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DEVELOPMENT OF A RAPID STRESS-CORROSION TEST FOR ALUMINUM ALLOYS

for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
GEORGE C. MARSHALL SPACE FLIGHT CENTER
HUNTSVILLE, ALABAMA

May 15, 1968

Final Summary Report

KAISER ALUMINUM & CHEMICAL CORPORATION
Department of Metallurgical Research

FINAL SUMMARY REPORT

on

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for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
GEORGE C. MARSHALL SPACE FLIGHT CENTER
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May 15, 1968

W. J. Helfrich

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KAISER ALUMINUM & CHEMICAL CORPORATION
Department of Metallurgical Research
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May 15, 1968
Spokane, Washington

National Aeronautics and Space Administration
George C. Marshall Space Flight Center
Huntsville, Alabama 35812

Attention: PR-SC
R-P&VE-MMC (Mr. T. S. Humphries)
MS-IL
MS-T
MS-I

Gentlemen:

Contract No. NAS8-20285
Control No. DCN 1-7-54-20105(1F)

Enclosed are seventeen copies of the Final Summary Report on "Development of a Rapid Stress-Corrosion Test for Aluminum Alloys", covering work performed during the period March 1, 1966 to March 1, 1968. Distribution of these copies has been made as noted below.

Very truly yours,

T R Pritchett

T. R. Pritchett
Laboratory Manager

TRP:pj

Enc. (17)
PR-SC (1)
R-P&VE-MMC /
MS-IL (1)
MS-T (1)
MS-I (2)

FOREWORD

This report was prepared by Kaiser Aluminum & Chemical Corporation, Department of Metallurgical Research, Spokane, Washington, under Contract No. NAS8-20285, "Development of a Rapid Stress-Corrosion Test for Aluminum Alloys", for the George C. Marshall Space Flight Center of the National Aeronautics and Space Administration. The work was administered under the technical direction of the Propulsion and Vehicle Engineering Laboratory, Materials Division of the George C. Marshall Space Flight Center with T. S. Humphries acting as project manager.

ABSTRACT

A new accelerated laboratory test was developed for characterizing the stress-corrosion performance of aluminum alloys 2024, 2014, 2219, 7075, 7079 and 7039. This test is based on continuous immersion of chemically etched and stressed C-ring or tensile round specimens in a 1% NaCl-2% $K_2Cr_2O_7$ solution at pH = 4 and 60C (140F). For most purposes, the salt-(di)chromate solution (SDS) test can be completed in one week, after which a simple visual or low-power microscopic examination of the specimen surface will reveal whether cracking did or did not occur. This represents considerable improvement over longer and more corrosive tests, where examinations of metallographic sections are often required to determine the nature and cause of failure.

The applicability and limitations of the developed test were demonstrated through correlation with exposures in marine and industrial environments and with laboratory tests conducted by alternate immersion in 3.5% NaCl solution. The SDS test promoted short-transverse failures in susceptible tempers of 2024, 2014 and 2219 at essentially the same stress levels as those which caused failure in outdoor environments or 3.5% NaCl alternate immersion. The SDS test also offered some improvement over the 3.5% NaCl alternate immersion test in promoting low stress-level failures of alloy 7039, but not at the lowest stresses which caused failure in either the marine or industrial environments. Alloys 7075-T651 and 7079-T651 behaved similarly; at low stresses, specimens were more prone to failure in the outdoor environments or in 3.5% NaCl alternate immersion than in the SDS test. This detracted somewhat from the general usefulness of the salt-(di)chromate solution test as a means of predicting the natural environment performance of these aluminum alloys. But, the deficiency was more than compensated for by the speed, non-corrosiveness, and simplicity associated with the SDS test -- particularly, as compared with 3.5% NaCl alternate immersion.

The salt-(di)chromate solution test also showed considerable promise as a method for rapidly separating artificially aged tempers of 2024, 2219 and 7075 which differed in their susceptibility to short-transverse stress-corrosion cracking. At appropriate levels of applied stress, the SDS test ranked the relative susceptibilities of underaged and peak-aged tempers of 2024 and 2219 and overaged tempers of 7075 in the same order as 3.5% NaCl alternate immersion. Moreover, both tests showed the same high resistance to stress-corrosion cracking in overaged tempers, which included 2024-T6, -T851, 2219-T62, -T851, -T87 and 7075-T7351. But more important, the SDS test accomplished these separations in seven days as compared with a 30-day exposure in 3.5% NaCl alternate immersion.

A brief study of the initiation of stress-corrosion cracking in aluminum alloys showed that cracking started at grain boundaries in 2024-T4, 2219-T37 and 7075-T651 exposed to an acidified (pH=0.5) salt-(di)chromate solution at 30C. On the other hand, constituent particles were preferred sites for crack initiation in 7039-T64 exposed to a boiling 1M NaCl solution and in 2024-T4 or 2219-T37 immersed in a 6% NaCl-2% $K_2Cr_2O_7$ solution at pH=4 and 60C. It appeared that cracking of alloy 7039 was preceded by corrosion attack at constituent particle-matrix interfaces; whereas apparently only the constituents were attacked prior to crack initiation in 2024 and 2219. When corrosion attack did not occur at either the grain boundaries or constituent particles, eg, 7075-T651 immersed in salt-(di)chromate solutions at pH=4 and 30C or 60C, chemical etching apparently served the same purpose in initiating stress-corrosion failure. These results prompted the suggestion that the environmental dependence of stress-corrosion cracking in aluminum alloys may be related, in large measure, to both how and where cracking is initiated.

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DEVELOPMENT OF A RAPID STRESS-CORROSION TEST FOR ALUMINUM ALLOYS

Final Summary Report

By

W. J. Helfrich

INTRODUCTION

The objective of this research was the development of an accelerated stress-corrosion susceptibility test for aluminum alloys which could be completed in one week or less. The applicability of the test was to be established (1) through correlation with conventional laboratory and outdoor exposure tests and published data, and (2) by comparison with the threshold stresses obtained in conventional stress-corrosion tests and natural environments. It was also the objective of this study to gain additional insight into the processes which contribute to stress-corrosion cracking of aluminum alloys.

Our approach was to characterize in detail the short-transverse stress-corrosion performance of several representative 2000 and 7000 series alloys. During the first year of effort, we concentrated on the commercially important tempers of alloys 2024, 2219, 7075 and 7039. Outdoor exposures of these alloys were started in marine and industrial environments. Laboratory tests were conducted in 3.5% NaCl alternate immersion. And, for the most part, we completed the exploratory continuous immersion tests in salt-(di)chromate solutions over the range of pH=1 to 7 and temperatures of 30C to 100C. These latter studies provided the foundation for specifying the conditions under which stress-corrosion tests for a wide range of alloys could be conducted. There remained for consideration the selection, if possible, of the unique conditions of solution make-up, pH and temperature which would form the basis for development and evaluation of an accelerated test. Most of the work conducted during this past year was devoted to these tasks.

Other work conducted during this past year included comparison tests of C-ring and tensile round specimens in 3.5% NaCl alternate immersion and salt-(di)chromate solutions. In addition to the 2024, 2219, 7075 and 7039 tested previously, we included alloys 2014-T651 and 7079-T651; anticipating that the developed test might be applicable to these alloys as well. A considerable number of tests were performed on alloys 2024, 2219 and 7075, artificially aged to exhibit a range of short-transverse stress-corrosion performance in 3.5% NaCl alternate immersion. The results of these tests provided a basis for separating materials of borderline and maximum resistance to stress-corrosion cracking in salt-(di)chromate solution tests. And, finally, we briefly considered the factors affecting the initiation of stress-corrosion cracking in 2024, 2219, 7075 and 7039 when subjected to various corrosive environments and test conditions.

I. MATERIALS AND SPECIMENS

Materials

The majority of our stress-corrosion tests were performed on plant-fabricated plate of the following alloys and tempers of commercial interest:

2024-T351, -T851, -T4, -T6

2014-T651

2219-T42, -T62, -T351, -T851, -T37, -T87

7075-T651, -T7351

7079-T651

7039-T64, -T61, -T6E132*

Table I gives the chemical compositions, tensile properties, and, where appropriate, the electrical conductivities for these test items. The data are typical of the respective alloys and tempers and indicative of proper heat treatment in all cases. We remind the reader, however, that the results of our stress-corrosion tests must be interpreted in the light of tests performed on one or two lots of each item.

In addition to the items listed above, we conducted a number of stress-corrosion tests on 2024-T4, -T351, 2219-T42, -T351, -T37 and 7075-T651 plate artificially aged in the laboratory to exhibit a range of susceptibility to short-transverse stress-corrosion cracking. Table II gives the schedule of heat treatments (the aging times are in addition to the $1\frac{1}{2}$-hour heat-up to the aging temperature), the tensile properties and the electrical conductivities for these test items.

Specimens

Smooth specimens -- C-rings and tensile rounds -- were employed in this

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* -T6E132, experimental armor-plate temper -- Aluminum Company of America.
-T64, armor-plate temper -- Kaiser Aluminum.
-T61, temper for cryogenic and non-fired pressure vessels -- Kaiser Aluminum.

study. The short-transverse C-rings (Figure 1) were 0.75 inch wide, with a 0.948-inch outside diameter and a 0.060-inch wall thickness. The fixture used for stressing C-rings is shown in Figure 2.

Figure 1 shows the two methods employed to prevent galvanic interaction between the C-ring and the 2024 alloy machine screw used to apply the stress. A solution of 5% polyethylene in paraffin wax formed a very durable coating on specimens tested at room temperature. However, because this wax formulation softens at temperatures in the range of 50C to 60C, hemispherical ceramic bushings were placed between the aluminum machine screw and the C-ring specimens tested at elevated temperatures and in the atmosphere.

The 2-inch long, $\frac{1}{8}$-inch diameter tensile specimen and the 6061 aluminum alloy frame used to stress this specimen are shown in Figure 3. The components of the frame are assembled and the nuts tightened sufficiently to hold the specimen in place. Inward movement of the wedge-shaped side pieces induces axial tensile stress in the specimen (Figure 4). Again, in those tests conducted at room temperature, the polyethylene-paraffin wax coating was used to prevent galvanic interactions between the specimen and the components used to apply the stress (Figure 3). Anodizing the internal threads of the retaining nuts on the frame proved effective in insulating the specimen from the frame in repeated elevated temperature tests of specimens stressed at loads up to 45,000 psi. Undoubtedly, the successful use of the anodic coatings was related to the non-corrosiveness of the salt-(di)chromate solutions employed in our accelerated tests. We would not recommend, nor did we use, this system in instances where excessive corrosion attack of aluminum was anticipated.

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Figure 1
C-RING STRESS-CORROSION TEST SPECIMENS

Left: Specimen partially coated with 5% polyethylene-paraffin wax.

Right: Specimen for atmospheric and elevated temperature tests. Ceramic bushing isolates C-ring from the aluminum machine screw used in stressing the specimen.

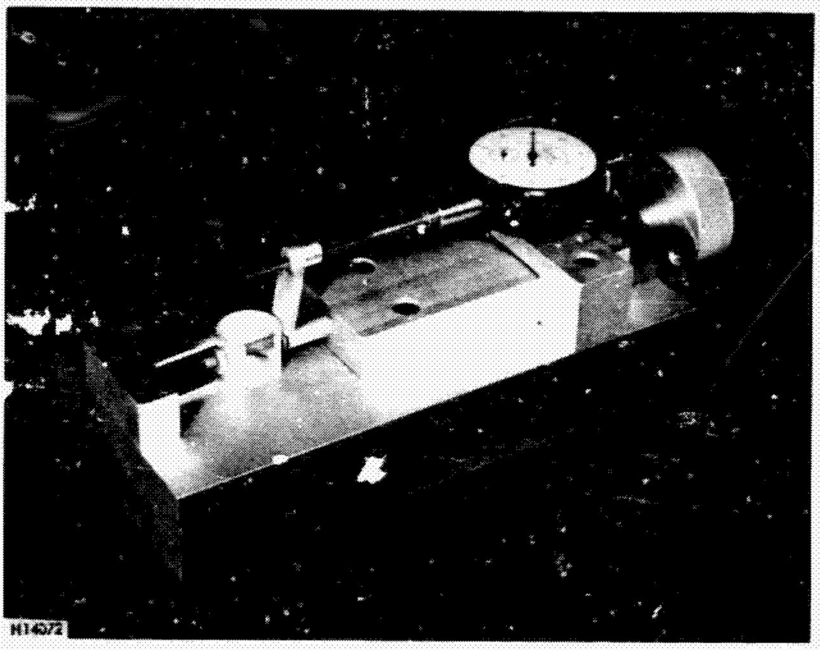

Figure 2
FIXTURE FOR STRESSING C-RING SPECIMENS
C-rings are stressed with this tool. The outside diameter is reduced by applying a force directly to the C-ring along the axis of the through-bolt. The change in diameter along this axis is read directly from a dial micrometer which contacts the edge of the C-ring adjacent to the machine screw head. When the required deflection for the desired stress is reached, the nut is tightened.

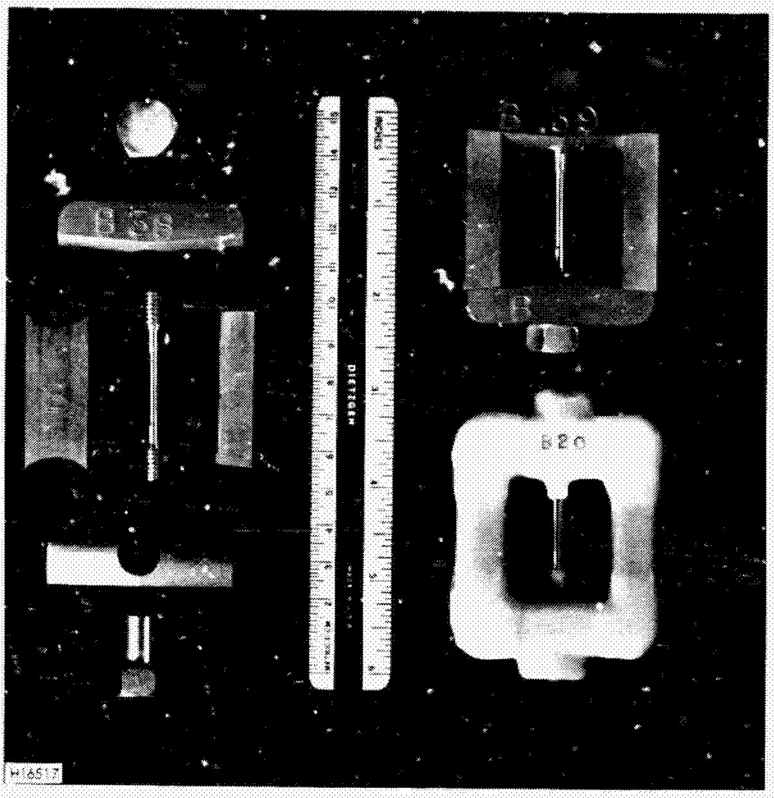

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Figure 3
TENSILE ROUND STRESS-CORROSION SPECIMEN
AND STRESSING FRAME

Left: $\frac{1}{8}$-inch diameter tensile specimen and components of the stressing frame.

Upper Right: Assembled frame with specimen as it appears before stressing.

Lower Right: Stressed specimen and frame coated with 5% poly-ethylene-paraffin wax.

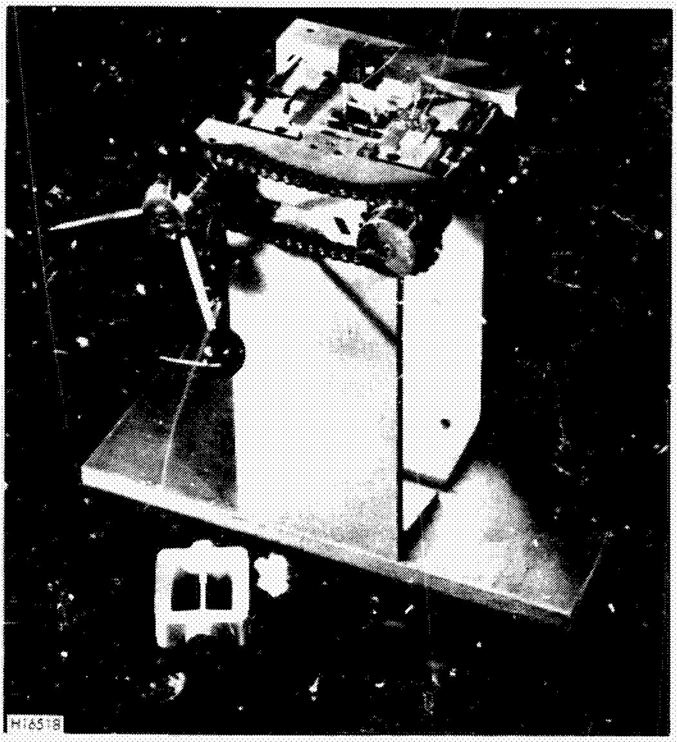

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Figure 4
SYNCHRONOUS LOADING DEVICE FOR STRESSING TENSILE SPECIMENS

Axial loading of the tensile specimen is achieved by synchronous inward displacement of the side members of the stressing frame. Strain in the specimen is measured with a strain gage extensometer (shown attached to the specimen) and strain indicator (not shown). A specimen, assembled in a frame and ready for stressing, is shown in the foreground.

Prior to testing, each specimen was etched for 30 seconds in 5% NaOH solution at 170F. This was followed by desmutting in cold concentrated HNO_3 for 15 to 30 seconds with a final hot water rinse. This procedure gave a quick check of proper short-transverse orientation of the C-ring specimens and a clean water-break-free surface. The etch also removed surface cold work introduced during the machining of the specimens.

II. STRESS-CORROSION TESTS IN NATURAL ENVIRONMENTS

During the first year of effort on this contract, stress-corrosion tests of alloys 2024, 2219, 7075 and 7039 were initiated at (a) the marine exposure site, Battelle Memorial Institute, North Florida Research Station, Daytona Beach, Florida, and (b) an industrial exposure site, McKees Rocks Industrial Park, Pittsburgh, Pa. The purpose of these tests was, of course, to provide the necessary background data for comparison with results obtained in laboratory tests. It was also our purpose to show that different outdoor environments are not necessarily equally effective in promoting stress-corrosion cracking of any one alloy or temper.

Tests of those alloys and tempers which were most susceptible to stress-corrosion cracking, ie, 2024-T4, -T351, 2219-T42, -T351, -T37, 7075-T651 and 7039-T64, -T61 and -T6E132, were terminated after 450 days' exposure at the marine site and 505 days' exposure at the inland industrial site. Failures have not been observed during these periods in 2024-T6 or -T851 stressed at 50 ksi, 2219-T62, -T851 and -T87 stressed at 35, 45 and 55 ksi, respectively, nor in 7075-T7351 stressed at 50 ksi. Therefore, tests of these alloys will be continued, and the results will be reported after a minimum of two years' exposure.

Marine Exposures

For the most part, a 450-day exposure at the Daytona Beach, Florida marine site was sufficient to demonstrate susceptibility to short transverse stress-corrosion cracking in 2024-T4, -T351, 2219-T42, -T35, -T37, 7075-T651, and all tempers of 7039. The data presented in Table III show that stresses of upwards of 10 ksi were effective in promoting failure of the copper-bearing alloys and 7039-T61 and -T6E132, whereas 7039-T64 failed at the lowest applied stress of 5 ksi.

Industrial Exposures

As shown in Table IV, the industrial environment was not nearly as effective as the marine environment in promoting failures of 2024-T4, -T351 or 2219-T42, -T351 and -T37 at low levels of applied stress, even though the period of exposure was 50 days longer in the industrial environment. In a like manner, 7075-T651 was somewhat less prone to failure in the industrial environment at stresses of 10 and 15 ksi. And, while it appeared that failures of 7039 did not occur as rapidly in the industrial environment, failures occurred with much greater frequency at an applied stress of 5 ksi. In fact, at low stress levels the difference noted in the performance of 7039-T64, -T61 and -T6E132 exposed to the marine environment simply did not exist in the industrial environment.

These results, while neither new or startling to those familiar with the stress-corrosion performance of aluminum alloys in natural environments (Refs 1 & 2), again demonstrate that stress-corrosion performance is dependent upon the environment. Certainly, this is an important observation which cannot be overlooked in the development and use of accelerated laboratory stress-corrosion tests for aluminum alloys.

III. ACCELERATED STRESS-CORROSION TESTS IN LABORATORY ENVIRONMENTS

The most reliable measures of susceptibility to stress-corrosion cracking are obtained from natural environment exposures -- preferably made under the conditions of exposure and stress that the alloy would encounter in final use. In most instances, however, this is simply not very practical. Moreover, we have just seen that prohibitively long periods of exposure are required to insure that failure will or will not occur in outdoor exposures. As a result, laboratory tests, which greatly accelerate the rate of failure, must be used.

3.5% NaCl Alternate Immersion Tests

Alternate immersion in 3.5% NaCl solution is used most frequently in accelerated laboratory tests of aluminum alloys. It is an effective test for many alloys and, therefore, it provided much of the background data needed for the development of a test based on the use of salt-(di)chromate solutions. The procedures for conducting the 3.5% NaCl alternate immersion tests were described in our First Annual Summary Report. Briefly, the test consists of 10 minutes' immersion and 50 minutes' emersion of specimens in a 3.5% NaCl solution at room temperature.

C-Rings. Our First Annual Summary Progress Report contained the results of 3.5% NaCl alternate immersion tests on short-transverse C-rings of 2024-T4, -T6, -T351, -T851, 2219-T42, -T62, -T351, -T851, -T37, -T87, 7075-T651, -T7351 and preliminary results for 7039-T64, -T61 and -T6E132. During this past year, the tests of 7039 were completed and additional testing was performed on short-transverse C-rings of 2014-T651 and 7079-T651. All these data are compiled in Table V.

For the purpose of this discussion, it is sufficient to note that the 2024-T6, -T851, 2219-T62, -T851, -T87 and 7075-T7351 showed the expected high resistance to stress-corrosion cracking. When failures occurred, they were associated with relatively long periods of exposure and high initial levels of stress. The remaining alloys and tempers were, however, susceptible to short-transverse stress-corrosion cracking; with failures occurring sooner and with greater frequency at high initial stress levels. As the initial levels of stress decreased, the failure times and the frequency of failures also decreased, suggesting an approach to an endurance limit or threshold stress below which cracking would not occur.

Unfortunately, with the exception of alloy 7039, the determination of threshold stresses in alternate immersion testing was quite subjective. If failure of the copper-bearing alloys, ie, 2024, 2219, 2014, 7079 and 7075, was not detected during the first week or so of testing, subsequent failures went undetected because of excessive general surface corrosion. As a result, the majority of the low stress-level failures in susceptible tempers of 2024, 2219 and 7075 and in 2014-T651 and 7079-T651 were detected solely on the basis of metallographic examination of specimen cross sections. This did not entirely remove the subjectiveness inherent in alternate immersion testing, since we still questioned whether failures had occurred in the 2024-T4, -T351, 2219-T42, -T351, -T37 and 7075-T651 specimens initially stressed at 5 ksi; intergranular attack of both the compression and tension surfaces of the C-rings was so extensive as to preclude adequate separation of the stress-corrosion cracking and general intergranular attack.

