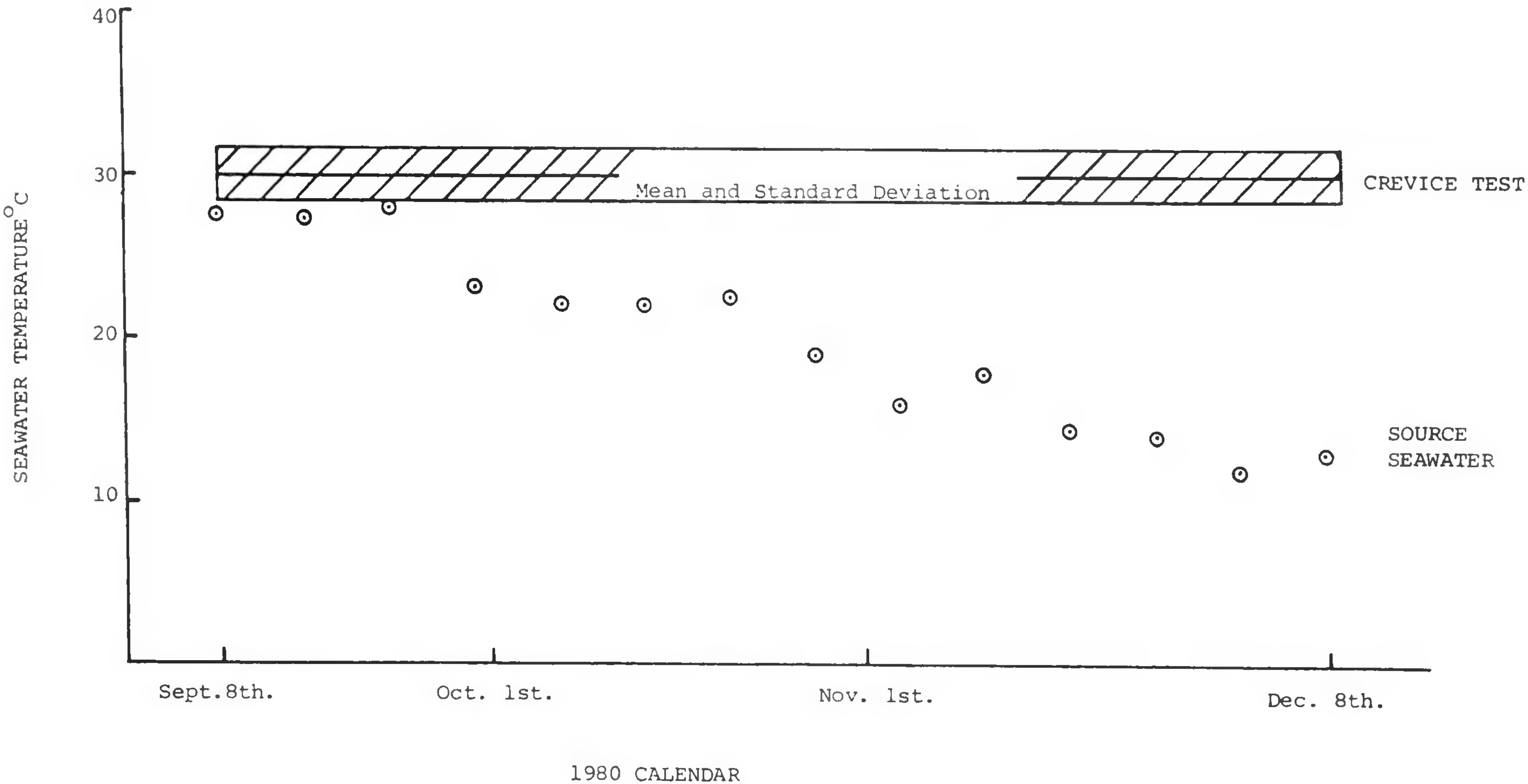


Figure 3. Seawater temperature variations for the test period 9/8/80 - 12/8/80.

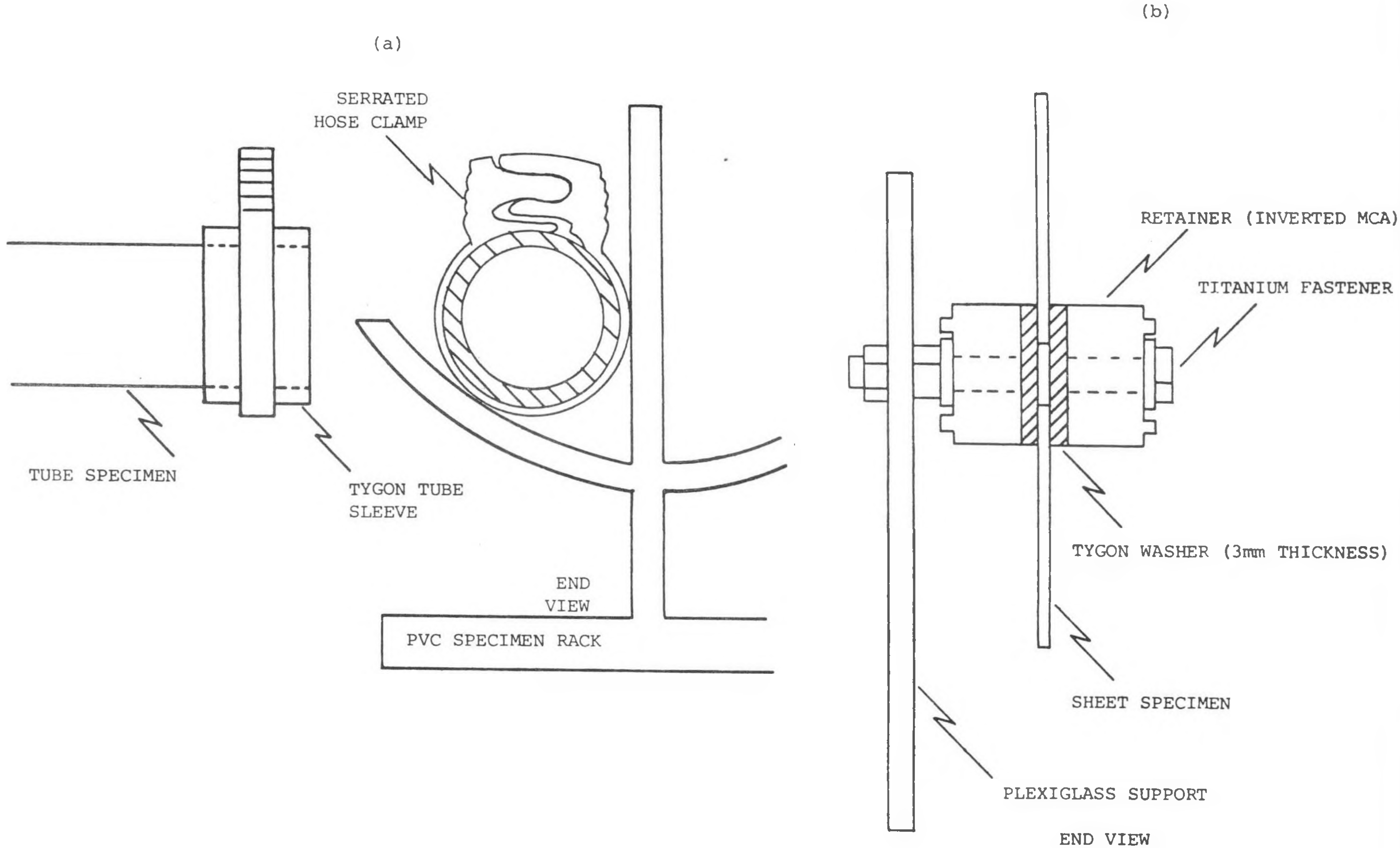
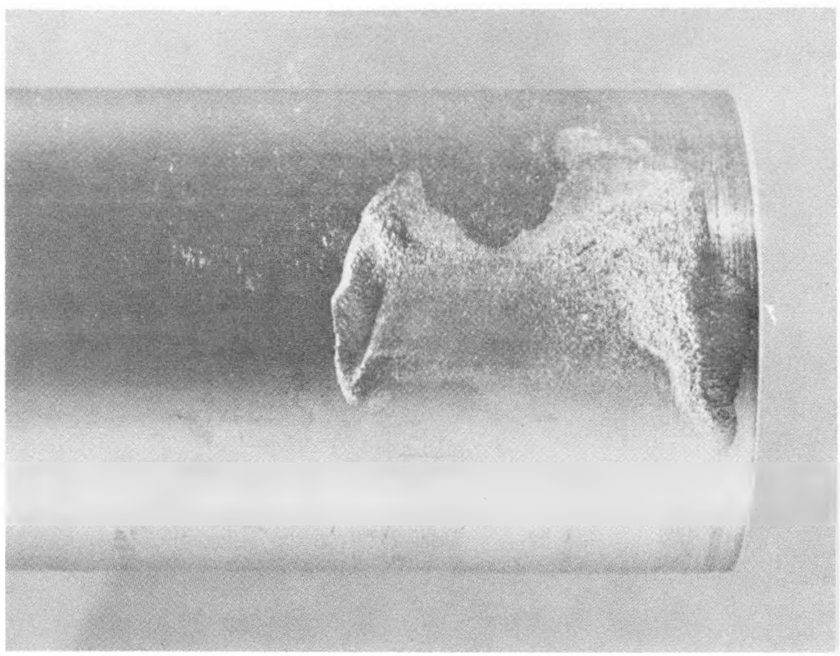


Figure 4. Application of Tygon crevice formers for testing of AL-6X sheet and tubing specimens.



