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TIDEWATER AND WEATHER-EXPOSURE TESTS ON METALS USED IN AIRCRAFT - II

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SUMMARY

This report is an addendum to NACA Technical Note No. 736, which dealt with tidewater and weather-exposure tests being conducted by the National Bureau of Standards on various aluminum alloys, magnesium alloys, and stainless steels used in aircraft. The exposures were begun in June 1938 and were terminated, for this particular series, in June 1941. The methods of exposure and the materials being investigated are described, and the more important results obtained up to the conclusion of the second year's exposure are reported.

INTRODUCTION

Tidewater and weather-exposure tests on various aluminum alloys, magnesium alloys, and stainless steels are now being conducted by the National Advisory Committee for Aeronautics, the Army Air Corps, and the Bureau of Aeronautics of the Navy Department. Reference 1 described the materials and the methods of test and presented the results obtained during the first year of exposure, using the surface appearance of the panels as criterions. The present paper discusses the changes in surface appearance that occurred during the second year of exposure and contains the results of the microscopic examination of the panels.

The style of this paper has been made to conform closely to that of reference 1 in order to permit ready comparison. In order to facilitate comparison, a number within parentheses appears at the end of the legend for each photograph in this paper; this number indicates the figure number in reference 1 to which the photograph is related. Although reference to the preceding paper will be necessary when information is desired regarding the exact chemical compositions of the alloys and the details of the methods of surface treatments, such information is sufficiently summarized herein to make the present report a self-contained unit.

EXPOSURE TESTS ON LIGHT METALS

Procedure

Materials.- The aluminum alloys used in the investigation were: (1) 24ST, 14ST, and Major metal, which are duralumin-type alloys containing approximately 4 percent copper, from 0.5 to 1.5 percent magnesium, and 0.6 percent manganese, and exposed as sheet, extrusions, or forgings; (2) Alclad 24ST sheet, in which a coating on both surfaces, consisting of approximately 99.7 percent aluminum, protects the 24ST core; (3) 53ST sheet and extrusions; and (4) 52S-½H sheet. The last two are essentially binary alloys containing 1.25 and 2.5 percent magnesium, respectively. The two magnesium alloys used were: (1) Dowmetal M, a binary alloy with 1.4 percent manganese; and (2) Dowmetal H, containing approximately 6.5 percent aluminum and 3 percent zinc.

Types of panel.- All the panels have over-all dimensions of 4 by 14 inches. The sheet panels are usually 0.040 inch thick, but the thickness of extrusions or forgings varies to a maximum of 0.25 inch. Panels are of three types. Type 1, for the investigation of rivets or paint schedules, has one strip 1½ by 4 inches (identical with the main panel sheet) joined to each surface by a double row of four rivets spaced approximately 3/4 inch. Type 2, for welds, is assembled from three sections, each of which overlaps 1½ inches and has a double row of either four spot welds spaced 3/4 inch or seam welds spaced similarly. Type 3, for dissimilar metals in contact, has two similar strips 1 by 4 inches on opposite sides of the main panel and joined to it by a single row of four rivets. The main panel differs from the strips in composition.

Methods of exposure.- The tidewater and the weather-exposure tests were conducted at Boush Creek, at the Naval Air Station, Hampton Roads, Va. During the first 2½ years of exposure the location of the racks was essentially as shown in figure 1. The tidewater racks were moved in November 1940 to a lagoon where the salinity of the water was somewhat higher, while the weather-exposure racks were temporarily placed on land, approximately one-quarter mile distant from salt water.

The exposure tests were begun during the week of June 11, 1938. Table I shows the intervals after which the various kinds of panels were withdrawn. Tests on the panels withdrawn after 3 years' exposure are still in progress, and most of the panels reported upon in the present paper were removed from the racks during June 1940, that is, after 2 years' exposure. The water at Boush Creek has a chloride content of 12.2 parts per thousand, a sulphate content of 1.75 parts per thousand, a pH of 8.0, and a normal mean temperature of approximately 35° F in January, as contrasted with a normal mean temperature of 80° F in July and August. Panels exposed to the tidewater gradually became covered with a mixture of green organic growths and colloidal mud, but barnacles were surprisingly few until August 1940 when they began to appear in some numbers.

Investigation of Rivets

Riveted aluminum-alloy panels.- The main panels and strips of the 52S-½H, 53ST, Alclad 24ST, and anodized 24ST sheets were each joined to themselves with 53ST and anodized 17ST and A17ST brazier-head rivets, to determine the electrolytic effects involved. Neoprene PAW tape was inserted between the strips and the main panel sheet to effect their separation. In each row of anodically treated rivets, alternate ones were anodized: (1) in 9.5 percent chromic acid electrolyte for 30 minutes at 40 volts and at 35° C; and (2) by the Alumilite 205 process, which involves treatment in a sulphuric acid electrolyte followed by sealing in a potassium dichromate solution (not with lead salts, as stated in reference 1). The 24ST sheets were anodized in the chromic-acid electrolyte, except that the sulphuric-acid electrolyte was used on sheets joined with 53ST rivets.

An important fact emerging from the tidewater tests for this series of panels was that the 53ST and the anodized A17ST rivets were very severely attacked when used to join 24ST sheets (fig. 2). These combinations should therefore be avoided in aircraft parts, such as pontoons, likely to be subjected to immersion in salt water. Equally important was the fact that practically no attack occurred on panels with anodized 17ST rivets on anodized 24ST sheets (fig. 2), or with any of the three kinds of rivets on Alclad 24ST, 53ST, or 52S-½H sheets (fig. 3).

The small vertical black lines appearing in figure 2, and on the other composite photomacrographs that follow, indicate the planes on which the microexaminations were made. The actual cross sections examined are pictured in the small black squares inserted at the corners of the photomicrographs in composites such as figure 4. On the cross sections, in turn, appear small circles that define the area on which the photomicrograph was taken.

The attack on the 53ST and the anodized A17ST rivets on 24ST sheet was but little worse after the second than after the first year of exposure. The corrosion on rivets treated with sealed Alumilite coatings was almost as severe as that on rivets anodized in the chromic-acid electrolyte. Sufficient disintegration had occurred during the first year to make it evident that both alloys were anodic with respect to 24ST. The photomicrographs (fig.4) disclose the severity of the attack on the rivet heads and reveal no corrosion on portions of the 24ST sheat adjacent to, or in contact with, the rivets. The attack on the 53ST rivets was in part intercrystalline, and corrosion was occasionally noted on the shanks of both 53ST and anodized A17ST rivets.

The microscopic examinations confirmed the practical absence of corrosive attack on either the rivets or the sheets where any of the three kinds of rivet were used to join Alclad 24ST, 52S-½H, or 53ST (fig. 4) sheet. Such corrosion as occurred seldom exceeded 0.002 inch in depth and was of the pitting type on all the alloys.

The tests also indicated that the Neoprene PAW tape promoted corrosive attack on 24ST sheets. In several instances the metal was practically disintegrated and the accumulation of corrosion products appreciably increased the distance between the outer edges of the 1½- by 4-inch strips and the main panel (fig. 4, cross sections). Considerable shallow pitting, to depths of 0.003 inch, also occurred on the surfaces of 53ST sheets in contact with the Neoprene. The extent to which corrosion occurred was doubtless related, in large measure, to the original watertightness of the contacts between the metal and the tape.

In the weather-exposure tests, at the end of the first year small localized areas of corrosion products were noted on most of the rivet heads, as well as on the sheet alloys, but were least in evidence on the anodized 24ST sheet. At the end of the second year the areas were slightly larger, somewhat more numerous, and the deposits of corrosion products were somewhat heavier (fig. 5), and there was considerably more attack on the anodized 24ST sheets (fig. 2). At the end of the second year, also, corrosion on the 53ST and the anodized A17ST rivets joined to anodized 24ST sheet was noticeably more advanced than on any of the other rivets (fig. 2). The microscopic examinations revealed that the attack on the A17ST and 53ST rivets was deepest (0.004 and 0.009 in., respectively) at the base of the heads near the circumference, where water would tend to be retained longest and permit cell reactions. Scattered areas of attack on the 24ST sheet seldom exceeded 0.002 inch in depth. Severe attack (0.01 in. deep) was also found on 53ST rivets on 53ST sheets. On the Alclad 24ST and 53ST sheets slight attack was noted adjacent to or under the anodized A17ST and 17ST rivet heads. The restricted volume of electrolyte occasionally present at such areas was perhaps responsible for such attack for, in the tidewater tests, where the water covered the entire panel, the phenomenon was not noted. Although corrosive attack was more prevalent on all the rivets and panels exposed to the weather than on the corresponding specimens exposed to tidewater, its depth seldom exceeded 0.003 inch. The corrosion on the 53ST alloy in the weather-exposure tests, as in the tidewater tests, was partly intercrystalline in character.

Unriveted aluminum-alloy panels.- The forged 14ST panels, not anodically treated, were the most severely attacked of all the aluminum alloys, both in the tidewater and weather-exposure tests (fig. 6). The corrosion was predominantly intercrystalline and attained a depth of 0.015 inch in tidewater and of 0.01 inch in the weather after 2 years. These panels were solution heat-treated in air at approximately 940° F, given a quench in an aqueous solution (not in air, as erroneously stated in table II of reference 1), and aged 10 hours at 340° F.

The Major metal sheets (fig. 6), anodized and unanodized, corroded in a fashion quite similar to the 14ST alloy. The attack was largely intercrystalline and the unanodized sheet panels 0.060 inch thick were penetrated in spots after 6 months in the tidewater. The specimens exposed as forged and heat-treated bars, 0.375 inch diameter, had an initial (uncorroded) ultimate tensile strength of 46,000 pounds per square inch and an elongation in 1½ inches of 25 percent. After a year in tidewater the values dropped to 36,500 pounds per square inch and 9 percent, respectively.

Riveted magnesium-alloy panels.- The Dowmetal M strips and sheet anodized in accordance with Navy specification PT13a were joined with AM55S (approximately 4 percent magnesium, 96 percent aluminum), 53ST, and anodized 17ST rivets, and exposed both unpainted and painted. The tidewater tests, which were discontinued after 1 year, demonstrated the superiority of the AM55S rivets for joining this alloy. These rivets remained in good condition; whereas the 53ST and the 17ST rivets were almost entirely disintegrated.

The anodized 17ST rivets on unpainted panels, after 2 years of exposure to the weather, were in advanced stages of disintegration (fig. 7), while the 53ST rivets were also severely attacked. Both were much worse attacked than after 1 year of exposure. The AM55S rivets, however, continued to exhibit relatively little attack. The Dowmetal M sheets were discolored brown on the skyward surfaces and were partly covered with a thin nonuniform grayish-white film of corrosion product on the earthward surfaces. Microscopic examinations (fig. 8) revealed a few pits 0.001 inch deep on the AM55S rivets, but the 53ST rivets had several pits 0.003 inch deep. Numerous pits from 0.002 to 0.008 inch deep were found on the Dowmetal M sheet, and its edges were rounded off by corrosion. Relatively little corrosion occurred on the Dowmetal M surfaces which were in contact with the Neoprene tape.

The painted panels were still in excellent condition after 2 years of exposure. The paint schedule, which proved one of the most effective used on the magnesium alloys, consisted of two coats of Watson Standard Dowmetal Primer No. 1 (Navy specification P27) with the second coat pigmented with 1 pound of aluminum paste per gallon, plus two coats of Brooklyn Varnish No. 74 (Navy specification V10) with 1½ pounds of aluminum paste per gallon. The microscopic examination revealed considerable pitting on the 53ST rivet heads, from 0.001 to 0.002 inch deep, and some pits of the same depth on the Dowmetal M sheet at areas immediately adjacent to these rivets.

Most of the other paints applied to Dowmetal panels failed to adhere well to the unanodized rivets. A few additional panels were made on which both anodized and unanodized AM55S rivets were used, with and without painting. These were placed in the tidewater and weather racks during June 1940. After 1 year, on unpainted panels, the unanodized rivets showed considerably more corrosion than the anodized ones. Paints on both types of rivet failed, but the amount of failure on the anodized heads was somewhat less than on the others. Anodization in chromic acid, therefore, does not improve paint adherence on AM55S alloy to the same degree that it does on 24ST alloy.

Investigation of Welds

Welded aluminum-alloy panels.- The Alclad 24ST, 52S-½H, 53ST sheets, and 53ST extrusions were joined to themselves with electric-resistance spot and seam welds. In addition, the 52S-½H sheets were spot-welded to Alclad 24ST or 53ST sheets, and extruded 53ST sections were similarly joined to Alclad 24ST and 53ST sheets. Sheets of 52S-½H alloy were also gas-welded (butt joints) to each other, using 52S filler rods, and to sheets and extrusions of 53ST, using 2S filler rods.

None of the welded panels exhibited much corrosion after 2 years of exposure to tidewater (fig. 9). This result indicates that either the metal on the surfaces of the welds had potentials approximately equivalent to that of the remainder of their respective panels or else were somewhat cathodic thereto. The microscopic examinations (fig. 10) revealed that corrosion on the welded or unwelded parts of the panels was largely confined to a relatively few small pits, nearly all being less than 0.001 inch deep. On the 53ST and the 52S-½H panels a few small areas of intercrystalline corrosion occasionally appeared; a very few had depths of 0.004 inch. The 53ST panels exhibited more attack, however, than the 52S-½H panels. The surfaces of welds joining dissimilar alloys were corroded similarly to those joining alloys of the same compositions. The faying surfaces, which were in metallic contact, were relatively free from corrosion.

The panels exposed to the weather for 2 years (fig. 11) were much more corroded, especially on the welds, than those in tidewater. In general, the attack was somewhat worse on the earthward surfaces than on the skyward surfaces. The seam welds were more corroded than the spot welds, while the gas welds exhibited but little attack.

The microscopic examinations (figs. 12 and 13) of the spot welds disclosed many pits (0.001 and 0.002 in.) on the Alclad 24ST panels, but in no case was penetration of the aluminum protective coating found. On 52S-½H welds numerous pits were found associated with some intercrystalline attack, generally 0.002 inch deep, but occasionally 0.006 inch. The welds on the sheet and extrusions of 53ST alloy were attacked similarly to those on 52S-½H but intercrystalline attack was more in evidence; and occasionally pit depths of 0.010 inch were noted. Little attack occurred at the faying surfaces, but some pits 0.005 inch deep were detected on the 53ST materials.

On the seam welds the attack was somewhat more severe. The aluminum coating on the Alclad 24ST panels was penetrated in some instances and the attack reached a depth of 0.004 inch, as it did also on the 52S-½H welds. Seam welds on the 53ST alloys were occasionally corroded to depths from 0.007 to 0.012 inch. The gas welds proper showed but slight attack. At the junction of the weld metal with the unwelded parts of the sheets, however, corrosion sometimes attained a depth approximating 0.004 inch.

The seam welds were uniformly sound, but cracks occurred on some of the Alclad 24ST spot welds (fig. 13); whereas very small cavities, 0.001 inch in diameter, were present on a few of the 52S-½H welds and cavities as wide as 0.010 inch were found in several of the welds on extruded 53ST panels. Numerous cavities, ranging from 0.005 to 0.010 inch in diameter, were found in the gas welds.

Welded magnesium-alloy panels.- The anodized Dowmetal M panels were exposed with electric-resistance spot welds and with gas welds, both in the unpainted and the painted conditions. The tidewater tests were discontinued at the end of the first year when it became evident that the spot welds were disintegrated on the unpainted panels and severely corroded on the painted panels. The gas welds on the unpainted panels were no worse corroded than the rest of the sheet but, on the painted panels, pits 0.03 inch deep were found in areas of paint failure that occurred at the junction of the sheet and the weld.

After 2 years of exposure to the weather (fig. 14) the spot welds on the unpainted panels were very severely pitted, often to depths of 0.040 inch, while the sheet thickness was only 0.064 inch. On the gas welds, as on the remainder of the sheet, pitting seldom exceeded 0.007

inch in depth. On the painted panels both the spot welds and the gas welds were practically unattacked. The paint schedule consisted of 2 coats of Watson Standard Dowmetal Primer No. 1 plus 2 coats of Brooklyn Varnish No. 74, pigmented with $1\frac{1}{2}$ pounds of aluminum paste per gallon.

Contacts with Dissimilar Metals

Inasmuch as the ratio of the areas of the two dissimilar metals is often a determining factor in the resulting corrosion, most of the panels in this series were prepared so that the ratio of the area of alloy A was approximately 7:1 with respect to that of alloy B on some, while on others this ratio was reversed. No insulating materials were used at the faying surfaces and the panels were not painted, except where noted. No panels were removed from the tidewater racks at the end of the second year, and the results covered in this report pertain to the microscopic examinations of panels removed after 1 year in the tidewater and 2 years in the weather racks.

<u>Contacts of aluminum alloys with each other</u>.- The contacts investigated included two-member combinations of alloys 24ST, Alclad 24ST, 52S-$\frac{1}{2}$H, and 53ST sheets, and 24ST and 53ST extrusions. Joining was effected by means of 17ST rivets, all anodized in chromic-acid electrolyte, on all the aluminum alloy panels with dissimilar metals in contact. Macroexaminations of tidewater panels removed at the end of the first year had revealed that the Alclad 24ST, 52S-$\frac{1}{2}$H, and 53ST alloys were anodic to 24ST and that severe corrosion occurred on these alloys, particularly when they were small in area as compared with the 24ST. Microscopic examinations confirmed these observations (fig. 15) and measurements of the depths of attack on the various combinations are given in table II.

The surface appearance of the panels exposed for 2 years to the weather (fig. 16) indicates that, though corrosion products in some instances accumulated along the edges of and under the 1- by 4-inch strips, the quantities of such products were usually less than the quantities on the panels exposed to tidewater. The results of the microscopic examinations (fig. 17 and table II) are included for comparison with the panels exposed to tidewater.

<u>Contacts of aluminum alloys with plated steel</u>.- One-inch-wide strips of SAE X4130 steel, electroplated with

0.0005 inch of cadmium or zinc, were joined to the various aluminum alloys. After 2 years of exposure to tidewater the cadmium coatings were mostly corroded off and rust was visible on more than 50 percent of the area where contacts were with 24ST, 53ST, and 52S-½H alloys. The coating was entirely off where contact was with Alclad 24ST sheet and the whole strip was rusted. The zinc coatings were almost entirely off all the strips and there was more rust than on the cadmium-plated strips.

The cadmium-plated strips exposed for 2 years to the weather were all in excellent condition (fig. 18) although faint traces of rust were visible on the strip in contact with Alclad 24ST. The zinc coatings were entirely corroded off strips in contact with Alclad 24ST, were mostly off when in contact with 53ST, but were fairly intact when joined to 24ST and 52S-½H sheets. Microscopic examinations revealed little corrosion at the faying surfaces of either coating with the aluminum-alloy sheets except near the edges of the strips, where the attack on the aluminum alloys was usually very severe (fig. 19 and table II). The results at the end of the second year, in general, demonstrate that zinc is anodic to all the aluminum alloys tested and that cadmium is either slightly cathodic or has a potential equivalent to that of these alloys. The tests show that zinc sheets attached to aluminum alloys may be sacrificially attacked and prevent corrosion of the aluminum where cell action can be maintained more or less continuously.