Alloy 7039, essentially copper-free, exhibited excellent resistance to general corrosion in 3.5% NaCl alternate immersion. As a result, we had little difficulty in visually determining whether or not failure had occurred. Moreover, most of the failures took place during the first 180 days of testing. As such, it appeared that a 365-day exposure was more than sufficient to characterize the performance of alloy 7039 in 3.5% NaCl alternate immersion. However, 3.5% NaCl alternate immersion was not completely effective for testing 7039; at low levels of applied stress, specimens were more prone to failure in outdoor exposures than in alternate immersion testing.

It is well known that artificial aging of 2024 and 2219 and overaging of 7075-T6 results in marked improvement in their stress-corrosion performance. Thus, as shown in Table VI, artificial aging of 2024 eight hours or more at 375F resulted in a significant increase in stress-corrosion resistance, in that failures did not occur during the 30-day test. Subsequent metallographic examination did reveal, however, that even the overaged 2024 was still susceptible to intergranular attack. As such, we concluded that an applied stress of 40 ksi was too high to allow fine separations in the performance of peak-aged and overaged tempers of 2024.

Naturally aged and underaged tempers of 2219 were highly susceptible to stress-corrosion cracking in 3.5% NaCl alternate immersion. Metallographic examinations revealed some tendency for grain boundary corrosion of the 2219-T42 + 12 hours at 375F specimens, but the overaged tempers were completely free of intergranular attack. The 2219-T351 aged 8 to 18 hours at 350F and 2219-T37 aged 12 to 24 hours at 325F were also immune to stress-corrosion cracking. Except for deep pitting, metallographic examination of the C-rings failed to reveal any evidence of grain boundary attack in these items.

Specimens of 7075-T651 and -T651 + 2 hours at 350F were visibly cracked after a brief exposure to 3.5% NaCl alternate immersion testing. However, because of the excessive general surface corrosion, it was not until after the 30-day test that metallographic examination revealed intergranular attack of the 7075-T651 specimens that had been aged an additional four hours at 350F. All evidence of intergranular attack disappeared with further overaging of the 7075, suggesting that the aging time of six hours at 350F was sufficient to impart the high stress-corrosion resistance associated with the -T73 temper.

Tensile Rounds. Most investigators feel that the advantage in testing tensile specimens is that losses in tensile strength can be used to separate the effect of general corrosion from that due to corrosion with superimposed stress (stress-corrosion cracking). The per cent loss in tensile strength of a stressed and corroded specimen is given by:

$$\% \, LTS_s = \frac{TS_n - TS_s}{TS_n} \times 100 \qquad (1)$$

and the per cent loss in tensile strength of an unstressed and corroded specimen by:

$$\% \, LTS_u = \frac{TS_n - TS_u}{TS_n} \times 100 \qquad (2)$$

The per cent stress-corrosion cracking in a stressed and corroded specimen is then expressed as:

$$\% \, SCC = \frac{\% \, LTS_s - \% \, LTS_u}{\% \, LTS_s} \qquad (3a)$$

or

$$\% \, SCC = \frac{TS_u - TS_s}{TS_n - TS_s} \times 100 \qquad (3b)$$

in terms of:

TS_s = tensile strength of a stressed and corroded specimen.

TS_u = tensile strength of an unstressed specimen corroded for the same time as the stressed specimen.

TS_n = tensile strength of an unstressed and uncorroded specimen, tensile tested upon completion of the stress-corrosion test.

The % SCC factor, also referred to as the stress-corrosion index (Refs 3 & 4), supposedly represents that fraction (per cent) of the total per cent loss in tensile strength of a stressed specimen due to stress-corrosion cracking. As such, calculating a % SCC factor for 3.5% NaCl alternate immersion tests might possibly remove some of the subjectiveness inherent in determining if stress did or did not influence corrosion performance. Several reasons can be given why this should not be so. When a stressed specimen fails during the corrosion test, the fracture stress (TS_s) is undefined. It is patently incorrect to assume that the fracture stress bears any relation to the initial applied stress -- if for no other reason than the net section stress on the tensile specimen increases with corrosion attack, regardless of the type of attack (Ref 4).

It is also unreasonable to assume that the difference between losses in tensile strength of stressed and unstressed specimens gives an absolute measure of the damage caused by stress-corrosion cracking. That is, no simple mathematical expression, such as that given by Equation (3a), will allow a separation of the loss in tensile strength due to stress-corrosion from that due to general corrosion. To do so, one must assume that the deteriorating effects of general corrosion and stress-corrosion cracking on tensile strengths are strictly additive. When, in fact, the opposite is more likely nearer the truth; general corrosion processes have a moderating effect on stress-corrosion cracking. This was particularly evident in 3.5% NaCl alternate immersion tests of alloys and tempers exhibiting high resistance to stress-corrosion cracking.

If corrosion of aluminum alloys is dependent upon stress (stress-corrosion cracking), then after a given test period we expected a decrease in the loss in tensile strength of stressed specimens (% LTS_s) with decreasing applied stress. In general, this was not observed in tests of alloys and tempers exhibiting high resistance to stress-corrosion cracking. As shown in Table VII, the per cent loss in tensile strength of stressed 2024-T851 and 2219-T87 specimens increased with decreasing applied stress; whereas in tests of 2024-T6, the initial increase in % LTS_s was followed by a decrease in % LTS_s with decreasing stress. Furthermore, while the % LTS_s of 2219-T62 and -T851 seemed to decrease with decreasing applied load, only in tests of 2219-T851 and 2014-T651 did it appear that stress significantly affected the loss in tensile strength.

For the most part, tests of 7075-T7351, 7079-T651 and 7039-T64, -T61 and -T6E132 also failed to demonstrate a stress dependence of loss in tensile strength. Of course, it was unfortunate that most of the failures in 7079-T651 went undetected, ie, until complete rupture of the specimen had occurred. As a result, we had no reliable measure of the loss in tensile strength of stressed specimens. Similarly, in tests of 7039 where general corrosion was not expected to interfere with the detection of stress-corrosion cracking, the tensile specimen often ruptured completely before fine cracks could be detected.

Other analyses of these data, such as relating the per cent stress-corrosion cracking factor (% SCC) to the applied stress, were complicated by the fact that the per cent loss in tensile strength of unstressed specimens was more often greater than that in stressed specimens. Certainly, this can hardly be regarded as an expected result. If anything, these results merely demonstrate the variability associated with alternate immersion tests and the probable influence of small changes in the depth and shape of corrosion attack on the fracture strength of a $\frac{1}{8}$-inch diameter tensile specimen. Originally, these analyses of losses in tensile strength were intended to apply in tests of Al-Mg alloys, which exhibit excellent resistance to general corrosion in most chloride-bearing environments (Ref 5). The excessive general corrosion of copper-bearing alloys in 3.5% NaCl alternate immersion may, therefore, mask the influence of stress on corrosion performance -- particularly in those tempers which exhibit high resistance to stress-corrosion cracking. As such, we might expect that analysis of losses in tensile strength would have greater meaning and significance if general corrosion processes were minimized during stress-corrosion testing. Some support for this hypothesis was obtained in stress-corrosion tests of tensile specimens in salt-(di)chromate solutions.

Lastly, we note that while the analysis of losses in tensile strength were not particularly useful in these 3.5% NaCl alternate immersion tests of 2024, 2219 and 7075, the 2024-T6, -T851, 2219-T62, -T851, -T87 and 7075-T7351 again demonstrated high resistance to stress-corrosion cracking. The failures of 2024-T6 tensile rounds at upwards of 35 ksi stress probably indicate some tendency toward stress corrosion, which was also detected in 3.5% NaCl alternate immersion tests of C-rings. On the other hand, failures in 2014-T651, 7079-T651 and 7039 (all tempers) must be attributed to stress-corrosion cracking. In fact, complete rupture of the tensile specimen finally proved to be a reasonably effective measure of whether or not stress-corrosion cracking of these alloys occurred in our 3.5% NaCl alternate immersion tests.

In general, artificial aging of 2024 and 2219 or overaging of 7075 reduces their resistance to general corrosion. However, 7075-T651 and the naturally aged and underaged tempers of 2000 series alloys are quite prone to intergranular attack in 3.5% NaCl alternate immersion. The intergranular attack has a greater deteriorating effect on mechanical properties and, therefore, for any given period of exposure, losses in tensile strengths decrease with artificial aging of 2024 and 2219 and overaging of 7075. We do not show this in Table VIII, because the un-stressed specimens were removed from test whenever a corresponding stressed specimen failed. These data do show, however, that the losses in tensile strength can be large in 3.5% NaCl alternate immersion testing.

Because the losses in tensile strength of 2000 and copper-bearing 7000 series alloys tested in 3.5% NaCl alternate immersion can be excessive, it was quite difficult to determine to what extent artificial aging affected the stress-corrosion behavior of 2024, 2219 and 7075. This can be seen in Table VIII. Admittedly, in the underaged temper of 2024 and 2219, losses in tensile strength of stressed specimens were consistently greater than the losses in unstressed specimens. From this, we concluded that stress-corrosion cracking must have contributed in large measure to the losses of tensile strength. It was interesting to note, however, that with the exception of the 2024-T4 aged four hours at 375F, residual tensile strengths of stressed specimens of underaged 2024 and 2219 were smaller than the initial applied stress. We can only interpret this as proof that no fixed relationship exists between the tensile breaking stress and the net section stresses which contributed to failure. Moreover, the fact that tensile overload failures did not occur suggests that through-section yielding accompanied stress-corrosion cracking, with the net result that the notch-fracture strength was not obtained.

The most reasonable measures of the effect of artificial aging on stress-corrosion performance of 2024, 2219 and 7075 were (a) whether tensile fracture did or did not occur during the 30-day alternate immersion test, and/or (b) the time required for complete failure. In this context, we obtained quite reasonable agreement between tests of C-rings and round tensile specimens. As in the tests of C-rings, overaging of 2024 apparently did not completely eliminate the tendency for intergranular attack and stress-corrosion cracking at an applied stress of 40 ksi. The performance of overaged 2219 was also similar in both tests, with the expected freedom from cracking in

2219-T42 aged 24 and 36 hours at 375F and 2219-T351 aged 12 and 18 hours at 350F. Tensile overload failures did occur in the 2219-T37 peak aged (12 hr at 325F) and overaged (18 and 24 hr at 325F), but for the most part, it appeared that adequate stress-corrosion resistance was obtained in 2219-T37 aged 12 hours or more at 325F. And, finally, the 7075-T651 aged an additional six hours or more at 350F also showed the expected freedom from cracking in the 30-day alternate immersion test.

Continuous Immersion Tests in Salt-(Di)Chromate Solution

Our first annual summary report described the phenomenological effects of pH and temperature on the stress-corrosion behavior of aluminum alloys in salt-(di)chromate solutions. A considerable number of experiments were performed in an attempt to define the optimum conditions of temperature and pH for an accelerated stress-corrosion test of alloys 2024, 2219, 7075 and 7039. Our preliminary findings indicated that no unique condition of pH and temperature would be suitable for testing all of these alloys. We gave brief consideration to the use of an impressed (anodic) current test in a neutral salt-(di)chromate solution. And, while this test looked quite promising, it was finally abandoned in favor of free-corrosion tests which are easier to conduct and somewhat more suited to testing large numbers of specimens.

We selected NaCl - $K_2Cr_2O_7$ solutions for this study, on the premise that minimal general corrosion would be desirable in an accelerated stress-corrosion test. The majority of our preliminary tests were conducted in solutions containing 2% $K_2Cr_2O_7$ and upwards of 5% NaCl. Since these solutions exhibited an unadjusted pH of 3.7 to 4.0, this appeared to be a convenient range of pH to begin further studies on the development of solutions for use in a free-corrosion stress-corrosion test. Moreover, a solution containing 6% NaCl and 2% $K_2Cr_2O_7$ at pH=3.7 and 60C had proved quite effective in causing rapid failure of susceptible tempers of 2024, 2219 and 7039. This same solution had not proved effective as an accelerated cracking medium for 7075-T651. But we soon discovered that by simply lowering the salt concentration to 1% NaCl, rapid stress-corrosion cracking could be induced in 7075-T651 as well. As a result, most of our effort concentrated on continuous-immersion stress-corrosion tests conducted in a 1% NaCl - 2% $K_2Cr_2O_7$ solution at pH=4 and temperature of 60C* (see Appendix). In the following sections, we discuss the advantages and limitations of this solution in tests of 2024, 2219, 2014, 7075, 7079 and 7039.

C-Rings. As shown in Table IX, a 1% NaCl - 2% $K_2Cr_2O_7$ solution at pH=4 and temperature of 60C was quite effective in promoting rapid short-transverse cracking in 2024-T4, -T351, 2219-T42, -T351 and -T37 C-rings stressed at 10 ksi and above. By comparison, the stress-corrosion performance of 2024-T6, -T851 and 2219-T62, -T851 and -T87 was much better. Failures of 2024-T6 and -T851 were observed only in specimens stressed at 50 ksi. This was expected from our 3.5% NaCl alternate immersion tests of C-rings, as was the performance of the 2014-T651, which failed as a result of stress-corrosion cracking at lower applied stresses than did the 2024-T6 and -T851. However, in contrast to the alternate immersion tests, little general corrosion of these 2000 series alloys occurred during the 7-day exposure to the salt-(di)chromate solution. This facilitated the detection of cracking, if any, in the artificially aged tempers of 2024, 2014 and 2219. For example, compared with a 7-day 3.5% NaCl alternate immersion test, the salt-(di)chromate solution caused very little general attack of 2024-T6, 2014-T651 or 2219-T851 (Figures 5, 6 & 7). Moreover, as shown in Figures 5 and 6, when cracking occurred in the 2024-T6 and

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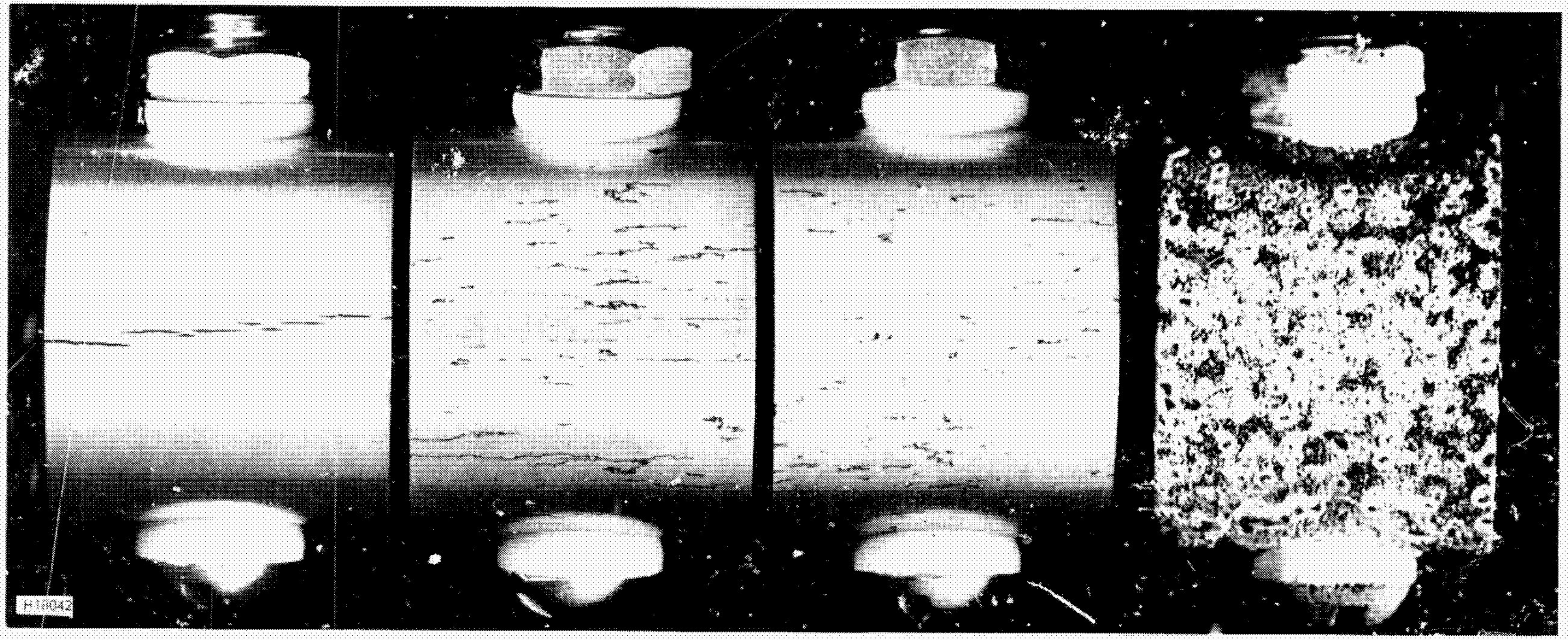
* Solutions made up on a weight basis with reagent grade chemicals and distilled water exhibited an unadjusted pH=3.7. A final pH=4.0 was obtained with the addition of a few drops of 1 N NaOH solution.



(a)
50 ksi, 2 days

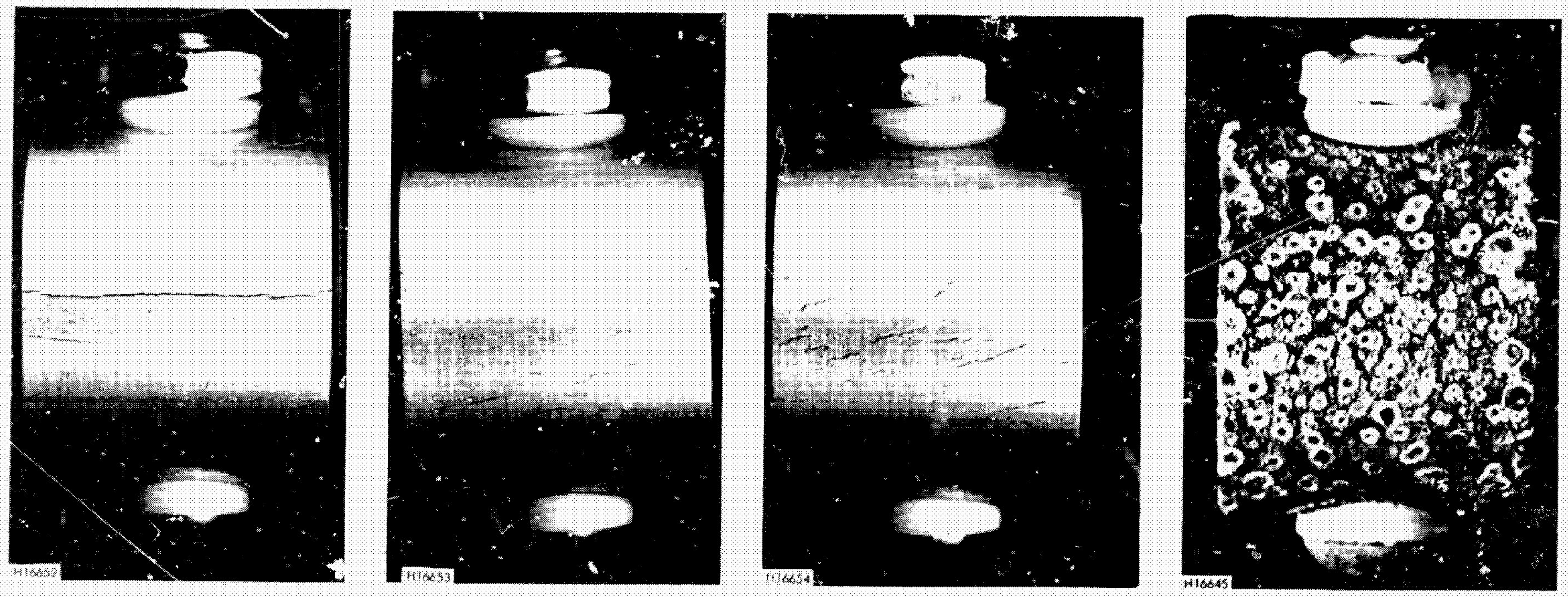
(b)
40 ksi, NF 7 days

(c)
30 ksi, NF 7 days

(d)
Unstressed, 7 days

2.5X

Figure 5
SURFACE APPEARANCE OF 2024-T6 SHORT-TRANSVERSE C-RINGS
Specimens a, b and c tested in 1% NaCl - 2% $K_2Cr_2O_7$ solution at pH=4 and 60C. Applied stress and failure times as noted. NF = no failure in test period. Specimen d. unstressed, seven days 3.5% NaCl alternate immersion.



(a)
30 ksi, 1 day

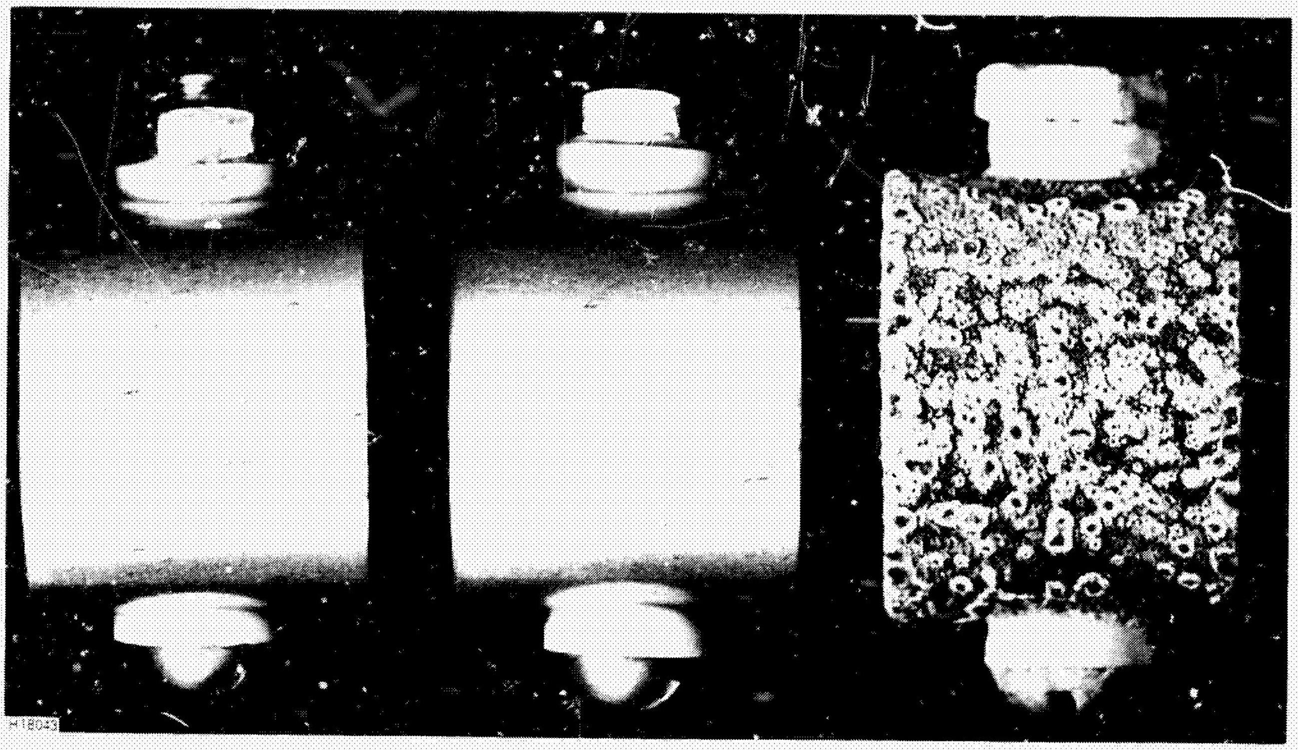
(b)
20 ksi, 1 day

(c)
10 ksi, NF 7 days

(d)
Unstressed, 7 days

2.5X

Figure 6
SURFACE APPEARANCE OF 2014-T651 SHORT-TRANSVERSE C-RINGS
Specimens a, b and c tested in 1% NaCl - 2% $K_2Cr_2O_7$ solution at pH=4 and temperature of 60C. Applied stress and failure times as noted. NF = no failure in test period. Specimen d, unstressed, seven days 3.5% NaCl alternate immersion.