80214-18A 2.5X

Figure 5. Extent of crevice attack for AL-6X tubing beneath Tygon sleeve. Exposure time: 30 days.

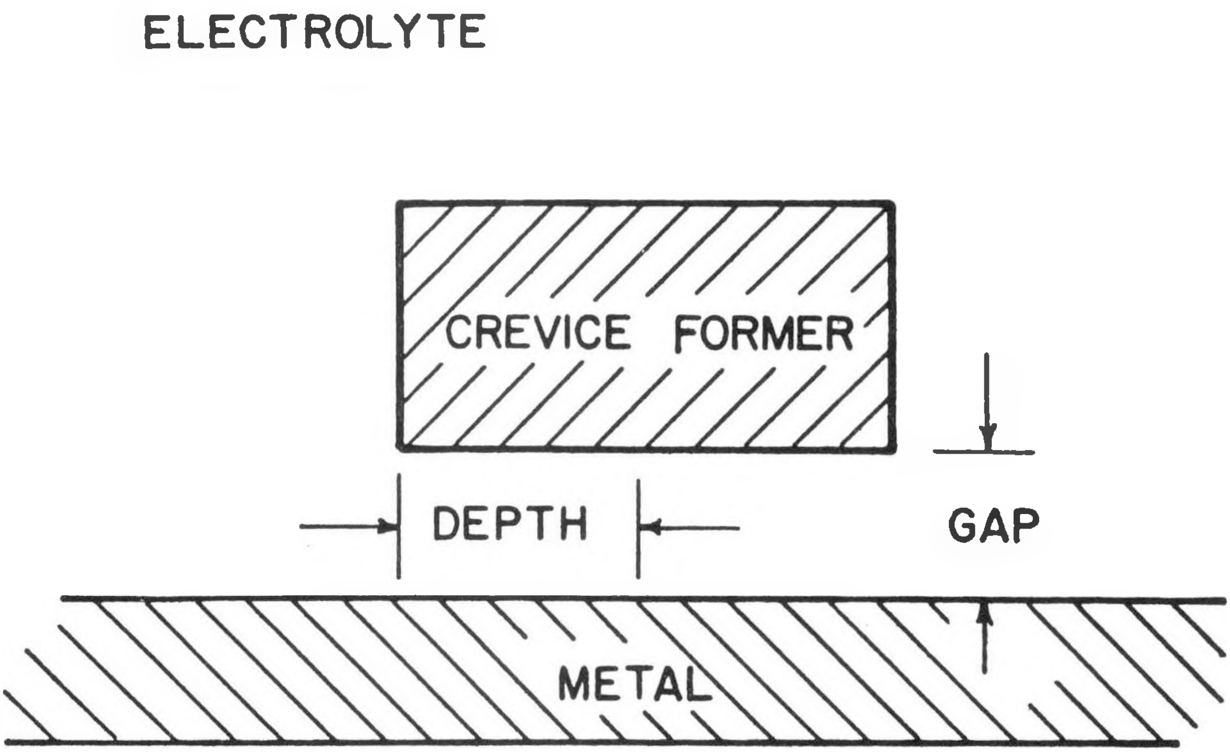


Figure 6. Schematic representation of crevice geometric factors, gap and depth.

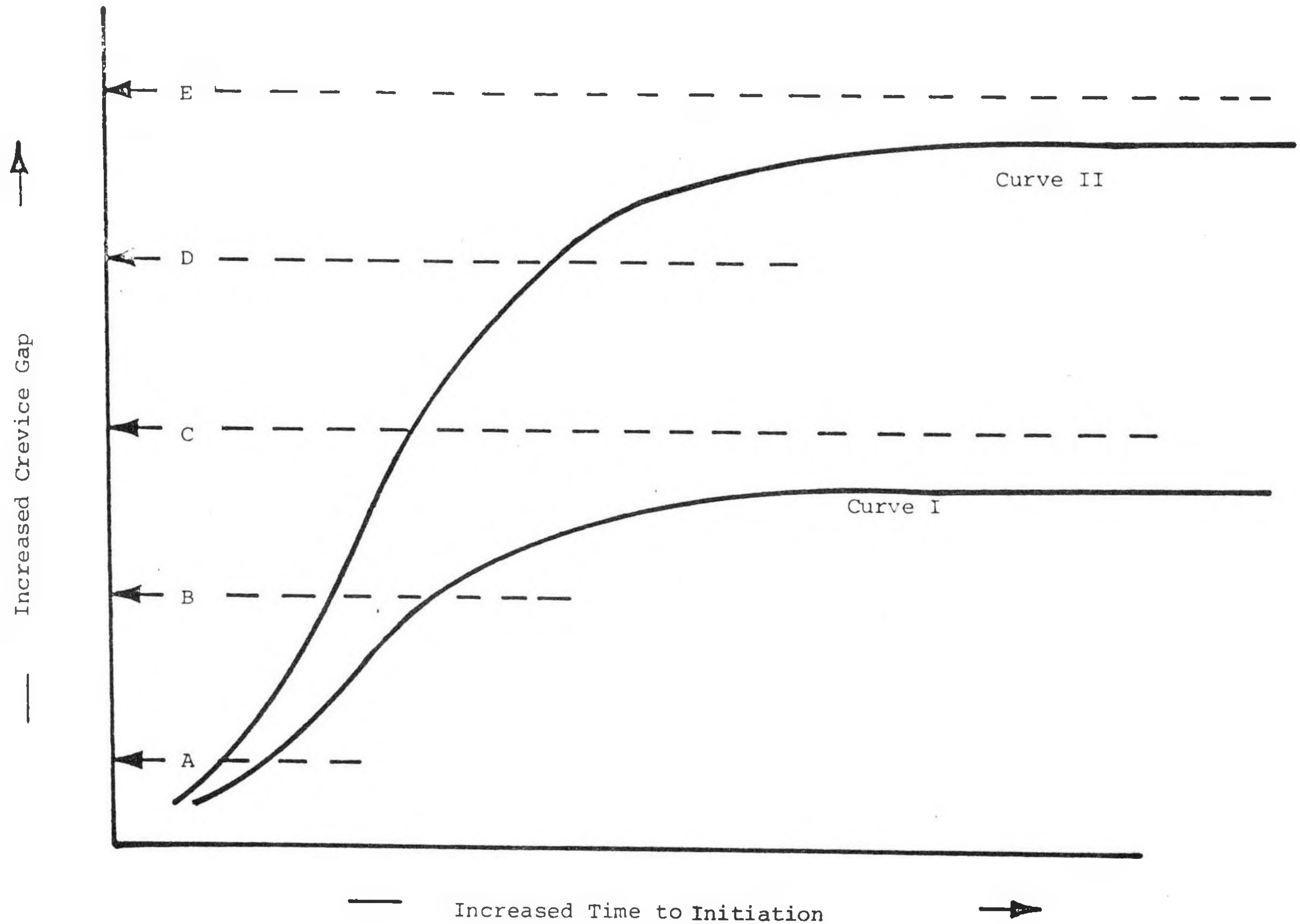


Figure 7. Schematic showing effect of crevice gap on initiation as predicted by mathematical modelling.

APPENDICES I TO XIII

Further discussion of results of multiple crevice testing are covered in the following sections. Alloy data have been assembled alphabetically according to the respective producer. No order of ranking is intended. Accompanying photographs of attacked specimens may or may not represent the severest case.

APPENDIX I

ALLEGHENY LUDLUM ALLOY AL-6X

From the summary of results for AL-6X shown in Figure I.1, it can be seen that the earliest confirmation of ongoing attack was noted during an inspection at 388 hours. Within 673 hours, two of the six specimens with crevice formers tightened to 8.5 Nm, exhibited visible accumulations of corrosion product. Examination of one of these corroding specimens at the end of 30 days revealed crevice attack at only one site beneath each of the two grooved washers (Figure I.2). Two other specimens removed at that time had not initiated.

All three specimens exposed for 60 days at the 8.5 Nm torque level were attacked. However, in contrast to specimen 258AL-3 which initiated within 673 hours, penetrations in the other two specimens were quite shallow. It is not known if the observed increase in incidence of attack is solely related to the extended duration of testing.

As reported in Part I, no evidence of attack was detected for similarily prepared specimens exposed for 6 months in ambient temperature, unfiltered seawater flowing at 0.5 m/sec. It is not known if the observed difference in behavior is attributable to environmental differences (i.e., seawater velocity, level of filtration) or to combined environmental-geometric factors.

For the triplicate specimens exposed with crevice formers tightened to 2.8 Nm, only a single crevice site on one specimen was attacked in a 60 day test. Both the low incidence of attack and the somewhat longer time to initiation as noted in I.1 suggest an effect of crevice tightness.

Other Tests

In comparison with the results of the OTEC program, specimens of the same heat of AL-6X exposed in the U.S.N./LCCT tests exhibited shorter times to initiation. Two of three surface ground specimens with crevice formers tightened at 8.5 Nm exhibited attack within 51 hours. The third panel initiated within 356 hours.