<u>Contacts of aluminum alloys with stainless steel</u>.- The stainless steel joined to the various aluminum alloys was one known as U.S.S. Type 321, containing nominally 18 percent chromium, 8 percent nickel, and 0.5 percent titanium. The first year's tests in tidewater disclosed that the four aluminum alloys were highly anodic and that they were severely corroded, especially when their surface areas were small as compared with the steel. The surface appearance of the panels exposed to the weather for 2 years (fig. 18) likewise revealed much corrosion on the aluminum alloys. Microscopic examinations showed that alloys 24ST and Alclad 24ST were the most severely attacked (fig. 19 and table II), with 53ST somewhat less so, and 52S-½H the least. This result does not necessarily indicate the order of the potential differences involved since the 52S-½H and Alclad 24ST alloys are inherently the most resistant to corrosion, while 24ST is the most susceptible. The 24ST strips on stainless-steel main panels had several intercrystalline cracks, attributed to stress corrosion.

<u>Contacts of aluminum alloys with nickel alloys</u>.- The aluminum alloys formed the 1- by 4-inch strips attached to main panels of nickel, monel metal, or Inconel. Microscopic examinations of the panels exposed for 1 year to tidewater (fig. 20 and table II) indicated that the aluminum alloys were probably more anodic to the nickel alloys than to the stainless steels. Monel-aluminum alloy couples resulted in the worst corrosion on aluminum, but the corrosion was sufficiently severe with all these combinations to indicate that coupling with these nickel alloys should be avoided. Cracks resulting from the combined action of stresses and corrosion were found on all strips of 24ST and Alclad 24ST in contact with these alloys.

The panels exposed to the weather for 2 years were almost as severely attacked as those in tidewater for 1 year (figs. 21 and 22 and table II) as evidenced by the quantity of corrosion products at faying surfaces of the strips and the main panels. Cracks due to stress corrosion were present only on 24ST strips.

The nickel and the monel panels on the skyward surfaces exposed to the weather were discolored a greenish-gray that was darker on the monel. Their earthward surfaces were discolored grayish green. Faint rustlike spots, from approximately 1/8 to 1/4 inch in diameter, occurred on the Inconel panels, particularly on the earthward surfaces.

<u>Contacts of aluminum alloys with magnesium alloys</u>.- Dowmetals M and H were exposed in contact with alloys 24ST, Alclad 24ST, 53ST, and 52S-$\frac{1}{2}$H. The tidewater tests early demonstrated that the two magnesium alloys were anodic to the aluminum alloys. Corrosion resulted in the deposition of a coating of basic magnesium carbonate upon the aluminum alloys. A base, perhaps sodium hydroxide, was doubtless formed at some stage in the reaction, which in turn caused extremely severe attack on the 24ST and the Alclad 24ST alloys. The attack was not so severe on the 53ST and 52S-$\frac{1}{2}$H alloys, probably owing to their inherent resistance to corrosion.

Few measurements of the depth of penetration were made, since visual examination of the original surfaces and of cross sections (fig. 23) depicted the extent of the attack satisfactorily.

Corrosion was also severe on the unpainted panels exposed to the weather (fig. 23), but the painted panels were in relatively good condition after 2 years (figs. 23, 24, and 25). The panels were painted with 1 coat of Watson Standard Dowmetal Primer No. 1 plus 3 coats of Brooklyn Varnish No. 74 pigmented with 1½ pounds of aluminum paste per gallon. The photographs illustrate that corrosion was much less severe where Dowmetal H, instead of Dowmetal M, was coupled with the aluminum alloys.

Contacts of magnesium alloys with each other.- The tidewater tests, which were discontinued at the end of the first year, indicated that Dowmetal M was severely attacked when in contact with Dowmetal H. The unpainted panels, after 2 years of exposure to the weather, were in fairly good condition although considerable pitting was found on the Dowmetal M sections (figs. 24 and 25). The panels painted with 1 coat of Watson Standard Dowmetal Primer No. 1 and 3 coats of aluminum-pigmented Brooklyn Varnish remained in good condition.

Contacts of magnesium alloys with stainless steel.- The couplings of magnesium alloys with stainless steel proved the worst of all the dissimilar metal contacts tested, and corrosion of the magnesium alloys in the tidewater tests was exceedingly rapid and resulted in their quick disintegration. The unpainted panels exposed to the weather for 2 years were much more severely attacked than after 1 year (figs. 24 and 25). Cracks resulting from the combined action of stress and corrosion were found on some of the Dowmetal couplings, as noted later. The painted panels, however, were in fairly good condition, although paint failures by reason of poor adherence occurred on the stainless-steel strips.

Stress corrosion.- The presence of cracks, which tended to follow intercrystalline boundaries, was noted on the following: (1) 24ST strips coupled with the nickel alloys or stainless steel, in both the tidewater and weather tests; (2) Alclad 24ST strips coupled with the nickel alloys or stainless steel (fig. 26) in the tidewater tests only; (3) Dowmetal H strips joined to 24ST and 52S-½H alloys, after 2 years of exposure to the weather; (4) stainless-steel strips joined to Dowmetal M (fig. 26), after 2 years of exposure to the weather.

The cracks were undoubtedly caused by the combined action of corrosion and stress. The stresses were markedly increased by the accumulation of corrosion products at the faying surfaces. It was suspected that the presence of the compound $MgCl_2$ among the corrosion products may have augmented the cracking of the stainless steel strips on Dowmetal M panels. Microanalytical and electron diffraction tests, however, indicated that no solid phase of that compound was present. The products were adjudged to consist mainly of a jelly of hydrous magnesium carbonate. Between the steel and the Dowmetal M sheet and adjacent to the steel there was a film of nearly opaque white matter. Next to the magnesium was a translucent, dense, slightly amber layer containing an undissolved residue in which iron rust predominated.

Additional tests are shortly to be started in which panels are to be exposed with varying amounts of stresses applied by bending the panels at different degrees.

Investigation of Protective Coatings

Paints on anodized 24ST aluminum alloy.- The paint schedules (fig. 27) applied to 24ST aluminum alloy were generally in excellent condition in both the tidewater and the weather-exposure tests at the end of 2 years. In the tidewater tests aluminum-pigmented finish coats of Fuller lacquer (Navy specification L12a) and of Pratt and Lambert Number 10 aluminum mixing varnish (Navy specification 52V15b) failed to adhere in some areas when applied, respectively, over Berry Brothers 316A Primer (Navy specification P27) and Brooklyn Varnish P-14 Primer (Navy specification P23). Microscopic examinations, however, revealed no corrosive attack on any of the painted panels.

Surface treatments and paints on magnesium alloys.- The protective surface coatings on the magnesium alloys were applied to determine which of the paint schedules would prove the most effective, and to determine the relative merits of the "chrome-pickle" and of the anodic (Navy specification PT13a) surface treatment with respect to improving adherence of the paints.

No painted panels were removed from the tidewater racks at the end of the second year, but inspections revealed that paint failures were becoming general on all but four of the schedules. These were:

(1) One coat of Watson Standard Dowmetal Primer No. 1, one coat of the same with 1 pound of aluminum paste (No.

1571 Albron Extra Fine Lining Paste used throughout) per gallon, two coats of Brooklyn Varnish No. 74 with 1½ pounds of aluminum paste per gallon.

(2) Same as (1) except that a third coat of the pigmented Brooklyn varnish replaced the second coat of pigmented primer.

(3) One coat of Bakelite XE8483 primer, one coat of the same with 1½ ounces of aluminum paste per gallon, and two coats of Bakelite XE3944 with 1½ pounds of aluminum paste per gallon.

(4) Same as (3) except that an aluminum-pigmented Bakelite XE6440 vehicle was used for the last 2 coats.

The superiority of four-coat paint schedules on magnesium alloys was demonstrated, and the advisability of pigmenting the second coat of primer with aluminum was indicated from the tidewater tests.

In the tidewater tests, also, failures on the anodized Dowmetal M penels were, in general, much more advanced than on the chrome-pickled panels, even with the paint systems already listed as superior. On the Dowmetal H panels, at the end of the second year, no differences in the amount of paint failure were observed on panels given either of the two surface treatments.

In the weather-exposure tests, at the end of the second year, most of the paints were in good condition (fig. 28). Failures were generally confined to the unanodized AM55S rivet heads and to the edges of the panels. Microscopic examinations (fig. 29) revealed occasional deep pits at areas adjacent to rivet heads.

EXPOSURE TESTS OF STAINLESS STEELS

Materials and Procedure

The principal purpose of the exposure tests of stainless steel was to establish the relative corrosion resistance of the 18:8 type alloys, with and without addition of the customary alloying elements, such as molybdenum, titanium, and columbium. The steels were nearly all cold-rolled sheet, 0.018 inch thick, with polished surfaces passivated by immersion in 20-percent nitric acid at about 60° C for 1 hour. Electric-resistance shot-welded panels of each steel were also exposed, each protected at the faying surfaces with a petrolatum paste containing copper. Each weld was rubbed lightly with emery to remove the light film of oxide (not carbide precipitates) which forms owing to the high welding temperature and which may corrode to produce undesirable staining.

The steels had the following approximate percentage compositions:

U.S.S. type	Chromium	Nickel	Carbon	Addition element
302	18	7	0.10	--
306	19	9	.09	--
317	18	11	.08	3.7 molybdenum
321	18	9	.07	.5 titanium
347	18	10	.08	.5 columbium
---	16	1	.08	--

Macroscopic examinations were supplemented by flexural fatigue tests on unwelded panels, a Krouse machine intended specifically for testing sheet specimens being used. These tests were conducted by J. A. Kies, who designed the specimen (fig. 30) and perfected the method of testing, W. L. Holshouser, and G. R. McConnell (all of the National Bureau of Standards), to whom the authors express their indebtedness.

Results of Tests

The panels exposed to tidewater at the end of the second year still exhibited practically no rust except for a number of localized areas on the 16:1 chromium-nickel alloys. Rust on the panels exposed to the weather was greater in extent and somewhat more heavily deposited at the end of the second year than at the end of the first year (fig. 31). Rusting continued to be worse on the 16:1 alloy, and notably much less on the steel containing

3.7 percent molybdenum than on the others. At intervals of 6 months or less after the first year the rust was cleaned from some panels of the straight 18:8 type. A cleaner commercially known as Nu Steel proved very effective in removing the rust. Minute pits were then observed under many of the rusted areas.

The endurance limits of some 300 specimens have been determined since reference 1 was released, both on panels as received (uncorroded) or on panels removed from the exposure racks during the first 2 years. The endurance limit values reported may be regarded as accurate only insofar as they serve to present a basis of comparison between the alloys tested. The values given (fig. 32 and table III) represent a stress, the half range of which was calculated to be within 800 pounds per square inch of the next highest stress, which resulted in fatigue failure, provided that at least two runs past 10^6 cycles had been made.

The fatigue tests disclosed that steels exposed to the weather consistently showed greater loss in endurance limit than when exposed to tidewater for the same period of time. The steels containing 3.7 percent molybdenum or 0.5 percent titanium behaved similarly and both exhibited appreciably less loss in endurance limits than did the ordinary 18:8 steel or one containing 0.5 percent columbium. The results illustrate that the greater part of the losses for all the steels occurred during the first year of exposure and that the rate of corrosion decelerated during the second year.

Some panels of stainless steels containing 3.7 and 2.5 percent molybdenum, respectively, were placed in the exposure tests after the main series began. None of these panels has yet been removed for test, but visual examinations have shown that rust was slightly more prevalent on the steel with less molybdenum at the end of the second year. The difference was so little, however, as to be adjudged immaterial for most practical purposes.

A few stainless-steel panels coated with Hercose AP, Hercose C, Dupont RCX5555A, and Dupont RCX5556A clear lacquers were inserted only in the tidewater racks. The coatings all began to peel from the sheets during the first year and were almost entirely off at the end of the second year. Polished stainless steel presents a surface to which most paints are not adherent.

A series of stainless-steel panels of various compositions was also inserted in the tidewater racks at monthly intervals from June 1939 through May 1940. Panels inserted from June through September were covered with organic growths, which were thicker and differed markedly in appearance from the others at the end of the year, but such differences in time became less noticeable. None of the panels has yet been removed for test.

A few straight 18:8 panels were exposed both as cold-rolled and after heating at 440° F for 24 hours. The heat-treated specimens contained less rust after a year than the cold-rolled panels.

Currently in progress are programs embracing (1) the corrosion behavior of stainless steels with various surface treatments and with different finishes, (2) different systems of insulation designed to minimize electrolytic corrosion when magnesium alloys are in contact with steel or aluminum alloys and, (3) a comparison of the results obtained on metals exposed to the weather and sea water at Hampton Roads, Va., Chapman Field, Fla., and Cape Fear, N.C. Proposed for early investigation are programs covering (1) the relative corrosion rates of all the commercially available alloys of magnesium, (2) the relative efficiencies of various surface treatments on magnesium alloys, particularly with respect to their ability to improve paint adherence, (3) spot welds on aluminum alloys applied under various controlled conditions of current and time, and (4) metals stressed by being suspended in the racks under various predetermined amounts of bending.

CONCLUSIONS

The conclusions that follow are pertinent to panels exposed for 2 years under extreme saline conditions, as exemplified by tidewater tests or weather exposure with the metals in close proximity to salt water.

1. The panels were, in general, somewhat more corroded at the end of the second than of the first year, particularly those with dissimilar metals in contact. In most instances the rate of corrosion during the second year was not as rapid as during the first.

2. Alloys Alclad 24ST and 52S-½H proved the most re-

sistant to corrosion of the aluminum alloys tested and were but slightly attacked during 2 years. Alloys 53ST and anodized 24ST were somewhat more susceptible to attack, while the alloys containing copper, such as 24ST, 14ST, and Major metal were much more susceptible.

3. Anodized Dowmetal M appeared more resistant to corrosion during the first year than anodized Dowmetal H, but during the second year developed considerably larger pits than Dowmetal H.

4. Stainless steels containing 2.5 percent molybdenum were very slightly more susceptible to corrosion than those containing 3.5 percent molybdenum, as judged by the rust on panels exposed to the weather for 2 years. At the end of 3 years the stainless steel containing 3.7 percent molybdenum was much less rusted than steels with additions of columbium or titanium, or than those without additional alloying elements. A 16:1 chromium-nickel alloy was more susceptible to attack than any of the others and was practically the only one on which rust was present in the tidewater tests.

The flexural fatigue tests on corroded panels demonstrated that endurance limit losses were lower for the steels containing molybdenum or titanium (approximately 9,000 lb/sq in.) than for those containing columbium or no additional alloy element (approximately 14,000 lb/sq in.).

5. Anodized 17ST rivets proved far better than 53ST or anodized A17ST rivets for joining aluminum alloy 24ST. All three were satisfactory for joining aluminum alloys 52S-½H, 53ST, or Alclad 24ST, but the 53ST rivet heads on these alloys, in the weather-exposure tests only, were somewhat more corroded and exhibited intercrystalline attack.

6. AM55S rivets proved far superior to 53ST or anodized 17ST rivets for joining magnesium alloys. Anodically treated AM55S rivets were somewhat more resistant to attack and paints applied to them adhered somewhat better than on unanodized rivets. Anodization was not so effective in improving adherence of paints to AM55S as it was to alloy 24ST.

7. The welds on alloys 52S-½H, 53ST, or Alclad 24ST were anodically protected in the tidewater tests but were corroded in the weather tests. Gas welds were the least

attacked, spot welds next, and seam welds the most attacked. Welds on 53ST alloy were more prone to attack than on the other two. The aluminum coating on the Alclad 24ST welds was sacrificially attacked and thus prevented deep penetration of corrosion.

8. Anodized gas welds on Dowmetal M proved as resistant to corrosion as the rest of the sheet, but spot welds were severely attacked. Welds on painted panels were practically unattacked after 2 years of exposure to the weather.

9. Shot welds on stainless steels exposed to the weather possessed heavier formations of rust than the rest of the panel. The rusting was quite superficial on welds on the steel containing molybdenum.

10. The area ratio between any two dissimilar metals in contact proved very important and was frequently the determining factor in the amount of corrosion. The anodic metal was usually very much more severely corroded when its area was small as compared with that of the cathodic metal.

11. Alloys 52S-½H, 53ST, and Alclad 24ST were but slightly corroded when in contact with each other but all were anodic to alloy 24ST and were attacked when in contact with it.

12. Alloy 52S-½H invariably was the least attacked of the aluminum alloys when they were in contact with dissimilar metals. Alloy 53ST was usually considerably more corroded, while attack on 24ST and Alclad 24ST alloys was severe. This result does not necessarily reflect the true potential relationships involved, owing principally to inherent differences in the resistance of the various aluminum alloys to corrosion.

13. The aluminum alloys were anodic to stainless steel, nickel, monel, and Inconel and were very severely attacked when exposed in contact with them.

14. Electrodeposited coatings of cadmium on SAE X4130 steel strips attached to aluminum-alloy panels were in excellent condition and intact after 2 years of weather exposure. Electrodeposited zinc coatings on the same steel were mostly corroded off when joined to Alclad 24ST and 53ST sheets. When joined to 52S-½H and 24ST sheets, the zinc was attacked but was not corroded off to the same extent.

15. The magnesium alloys were very anodic to aluminum alloys, or to stainless steel. The adjacent aluminum alloys, especially 24ST and Alclad 24ST, were in turn severely corroded by a base produced during the formation of the resulting corrosion product, which was a basic magnesium carbonate. Dowmetal M proved anodic to Dowmetal H alloy. Painted panels exposed for 2 years to the weather were but slightly corroded.

16. Corrosion products that accumulated at the faying surfaces of the dissimilar metals raised the stresses in some instances enough, with the combined corrosive action, to cause cracks to form in the strips. Such cracks were found on 24ST and Alclad 24ST strips coupled with nickel alloys or stainless steel, on Dowmetal H strips coupled with aluminum alloys or stainless steel, and on stainless-steel strips coupled with Dowmetal M.

17. Painted anodized 24ST panels, with paint schedules utilizing good grades of aluminum-pigmented varnishes conforming to Navy Department Specifications V10, V11, or 52V15b, were in excellent condition after 2 years of exposure.

18. The magnesium-alloy panels, painted with good grades of aluminum-pigmented varnishes, were in excellent condition after 2 years of exposure to the weather, except for slight failures at the edges of and adjacent to those rivet heads from which the paints were off. Paint failures in the tidewater tests became advanced during the second year on three-coat paint schedules. Schedules involving two coats of P27 type (zinc-chromate pigments) primers and two additional coats of aluminum-pigmented varnishes of good grade usually remained in good condition, especially when the second coat of primer was also aluminum pigmented. Primers of the P23 type (iron-oxide pigments) reacted to accelerate attack on the magnesium alloys, after coating failures had occurred.

19. Paint failures were considerably more advanced on the anodized (PT13a) Dowmetal M panels than on those given the chrome-pickle surface treatment and exposed to tidewater. On the Dowmetal H panels, after 2 years of exposure, no differences were observed in the amount of paint failure regardless of which method of surface treatment was used.

National Bureau of Standards,
Washington, D. C., October 2, 1941.

REFERENCES

1. Mutchler, Willard, and Galvin, W. G.: Tidewater and Weather-Exposure Tests on Metals Used in Aircraft. T.N. No. 736, NACA, 1939.