(a)
50 ksi, NF 7 days

(b)
40 ksi, NF 7 days

(c)
Unstressed, 7 days

2.5X

Figure 7
SURFACE APPEARANCE OF 2219-T851 SHORT-TRANSVERSE C-RINGS
Specimens a and b tested seven days in 1% NaCl - 2% $K_2Cr_2O_7$ solution at pH=4 and temperature of 60C. Applied stress as noted. NF = no failure in test period. Specimen c, unstressed, seven days 3.5% NaCl alternate immersion.

2014-T651, it was easily distinguished from the limited and random general surface corrosion. Thus, provided that a 7-day test in the 1% NaCl - 2% $K_2Cr_2O_7$ solution would also separate 2024 and 2219 tempers of borderline and maximum resistance to stress-corrosion cracking, its use for this purpose should be preferred to the more corrosive 3.5% NaCl alternate immersion test.

Table IX shows that highly stressed specimens of 7075-T651, 7079-T651 and 7039 (all tempers) were susceptible to short-transverse stress-corrosion cracking in the 1% NaCl - 2% $K_2Cr_2O_7$ solution. If it were merely our purpose to demonstrate this susceptibility, adequate response was obtained in these tests. And, at least for alloy 7039, this test was more aggressive than 3.5% NaCl alternate immersion. Moreover, because failures were not observed in 7075-T7351, we believed that the salt-(di)chromate solution test could prove useful for separating 7075 tempers of borderline and maximum resistance to stress-corrosion cracking.

On the other hand, the 1% NaCl - 2% $K_2Cr_2O_7$ solution did not prove very useful for predicting the natural environment performance of 7075, 7079 and 7039 at low stress levels. In the Daytona Beach marine atmosphere, 7075-T651 failed at an applied stress of 10 ksi. This was 10 ksi lower than that required for failure in the salt-(di)chromate solution. Both the Daytona Beach marine environment and the Pittsburgh industrial environment were effective in causing failure of 7039-T64 at stresses at least 5 to 10 ksi lower than that required for failure in the laboratory test. Alloy 7079-T651 was not tested in a natural environm [illegible] But, based on the performance obtained in 3.5% NaCl alternate immersion tests, 7079-T651 stressed at 10 ksi should have failed in the salt-(di)chromate solution. However, it didn't, and only one failure of 7079-T651 occurred at 20 ksi. These deviations from the performance observed or expected in natural environments detracted somewhat from the general usefulness of the 1% NaCl - 2% $K_2Cr_2O_7$ solution in accelerated tests of 7075, 7079 and 7039. As a result, some effort was expended during this past year to obtain more aggressive conditions for accelerated testing of these alloys.

We knew, from some of our previous studies, that boiling salt solutions were very effective in causing short-transverse failures of alloy 7039. We also recognized that boiling salt-(di)chromate solutions would induce rapid failure in 7079-T651 and, dependent upon the NaCl concentration, in 7075-T651 as well.

Significantly, a boiling 0.5% NaCl - 2% $K_2Cr_2O_7$ solution at pH=4 proved to be one of the most effective tests for 7079 and 7039 -- particularly, as shown in Table X, at applied stresses of 5 and 10 ksi. However, the boiling solution test offered no real improvement over tests conducted at 60C in causing failure of 7075-T651 stressed at 10 ksi. In fact, excepting the single failure of 7075-T651 at 10 ksi, the longer times required for failure at 20 and 30 ksi suggested that the boiling 0.5% NaCl - 2% $K_2Cr_2O_7$ solution was even less aggressive than the 1% NaCl - 2% $K_2Cr_2O_7$ solution at 60C. Moreover, subsequent tests showed that the boiling 0.5% NaCl - 2% $K_2Cr_2O_7$ solution was completely ineffective in promoting failures of overaged tempers of 7075, ie, -T651 + 2 and 4 hours at 350F, which were quite susceptible to stress-corrosion cracking in 3.5% NaCl alternate immersion and in the 1% NaCl - 2% $K_2Cr_2O_7$ solution at 60C.

There was little doubt that the boiling 0.5% NaCl - 2% $K_2Cr_2O_7$ solution was a more aggressive test for 7079 and 7039 than the 1% NaCl - 2% $K_2Cr_2O_7$ solution at 60C. It was somewhat too severe, however, for realistic comparison with natural environments. Only the 7039-T64 failed at an applied stress of 5 ksi in both marine and industrial environments. Moreover, on the basis of 3.5% NaCl alternate immersion tests, we had no reason to expect natural environment failures of 7079-T651 at a stress of 5 ksi. Since the temperature of the salt-(di)chromate solutions determined if, or how rapidly, cracking would occur in 7079 and 7039 at low levels of stress, there was little doubt that a test temperature between 60C and 100C would yield better correlation with tests in natural environments. However, this approach would not solve the problem of obtaining better correlation with the performance of alloy 7075-T651 in a marine environment. If anything, it appeared that the salt-(di) chromate solution tests were better suited to separating alloys and tempers which simply differed in their susceptibility to short-transverse stress-corrosion cracking, and not as a test which would also promote failures of these same alloys and tempers at the same stresses as could be obtained in outdoor exposures.

Tests in 3.5% NaCl alternate immersion demonstrated that 2024-T4 and -T351 and the -T4 and -T351 tempers artificially aged for four hours at 375F were highly susceptible to short-transverse stress-corrosion cracking. Longer aging treatments resulted in significant increases in short-transverse stress-corrosion resistance, in that failures did not occur during the 30-day test. But subsequent metallographic examinations of the unfailed specimens stressed at 40 ksi revealed that even the -T6 and -T851 tempers were susceptible to intergranular attack.

Identical performance of the 2024 was observed in the 1% NaCl - 2% $K_2Cr_2O_7$ solution at pH=4 and 60C and 3.5% NaCl alternate immersion tests (Table VI), except that salt-(di)chromate solution promoted faster failure of the underaged tempers. Well-defined cracking was not observed in items artificially aged for eight hours or more at 375F, but there was evidence that the C-rings stressed at 40 ksi had suffered some intergranular attack. Figures 8 and 9 illustrate the change in the mode of corrosion attack on 2024 as the period of artificial aging was extended. Compared with the singularity of cracking in the naturally aged and underaged (+ 4 hr at 375F) specimens,

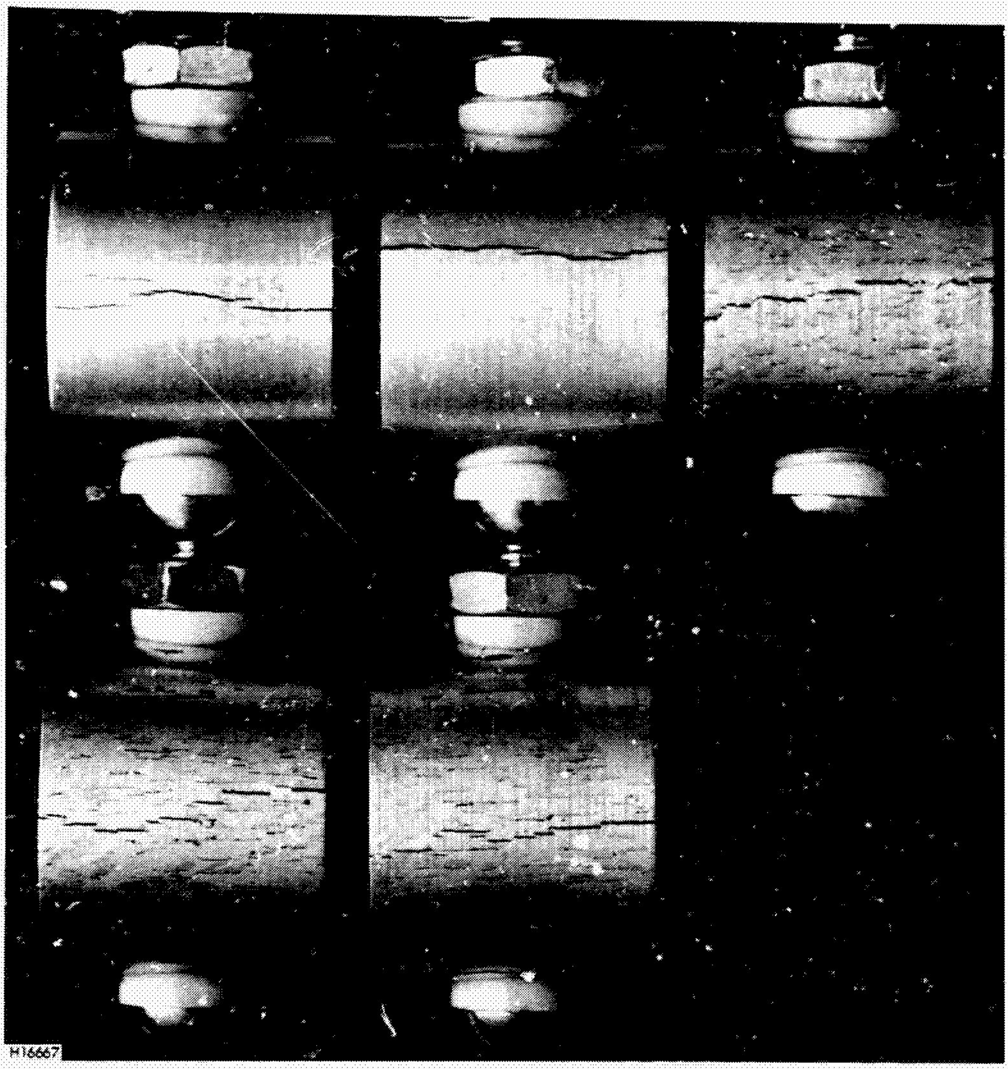


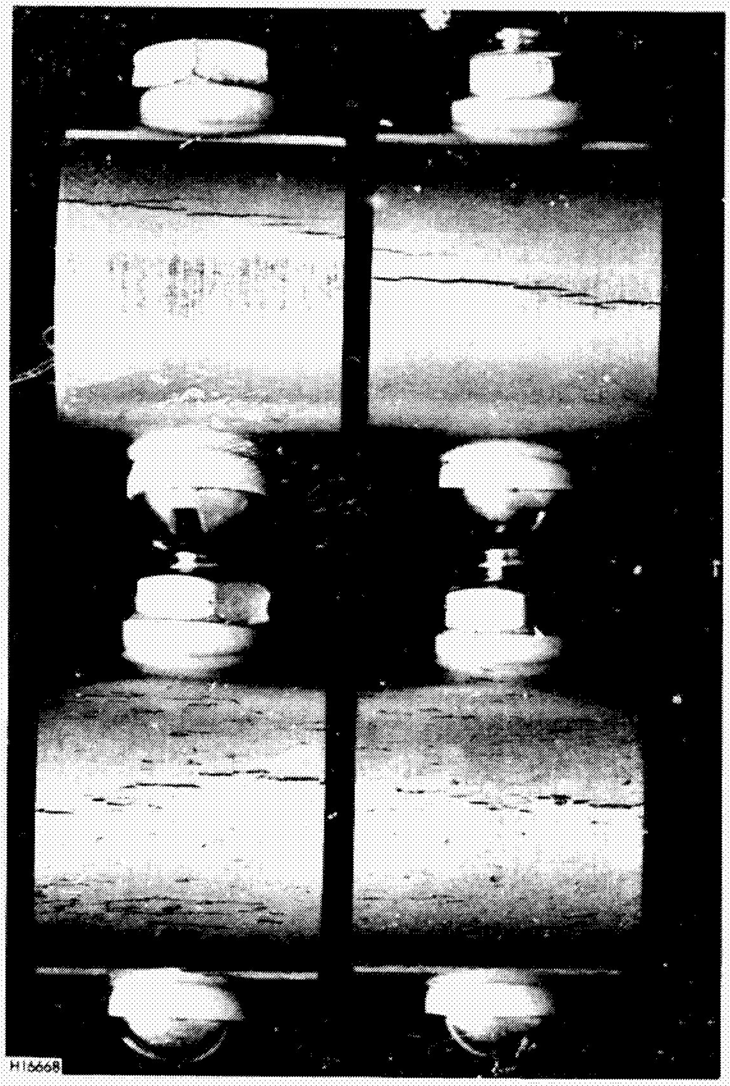
Figure 8

SURFACE APPEARANCE OF 2024 (-T4 + AA) C-RINGS STRESSED AT 35-40 KSI AND TESTED IN 1% NaCl - 2% $K_2Cr_2O_7$ SOLUTION AT pH=4 AND 60C

Aging period and applied stress as noted. Specimens from plate aged 8, 12 and 16 hours at 375F were fractured in a slow bend test after completing seven days in the salt-(di)chromate solution.

-T351
35 ksi

+ 4 hr at 375F
40 ksi



+ 8 hr at 375F
40 ksi

+ 12 hr at 375F (-T851)
40 ksi

2X

Figure 9
SURFACE APPEARANCE OF 2024 (-T351 + AA) C-RINGS STRESSED AT 35-40 KSI AND TESTED IN 1% NaCl - 2% $K_2Cr_2O_7$ SOLUTION AT pH=4 AND 60C
Aging period and applied stress as noted. Specimens from plate aged 8 and 12 hours at 375F were fractured in slow bending after seven days in the salt-(di)chromate solution.

multiple sites of intergranular attack occurred in specimens aged eight or more hours at 375F. Moreover, as shown in Figures 8 and 9, when these unfailed specimens were subjected to a slow bend test*, sufficient intergranular attack had occurred during corrosion testing to initiate fracture across the apex of the C-rings.

Interestingly, in addition to the effects of artificial aging, the initial level of applied stress also influenced the mode of corrosion on 2024 tested in the 1% NaCl - 2% $K_2Cr_2O_7$ solution (Figures 10 through 13). For example, specimens of 2024-T4 or -T351 aged four hours at 375F and stressed at 30 ksi were visibly cracked after brief exposure to the salt-(di)chromate solution (Figures 10 & 11). However, at a stress of 20 ksi (Figures 12 & 13), cracking was replaced by a random and superficial type of corrosion which apparently was unrelated to the fact that this temper was susceptible to stress-corrosion cracking. This superficial corrosion attack persisted in all of the artificially aged 2024, becoming somewhat more random with longer periods of aging and lower levels of applied stress. Yet, curiously enough, the random corrosion of the artificially aged 2024 was often confined to the tension surface of the C-ring, with little or no attack of the compression surface -- suggesting that under certain conditions, corrosion of aluminum alloys is a stress-activated process.

Not only was the salt-(di)chromate solution test more aggressive than 3.5% NaCl alternate immersion in causing failures of susceptible tempers of 2219, but it was also a more discriminating test (Table VI). All of the underaged and peak-aged tempers failed rapidly, ie, -T42 to -T42 + 12 hr at 375F, -T351 to -T351 + 8 hr at 350F, and -T37 to -T37 + 12 hr at 325F. On the other hand, all of the overaged tempers, particularly -T62, -T851 and -T87, exhibited complete freedom from both stress-corrosion cracking and intergranular attack.

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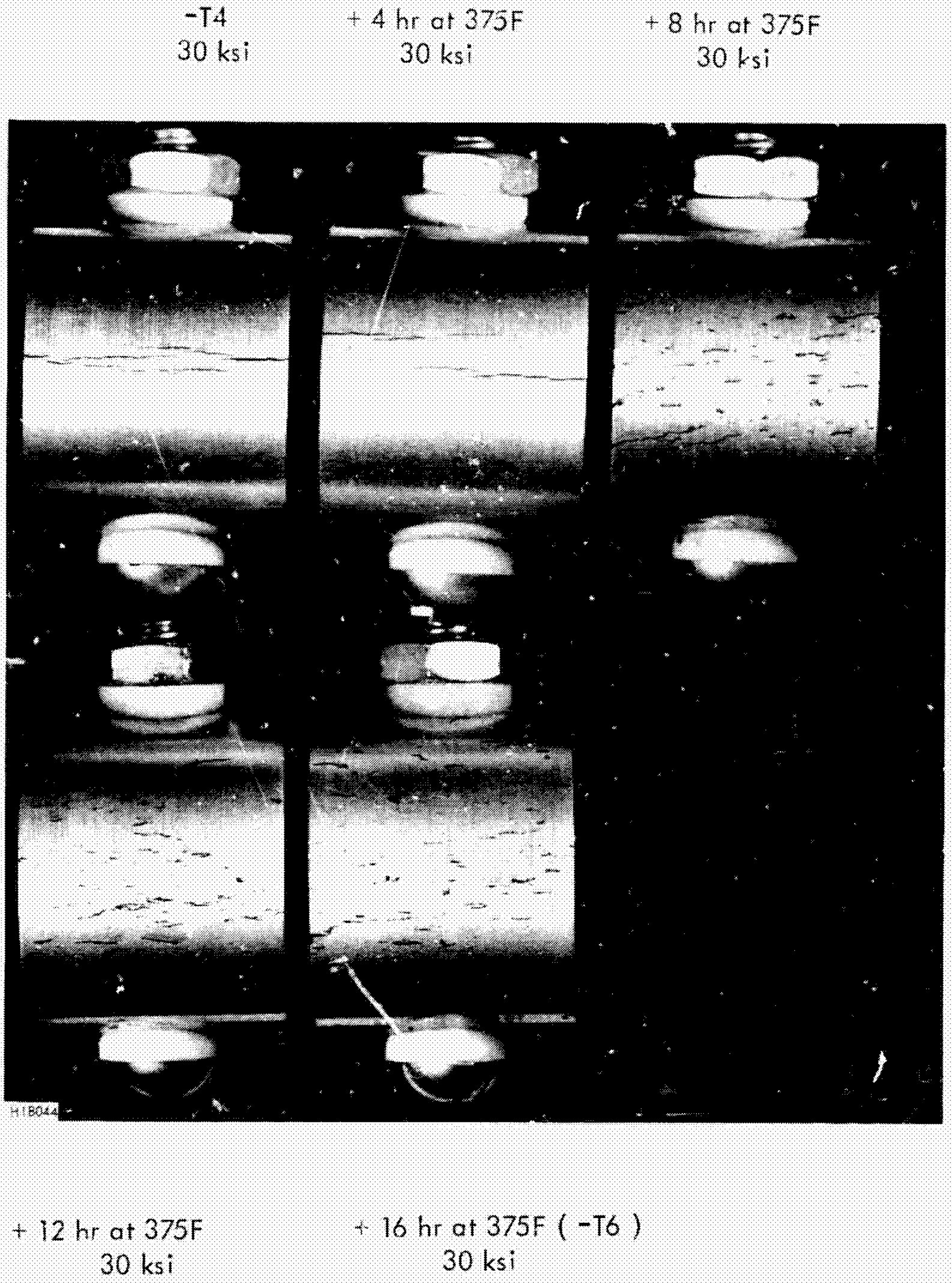
* Upon termination of the 7-day test, the specimens were washed with cold concentrated nitric acid to remove the small amount of accumulated corrosion product. They were then slowly compressed in a vise to obtain a "permanent set", or in the case of 2024, to cause fracture.

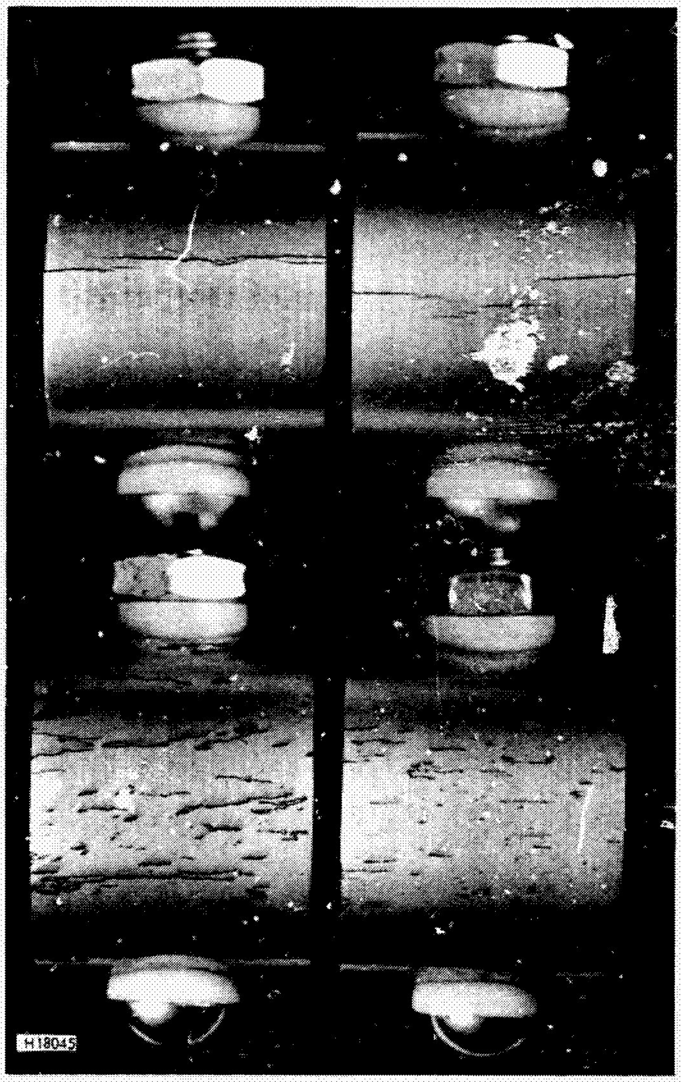


2X

Figure 10

SURFACE APPEARANCE OF 2024 (-T4 + AA) C-RINGS STRESSED AT 30 KSI AND TESTED IN 1% NaCl - 2% $K_2Cr_2O_7$ SOLUTION AT pH=4 AND 60C

Aging period and applied stress as noted. Specimens from plate aged 8, 12 and 16 hours at 375F were exposed for seven days in the salt-(di)chromate solution with no failure.