Subsequent testing of two additional ground specimens at the 8.5 Nm torque level for 60 days produced results similar to the 30 day test.

All three of the surface ground AL-6X specimens with crevice formers tightened to 2.8 Nm exhibited attack within 127 hours. Examination of the panels after a 60 day exposure revealed relatively few attacked sites.

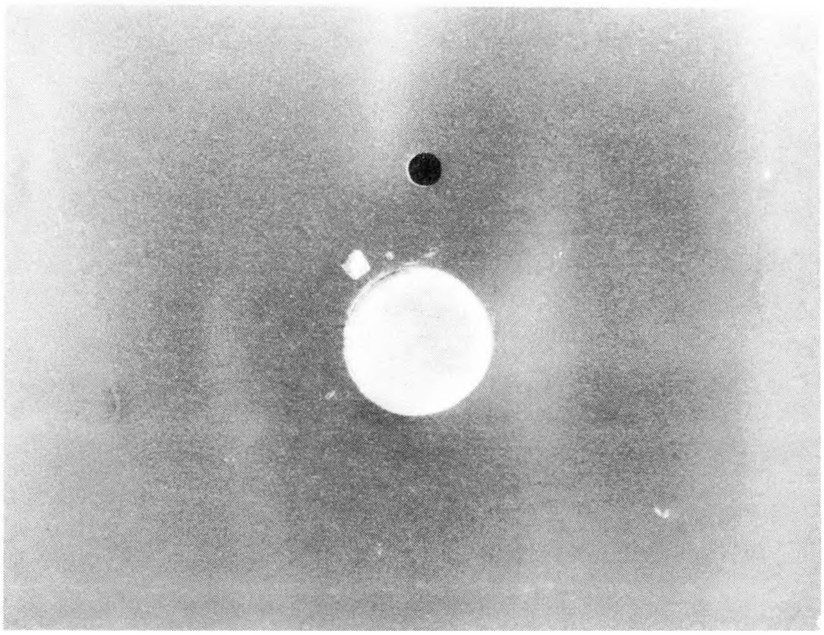
Figure I.1

MULTIPLE CREVICE TESTS RESULTS

AL-6X
ALLEGHENY LUDLUM

Condition	Specimen Code	Initiation Time (HRS) Code Side	Initiation Time (HRS) Back	No. of MCA Sites Attacked Code Side	No. of MCA Sites Attacked Back	Depth of Attack Range (MM) Code Side	Depth of Attack Range (MM) Back
30 DAYS (8.5Nm)	258AL-6	OK	OK	none	none	--	--
	7	OK	OK	none	none	--	--
	8	673	388	1	1	0.09	0.23
60 DAYS (8.5Nm)	258AL-1	ND	ND	6	1	<0.01	<0.01
	2	ND	ND	2	2	<0.01	<0.01
	3	673	OK	10	none	<0.01 to 0.34	--
60 DAYS (2.8Nm)	258AL-9	OK	772	none	1	--	0.02
	10	OK	OK	none	none	--	--
	11	OK	OK	none	none	--	--

Heat No. 02145



80213-13A ~1.5X

Specimen 285AL-8 (Back)

Figure I.2. Appearance of crevice area of AL-6X specimen exposed for 30 days at 8.5 Nm torque level.

APPENDIX II

ALLOY 29-4C (ALLEGHENY LUDLUM)

No evidence of crevice attack was detected on any of the nine specimens of alloy 29-4C exposed with crevice formers tightened to 8.5 Nm. As indicated in Figure II.1 triplicate specimens were exposed for test periods of 30, 60 and 90 days duration.

Other Tests

No evidence of attack was found for surface ground specimens of a second heat of 29-4C in a 30 day U.S.N./LCCT test. In that test, triplicate specimens were exposed with crevice washers tightened to 8.5 Nm. Additional tests lasting up to 82 days did not reveal any susceptibility under these conditions.

Figure II.1

MULTIPLE CREVICE TESTS RESULTS

29-4C
ALLEGHENY LUDLUM

Exposure	SPECIMEN CODE	INITIATION TIME (HRS) CODE SIDE	INITIATION TIME (HRS) BACK	NO. OF MCA SITES ATTACKED CODE SIDE	NO. OF MCA SITES ATTACKED BACK	DEPTH OF ATTACK RANGE (MM) CODE SIDE	DEPTH OF ATTACK RANGE (MM) BACK
30 DAYS (8.5 Nm)	271AC-7, 8, 9	NO EVIDENCE OF ATTACK ON TRIPLICATE SPECIMENS					
60 DAYS (8.5 Nm)	271AC-1, 2, 3	NO EVIDENCE OF ATTACK ON TRIPLICATE SPECIMENS					
90 DAYS (8.5 Nm)	271AC-4, 5, 6	NO EVIDENCE OF ATTACK ON TRIPLICATE SPECIMENS					

Heat No. 740966

APPENDIX III

NITRONIC 50 (ARMCO)

Results of crevice corrosion testing of NITRONIC 50 are summarized in Figure III.1.

One specimen at the 8.5 Nm assembly torque level exhibited attack within 24 hours. Within 336 hours, four of the original six specimens were corroding. Subsequent examination of three of these specimens after 30 days of testing revealed several areas of attack with a maximum depth of attack of 0.67 mm (see Figure III.2).

From these results, it can be seen that extending the test duration of the remaining three specimens from 30 days to 60 days had no apparent effect on initiation or penetration resistance of the alloy.

For specimens with crevice formers tightened to 2.8 Nm, both the observed times to initiation and the overall incidence of attack are comparable with the general behavior for specimens in the 8.5 Nm tests. While most of the measured depths of attack were within the range of those measured in the other 30 and 60 day test, several areas with deeper attack, including at least one perforation, were noted in the 2.8 Nm test.

Several of the NITRONIC 50 samples exhibited edge attack.

Other Tests

Testing of surface ground specimens of the same heat of NITRONIC 50 in the U.S.N./LCCT program resulted in a generally greater incidence of attack. Visible signs of on-going attack were detected on both sides of triplicate specimens (8.5 Nm torque) within 77 hours. Examination of the specimens at the end of 30 days revealed that more than 90 percent of the available crevice sites were attacked (maximum depth 1.1 mm).

Lowering the torque to 2.8 Nm had little effect on the initiation resistance of ground specimens of NITRONIC 50. On-going attack was detected on at least one side of each of six specimens within 72 hours. Examination of the specimens after 60 days again revealed a generally high incidence of attack. Again, a number of penetrations of the specimen thickness occurred.

Figure III.1

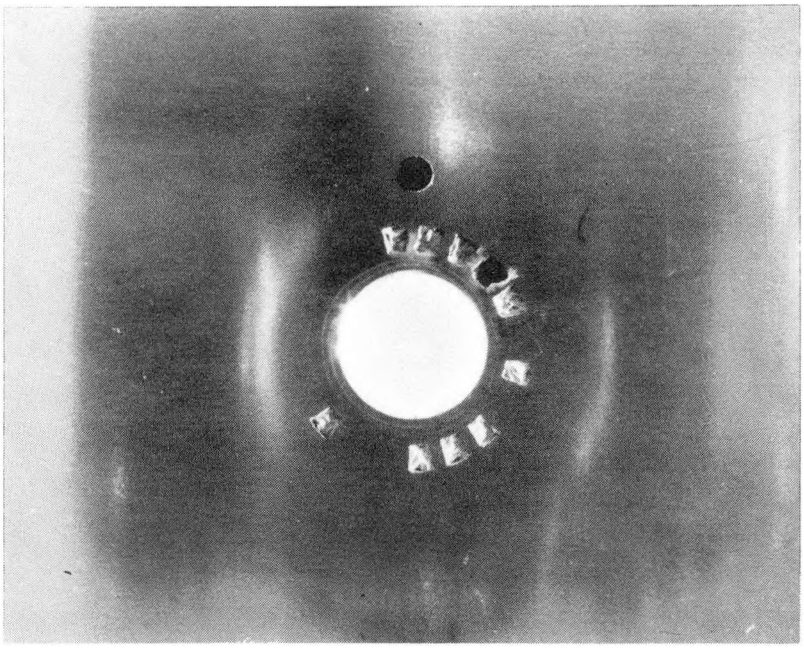
MULTIPLE CREVICE TESTS RESULTS

NITRONIC 50

Condition	SPECIMEN CODE	INITIATION TIME (HRS) CODE SIDE	INITIATION TIME (HRS) BACK	NO. OF MCA SITES ATTACKED CODE SIDE	NO. OF MCA SITES ATTACKED BACK	DEPTH OF ATTACK RANGE (MM) CODE SIDE	DEPTH OF ATTACK RANGE (MM) BACK
30 DAYS (8.5 Nm)	275AB-10	72	24	7	5	0.20 to 0.45	0.18 to 0.41
	11	96	OK	2	none	0.38, 0.55	---
	12	336	72	2	9	0.23, 0.31	0.21 to 0.67
60 DAYS (8.5 Nm)	275AB-13	336	96	6	7	<0.01 to 0.26	<0.01 to 0.21
	14	ND	ND	6	5	<0.01 to 0.04	<0.01, 0.24
	15	ND	ND	2	1	<0.01, 0.03	<0.01
60 DAYS (2.8 Nm)	275AB-16	966	100	3	11	0.19 to 1.15	0.13 to 0.77*
	17	ND	170	1	5	0.21	0.15 to 0.34
	18	290	100	3	7	0.11 to 0.21	0.05 to 0.25

* Penetration through sample thickness (1.20 mm) resulting from attack on opposite sides of specimens.

