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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

REPORT No. 663

THE EFFECT OF CONTINUOUS WEATHERING ON LIGHT METAL ALLOYS USED IN AIRCRAFT

By WILLARD MUTCHLER

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AERONAUTIC SYMBOLS

1. FUNDAMENTAL AND DERIVED UNITS

	Symbol	Metric		English	
		Unit	Abbreviation	Unit	Abbreviation
Length	l	meter	m	foot (or mile)	ft. (or mi.)
Time	t	second	s	second (or hour)	sec. (or hr.)
Force	F	weight of 1 kilogram	kg	weight of 1 pound	lb.
Power	P	horsepower (metric)		horsepower	hp.
Speed	V	kilometers per hour	k.p.h.	miles per hour	m.p.h.
		meters per second	m.p.s.	feet per second	f.p.s.

2. GENERAL SYMBOLS

W, Weight$=mg$

g, Standard acceleration of gravity$=9.80665$ m/s^2 or 32.1740 ft./sec.^{2}

m, Mass$=\frac{W}{g}$

I, Moment of inertia$=mk^2$. (Indicate axis of radius of gyration k by proper subscript.)

μ, Coefficient of viscosity

ν, Kinematic viscosity

ρ, Density (mass per unit volume)

Standard density of dry air, 0.12497 kg-m^{-4}-s^2 at 15° C. and 760 mm; or 0.002378 lb.-ft.$^{-4}$ sec.^{2}

Specific weight of "standard" air, 1.2255 kg/m^3 or 0.07651 lb./cu. ft.

3. AERODYNAMIC SYMBOLS

S, Area

S_w, Area of wing

G, Gap

b, Span

c, Chord

$\frac{b^2}{S}$, Aspect ratio

V, True air speed

q, Dynamic pressure$=\frac{1}{2}\rho V^2$

L, Lift, absolute coefficient $C_L=\frac{L}{qS}$

D, Drag, absolute coefficient $C_D=\frac{D}{qS}$

D_0, Profile drag, absolute coefficient $C_{D_0}=\frac{D_0}{qS}$

D_i, Induced drag, absolute coefficient $C_{D_i}=\frac{D_i}{qS}$

D_p, Parasite drag, absolute coefficient $C_{D_p}=\frac{D_p}{qS}$

C, Cross-wind force, absolute coefficient $C_C=\frac{C}{qS}$

R, Resultant force

i_w, Angle of setting of wings (relative to thrust line)

i_t, Angle of stabilizer setting (relative to thrust line)

Q, Resultant moment

Ω, Resultant angular velocity

$\rho\frac{Vl}{\mu}$, Reynolds Number, where l is a linear dimension (e.g., for a model airfoil 3 in. chord, 100 m.p.h. normal pressure at 15° C., the corresponding number is 234,000; or for a model of 10 cm chord, 40 m.p.s., the corresponding number is 274,000)

C_p, Center-of-pressure coefficient (ratio of distance of c.p. from leading edge to chord length)

α, Angle of attack

ϵ, Angle of downwash

α_0, Angle of attack, infinite aspect ratio

α_i, Angle of attack, induced

α_a, Angle of attack, absolute (measured from zero-lift position)

γ, Flight-path angle

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By WILLARD MUTCHLER

National Bureau of Standards

138459—39——1

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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THE EFFECT OF CONTINUOUS WEATHERING ON LIGHT METAL ALLOYS USED IN AIRCRAFT

By Willard Mutchler

SUMMARY

An investigation of the corrosion of light metal alloys used in aircraft was begun at the National Bureau of Standards in 1925 and has for its purpose the study of the causes of corrosion in aluminum-rich and magnesium-rich alloys together with the development of methods for its prevention.

The results, obtained in an extensive series of laboratory and weather-exposure tests, reveal the relative durability of a number of commercially available materials and the extent to which the application of various surface coatings of oxide alone and with paint coatings afforded additional protection. The paper may be considered as a supplement to N. A. C. A. Report No. 490.

INTRODUCTION

The results of earlier laboratory corrosion and weather-exposure tests, which yielded information of considerable value, have previously been published (references 1 to 9). The present report is, in effect, a résumé of the most important features and findings from additional weather-exposure and laboratory tests, started in 1932 and covering a period of 5 years, in which more than 7,000 specimens of aluminum and magnesium alloys were tested.

In the previously published papers, emphasis was placed primarily upon the causes and elimination of deterioration by embrittlement of high-strength aluminum alloys of the so-called "duralumin" type. It was learned that, although the seriously objectionable intercrystalline type of corrosion could be eliminated by correct procedures in heat treatment, the copper-containing duralumin alloys were more prone to attack than lower-strength alloys in which this constituent was absent. It was learned further that duralumin could be adequately protected against severe saline conditions when covered with outer layers of aluminum of high purity and that certain combinations of surface oxidation treatments and pigmented varnishes afforded the next best degree of protection.

In line with these findings, manufacturers developed noncopper-containing alloys of higher strengths than were previously available. The more important of these alloys were included in the present investigation for the purpose of securing comparative data. Also, emphasis was placed upon a rather systematic study of the most promising methods of surface treatment as a means of protecting duralumin-type alloys from corrosion. The entire program embraced in the present series of tests had for its objectives the accumulation of data regarding the relative corrosion resistance of commercially available aluminum and magnesium alloys uncoated and coated with different protective surfaces.

The author acknowledges his great indebtedness to H. O. Willier, who assisted in examining and testing all the samples. He also thanks H. C. Dudley, who assisted in their preparation and heat treatment. The cooperation furnished by the sponsors, the National Advisory Committee for Aeronautics, the Army Air Corps, and the Bureau of Aeronautics, Navy Department, as well as by officials and inspectors at the Naval Air Station, Hampton Roads, Va., and the Fleet Air Base, Coco Solo, C. Z., is also appreciated.

WEATHERING OF ALUMINUM ALLOYS

EXPERIMENTAL PROCEDURE

All the aluminum alloys consisted of 0.064 inch (14 gage) sheet of which by far the greater number were in the form of 9- by ¾-inch strips. These strips were machined, after corrosion, into standard A. S. T. M. tensile bars with ½-inch reduced section (fig. 1a). Some samples were initially exposed in the form of tensile bars of the dimensions given in figure 1b. All spot-welded and riveted assemblies had a width of 1 inch and an over-all length of 9 inches, of which 1¾ inches represented the faying surfaces. All machining operations prior to exposure were done by the cooperating manufacturers, and all after exposure at the National Bureau of Standards.

All specimens, before corrosion tests and prior to the application of protective coatings, were cleaned free from grease by washing twice with clean benzol and once with alcohol. Specimens having identical chemi-

cal compositions and/or surface treatments were designated as "sets." Each set usually consisted of 52 specimens that were distributed thus: 6 tested for initial tensile properties; 10 kept in sealed containers (dry atmosphere); 10 each exposed to the weather at Washington, D. C., at Hampton Roads, Va., and at Coco Solo, C. Z.; and 6 exposed to laboratory salt-spray test. In those instances where a set consisted of both strips and tensile bars, the number of specimens at each locality was, of course, doubled.

The racks for the weather-exposure tests were installed at the same three locations used in the previous series (reference 9), namely:

(1) National Bureau of Standards, Washington, D. C., representative of a temperate inland atmosphere,

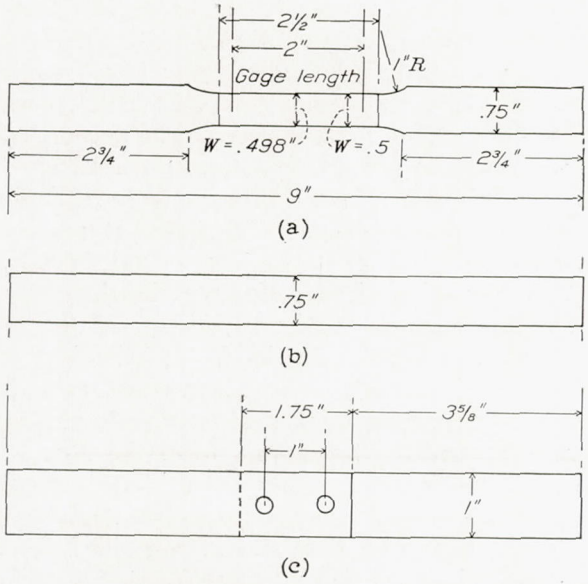

FIGURE 1.—Dimensions of 0.064-inch thick aluminum-alloy materials used in the weathering tests. (a), tensile bar; (b), strip sample; (c), spot-welded or riveted panel. The welds and rivet heads were approximately ¼ inch in diameter; the rivet shanks were ⅛ inch in diameter.

free from industrial contamination and from marine conditions.

(2) Naval Air Station, Hampton Roads, Va., representative of temperate seacoast conditions, with occasional contact with salt water (fig. 2).

(3) Fleet Air Base, Coco Solo, C. Z., representative of tropical seacoast conditions (fig. 2).

In the preceding series of tests, the racks at Coco Solo were so situated as to assure frequent contact of the specimens with spray from the Caribbean Sea. In the present series they were located approximately 15 feet back from the shore line, and thus received spray much less frequently. This change resulted in making corrosive conditions at Coco Solo less severe than at Hampton Roads, the reverse of which was true in the previous investigation.

Withdrawals of samples at all three weather-exposure sites, and from the sealed containers, were made after periods of 12, 24, 36, and 48 months. Other withdrawals were made as follows: At Washington, Coco Solo, and from the sealed containers after 18, 30, and 60 months; at Hampton Roads and Coco Solo after 3 months; and at Coco Solo after 42 months. A few racks still remain at Washington and Hampton Roads, and it is planned to remove these after more prolonged periods, probably 10 or more years. Withdrawals of samples from the laboratory salt-spray tests were governed by the susceptibility to corrosion of the various sets, the better ones being left for longer periods, the intervals being as follows: ¼, ½, 1, 2, 4, 6, 8, 9, 12, and 18 months. The salt-spray tests were conducted in an apparatus conforming strictly to Navy Department Specifications (references 10 and 11). A 20-percent solution of chemically pure sodium chloride was atomized to serve as the corroding medium and the temperature of the chamber was maintained at 95° F. ±2°.

The progress of corrosion on all the samples was followed in three ways:

(1) By direct visual examination, supplemented by macrophotographs at natural size of both sides of each specimen.

(2) By a comparison of the tensile properties of the corroded bars, with those of uncorroded bars, which served as an indirect measure of corrosion. Elongation values were measured over a 2-inch gage length.

(3) By direct measurement of the depth and the area of corroded portions. Two random cross sections, each having an area of 0.5 by 0.064 inch, were photographed in their entirety at 50 magnification, thus yielding a permanent record of the micrographic features of the corrosive attack. The photomicrographs were made by a rapid method, developed at the National Bureau of Standards, on photostat paper negatives (reference 12).

UNCOATED MATERIALS COMMERCIALLY AVAILABLE

The chemical compositions of these materials, which were exposed in the condition "as received" from their manufacturers, are given in table I. Alloys 25SW, 51SW, and 51ST were exposed only in strip form and represented materials from the same lots as were used in the previous series of exposure tests. All of the remaining materials were exposed both as strips and as tensile bars.

It will be seen from the table that the alloys fall naturally into two groups: (1) those in which copper is present as an alloying constituent, and (2) those in which it is absent. The alloys of the first group are commonly considered as being of the duralumin type. Alloy 17S is considered representative and nominally contains 4 percent of copper, 0.5 magnesium, and 0.5 manganese, with minor quantities of silicon and iron. Alloy 24S differs only in having an additional 1 percent of magnesium, while the Aeral alloy contains 2 percent of cadmium. In alloy 25S the magnesium is omitted,

while in Nicralumin most of the copper is replaced by heavy metal substitutes, supposedly less conducive to intercrystalline attack, such as nickel, chromium, tungsten, and molybdenum. The aluminum-coated (Alclad) material might be regarded as duralumin with a protective metallic coating but, for practical purposes, it is considered as a distinct commercial product.

The copper-free alloys may be further subdivided into (1) the essentially binary alloys of aluminum and magnesium, and (2) the essentially ternary alloys of aluminum, magnesium, and a third element. In the first group are X52S, XB52S, and 56S which nominally contain, respectively, 1.25, 3.5, and 6 percent of magnesium. In the second group are: alloys 4S, with 1 percent of magnesium and 1.25 maganese; 51S, with 0.6 magnesium and 1 silicon; and Inalium, with 0.8 magnesium and 2 cadmium.

The Aeral and Inalium materials were prepared by the Société des Brevets Berthelemy de Montby of Paris, France. These alloys apparently offer difficulties in fabrication because the surface finishes were much rougher than usual and approximately 5 percent of the individual strips and tensile bars contained internal cracks and flaws. The Nicralumin samples were furnished by the Nicralumin Co. and the remaining

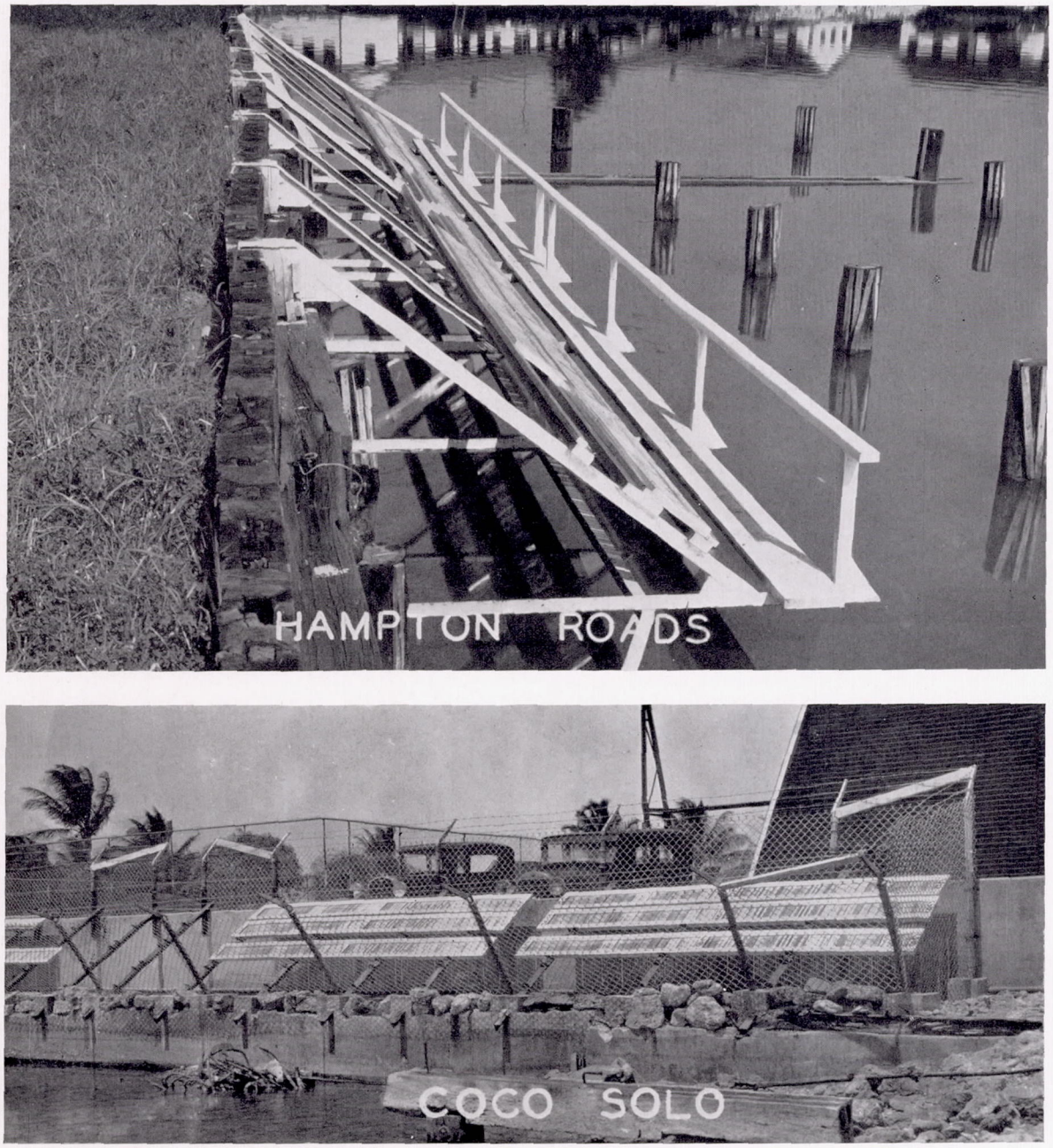

FIGURE 2.—Views of the weather-exposure racks and specimens situated at the two marine locations.

alloys were supplied by the Aluminum Co. of America. All materials were representative of commercial products prepared in accordance with the manufacturer's recommended procedure.