TABLE I. EXPOSURE PERIODS FOR THE VARIOUS KINDS OF PANEL
(The symbol x indicates that one panel of each kind was withdrawn from the exposure rack)

Kinds of panels withdrawn from exposure racks	Exposure period, months										
	Tidewater							Weather			
	1/15	1	3	7½	12	24	36	7½	12	24	36
Aluminum alloys, (1) riveted, (2) spot-welded, (3) seam-welded, (4) painted				x	x	x	x		x	x[a]	x
Aluminum alloys, (1) gas-welded; (2) in contact with (a) each other, (b) plated X4130 steel, (c) stainless steel; (3) alloy 14ST			x	x	x		x	b	x	x	x
Major metal (MK9AS)					x	x			x	x	
Aluminum alloys, insulated from stainless steel						x					
Aluminum alloys, in contact with magnesium alloys Stainless steels, in contact with aluminum alloys Nickel alloys, in contact with aluminum alloys Magnesium alloys, painted with (a) chrome pickled surface, (b) anodized surface			x	x	x		x	x		x	x
Stainless steels (original series)				x	x	x	x	x		x	x[c]
Magnesium alloys (painted), (1) in contact with (a) each other, (b) aluminum alloys, (c) stainless steel; (2) riveted; (3) gas-welded; (4) spot-welded		x	x	x	x			x		x	x
Magnesium alloys (unpainted); (1) in contact with (a) each other, (b) aluminum alloys, (c) stainless steel; (2) riveted; (3) gas-welded; (4) spot-welded	x	x	x		x			x		x	x
Stainless steel, in contact with magnesium alloys	x			x	x		x	x		x	x[c]

[a]Riveted panels, numbers 2, 3, and 6 were lost
[b]Contact panels, numbers 36 and 37 removed at 7½ months instead of at 1 year.
[c]Panels, numbers 4, 7, and 47 were lost

TABLE III. SUMMARY OF THE APPROXIMATE ENDURANCE LIMITS OF STAINLESS STEELS TESTED IN KROUSE FLEXURAL FATIGUE MACHINES BEFORE AND AFTER EXPOSURE TO TIDEWATER OR THE WEATHER AT HAMPTON ROADS, VA.

Exposure	Fatigue properties of stainless steels							
	Straight 18:8		18:8 + 0.5% Cb		18:8 + 0.5% Ti		18:8 + 3.7% Mo	
	Endurance limit (lb/sq in.)	Loss percent	Endurance limit (lb/sq in.)	Loss percent	Endurance limit (lb/sq in.)	Loss percent	Endurance limit (lb/sq in.)	Loss percent
None, uncorroded	68,000	--	75,700	--	74,500	--	64,700	--
Tidewater, 7½ months	61,000	10.3	64,000	15.4	70,500	5.4	61,500	4.9
Tidewater, 1 year	56,500	16.9	66,000	12.8	71,000	4.7	59,500	8.0
Tidewater, 2 years	62,000	8.8	64,000	15.4	68,500	8.1	59,000	8.8
Weather, 7½ months	56,000	17.6	62,000	18.1	65,000	12.8	56,500	12.7
Weather, 2 years	55,000	19.1	59,500	21.4	65,000	12.8	55,500	14.2

TABLE II. DEPTH OF CORROSION MEASURED ON PANELS HAVING ALUMINUM ALLOYS EXPOSED IN CONTACT WITH EACH OTHER OR WITH DISSIMILAR METALS

Main panel	1- by 4-inch strips	Corrosion range of average maximum depths, thousandths inch[1]					
		On main panel at faying surfaces		On strips, outer surfaces		On strips at faying surfaces	
		Tidewater	Weather	Tidewater	Weather	Tidewater	Weather
		1 year	2 years	1 year	2 years	1 year	2 years
24ST	Alclad 24ST	5-6[a]	0-1[b]	2-2.5[c]	1-2[d]	3-4[c]	1-2[d]
24ST	53ST	2-3[a]	0-1[b]	5-10[e]	2-3[e]	15-24[e]	6-8[e]
24ST	53ST, extrusion	1.5-2[a]	0.1[b]	10-17[e]	7-8[e]	12-20[e]	8-12[e]
24ST	52S-½H	3-4[a]	0.1[b]	11-13[f]	0-1	12-15[f]	15-18[f]
Alclad 24ST	24ST	2-2.5[b,c]	2-2.5[b,c]	0-1	1-1.5	1-3	1.5-2
Alclad 24ST	24ST, extrusion	2-2.5[b,c]	2-2.5[g,c]	0-1	1-1.5	1-2	2-3
Alclad 24ST	53ST	1.0-1.5[g,d]	1-2[g]	0-1	2-4[e]	0-1	1-2[e]
Alclad 24ST	53ST, extrusion	1-1.5[g,d]	1-1.5[g]	1-2	3-4[e]	1.5-2[e]	2-2.5[e]
Alclad 24ST	52S-½H	0-1[g,d]	0-1[g]	0-1	0-1[f]	0-1	0-1[f]
53ST	24ST	7-14[b,e]	5-7[b,e]	0-1	0-1	0-1	0-1
53ST	24ST, extrusion	2-3[g,e]	5-6[g,e]	0-1	1-3	0-1	0-1
53ST	Alclad 24ST	0-1[g]	1-2[g,e]	0-1[d]	1-1.5[d]	0-1[j]	1-1.5[d]
53ST	52S-½H	0-1[g]	1-2[g,f]	0-1	1-2	0-1	1-2
52S-½H	24ST, extrusion	2.5-3[b,f]	10-16[b,g]	0-1	0-1	0-1	0-1
52S-½H	Alclad 24ST	1.5-2[g,f]	0-1[g]	0-1[d]	1-2[d]	1-1.5[d]	1-2[d]
52S-½H	53ST	0-1[g]	1-2[g]	0-1	3-5[e]	0-1	0-1
52S-½H	53ST, extrusion	0-1[g]	1-1.5[g]	0-1	2-3[e]	0-1	0-1
24ST	X4130 Steel + Cd	10-60[a,h]	0-1[b]	2-3[i]	0-1[d]	1-2[i]	0-1[d]
Alclad 24ST	X4130 steel + Cd	0-2[b,c,h]	0-1[g,d]	0-1[c]	0-1[c]	0-1[d]	0-1[c]
53ST	X4130 steel + Cd	12-60[b,h]	0-1[g]	0-1[c]	0-1[d]	0-1[d]	0-1[d]
52S-½H	X4130 steel + Cd	10-60[b,h]	0-1[g]	0-1[c]	0-1[d]	0-1[d]	0-1[d]
24ST	X4130 steel + Zn	1-5[b,h]	1-2[b]	3-4[i]	2-3[i]	1-2[i]	1-2[c]
Alclad 24ST	X4130 steel + Zn	3-20[a,h]	0-1[b]	1-2[i]	0-1[c]	0-1[i]	0-1[i]
53ST	X4130 steel + Zn	10-25[a,e,h]	20-60[b,e]	1-2[i]	2-3[i]	0-1[i]	1-2[i]
52S-½H	X4130 steel + Zn	5-10[a,g]	0-1[b]	1-2[i]	0-1[d]	1-2[i]	0-1[c]
24ST	18Cr,8 Ni,0.5 Ti	40[a,h]	40[a,h]	0	0	0	0
Alclad 24ST	18Cr,8 Ni,0.5 Ti	15-24[a,h,c]	2-2.5[a,i]	0	0	0	0
53ST	18Cr,8 Ni,0.5 Ti	5-6[g]	4-5[b,e]	0	0	0	0
52S-½H	18Cr,8 Ni,0.5 Ti	10-20[b,f]	5-8[a]	0	0	0	0
18Cr,8 Ni, 0.5 Ti	24ST	0	0	20-24[a]	3-5[a]	10-18	20-24[j]
Do	Alclad 24ST	0	0	2.5-3[a,i]	2-6[a]	18-20	3-6[h,i]
Do	53ST	0	0	20-30[a,e]	4-5[b,e]	30-40[e]	15-40[e,h]
Do	52S-½H	0	0	3-7[a]	1-4[b]	28-40	5-6
Nickel	24ST	0[a]	0[a]	3-4	2-3[h]	25-35[k,j]	20-23[k,d]
Nickel	Alclad 24ST	0[a]	0[b]	1-3[c,h]	2.5-3[c]	30-32[k,j]	2.5-3.5
Nickel	53ST	0[b]	0[b]	18-20[e,h]	5-8[e,h]	15-20[e,h]	10-15[e,h]
Nickel	52S-½H	0[b]	0[a]	12-15[h]	2-4[f,h]	15-20[h]	10-20[f,h]
Monel	24ST	0[a]	0[a]	3-5	4-5[h]	35-40[k,j]	30-37[k,j]
Monel	Alclad 24ST	0[a]	0[a]	2.5-3[a,h]	2.5-3[i,h]	35-40[k,j]	13-22[k,h]
Monel	53ST	0[a]	0[b]	13-15[e,h]	4-10[e,h]	35-40[k,e]	10-12[e,h]
Monel	52S-½H	0[a]	0[b]	20-23[h]	2-4[g]	20-30[h]	28-30[e,h]
Inconel	24ST	0[a]	0[a]	2-4	5-7[h]	25-27[k,j]	35-40[k,j]
Inconel	Alclad 24ST	0[a]	0[b]	2-3[a]	2-2.5[i,h]	22-25[k,j]	18-35[k,h]
Inconel	53ST	0[b]	0[g]	10-15[e,h]	2-4[e,h]	15-20[k,e]	8-10[e,h]
Inconel	52S-½H	0[b]	0[g]	5-8[h]	3-4[f,h]	20-24[k]	6-10[h]

[1]Values from 0-1 indicate that corrosion was usually less than 0.0005 inch deep.
[a]Considerable corrosion products accumulated at faying surfaces, strips forced away from panel.
[b]Some corrosion products accumulated at faying surfaces, strips partially forced away from panel.
[c]Protective coating penetrated in some places.
[d]Protective coating not penetrated.
[e]Intercrystalline attack present, usually associated with pits.
[f]Traces of intercrystalline attack present, usually associated with pits.
[g]Very little corrosion products at faying surfaces.
[h]Attack segregated or especially severe along line where edge of strips contact the main panel.
[i]Protective coating practically all corroded off.
[j]Stress-corrosion cracks present.
[k]Strips or panel in advanced stages of disintegration.

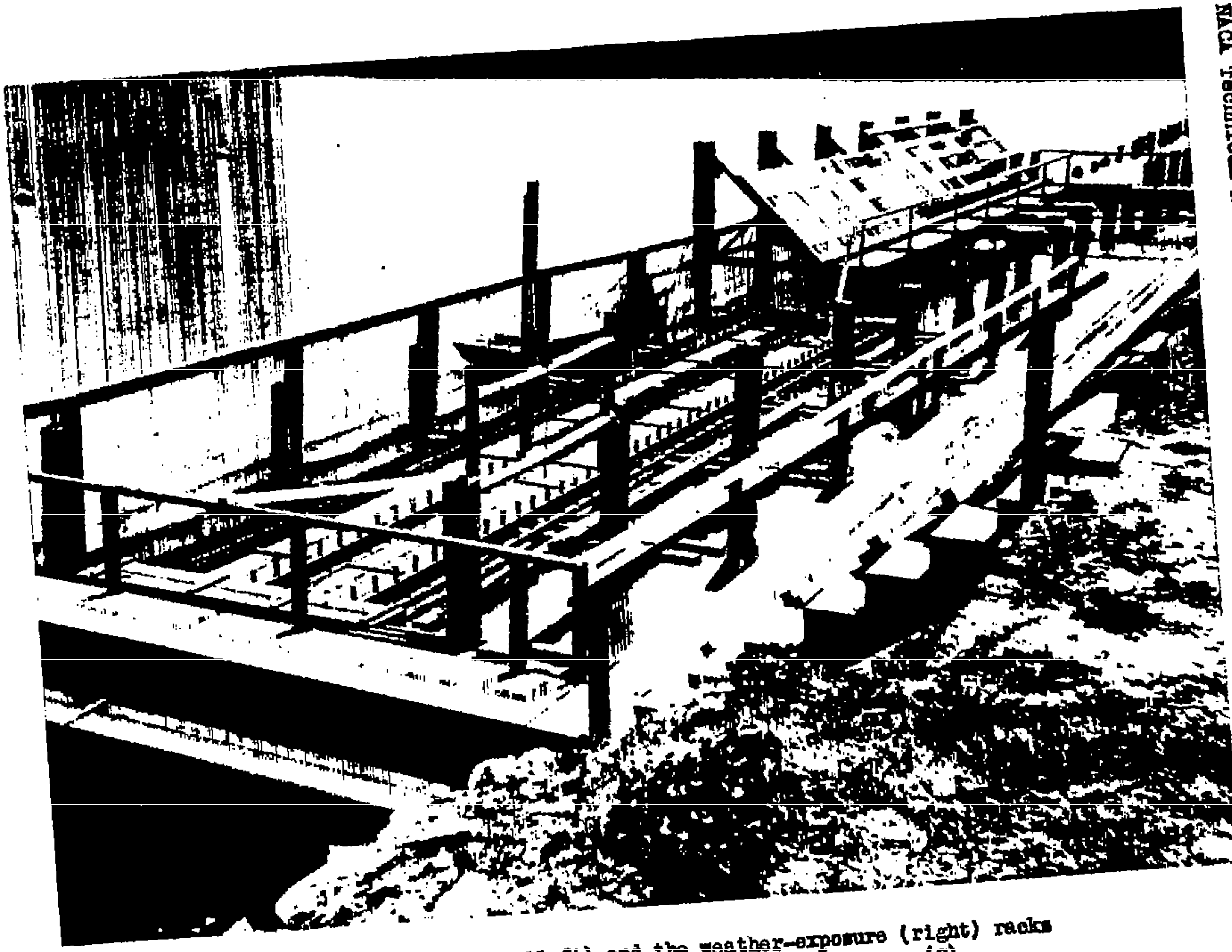


Figure 1.- The tidewater (left) and the weather-exposure (right) racks at Boush Creek, Hampton Roads Naval Air Station (2).

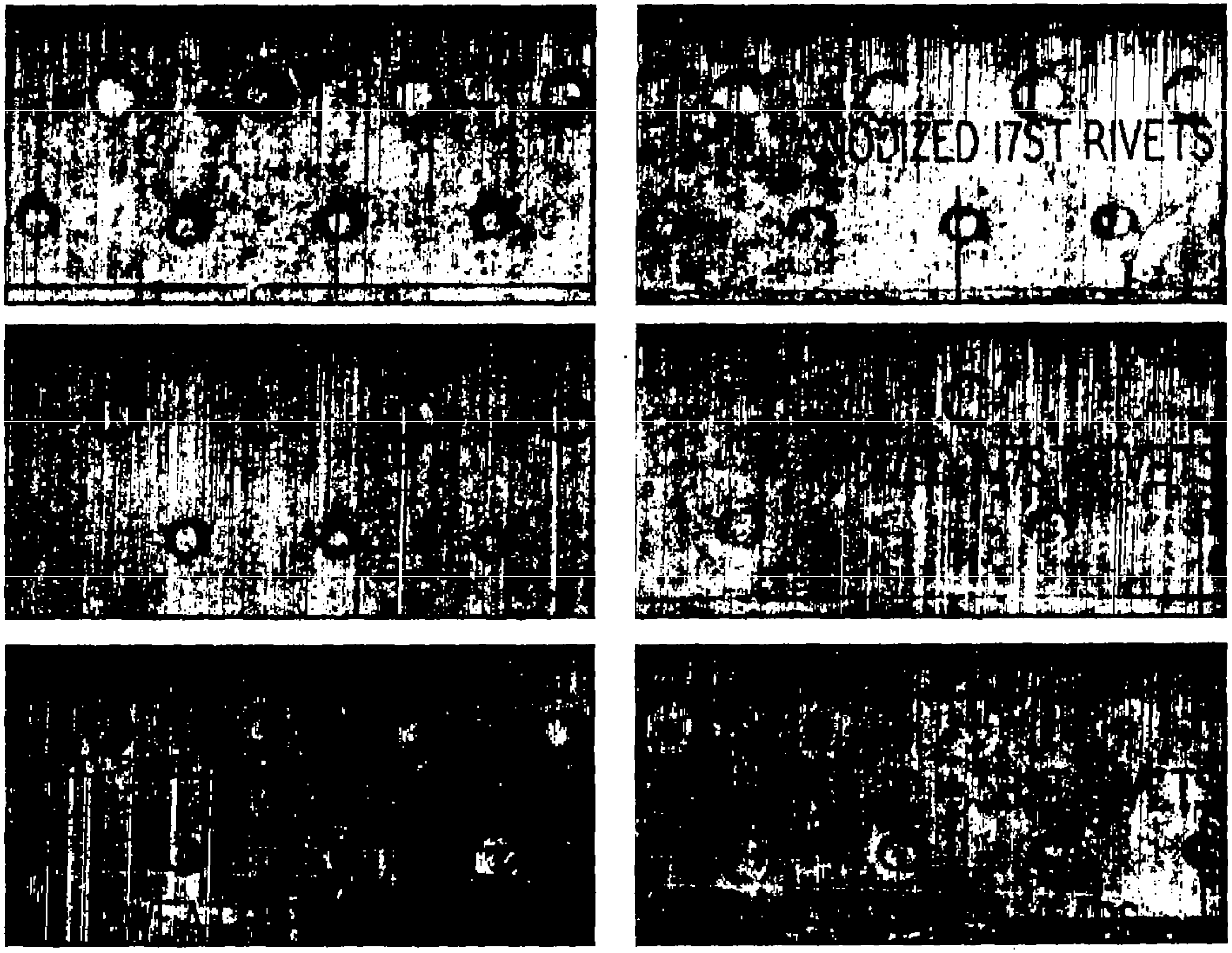


Figure 2.- Rivets used on 24ST alloy panels exposed for 2 years. Note the advanced disintegration of the 53ST and the anodized A17ST rivets exposed to the tidewater as compared with those exposed to the weather, and the relative absence of attack on the anodized 17ST rivets. In this, and all similar photographs that follow, the large letters at the right apply to the entire horizontal rows, while those at the tops or bottoms apply to the entire vertical rows. x 1 (4 and 6).

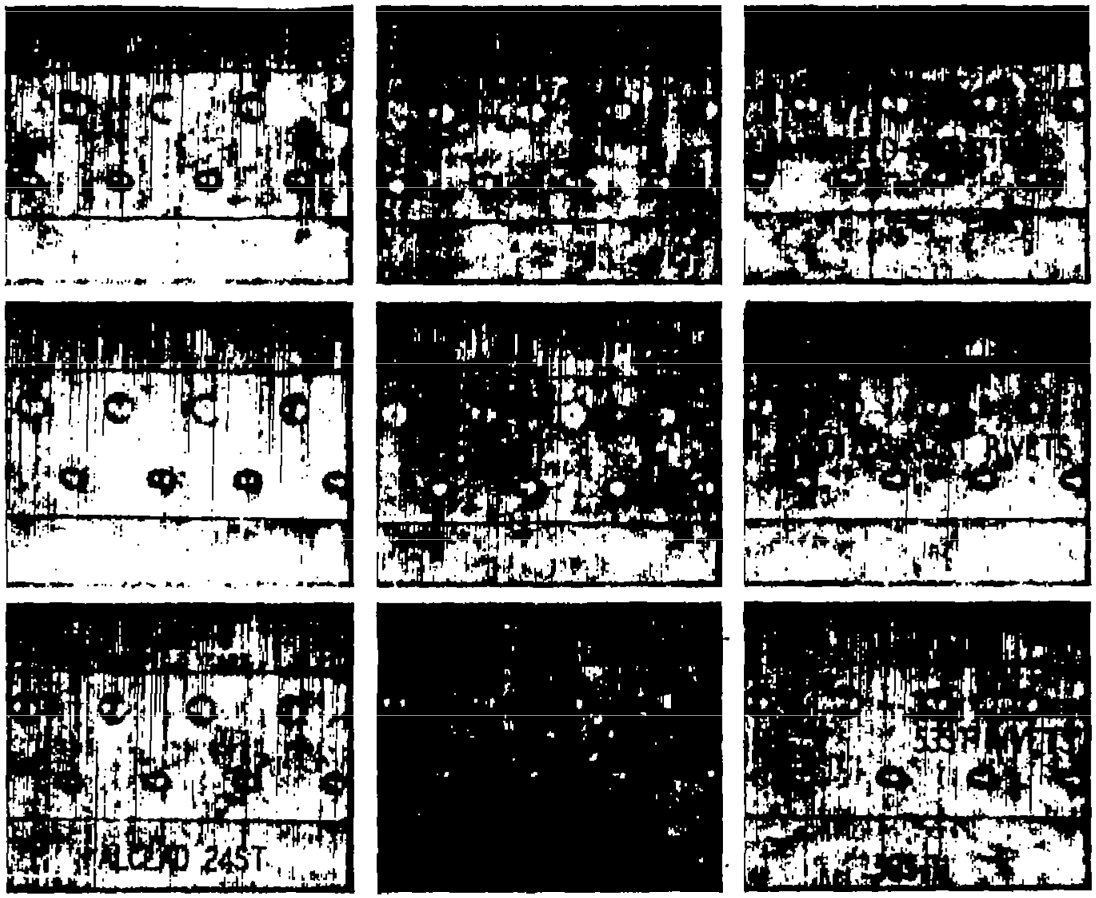


Figure 3.- Rivets used on panels of Alclad 24ST, 53ST, and 52S-½H alloys exposed to tidewater. Neither the rivets nor the sheets are corroded. x 1/2 (5).