2X

Figure 11
SURFACE APPEARANCE OF 2024 (-T351 + AA) C-RINGS STRESSED AT 30 KSI AND TESTED IN 1% NaCl - 2% $K_2Cr_2O_7$ SOLUTION AT pH=4 AND 60C
Aging period and applied stress as noted. Specimens from plate aged 8 and 12 hours at 375F were exposed for seven days in the [illegible] (di)chromate solution with no failures.

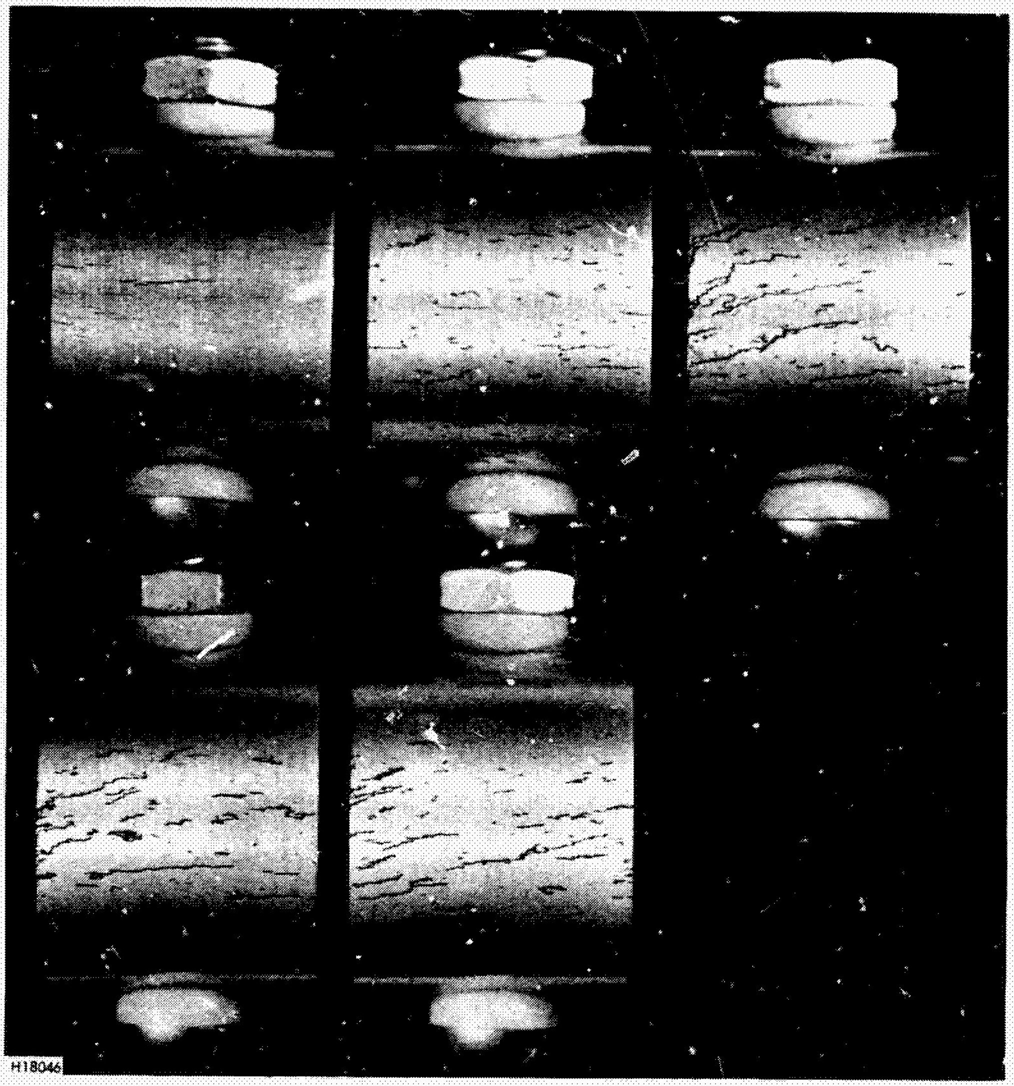
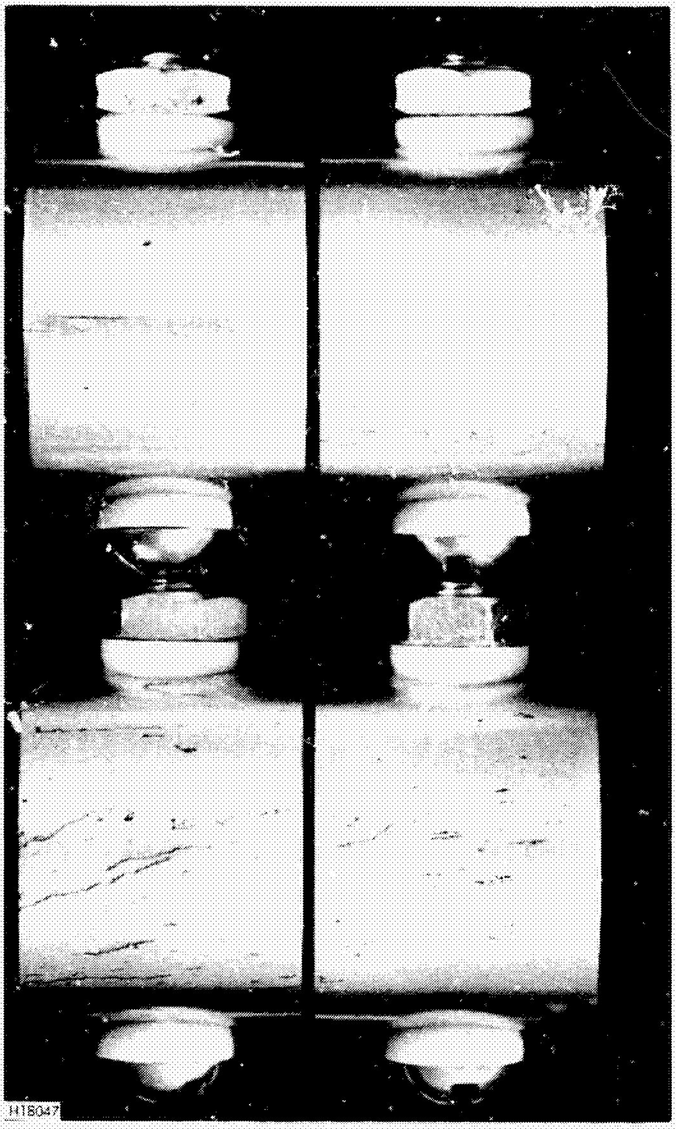


Figure 12
SURFACE APPEARANCE OF 2024 (-T4 + AA) C-RINGS STRESSED AT 20 KSI AND TESTED IN 1% NaCl - 2% $K_2Cr_2O_7$ SOLUTION AT pH=4 AND 60C
Aging period and applied stress as noted. Specimens from plate aged 4, 8, 12 and 16 hours at 375F were exposed for seven days in the salt-(di)chromate solution with no failures.

-T351
20 ksi

+ 4 hr at 375F
20 ksi



+ 8 hr at 375F
20 ksi

+ 12 hr at 375F (-T851)
20 ksi

2X

Figure 13
SURFACE APPEARANCE OF 2024 (-T351 + AA) C-RINGS STRESSED AT 20 KSI AND TESTED IN 1% NaCl - 2% $K_2Cr_2O_7$ SOLUTION AT pH=4 AND 60C
Aging period and applied stress as noted. Specimens from plate aged 4,8 and 12 hours at 375F were exposed for seven days in the salt-(di)chromate solution with no failures.

The surface appearances of the 2219 C-rings after salt-(di)chromate solution testing are pictured in Figures 14, 15 and 16. A marked transition from stress-corrosion cracking to a complete absence of cracking was apparent in the peak-aged to overaged tempers, eg, no failures occurred in the 2219-T42 + 24 hr or 36 hr at 375F, 2219-T351 + 12 hr or 18 hr at 350F, or 2219-T37 + 18 hr or 24 hr at 325F. In fact, in contrast to the highly stressed 2024-T6 and -T851, all of the unfailed 2219 specimens subjected to slow bending performed in a completely ductile manner, indicating that the random general corrosion of the tension surface of the C-rings was quite superficial. There was, however, slightly more general corrosion of the 2219-T42 + 24 hr to 36 hr at 375F (compared Figure 14 with Figures 15 and 16). We feel that this may reflect more homogeneous precipitation in the -T851 and -T87 tempers (cold worked 3% and 9%, respectively) as compared with the -T62 temper (no cold work).

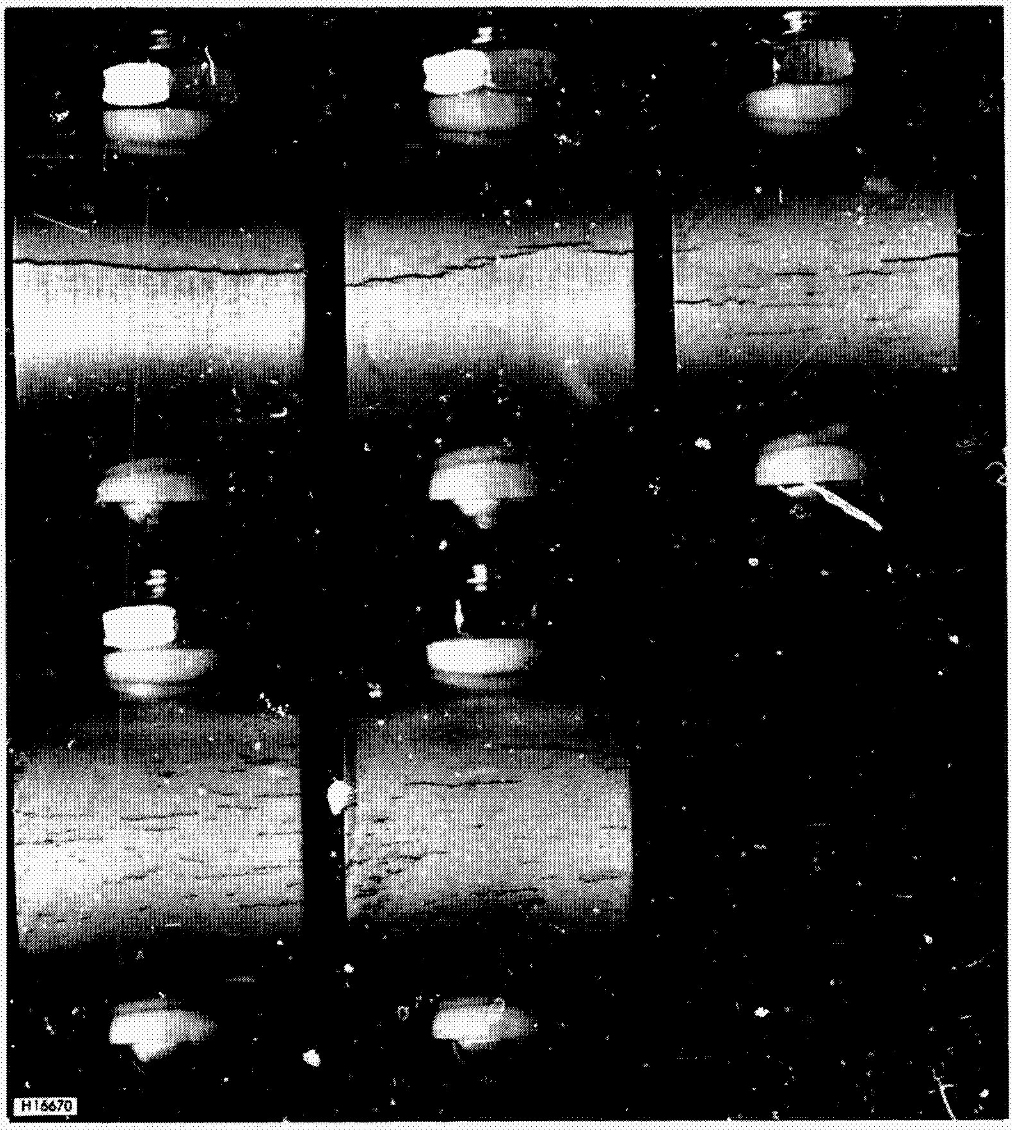
The salt-(di)chromate solution test did not prove very effective in promoting stress-corrosion cracking of 7075-T651 at low stresses. But, as we have shown, cracking can be very rapid, provided the applied stress is high enough. As shown in Table VI, a stress of 45 ksi induced rapid failure in two overaged tempers: -T651 + 2 hr at 350F and -T651 + 4 hr at 350F, but not in material overaged six hours or more at 350F. As such, the performance of 7075 was quite similar in both the salt-(di) chromate solution and 3.5% NaCl alternate immersion tests.

However, compared with 3.5% NaCl alternate immersion testing, the salt-(di) chromate solution test was much less corrosive toward 7075. There was no deep pitting of the specimen surfaces and, as shown in Figure 17, cracking was readily detected under low-power microscopic examination. The limited cracking and random surface corrosion were apparently unique to the 7075-T651 specimens aged an additional four hours at 350F.

2219-T42
20 ksi

+ 6 hr at 375F
35 ksi

+ 12 hr at 375F
35 ksi



+ 24 hr at 375F
35 ksi

+36 hr at 375F (-T62)
35 ksi

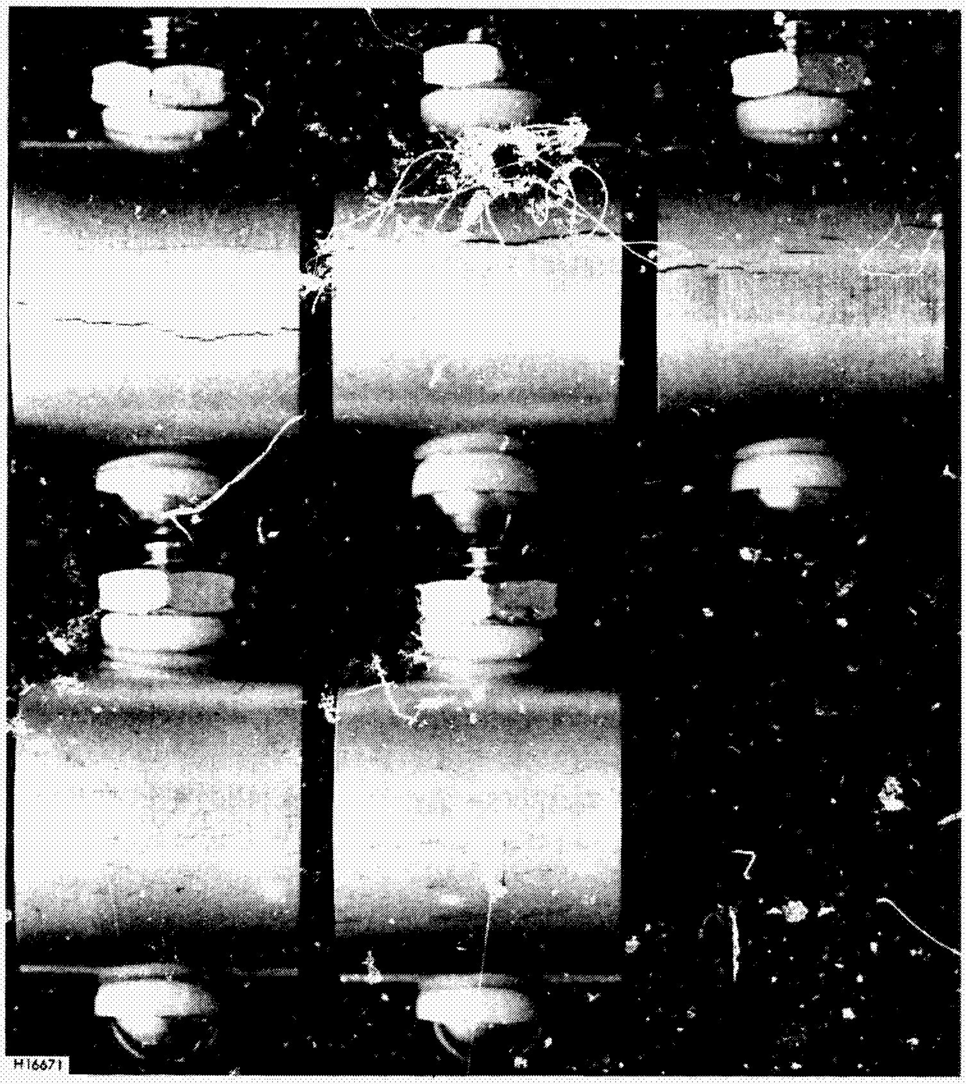
2X

Figure 14
SURFACE APPEARANCE OF 2219 (-T42 + AA) C-RINGS STRESSED AT 20-35 KSI AND TESTED IN 1% NaCl - 2% $K_2Cr_2O_7$ SOLUTION AT pH=4 AND 60C
Aging period and applied stress as noted. Specimens from plate aged 24 and 36 hours at 375F did not fracture in slow bending after seven days in the salt-(di)chromate solution.

2219-T351
30 ksi

\+ 4 hr at 350F
40 ksi

\+ 8 hr at 350F
40 ksi

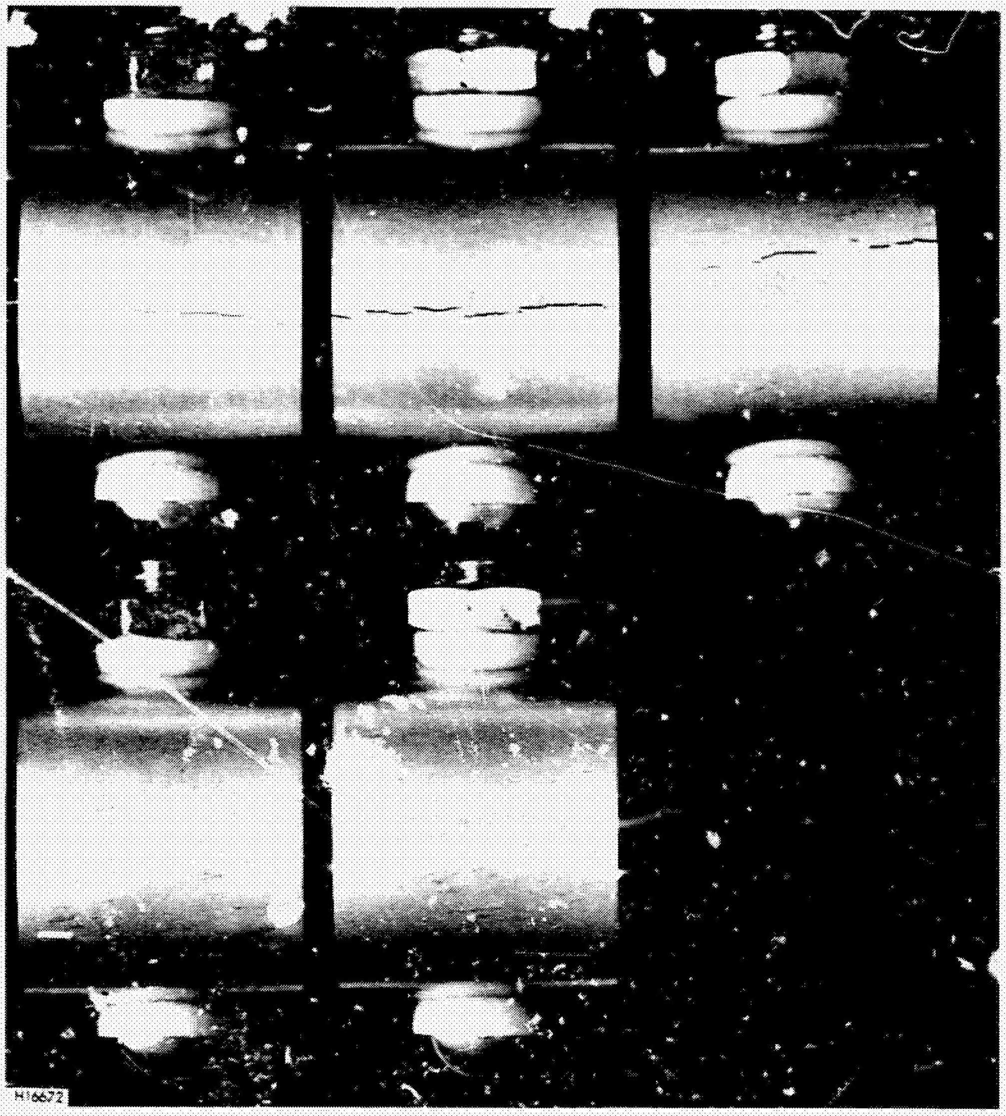


\+ 12 hr at 350F
40 ksi

\+ 18 hr at 350F (-T851)
40 ksi

2X

Figure 15
SURFACE APPEARANCE OF 2219 (-T351 + AA) C-RINGS STRESSED AT 30-40 KSI AND TESTED IN 1% NaCl-2% $K_2Cr_2O_7$ SOLUTION AT pH=4 AND 60C
Aging period and applied stress as noted. Specimens from plate aged 12 and 18 hours at 350F did not fracture in slow bending after seven days in salt-(di)chromate solution.