The average tensile properties of the materials are given in table II where also appear the ultimate tensile strength, elongation, and maximum depth of penetration of corrosive attack after 5 years' exposure at Washington and Coco Solo, 4 years at Hampton Roads, and the maximum period in the salt-spray test. For purposes of convenience in comparison, the data are repeated in table III, expressed in terms of percentage loss from the initial properties.

These data indicate that the binary aluminum-magnesium alloys (X52S–½H and XB52S) proved exceptionally corrosion resistant. No loss in tensile properties occurred and the maximum depth of penetration of attack was approximately 0.002 inch. The higher strength Alclad materials were likewise very resistant. Losses in tensile properties were small and the attack did not penetrate beyond the protective aluminum layers.

Somewhat less corrosion resistant, but definitely superior to the remaining materials, were the copper-free alloys (4S–½H, 56S–½H, and Inalium). As previously pointed out, however, the Inalium material was inferior from considerations of original surface finish. The 6 percent magnesium alloy (56S–½H) was peculiar in that it exhibited no pronounced corrosion or loss in tensile properties until after the third year at Hampton Roads and at Coco Solo, and after the ninth month in the salt spray. Then intercrystalline attack developed and the tensile properties dropped rapidly.

Increasingly inferior, in the order named, were the magnesium-silicon alloys (51SW, XA51ST, 51ST), and the complex "heavy-metal" alloy Nicralumin, on which marked loss in tensile properties occurred and corrosive attack penetrated approximately 0.01 inch at the severe localities. Except on the Nicralumin material, the attack tended to be intercrystalline in nature.

Under severe conditions of exposure, as exemplified in the salt spray, the copper-containing materials (17ST, 17SRT, 24SRT, and Aeral) proved much more susceptible to attack, which was confined to the pitting type. For all practical purposes, little difference was to be noted in their behavior when compared with each other.

Worst from considerations of corrosion resistance was the copper-aluminum alloy, 25SW, in which a very pronounced loss in tensile properties occurred, and in which a severe intercrystalline attack took place.

The changes in surface appearance of representative materials are shown in figure 3, where it may be seen that the amount of corrosion products was much greater on the more susceptible alloys and that they tended to accumulate more on the earthward surfaces of the weather-exposure samples than on the skyward.

The character of the attack on the various alloys, when viewed at 50 diameters, is shown in figures 4 and 5. Differences in the area and the depth of attack between the different alloys are plainly shown, as well as differences dependent upon the severity of the locality.

Thus far, attention has been confined to the appearances and properties of the alloys at the expiration of the maximum periods of exposure. Marked differences in the rates of attack were, of course, found also in the earlier stages of the tests. The more important of these are illustrated in figure 6, where the relation is shown between time of exposure and percentage loss in elongation and maximum depth of attack.

Effect of corrosion on the cut edges.—Specimens of all the more corrosion-resistant alloys, exposed as tensile bars and those from which such bars were cut after exposure, possessed practically identical tensile properties. The properties of some of the copper-containing alloys, such as 17ST, 17SRT, and 24SRT, when exposed as tensile bars, were appreciably lower, especially in the laboratory salt-spray tests. Table IV illustrates the magnitude of the differences. The microscopic examinations disclosed a pronounced tendency for the attack to penetrate very much more rapidly from the cut edges than from the sides of the sheet. The attack frequently presented a characteristically elongated course suggesting that relatively thin layers were much more prone to attack than adjacent metal. This suggestion is confirmed by the appearance of corroded areas, other than those originating on the cut edges, indicated by the arrow in figure 7. The typical elongated shape of the areas indicates strongly that fabrication processes play an important part in originating the "layers" susceptible to attack.

Corrosion of spot-welded and riveted joints.—The chemical compositions of the alloys used for the spot-welded and riveted panels are given in table I, and the breaking loads before and after corrosion for the maximum periods are given in table V. The locations of the rivets and welds and the dimensions of the exposure panels are shown in figure 1c. Owing to the rather wide range of the breaking loads on uncorroded samples, 30 of these panels were exposed at each locality instead of 10, and 3 were removed at each test period.

It is evident from table V that the strength of the spot-welded joints was considerably higher than that of the riveted joints but that the former varied over a much wider range. Marked loss in breaking load occurred only on the Alclad 17ST sheets joined by rivets of the alloy containing magnesium (X56S–1/4H). These specimens developed severe intercrystalline at-

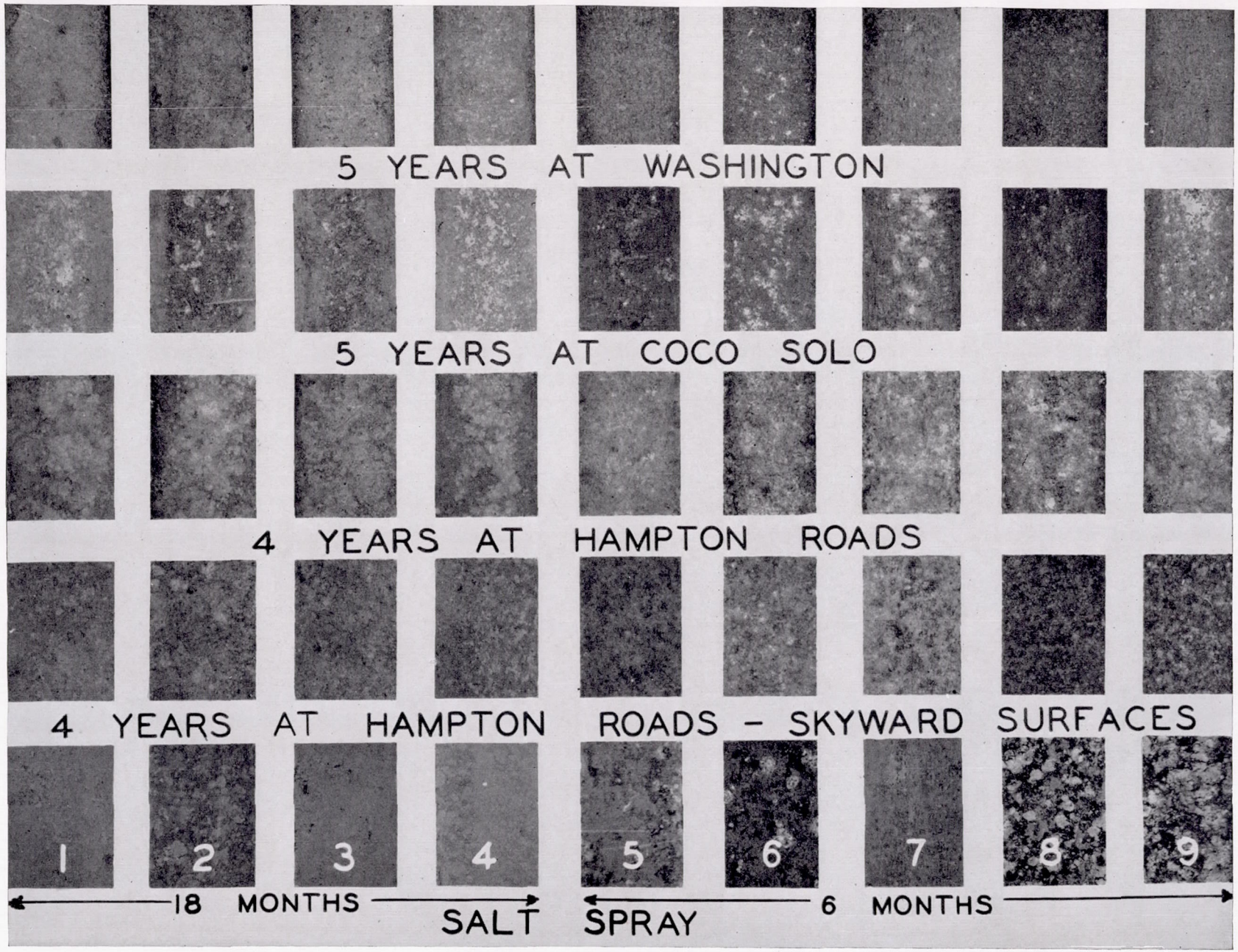

FIGURE 3.—Surface appearance of the various unprotected sheet materials after the maximum exposure at each locality. Earthward surfaces are shown in all except the fourth row. The materials are: (1) X52S-½H; (2) Alclad 17ST; (3) 4S-½H; (4) 56S-½H; (5) XA51ST; (6) Nicralumin; (7) Inalium; (8) 17SRT; (9) 25SW. × 1.

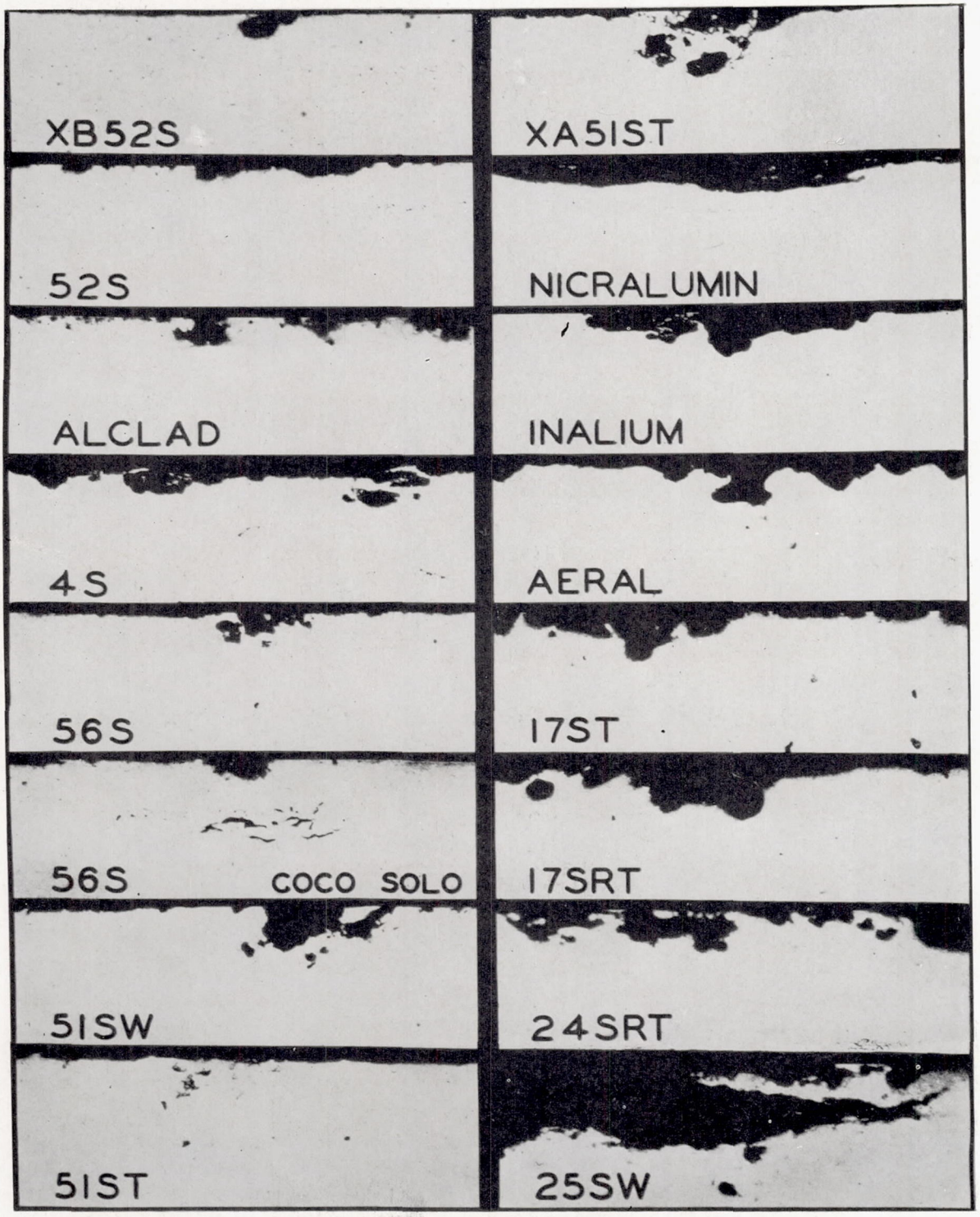

FIGURE 4.—Representative cross sections showing the maximum penetration of corrosive attack on sheets exposed 4 years at Hampton Roads. × 50.

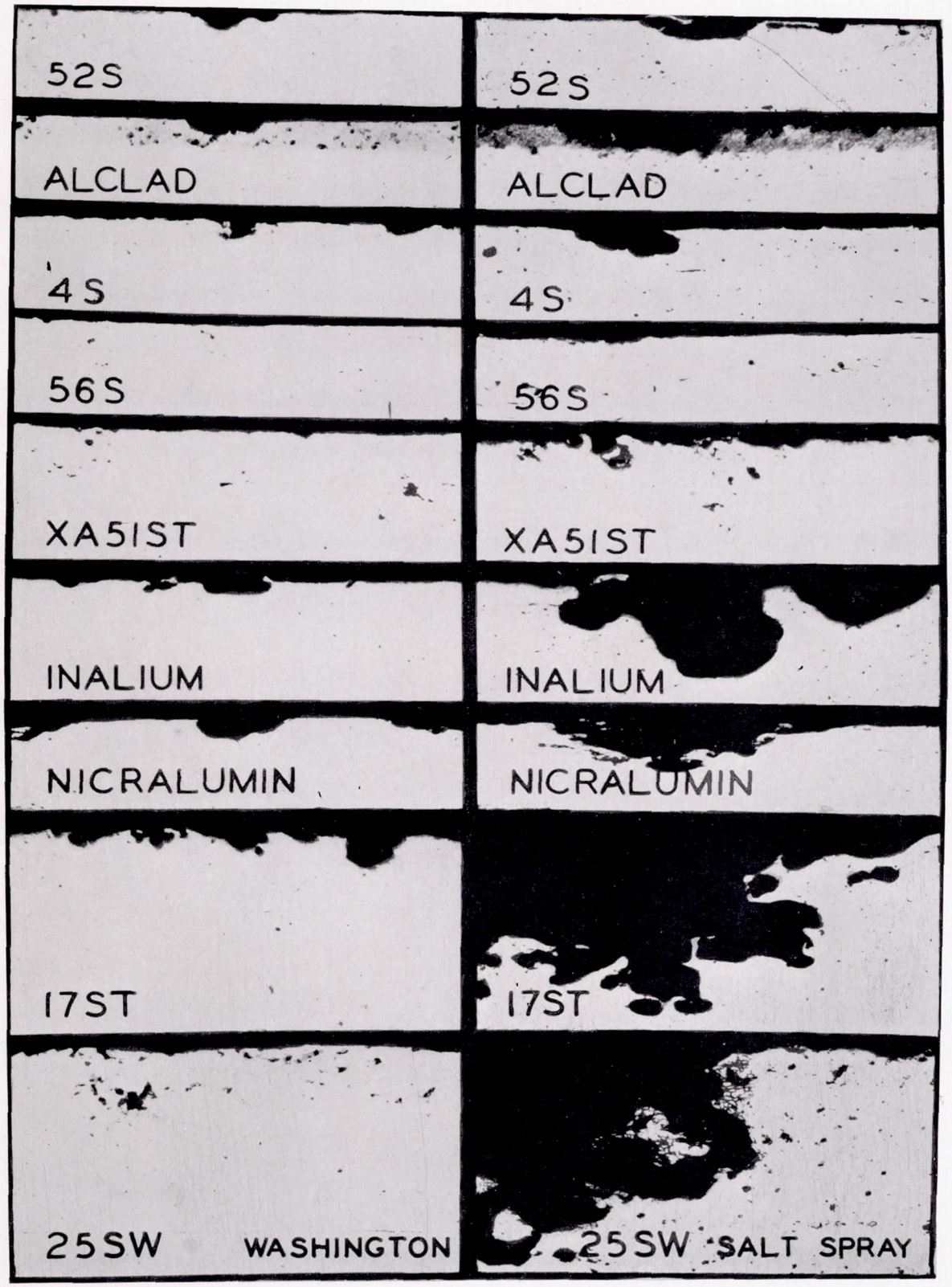

FIGURE 5.—Representative cross sections showing the maximum penetration of corrosive attack on sheets exposed 5 years at Washington (left column) and in the laboratory salt-spray tests (right column). The Nicralumin, XA51ST, 17ST, and 25SW materials were exposed 6 months to the spray; the others were exposed 18 months. Note the intercrystalline attack on alloys 56S, XA51ST, and 25SW. × 50.