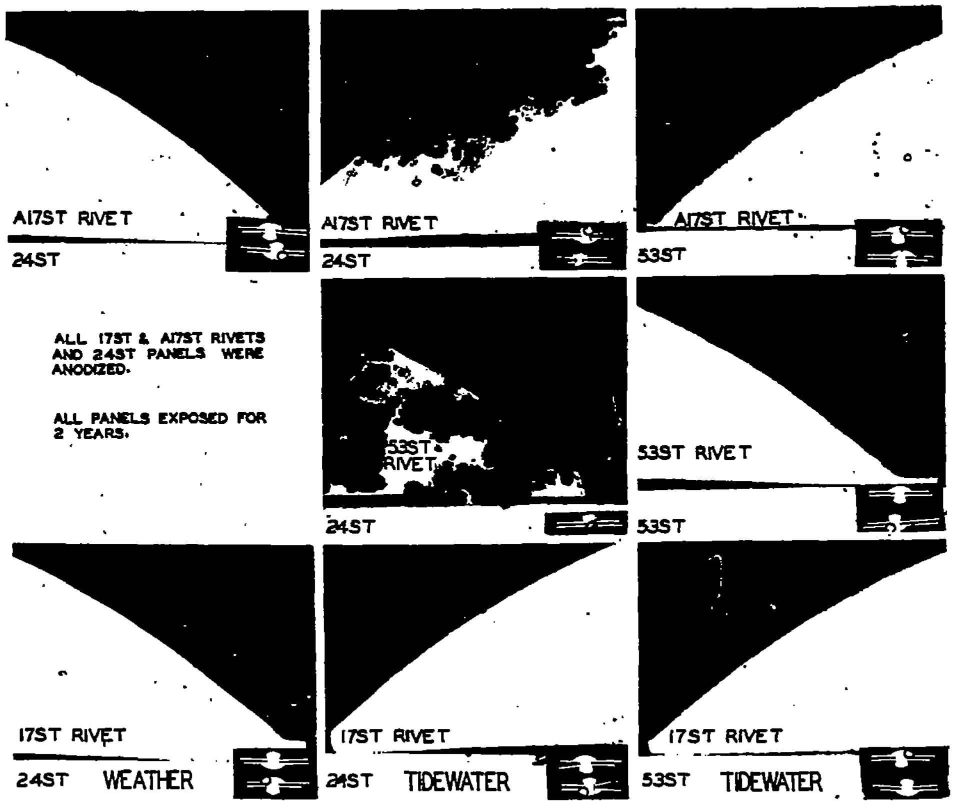


Figure 4.- Corrosion on rivet heads and 53ST and anodized 24ST sheets. Attack was especially severe on 53ST and anodized A17ST rivets joined to 24ST sheet and exposed to tidewater. Photomicrographs, x 25; cross sections (in black rectangles), x 1/2.

Figure 5.- Rivets used on panels of Alclad 24ST, 53ST, and 52S-½H alloys exposed to the weather. Attack on both rivets and sheet was, in general more severe than in the tidewater tests. x 1/2 (6).

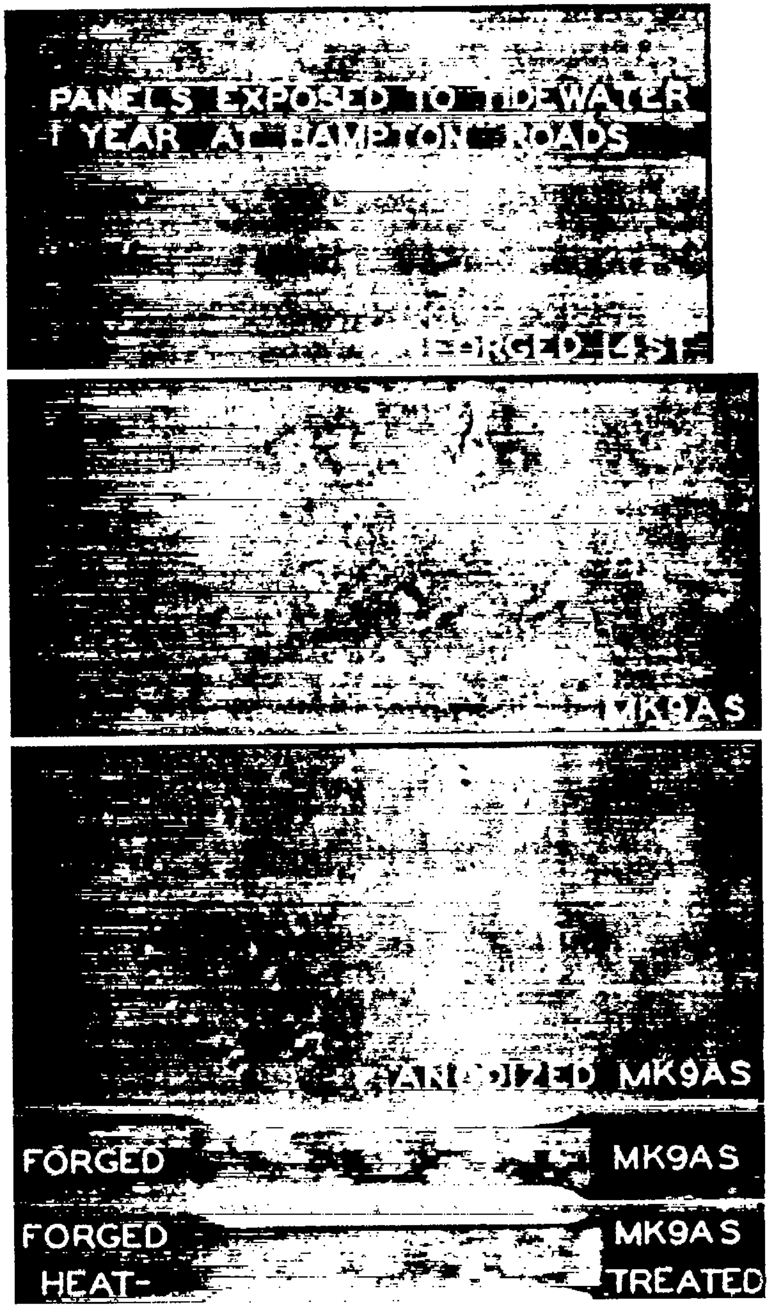


Figure 6.- Forged 14ST and Major metal (MK9AS) panels exposed to tide-water. These alloys were the most susceptible to corrosion of all the aluminum alloys included in the test. x 1.

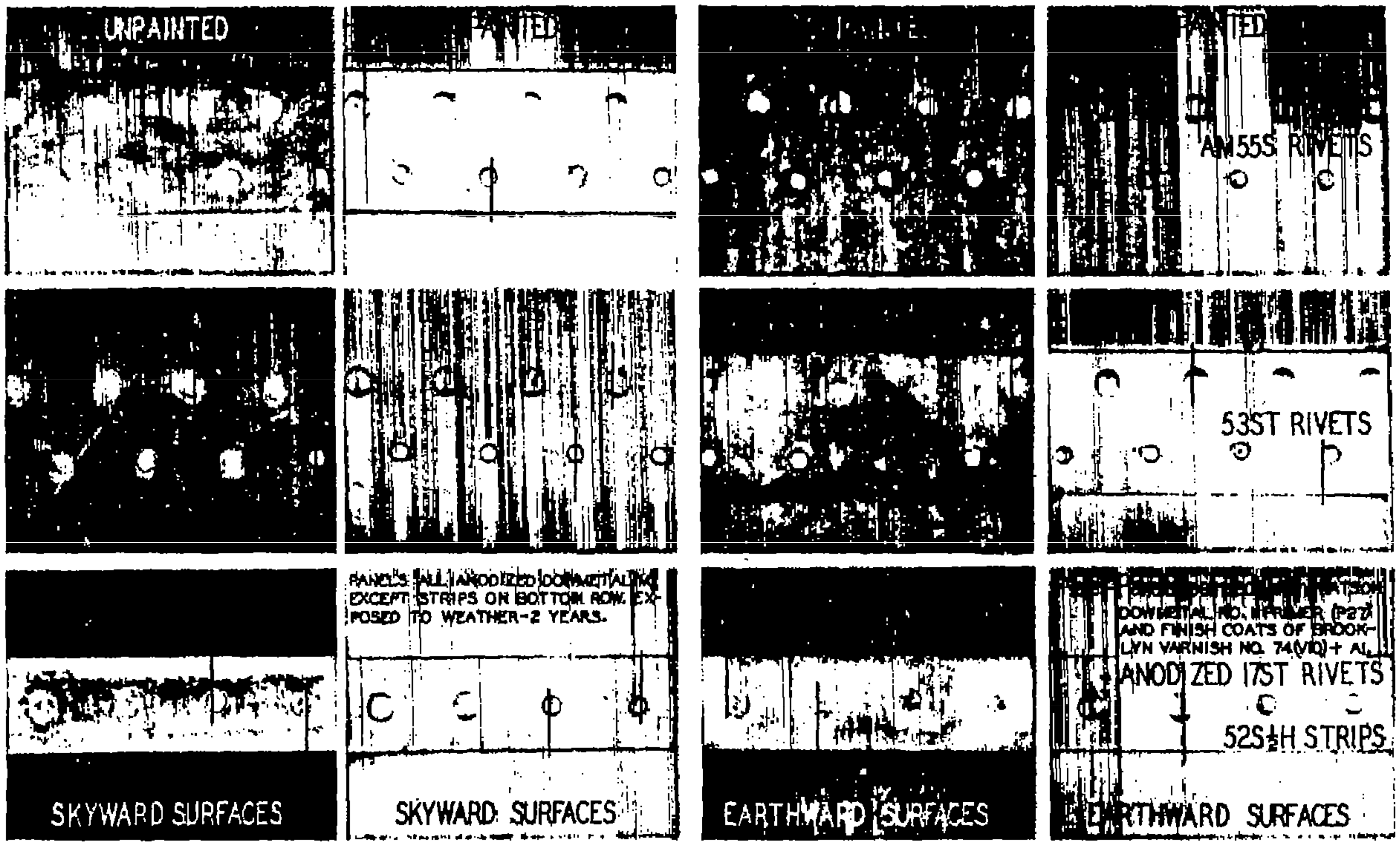


Figure 7.- Rivets on Dowmetal M panels exposed to the weather. The AM 55S rivets were very much less attacked than the 53ST or anodized 17ST rivets. The paint coating, however, protected both the rivets and the sheet from attack. x 1/2 (8).

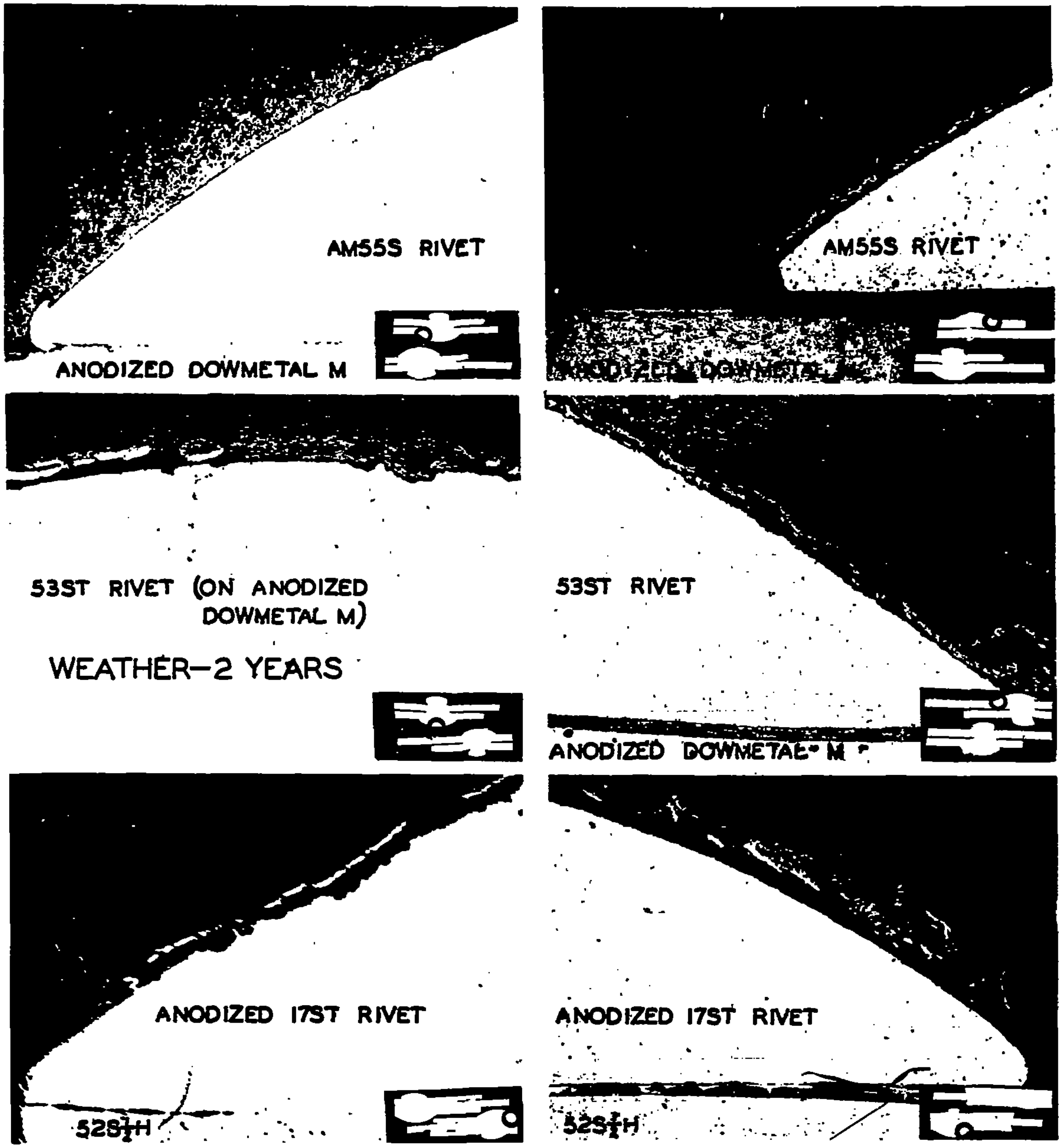


Figure 8.- Corrosion on rivets used for joining Dowmetal M sheets. Attack was least on the unanodized AM55S, intermediate on the 53ST, and most on the anodized 17ST rivets on unpainted panels. None of the rivets on painted panels were corroded. Micrographs, x 40; cross-sections, x 1.

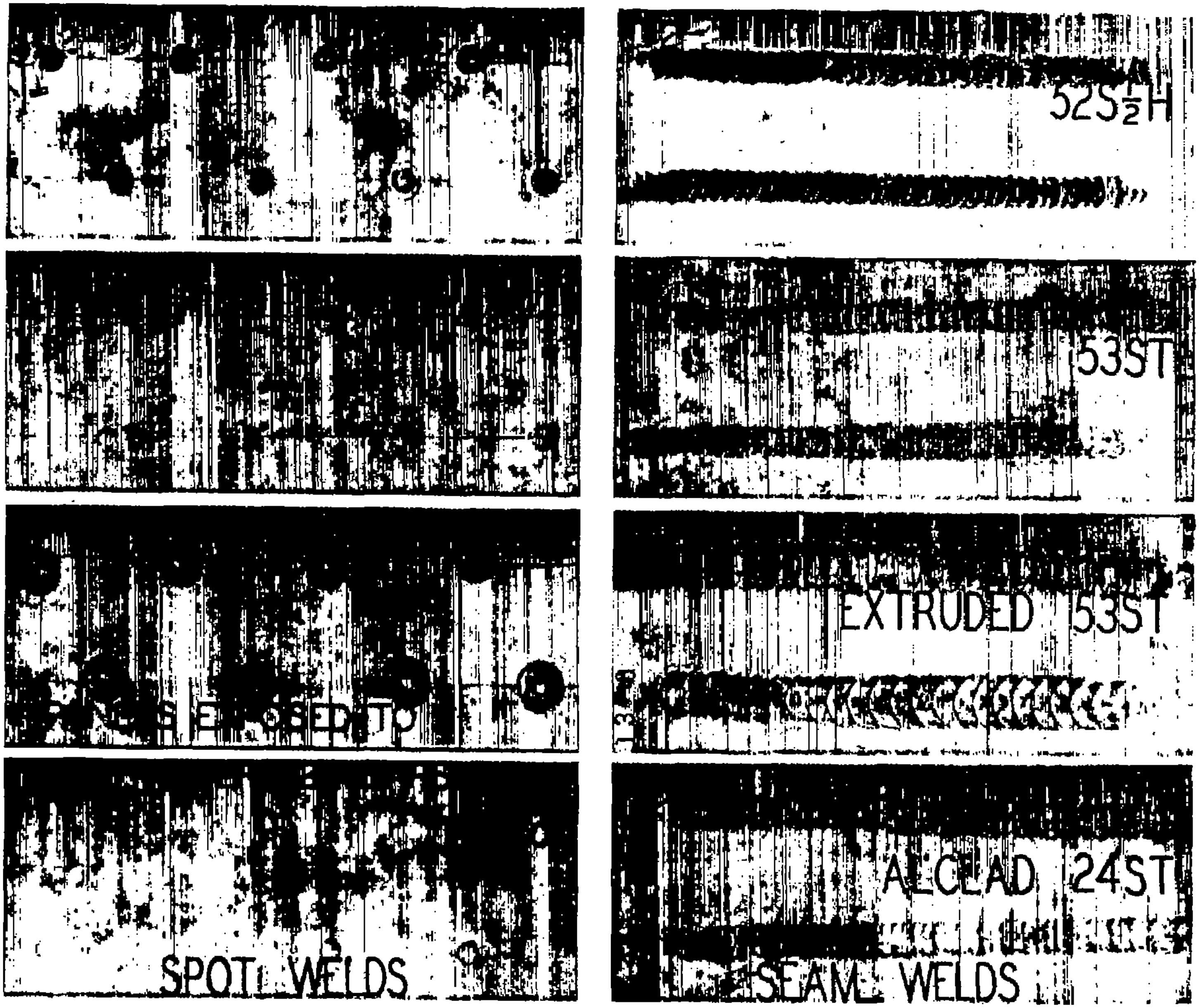


Figure 9.- Welded aluminum alloy panels remained practically unattacked after 2 years of exposure to tidewater. The dark colorations on some of the welds were caused by the copper electrodes used for welding. x 1 (10).