Heat No. 326236



80212-6A ~1.5X

Specimen 275AB-12 (Back)

Figure III.2. Localized attack beneath multiple crevice washer fastened (8.5 Nm) to NITRONIC 50 specimen in a 30 day test.

APPENDIX IV

AVESTA ALLOY 254SMO

Figure IV.1 summarizes the initiation and penetration behavior exhibited by specimens of Avesta alloy 254SMO. In these tests, crevice attack was limited to specimens exposed with crevice washers tightened to 8.5 Nm. Evidence of on-going attack was detected for two of the six specimens within 245 hours (earliest observation 72 hours). Figure IV.2 shows the appearance of one of these specimens after 30 days. Although all three specimens in the 60 day test exhibited attack, increasing the test duration had no effect on initiation. In each case, only one or two of the available sites were attacked. Maximum depth of attack in both the 30 and 60 day tests were comparable.

Other Tests

Surface ground specimens of the same heat of AVESTA alloy 254SMO were evaluated in the U.S.N./LCCT program. Except for a somewhat greater incidence of attack, results were generally consistent with those of the OTEC crevice test. For ground specimens with crevice washers tightened to 8.5 Nm, the earliest observed time of on-going attack was recorded at 51 hours. Both sides of two specimens and one side of a third specimen were attacked in an initial 30 day test. Increasing the test duration had no apparent effect on initiation. In a subsequent 60 day test (8.5 Nm), only a few sites on one of three specimens were attacked. These had initiated within 174 hours.

Additional testing of surface ground specimens with crevice formers tightened to 2.8 Nm produced no attack in a 60 day exposure.

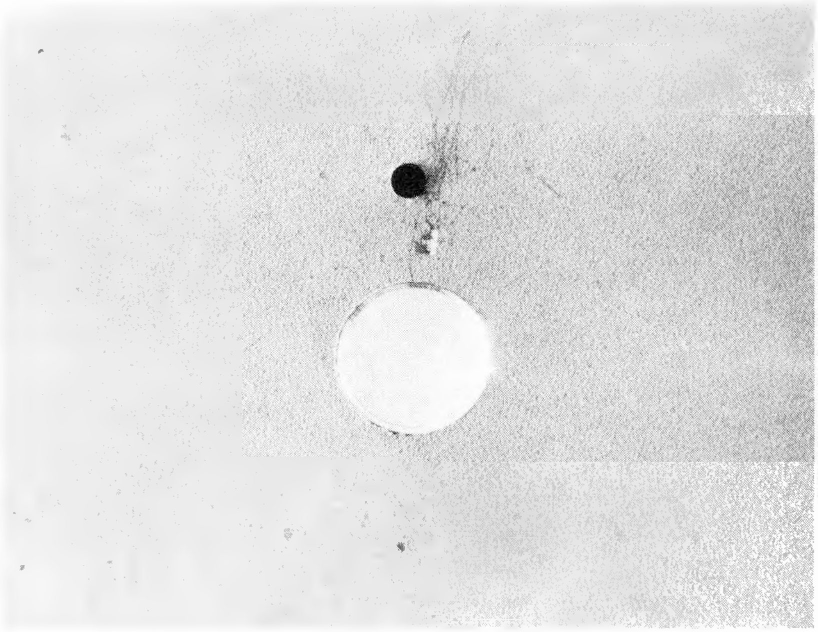
Figure IV.1

MULTIPLE CREVICE TESTS RESULTS

AVESTA 254 SMo

	SPECIMEN CODE	INITIATION TIME (HRS) CODE SIDE	INITIATION TIME (HRS) BACK	NO. OF MCA SITES ATTACKED CODE SIDE	NO. OF MCA SITES ATTACKED BACK	DEPTH OF ATTACK RANGE (MM) CODE SIDE	DEPTH OF ATTACK RANGE (MM) BACK
30 DAYS (8.5 Nm)	278AB-13	269	72	1	1	0.19	0.13
	14	OK	OK	none	none	--	--
	15	OK	OK	none	none	--	--
60 DAYS (8.5 Nm)	278AB-10	ND	OK	2	none	0.18, 0.01	--
	11	245	ND	1	1	<0.01	<0.01
	12	ND	OK	1	none	<0.01	--
60 DAYS (2.8 Nm)	278AB-16	NO EVIDENCE OF ATTACK ON TRIPLICATE SPECIMENS.					
	17						
	18						

Heat No. 174827



80214-4 ~1.5X

Specimen 278AB-13 (Code Side)

Figure IV.2. Crevice corrosion incurred by multiple crevice specimen of AVESTA alloy 254SMO exposed for 30 days at 8.5 Nm torque level.

APPENDIX V

FERRALIUM (CABOT CORPORATION)

Only a single crevice site on one FERRALIUM specimen (8.5 Nm torque level) was attacked. Increasing the test duration from 30 days to 60 days did not promote additional attack on this as-received material (see Figures V.1 and V.2).

No evidence of attack was found on any of the specimens exposed for 60 days at the 2.8 Nm torque level.

Other Tests

Testing of surface ground specimens of the same heat of FERRALIUM in the U.S.N/LCCT program produced similar results. In a 30 day test, only a single site on two of the three specimens was attacked.

Subsequent exposure of an additional set of triplicate specimens at 8.5 Nm torque for 60 days resulted in attack at only a single crevice site.

No evidence of crevice attack was found on triplicate surface ground specimens exposed for 60 days at the lower 2.8 Nm torque level.

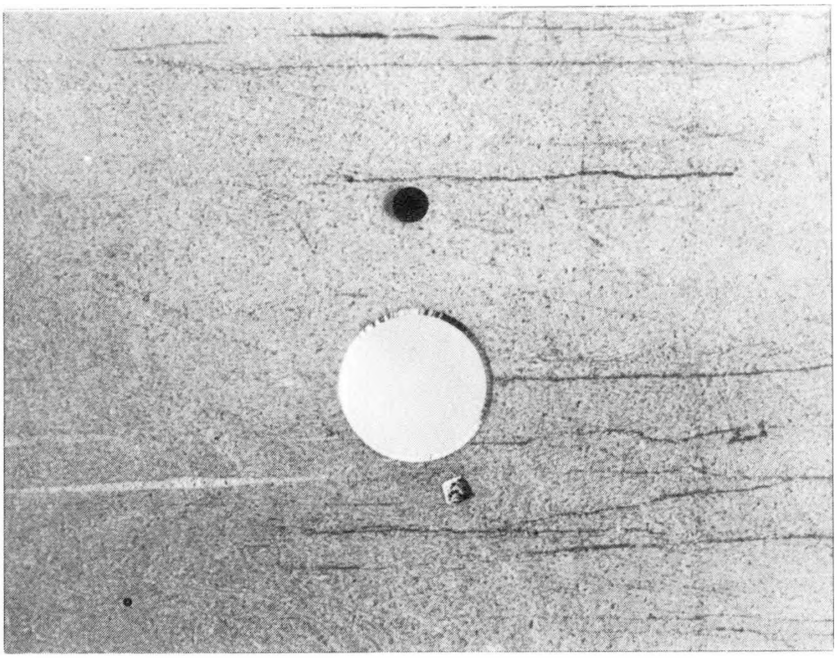
Figure V.1

MULTIPLE CREVICE TESTS RESULTS

FERRALIUM 255

Test	Specimen Code	Initiation Time (HRS): Code Side	Initiation Time (HRS): Back	No. of MCA Sites Attacked: Code Side	No. of MCA Sites Attacked: Back	Depth of Attack Range (MM): Code Side	Depth of Attack Range (MM): Back
30 DAYS (8.5 Nm)	449AC-13	OK	OK	none	none	--	--
	14	OK	509	none	1	--	0.09
	15	OK	OK	none	none	--	--
60 DAYS (8.5 Nm)	449AC-10	NO EVIDENCE OF ATTACK ON TRIPLICATE SPECIMENS.					
	11						
	12						
60 DAYS (2.8 Nm)	449AC-16	NO EVIDENCE OF ATTACK ON TRIPLICATE SPECIMENS.					
	17						
	18						

Heat No. 8537.8.7443



80214-8A ~1.5X

Specimen 449AC-14 (Back)

Figure V.2. Single incidence of attack found on FERRALIUM specimens: 30 day test, 8.5 Nm torque.

APPENDIX VI

HAYNES ALLOY 20MOD (CABOT CORPORATION)

Figure VI.1 summarizes the crevice test results for specimens of HAYNES alloy 20MOD. As indicated, several specimens exposed at both torque levels exhibited attack. In each case, only one or two of the available sites formed by the grooved washers were corroded (see Figure VI.2). Observed times to initiation were varied with no apparent effect of torque level being noted. Neither increasing the duration of the 8.5 Nm tests from 30 days to 60 days nor lowering the assembly torque to 2.8 Nm had any effect on the incidence of attack. Depths of attack incurred by speciens in the 30 day tests were within the range measured for specimens exposed for 60 days.