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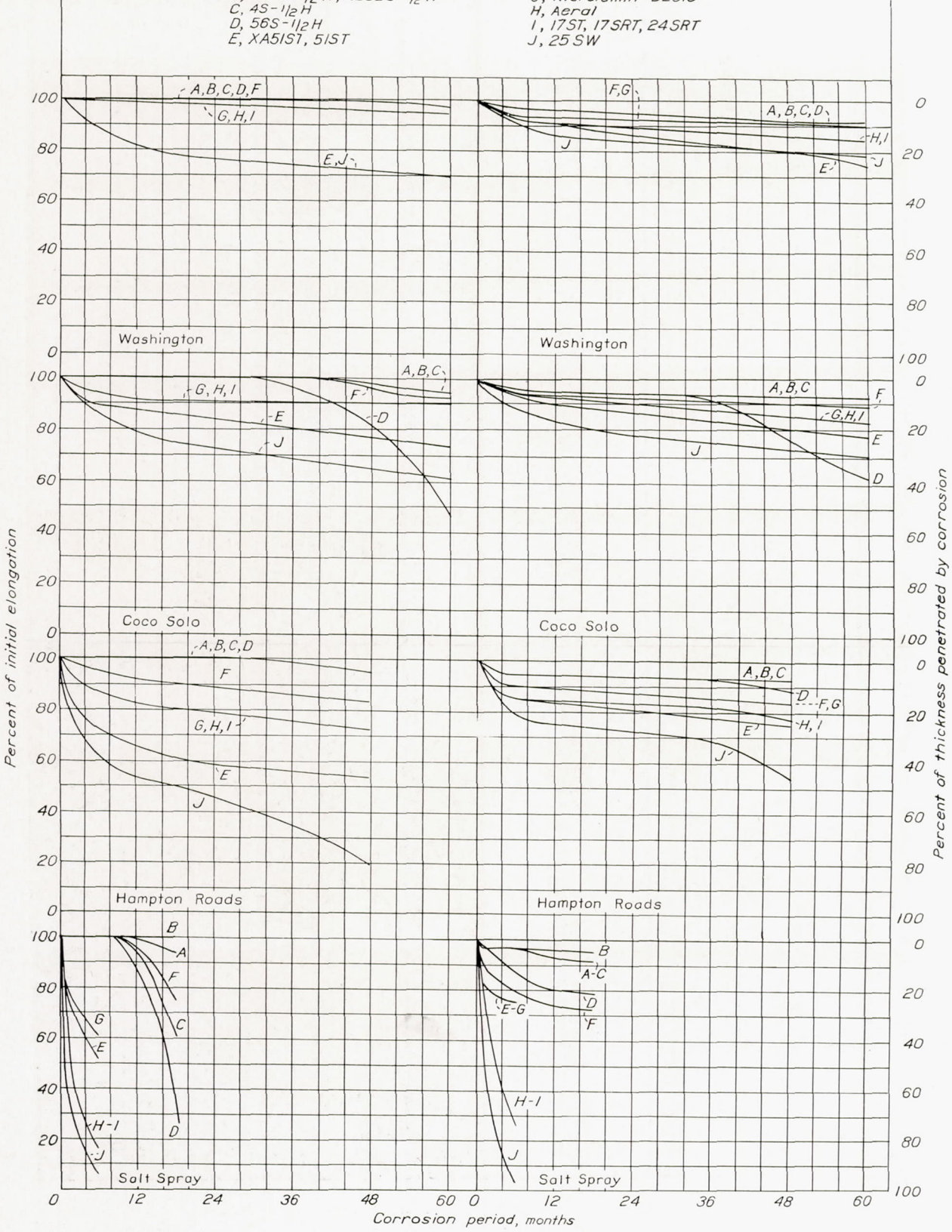


FIGURE 6.—The rates of penetration of corrosive attack and of loss in ductility for the various materials at each exposure locality. Note the marked superiority of the Alclad and X52S materials.

tack (fig. 8). In general, less corrosion was present at the faying surfaces of the spot-welded specimens than of the riveted ones. This result may be attributed, in part, to the fact that it was impossible to remove all the oil from the faying surfaces of the spot-welded panels prior to exposure. There was a definite tendency for localization of attack on the spot welds of all four materials, the attack being least on the copper-free alloys (X52S–1/2H and 4S–1/2H). In no instance, as far as could be determined, was the penetration sufficient to influence greatly the breaking load.

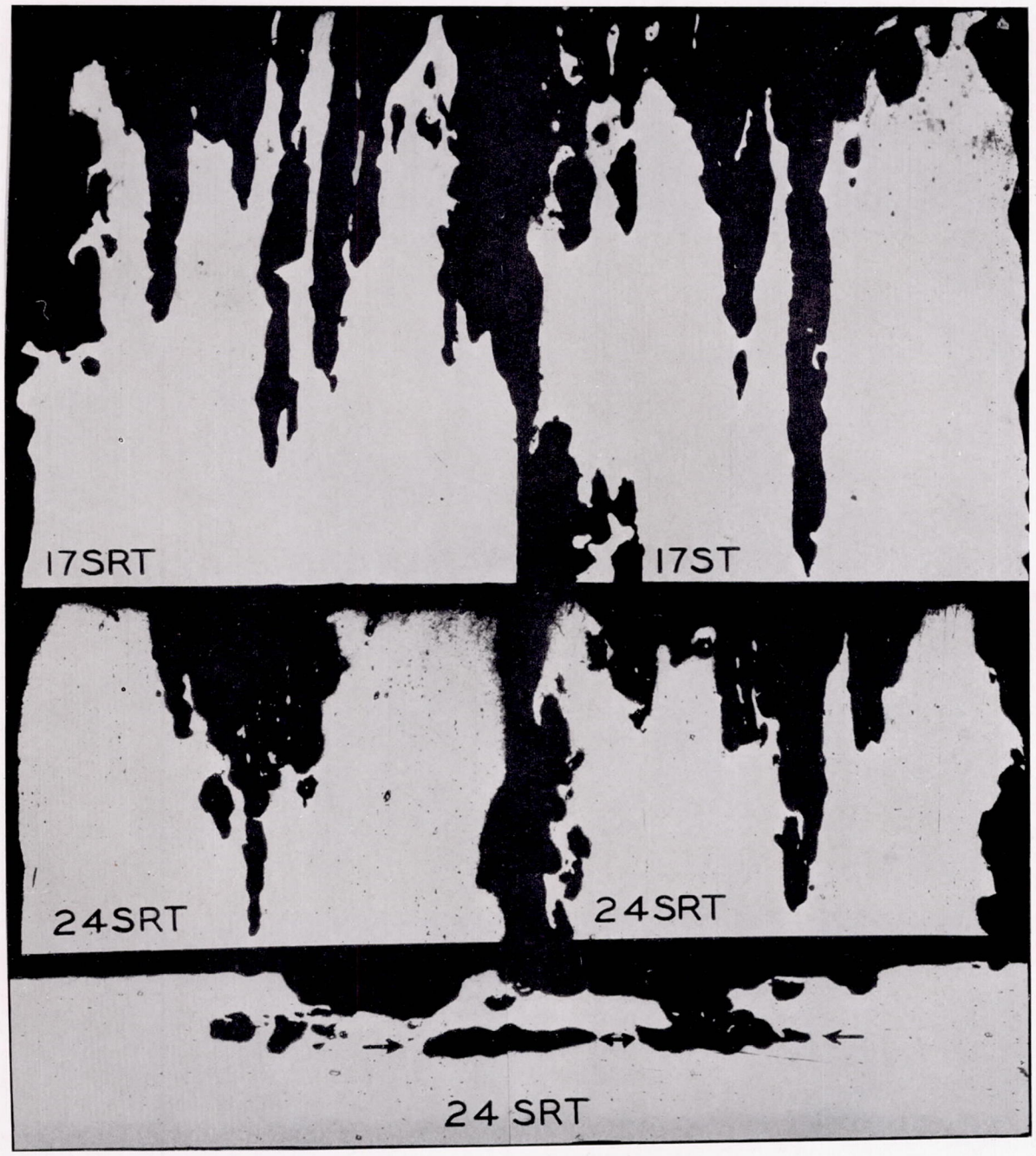


FIGURE 7.—Representative cross sections from specimens exposed 6 months to the laboratory salt-spray test, showing much greater penetration of attack from the cut edges, along "susceptible layers," than from the side surfaces. The cut edges are those at the top of the four upper specimens. The bottom specimen shows a side surface upon which the base of the corrosive attack spread laterally along a susceptible layer. × 50.

Effect of heat treatment on the corrosion of duralumin.—The corrosion of the duralumin-type alloy (17S) as influenced by various heat treatments has already been reported in considerable detail (reference 9). A relatively few additional treatments were included in the investigation, in which "as received" 17S-H material (table I) was treated as follows:

(1) "Solution heat-treated" at 505° C., removed from the furnace and held in air for 5 seconds before quenching in ice water. Measurements indicated that the temperature of the samples was approximately

470° C. on entering the quenchant.

(2) Same as (1), but held 30 seconds in air, at the end of which the temperature of the samples was approximately 375° C.

(3) Solution heat-treated at 475° C. ("underheated") and quenched in ice water.

(4) Solution heat-treated at 550° C. ("overheated") and quenched in ice water.

(5) Solution heat-treated at 505° C. and quenched in ice water.

(6) Solution heat-treated at 505° C. and quenched in boiling water.

(7) Solution heat-treated at 505° C., quenched in ice water, and "baked" 3 hours, some at (a) 100° F. (38° C.), some at (b) 200° F. (93° C.), and others at (c) 300° F. (149° C.).

A 30-minute solution heat-treatment was employed throughout, and all samples were allowed to age-harden for 3 months at room temperature prior to exposure. The treatments listed as (5) and (6) were the ones used on 17S samples subsequently given protective surface coatings, most of which were heat-treated at the National Bureau of Standards.

The properties of the uncorroded specimens and those exposed for the maximum periods are given in table VI. Those quenched in boiling water or baked at 300° F. were very susceptible to intercrystalline attack and exhibited great loss in tensile properties. Specimens baked at 300° F. were characterized by "pock-form" corrosion (reference 9) and were the most susceptible to attack of all the materials tested. Reference to table III will show that samples heat-treated by the other methods closely resembled the 17ST and related alloys in their corrosion behavior.

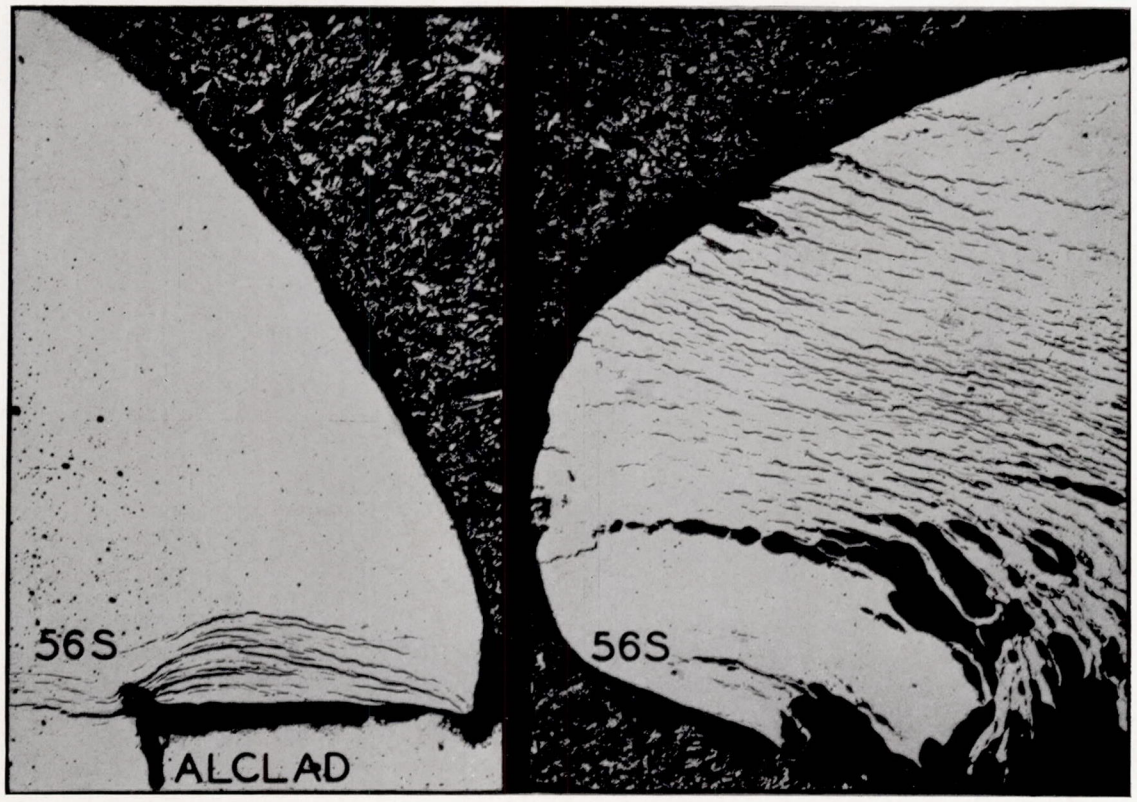


FIGURE 8.—Severe intercrystalline corrosive attack on X56S-¼H rivet heads exposed 2½ years at Coco Solo. × 50.

PROTECTIVE COATINGS APPLIED TO DURALUMIN

Oxide surface coatings.—A brief description will be given of the methods of application of the various oxide surface treatments used in the present investigation. The treatments were made at the National Bureau of Standards on a duralumin alloy (17S) quenched in boiling water after solution heat treatment at 505° C. Since underlying metal was thus purposely rendered susceptible to corrosion, failure of the coatings to afford protection was immediately reflected in a loss of tensile properties and the presence of intercrystalline attack. A number of the treatments, however, were also applied to cold-water-quenched 17S material, so as to obtain a more reliable criterion of their probable behavior in service. The coatings designated as Alcoa were applied solely to cold-water-quenched 17S material and to commercially heat-treated Alclad 17ST material. These treatments were applied at the Aluminum Co. of America Research Laboratories.

The objectives were (1) to determine the relative efficiencies of the various surface treatments as evidenced by the time required for their failure, and (2) to determine their behavior when painted with three coats

of a "standard" aluminum-pigmented spar varnish. The varnish selected for the latter purpose was one of the "long-oil" type which conformed to Federal Specification TTV81. (See table IX, schedule 11.)

The surface oxide coatings applied may be grouped into three categories, namely, those in which the protective film was formed by (1) simple immersion methods such as the Deoxidine, Jirotka, McCulloch, and Alcoa Dip processes; (2) anodic treatments in chromic or sulphuric acid electrolytes such as the Bengough, 10-percent chromic acid, chromic acid-dichromate, and Alcoa Electrolytic processes, and (3) impregnating anodically treated samples with inhibitive chromates, or "sealing."

(1) *Deoxidine process.*—Samples were immersed for 15 minutes in a 15-percent aqueous solution of phosphoric acid maintained at 55° C.

(2) *Jirotka "American" process.*—Specimens were immersed 1 hour at 96° C. in a bath consisting of 3½ liters of water, 4 grams of chromium sulphate, 50 grams of anhydrous sodium carbonate, and 12 grams of potassium dichromate.

(3) *McCulloch process.*—Samples were immersed 1 hour at 96° C. in a bath containing 10 grams of anhydrous calcium sulphate and 10 grams of calcium oxide per liter of water.

(4) *Alcoa Dip process (sealed).*—Specimens were immersed 15 minutes at 98° C. in a solution containing 20 grams of sodium carbonate and 5 grams of potassium dichromate per liter of water. Samples were sealed by impregnation with lead chromate formed by successive immersions in solutions of potassium dichromate and lead acetate.

(5) *Bengough process.*—Samples were given an anodic treatment in an electrolyte of 3 percent chromium trioxide at 40° C. The voltage across the bath was raised gradually from zero to 40 volts in 15 minutes, maintained at 40 volts for 35 minutes, raised to 50 volts in 5 minutes, and maintained at 50 volts for 5 minutes. The electrolyte was changed frequently to preclude loss in its efficiency. Current densities were maintained between 3.8 and 4.8 amperes per square foot. The treatment was applied to 17S and Alclad 17S materials quenched (1) in ice water and (2) in boiling water.