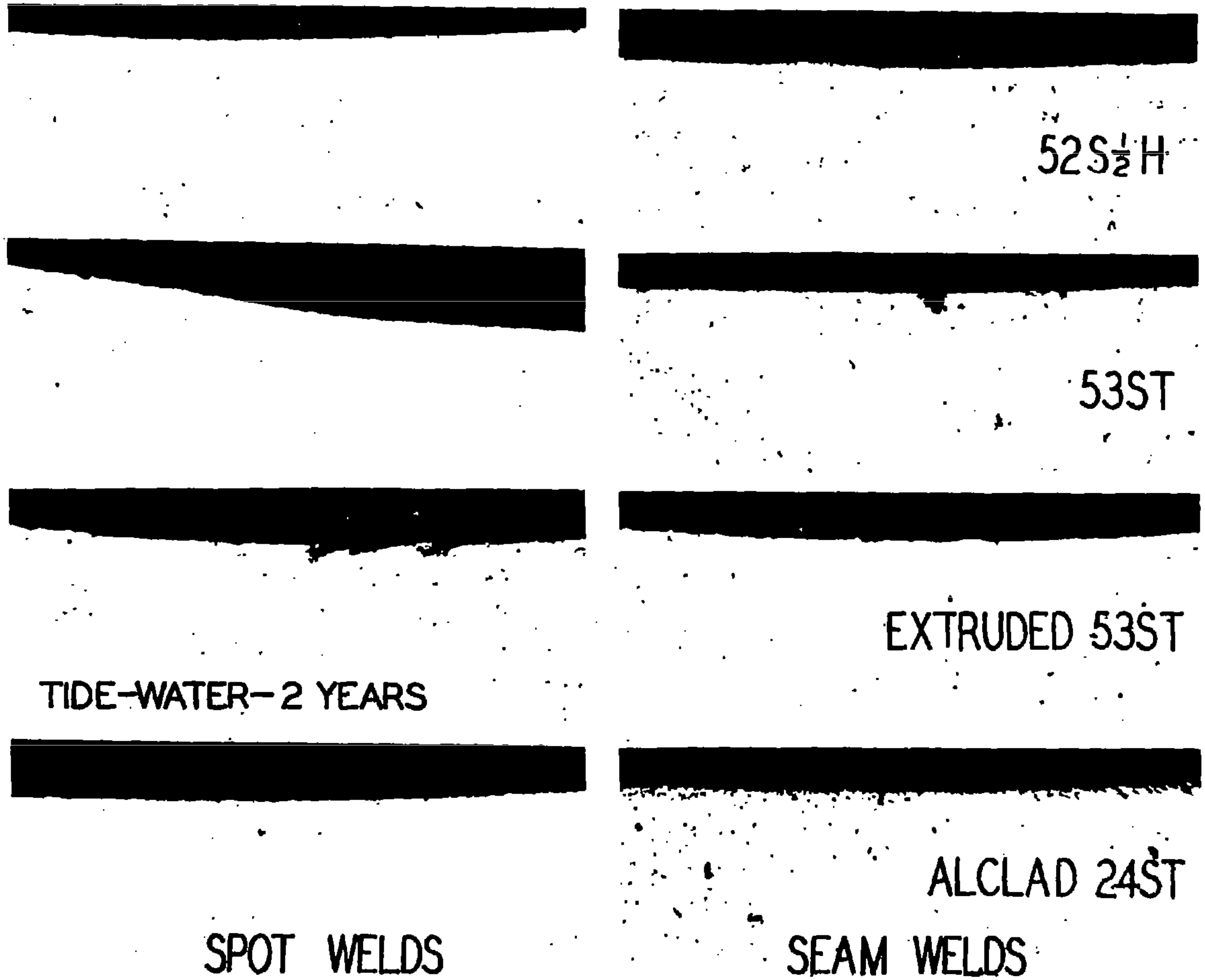


Figure 10.- Microscopic examinations of welds on aluminum-alloy panels exposed to tidewater revealed that corrosion was confined to small isolated areas and that corrosion depth seldom exceeded 0.002 inch. x 50.

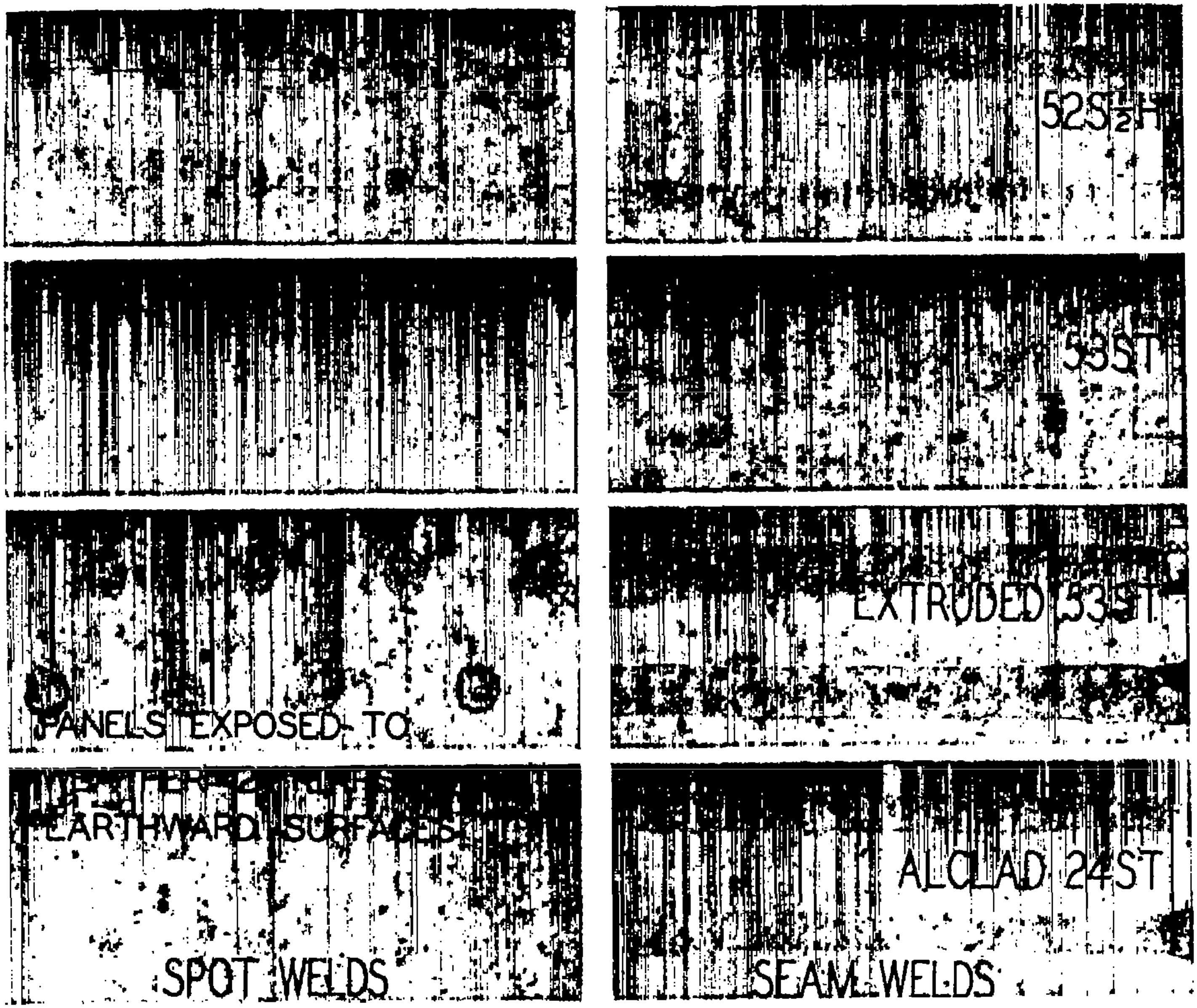


Figure 11.- Welded aluminum-alloy panels exposed to the weather were more corroded than those exposed to tidewater, especially at the welds. x 1 (11).

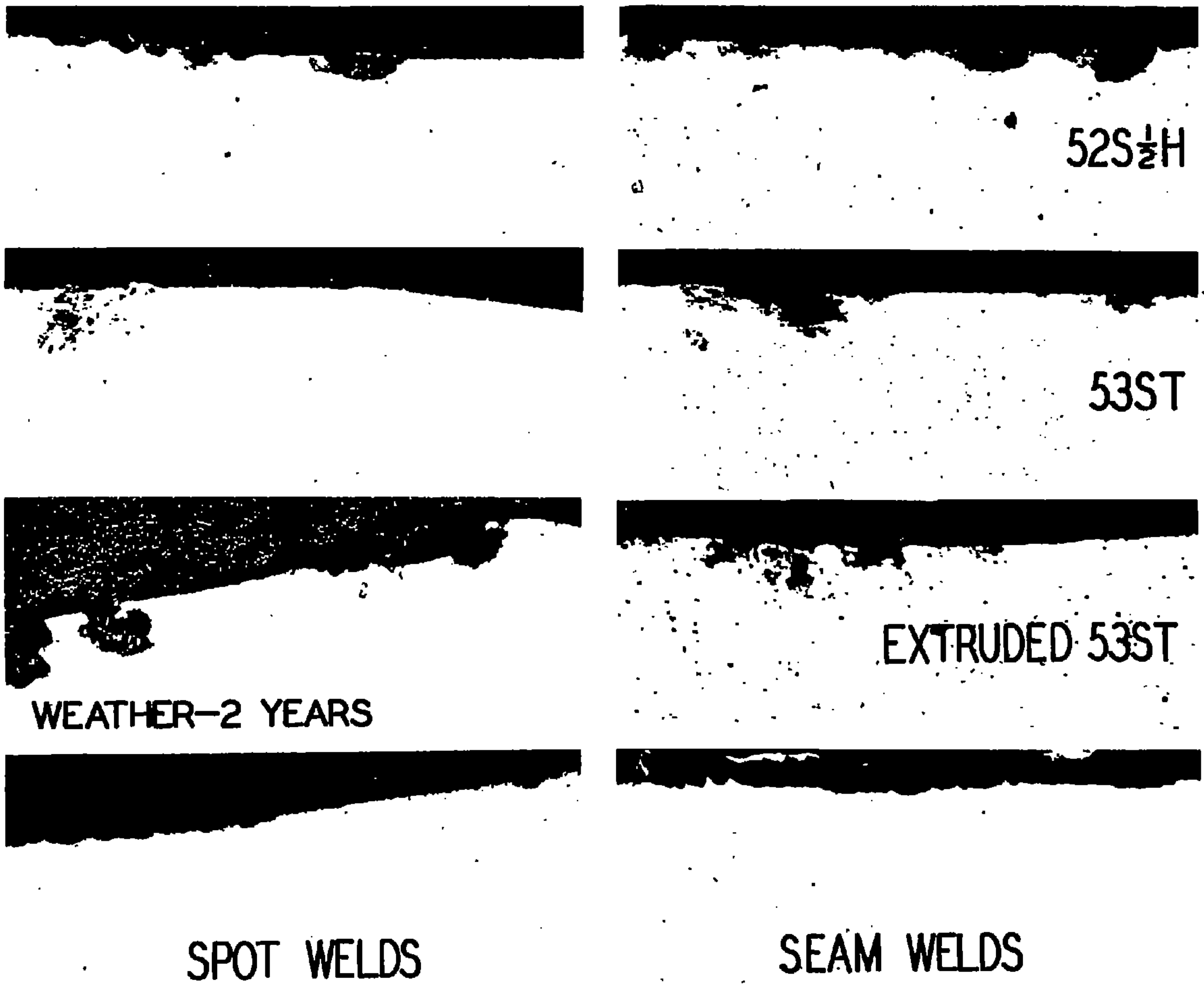


Figure 12.- Microscopic examination of welds on aluminum-alloy panels exposed to the weather revealed considerable corrosion of greater depth than occurred on unwelded portions. Seam welds were the most severely attacked. Corrosion on welds on Alclad 24ST was shallower than on the other alloys but penetrated the protective aluminum coating in some instances. x 50.

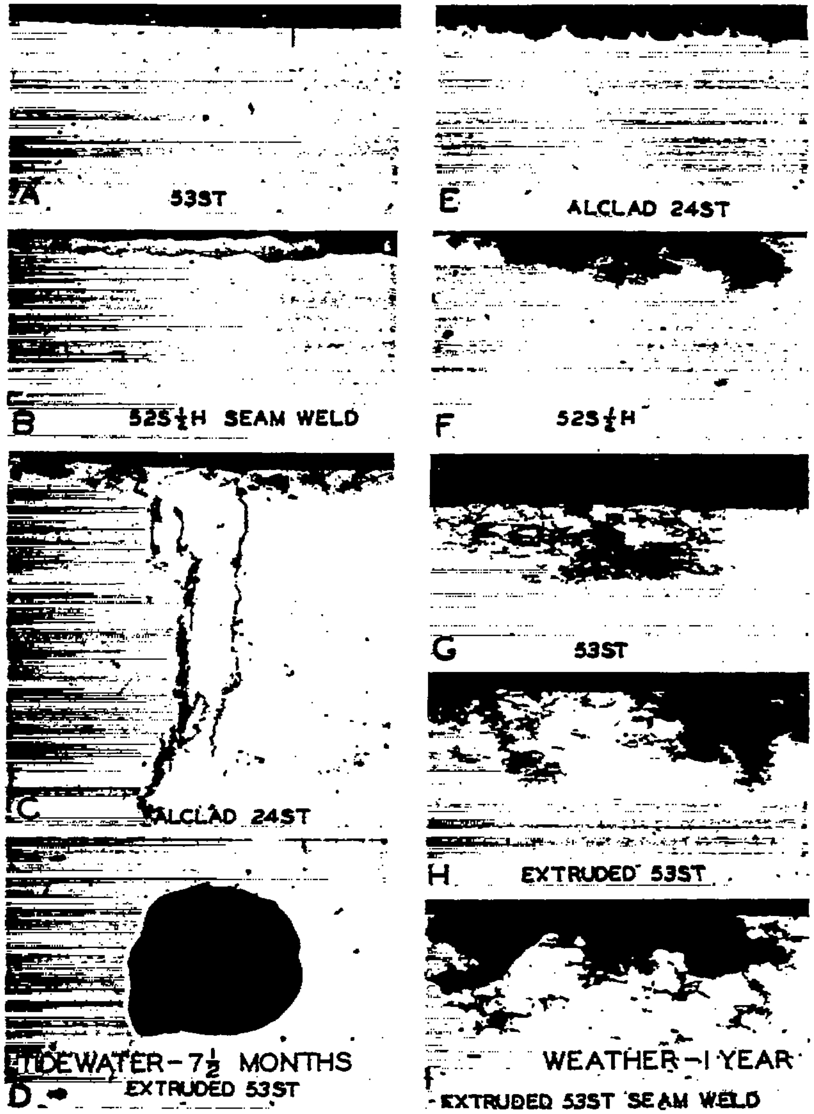


Figure 13.- Photomicrographs of welds on aluminum-alloy panels exposed to weather or to tidewater. Spot welds are pictured, unless otherwise noted. A - Formative stage of intercrystalline corrosion. B - Coating on weld, perhaps resulting from reaction with the electrode. C - Cracks present in some of the spot welds in this alloy. D - Cavity, representative of those of average size found in some spot or gas welds. E - Pitting, though general, had not penetrated the aluminum protective coating during the first year. F - Traces of intercrystalline attack were occasionally associated with pits on the 52S-½H alloy. G - Intercrystalline corrosion on an area of the sheet remote from a weld. H and I - Intercrystalline corrosion on welds. x 60.

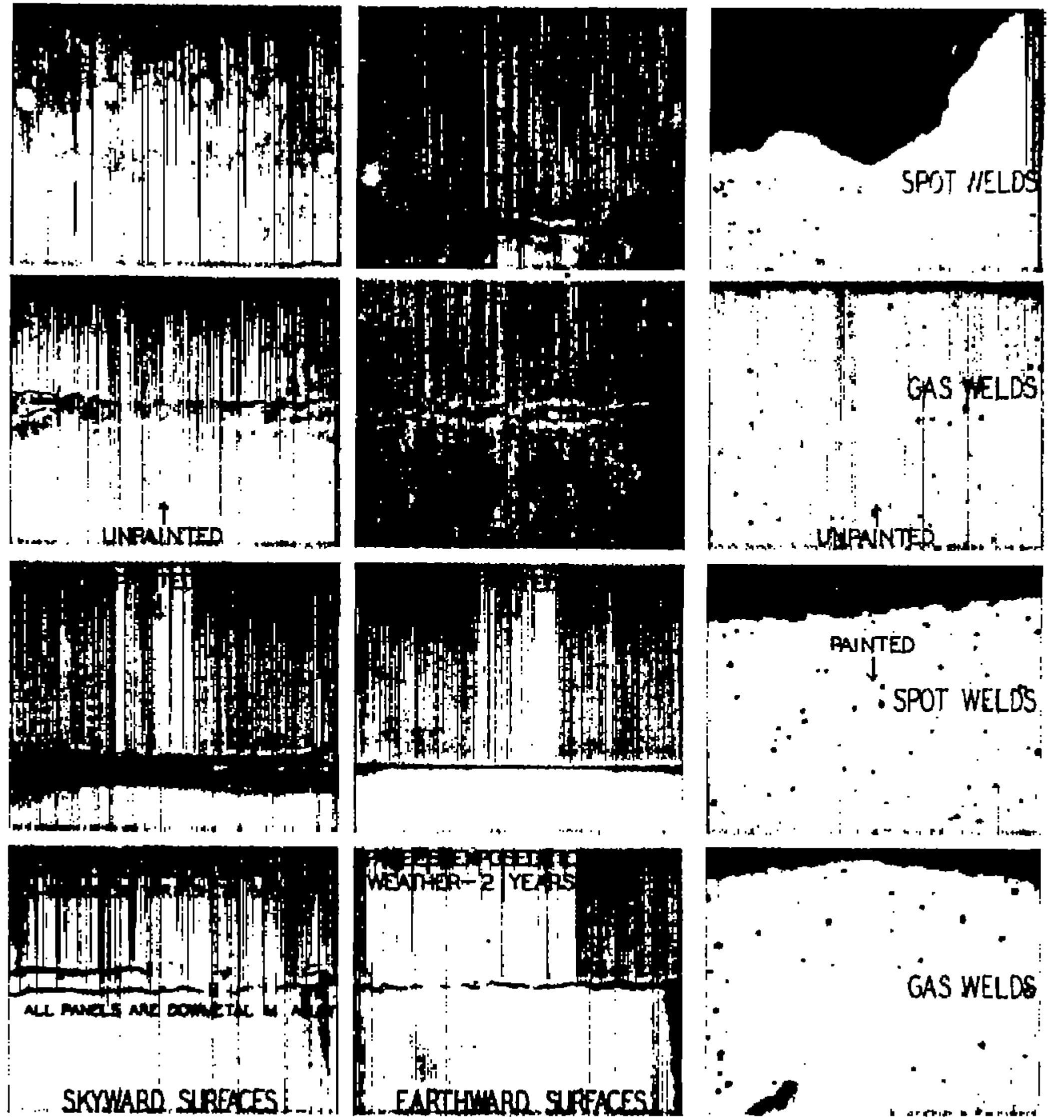


Figure 14.- Surface appearance and cross section of Dowmetal M panels with spot and gas welds exposed to the weather. The spot welds were susceptible to corrosion owing to contaminations of copper derived from the electrodes used in welding. The gas welds were quite resistant to corrosion and were attacked, in general, less than the rest of the panel. Painted panels were relatively free from corrosion. Micrographs, x 1/2; photomicrographs, x 25. (12).