Other Tests

Results of 30 day and 60 day U.S.N./LCCT tests for surface ground specimens of the same heat of alloy 20MOD were generally comparable with the OTEC results for as produced material. Testing of the ground specimens, however, resulted in a slightly higher incidence of corrosion with respect to the number of individual sites being attacked. Again, no effect of test duration or torque level was evident.

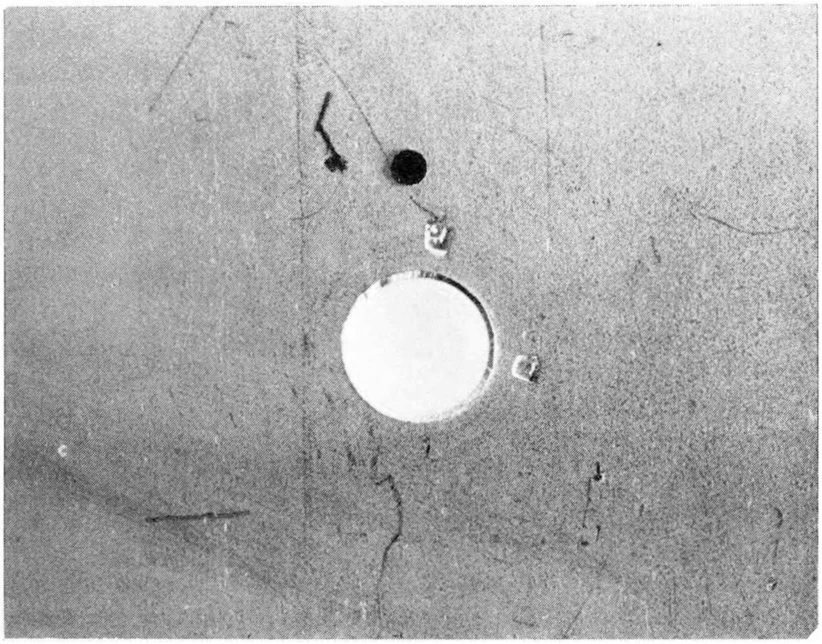
Figure VI.1

MULTIPLE CREVICE TESTS RESULTS

HAYNES 20 MOD

Test condition	SPECIMEN CODE	INITIATION TIME (HRS) CODE SIDE	INITIATION TIME (HRS) BACK	NO. OF MCA SITES ATTACKED CODE SIDE	NO. OF MCA SITES ATTACKED BACK	DEPTH OF ATTACK RANGE (MM) CODE SIDE	DEPTH OF ATTACK RANGE (MM) BACK
30 DAYS (8.5 Nm)	128AG-10	48	OK	2	none	0.39, 0.05	--
	11	OK	OK	none	none	--	--
	12	96	OK	2	none	0.38, 0.35	--
60 DAYS (8.5 Nm)	128AG-13	OK	937	none	1	--	0.05
	14	272	OK	1	none	0.39	--
	15	72	OK	2	none	0.80, 0.46	--
60 DAYS (2.8 Nm)	128AG-16	100	ND	2	1	0.07, 0.07	0.15
	17	OK	100	none	1	--	0.50
	18	OK	OK	none	none	--	--

Heat No. 53206.6.013



80213-10A 1.5X

Specimen 128AG-12 (Code Side)

Figure VI.2. Extent of crevice attack incurred by HAYNES alloy 20 mod specimen in 30 day test at 8.5 Nm torque level.

APPENDIX VII

CARPENTER EXPERIMENTAL ALLOY 00058

Figure VII.1 summarizes the crevice test results for the Carpenter experimental alloy. Visible signs of on-going attack were detected within 30 days for five of the six specimens at the 8.5 Nm torque level. As shown in VII.2, relatively few sites were attacked during the course of the 30 day test. While a slightly higher incidence of attack was noted for specimens exposed for 60 days, depths of attack were comparable.

Lowering the torque to 2.8 Nm had little, if any, apparent effect on the initiation resistance of material.

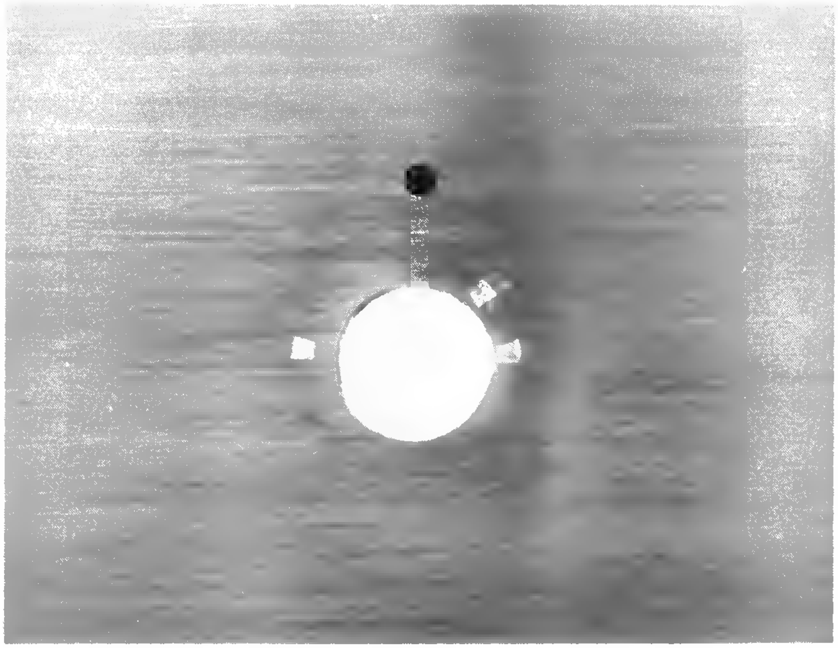
Carpenter experimental alloy 00058 was not included in the U.S.N./LCCT crevice test program.

Figure VII.1

MULTIPLE CREVICE TESTS RESULTS

400058 EXP. CARPENTER

Test condition	SPECIMEN CODE	INITIATION TIME (HRS) CODE SIDE	INITIATION TIME (HRS) BACK	NO. OF MCA SITES ATTACKED CODE SIDE	NO. OF MCA SITES ATTACKED BACK	DEPTH OF ATTACK RANGE (MM) CODE SIDE	DEPTH OF ATTACK RANGE (MM) BACK
30 DAYS (8.5 Nm)	501AA-1	120	OK	3	none	0.03 to 0.10	--
	2	OK	673	none	--	--	0.02
	3	269	673	1	4	0.20	0.01 to 0.02
60 DAYS (8.5 Nm)	501AA-4	431	673	6	6	<0.01 to 0.20	<0.01, 0.32
	5	336	673	9	4	<0.01 to 0.30	0.04 to 0.17
	6	ND	OK	6	none	<0.01	--
60 DAYS (2.8 Nm)	501AA-7	290	ND	4	1	<0.01, 0.04	<0.01
	8	703	100	3	1	0.03 to 0.12	0.01
	9	OK	703	none	2	--	0.01, 0.15



80214-9A ~1.5X
Specimen 501AA-1 (Code Side)

Figure VII.2. Appearance of corroded area on Carpenter experimental alloy 00058 specimen after 30 day test at 8.5 Nm.

APPENDIX VIII

CARPENTER TYPE 329 STAINLESS STEEL

Results of crevice testing of Type 329 stainless steel provided by Carpenter Technology are summarized in Figure VIII.1. As indicated, five of the six specimens exposed with the crevice formers tightened to 8.5 Nm exhibited attack within 72 hours. In both the 30 day and 60 day tests, specimens exhibited perforations resulting from the progression of attack from both sides of the panel (see Figure VIII.2). Increasing the test duration had no apparent effect on either the initiation or penetration resistance of the material. One specimen in the 60 day test exhibited only shallow penetrations (<0.01 mm).

Decreasing the torque to 2.8 Nm had little effect on the initiation resistance. Observed times to initiation were within the range of those noted in the 8.5 Nm test. Again, a broad range of penetrations were measured with at least one specimen being perforated. The severity of attack for specimen 500AA-8 is further noted by the fact that perforations occurred at 12 locations.

Other Tests

Testing of surface ground specimens of another heat of Type 329 in the U.S.N./LCCT exposure was limited to a single 30 day test. Triplicate specimens with crevice formers tightened to 8.5 Nm exhibited attack within 51 hours. Within 171 hours, evidence of on-going attack was detected on both sides of all three specimens. Both the incidence of attack and overall penetration behavior were found to be comparable with the OTEC test results. Each specimen exhibited at least one perforated site.