(6) *Bengough process ("spent" bath).*—The procedure used was the same as in (5) except that the bath had been used until its efficiency was very definitely impaired. The current density was approximately 1 ampere per square foot.

(7) *Ten-percent Chromic-Acid process.*—The specimens were anodically treated in accordance with Navy Department Specifications (reference 13). The electrolyte was a 10-percent solution of chromium trioxide maintained at 35° C. The voltage was raised as rapidly as possible to 30 volts and maintained there 1 hour. The average current density was approximately 5 amperes per square foot.

(8) *Chromic Acid-Dichromate Process.*—Samples were given an anodic treatment in a bath at 40° C. containing 4.6 percent by weight each of chromium trioxide and potassium dichromate. Anodization was effected by raising the voltage as rapidly as possible to 40 volts and maintaining it for 1 hour.

(9) *Alcoa Electrolytic No. 1 Process (Sealed).*—Specimens were anodically oxidized in 15-percent sulphuric acid electrolyte at 25° C., with a current density of 12 amperes per square foot for 30 minutes, and sealed in boiling water for 30 minutes.

(10) *Alcoa Electrolytic No. 2 process (sealed).*—Specimens were anodized as in (9), but were sealed by impregnation with lead chromate formed by immersion in lead acetate solution, washing, and immersing in potassium dichromate solution.

(11) *Bengough process (sealed).*—Samples were treated as in (5) but the electrolyte was permitted to impregnate the oxide film and dry thereon.

(12) *Ten-percent Chromic-Acid process (sealed).*—Samples were treated as in (7) but the electrolyte was permitted to impregnate the oxide film and dry thereon.

The unpainted specimens receiving the oxide treatments designated as McCulloch, Deoxidine, Jirotka American, Alcoa Dip, Bengough ("spent" bath), and Chromic Acid-Dichromate all, on visual examination, exhibited more or less advanced stages of failure after an exposure of 6 months at Washington, 3 months at Coco Solo and Hampton Roads, and 1 month in the laboratory salt-spray tests. These oxide treatments were definitely inferior to the others tested and, for all practical purposes, may be considered as similar to each other in their failure to protect against corrosion. Their failure to afford protection was reflected in loss of tensile properties (table VII). The cold-water-quenched material coated by the Alcoa Dip process exhibited no loss in tensile properties after 5 years' exposure at Washington. This result, however, is to be attributed to the inherent corrosion resistance resulting from the heat treatment. Small, localized areas of corrosion product were visible on the samples after 6 months at Washington, which indicated that the coating had failed to protect completely.

The coatings produced by anodic treatment (10-percent Chromic Acid, Bengough, and Alcoa) were definitely much superior and retarded corrosive attack on the hot-water-quenched 17S material for an appreciable period. The first two were especially effective, on cold-water-quenched samples, at all the weather-exposure locations.

By far the best protection was afforded, however, by the oxide films sealed with an inhibitive chromate. Sheets anodized in chromic acid, and from which the electrolyte has not been thoroughly removed, present a somewhat undesirable mottled appearance. Since such sheets are ordinarily painted, this feature becomes relatively unimportant.

An excellent idea of the relative efficiencies of the various oxide coatings may be gleaned from figure 9, which shows their surface appearance at various stages of the laboratory salt-spray tests.

Painted with a standard aluminum-pigmented spar varnish.—Past experiments and experience have proved that, under severe corrosive conditions, the greatest value of the oxide coatings lies in their ability to improve the adherence of additional protective coatings of the organic types. This fact was confirmed in the present investigation when a good grade of aluminum-pigmented spar varnish was applied in conjunction with the oxide surface treatment.

Specimens initially treated by the McCulloch, Deoxidine, Jirotka, and Alcoa Dip processes and then painted, showed no loss in tensile properties after 5 years' exposure at Washington. Small localized areas, indicative of the commencement of paint failure, began to appear on the edges of the specimens during the fifth year. In the absence of saline conditions, however, these combination coatings afforded practically complete protection over this period despite the fact that the metal had purposely been made susceptible to intercrystalline attack. At Coco Solo and Hampton Roads, paint failures became more or less complete during the second year and, in the salt-spray tests, in 2 months.

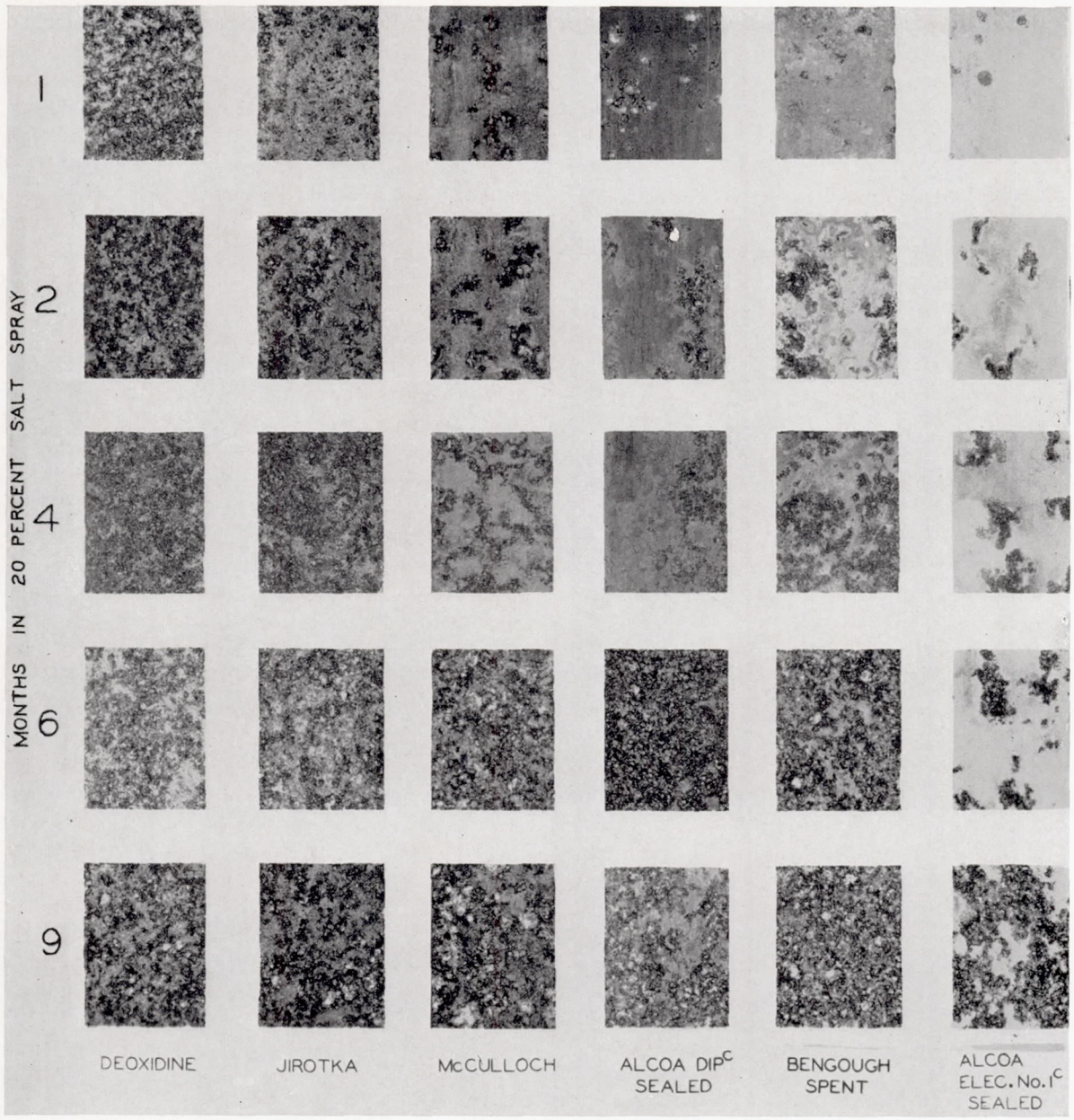
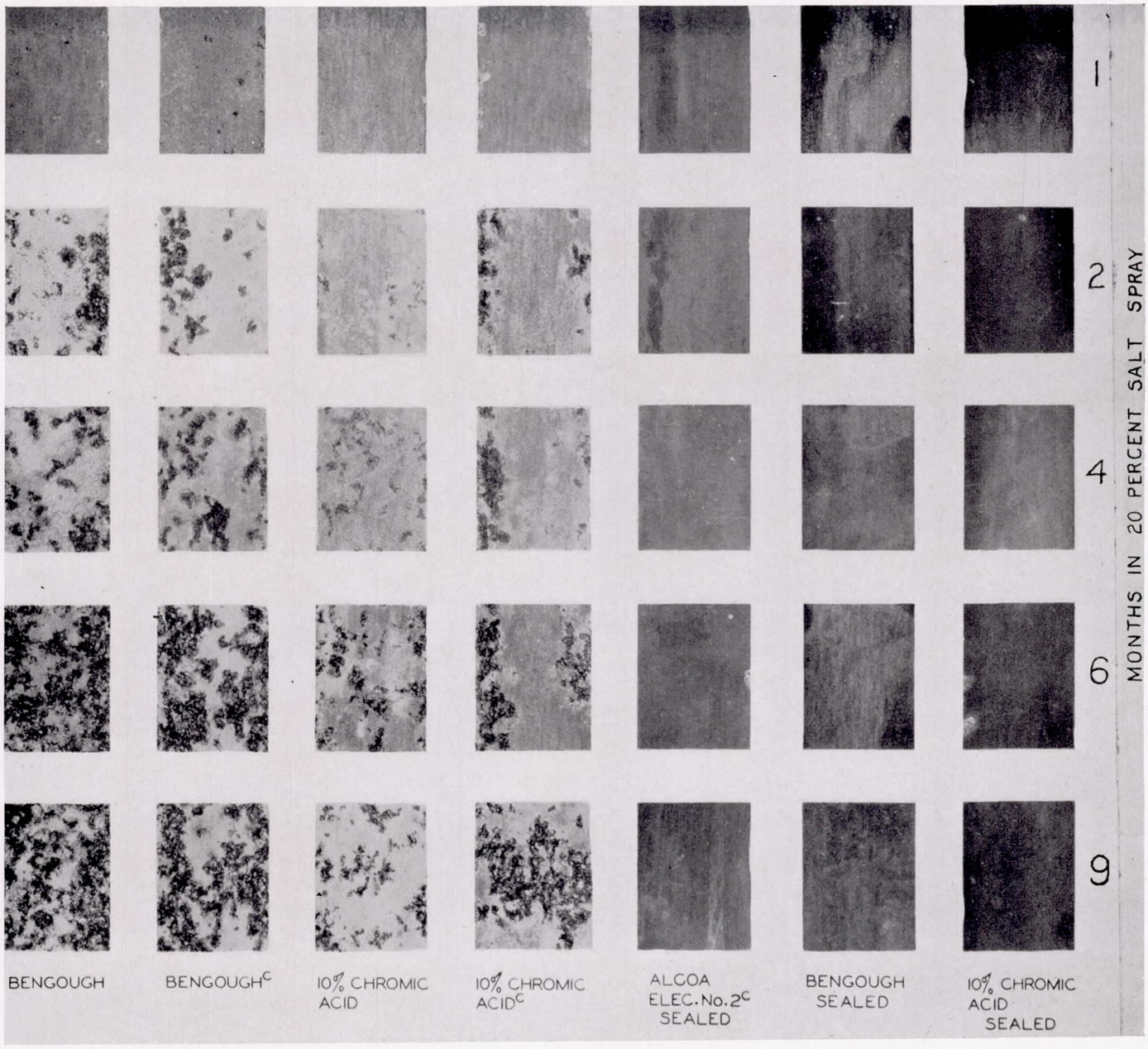


FIGURE 9.—Surface appearance, showing relative efficiencies of various surface oxide coatings applied to 17S specimens that were exposed to the laboratory salt-spray applied anodically and subsequently

Evidences of the beginning of paint failure on the improperly heat-treated, anodically treated duralumin made their appearance during the third year at Hampton Roads and Coco Solo, but failure was still in the initial stage at the conclusion of the tests. Loss in tensile properties (table VIII) was not appreciable. No loss occurred on the correctly heat-treated material or on the aluminum-coated (Alclad) specimens similarly protected, but traces of failure occurred during the fourth year and were confined usually to the edges of the samples. In the laboratory salt-spray tests the specimens presented a comparable appearance at the end of the 1½-year test period.

Paint and varnish coatings.—The vehicles used were all marine spar varnishes designed primarily to withstand exposures to saline conditions. Details relative to the nature of the vehicles, the trade names, and the specifications to which the varnishes conformed are listed in table IX. All the varnishes were applied by spraying. Schedules 2, 3, and 10 were applied at Hampton Roads Naval Air Station. Schedule 5 was applied by Stoner-Mudge, Inc., of Pittsburgh, Pa., and the remaining specimens were painted at the National Bureau of Standards.



test for the periods indicated. Coatings were applied to hot-water-quenched and cold-water-quenched (c) specimens. Note the marked superiority of the coatings given sealing treatments. × 1.

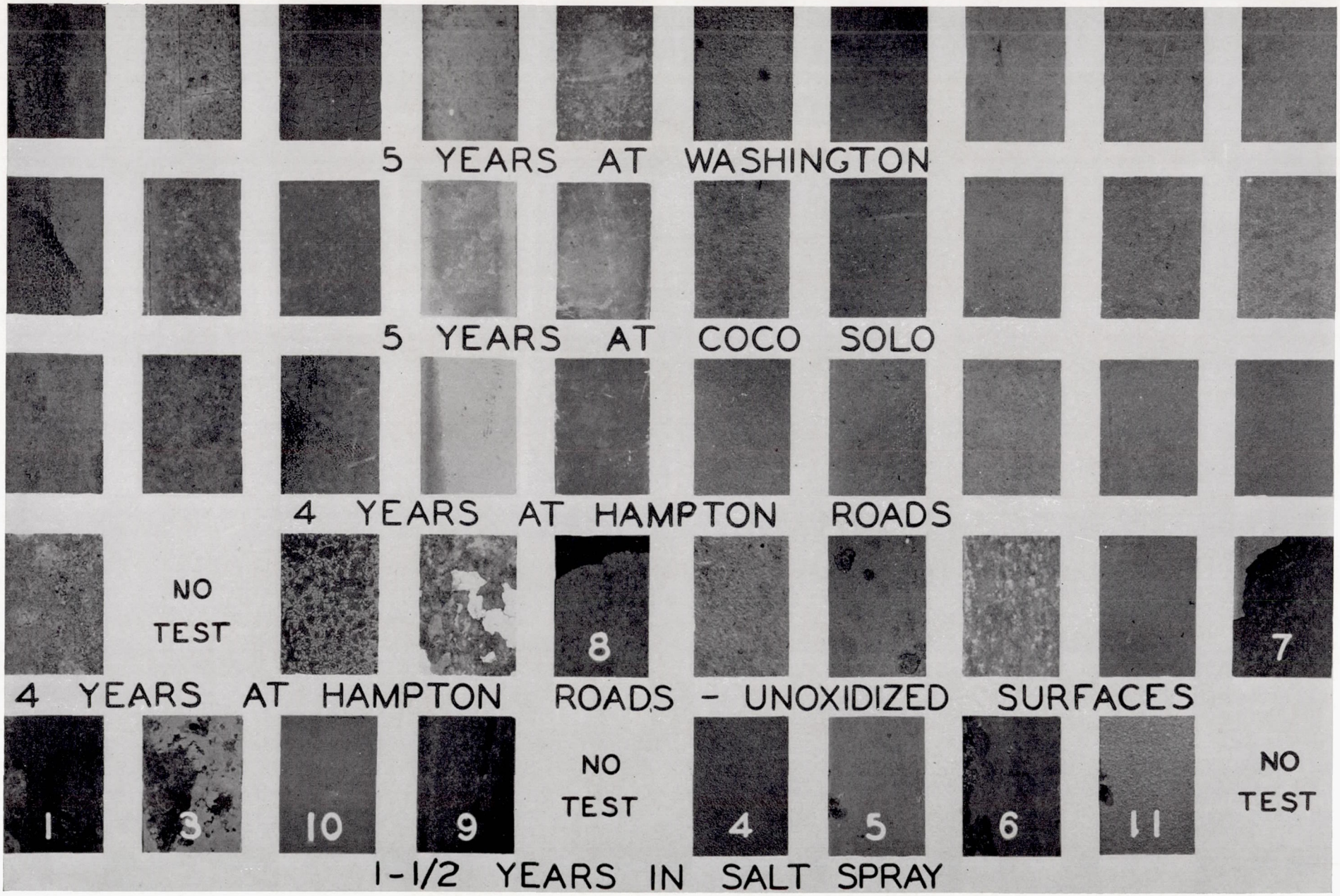


FIGURE 10.—Surface appearance of paint coatings applied to anodically treated 17S material and exposed for the maximum period at each locality. The superiority of the aluminum-pigmented varnishes is quite evident. The coatings were (1) clear Dulux, (3) aluminum foil over Thresher varnish, (10) Navy gray on red oxide primer, (9) zinc-pigmented Bakelite Marine Spar varnish, (8) zinc chromate-zinc oxide pigmented Bakelite Marine Spar varnish, (4) aluminum-pigmented Dulux, (5) aluminum-pigmented Vinylite, (6) aluminum-pigmented Thresher varnish, (11) aluminum-pigmented long-oil varnish, (7) aluminum-pigmented long-oil varnish on zinc chromate-zinc oxide pigmented primer. × 1.