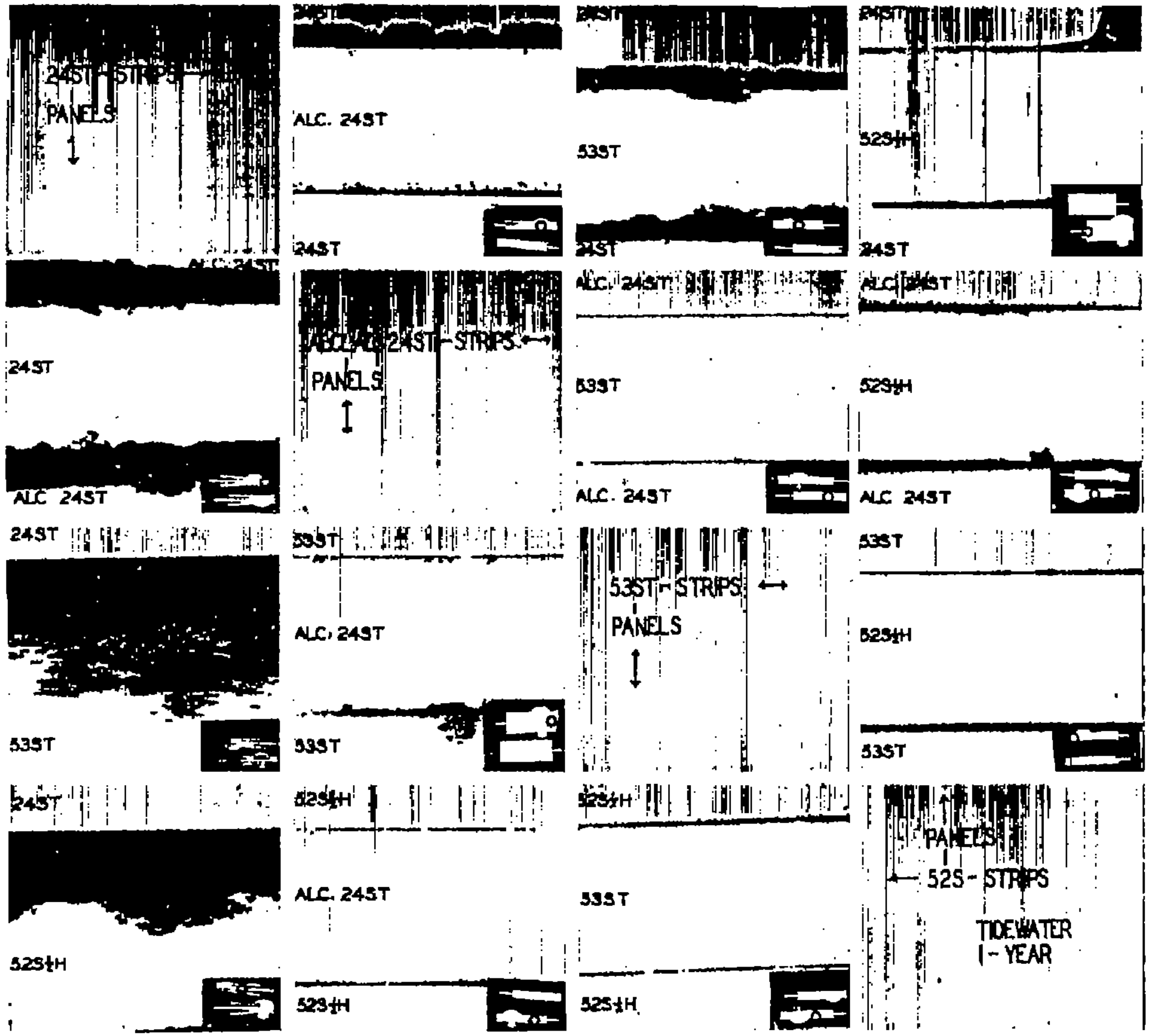


Figure 15.- Cross sections showing aluminum alloys exposed to tidewater in contact with each other. Note that the Alclad 24ST, 52S-½H, and 53ST were anodic to 24ST alloy and were especially severely attacked when 24ST was the main panel. The lack of proximity of strips to the panels, in some instances, is a criterion of the amount of accumulated corrosion products at the faying surfaces which forced the sheets to separate. Photomicrographs, x 25; smaller cross section, x 1/2. (13 and 14).

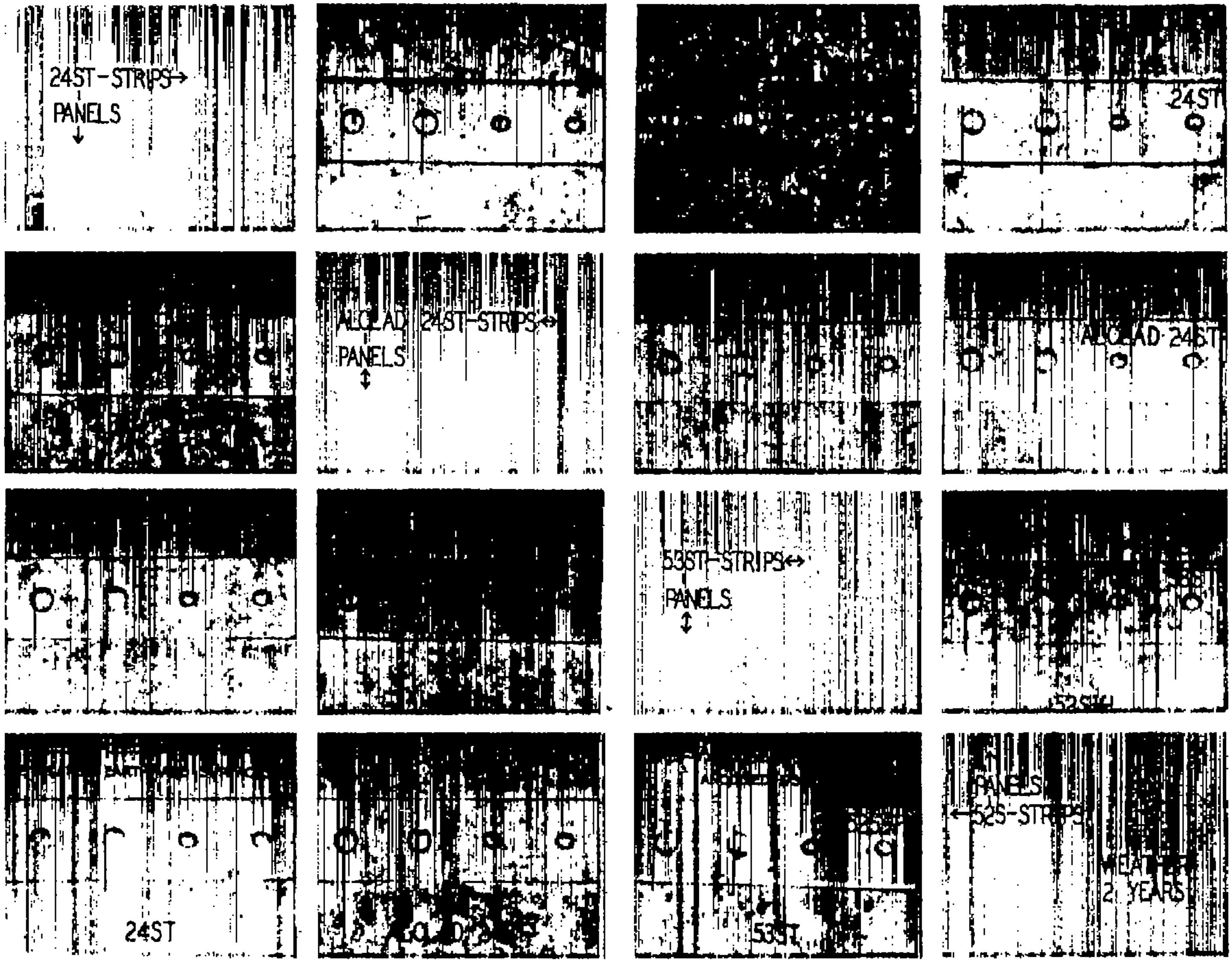


Figure 16.- Surface appearance of aluminum alloys exposed to the weather in contact with each other. Accumulations of corrosion products at the faying surfaces were usually much less than when the same alloys were exposed to tidewater or were in contact with more dissimilar metals. x 1/2 (13 & 14)

Figure 17.- Cross sections showing aluminum alloys exposed to the weather in contact with each other. Corrosion owing to electrolytic effects were similar to those observed in the tidewater tests but were usually less severe. Photomicrographs, x 25; smaller cross sections, x 1/2.

Figure 18.- Aluminum-alloy panels in contact with SAE X4130 steel having electrodeposited coatings of zinc and cadmium, and with stainless steel. Cadmium-plated strips remained in relatively excellent condition, but the zinc coatings were in either partial or complete stages of disintegration. Corrosion products at the faying surfaces of one of the 24ST-stainless steel combinations separated the metals enough to cause one of the rivet heads to break off. x 1/2 (15-16).

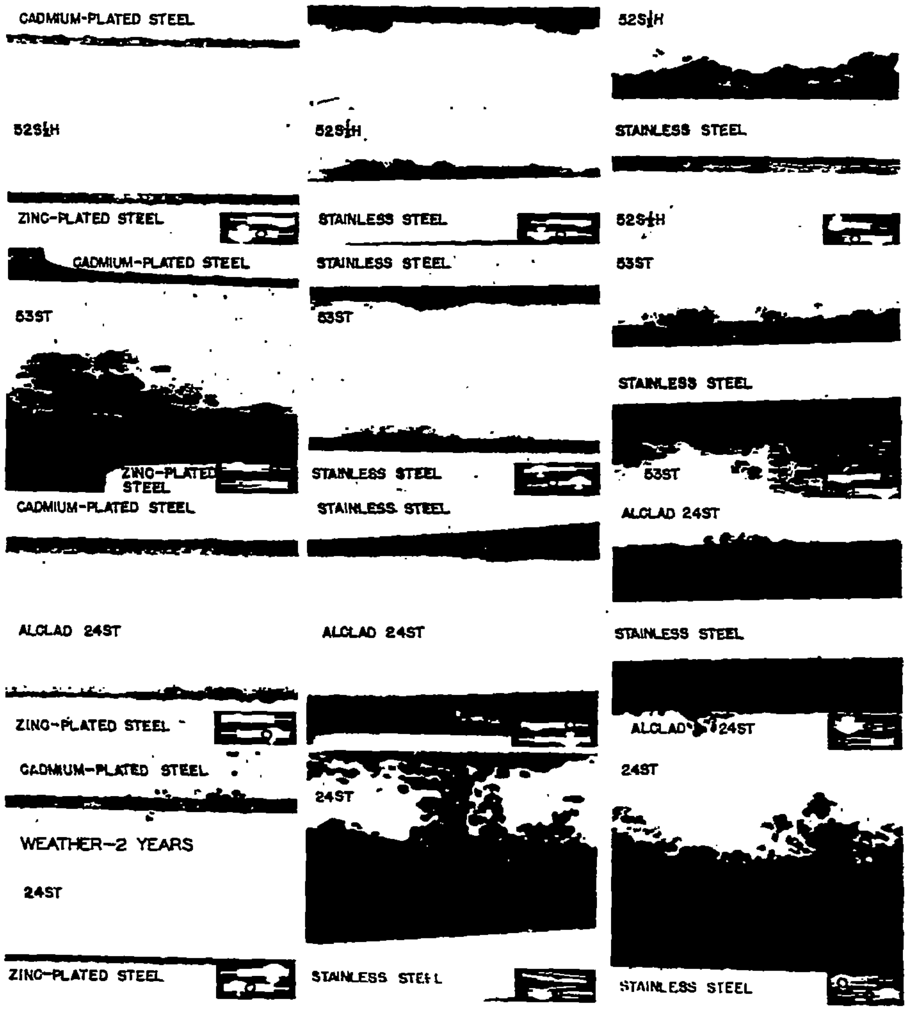


Figure 19.- Cross section showing aluminum alloys exposed to the weather in contact with electrodeposited coatings of cadmium and zinc or with stainless steel. Attack at the faying surfaces was usually deepest on the main panel at areas near the edges of the strips, especially when corrosion products were present in quantity. Photomicrographs, x 25; smaller cross sections, x 1/2.

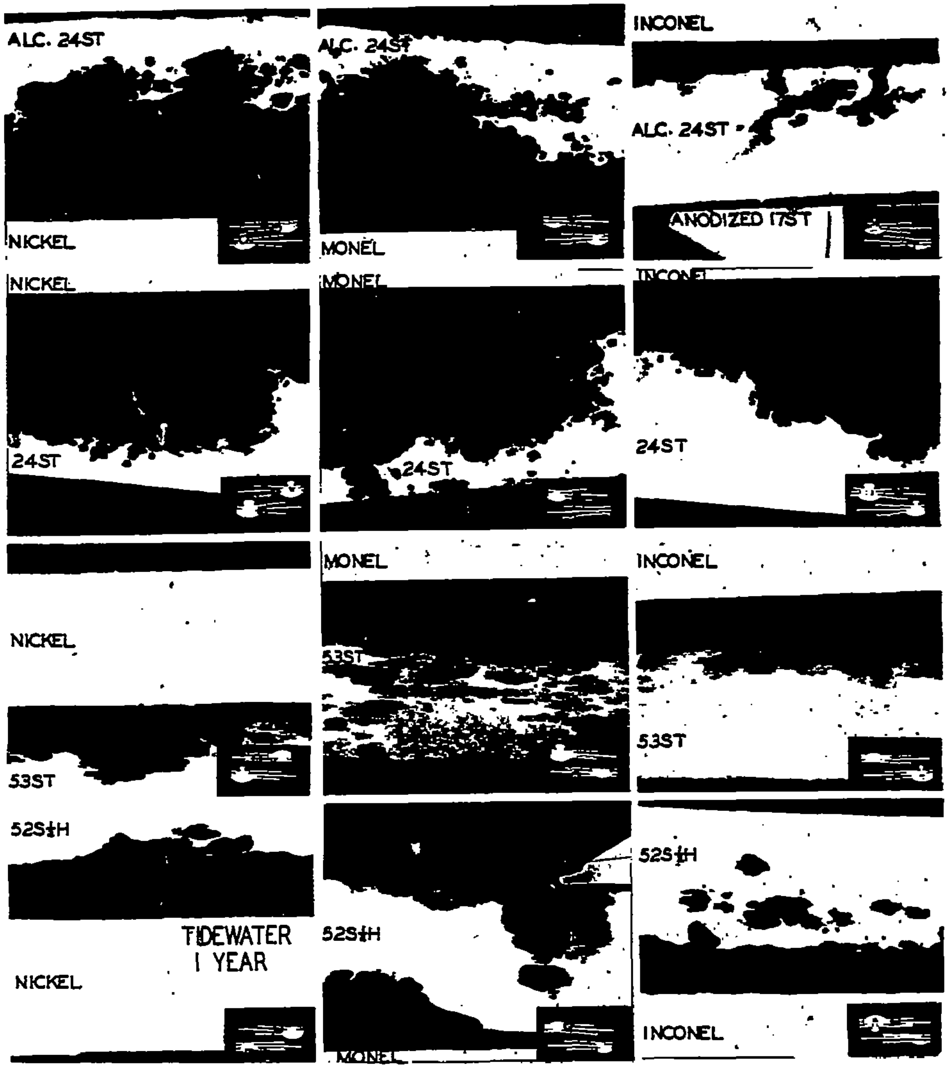


Figure 20.- Cross sections showing nickel alloy panels exposed to tide-water in contact with aluminum alloys. Attack on the aluminum alloys was very severe in every instance. Note the stress-corrosion cracking on the Alclad 24ST strips joined to Inconel (upper right corner). Photomicrographs, x 25; smaller cross sections, x 1/2 (17).

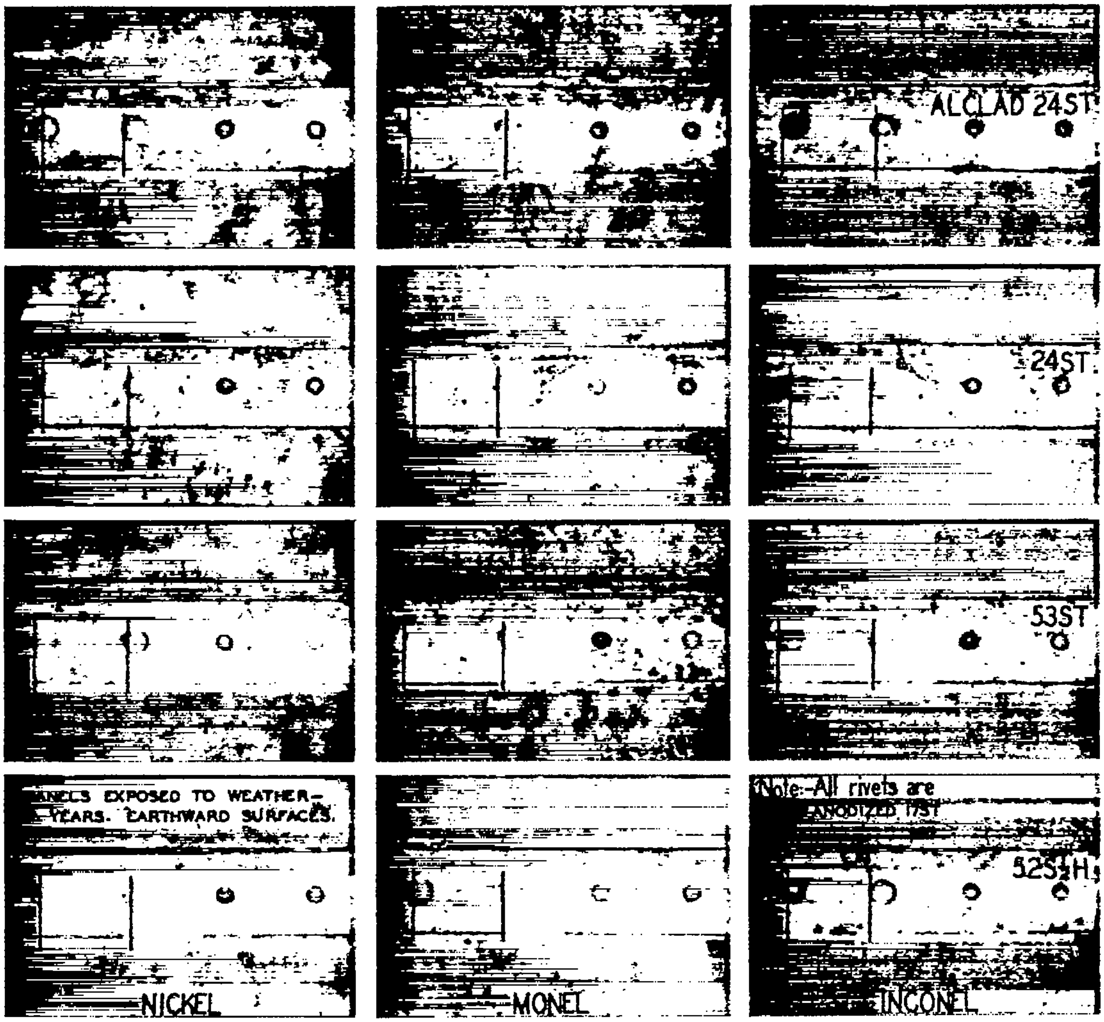


Figure 21.- Nickel alloy panels exposed to the weather in contact with aluminum alloy strips. The presence of considerable corrosion products along the edges of the strips indicates severe attack owing to electrolytic effects. x 1/2 (17).