2219-T37
35 ksi

+ 6 hr at 325F
45 ksi

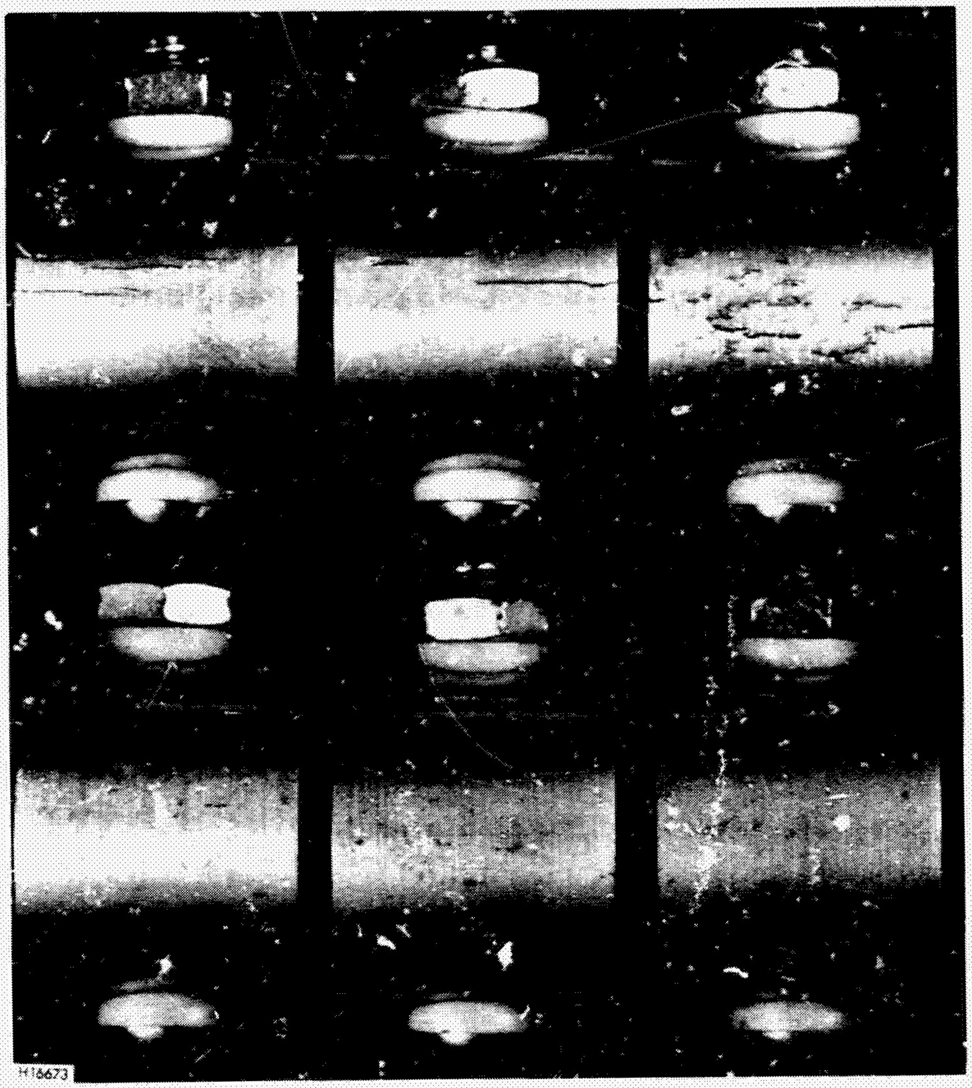
+ 12 hr at 325F
45 ksi

+ 18 hr at 325F
45 ksi

+ 24 hr at 325F (-T87)
45 ksi

2X

Figure 16
SURFACE APPEARANCE OF 2219 (-T37 + AA) C-RINGS STRESSED AT 35-45 KSI AND TESTED IN 1% NaCl - 2% $K_2Cr_2O_7$ SOLUTION AT pH-4 AND 60C
Aging period and applied stress as noted. Specimens from plate aged 18 and 24 hours at 325F did not fracture in slow bending after seven days in salt-(di)chromate solution.



2X

Figure 17
SURFACE APPEARANCE OF 7075 (-T651 + AA) C-RINGS STRESSED AT 45 KSI AND TESTED IN 1% NaCl - 2% $K_2Cr_2O_7$ SOLUTION AT pH=4 AND 60
Aging period and applied stress as noted. Specimens from plate aged 6 to 10 hours at 350F were virtually unattacked after seven days in the salt-(di)chromate solution.

We suggest that more extensive cracking may be observed at higher stresses, eg. 50 to 55 ksi, and, in this range, the test may be more discriminating. Certainly, since there is little general corrosion in the salt-(di)chromate solution, higher stress could be employed without the danger of incurring failures due to tensile overload.

Tensile Rounds. Compared with 3.5% NaCl alternate immersion testing, losses in tensile strength of unstressed specimens show that only minimal general attack of 2024, 2219 or 7075 occurred in the 1% NaCl - 2% $K_2Cr_2O_7$ solution (Table XI). All of the unstressed specimens were subjected to the full 7-day test. If the unstressed specimens had been removed when the corresponding stressed specimens failed, general corrosion simply would not have influenced loss in tensile strength. As it was, small losses in tensile strength of unstressed specimens were limited to the artificially aged 2024 and overaged 7075. Therefore, when failures did occur in the stressed specimens, we had much greater assurance that failure was a result of stress-corrosion cracking and not simply tensile overload due to general corrosion attack.

In general, the tensile round tests of artificially aged 2024 paralleled the results obtained with C-rings. As shown in Table XI, a stress of 40 ksi was not uniquely suited to separating the performance of peak-aged and overaged tempers of 2024. An applied stress of 35 ksi resulted in failure of the underaged tempers but not in 2024-T6 or -T851. Obviously, if adequate separations of stress-corrosion performance are to be achieved in a practical test, it will be necessary to test alloy 2024 at both the 35 and 40 ksi stress levels.

As in the tests of 2024, failure of alloy 2219 in the 1% NaCl - 2% $K_2Cr_2O_7$ solution was dependent upon the period of artificial aging. Moreover, as observed in previous tests, overaged tempers of 2219 were considerably more resistant to stress-corrosion cracking than was 2024 at comparable levels of applied stress. Interestingly, in tests of either the -T42, -T351 or -T37 temper series, the transition from susceptibility to resistance to stress-corrosion cracking occurred after 12 hours' artificial aging. The results for the artificially aged -T42 and -T37 tempers differed somewhat from previous tests of C-rings (Table VI), where this transition occurred in the -T42 + 24 hr at 375F and in the -T37 + 18 hr at 375F.

Finally, the susceptibility of the 7075-T651 temper and -T651 + 4 hr at 350F and the relative immunity to stress-corrosion cracking of the -T651 + 6 hr at 350F, as predicted from 3.5% NaCl alternate immersion tests were borne out in the salt-(di) chromate solution tests (Table XI). But again, the tensile specimen gave somewhat different results than did C-rings (Table VI), as indicated by the singular failure in the group of -T651 + 4 hr at 350F tensile specimens. Granted that there is some variability associated with all stress-corrosion tests, the results for the overaged 2219 and 7075 suggest that the C-rings may have been more decisive indicators of stress-corrosion performance in salt-(di)chromate solution tests.

IV. STUDIES OF THE INITIATION OF STRESS-CORROSION CRACKING

We have frequently commented on the minimal general surface corrosion on specimens exposed to salt-(di)chromate solutions at pH=4 and 60C. Most conspicuous was the lack of evidence, either metallographic or loss in tensile strength, for intergranular attack in unstressed specimens of alloys which were quite susceptible to intergranular stress-corrosion cracking. This raises the interesting question -- if any alloy is not susceptible to intergranular attack, how does intergranular stress-corrosion cracking start? It would be futile to attempt to answer this question after a specimen fails, because cracking and even the most limited general corrosion virtually obliterate the associated metal structure at the environment-specimen interface. As a consequence, we had to make our observations, not only before extensive damage to the specimen had occurred, but also during the interval before cracking started.

Hunter (Ref 6) has made direct observations of stress-corrosion cracking in aluminum alloys using optical microscopy. The experimental technique is simple, but there are limitations to this approach for studying crack nucleation. Specimens must be sufficiently flat to satisfy the limited depth of focus inherent in optical microscopy. As a result, C-rings or tensile rounds cannot be easily tested. Moreover, the limited field of view at reasonably high optical magnification precludes the possibility of selecting an area for examination which will eventually contain a crack. Consequently, there is virtually no chance of observing a crack as it forms or of photographically recording the area of crack initiation.

For metallographic studies requiring a resolution of not greater than about 0.02 micron, the dry-stripped plastic replica method is simple, rapid, reproducible and does not require destruction of the sample. One replica gives almost 100%

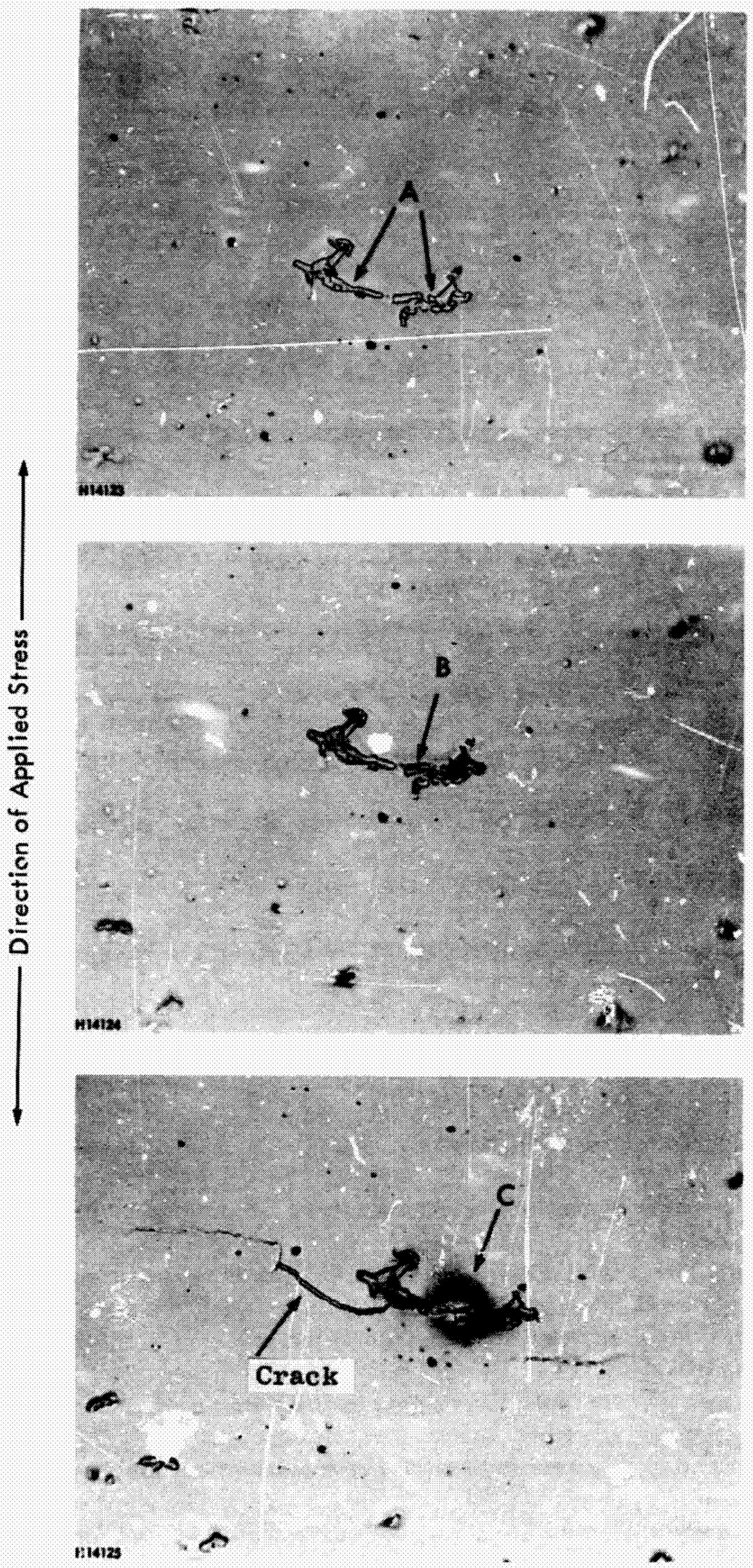
coverage of a surface. Also, if tensile bars or C-rings are tested, the replica converts a cylindrical surface into a flat one, greatly facilitating observations with the light microscope. Finally, after a replica is made, further testing on a specimen is immediately possible. If several replicas are made during testing, one can trace back in time the initiation and propagation of cracks in any given area of the specimen.

Our first observations of the initiation of stress-corrosion cracking were made on 7039-T64 short-transverse C-rings exposed to a boiling 6% NaCl solution. The upper tension surface of the specimen was metallographically polished and then electropolished to remove the last trace of scratches. Replicas were taken from these polished surfaces before testing (specimen stressed but unexposed) and periodically during testing until cracking was observed visually.

Figure 18 shows the sequence of events leading to the formation of a stress-corrosion crack in 7039-T64 exposed to a boiling 6% NaCl solution. Of particular interest is the constituent particle at A, Figure 18(a), which was the site for formation of a stress-corrosion crack.

During the first 1-minute exposure to the boiling salt solution, Figure 18(b), general darkening occurred at the constituent-matrix interface. This darkening is believed to be associated with electrochemical attack. Also note that a small crack appeared in the constituent particle at B, Figure 18(b). It is suggested that this crack must be associated with local separation of the constituent particle from the matrix and, therefore, represents an incipient stress-corrosion crack.

During the next 1-minute exposure to the boiling salt solution, Figure 18(c), extensive cracking occurred at the constituent-matrix interface. The constituent completely separated from the matrix at several points, and a definite crack was



(a)
t = 0 min

(b)
t = 1 min

(c)
= 2 min

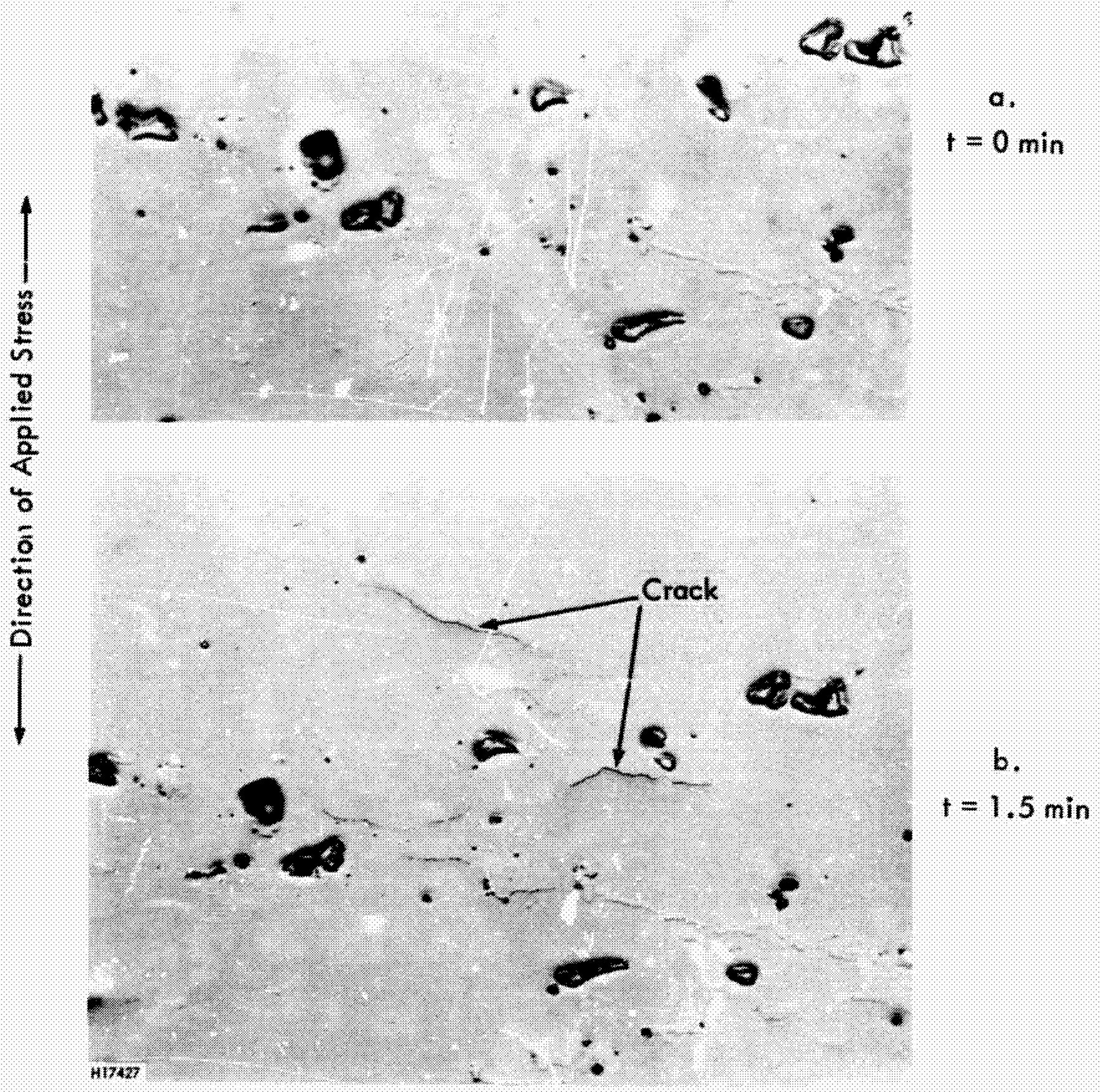
Replica 1000X

Figure 18
INITIATION OF SHORT-TRANSVERSE STRESS-CORROSION CRACKING OF 7039-T64
C-ring stressed at 35,000 psi and subject to continuous immersion in boiling 1 N NaCl solution for total elapsed times, t.

propagated along the adjacent grain boundary. The stained area at C is probably associated with egression of reaction products from the stress-corrosion crack. A total of four minutes' exposure to the boiling salt solution resulted in the formation of numerous stress-corrosion cracks, and the area shown in Figure 18 is representative of only a small fraction of the total damage to the specimen. Yet, we noted that all observable cracks were, or could be, associated with constituent particles.

Apparently, however, constituents are not always associated with crack initiation. Hunter (Ref 6) noted that cracking of 2219-T37 and 7075-T6 in an acid (pH=1) NaCl-$AlCl_3$ solution started at grain boundaries -- an entirely reasonable conclusion, since unstressed specimens were also attacked preferentially at grain boundaries in this highly aggressive solution. Obviously, either crack nucleation is different in different alloys or, for any one alloy, crack nucleation is dependent upon the acidity, chemistry or temperature of the environment to which the alloy is exposed. The results of our latest experiments tend to support the latter hypothesis.

Figure 19 shows short-transverse stress-corrosion cracking in 7075-T651 exposed to a 0.3% NaCl - 3.6% CrO_3 - 3% $K_2Cr_2O_7$ solution at pH=0.5 and 30C. This is a highly aggressive solution, as attested to by the rapid nucleation of cracks in a period of less than 1.5 minutes. Significantly, there was no association between the constituent particles and stress-corrosion cracking in this alloy (Figure 19b). Nor were constituent particles related to stress-corrosion cracking in 2024-T4 or 2219-T37 exposed to this same solution. These observations are, therefore, in agreement with those of Hunter; grain boundaries are preferred sites for crack initiation in 7075-T6 and 2219-T37 in highly acid solutions -- interestingly, of quite different chemical makeup. Presumably, cracking of 2024-T4 in an acid NaCl-$AlCl_3$



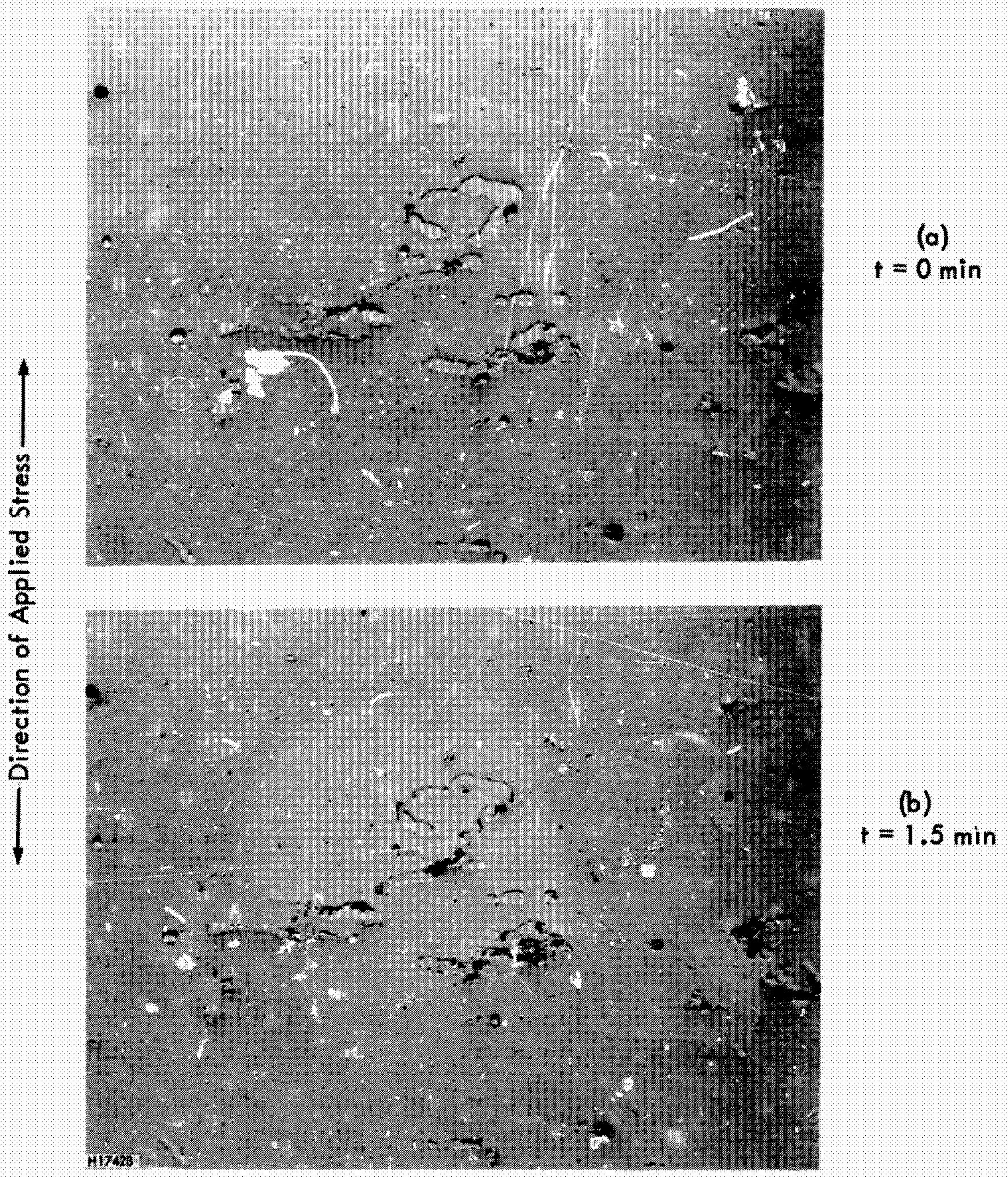
a.
t = 0 min

b.
t = 1.5 min

Replica 500X

Figure 19
INITIATION OF SHORT-TRANSVERSE STRESS-CORROSION CRACKING OF 7075-T651

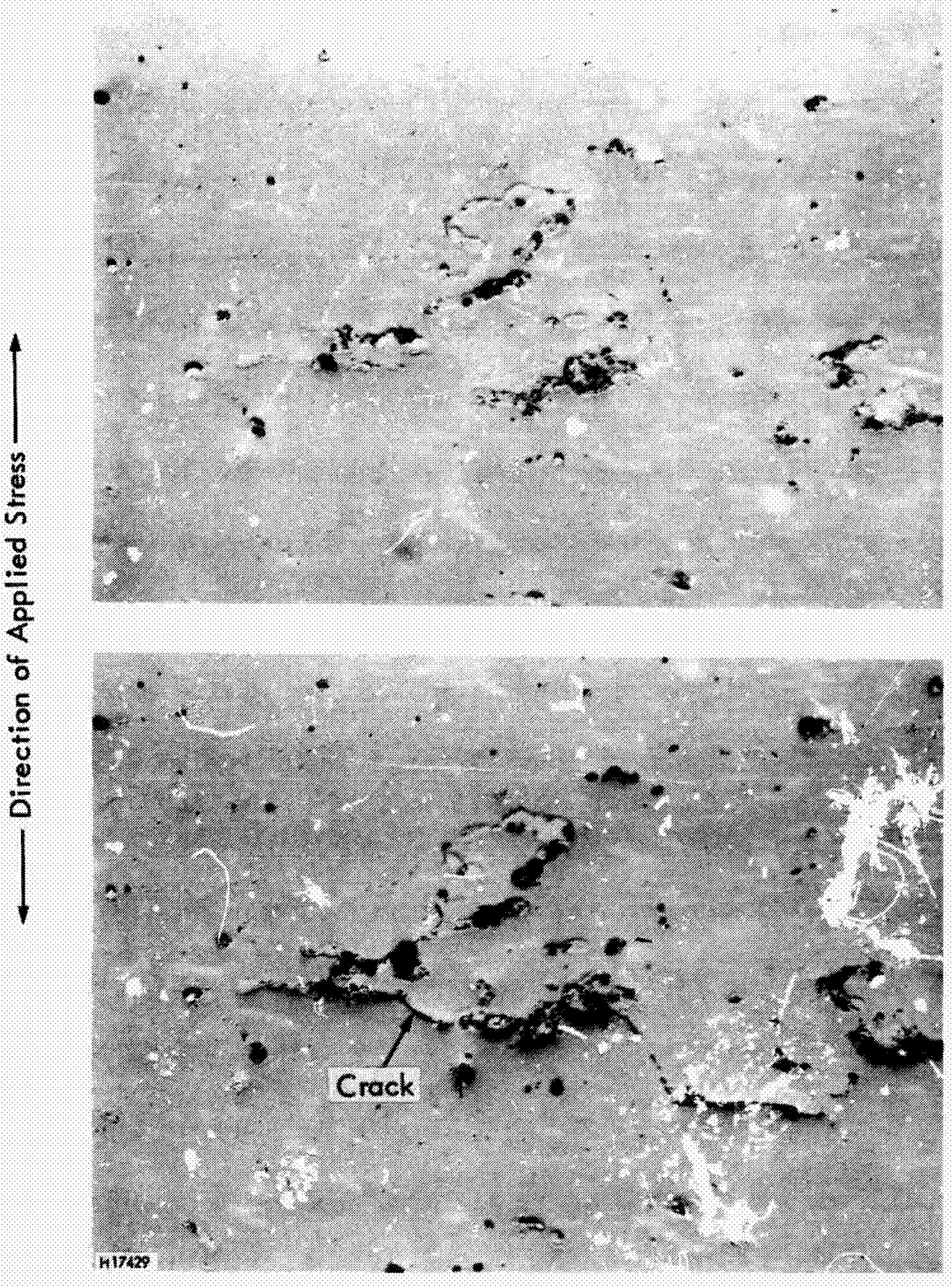
C-ring stressed at 35 ksi and exposed to a 0.3% NaCl - 3.6% CrO_3 - 3% $K_2Cr_2O_7$ solution at pH=0.5 and 30C for total elapsed times, t.