The tensile properties of the painted specimens at the conclusion of the exposure periods are given in table X, and the approximate times at which paint failure was noted are shown in table XI. The surface appearance of specimens after weather exposure for prolonged periods at each location is shown in figure 10.

The marked improvement of the durability of paints applied to an anodically treated surface makes it strongly advisable to use such a treatment if optimum service is to be attained under severe weathering conditions. The data show that the aluminum-pigmented varnishes on anodized panels all afforded relatively excellent protection irrespective of whether the vehicle was of the long oil, glyceryl phthalate, vinyl resin, or phenol formaldehyde varieties. Failure was confined almost entirely to small areas on the edges of the samples and commenced during the third year, although faint yellow discolorations were present during the first year. At the end of the tests all the aluminum-pigmented coatings on anodically treated surfaces were in relatively good condition. Even when this paint was applied to unanodized specimens the protection was greater than that obtained on the unpainted anodically treated specimens.

The zinc chromate-zinc oxide primer (coating 8) exhibited very poor adherence qualities on the unanodized samples but afforded good protection on the anodized samples, especially when finish coats of aluminum-pigmented varnish were employed. Owing to the lower flexibility of varnishes thus pigmented, it is to be questioned whether they would prove as satisfactory as aluminum-pigmented primers on aircraft parts subjected to vibratory or flexural stresses.

The tests with zinc dust-zinc oxide pigment indicated that it was not protective to the vehicle, as was the case with aluminum, and under marine conditions the zinc pigment was attacked more or less rapidly, giving rise to a uniform whitish-gray discoloration. The Navy gray enamel pigment also proved inferior in the exposure tests, as chalking, cracking, and alligatoring occurred within 6 months at all the outdoor locations. On the unanodized specimens failure was complete within a year and large areas of metal were visible. On the anodized samples, the red oxide primer became visible but it adhered well to the end of the tests. The unpigmented varnishes likewise proved unsatisfactory, as practically complete failure occurred during the first year on unanodized material and from the second to the fourth year on anodized samples. Although no loss in tensile properties appeared on anodized samples upon which aluminum foil had been applied over a "tacky" varnish, the use of this coating under saline conditions does not appear promising for the reason that the foil was attacked when subjected to salt-water conditions.

WEATHERING OF MAGNESIUM ALLOYS

The weathering tests on the magnesium-alloy panels furnished by the American Magnesium Corporation were conducted only at Washington and Coco Solo. The purpose of the tests was threefold: (1) to obtain information relative to the probable behavior in service of alloys exposed after surface treatment and painting; (2) to determine which of two surface treatments yielded better adherence of paint; and (3) to determine the relative inherent corrosion resistance of the various alloys as manifested by the rapidity of their attack when the coatings failed to protect them completely.

The eight alloys tested are listed in table XII. The exposure panels were approximately 9 by 6 by ¼ inches and, after surface treatment, all were protected with 4 coats of paint applied at the manufacturer's research laboratories. The paint consisted of Bakelite XV952 Aluminum Vehicle containing 2 pounds per gallon of Albron Standard Varnish Powder. The first coat was brushed on, and the rest were sprayed. Two surface treatments were used:

(1) *Chrome-pickle treatment.*—The panels were immersed for approximately 2 minutes at room temperature in a bath containing 1.5 pounds of sodium dichromate and 1.8 pints of concentrated nitric acid (specific gravity 1.42) per gallon of water. This treatment has been used commercially to a considerable extent

(2) *Phosphoric-acid treatment.*—The panels were immersed for approximately 30 minutes at 125° F. in a solution consisting of 1 pound of 85-percent phosphoric acid and 3 ounces of magnesium oxide per gallon of water.

A single panel representative of each treatment and material was exposed for 5 years at each location. The progress of attack was followed closely by means of monthly inspections. At the end of the exposure tests the panels were photographed, the number of corroded spots or blisters was counted, and their areas were determined. The paint coatings were stripped off to determine to what extent corrosion appeared underneath.

Representative sections from the panels, showing the worst areas of attack, appear in figure 11; figure 12 illustrates that corrosion beneath the paint coating was quite superficial. Data on the number and area of blisters and corroded portions are given in table XIII.

The superiority of the phosphoric-acid surface treatment as a basis for paints is apparent from the table but, from practical considerations, there appears to be little evidence to support a choice of either of the methods investigated. Under mild exposure conditions, as at Washington, the paint coatings, although somewhat discolored, remained intact for 5 years. No appreciable corrosion of the panels took place but small blisters were fairly numerous on the paints applied to two of the chrome-pickled alloys (AM240 and AZM).

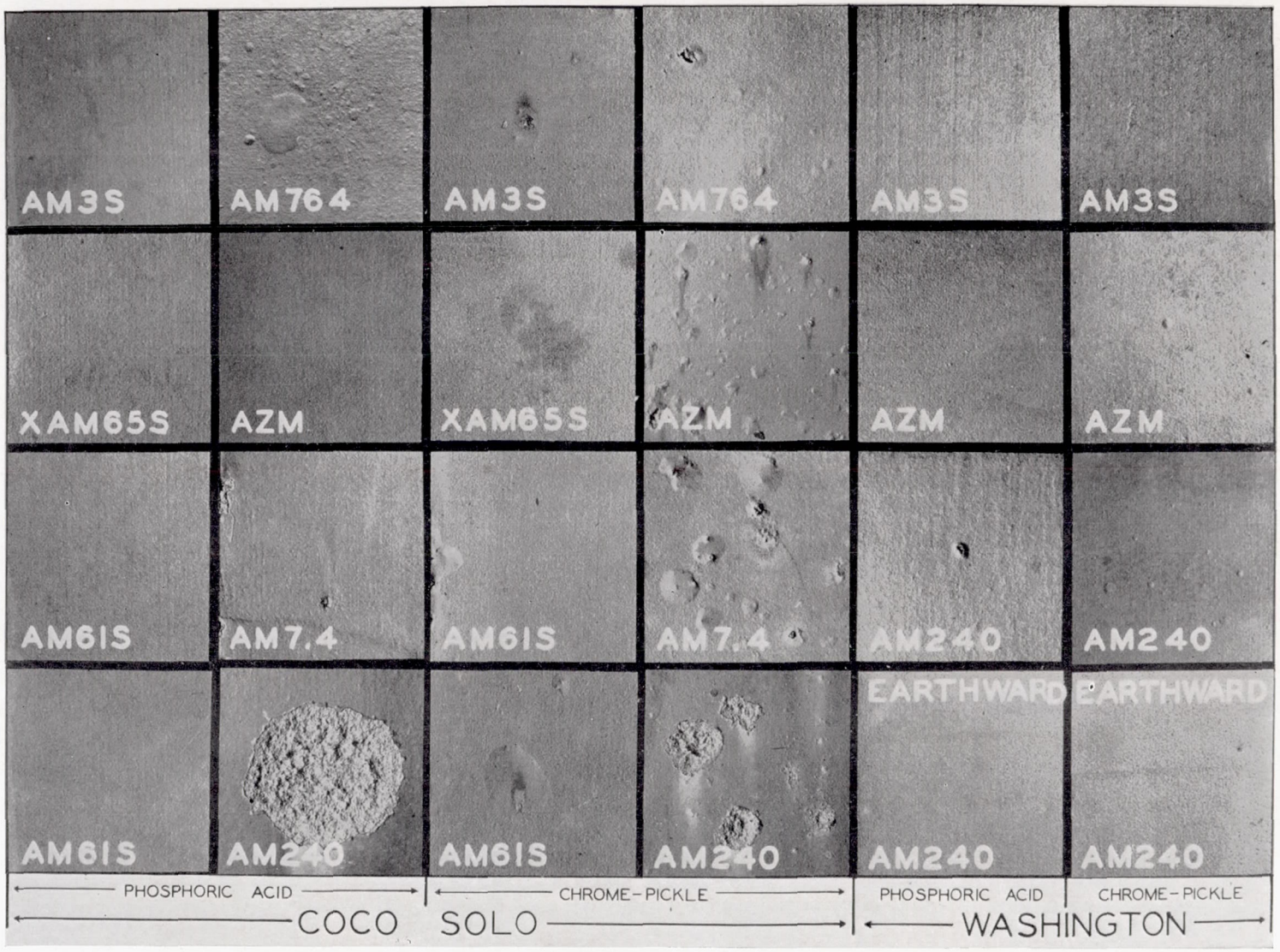


FIGURE 11.—Surface appearance of magnesium alloy panels given the surface treatments indicated, painted with aluminum-pigmented spar varnish, and exposed 5 years at each locality. Note the superiority of the phosphoric-acid surface treatment in improving paint adherence, and the excellence of the AM3S, XAM65S, and AM61S panels. × ½.

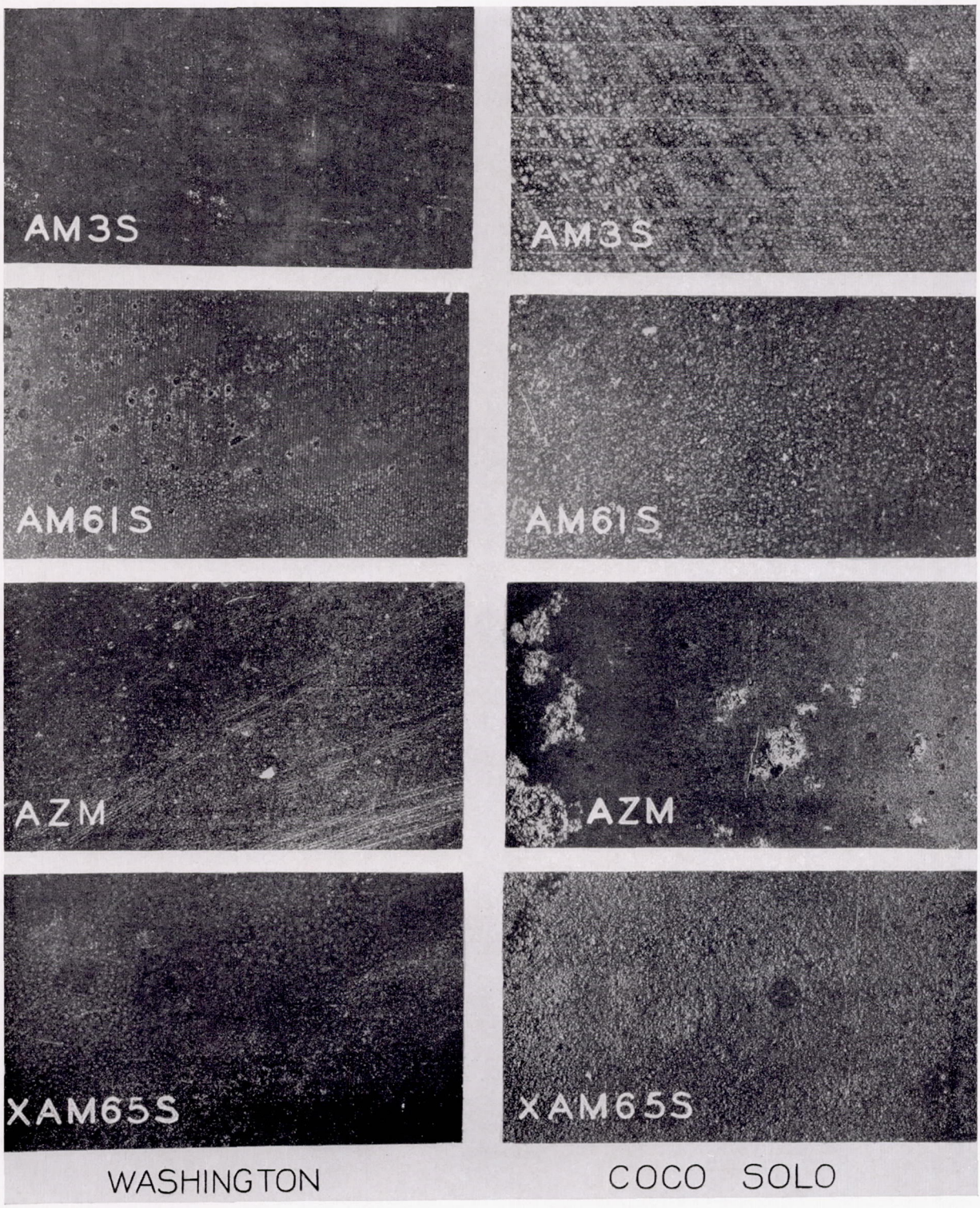


FIGURE 12.—Surface appearance of chrome-pickle treated magnesium alloys, exposed 5 years at Washington (left column) and Coco Solo, from which the protective paint was removed after exposure. The small amount of corrosion product indicates the comparative absence of attack on all except the AZM panel at Coco Solo. × 1.

At Coco Solo, corrosion of serious proportions occurred on only one of the alloys (AM240), upon which approximately 35 percent of the total surface area was affected. On none of the others was more than 3 percent of the surface affected. The severity of the attack was approximately as follows: Alloys AM7.4 and AZM, 3 percent; alloys AM764 and AM61S, less than 2 percent; and alloys XAM65S and AM3S, about 0.2 percent. It is apparent from the data that alloys of magnesium containing between 6 and 10 percent aluminum (AM7.4 and AM240) were comparatively susceptible to attack, the more so with the higher aluminum contents. Much more resistant to attack were the tin-containing alloys (AM764, AM61S, and XAM65S), while the aluminum-manganese alloy AM3S was the most resistant.

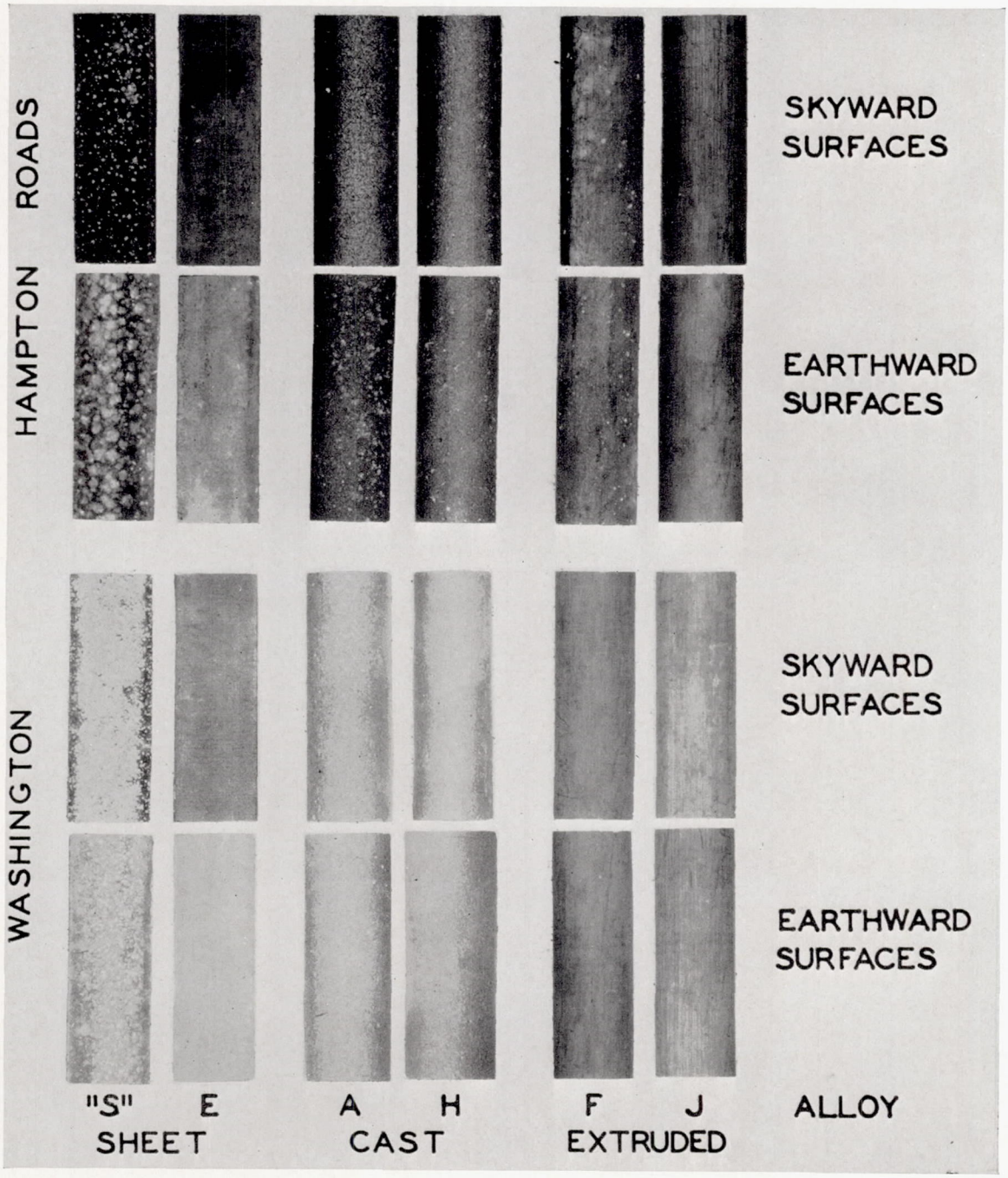


FIGURE 13.—Typical surface appearance of chrome-pickle treated Dowmetal materials after 1 year's exposure at Washington and Hampton Roads. Note the uniformly heavy deposition of corrosion products on "S" and the absence of the same on alloys H and J. × 1.