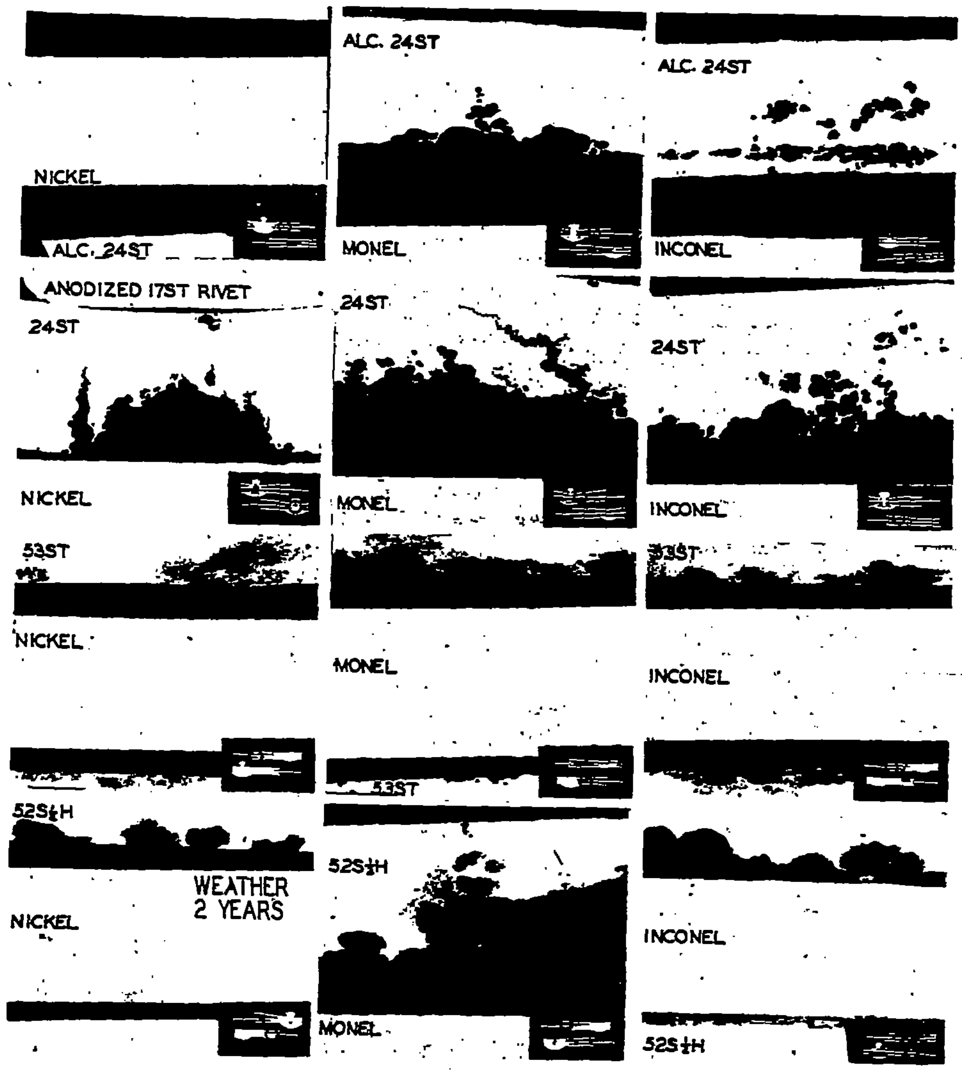


Figure 22.- Cross section showing nickel alloy panels exposed to the weather in contact with aluminum alloys. Compare with Figure 20. Note cracks on 24ST strips in contact with nickel and monel metal. Photomicrographs, x 25; small cross section, x 1/2.

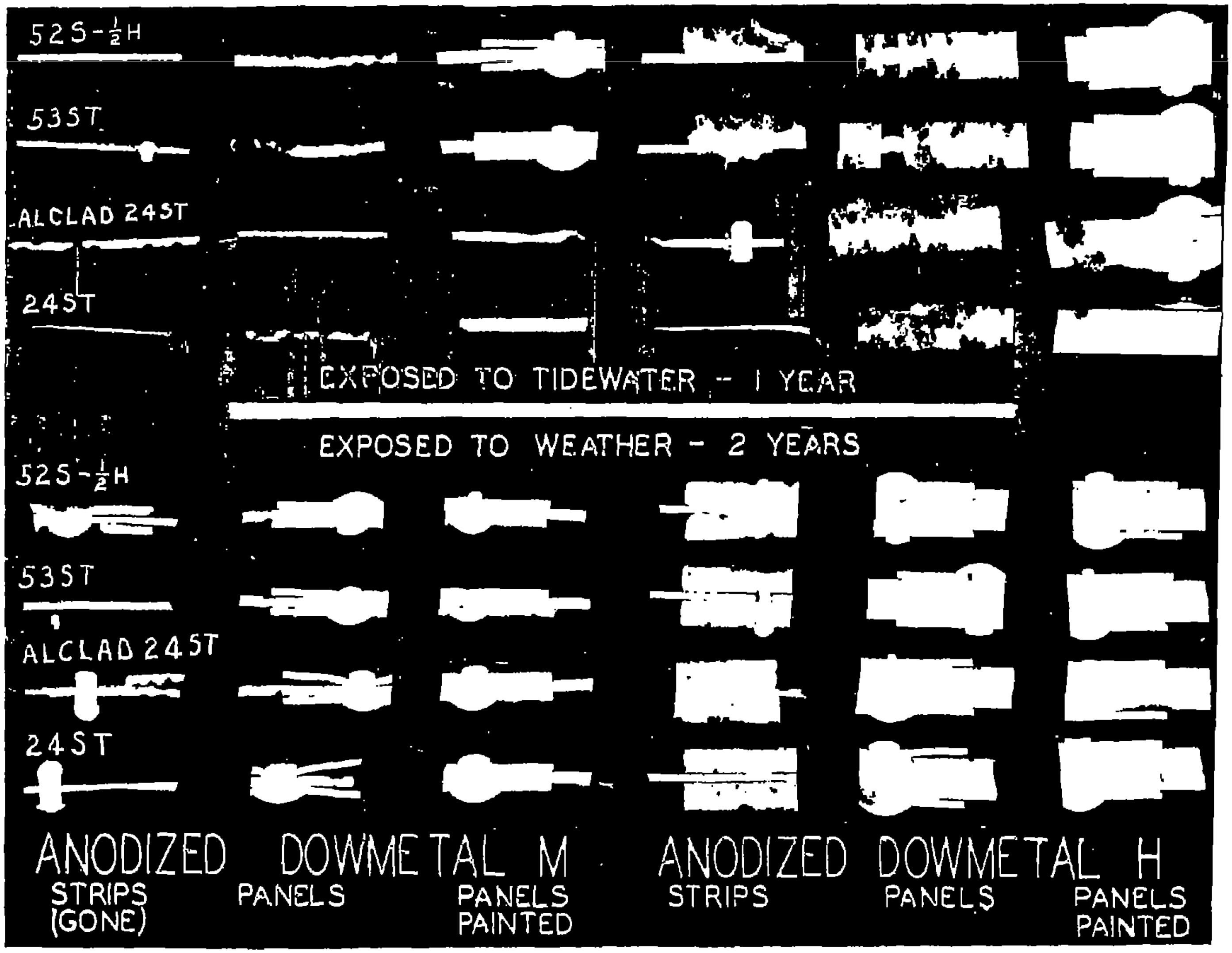


Figure 23.- Cross sections showing aluminum alloys exposed to tidewater and to the weather in contact with magnesium alloys. The magnesium alloys were the strips attached to larger areas of aluminum alloys in the first and fourth vertical columns; in the other vertical columns the aluminum alloys were the strips. Panels in the tidewater tests were in advanced stages of disintegration, except when painted. Unpainted panels with Dowmetal M strips were also severely attacked in the weather. x 1 (18).

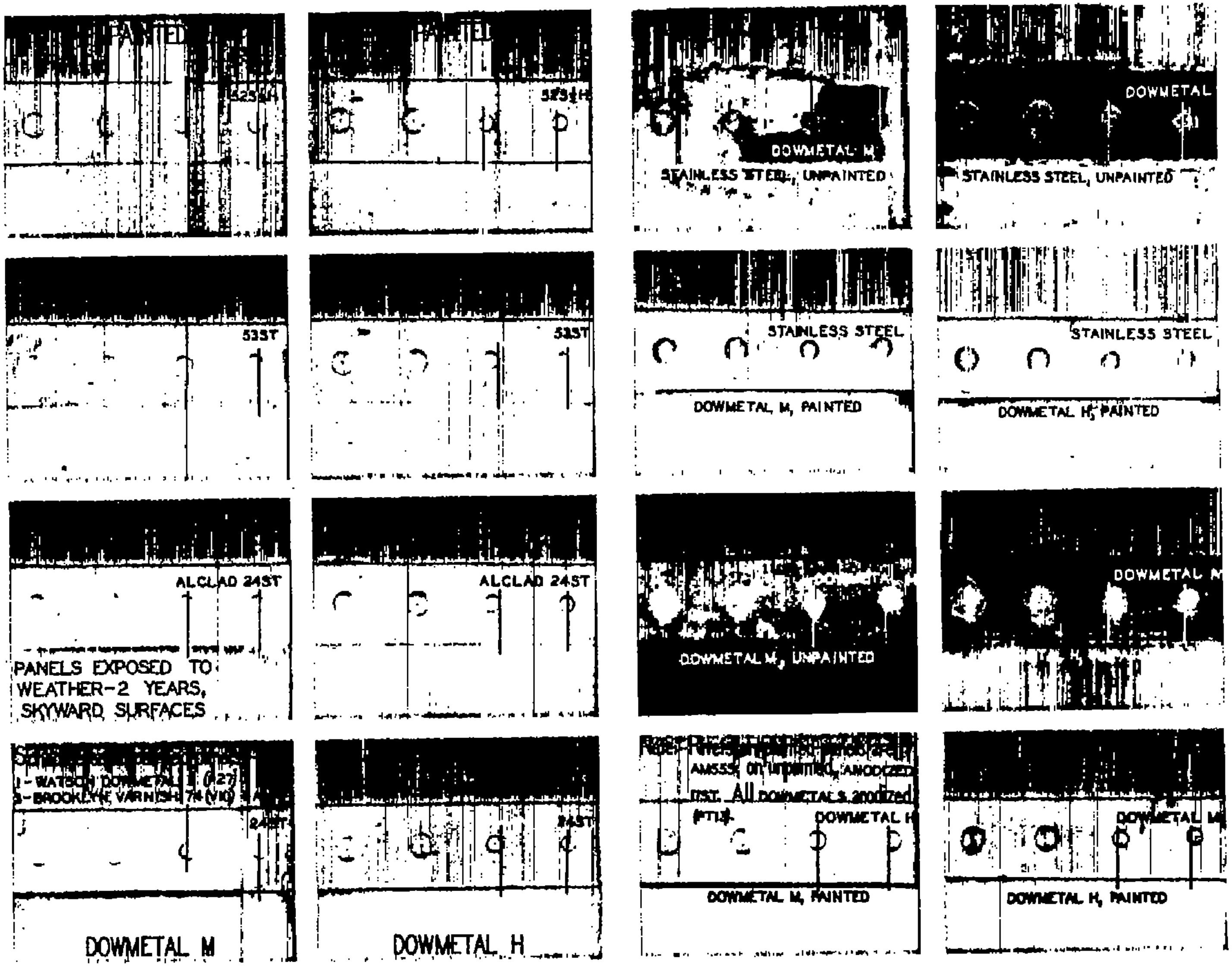


Figure 24.- Surface appearance of panels exposed to the weather with magnesium alloys in contact with each other, with aluminum alloys, or with stainless steel. The painted panels remained in relatively good condition. x 1/2 (19-20).

Figure 25.- Cross sections of panels exposed to the weather with magnesium alloys in contact with each other, with aluminum alloys, or with stainless steel. Painting was effective in preventing electrolytic reactions at the faying surfaces except near the edges of Alclad 24ST, 24ST, and stainless-steel strips. Severe corrosion was present on corresponding unpainted panels. Photomicrographs, x 25; smaller cross sections, x 1/2.

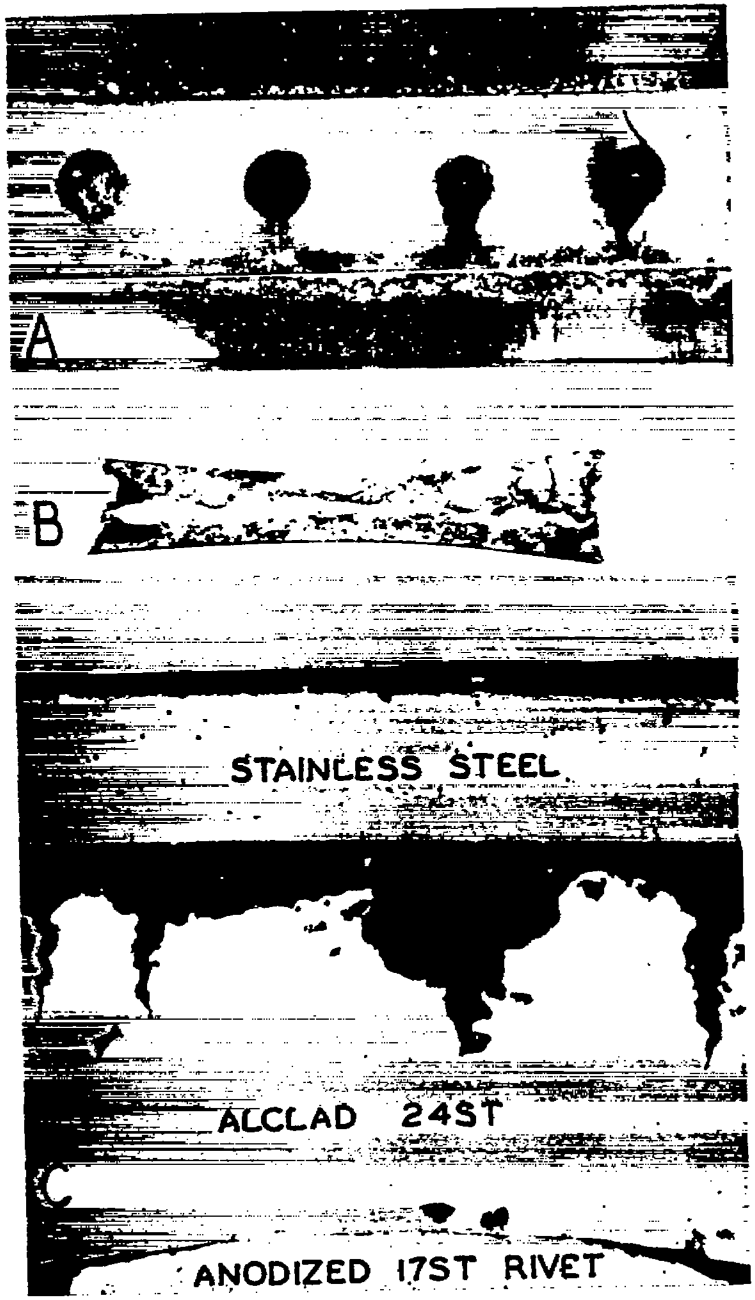


Figure 26.- Examples of stress-corrosion. A - Crack on stainless steel strip joined to Dowmetal M panel. x 1. B - Cross section showing large amount of corrosion product present on couple of (A). x 2½. C - Cracks in Alclad 24ST strip attached to a stainless steel panel. x 50.

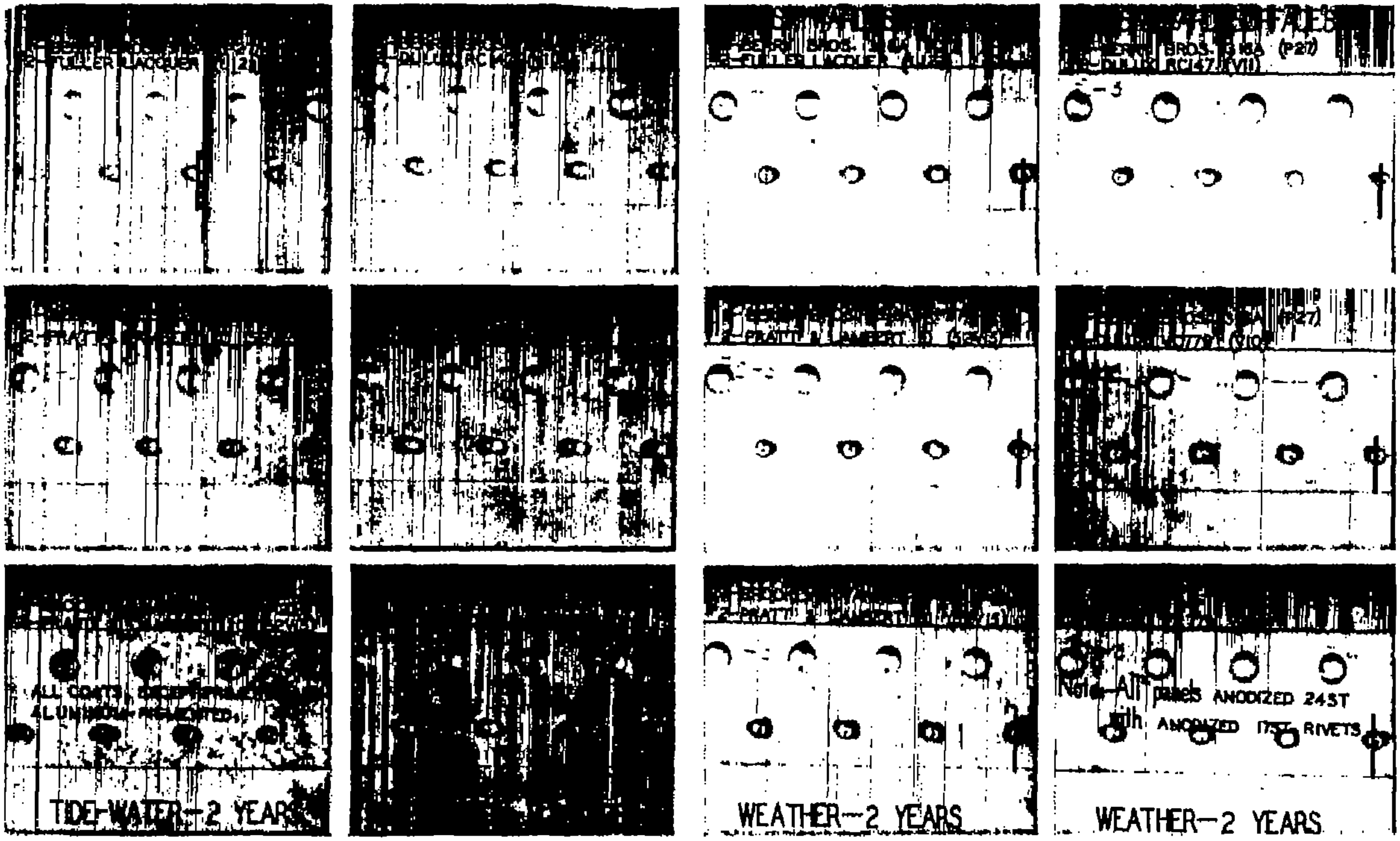


Figure 27.- Skyward surfaces of anodically treated 24ST panels exposed to tidewater or to the weather with various protective paint coatings. The finish coats on panels at the top and the bottom of the first vertical column at the left failed, in some areas, to adhere to the primers. This condition was somewhat more pronounced than at the end of the first year. The rest of the coatings were in excellent condition. x 1/2 (21).