Replica 500X

Figure 20
INITIATION OF SHORT-TRANSVERSE STRESS-CORROSION CRACKING OF 2219-T37

C-ring stressed at 35 ksi and exposed to a 6% NaCl - 2% $K_2Cr_2O_7$ solution at pH=4 and 60C for total elapsed times, t. (Series of photomicrographs are continued on facing page.)



c.
t = 10 min

d.
t = 20 min

Replica 500X

solution would start at grain boundaries as well. It appears, therefore, that the propensity for selective grain boundary attack of these alloys in acid media dictates, in large measure, the mode of crack nucleation.

In this context, it would seem reasonable that crack nucleation might be quite different in media which are not so effective in initiating intergranular attack, eg, the salt-(di)chromate solutions at pH=4 and 60C. Figures 20 and 21 show that this is indeed the case. Figures 20(a), 20(b) and 20(c) (see pages 48 and 49) show the initial stages of corrosion of 2219-T37 in a 6% NaCl - 2% $K_2Cr_2O_7$ solution* at pH=4 and 60C before crack nucleation occurred. Interestingly, the corrosion attack was confined almost entirely to constituent particles; the attack becoming more intense with longer exposure. Finally (Figure 20d, page 49), a crack formed; but in this instance, cracking was associated with the constituent particles. Similarly, as shown in Figure 21, stress-corrosion cracking of 2024-T4 in the salt-(di)chromate solution also appeared to start at a constituent particle (Figure 21c) -- but only after an initial period of pre-corrosion of this same constituent (Figure 21b). Thus, at least for alloys 2024-T4 and 2219-T37, cracking occurred at constituents which were subject to electrochemical attack. The attack of constituent particles similarly preceded stress-corrosion cracking of 7039-T64 in a boiling 6% NaCl solution. However, in this instance, it appeared that the attack was more localized at constituent particle-matrix interfaces.

There remained for consideration comparative tests of alloys 7039-T64 and 7075-T651 in the salt-(di)chromate solutions. Time did not permit a thorough study, but preliminary results obtained with 7075-T6 deserve brief mention, since they relate

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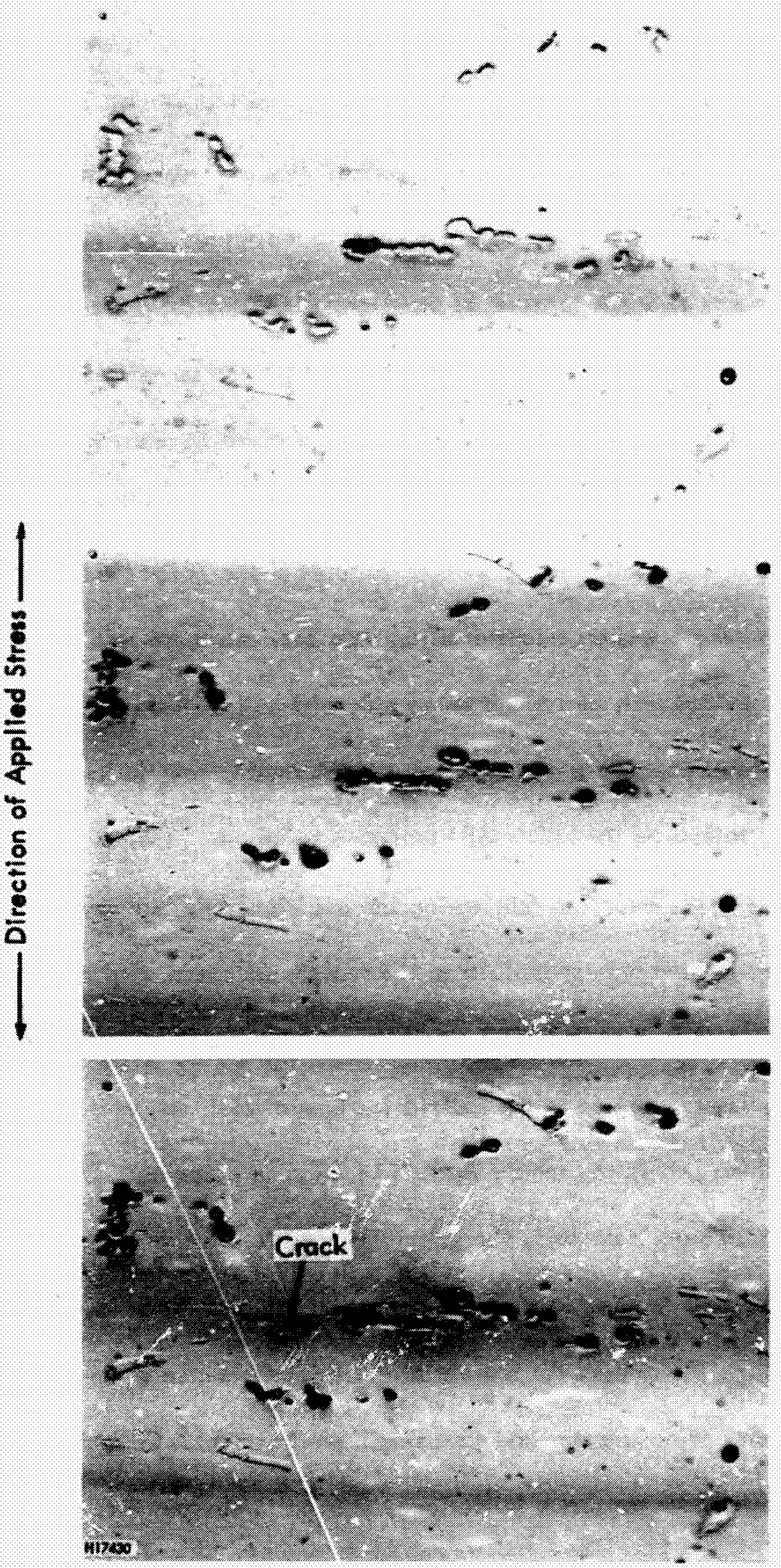
* The salt concentration of the salt-(di)chromate solution was increased to 6% NaCl merely to shorten the times required to initiate stress-corrosion cracking.



Replica 500X

Figure 21
INITIATION OF SHORT-TRANSVERSE STRESS-CORROSION CRACKING OF 2024-T4
C-ring stressed at 35 ksi and exposed to a 6% NaCl - 2% $K_2Cr_2O_7$ solution at pH=4 and 60C for total elapsed times, t.

to our discussion of accelerated stress-corrosion tests. As before, the C-rings received a metallographic polish and final electropolish to remove surface scratches. The polished specimens were then stressed at 45 ksi, replicated, and exposed to (a) a 1% NaCl - 2% $K_2Cr_2O_7$ solution at pH=4 and 60C, and (b) a 6% NaCl - 2% $K_2Cr_2O_7$ solution at pH=4 and 30C. Previous experience led us to believe that testing for one or two hours in either of these solutions would result in stress-corrosion cracking of the 7075. But, after two days' continuous immersion of duplicate specimens in these media, we discontinued testing with no failures of the 7075-T651.

Obviously, there was an essential difference between these tests of polished specimens and previous tests performed on caustic-etched specimens. In fact, when the unfailed polished specimens were etched and returned to salt-(di)chromate solution testing, failure of the 7075-T651 occurred in less than two hours. Considerable difficulty was experienced in replicating the caustic-etched specimens. At this point, therefore, we can only speculate on the reasons for these results. Since selective attack, either at grain boundaries or constituent particles, did not occur on the polished specimens exposed to the salt-(di)chromate solutions, quite possibly pre-corrosion by etching served the same purpose in initiating cracking. Once the initiation stage had been breached, the salt-(di)chromate solutions readily supported the corrosion processes leading to stress-corrosion cracking of 7075-T6. In this context, we can begin to see the reasons for the variations in performance of any alloy in different environments or of different alloys in a single environment. Given only a limited number of possible modes for crack initiation*, it is quite obvious that there would exist only a limited number of environments which would cause failure of any one alloy.

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* Surface-flawed or pre-cracked specimens excepted. Of course, it is possible that pre-corrosion (etching) produces surface defects which can be likened to cracks. A low toughness material such as 7075-T6 might, therefore, be expected to undergo stress-corrosion cracking in a wider range of environments than would have been predicted on the basis of tests of "smooth" specimens.

We might also expect that an even smaller number of environments would be capable of producing failures in all aluminum alloys -- as observed experimentally. Thus, in the development of accelerated stress-corrosion tests, some consideration must be given to crack initiation and the manner in which test environments influence crack initiation.

DISCUSSION

Interest in the development of accelerated stress-corrosion tests for aluminum alloys is not new. More than 20 years ago, alternate immersion, spraying, and continuous immersion in solutions of sodium chloride, sodium chloride-hydrogen peroxide, sodium chloride-sodium chromate, acidified salt-dichromate and even dilute sulfuric acid were advocated for use in accelerated tests of aluminum alloys (Ref 7). In recent years the number of tests has increased to the point where, today, there exist as many accelerated tests (Refs 2, 4, 8, 9, 10 & 11) or modifications of these same tests as there are aluminum alloys which are susceptible to stress-corrosion cracking.

This intense interest in the development of new tests shows that one major objective -- predicting the natural environment performance of aluminum alloys -- has yet to be achieved in a single test. Not even the 3.5% NaCl alternate immersion test, which has gained the widest acceptance for this purpose, is completely effective for all aluminum alloys. Failure of alloy 7039 occurred in outdoor exposures at stresses 5 to 15 ksi lower than that required for failure in 3.5% NaCl alternate immersion. Lifka and Sprowls (Ref 2) obtained the same result, not only for alloy 7039, but 7079-T6 as well; at low stresses, failures of these alloys were less likely to occur in alternate immersion than in atmospheric exposures.

We can offer only one reasonable explanation as to why the performance of 7079-T651 might differ from that of other Al-Zn-Mg-Cu alloys in alternate immersion: alloy 7079 contains less copper and, therefore, exhibits better corrosion resistance than such alloys as 7178 or 7075. At least for Al-Cu, Al-Cu-Mg and Al-Zn-Mg-Cu alloys in 3.5% NaCl alternate immersion, it would be impossible to exclude copper ions from the test solution. And, since dissolved copper accelerates the stress-corrosion cracking of these alloys (Refs 12, 13 & 14), it might be expected that general dissolution in an alternate immersion test would, by and large, determine their stress-corrosion behavior. This would explain why alternate immersion tests which promote greater general corrosion attack of copper-bearing alloys also appear to be more effective in causing stress-corrosion cracking of these same alloys (Ref 15). Since our 3.5% NaCl alternate immersion tests were more corrosive than those conducted by Lifka and Sprowls (Refs 2 & 15)*, it may not be too surprising that we experienced little difficulty in promoting failures of 7079-T651 at stresses as low as 10 ksi.

These same arguments cannot reasonably be expecred to explain the behavior of copper-free alloys, such as 7039, in alternate immersion tests and marine or industrial environments. On the other hand, some understanding of this behavior may be found in noting that 3.5% NaCl alternate immersion tests were not as effective as a marine environment which, in turn, was not as effective as an industrial environment in causing failures of 7039. Conversely, most copper-bearing alloys were just as likely, if not more prone, to fail in alternate immersion tests than in a marine environment; however, they were least likely to fail in an industrial environment. This reversal in the stress-corrosion behavior of these alloys indicates that while 3.5% NaCl alternate immersion tests may in some ways approximate the corrosive conditions of a marine environment, they bear little likeness to those existing in an industrial environment. Thus, the reason why the alternate immersion test was least effective in promoting failures of 7039 may be accounted for simply by the inherent differences between laboratory and natural environments.

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* Lifka and Sprowls 3.5% NaCl alternate immersion tests of 7079-T6 were conducted in solutions made up with New Kensington tap water (Ref 2). In general, these tests are far less corrosive than tests conducted in solutions made with distilled water.

This point also appears relevant in the case of accelerated tests performed in salt-(di)chromate solutions.

Results presented in the preceding sections showed that a 1% NaCl - 2% $K_2Cr_2O_7$ solution at pH=4 and 60C would not be suited to the task of predicting the natural environment stress-corrosion performance of alloys 7075-T651, 7079-T651 or 7039-T64. With due regard for the very marked differences between the chemistry of the salt-(di)chromate solution and that of natural environments, these results cannot be regarded as entirely unexpected. However, since there was virtually no general corrosion attack of these alloys in the salt-(di)chromate solution, it is also quite possible that this test was simply not aggressive enough. Our limited studies of the initiation of stress-corrosion cracking of 7075-T6 in salt-(di)chromate solutions lent some support to this hypothesis -- chemical etching was necessary for failure. And, since it appeared that the initiation of stress-corrosion cracking was in some way sensitivie to this etching or general corrosion attack at high levels of stress, it might be even more sensitive to general corrosion at stresses approaching the endurance or threshold stress.

Interestingly, the salt-(di)chromate solution test promoted rapid failures of susceptible tempers of 2024 and 2219 at the lowest stresses which caused failure in environmental exposures. Furthermore, it offered some improvement over 3.5% NaCl alternate immersion tests in promoting faster failures of 2014-T651 at low stresses. In this sense, the salt-(di)chromate solution test appears to be one of the most effective tests yet developed for these 2000 series alloys. Certainly, for the purpose of separating tempers of alloy 2219 on the basis of their relative susceptibilities to short-transverse stress-corrosion cracking, the salt-(di)chromate solution offers considerable improvement over the standard 3.5% NaCl alternate immersion test or the 3.5% NaCl - 0.7% CrO_3 - 1% $K_2Cr_2O_7$ alternate immersion test developed by Sprowls et al (Ref 11).

This latter test, which is simply a modification of the standard alternate immersion test, was shown to be useful for separating susceptible and resistant tempers of alloy 2219 in much the same order as did 3.5% NaCl alternate immersion. But, it also suffered from the inherent deficiency of 3.5% NaCl alternate immersion and most acid (pH=1) salt-(di)chromate solutions. It was too corrosive. It produced excessive general surface attack of the test specimens and increased the difficulty of determining the cause of failure. This was not a problem with tests conducted in the 1% NaCl - 2% $K_2Cr_2O_7$ solution at pH=4 and 60C. And yet, without being too corrosive, the salt-(di)chromate solution test appears to be equally, if not more, effective in separating borderline and resistant tempers of 2219 than either the standard 3.5% NaCl or the acidified salt-(di)chromate alternate immersion tests.

The salt-(di)chromate solution test also shows promise as a method for characterizing the short-transverse stress-corrosion performance of overaged tempers of 2024 and 7075. Again, the absence of general corrosion attack of the test specimens facilitated the separation of tempers representing borderline and maximum resistance to stress-corrosion cracking. The salt-(di)chromate solution tests of artificially aged 2024, which included the -T6 and -T851 tempers, were particularly interesting. In these tests, intergranular attack at sufficiently high stresses gradually changed to a random and superficial corrosion attack at lower levels of applied stress. It is generally recognized that intergranular corrosion of aluminum alloys is sensitive to stress, but these results tended to provoke the suggestion that general corrosion processes can be stress-activated as well (Ref 16).

Finally, because of the minimal general corrosion attack of aluminum alloys in the salt-(di)chromate solution, we feel certain that caustic etching of the specimens is necessary for reproducible response in this test. (See Appendix). The use of the etch does not complicate the test. In fact, it may reduce the variability associated with most stress-corrosion tests in assuring complete removal of oils, residual oxides and smeared metal introduced during the machining of the specimens.

STATUS

The investigation conducted under contract NAS8-20285 has been completed with the writing of this report. However, the atmospheric exposures initiated during the first year of effort will be continued. A supplemental letter report on the results of these tests will be submitted later.

REFERENCES

1. D. O. Sprowls and R. N. Brown, "What Every Engineer Should Know About Stress-Corrosion of Aluminum", *Metal Progress*, April, 1962, pp 79-85, May 1962, pp 77-84.

2. B. W. Lifka and D. O. Sprowls, "Stress Corrosion Testing of 7079-T6 Aluminum Alloy in Various Environments", ASTM STP 425, Stress Corrosion Testing, 1967, pp 342-359.

3. B. W. Lifka, W. King, M. B. Shumaker, R. A. Kelsey and D. G. Vandenburgh, "Investigation of the Stress Corrosion Cracking of High Strength Aluminum Alloys", NAS8-5340, Summary Report, August, 1965, p 25.

4. F. F. Booth and H. P. Godard, "An Anodic Stress Corrosion Test for Aluminum Magnesium Alloys", *First International Congress on Metallic Corrosion*, London, 1961, Butterworths & Co., Ltd, London, 1962, pp 703-704.

5. E. Lloyd Jones, "Stress Corrosion of Aluminum Magnesium Alloys - II, Methods of Expressing Stress Corrosion Susceptibility on a Comparative Basis", *J. Appl. Chem.*, Vol 4, January, 1954, pp 7-10.

6. M. S. Hunter, "Study of Crack Initiation Phenomena Associated with Stress Corrosion of Aluminum Alloys", NAS8-20396, First Annual Report, September, 1967.

7. G. F. Sager, R. H. Brown, and R. B. Mears, "Tests for Determining Susceptibility to Stress-Corrosion Cracking", ASTM-AIME Symposium on Stress Corrosion Cracking of Metals. 1944, pp 264-267.

8. H. L. Craig, Jr., and H. B. Romans, "A Rapid Stress Corrosion Test for Aluminum-Magnesium Alloys", ASTM STP 425, Stress Corrosion Testing, 1967, p 51.

9. H. Rosenthal and H. R. Pritchard, "A Quantitative Stress Corrosion Test for Al-Zn-Mg Alloy Plate", *ibid*, p 165.

10. M. K. Budd and F. F. Booth, "Structure-Corrosion Testing of Aluminum Alloys by Electrical Methods", Second International Congress on Metallic Corrosion, NACE, 1966, pp 44-53.

11. D. O. Sprowls, B. W. Lifka, D. G. Vandenburgh, R. L. Horst, M. B. Shumaker, "Investigation of the Stress-Corrosion Cracking of High Strength Aluminum Alloys", NAS8-5340, Final Report for the period May 6, 1963 - October 6, 1966, pp 3-20 and pp 43-50.

12. H. K. Farmery and U. R. Evans, "The Stress Corrosion of Certain Aluminum Alloys", J. Inst. Metals, Vol 84, 1956, p 413.

13. F. C. Althof and H. Spindler, "The Influence of Cations on Intercrystalline and Stress Corrosion of Aluminum Alloys", Z. Metallkunde, Vol 60, No. 10, 1959, pp 574-581.

14. W. Gruhl, "Influence of Corrosion Conditions on the Stress Corrosion Cracking Behavior of AlZnMg3 ", Metall, Vol 17, No. 3, 1963, pp 197-201.

15. Reference 11, pp 14-20, loc. cit.

16. W. J. Helfrich, "Influence of Stress and Temperature on Short-Transverse Stress-Corrosion Cracking of an Al-4.2% Zn-2.5% Mg Alloy", ASTM STP 425, Stress Corrosion Testing, 1967, pp 21-30.