Another series of exposure tests was begun on a group of selected Dowmetal materials at both Washington and Hampton Roads. At Washington one rack, containing three specimens of each material, remains

to be removed, pending the completion of a 5-year exposure period. At Hampton Roads an identical rack was removed after a year's exposure and shortly thereafter the remaining specimens were lost in a hurricane. Information of some value was obtained, however, and its inclusion here is warranted. The materials used are listed in table XII. Alloys S and E were exposed in the form of sheet, cut into tensile bars having a half-inch reduced section, while alloys H, F, J, and A were exposed as standard A. S. T. M. half-inch round tensile bars.

The samples were prepared by the Dow Chemical Co. Specimens were given the chrome-pickle treatment previously described, and were exposed (1) with no additional coating, (2) coated according to paint schedule A, and (3) coated according to paint schedule B. Paint schedule A consisted of one coat of Brooklyn Varnish Co. P–15 primer, one coat Dux Surfacer No. 2304, and two coats of Brooklyn Varnish Co. Bakelite Varnish 74 plus 2 pounds of aluminum pigment per gallon. Schedule B included coats of the aforementioned primer and surfacer, each baked one hour at 225° F., and two coats of Dulux Black Baking Enamel No. 94005, each baked one hour at 200° F.

Specimens so protected showed no evidence of paint failure at the expiration of the 1-year exposure period at Hampton Roads and, except for a slight yellowish discoloration on the aluminum-pigmented finish and a pronounced dulling of the black enamel, are still in fairly good condition as they near the end of their fourth year at Washington.

Figure 13 shows selected portions of the surface of unpainted samples after 1 year's exposure at each locality. Representative cross sections picturing the extent of corrosion on the materials exposed at Hampton Roads are shown in figures 14 and 15; the results of the tensile tests and microscopic examination are given in table XIV.

The results confirm those obtained in the other series of tests on magnesium-alloy panels, in that the magnesium-aluminum alloys, namely, F, E, and A, were definitely inferior in corrosion resistance to alloys H and J, which were essentially magnesium-aluminum-zinc alloys. The corrosion resistance decreased as the aluminum content of the materials increased. The magnesium-cadmium-zinc alloy S was decidedly the most corrosion-susceptible of the lot, which indicates that the substitution of cadmium for aluminum is not to be recommended in alloys of this type.

CONCLUSIONS

Weather-exposure tests of the kind undertaken in the present investigation require a period of years for the accumulation of data. Inasmuch as they simulate actual service conditions more closely than is practicable by any other means, however, the results of such tests should be especially useful in the selection of corrosion resistant materials and coatings for use in aircraft, particularly the ones likely to be used at or near marine localities. The correlation of results of the weathering tests with those obtained in laboratory tests, such as by the salt-spray method used in this investigation, yields valuable data concerning the extent to which laboratory corrosion tests are indicative of the probable behavior of materials in service. From the results of the systematic program of the present investigation, which embraced tensile, macrographic, and microscopic tests on approximately 7,000 samples, the following outstanding conclusions may be drawn regarding the corrosion behavior of light alloy sheet materials for use in aircraft.

DURABILITY OF VARIOUS ALUMINUM ALLOYS

1. Aluminum-rich alloys containing 1.25 or 3.5 percent magnesium and 0.25 percent chromium were exceedingly resistant to corrosive attack in saline atmospheres. Where their somewhat lower tensile strength is of relatively minor importance, the use of these alloys, commercially designated as X52S and XB52S, can be strongly recommended. No loss in tensile properties had occurred on these materials at the end of the maximum exposure periods, and corrosion was confined to very small isolated pitted areas less than 0.002 inch in depth.

2. The aluminum-rich sheet alloy containing 6 percent magnesium (56S) proved very resistant to attack for periods approximating three years at the marine localities. Thereafter, severe intercrystalline attack developed, accompanied by rapid loss in tensile properties. Rivets made from this material exhibited very severe intercrystalline attack after the second year.

3. Aluminum-rich alloys with no copper, but containing small amounts of magnesium and added manganese, silicon, or cadmium (4S, 51S, XA51S, and Inalium alloys) were definitely much superior in corrosion resistance, under saline conditions, to materials that contained copper as a chief alloying constituent. The 4S and Inalium materials showed an absence of the intercrystalline attack present in the 51S alloys.

4. The corrosion resistance of the aluminum-magnesium-silicon alloy (51SW) when aged at room temperature was somewhat better than it was when aged at elevated temperature (51ST or XA51ST); whereas XA51ST, in turn, proved better than 51ST. Additional protective coatings are advisable, however, if these alloys are to be exposed to severe conditions.

5. The high-strength copper-bearing alloys of the duralumin type (Nicralumin, Aeral, 17ST, 17SRT, 24ST, and 24SRT) were shown to be appreciably inferior in corrosion resistance to the non-copper-containing materials. Even though these alloys are properly heat treated, the application of additional surface protective coatings is strongly recommended. For all practical purposes, the corrosion behavior of these materials

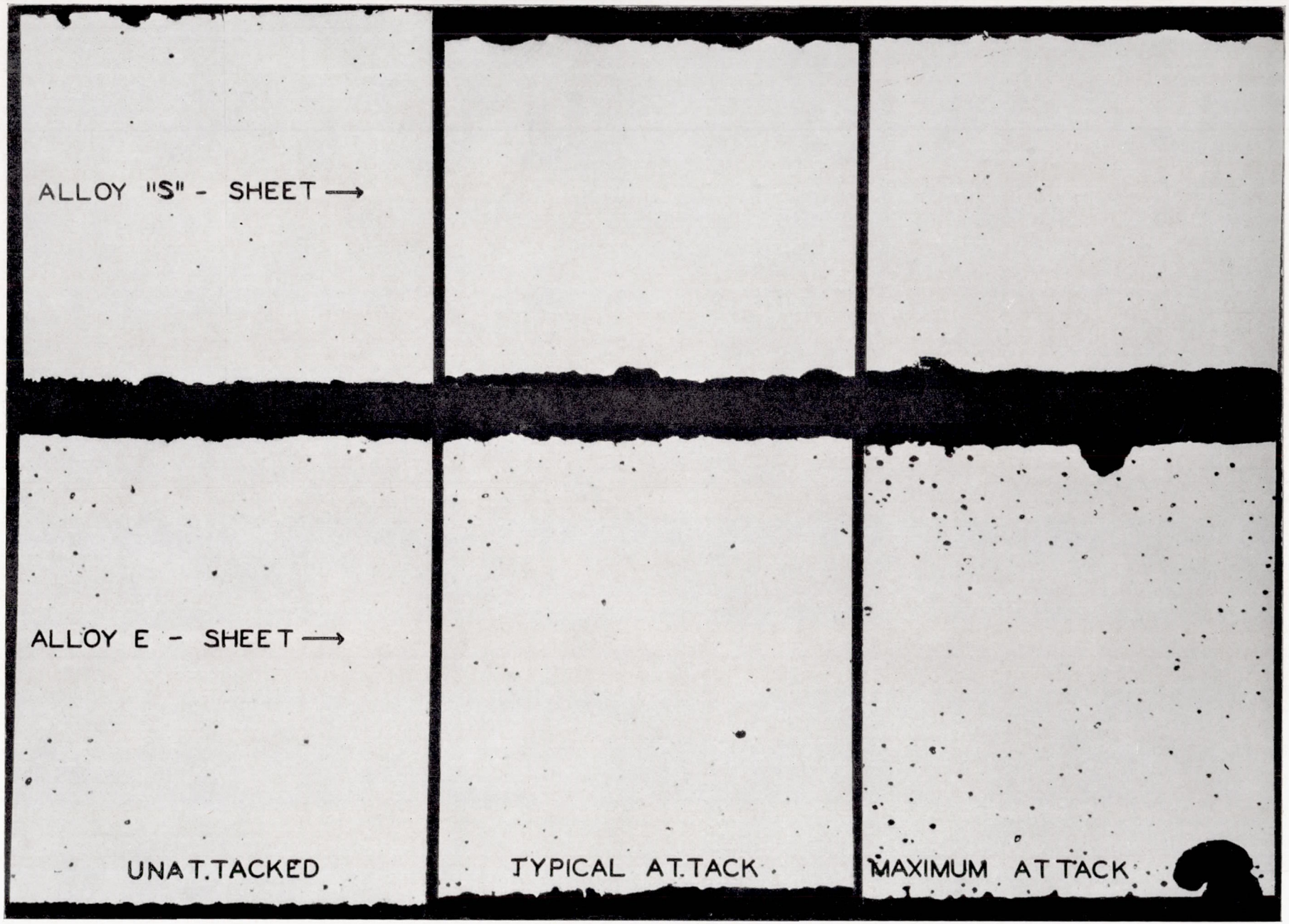


FIGURE 14.—Representative cross sections showing corrosion on Dowmetal sheet materials given the chrome-pickle surface treatment. The unattacked specimens were stored 1 year in sealed containers, and the others were exposed 1 year at Hampton Roads. The upper edges are the skyward surfaces. Note the absence of localized attack on alloy "S," on which the uniform attack resulted in reducing the thickness. × 50.

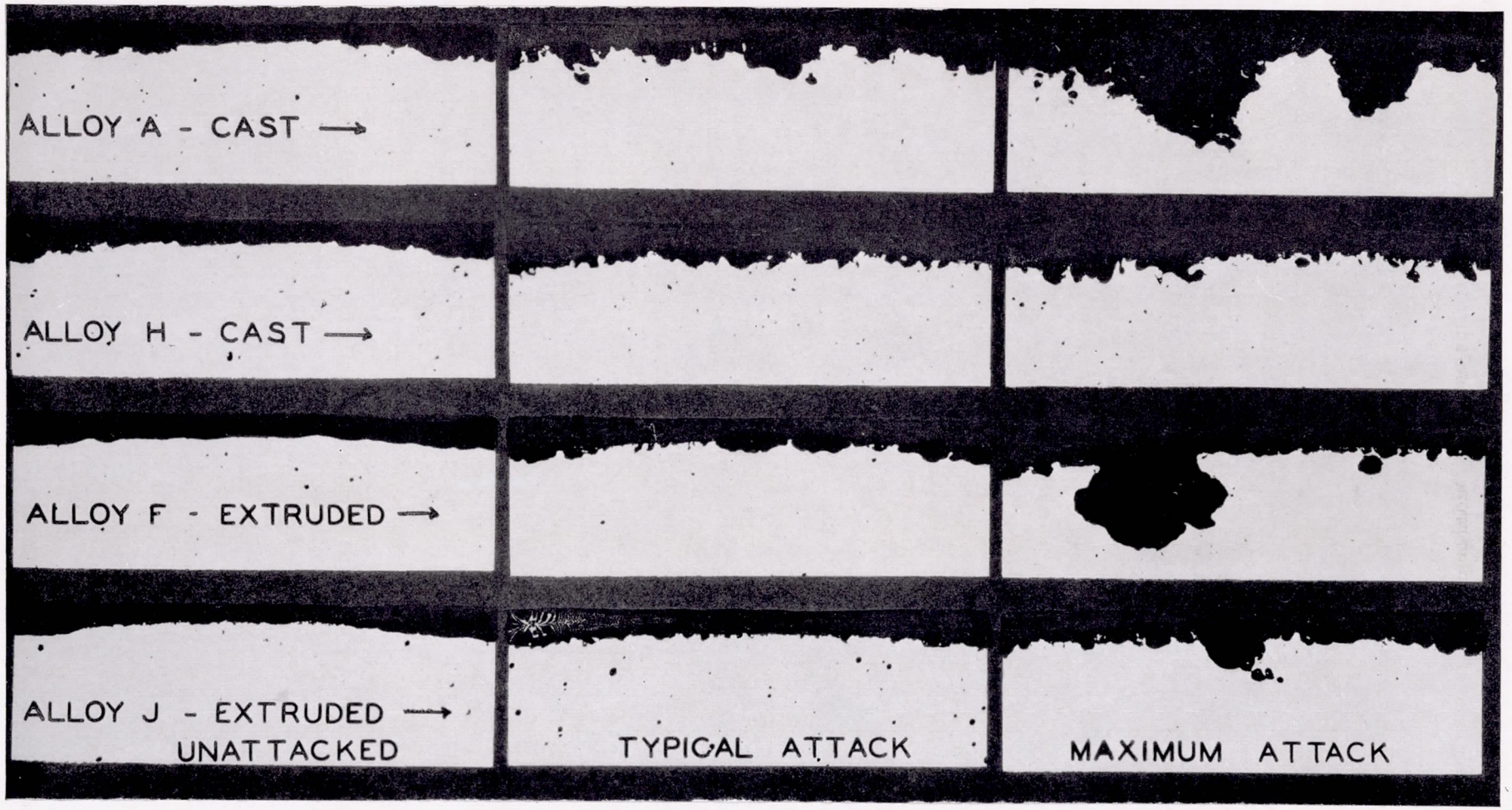


FIGURE 15.—Representative cross sections showing corrosion on Dowmetal tensile bars 0.5 inch diameter exposed at Hampton Roads for 1 year. The specimens were all given the chrome-pickle surface treatment. Those designated "unattacked" were given additional paint protection. Note the superiority of alloys H and J, and the areas of localized attack on alloys A and F. × 50.

may be regarded as similar. Under inland conditions of exposure, no appreciable loss in tensile properties occurred in 5 years and pitting attack penetrated less than 0.005 inch.

6. The Aeral and Inalium alloys, containing 2 percent of cadmium, appeared relatively unsatisfactory from considerations of surface finish. Approximately 5 percent of the samples contained internal flaws, which in some instances markedly lowered the tensile properties.

7. Alloy 25SW was the most susceptible to corrosion of the commercially available sheet materials investigated. Its behavior was quite similar to that of duralumin (17S) improperly heat treated by quenching in boiling water.

8. In general, corrosion at the cut edges, on the various materials exposed as tensile bars, was similar in depth and extent to that present on the sides of the sheet and the tensile properties were not lowered appreciably. The copper-bearing alloys (17ST, 17SRT, and 24SRT) were characterized by the presence of relatively thin longitudinal layers more prone to attack than adjacent metal. Along these layers, corrosion penetrated very much more rapidly and deeply than on the sides. This preferential attack occurred only under saline exposures and caused an appreciable lowering of the tensile properties. It was not noted with the Alclad materials.

9. Aluminum-coated (Alclad) products, containing high-strength cores of 17S or 24S alloys, proved exceptionally resistant to attack. No consistent loss in tensile properties was found at the end of the tests at any of the locations and corrosion had not penetrated the alloying zone.