Figure VIII.1

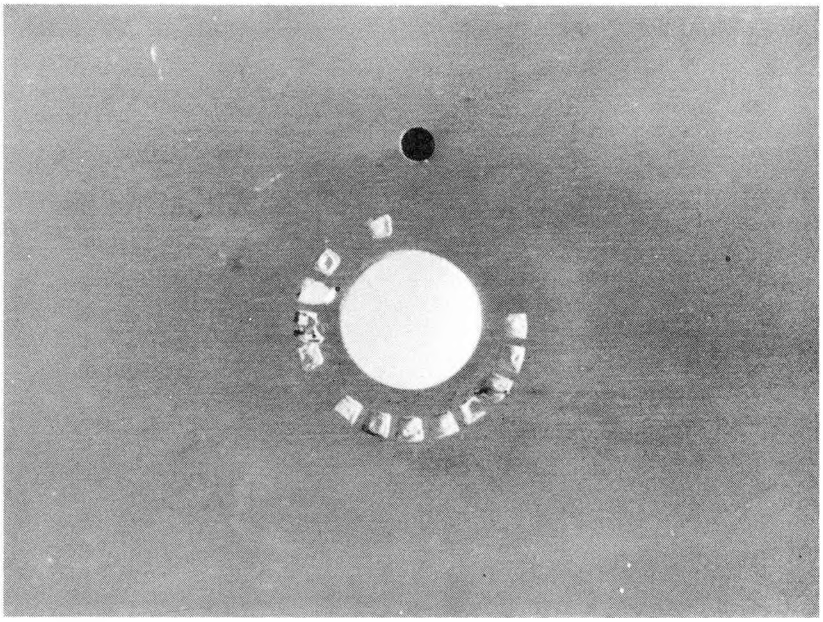
MULTIPLE CREVICE TESTS RESULTS

Type 329 Stainless Steel

Test condition	SPECIMEN CODE	INITIATION TIME (HRS) CODE SIDE	INITIATION TIME (HRS) BACK	NO. OF MCA SITES ATTACKED CODE SIDE	NO. OF MCA SITES ATTACKED BACK	DEPTH OF ATTACK RANGE (MM) CODE SIDE	DEPTH OF ATTACK RANGE (MM) BACK
30 DAYS (8.5 Nm)	500AA-4	336	48	11	8	0.09 to 0.56	0.20 to 1.30
	5	48	72	20	13	0.18 to 1.39	0.05 to 0.90 *
	6	48	269	14	4	0.24 to 1.48	0.20 to 1.30
60 DAYS (8.5 Nm)	500AA-1	173	24	8	12	0.06 to 0.90	0.15 to 0.96 *
	2	ND	OK	8	none	<0.01	--
	3	72	144	8	8	0.20 to 0.90	0.19 to 1.62 *
60 DAYS (2.8 Nm)	500AA-7	193	100	2	2	0.06, 0.09	0.12, 0.12
	8	100	100	15	16	0.15 to 1.55	0.07 to 0.30*
	9	170	100	3	5	0.08 to 0.41	0.09 to 0.14

* Penetration through sample thickness (1.80 mm) resulting from attack on opposite sides of specimens.

Heat No. X30559



80212-6 ~1.5X

Specimen 500AA-5 (Back)

Figure VIII.2. Appearance of perforated multiple crevice specimen of Type 329 stainless steel. Similar behavior was exhibited by specimens at both torque levels.

APPENDIX IX

CRUCIBLE ALLOY SC-1

A summary of results are provided in Figure IX.1. Traces of corrosion product were detected on two of the original SC-1 specimens (8.5 Nm torque level) during an inspection at 703 hours. These specimens, as well as third which initiated within 823 hours, were allowed to continue in test for a total of 90 days. Subsequent examination revealed several penetrations in the range <0.01 to 0.05 mm (see Figure IX.2). Although no other evidence of on-going attack was noted during the course of additional tests, two of three samples exposed for 30 days and three of three samples exposed for 60 days exhibited attack. As indicated, relatively few of the available sites beneath each of the grooved washers were corroded. Little, if any, effect of test duration on the incidence or extent of crevice attack appears evident.

Other Tests

Surface ground specimens of another heat of SC-1 were exposed in the U.S.N./LCCT program. For the initial exposure of triplicate specimens at the 8.5 Nm torque level, only a single crevice site on one panel was attacked in a 30 day test. Identical results were found for a subsequent 60 day test. In both cases, no evidence of accumulated corrosion product was noted during the test period.

None of the three specimens of SC-1 with crevice formers tightened to 2.8 Nm were attacked in a 60 day test.

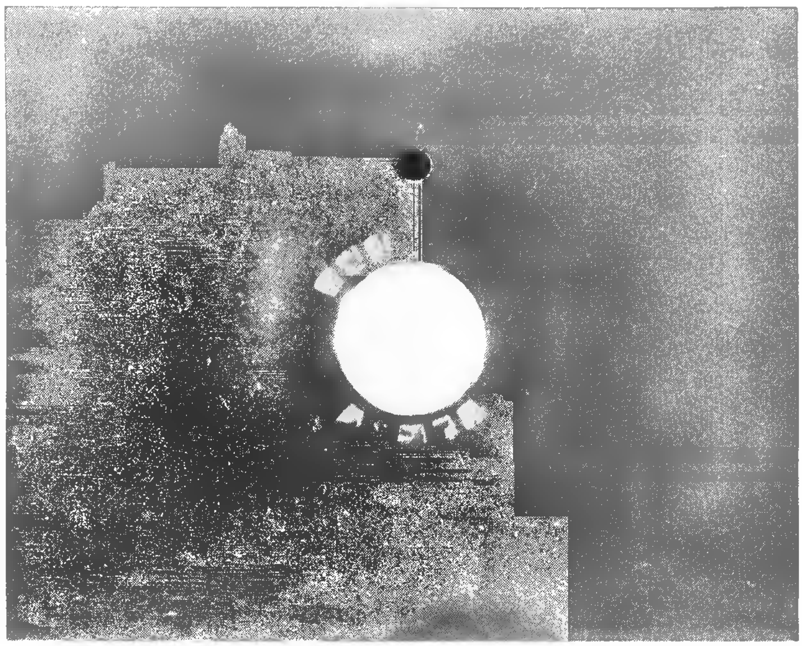
Figure IX.1

MULTIPLE CREVICE TESTS RESULTS

SC-1 CRUCIBLE

Test	Specimen Code	Initiation Time (HRS) Code Side	Initiation Time (HRS) Back	No. of MCA Sites Attacked Code Side	No. of MCA Sites Attacked Back	Depth of Attack Range (MM) Code Side	Depth of Attack Range (MM) Back
30 DAYS (8.5 Nm)	279AA-7	OK	OK	none	none	--	--
	8	ND	ND	1	1	<0.01	<0.01
	9	ND	ND	1	4	0.04	≤0.01
60 DAYS (8.5 Nm)	279AA-1	ND	OK	1	none	0.11	--
	2	ND	OK	6	none	<0.01	--
	3	ND	ND	3	2	<0.01	<0.01
90 DAYS (8.5 Nm)	279AA-4	703	772	2	1	≤0.01	0.03
	5	ND	823	1	1	0.04	0.01
	6	ND	703	1	7	0.01	<0.01 to 0.05

Heat No. 162097



80268-6A ~1.5X

Specimen 279AA-6 (Back)

Figure IX.2. Extent of crevice attack incurred by SC-1 specimen exposed for 90 days at 8.5 Nm torque level.

APPENDIX X

JESSOP ALLOY 777

Results describing the initiation and penetration behavior for specimens of JESSOP alloy 777 are summarized in Figure X.1.

All six of the specimens initially exposed with crevice formers tightened to 8.5 Nm exhibited on-going corrosion within 173 hours. The earliest observed time to initiation was established during an inspection at 72 hours. Relatively few of the sites formed by the grooved washer were attacked during both the 30 day and 60 day exposure. Despite the extended test duration, crevice attack remained limited to only one side of each specimen. Figure X.2 shows the extent of attack incurred by specimen 274AB-6.

Evidence of localized attack on machined specimen edges was noted in a number of cases. No evidence of crevice attack was found on any of the triplicate specimens with the washers tightened to only 2.8 Nm.

While only a few instances of attack were noted for the JESSOP alloy 777 specimens in this program, penetrations approximating 2 mm in depth were incurred by four of the six specimens loaded to 8.5 Nm. Specimen to specimen variation in the maximum depth of attack for a given test duration, e.g., 274AB-4 and 6 and 274AB-1 and 3, is greater than that observed as a function of extended test duration.

Other Tests

Multiple crevice testing of a second heat of JESSOP alloy 777 in the U.S.N./LCCT program resulted in somewhat more rapid initiation. For these surface ground specimens with crevice formers tightened to 8.5 Nm, visible signs of on-going attack were detected on both sides of each panel within 72 hours. Subsequent examination of specimens exposed for 30 days revealed a consistently higher incidence of attack beneath the grooved washers.

In contrast to the OTEC program results, exposure of ground specimens with crevice formers tightened to 2.8 Nm resulted in attack of triplicate specimens within 174 hours. Attack was found on both sides of four specimens after a 60 day test.