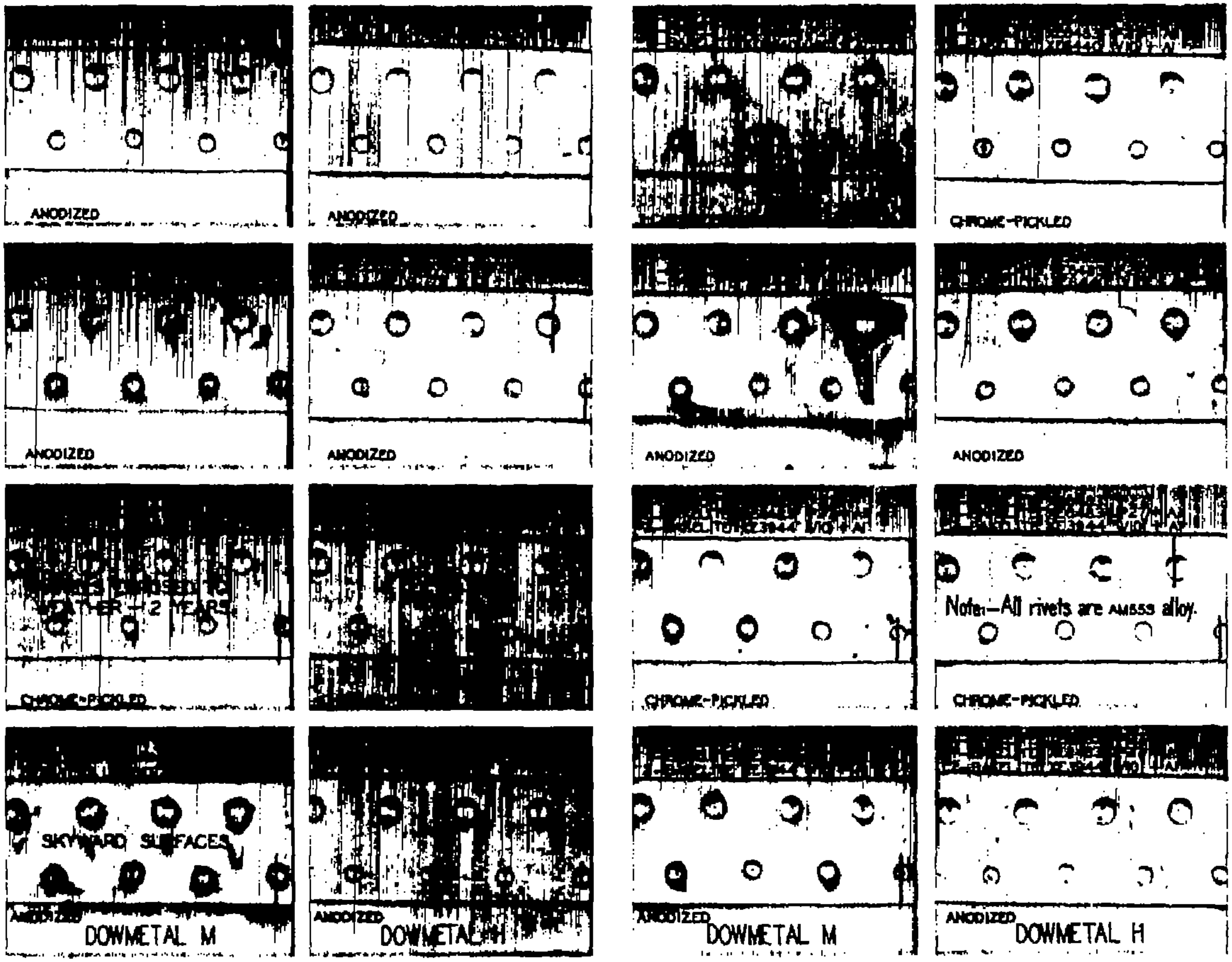


Figure 28.- Surface appearance of magnesium alloys exposed to the weather with various protective paint coatings. Most of the paints remained in good condition, except at the rivet heads and at the edges of the strips of the main panel. x 1/2 (22).

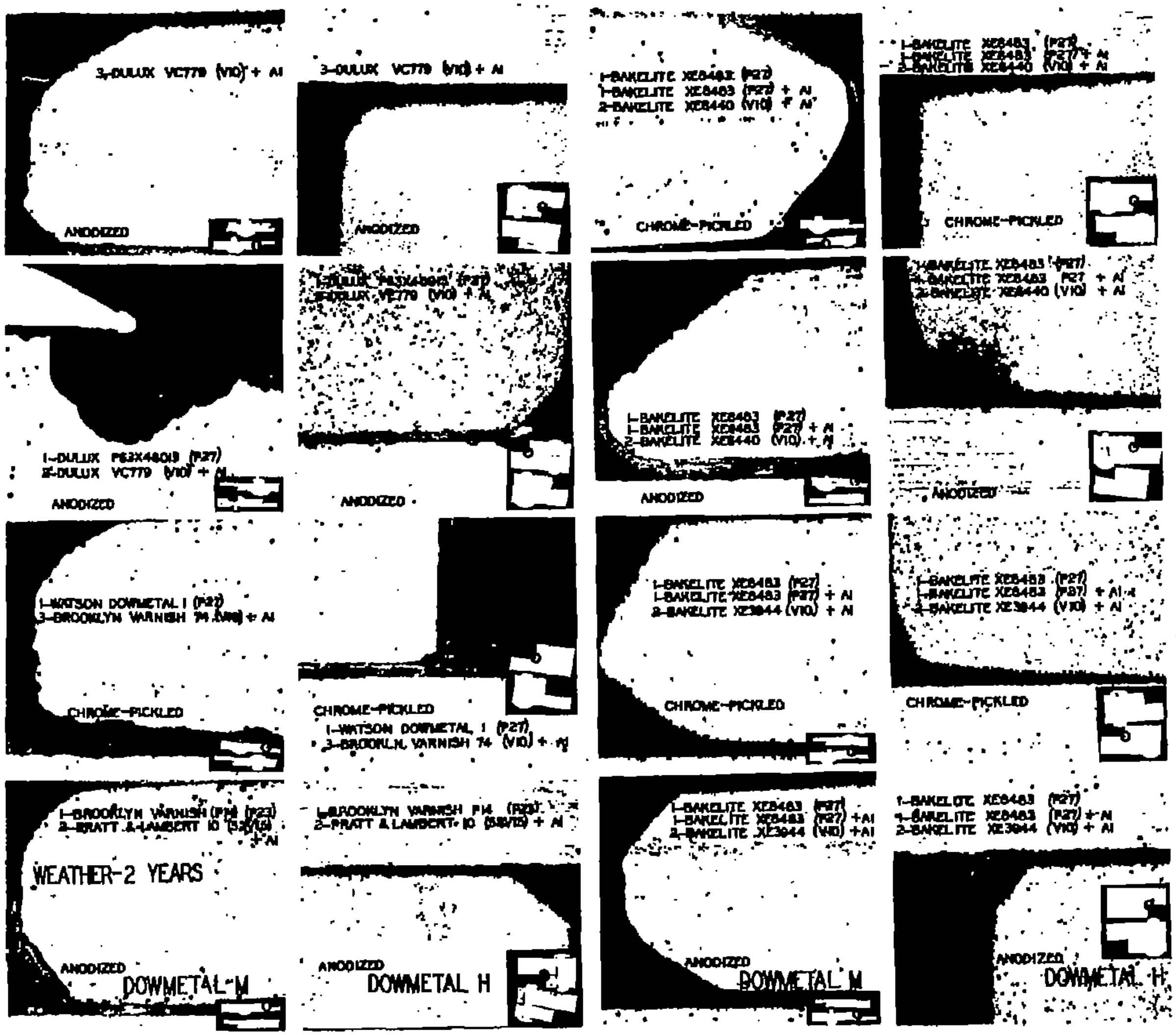
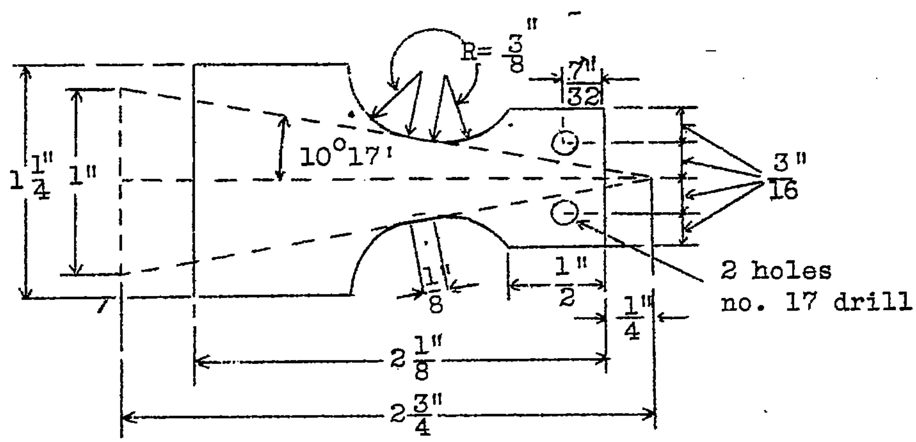


Figure 29.- Cross sections of magnesium alloys exposed to the weather with various protective paint coatings. Edges of strips were purposely rounded prior to painting. Much of the corrosion present occurred on these edges or at areas of paint failure adjacent to the AM55S rivet heads. Photomicrographs, x 25; smaller cross sections, x 1/2.



Krouse sheet fatigue specimen

Figure 30.- Sketch showing design and dimensions of specimens for tests in the Krouse flexural fatigue machines. x 1.

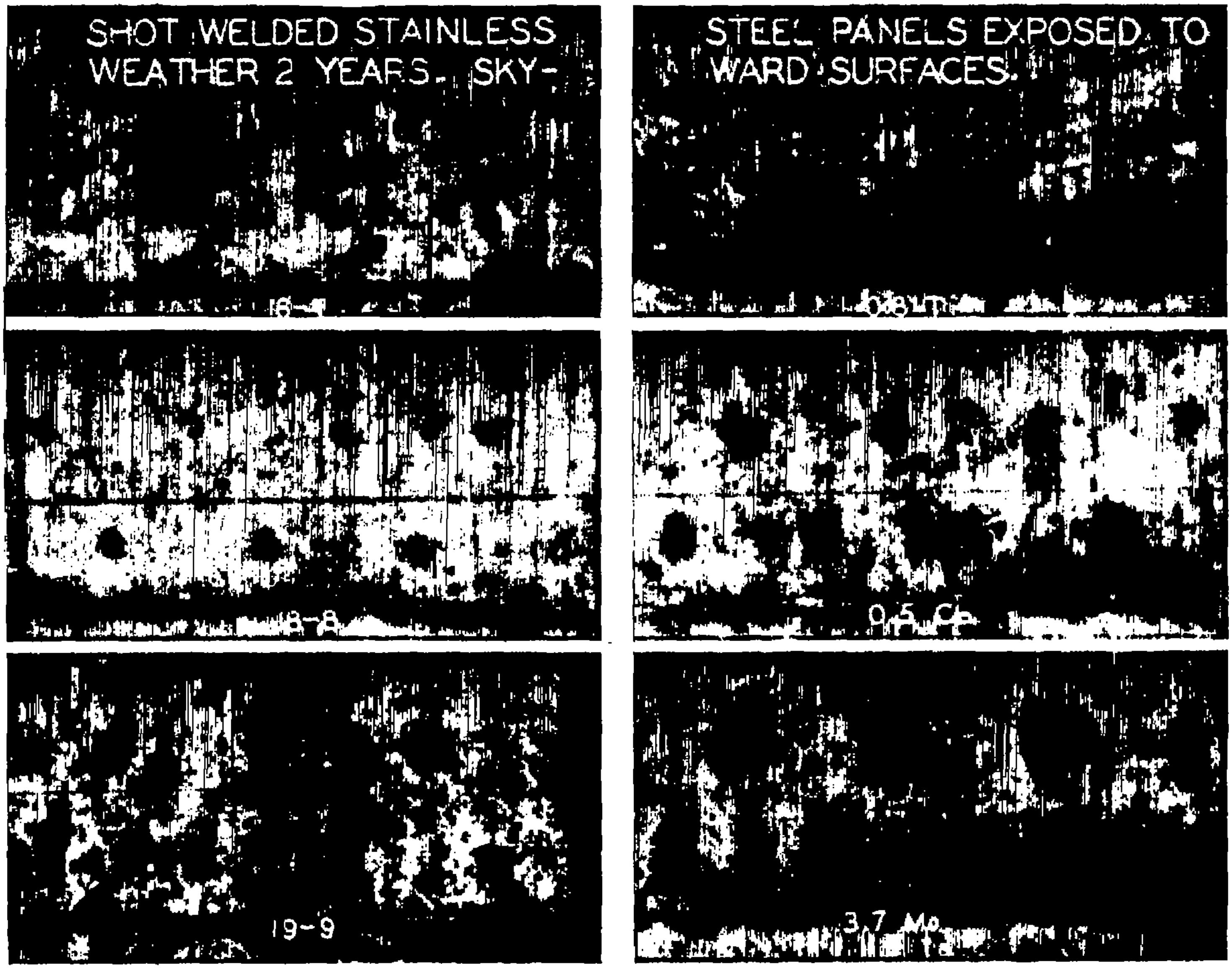


Figure 31.- Stainless steel panels of various compositions, exposed to the weather. Rust deposits were considerably heavier at the end of the second than the first year. Figures in the left column indicate percentages of chromium and nickel, respectively. Figures in the right column give the percentage of the addition element shown. Rust on the welds was generally worse than on the rest of the panels. Deposits on the steel containing molybdenum were very much lighter than on the other steels. x 1 (26).

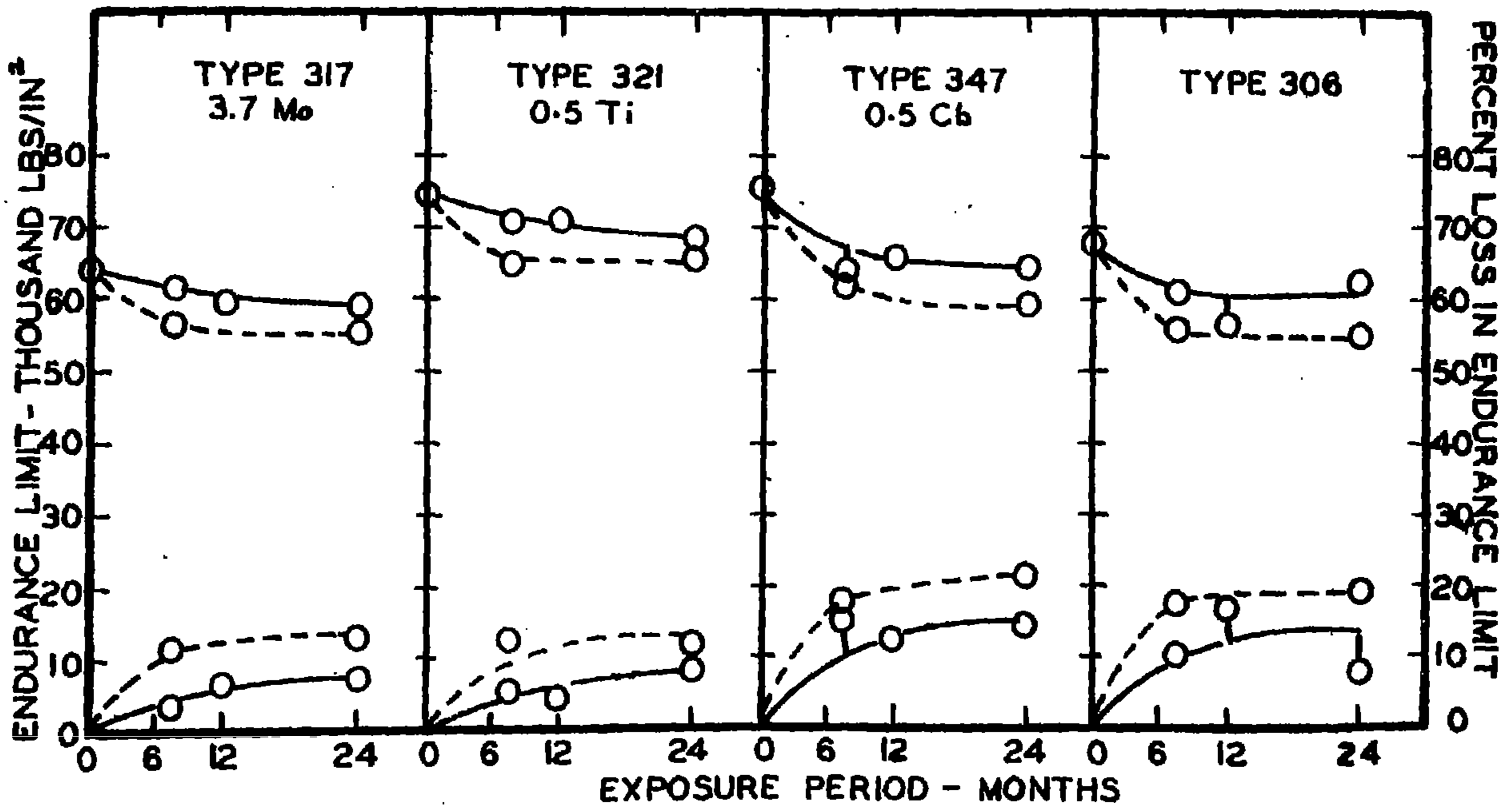


Figure 32.- Results of flexural fatigue tests on stainless steel. Solid line curves pertain to specimens exposed to tidewater; broken-line curves pertain to specimens exposed to the weather. The upper curves, in each instance, refer to values for endurance limits; the lower curves to percentage loss. Panels exposed to the weather consistently showed greater loss than those exposed to tidewater for equal periods. Steels containing molybdenum or titanium exhibited appreciably lower losses than those with columbium, or with no elements added to the typical 18 percent chromium, 8 percent nickel alloy (Type 306).

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ABSTRACT

Panels more corroded at end of second year than of the first year, particularly those with dissimilar metals in contact. Alclad 24ST and 52S-1/2 H proved most corrosion resistant of aluminum alloys tested. Anodized 17ST rivets gave best results in the joining of aluminum alloy sheets. Gas welds were least attacked by corrosion. Various metals found to be anodic to other metals. Steels containing 2.5% molybdenum are slightly more susceptible to corrosion than those containing 3.5%.

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