HEAT TREATMENT OF ALUMINUM ALLOYS

1. The recommended heat-treatment procedure for sheet duralumin (17S alloy) entails solution-heat-treatment from 15 to 30 minutes at 505° C., followed by quenching quickly into cold water, and aging at room temperature. Minor delays in the quenching operation, for intervals of from 5 to 30 seconds between the withdrawal of specimens from the furnace and their immersion in the quenchant, resulted in no appreciable differences in corrosion behavior. Neither did variations in the solution-heat-treatment temperature, between 475° and 545° C. Samples treated at the lower temperature, however, possessed somewhat lower initial properties. It is therefore advisable to follow strictly the recommended procedure in heat treatment.

2. Baking of properly quenched-and-aged duralumin at temperatures in excess of 100° C. rendered the material exceptionally susceptible to intercrystalline attack.

JOINING OF ALUMINUM ALLOYS

Spot welding appears to offer considerable promise as a method of joining Alclad, X52S, and 4S materials. The strengths of such joints were consistently much higher than those formed with similarly spaced aluminum-alloy rivets; but the range in breaking loads was appreciably greater, indicating a need for more precise control of welding operations. Although localized corrosive attack occurred on the welds, penetration was insufficient to result in pronounced lowering of the breaking loads at the end of the exposure tests.

SURFACE TREATMENT OF ALUMINUM ALLOYS

1. Surface oxide coatings, when used alone, proved inadequate to protect duralumin over prolonged exposure to saline conditions. Coatings formed by various immersion methods, such as the McCulloch, Deoxidine, Jirotka, and Alcoa Dip processes, were decidedly inferior from protective considerations to coatings formed by anodic treatment in chromic-acid or sulphuric-acid electrolytes.

2. Although unsealed anodic coatings applied by the Bengough or by the 10-percent chromic-acid processes afforded somewhat better protection than the Alcoa electrolytic No. 1 process, these coatings may, for all practical purposes, be considered essentially similar in behavior.

3. Anodized coatings sealed with chromic-acid electrolytes or with chromates rendered properly heat-treated duralumin very resistant to corrosive attack under severe saline conditions.

4. Good grades of aluminum-pigmented spar varnish coatings, applied to duralumin surfaces given no previous oxide treatment, afforded better protection than unpainted and unsealed oxide surface coatings.

5. Similar paints, applied to surfaces oxidized by immersion methods, afforded good protection for 5 years at Washington but failed during the second year at the marine localities. When applied to anodically treated surfaces, no loss in tensile properties occurred at the marine localities until after the third year.

6. Optimum protection of duralumin may be expected when good grades of aluminum-pigmented marine spar varnishes are applied to anodically treated surfaces that have been sealed with chromium trioxide or chromates.

7. The tests indicated that increased protection with the paint coatings was due to the aluminum pigment. The results obtained with pigments consisting of zinc dust, zinc oxide, zinc chromate, iron oxide, titanium oxide, or mixtures thereof were very much inferior. The results with unpigmented varnishes were, in general, unsatisfactory.

8. Zinc chromate-zinc oxide primers, generally highly regarded because of the inhibitive effect of the chromate ions, afforded no better protection on anodized material than aluminum-pigmented primers and, owing to their lower flexibility, may be disadvantageous on flexed or vibrated aircraft parts.

9. Aluminum-pigmented varnishes, irrespective of whether the vehicle was of the long oil, glyceryl phthalate, vinyl resin, or phenol formaldehyde type, all

afforded adequate protection when applied to anodized surfaces. The occasional variations in quality between different lots of any one of these varnishes are greater than can be attributed to the different vehicles. It is therefore desirable to develop specifications that will assure the required properties.

DURABILITY OF VARIOUS MAGNESIUM ALLOYS

1. Magnesium-alloy sheets containing 1 percent of zinc and 3 percent of cadmium proved very susceptible to attack.

2. Magnesium alloys of essentially the binary type, containing from 4 to 10 percent of aluminum (Dowmetals F, E, A, and G, AM7.4 and AM240) were increasingly susceptible to corrosive attack in the order of their higher aluminum contents. Binary alloys containing more than 7 percent of aluminum are not suited for exposed structures under severe saline conditions, even though protected by surface treatment and painting.

3. The addition of zinc to magnesium-aluminum alloys tends to render them definitely more resistant to attack. Cast alloys containing approximately 3 percent of zinc and 6.5 percent of aluminum (Dowmetal H), if given adequate protection, should prove satisfactory for use in nonsaline atmospheres. Somewhat less resistant were alloys AZM and Dowmetal J, which contained approximately 6 to 7 percent of aluminum and 1 percent of zinc.

4. Magnesium alloys containing additions of tin, such as AM764, AM61S, and XAM65S, and especially the last two, exhibited better corrosion resistance than the binary magnesium-aluminum alloys. These alloys and the magnesium-manganese alloy AM3S, proved definitely superior to the others in the weathering tests.

SURFACE TREATMENT OF MAGNESIUM ALLOYS

1. Surface treatment by the phosphoric-acid process yielded somewhat better adherence of paint on the magnesium alloys than did the chrome-pickle process but, for all practical purposes, either method is suitable.

2. Aluminum-pigmented paint, used in conjunction with the foregoing surface treatments, adequately protected the more corrosion-resistant magnesium alloys for a period of 5 years at Coco Solo. These alloys, so protected, may therefore be expected to prove satisfactory for use in saline atmospheres provided that they are not subjected to frequent thorough wettings.

NATIONAL BUREAU OF STANDARDS,
WASHINGTON, D. C., *December 2, 1938.*

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TABLE I.—CHEMICAL COMPOSITION OF ALUMINUM-ALLOY SHEET MATERIALS

Designation of material [a]	Chemical composition (percent)							
	Al [b]	Cu	Mg	Mn	Fe	Si	Cr	Other elements
X52S-1/2H	97.98	0.02	1.24	0.00	0.37	0.20	0.19	
XB52S–50 percent red.	95.79	.02	3.57	0.00	.23	.14	.25	
Alclad 17ST [c]	93.75	4.10	.59	.58	.48	.50	-----	
Alclad 24ST [c]	93.44	4.17	1.59	.57	.14	.09	-----	
Alclad 24SRT [c]	93.44	4.17	1.59	.57	.14	.09	-----	
4S-1/2H	97.32	.10	.89	1.04	.43	.22	-----	
56S-1/2H	93.73	.05	6.01	0.00	.13	.08	-----	
Inalium [d]	96.50	-----	.80	-----	.25	.45	-----	Cd 2.0.
51SW [e]	97.95	.05	.61	.01	.38	1.00	-----	
51ST [e]	97.95	.05	.61	.01	.38	1.00	-----	
XA51ST	97.61	.05	.51	.01	.52	1.08	.22	
Nicralumin D4018	96.52	.45	.48	.19	.42	.30	.20	Ni 1.01; Mo 0.17; Zn 0.18; W 0.08.
Aeral [d]	92.55	3.75	.80	.25	.25	.40	-----	Cd 2.0.
17ST	94.02	3.94	.56	.57	.47	.44	-----	
17SH [f]	93.73	4.20	.58	.62	.40	.47	-----	
17SH [f]	94.17	3.76	.55	.53	.48	.51	-----	
17SRT	94.45	4.17	.53	.58	.16	.11	-----	
24SRT	93.44	4.17	1.59	.57	.14	.09	-----	
25SW [f]	93.67	4.20	-----	.68	.45	.90	-----	
4S rivets	97.21	.08	1.05	1.11	.41	.14	-----	
X56S rivets	93.72	0.00	6.12	0.00	.11	.05	-----	

[a] Analyses by the cooperating manufacturer, the Aluminum Co. of America, unless otherwise indicated. The letter symbols indicate: S, sheet; W, heated and quenched; T, heated, quenched, and aged; R, heated, quenched, aged, and cold-rolled; H, hard worked.

[b] By difference.

[c] Analysis of the core. Material coated with 99.75 percent aluminum.

[d] Nominal composition furnished by manufacturer, the Société des Brevets Berthelemy de Montby.

[e] Analyzed at National Bureau of Standards. Material was also used in previous series of exposure tests.

[f] Material subsequently heat treated at the National Bureau of Standards and used for the application of protective surface coatings, etc.

TABLE II.—PHYSICAL PROPERTIES AND DEPTH OF PENETRATION OF CORROSIVE ATTACK ON UNCOATED ALUMINUM-ALLOY SHEET MATERIALS BEFORE AND AFTER THEIR MAXIMUM PERIOD OF EXPOSURE AT EACH LOCALITY

Material	Tensile properties										Maximum depth of penetration [a]			
	Ultimate tensile strength					Elongation in 2 inches								
	Uncorroded [b]	Washington [c]	Coco Solo [c]	Hampton Roads [d]	Salt spray [e]	Uncorroded [b]	Washington [c]	Coco Solo [c]	Hampton Roads [d]	Salt spray [e]	Washington [c]	Coco Solo [c]	Hampton Roads [d]	Salt spray [e]
	Lb./sq. in.	*Lb./sq. in.*	*Lb./sq. in.*	*Lb./sq. in.*	*Lb./sq. in.*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Thousandths inch*	*Thousandths inch*	*Thousandths inch*	*Thousandths inch*
X52S-1/2H	26,100	26,000	26,000	26,200	26,500	8.1	7.8	8.5	8.2	8.3	2	1	2	2
XB52S-50 percent red	48,500	47,850	47,200	48,200	48,100	7.5	8.5	8.0	6.9	7.5	2	2	3	2
Alclad 17ST	58,300	59,300	59,000	59,000	59,300	20.3	20.0	20.0	19.5	18.9	2	3	3	3
Alclad 24ST	64,900	65,000	65,100	64,600	64,750	19.6	19.3	19.3	17.8	16.2	2	3	3	3
Alclad 24SRT	65,400	66,200	66,200	65,850	65,600	14.5	15.5	14.3	13.5	13.0	3	3	3	3
4S-1/2H	33,700	34,000	34,450	33,550	33,200	5.6	5.5	6.0	5.0	4.0	2	2	4	2
56S-1/2H	54,900	53,500	44,650	54,900	44,150	12.0	12.3	5.5	11.4	3.0	4	12	4	7
Inalium CR	31,400	31,900	32,600	31,300	32,500	5.4	6.5	7.0	5.5	5.3	4	5	6	8
Inalium HT	41,400	42,300	41,600	41,900	41,800	15.5	16.5	15.0	15.2	11.1	3	4	7	14
51SW	40,700	40,500	41,700	40,300	39,000	24.9	20.5	25.0	18.5	12.0	4	4	9	7
XA51ST	47,100	48,100	45,850	45,850	45,850	13.6	11.3	12.5	8.2	6.8	10	8	9	7
51ST	49,300	49,100	48,700	45,500	45,300	12.6	8.2	7.5	4.3	3.2	5	9	10	10
Nicralumin D 4018	45,800	45,700	45,350	43,900	44,500	8.4	8.3	8.0	5.8	5.0	6	7	7	8
Aeral HT	56,800	56,000	54,500	54,500	34,400	21.4	22.0	22.0	16.2	4.1	4	5	7	20
Aeral CR	57,850	57,900	58,200	55,750	38,600	22.0	22.0	19.5	14.5	4.8	4	5	8	24
17ST	64,100	64,400	65,100	63,300	38,600	20.5	19.5	19.3	14.3	3.0	4	6	7	28
17SRT	64,000	64,000	63,750	62,600	38,400	16.3	15.8	16.3	13.1	2.0	5	7	8	27
24SRT	70,100	70,000	68,400	67,500	47,200	15.4	14.0	12.0	9.1	1.5	6	7	7	22
25SW	54,900	53,200	52,050	40,000	28,700	18.7	14.2	12.0	3.0	1.0	5	10	15	31

[a] Measured from the earthward surface of weather-exposure specimens, on which the depth was usually greater than on the skyward surface.
[b] Average of 6 initial specimens, and 10 from sealed containers.
[c] Exposed 5 years.
[d] Exposed 4 years.
[e] The Alclad, 52S, 4S, Inalium, and 56S materials were exposed 18 months in the salt spray. All of the other alloys were exposed 6 months.

TABLE III.—PERCENTAGE LOSS IN TENSILE PROPERTIES AND PERCENTAGE PENETRATION OF CORROSIVE ATTACK ON UNCOATED ALUMINUM-ALLOY SHEET MATERIALS EXPOSED AS INDICATED

Material	Percentage loss in tensile properties										Percentage of thickness penetrated [a]			
	Ultimate tensile strength					Percentage loss in elongation								
	Uncorroded [b]	Washington [c]	Coco Solo [c]	Hampton Roads [d]	Salt spray [e]	Uncorroded [b]	Washington [c]	Coco Solo [c]	Hampton Roads [d]	Salt spray [e]	Washington [c]	Coco Solo [c]	Hampton Roads [d]	Salt spray [e]
	Lb./sq. in.					*Percent*								
X52S-1/2H	26,100	0	0	0	0	8.1	0	0	0	0	6	3	6	6
XB52S-50 percent red	48,500	0	0	0	0	7.5	0	0	0	0	6	6	9	6
Alclad 17ST	58,300	0	0	0	0	20.3	0	0	0	3	6	9	9	9
Alclad 24ST	64,900	0	0	0	0	19.6	0	0	6	12	6	9	9	9
Alclad 24SRT	65,400	0	0	0	0	14.5	0	0	4	7	9	9	9	9
4S-1/2H	33,700	0	0	0	2	5.6	0	0	9	20	6	6	12	6
56S-1/2H	54,900	2	19	0	19	12.0	0	54	5	75	12	37	12	22
Inalium CR	31,400	0	0	0	0	5.4	0	0	0	0	12	16	19	25
Inalium HT	41,400	0	0	0	0	15.5	0	5	0	17	9	12	22	44
51SW	40,700	0	0	0	3	24.9	13	10	23	49	12	12	28	22
XA51ST	47,100	0	1	1	1	13.6	13	18	33	44	31	25	28	22
51ST	49,300	1	1	7	8	12.6	34	48	66	74	16	28	31	31
Nicralumin D 4018	45,800	0	0	3	3	8.4	0	15	33	40	19	22	22	25
Aeral HT	56,800	0	4	2	49	21.4	0	0	23	81	12	16	22	62
Aeral CR	57,850	0	0	2	33	22.0	0	10	28	77	12	16	25	75
17ST	64,100	0	0	0	39	20.5	3	7	28	85	12	19	22	87
17SRT	64,000	0	1	1	39	16.3	0	7	20	88	16	21	25	84
24SRT	70,100	0	2	3	30	15.4	2	18	37	90	19	21	22	69
25SW	54,900	3	5	30	48	18.7	24	50	84	95	16	31	47	97

[a] Computed on the basis of the thickness of half a sheet, namely, 0.032 inch.
[b] Average values of 6 initial specimens, and 10 from sealed containers.
[c] Exposed 5 years.
[d] Exposed 4 years.
[e] The Alclad, 52S, 4S, Inalium, and 56S materials were exposed 18 months in the salt spray. All of the other alloys were exposed 6 months.

TABLE IV.—DIFFERENCES IN TENSILE PROPERTIES ON ALUMINUM-ALLOY SHEET MATERIALS EXPOSED TO THE 20 PERCENT SALT-SPRAY TEST AS STRIPS (TENSILE BARS MACHINED AFTER CORROSION) AND AS TENSILE BARS

Material	Exposure period	Ultimate tensile strength		Elongation in 2 inches	
		Strip	Tensile bar	Strip	Tensile bar
	Months	*Lb./sq. in.*	*Lb./sq. in.*	*Percent*	*Percent*
17ST	¼	62, 500	61, 800	20. 0	19. 0
	½	62, 500	62, 200	17. 5	16. 0
	1	63, 500	60, 900	16. 5	14. 5
	2	59, 600	53, 200	10. 5	6. 5
	4	49, 300	46, 700	6. 0	5. 0
	6	40, 200	37, 100	3. 0	3. 0
17SRT	¼	62, 200	64, 300	16. 5	18. 0
	½	61, 200	63, 400	15. 0	15. 0
	1	61, 200	57, 800	12. 0	7. 5
	2	53, 100	51, 600	5. 5	4. 0
	4	45, 300	46, 600	2. 5	3. 5
	6	40, 600	36, 200	2. 0	2. 0
24SRT	¼	67, 800	68, 800	16. 0	15. 5
	½	67, 200	67, 500	12. 0	13. 0
	1	66, 000	66, 600	8. 0	10. 0
	2	64, 000	60, 300	7. 5	4. 0
	4	60, 900	52, 500	4. 0	2. 0
	6	48, 800	45, 600	1. 6	1. 5

TABLE V.—BREAKING LOADS OF SPOT-WELDED AND RIVETED SAMPLES BEFORE AND AFTER WEATHER-EXPOSURE TESTS. THE PANELS WERE 1 INCH WIDE. (Cf. fig. 1c)

Material	Joined by—	Breaking load					
		Uncorroded			Washington 5 years[b]	Coco Solo 5 years[b]	Hamton Roads 4 years[b]
		Maximum	Average[a]	Minimum			
		Lb.	*Lb.*	*Lb.*	*Lb.*	*Lb.*	*Lb.*
Alclad 24SRT	Spot-welds[c]	2, 550	2, 190	1, 800	2, 270	2, 040	2, 150
Alclad 17ST	Spot-welds[c]	2, 460	2, 090	1, 650	1, 970	2, 010	1, 880
4S-½H	Spot-welds[d]	2, 110	1, 990	1, 900	2, 000	2, 020	2, 000
X52S-½H	Spot-welds[d]	1, 640	1, 570	1, 500	1, 590	1, 570	1, 570
Alclad 17ST	17S rivets[c]	1, 160	1, 070	1, 040	1, 150	1, 200	1, 150
Alclad 17ST	X56S-¼H rivets[c]	1, 010	985	960	825	600	760
X52S-½H	4S-¼H rivets[c]	565	540	510	570	550	575

[a] Average of 13 specimens tested initially or after being kept in sealed containers.
[b] Average of 3 specimens.
[c] The majority of specimens broke longitudinally, through the welds or rivets.
[d] The majority of specimens broke in areas immediately adjacent to the welds.