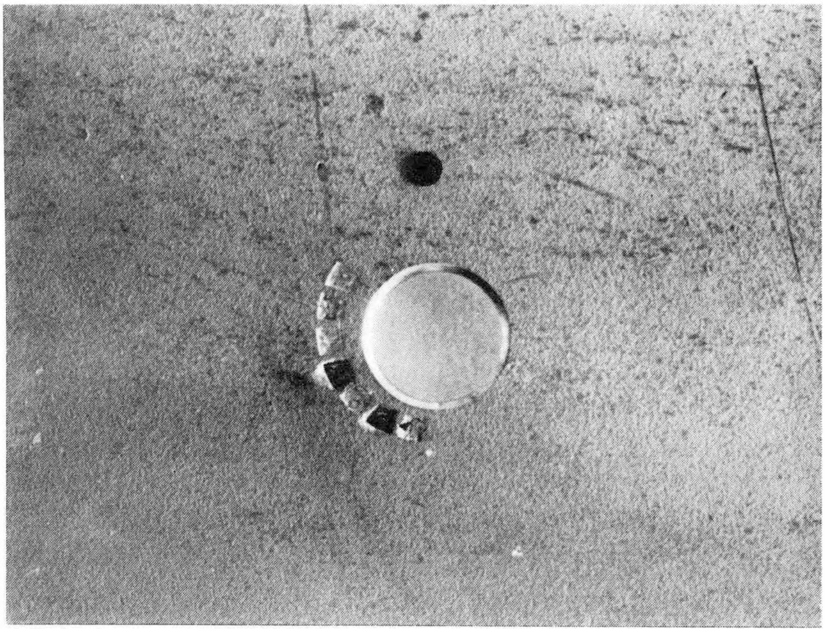
Figure X.1

MULTIPLE CREVICE TESTS RESULTS

JESSOP alloy 777

	SPECIMEN CODE	INITIATION TIME (HRS)		NO. OF MCA SITES ATTACKED		DEPTH OF ATTACK RANGE (MM)	
		CODE SIDE	BACK	CODE SIDE	BACK	CODE SIDE	BACK
30 DAYS (8.5Nm)	274AB-4	72	OK	4	none	0.11 to 0.51	
	5	96	OK	5	none	0.31 to 1.95	
	6	OK	72	none	7	--	0.40 to 2.18
60 DAYS (8.5Nm)	274AB-1	173	OK	1	none	0.27	---
	2	OK	96	none	3	--	0.11 to 2.11
	3	OK	173	none	2	---	0.48, 2.26
60 DAYS (2.8Nm)	274AB-7	NO EVIDENCE OF ATTACK ON TRIPLICATE SPECIMENS.					
	8						
	9						

Heat No. unknown



80214-2A ~1.5X

Specimen 274AB-6 (Back)

Figure X.2. Crevice attack incurred by JESSOP alloy 777 specimen during 30 day test at 8.5 Nm torque level.

APPENDIX XI

JESSOP ALLOY 700

Figure XI.1 summarizes the initiation and penetration behavior for specimens of JESSOP alloy 700.

For specimens exposed with crevice formers tightened to 8.5 Nm, evidence of on-going attack was first detected within 72 hours. Within 30 days, all six of the original specimens were corroding beneath at least one of the two crevice washers. As shown in XI.1, increasing the test duration from 30 days to 60 days had no apparent effect on the initiation resistance of JESSOP 700 at this level of crevice tightness. Except for one of the 30 day test specimens (270AC-4), relatively few of the available sites formed by the grooved washers were attacked. Figure XI.2 documents the appearance of specimen 270AC-4. The surface grinding evident for this specimen is not typical of the surface condition present for the majority of the JESSOP alloy 700 specimens in this program. Grinding may have been performed to remove possible mill scale particles embedded in the surface (see Figure XI.3). These particles were apparently also unaffected by the post exposure cleaning in nitric acid.

Observed times to initiation, as well as the incidence of attack for specimens with crevice formers tightened to 2.8 Nm were comparable to the behavior exhibited by specimens assembled at the higher torque level.

For JESSOP alloy 700, measured depths of attack ranged from <0.01 mm to 1.75 mm. Considering variations in the times for initiation, increasing the test duration had no apparent effect on the maximum depth of attack. Except for the two deepest penetrations in specimens 270AC-5 and 270AC-8 (2.75 and 2.19 mm respectively), the range of penetration for those specimens is comparable to other JESSOP alloy 700 specimens including 270AC-4.

Other Tests

Results of U.S.N./LCCT crevice corrosion testing of another heat of JESSOP alloy 700 are in general agreement with those of the OTEC program. That is, surface ground and as-produced materials exhibited attack in tests utilizing both the 8.5 Nm and 2.8 Nm torque levels. For surface ground specimens, however, the earliest observed times to initiation were somewhat shorter, e.g., 51 hours and 72 hours for the higher and lower torque levels respectively. In addition, a somewhat greater incidence of attack was noted for ground specimens. In a 60 day test with crevice formers tightened to 2.8 Nm, both sides of the triplicate specimens exhibited attack.

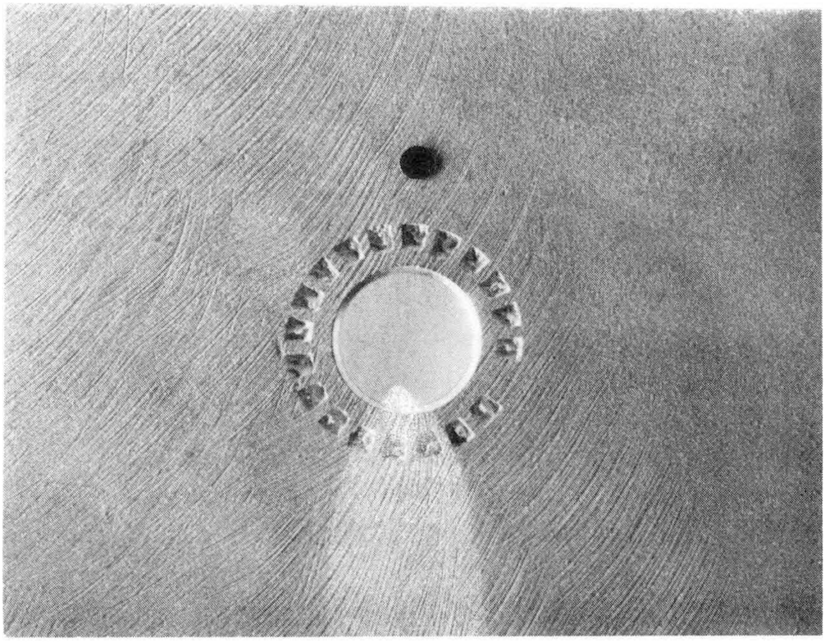
Figure XI.1

MULTIPLE CREVICE TESTS RESULTS

JESSOP alloy 700

Test condition	SPECIMEN CODE	INITIATION TIME (HRS) CODE SIDE	INITIATION TIME (HRS) BACK	NO. OF MCA SITES ATTACKED CODE SIDE	NO. OF MCA SITES ATTACKED BACK	DEPTH OF ATTACK RANGE (MM) CODE SIDE	DEPTH OF ATTACK RANGE (MM) BACK
30 DAYS (8.5Nm)	270AC-4	269	533	19	1	0.30 to 0.82	0.08
	5	OK	192	none	3	-----	0.39 to 1.75
	6	269	72	1	6	0.56	0.16 to 0.71
60 DAYS (8.5Nm)	270AC-1	ND	336	1	2	0.01	0.06. 0.30
	2	ND	245	1	3	0.08	0.13 to 0.36
	3	OK	673	none	1	---	0.44
60 DAYS (2.8Nm)	270AC-7	OK	319	none	1	--	0.07
	8	OK	100	none	4	--	0.20 to 1.29
	9	ND	703	1	1	<0.01	0.09

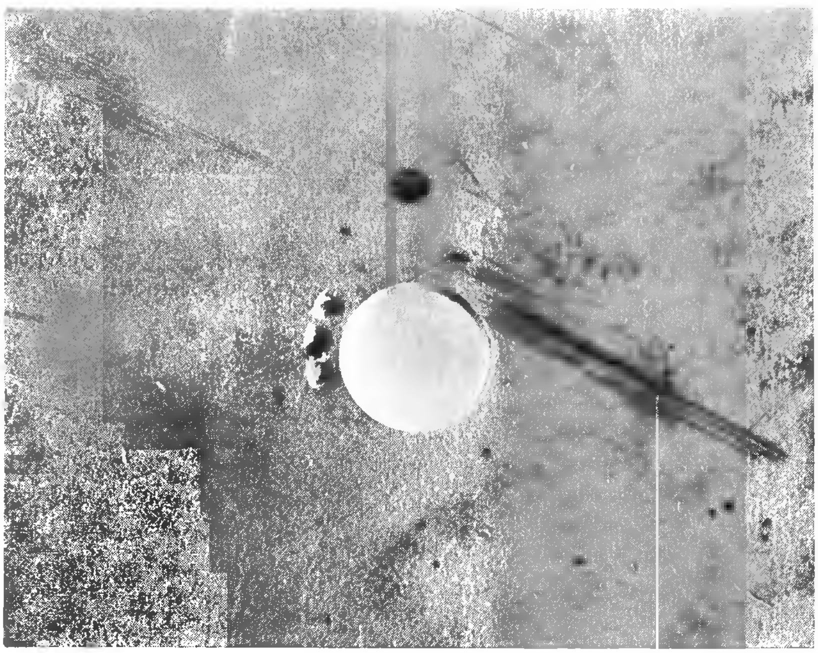
Heat No. 25092



80211-7A ~1.5X

Specimen 270AC-4 (Code Side)

Figure XI.2. Extent of crevice attack incurred by JESSOP alloy 700 specimen in 30 day test at 8.5 Nm torque level.