TABLE I
CHEMICAL COMPOSITIONS, TENSILE PROPERTIES, AND CONDUCTIVITIES OF EXPERIMENTAL MATERIALS

		Chemical Composition, Weight Per Cent [1]									
Alloy	Lot No.	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Zr	V
2024	777021	0.16	0.26	4.44	0.60	1.48	0.03	0.15	0.02	--	--
2024	863642	0.14	0.31	4.50	0.64	1.55	0.03	0.15	0.03	--	--
2014	347131	1.0	0.48	4.23	0.80	0.63	0.05	0.17	0.04	--	--
2219	(2)	0.15	0.27	6.24	0.30	0.02	0.01	0.06	0.06	0.14	0.08
7075	830882	0.14	0.29	1.68	0.13	2.71	0.19	5.59	0.04	--	--
7079	331661	0.14	0.24	0.65	0.21	3.59	0.11	4.56	0.03	--	--
7039	742101	0.08	0.13	0.05	0.16	2.58	0.16	3.78	0.02	--	--
7039	363251	0.14	0.30	0.03	0.24	2.50	0.16	4.20	0.01	--	--
7039	105108	0.10	0.18	0.03	0.26	2.91	0.18	4.00	0.01	--	--

			Long Transverse [3]			Short Transverse [4]			
Alloy-Temper	Lot No.	Thick., in.	TS, ksi	YS, ksi	Elong, % in 2 in.	TS, ksi	YS, ksi	Elong, % in 1 in.	Conductivity, [5] % IACS
2024-T4	777021	2.00	66.6	45.4	15.8	56.4	42.8	3.0	30.2-30.8
-T6	"	"	69.8	64.0	7.5	63.2	61.6	1.0	38.9-40.2
-T351	863642	2.11	66.6	48.0	13.0	55.2	43.5	3.0	29.5-30.4
-T851	"	"	70.0	63.9	6.5	64.9	62.1	1.0	38.8-39.6
2219-T42	142081 [2]	2.50	50.6	22.4	24.8	48.4	21.6	12.0	28.5-29.0
-T62	"	"	61.0	41.4	11.2	58.6	43.2	5.0	33.1-33.7
-T351	142101 [2]	"	54.2	37.3	20.0	49.3	30.9	12.0	28.1-28.6
-T851	"	"	69.5	55.5	9.5	65.9	54.2	5.0	32.3-33.0
-T37	142091 [2]	"	57.3	43.4	15.0	52.0	37.7	8.0	28.3-28.7
-T87	"	"	71.7	60.0	9.5	66.8	57.9	4.0	31.9-32.4
2014-T651	347131	3.0	67.2	60.8	4.9	63.1	59.6	1.5	38.3-39.6

7079-T651	331661	2.75	80.5	72.3	9.6	73.6	66.6	2.0	-- --
7075-T651	830882	2.50	80.6	69.6	8.2	72.4	64.2	2.0	29.3-31.6
-T7351	"	"	69.7	56.8	9.5	62.3	53.8	2.0	39.4-39.7
7039-T64	742101	2.00	62.6	53.1	13.8	60.4	50.6	5.0	-- --
-T61	"	"	61.4	51.4	14.2	59.2	50.5	6.0	-- --
-T64	363251	1.00	66.1	57.5	13.0	--	--	--	-- --
-T6E132	105108	2.00	64.6	54.6	14.0	64.0	55.0	4.5	-- --

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[1] Obtained quantometrically on plate samples.

[2] All experimental lots taken from a single 2.5-inch gage 2219-F plate.

[3] Long-transverse tensile rounds, average of duplicate tests, 0.500-inch diameter, 4-D gage length, 1/4 T position.

[4] Short-transverse tensile rounds, average of duplicate tests, 0.250-inch diameter, 4-D gage length.

[5] Range of measurements taken on 3-inch centers over top and bottom surfaces of plate.

TABLE II
TENSILE PROPERTIES AND ELECTRICAL CONDUCTIVITIES OF 2024, 2219 AND 7075 AFTER ARTIFICIAL AGING

Alloy-Temper and	Long Transverse[1]			Conductivity,[2]
Aging Treatment	TS, ksi	YS, ksi	El, % in 2 in.	% IACS
2024-T4 (777021)	66.5	45.2	16.0	30.5
+ 4 hr at 375F	70.4	64.2	8.7	37.5
+ 8 hr at 375F	70.4	65.1	7.0	39.4
+ 12 hr at 375F	70.4	64.2	7.2	40.0
+ 16 hr at 375F	70.4	63.1	7.0	40.1
(-T6)				
2024-T351 (863642)	66.6	48.0	13.0	30.0
+ 4 hr at 375F	70.5	64.2	8.0	36.3
+ 8 hr at 375F	70.7	65.6	7.0	38.4
+ 12 hr at 375F	69.9	64.1	6.5	38.8
(-T851)				
2219-T42 (142081)	50.6	22.4	24.8	28.7
+ 6 hr at 375F	63.4	44.4	12.5	31.8
+ 12 hr at 375F	63.4	45.7	11.8	32.6
+ 24 hr at 375F	61.7	42.9	11.0	33.1
+ 36 hr at 375F	60.4	40.1	10.0	33.4
(-T62)				
2219-T351 (142101)	54.2	37.3	20.0	28.4
+ 4 hr at 350F	70.3	55.6	12.0	30.5
+ 8 hr at 350F	70.8	57.2	9.0	31.4
+ 12 hr at 350F	70.3	56.7	9.0	31.8
+ 18 hr at 350F	70.0	55.8	9.0	32.2
(-T851)				
2219-T37 (142091)	57.3	43.4	15.0	28.5
+ 6 hr at 325F	71.9	59.0	10.5	30.3
+ 12 hr at 325F	73.4	61.8	10.0	31.2
+ 18 hr at 325F	72.4	61.3	8.8	31.6
+ 24 hr at 325F	72.2	60.8	8.8	32.1
(-T87)				
7075-T651 (830882)	80.6	69.6	8.2	30.6
+ 2 hr at 350F	77.6	66.7	9.5	35.9
+ 4 hr at 350F	76.0	65.0	10.0	37.3
+ 6 hr at 350F	74.6	63.2	10.0	38.0
+ 8 hr at 350F	73.0	61.0	10.0	38.6
+ 10 hr at 350F	72.1	60.0	10.0	38.7
(-T7351)				

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[1] Avg of duplicate long-transverse tensiles, 0.500-in. diameter, 4-D gage length, 1/4 T position.

[2] Avg of measurements taken on 3-inch centers over top and bottom surfaces of the plate.

TABLE III

STRESS-CORROSION PERFORMANCE OF 2024, 2219, 7075 AND 7039 IN THE MARINE ATMOSPHERE OF DAYTONA BEACH, FLORIDA

(0.948-inch short-transverse C-rings, etched 30 sec in 5% NaOH at 170F, desmutted in cold conc HNO_3.)

Alloy-Temper (Lot No.)	Applied Stress, ksi	F/N[1]	Days to Failure [2]
2024-T4 (777021)	40	5/5	2(5)
"	30	5/5	2,5(2),13(2)
"	20	5/5	2(2), 5, 8, 13
"	15	5/5	2, 14(2), 450(2)
"	10	4/5	14, 450(3)
"	5	0/5	NF 450
2024-T351 (863642)	40	5/5	2(5)
"	30	5/5	2(3), 5(2)
"	20	5/5	5(3), 12(2)
"	15	5/5	14(2), 16(2), 450
"	10	5/5	14, 33, 200, 450(2)
"	5	0/5	NF 450
2219-T42 (142081)	20	5/5	2(2), 8(2), 15
"	15	5/5	2(2), 21, 450(2)
"	10	5/5	8, 16, 450(3)
"	5	0/5	NF 450
2219-T351 (142101)	30	5/5	2(2), 8, 13(2)
"	20	1/5	28
"	15	3/5	450(3)
"	10	0/5	NF 450
"	5	0/5	NF 450
2219-T37 (142091)	35	4/5	2(3), 13
"	30	4/5	2(4)
"	20	2/5	16, 450
"	15	5/5	450(5)
"	10	2/5	450(2)
"	5	0/5	NF 450
7075-T651 (830882)	50	5/5	2(5)
"	40	5/5	2(5)
"	30	5/5	2(5)
"	20	5/5	2(5)
"	15	5/5	2(5)
"	10	5/5	7, 13, 14(3)
"	5	0/5	NF 450

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[1] F/N = Number of failures/number of specimens tested.

[2] Time to failure (number of specimens failed). Tests initiated 5 Oct 1966. Specimens in

TABLE III (CONT'D)

Alloy-Temper (Lot No.)	Applied Stress, ksi	F/N[1]	Days to Failure[2]
7039-T64 (363251)	40	5/5	1(4), 2
"	30	5/5	1(4), 2
"	20	5/5	2, 5, 7, 13, 33
"	15	5/5	1, 21, 42, 44, 103
"	10	5/5	2, 35, 40, 124, 159
"	5	5/5	208, 222, 258, 313, 348
7039-T64 (742101)	40	5/5	2(5)
"	30	5/5	2(3), 7(2)
"	20	5/5	2, 13, 56(2), 58
"	15	5/5	90(2), 96, 194(2)
"	10	5/5	244, 251, 271, 293, 450
"	5	2/5	450(2)
7039-T61 (742101)	40	5/5	2(4), 7
"	30	5/5	2, 7(2), 8, 9
"	20	5/5	2(2), 69, 159, 271
"	15	5/5	271, 313, 350, 383(2)
"	10	3/5	313, 450(2)
"	5	0/5	NF 450
7039-T6E132 (105108)	40	5/5	2, 7, 8(3)
"	30	5/5	8, 12, 19, 26, 44
"	20	5/5	159, 194, 208, 222, 258
"	15	4/5	258, 293(3)
"	10	2/5	450(2)
"	5	0/5	NF 450

---

[1] F/N = Number of failures/number of specimens tested.

[2] Time to failure (number of specimens failed). Tests initiated 5 October 1966. Specimens in test 450 days as of 29 December 1967.
NF = No failure in test period.

TABLE IV
STRESS-CORROSION PERFORMANCE OF 2024, 2219, 7075 AND 7039 IN THE INDUSTRIAL ATMOSPHERE OF PITTSBURGH, PA.

(0.948-inch short-transverse C-rings, etched 30 sec in 5% NaOH at 170F, desmutted in cold conc HNO_3.)

Alloy-Temper (Lot No.)	Applied Stress, ksi	F/N[1]	Days to Failure[2]
2024-T4 (777021)	40	5/5	505(5)
"	30	3/5	505(3)
"	20	2/5	505(2)
"	15	1/5	505
"	10	0/5	NF 505
"	5	0/5	NF 505
2024-T351 (863642)	40	5/5	505(5)
"	30	5/5	505(5)
"	20	3/5	505(3)
"	15	1/5	505(1)
"	10	0/5	NF 505
"	5	0/5	NF 505
2219-T42 (142081)	20	1/5	505
"	15	0/5	NF 505
"	10	0/5	NF 505
"	5	0/5	NF 505
2219-T351 (142101)	30	3/5	505(3)
"	20	0/4 (a)	NF 505
"	15	0/5	NF 505
"	10	0/5	NF 505
"	5	0/5	NF 505
2219-T37 (142091)	35	3/5	260(2), 505
"	30	3/5	505(3)
"	20	1/5	505(1)
"	15	0/5	NF 505
"	10	0/5	NF 505
"	5	0/5	NF 505

---

[1] F/N = Number of failures/number of specimens tested.

(a) One specimen of this variable was lost during testing.

[2] Time to failure (number of specimens failed). Tests initiated 13 October 1966. Specimens in test 505 days as of 1 March 1968.
NF = No failures in test period.

TABLE IV (CONT'D)

Alloy-Temper (Lot No.)	Applied Stress, ksi	F/N[1]	Days to Failure[2]
7075-T651 (830882)	50	5/5	92(3), 119(2)
"	40	5/5	92(2), 119(3)
"	30	5/5	92(2), 119, 260(2)
"	20	5/5	119(2), 260, 505(2)
"	15	4/5	505(4)
"	10	2/5	505(2)
"	5	0/5	NF 505
7039-T64 (363251)	40	5/5	14(3), 21(2)
"	30	5/5	14, 21, 43(3)
"	20	5/5	21, 43, 86(2), 92
"	15	5/5	43, 86(2), 92(2)
"	10	5/5	21, 92, 119(2), 260
"	5	4/5	260(4)
7039-T64 (742101)	40	5/5	14(2), 21(2), 43
"	30	5/5	86(4), 92
"	20	5/5	86, 92(4)
"	15	5/5	119(4), 260
"	10	5/5	260(5)
"	5	5/5	368(3), 505(2)
7039-T61 (742101)	40	5/5	14, 86(3), 92
"	30	5/5	21, 86(3), 92
"	20	5/5	86, 92, 119, 260(2)
"	15	5/5	260(5)
"	10	5/5	260(5)
"	5	4/4 (a)	260(2), 328, 368
7039-T6E132 (105108)	40	5/5	43(5)
"	30	5/5	86(4), 92
"	20	5/5	86(5)
"	15	5/5	86(2), 119, 260(2)
"	10	5/5	260(5)
"	5	4/4 (a)	368(2), 505 (2)

---

[1] F/N = Number of failures/number of specimens tested.

(a) One specimen of this variable was lost during testing.

[2] Time to failure (number of specimens failed). Tests initiated 13 October 1966. Specimens in test 505 days as of 1 March 1968.
NF = No failures in test period.

TABLE V

STRESS-CORROSION PERFORMANCE OF 2024, 2219, 2014, 7075, 7079 AND 7039 C-RINGS -- 3.5% NaCl ALTERNATE IMMERSION

(0.948-inch short-transverse C-rings, etched 30 sec in 5% NaOH at 170F, desmutted in cold conc HNO_3.)

Alloy-Temper (Lot No.)	Applied Stress, ksi	F/N[1]	Days to Failure[2]
2024-T351 (863642)	40	9/9	< 1(9)
"	30	9/9	< 1(9)
"	20	9/9	< 1(9)
"	15	9/9	1, 2(2), 3(2), 4(3), 30
"	10	7/9	4(2), 5, 6, 90(3)
"	5	0/9	NF 90
2024-T851 (863642)	50	7/9	4(3), 6, 90(3)
"	45	3/9	1, 5, 60
"	40	3/9	5(2), 60
"	35	0/9	NF 90
"	30	0/9	NF 90
2024-T4 (777021)	40	9/9	< 1(9)
"	30	9/9	< 1(9)
"	20	9/9	< 1(6), 1.5(2), 2
"	15	6/9	2(2), 3, 90(3)
"	10	3/9	90(3)
"	5	0/9	NF 90
2024-T6 (777021)	50	9/9	2, 3(4), 4(2), 60(2)
"	45	7/9	1, 3, 4(3), 60(2)
"	40	2/9	7(2)
"	35	0/9	NF 90
"	30	0/9	NF 90
2219-T42 (142081)	20	5/5	1.5, 2, 6(3)
"	15	5/5	6, 12(3), 14
"	10	5/5	15(5)
"	5	0/5	NF 30
2219-T62 (142081)	35	0/5	NF 30
"	30	0/5	NF 30
"	25	0/5	NF 30

---

[1] F/N = Number of failures/number of specimens tested.

[2] Time to failure (number of specimens failed). NF = No failure in the test period.

TABLE V (CONT'D)

Alloy-Temper (Lot No.)	Applied Stress, ksi	F/N[1]	Days to Failure[2]
2219-T351 (142101)	30	5/5	< 1(5)
"	20	5/5	< 1, 1, 2, 3(2)
"	15	5/5	2, 12(2), 15, 20
"	10	5/5	15, 23, 30(3)
"	5	0/5	NF 30
2219-T851 (142101)	50	1/5	30
"	45	0/5	NF 30
"	40	0/5	NF 30
"	35	0/5	NF 30
2219-T37 (142091)	35	5/5	< 1(5)
"	30	5/5	< 1(3), 2, 6
"	20	5/5	< 1(3), 15, 20
"	15	5/5	1, 3, 15(3)
"	10	5/5	15, 30(4)
"	5	0/5	NF 30
2219-T87 (142091)	55	3/5	30(3)
"	50	2/5	30(2)
"	45	2/5	30(2)
"	40	0/5	NF 30
2014-T651 (347131)	30	5/5	3, 30(4)
"	20	3/5	30(3)
"	15	0/5	NF 30
"	10	0/5	NF 30
"	5	0/5	NF 30
7075-T651 (830882)	50	9/9	1 hr(9)
"	40	9/9	1 hr(9)
"	30	9/9	1-2 hr(9)
"	20	9/9	1 hr(5), 2 hr, 10 hr(3)
"	15	9/9	5 hr(3), 6 hr, 10 hr(4); 4d
"	10	9/9	1, 14, 30, 32, 40(2), 60, 90(2)d
"	5	0/9	NF 90d
7075-T7351 (830882)	50	3/9	90(3)
"	45	0/9	NF 90
"	40	0/9	NF 90
"	35	0/9	NF 90
"	30	0/9	NF 90

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[1] F/N = Number of failures/number of specimens tested.

[2] Time to failure (number of specimens failed). NF = No failure in the test period.

TABLE V (CONT'D)

Alloy-Temper (Lot No.)	Applied Stress, ksi	F/N[1]	Days to Failure[2]
7079-T651 (331661)	30	5/5	<1(2), 1, 3, 8
"	20	5/5	4, 5(2), 9, 13
"	15	5/5	17(2), 28(3)
"	10	4/5	90(4)
"	5	0/5	NF 90
7039-T64 (363251)	40	9/9	1, 2, 5(2), 6, 7(3), 9
"	30	9/9	8, 9(3), 11(2), 14(2), 21
"	20	9/9	13, 18, 21(2), 24, 45, 79, 85, 133
"	15	6/9	18, 50, 91, 94, 121, 231
"	10	1/9	211
"	5	0/9	NF 365
7039-T64 (742101)	40	9/9	9, 23, 33(4), 35, 40, 74
"	30	8/9	48, 50, 54, 61, 82, 84, 103, 287
"	20	5/9	48, 54, 128, 188, 334
"	15	1/9	68
"	10	1/9	194
"	5	0/9	NF 365
7039-T61 (742101)	40	9/9	22, 29, 41, 42, 48, 63, 82(2), 84
"	30	6/9	48, 97(2), 121, 314(2)
"	20	0/9	NF 365
"	15	0/9	NF 365
"	10	0.9	NF 365
"	5	0/9	NF 365
7039-T6E132 (105108)	40	9/9	19,22,27,33,36,42,48,57,74
"	30	9/9	36,48,82,89,121(2),138,153,250
"	20	3/9	275, 314, 334
"	15	0/9	NF 365
"	10	0/9	NF 365
"	5	0/9	NF 365

---

[1] F/N = Number of failures/number of specimens tested.

[2] Time to failure (number of specimens failed). NF = No failure in the test period.

TABLE VI

STRESS-CORROSION PERFORMANCE OF 2024, 2219 AND 7075 GIVEN VARIOUS AGING TREATMENTS -- C-RINGS IN 1% NaCl-2% $K_2Cr_2O_7$ SOLUTION AND 3.5% NaCl ALTERNATE IMMERSION

(0.948-inch short-transverse C-rings etched 30 sec in 5% NaOH at 170F, desmutted in cold concentrated HNO_3.)

Alloy-Temper (Lot No.)	TS/YS[1]	Applied Stress, ksi	30 Days' Alternate Immersion in 3.5% NaCl Solution at 24C (75F)		7 Days' Continuous Immersion in 1% NaCl-2% $K_2Cr_2O_7$ Solution at pH=4 and 60C (140F)	
			F/N[2]	Time to Failure[3]	F/N[2]	Time to Failure[3]
2024-T4 (777021)	66/45	35	3/3	16(3) hr	3/3	1(3) hr
+ 4 hr at 375F	70/64	40	3/3	16(3) hr	3/3	2(3) hr
+ 8 hr at 375F	70/65	40	0/3	(a)	0/3	(b)
+ 12 hr at 375F	70/64	40	0/3	(a)	0/3	(b)
+ 16 hr at 375F (-T6)	70/63	40	0/3	(a)	0/3	(b)
2024-T4 (777021)	66/45	30			3/3	1(3) hr
+ 4 hr at 375F	70/64	30			3/3	1, 3(2) hr
+ 8 hr at 375F	70/65	30			0/3	NF
+ 12 hr at 375F	70/64	30			0/3	NF
+ 16 hr at 375F (-T6)	70/63	30			0/3	NF
2024-T351 (863642)	67/48	35	3/3	16(3) hr	3/3	1(3) hr
+ 4 hr at 375F	70/64	40	3/3	16(3) hr	3/3	2(3) hr
+ 8 hr at 375F	71/66	40	0/3	(a)	0/3	(b)
+ 12 hr at 375F (-T851)	70/64	40	0/3	(a)	0/3	(b)
2024-T351 (863642)	67/48	30			3/3	1(3) hr
+ 4 hr at 375F	70/64	30			3/3	3, 18(2) hr
+ 8 hr at 375F	71/66	30			0/3	NF
+ 12 hr at 375F (-T851)	70/64	30			0/3	NF
2219-T42 (142081)	51/22	20	3/3	1(2), 3d	3/3	2(3) hr
+ 6 hr at 375F	63/44	35	3/3	1(3) d	3/3	17([illegible]
+ 12 hr at 375F	63/46	35	0/3	(a)	3/3	2(3[illegible]
+ 24 hr at 375F	62/43	35	0/3	NF	0/3	NF
+36 hr at 375F (-T62)	60/40	35	0/3	NF	0/3	NF

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[1] Tensile strength/Yield strength, ksi. Average of duplicate long-transverse tensiles, 0.500-inch diameter, 4-D gage length, 1/4 T position.

[2] Number of Failures/Number of Specimens Tested.

[3] Time to failure (number of specimens failed). NF = No failure.

(a) Intergranular attack detected metallographically.

(b) Visual evidence of intergranular attack. Specimens fractured in slow bending.

TABLE V[illegible] (CONT'D)

Alloy-Temper (Lot No.)	TS/YS[1]	Applied Stress, ksi	30 Days' Alternate Immersion in 3.5% NaCl Solution at 24C (75F)		7 Days' Continuous Immersion in 1% NaCl-2% $K_2Cr_2O_7$ Solution at pH=4 and 60C (140F)	
			F/N[2]	Time to Failure[3]	F/N[2]	Time to Failure[3]
2219-T351 (142101)	54/37	30	3/3	18(3) hr	3/3	2(3) hr
+ 4 hr at 350F	70/56	40	3/3	22(3) hr	3/3	17(3) hr
+ 8 hr at 350F	71/57	40	0/3	NF	3/3	1, 2(2) d
+ 12 hr at 350F	70/57	40	0/3	NF	0/3	NF
+ 18 hr at 350F (-T851)	70/56	40	0/3	NF	0/3	NF
2219-T37 (142091)	57/43	35	3/3	14(3) hr	3/3	2(3) hr
+ 6 hr at 325F	72/59	45	3/3	22(3) hr	3/3	17(3) hr
+ 12 hr at 325F	73/62	45	0/3	NF	3/3	1, 2(2) d
+ 18 hr at 325F	72/61	45	0/3	NF	0/3	NF
+24 hr at 325F (-T87)	72/61	45	0/3	NF	0/3	NF
7075-T651 (830882)	81/70	45	3/3	7(3) hr	3/3	2(3) hr
+ 2 hr at 350F	78/67	45	3/3	17(3) hr	3/3	4(2), 5 hr
+ 4 hr at 350F	76/65	45	0/3	(a)	3/3	2, 3, 7d
+ 6 hr at 350F	75/63	45	0/3	NF	0/3	NF
+ 8 hr at 350F	73/61	45	0/3	NF	0/3	NF
+ 10 hr at 350F (-T7351)	72/60	45	0/3	NF	0/3	NF

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[1] Tensile strength/Yield strength, ksi. Average of duplicate long-transverse tensile, 0.500-inch diameter, 4-D gage length, 1/4 T position.

[2] Number of Failures/Number of Specimens Tested.

[3] Time to failure (number of specimens failed). NF = No failure.

(a) Intergranular attack detected metallographically.

TABLE VII

STRESS-CORROSION PERFORMANCE OF 2024, 2219, 2014, 7079, 7075 AND 7039 TENSILE ROUNDS -- 3.5% NaCl ALTERNATE IMMERSION

($\frac{1}{8}$-inch diameter short-transverse tensile specimens, etched 30 seconds in 5% NaOH at 170F, desmutted in concentrated HNO_3.)

Alloy-Temper (Lot No.)	Applied Stress, ksi	F/N[1]	Days to Failure[1]	Tensile Strength[2], ksi			% Loss in Tensile Strength[3]	
				Stressed	Unstressed	Nominal	Stressed	Unstressed
2024-T6	45	2/2	9, 12	0, 0	44, 45	66	(31), (31)	33, 31
(777021)	40	1/2	20, NF 30	0, 29	41, 41		(39), 56	37, 37
	35	1/2	28, NF 30	0, 44	36, 41		(47), 33	45, 37
	30	0/2	NF 30	40, 45	41, 41		39, 31	37, 37
2024-T851	45	0/2	NF 30	54, 58	36, 39	65	17, 10	45, 40
(863642)	40	0/2	NF 30	53, 57			18, 12	
	35	0/2	NF 30	38, 46			41, 29	
	30	0/2	NF 30	41, 43			37, 34	
19-T62	35	0/2	NF 30	37, 41	33, 34	59	37, 30	44, 42
2081)	30	0/2	NF 30	40, 47			32, 20	
	25	0/2	NF 30	44, 47			25, 20	
2219-T851	45	0/2	NF 30	28, 31	30, 35	66	58, 53	56, 44
(142101)	40	0/2	NF 30	33, 37			50, 44	
	35	0/2	NF 30	42, 45			36, 32	
	30	0/2	NF 30	49, 49			26, 26	
2219-T87	50	0/2	NF 30	55, 55	34, 36	67	18, 18	50, 47
(142091)	45	0/2	NF 30	46, 53			31, 21	
	40	0/2	NF 30	40, 44			40, 34	
	35	0/2	NF 30	42, 45			37, 33	
2014-T651	30	2/2	2, 28	0, 0	58, 34	63.1	(52), (52)	8, 46
(347131)	20	0/2	NF 30	17, 38	32, 36		73, 40	49, 43
	15	0/2	NF 30	40, 41			37, 35	
	10	0/2	NF 30	40, 41			37, 35	
	5	0/2	NF 30	40, 41			37, 35	

7075-T7351 (830882)	50	0/2	NF 60	32,33	43,44,48,48	66	52, 50	35,33,27,27
	45	0/2	NF 60	37, 46			44, 30	
	40	0/2	NF 60	30, 36			55, 46	
	35	0/2	NF 60	34, 35			49, 47	
7079-T651 (331661)	30	2/2	1, 1	0, 41	69, 72	74	59, 45	7, 3
	20	2/2	4, 13	26, 0	71, 69		65, 73	4, 7
	15	2/2	21, 22	0, 0	67, 64		80, 80	9, 14
	10	2/2	51, 71	0, 0	61, 61		86, 86	18, 18
	5	0/2	NF 90	56, 59	56, 57		24, 20	24, 23
7039-T64 (742101)	40	2/2	96, 180	0, 0	54, 52	59	(32), (32)	8, 12
	30	2/2	134, 243	0, 0	56, 55		(49), (49)	5, 7
	20	0/2	NF 300	48, 53	52, 54		19, 10	12, 8
	15	2/2	251, 277	0, 0	53, 53		(75), (75)	10, 10
	10	1/2	243	0, 52	55, 54		(83), 12	7, 8
7039-T61 (742101)	30	2/2	300, 300*	0, 0	50, 51	59	(49), (49)	15, 14
	20	1/2	300*	0, 50	54, 54		(67), 15	8, 8
	15	0/2	NF 300	53, 54	55, 55		10, 8	7, 7
	10	0/2	NF 300	53, 55	56, 56		10, 7	5, 5
7039-T6E132 (105108)	30	2/2	270, 300*	21, 0	54, 53	64	67, (53)	16, 17
	20	1/2	300*	0, 54	53, 54		(69), 16	17, 16
	15	1/2	300*	0, 53	55, 55		(77), 17	14, 14
	10	0/2	NF 300	54, 55	56, 56		16, 14	12, 12

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[1] F/N = Number of Failures/Number of Specimens Tested. NF = No failures during the test period. Failures defined as (a) cracking observed at a magnification of 15X, or (b) complete separation of the specimen.

[2] Short-transverse tensile strengths determined on (a) stressed and corroded specimens, (b) unstressed and corroded specimens, and (c) duplicate specimens not tested by alternate immersion (nominal).

[3] Parenthetic values calculated on the assumption that the load applied during the corrosion test corresponded to the tensile breaking load.

* Specimen broke when removed from the stressing frame.

TABLE VIII

STRESS-CORROSION PERFORMANCE OF 2024, 2219 AND 7075 TENSILE ROUNDS GIVEN VARIOUS AGING TREATMENTS -- 3.5% NaCl ALTERNATE IMMERSION

($\frac{1}{8}$-inch diameter short-transverse tensile specimens etched 30 sec in 5% NaOH at 170F, desmutted in cold concentrated HNO_3.)

Alloy and Aging Treatment	TS/YS[1]	Applied Stress, ksi	F/N[2]	Days to Failure[2]	Tensile Strength, ksi[3] Stressed	Unstressed	Nominal	% Loss in Tensile Strength[4] Stressed	Unstressed
2024-T4 (777021)	66/45	35	2/2	1, 1	17, 19	52,53	55	69, 65	5, 4
+ 4 hr at 375F	70/64	40	2/2	1, 1	43, 52	59, 61	64	33, 19	8, 5
+ 8 hr at 375F	70/65	40	2/2	2, 2	54, 47	57, 60	64	16, 27	11, 6
+ 12 hr at 375F	70/64	40	2/2	15, 15	0, 0	55, 58	65	(38), (38)	15, 11
+ 16 hr at 375F (-T6)	70/63	40	2/2	8, 30	0, 0	58, 52	63	(36), (36)	8, 17
2024-T351 (863642)	67/48	35	2/2	1, 1	0, 8.5	53, 55	56	(38), 85	5, 2
+ 4 hr at 375F	70/64	40	2/2	1, 1	0, 38	62, 63	66	(39), 42	6, 5
+ 8 hr at 375F	71/66	40	1/2	1, NF30	0, 54	59, 52	66	(39), 18	11, 21
+ 12 hr at 375F (-T851)	70/64	40	2/2	20, 22	0, 0	58, 55	66	(39), (39)	12, 17
2219-T42 (142081)	51/22	20	2/2	2, 2	4.3, 19	39, 42	48	91, 60	19, 12
+ 6 hr at 375F	63/44	35	2/2	1, 1	2.3, 11	53, 54	59	96, 81	10, 8
+ 12 hr at 375F	63/46	35	2/2	1, 1	0, 44	58, 58	58	(40), 24	0, 0
+ 24 hr at 375F	62/43	35	0/2	NF30	25, 32	42, 45	59	58, 46	29, 24
+ 36 hr at 375F (-T62)	60/40	35	0/2	NF30	38, 39	39, 47	59	36, 34	34, 20
2219-T351 (142101)	54/37	30	2/2	1, 1	24, 26	47, 47	51	53, 49	8, 8
+ 4 hr at 350F	70/56	40	2/2	1, 1	0, 36	62, 62	61	(34), 41	0, 0
+ 8 hr at 350F	71/57	40	2/2	19, 21	0, 0	54, 52	63	(36), (36)	14, 17
+ 12 hr at 350F	70/57	40	0/2	NF30	30, 36	53, 53	62	52, 42	15, 15
+ 18 hr at 350F (-T851)	70/56	40	0/2	NF30	30, 42	51, 51	64	53, 34	20, 20
2219-T37 (142091)	57/43	35	2/2	1, 1	0, 20	50, 52	54	(35), 63	7, 4
+ 6 hr at 325F	72/59	45	2/2	1, 1	42, 44	62, 62	63	33, 30	2, 2
+ 12 hr at 325F	73/62	45	1/2	21, NF30	0, 36	58, 52	65	(31), 45	11, 20
+ 18 hr at 325F	72/61	45	1/2	30, NF30	0, 33	52, 56	65	(31), 49	20, 14
+ 24 hr at 325F (-T87)	72/61	45	2/2	30, 30*	0, 0	55, 56	65	(31), (31)	15, 14

7075-T651 (930882)	81/70	45	2/2	2, 2(hr)	0, 0	73, 74	73	(38), (38)	0, 0
+ 2 hr at 350F	78/67	45	2/2	1, 1	0, 41	67, 67	71	(37), 42	6, 6
+ 4 hr at 350F	76/65	45	2/2	20, 30	0, 0	58, 54	70	(36), (36)	17, 23
+ 6 hr at 350F	75/63	45	0/2	NF 30	36, 43	53, 56	68	47, 37	22, 18
+ 8 hr at 350F	73/61	45	0/2	NF 30	44, 46	51, 52	66	33, 30	23, 21
+ 10 hr at 350F (-T7351)	72/60	45	0/2	NF 30	39, 39	52, 56	66	41, 41	21, 15

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[1] Tensile strength/Yield strength, ksi. Average of duplicate long-transverse tensiles, 0.500-inch diameter, 4-D gage length, 1/4 T position.

[2] Number of Failures/Number of Specimens Tested. Failures defined as (a) cracking observed at a magnification of 15X, or (b) complete separation of the specimen. FN = No failure in the test period.

[3] Short-transverse tensile strengths determined on (a) stressed and corroded specimens, (b) unstressed and corroded specimens, and (c) average of duplicate specimens not tested by alternate immersion (nominal).

[4] Parenthetic values calculated on the assumption that the load applied during the corrosion test corresponded to the tensile breaking load.

TABLE IX

STRESS-CORROSION PERFORMANCE OF 2024, 2014, 2219, 7075, 7079 AND 7039 IN A 1% NaCl-2% $K_2Cr_2O_7$ SOLUTION AT pH=4 AND 60C

(0.948-inch short-transverse C-rings etched 30 sec in 5% NaOH at 170F, desmutted in conc HNO_3.)

Alloy-Temper (Lot No.)	Applied Stress, ksi	F/N[1]	Time to Failure[2]
2024-T4 (777021)	35	3/3	30(3) min
	20	3/3	60(2), 90 min
	10	2/3	20(2) hr
	5	0/3	NF 7 d
2024-T6 (777021)	50	2/3	2, 7 d
	40	0/3	NF 7 d
	30	0/3	NF 7 d
	20	0/3	NF 7 d
2024-T351 (863642)	20	3/3	60(2), 90 min
	10	1/3	20 hr
	5	0/3	NF 7 d
2024-T851 (863642)	50	2/3	1, 2 d
	40	0/3	NF 7 d
	30	0/3	NF 7 d
	20	0/3	NF 7 d
2014-T651 (347131)	30	3/3	1(3) d
	20	3/3	1, 3(2) d
	10	0/3	NF 7 d
2219-T42 (142081)	20	3/3	90(3) min
	10	2/3	90(2) min
	5	0/3	NF 7 d
2219-T62 (142081)	35	0/3	NF 7 d
2219-T351 (142101)	30	3/3	90(3) min
	20	3/3	90(3) min
	10	2/3	17 hr, 7 d
	5	0/3	NF 7 d
2219-T851 (142101)	50	0/3	NF 7 d
	40	0/3	NF 7 d

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[1] F/N = Number of Failures/Number of Specimens Tested.

[2] Time to failure (number of specimens failed). NF = No failures in test period.

TABLE IX (CONT'D)

Alloy-Temper (Lot No.)	Applied Stress, ksi	F/N[1]	Time to Failure[2]
2219-T37 (142091)	30	3/3	90(3) min
	20	3/3	90(3) min
	10	2/3	17(2) hr
	5	0/3	NF 7 d
2219-T87 (142091)	50	0/3	NF 7 d
	40	0/3	NF 7 d
7075-T651 (830882)	30	3/3	1(3) hr
	20	2/3	2, 3(2) hr
	10	0/3	NF 7 d
	5	0/3	NF 7 d
7075-T7351 (830882)	50	0/3	NF 19 d
	40	0/3	NF 19 d
7079-T651 (331661)	30	3/3	1, 8, 11 d
	20	1/3	4 d
	10	0/3	NF 15 d
7039-T64 (363251)	40	3/3	2, 3(2) hr
	20	2/3	1, 7 d
	10	1/3	17 d
	5	0/3	NF 21 d
7039-T64 (742101)	40	3/3	8(2), 19 hr
	25	2/3	1, 3 d
	15	2/3	7, 10 d
	10	0/3	NF 21 d

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[1] F/N = Number of Failures/Number of Specimens Tested.

[2] Time to failure (number of specimens failed). NF = No failures in test period.

TABLE X

STRESS-CORROSION PERFORMANCE OF 7075, 7079 AND 7039 IN 0.5% NaCl-2% $K_2Cr_2O_7$ SOLUTION AT pH=4 AND 100C

(0.948-inch short-transverse C-rings etched 30 sec in 5% NaOH at 170F, desmutted in conc HNO_3.)

Alloy-Temper (Lot No.)	Applied Stress, ksi	F/N[1]	Time to Failure[2]
7075-T651 (830882)	45	3/3	1, 2, 3 hr
	30	3/3	3(3) hr
	20	3/3	5(3) d
	10	1/3	7 d
	5	0/3	NF 7 d
7075-T7351 (830882)	50	0/3	NF 7 d
	40	0/3	NF 7 d
7079-T651 (331661)	20	3/3	30, 45 min; 2 hr
	10	3/3	19(2) hr; 2 d
	5	3/3	1(2), 2 d
7039-T64 (363251)	20	3/3	3, 4, 5 min
	10	3/3	10(2), 12 min
	5	3/3	20, 70 min; 2 hr
7039-T64 (742101)	20	3/3	40, 50, 60 min
	10	3/3	100(2) min; 18 hr
	5	2/3	1, 2 hr; NF 7 d
7039-T61 (742101)	20	3/3	20, 50, 60 min
	10	3/3	2, 18(2) hr
	5	2/3	18(2) hr; NF 7 d
7039-T6E132 (105108)	20	3/3	30(2), 40 min
	10	3/3	2, 18 hr; 1 d
	5	3/3	18 hr; 2(2) d

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[1] F/N = Number of Failures/ Number of Specimens Tested.

[2] Time to failure (number of specimens failed). NF = No failures in test period.

TABLE XI

STRESS-CORROSION PERFORMANCE OF 2024, 2219 AND 7075 TENSILE ROUNDS GIVEN VARIOUS AGING TREATMENTS -- 1% NaCl-2% $K_2Cr_2O_7$ SOLUTION AT pH=4 AND 60C

($\frac{1}{8}$-inch diameter, short-transverse tensile specimens etched 30 sec in 5% NaOH at 170F, desmutted in cold concentrated HNO_3.)

Alloy and Aging Treatment	TS/YS[1]	Applied Stress, ksi	F/N[2]	Time to Failure[2]	Tensile Strength, ksi[3,4]			% Loss in Tensile Strength[4]	
					Stressed	Unstressed	Nominal	Stressed	Unstressed
2024-T4 (777021)	66/45	35	1/1	2 hr	28	55,57	55	49	0,0
+ 4 hr at 375F	70/64	40	2/2	1, 1 hr	0, 0	61,62	64	(38), (38)	5,3
+ 8 hr at 375F	70/65	40	2/2	2 hr, 1 d	0, 0	61,61	64	(38), (38)	5,5
+ 12 hr at 375F	70/64	40	1/2	3 hr	0, 56	62,62	65	(38), 14	5,5
+16 hr at 375F (-T6)	70/63	40	1/2	2 hr	0, 57	61,61	63	(37), 10	3,3
+4 hr at 375F	70/64	35	1/1	1 hr	34		64	47	
+ 8 hr at 375F	70/65	35	1/1	3 hr	0		64	(45)	
+ 12 hr at 375F	70/64	35	0/2	NF 7 d	43,55		65	34, 15	
+16 hr at 375F (-T6)	70/63	35	0/2	NF 7 d	51,54		63	19, 14	
+4 hr at 375F	70/64	30	1/1	2 hr	0		64	(53)	
+ 8 hr at 375F	70/65	30	0/1	NF 7 d	47		64	27	
+ 12 hr at 375F	70/64	30	0/1	NF 7 d	58		65	11	
+ 16 hr at 375F (-T6)	70/63	30	0/2	NF 7 d	52,59		63	17, 6	
+ 16 hr at 375F (-T6)	70/63	20	0/2	NF 7 d	59,60		63	6, 5	
2024-T351 (863642)	67/48	35	1/1	2 hr	11	47[a],57	56	80	16[a],0
+ 4 hr at 375F	70/64	40	2/2	2, 2 hr	0, 44	64,64	66	(39), 33	3, 3
+8 hr at 375F	71/66	40	1/2	< 1 d	0,60	63,64	66	(39), 9	5, 3
+ 12 hr at 375F (-T851)	70/64	40	0/2	NF 7 d	47,59	62,63	66	29,11	6,5
+ 4 hr at 375F	70/64	35	1/1	1 hr	49		66	26	
+ 8 hr at 375F	71/66	35	0/2	NF 7 d	58,58		66	12, 12	
+ 12 hr at 375F (-T851)	70/64	35	0/2	NF 7 d	57,59		66	14,11	
+ 4 hr at 375F	70/64	30	1/1	< 1 d	0		66	(55)	
+ 8 hr at 375F	71/66	30	0/1	NF 7 d	60		66	9	
+ 12 hr at 375F (-T851)	70/64	30	0/2	NF 7 d	60,61		66	9, 8	
+ 12 hr at 375F (-T851)	70/64	20	0/2	NF 7 d	62,63		66	6, 5	

2219-T42 (142081)	51/22	20	1/1	3 hr	17	51,52	48	65	0,0
+ 6 hr at 375F	63/44	35	2/2	3, 3 hr	0, <1	60,60	59	(41), 99	0,0
+12 hr at 375F	63/46	35	1/2	< 1 d	0, 48	58,59	58	(40), 17	0,0
+ 24 hr at 375F	62/43	35	0/2	NF 7 d	53,57	59,59	59	10, 3	0,0
+ 36 hr at 375F (-T62)	60/40	35	0/2	NF 7 d	54,55	58,61	59	8, 7	2,0
2219-T351 (142101)	54/37	30	1/1	3 hr	18	53,53	51	65	0,0
+ 4 hr at 350F	70/56	40	2/2	3, 3 hr	0, 2	61,62	61	(34),97	0,0
+ 8 hr at 350F	71/57	40	2/2	6, <18 hr	55,0	59,64	63	13, (37)	6,0
+ 12 hr at 350F	70/57	40	0/2	NF 7 d	60,63	63,63	62	3,0	0,0
+ 18 hr at 350F (-T851)	70/56	40	0/2	NF 7 d	64,64	64,65	64	0,0	0,0
2219-T37 (142091)	57/43	35	1/1	2 hr	9	54,55	54	83	0,0
+ 6 hr at 325F	72/59	45	2/2	1, 2 hr	0,0	64,64	63	(29),(29)	0,0
+ 12 hr at 325F	73/62	45	0/2	NF 7 d	52,57	63,64	65	20, 12	3,2
+ 18 hr at 325F	72/61	45	0/2	NF 7 d	58,63	65,65	65	11, 3	0,0
+ 24 hr at 325F (-T87)	72/61	45	0/2	NF 7 d	58,62	63,65	65	11, 5	3,0
7075-T651 (830882)	81/70	45	1/1	1 hr	0	72,72	73	(83)	1,1
+ 2 hr at 350F	78/67	45	2/2	2, 4 d	0	69,69	71	(37)	3,3
+ 4 hr at 350F	76/65	45	1/3	18 hr	0,62,68	64,68	70	(36),11,3	9,3
+ 6 hr at 350F	75/63	45	0/2	NF 7 d	63,66	62,69	68	7,3	9,0
+ 8 hr at 350F	73/61	45	0/2	NF 7 d	61,63	62,65	66	8,5	6,2
+ 10 hr at 350F (-T7351)	72/60	45	0/2	NF 7 d	61,62	61,67	66	8,6	8,0

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[1] Tensile strength/Yield strength, ksi. Average of duplicate long-transverse tensiles, 0.500-inch diameter, 4-D gage length, 1/4 T position.

[2] Number of Failures/Number of Specimens Tested. Failures defined as (a) cracking observed at a magnification of 15X, or (b) complete separation of the specimen. NF = No failure in the test period.

[3] Short-transverse tensile strengths determined on (a) stressed and corroded specimens, (b) unstressed specimens corroded for 7 days, and (c) average of duplicate specimens not tested by continuous immersion (nominal).

[4] Parenthetic values calculated on the assumption that the load applied during the corrosion test corresponded to the tensile breaking load. (a) Denotes low tensile strength due to fracture at a deep pit outside the gage length. All unstressed specimens exposed for 7 days.

APPENDIX

PROCEDURE FOR CONDUCTING THE SALT-(DI)CHROMATE SOLUTION TEST

This test is based on continuous immersion of specimens in a 1% $NaCl$-2% $K_2Cr_2O_7$ solution at about pH=4 and a temperature of 60C (140F). The solution is prepared on a weight basis using reagent grade chemicals and distilled water. As prepared, the solution should exhibit an unadjusted pH in the range of 3.7 to 4.0. If not, the pH should be brought within this range with additions of 1 N HCl or 1 N NaOH solution.

The test solution must be contained in an inert vessel, preferably glass, which will withstand the operating temperature of 60C. Provisions should be made for maintaining the temperature within ± 1C of 60C for the best reproducibility of test results. It is not necessary to reflux the vessel, but a suitable cover should be provided to minimize evaporation losses. Distilled water is added periodically to compensate for any losses which occur.

The recommended exposure period for the salt-(di)chromate solution test is seven days, but this period may be extended for several weeks with no danger of excessive general corrosion attack of the specimens. Failure of highly stressed susceptible alloys and tempers generally occurs during the first few hours of testing. Therefore, specimens should be inspected at least once during the first four hours' exposure and twice a day thereafter.

Reliable performance in this test necessitates chemical etching of the unstressed specimens. Specimens should be immersed for 30 seconds in a 5% NaOH solution at 75C (about 170F), desmutted in cold concentrated HNO_3 for 15 to 30 seconds, with a final rinse in hot tap water.