80211-5A ~1.5X

Specimen 270AC-5 (Back)

Figure XI.3. Appearance of JESSOP alloy 700 specimen with possible mill scale embedded in the surface.

APPENDIX XII

UDDEHOLM ALLOY 904L

Results of multiple crevice testing of UDDEHOLM alloy 904L are given in Figure XII.1. Except for a single attacked site on each of the three specimens in the 30 day test, no other evidence of crevice corrosion was detected. Figure XII.2 shows the appearance of the crevice area of specimen 276AF-12.

While none of the specimens in the 60 day tests at either torque level exhibited attack beneath the grooved washer, severe tunneling attack was incurred by two specimens (see Figure XII.3).

Other Tests

Testing of surface ground samples of the same heat of alloy 904L in the U.S.N./LCCT program produced significantly different results. For example, in a 30 day test at 8.5 Nm torque considerably shorter times to initiation (51 hours minimum) as well as a higher incidence of attack were noted. Subsequent exposure of six surface ground specimens at the 2.8 Nm torque level resulted in attack beneath both washers within 245 hours. (Five of the six specimens exhibited signs of on-going attack within 72 hours.) Examination of the specimens after 60 days revealed a generally high incidence of attack beneath each grooved washer. At least one specimen exhibited tunneling attack originating from one of the edges.

Figure XII.1

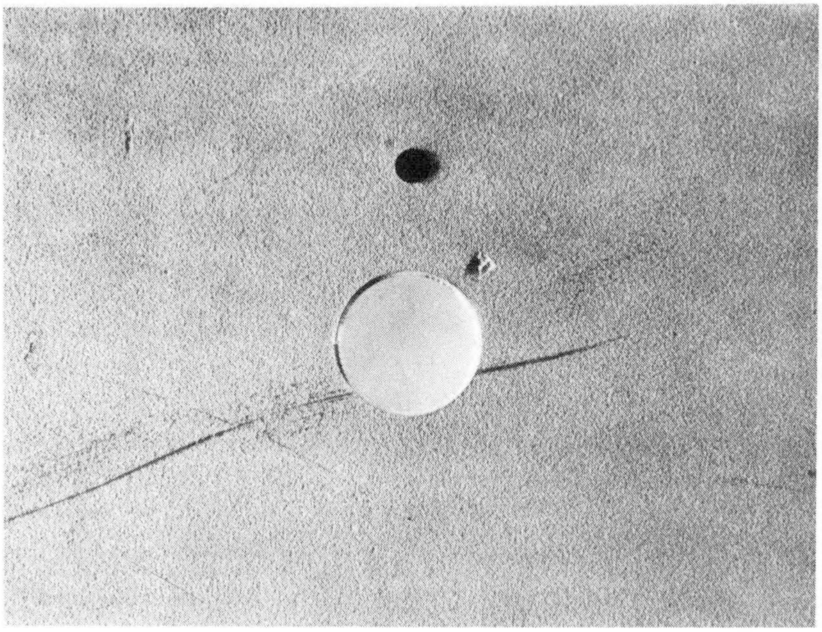
MULTIPLE CREVICE TESTS RESULTS

UHB 904L
UDDEHOLM

	SPECIMEN CODE	INITIATION TIME (HRS)		NO. OF MCA SITES ATTACKED		DEPTH OF ATTACK RANGE (MM)	
		CODE SIDE	BACK	CODE SIDE	BACK	CODE SIDE	BACK
30 DAYS (8.5 Nm)	276AF-10	OK	388	none	1	--	0.06
	11	ND	OK	1	none	0.05	--
	12	431	OK	1	none	0.37	--
60 DAYS (8.5 Nm)	276AF-13						
	14	NO EVIDENCE OF ATTACK ON TRIPLICATE SPECIMENS.*					
	15						
60 DAYS (2.8 Nm)	276AF-16						
	17	NO EVIDENCE OF ATTACK ON TRIPLICATE SPECIMENS.*					
	18						

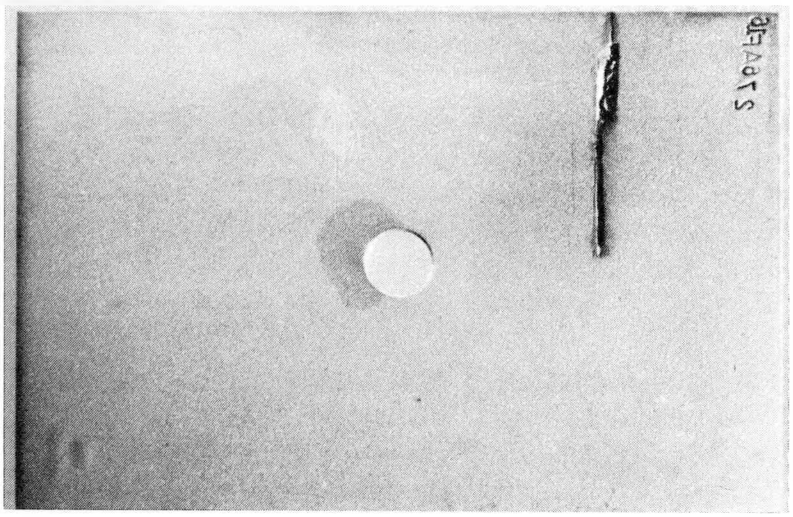
* Does not include tunneling on surface of 276AF-14 (code side)
276AF-16 (code side)

Heat No. 01152



80213-20A ∽1.5X
Specimen 276AF-12 (Code Side)

Figure XII.2. Extent of crevice attack incurred by specimens of UDDEHOLM alloy 904L (30 days, 8.5 Nm torque level).



80269-14A ∼1.5X

Specimen 276AF-16

Figure XII.3. Tunneling corrosion incurred by UDDEHOLM alloy 904L specimens. Attack progressed from the ground edge (as-received).

APPENDIX XIII

MONIT (UDDEHOLM)

Signs of on-going attack were detected on two MONIT specimens (8.5 Nm) just after a 30 day inspection. As indicated in Figure XIII.1, continued exposure through 90 days resulted in only a few shallow penetrations ($\leq$0.01 mm) (see also Figure XIII.2). No further evidence of attack was found on triplicate specimens of this as produced material exposed in other 30 and 60 day tests.

Other Tests

No evidence of crevice attack was detected on triplicate surface ground samples of the same heat of MONIT in a 30 and 82 day U.S.N./LCCT test (8.5 Nm).

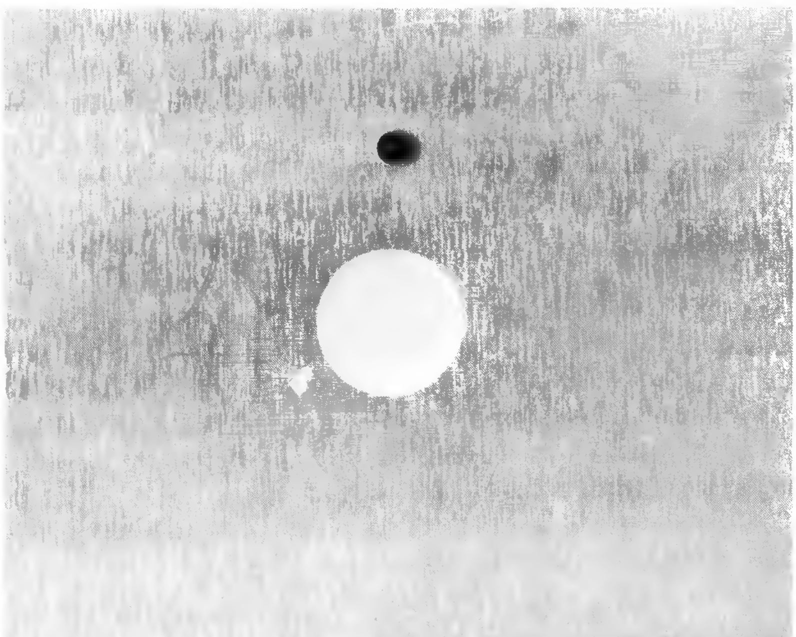
Figure XIII.1

MULTIPLE CREVICE TESTS RESULTS

MONIT

Exposure	SPECIMEN CODE	INITIATION TIME (HRS) CODE SIDE	INITIATION TIME (HRS) BACK	NO. OF MCA SITES ATTACKED CODE SIDE	NO. OF MCA SITES ATTACKED BACK	DEPTH OF ATTACK RANGE (MM) CODE SIDE	DEPTH OF ATTACK RANGE (MM) BACK
30 DAYS (8.5 Nm)	280AC-16						
	17	NO EVIDENCE OF ATTACK ON TRIPLICATE SPECIMENS					
	18						
60 DAYS (8.5 Nm)	280AC-10						
	11	NO EVIDENCE OF ATTACK ON TRIPLICATE SPECIMENS					
	12						
90 DAYS (8.5 Nm)	280AC-13	ND	772	1	1	<0.01	<0.01
	14	OK	OK	none	none	--	--
	15	772	OK	1	none	0.01	--

Heat No. 1-0840



80268-10 ~1.5X

Specimen 280AC-13 (Back)

Figure XIII.2. Appearance of crevice area of MONIT specimen exposed for 90 days at 8.5 Nm torque level.

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