TABLE VI.—PERCENTAGE LOSS IN TENSILE PROPERTIES AND PERCENTAGE PENETRATION OF CORROSIVE ATTACK ON UNCOATED 17S MATERIALS, HEAT TREATED AS INDICATED

Solution heat-treated for 30 minutes	Quenchant	Aged at room temperature before test	"Baking" temperature	Percentage loss in tensile properties								Percentage of thickness penetrated[a]		
				Ultimate tensile strength				Elongation in 2 inches						
				Uncorroded[b]	Washington 5 years	Hampton Roads 4 years	Salt spray ½ year	Uncorroded[b]	Washington 5 years	Hampton Roads 4 years	Salt spray ½ year	Washington 5 years	Hampton Roads 4 years	Salt spray ½ year
Temp. ° C.		*Months*	*° C.*	*Lb./sq. in.*				*Percent*						
505	Ice water	3		61, 800	0	0	41	21. 0	0	29	85	16	22	75
505	do.[c]	3		63, 100	0	0	31	21. 0	0	21	71	12	19	69
505	do.[d]	3		62, 700	2	2	47	20. 6	9	20	91	12	22	75
545+	do	3		60, 100	0	0	43	16. 0	0	24	90	12	31	75
475	do	3		57, 300	0	2	36	18. 9	11	17	73	16	25	72
505	do.[e]	1½	38	61, 600	0	2	52	20. 3	7	27	90	12	22	69
505	do.[e]	1½	93	62, 500	0	4	41	20. 3	4	26	83	31	19	69
505	do.[e]	1½	149	62, 100	8	100	97	20. 5	48	100	100	44	100	100
505	Boiling water	3		61, 900	3	58	63	21. 2	49	86	96	25	100	87

[a] Computed on the basis of the thickness of half a sheet, namely, 0.032 inch.
[b] Average value of 6 initial, and 10 sealed-container specimens.
[c] Quench delayed 5 seconds after removal from furnace.
[d] Quench delayed 30 seconds after removal from furnace.
[e] Prior to baking. Aged 3 months after baking.

TABLE VII.—EFFECT OF WEATHERING ON THE ELONGATION OF 17S ALLOY GIVEN VARIOUS SURFACE OXIDE TREATMENTS. SPECIMENS WERE QUENCHED IN BOILING WATER, UNLESS OTHERWISE INDICATED

Surface oxide treatment	Exposure time and elongation in 2 inches [a]					
	Washington		Hampton Roads		Salt spray	
	Months	*Percent*	*Months*	*Percent*	*Months*	*Percent*
None	6	14.0	3	8.0	1	10.0
	60	10.5	48	3.0	2	9.0
					6	.8
None [b]	6	20.5	3	18.0	1	19.0
	60	19.5	48	14.5	2	17.5
					6	3.0
Deoxidine	6	14.5	3	10.5	1	8.5
Jirotka	6	14.5	3	10.5	1	7.5
McCulloch	6	13.5	3	10.5	1	9.0
Alcoa Dip [b]	60	20.0	48	17.5	2	13.0
Bengough "spent"	6	16.0	3	15.5	1	13.0
Chromic acid-dichromate	6	17.5	3	12.5		
Alcoa Electrolytic No. 1 [b]	60	20.0	48	15.0	2	13.0
Bengough	6	17.5	3	17.0	1	13.5
Bengough [b]	60	20.5	48	19.0	2	13.0
10 percent Chromic acid	6	17.5	3	17.0	1	19.0
10 percent Chromic acid [b]	60	20.5	48	19.0	2	15.0
Alcoa Electrolytic No. 2 (sealed) [b]	60	20.0	48	19.5	18	20.0
Bengough (sealed)	18	20.0	3	19.0	9	20.5
10 percent Chromic acid (sealed)	18	20.0	3	18.0	9	18.5
Alcoa Dip [c]	60	20.5	48	17.5	18	18.8
Alcoa Electrolytic No. 1 [c]	60	20.0	48	20.5	18	20.0
Alcoa Electrolytic No. 2 [c]	60	20.0	48	20.0	18	19.8
Bengough [c]	60	20.0				
Bengough [d]	60	20.0	24	20.0		

[a] Values on uncorroded specimens ranged between 19.0 and 22.0, and averaged 20.5 percent.
[b] Quenched in ice water after solution heat treatment.
[c] Coatings on Alclad 17ST material.
[d] Coatings on Alclad 17S material quenched in boiling water after solution heat treatment.

TABLE IX.—THE PAINT SCHEDULES USED AND THE SPECIFICATIONS TO WHICH THE PRODUCTS CONFORMED

Schedule	Number of coats	Vehicle		Pigment	
		Type and trade name	Navy specification	Type	Navy specification
1	3	Glyceryl phthalate, Dulux RC-147.	V11	None	
2	3	Phenol formaldehyde, Thresher No. 440.	V10	None	
3	1	Phenol formaldehyde, Thresher No. 440.	V10	None. Covered with aluminum foil before varnish became dry.	47A5
4	3	Glyceryl phthalate, Dulux RC-165.	V11	Standard, Type A, aluminum powder.[a]	52A1
5	3	Vinyl resin, Vinylite N.[b]		Fine, Type B, aluminum powder.[a]	52A1
6	3	Phenol formaldehyde, Thresher No. 440.	V10	Fine, Type B, aluminum powder.[a]	52A1
7	1, 2	Primer as in 8, Finish coats as in 11.		Primer as in 8, Finish coats as in 11.	
8	3	Phenol formaldehyde [c]	V10	85 percent zinc chromate, 15 percent XX Process zinc oxide.	
9	3	Same as 8 [d]	V10	85 percent zinc dust, 15 percent XX Process zinc oxide.	52Z3
10	1	33-gallon varnish. Philadelphia Navy Yard Red oxide Primer No. 64.	P23	33 percent zinc chromate, 67 percent iron oxide.	P23
	2	Navy gray enamel, Dupont, Finish coats.[e]	M-67-B	48 percent titanium dioxide, 48 percent zinc oxide, 2 percent lampblack.	M-67-B
11	3	Long oil, ester gum, Pratt & Lambert No. 10.[f]	52V15	Standard, type A, aluminum pigment.[a]	52A1

[a] Two pounds of pigment per gallon of vehicle.
[b] The vehicle contained (parts by weight): 500, 20 percent ½ sec. R. S. Nitrocellulose in solvent S-7; 189, 53 percent Vinylite N in toluol; 20, dibutyl phthalate; 40, ethyl acetate; 500, solvent S-7. Solvent S-7 contained (parts by volume): 60, toluol; 10, butanol; 10, ethyl acetate; 10, cellosolve; 10, cellosolve acetate.
[c] The varnish contained 100 pounds phenol formaldehyde XR-821 resin, 50 gallons tung oil, 6.4 pounds lead resinate, 1.75 pounds cobalt resinate, 48.5 gallons mineral spirits, and 18.5 gallons xylol. The product contained approximately 55 percent vehicle and 45 percent pigment.
[d] Same varnish as in (c), but the final product contained approximately 27.5 percent vehicle and 72.5 percent pigment.
[e] The varnish contained approximately 50 percent pigment.
[f] A 66-gallon varnish with tung and linseed oils, the former predominating. The resin was a mixture of rosin ester and rosin. It contained a nonvolatile of approximately 52 percent and passed a kauri reduction of approximately 70 percent.

TABLE VIII.—EFFECT OF WEATHERING ON THE ELONGATION AND MAXIMUM DEPTH OF PENETRATION OF CORROSIVE ATTACK ON 17S MATERIAL GIVEN VARIOUS SURFACE OXIDE TREATMENTS AND PAINTED WITH THREE COATS OF ALUMINUM PIGMENTED VARNISH [a]

Oxide surface treatment	Percentage elongation in 2 inches [b]				Percentage maximum depth of penetration			
	Washington 5 years	Coco Solo 5 years	Hampton Roads 4 years	Salt spray 1½ years	Washington 5 years	Coco Solo 5 years	Hampton Roads 4 years	Salt spray 1½ years
Deoxidine	19.8	13.0	16.0	5.2	2	2	2	62
Jirotka	21.0	12.0	16.0	7.9	2	3	3	47
McCulloch	19.8	16.0	17.5	14.1	2	2	2	32
Alcoa Dip [c]	20.2	20.5	19.5	18.5	2	3	2	2
Bengough "spent"	19.0	13.0	18.5	18.5	2	2	2	2
Chromic acid-dichromate	21.0	16.5	15.0		2	2	2	x
Alcoa Electrolytic No. 1 [c]	20.8	20.5	20.5	20.0	2	2	2	2
Bengough	20.0	20.0	20.2	17.7	2	12	2	2
Bengough [c]	20.2	20.5	19.2	20.6	2	2	2	2
10 percent chromic acid	19.0	20.5	17.5	20.4	2	2	2	2
Alcoa Electrolytic No. 2 [c]	20.5	20.5	21.5	18.2	2	2	2	2
Bengough (sealed)	19.2	19.5	15.5	18.0	2	2	2	2
10 percent chromic acid (sealed)	21.0	20.0	20.0	18.5	2	2	2	2
Alcoa Dip [d]	20.2	19.5	19.5	19.8	2	2	2	2
Alcoa Electrolytic No. 1 [d]	19.5	20.0	19.5	17.6	2	2	2	2
Alcoa Electrolytic No. 2 [d]	19.0	19.0	19.5	18.4	2	2	2	2
Bengough [d]	20.2	21.0	19.5		2	2	2	2
Bengough [e]	21.2	21.0	20.0		2	2	2	2

[a] The only marked losses in tensile strength occurred on Jirotka and McCulloch coated specimens exposed 1½ years to the salt spray. The values dropped to 57,900 and 50,500 pounds per square inch, respectively.
[b] Values on uncorroded specimens ranged between 19.0 and 22.0, and averaged 20.5 percent.
[c] Quenched in ice water after solution heat treatment.
[d] Coatings on Alclad 17ST material.
[e] Coatings on Alclad 17S material, quenched in boiling water after solution heat treatment.

TABLE X.—EFFECT OF WEATHERING ON THE ELONGATION VALUES OF 17S MATERIAL, QUENCHED IN BOILING WATER, ON WHICH VARIOUS VARNISHES WERE APPLIED TO UNTREATED AND ANODICALLY TREATED SURFACES

Coating	Paint schedule	Percentage elongation in 2 inches [a]							
		Washington 5 years		Coco Solo 5 years		Hampton Roads 4 years		Salt spray	
								1 year	1½ years
		Untreated	Anodized	Untreated	Anodized	Untreated	Anodized	Untreated	Anodized
1	Clear Dulux RC-147	14.2	19.8	1.5	8.5	3.3	15.5	1.0	13.5
2 [b]	Clear Thresher Bakelite No. 440.		21.5		17.5		18.3		20.3
3 [b]	Clear, with aluminum foil		20.5		20.5		18.0		20.3
4	Dulux RC-165, aluminum pigment.	18.2	17.5	17.5	20.5	12.0	19.1	2.5	17.7
5	Vinylite N, aluminum pigment.	18.0	18.0	12.0	16.0	9.5	17.1	4.0	14.5
6	Thresher Bakelite No. 440, aluminum pigment.	14.2	20.0	12.5	19.0	15.5	20.0	4.0	17.3
7	Bakelite Varnish, aluminum pigment, on zinc chromate primer.	20.5	21.0	20.5	20.5	16.8	20.0		
8	Bakelite Varnish, zinc chromate pigment.	17.8	18.8	19.5	20.5	18.5	19.3		
11	Pratt & Lambert No. 10, aluminum pigment.	21.0	20.0	20.5	20.0	19.8	20.2	2.0	17.7
11 [b]	do	20.4	20.2	20.5	20.5	20.8	20.5	20.3	20.5
9	Bakelite Varnish, zinc dust pigment.	18.8	18.5	9.0	20.5	4.8	17.5	7.0	19.4
10	Navy Gray enamel on red oxide primer.	11.2	16.1	13.5	17.5	11.8	15.8	10.8	17.9
10 [b]	do	19.5	20.5	18.8	20.0	17.0	18.8	14.5	18.1

[a] Values of initial or uncorroded specimens ranged from 19.0 to 22.0, and averaged 20.5 percent.
[b] Applied to material quenched in ice water after solution heat treatment.

TABLE XI.—APPROXIMATE MONTH OF THE EXPOSURE PERIOD AT WHICH VISIBLE EVIDENCE OF PAINT FAILURES OCCURRED ON 17S MATERIAL, QUENCHED IN BOILING WATER

Coating	Paint schedule	Month failure was noted							
		Washington		Coco Solo		Hampton Roads		Salt spray	
		Untreated	Anodized	Untreated	Anodized	Untreated	Anodized	Untreated	Anodized
1	Clear Dulux RC-147	6	18	3	24	3	36	1	4
2 [a]	Clear Thresher Bakelite No. 440.	-----	48	-----	24	-----	36	-----	18
3 [a]	Clear with aluminum foil	-----	[b] 18	-----	[b] 3	-----	[b] 3	-----	[b] 1
4	Dulux RC-165, aluminum pigment.	48	60	[c] 24	48	12	36	4	18
5	Vinylite N, aluminum pigment.	[c] 48	([d])	[c] 48	48	[c] 24	48	2	8
6	Thresher Bakelite No. 440, aluminum pigment.	60	([d])	60	48	36	48	2	18
7	Bakelite Varnish, aluminum pigment on zinc chromate primer.	[c] 36	60	[c] 18	48	[c] 12	36	-----	-----
8	Bakelite Varnish, zinc chromate pigment.	[c] 36	([d])	[c] 30	60	[c] 24	48	-----	-----
9	Bakelite Varnish, zinc dust pigment.	6	[e] 12	3	[e] 3	3	[e] 3	1	18
10	Navy gray enamel on red oxide primer.	[c] 3	[f] 12	[c] 3	[f] 12	[c] 3	[f] 12	12	18
11	Pratt & Lambert No. 10, aluminum pigment.	([d])	([d])	48	48	36	48	4	18

[a] Applied only to material quenched in ice water after solution heat treatment.
[b] Pinholes present on the aluminum foil.
[c] Metal exposed to view.
[d] Failure confined to faint yellow discoloration at end of test period.
[e] Became white. No further evidence of failure occurred until after the 36th month.
[f] Chalked, cracked, and alligatored.

TABLE XII.—THE MAGNESIUM ALLOYS AND THEIR CHEMICAL COMPOSITIONS

Material	Fabrication	Panel thickness	Chemical composition, percent [a]					
			Mg [b]	Al	Zn	Sn	Mn	Cd
		In.						
AM240-T61	Cast	0.28	90.71	9.16	-----	-----	0.13	----
AM7.4-T4 [c]	Cast	.28	92.39	7.3	-----	-----	.31	----
Dowmetal A	Sand cast, sand blasted	[d] .505	92.28	7.5	-----	-----	.22	----
Dowmetal E	Sheet, wire brushed	[d] .067	93.76	5.9	-----	-----	.34	----
Dowmetal F	Extruded, machined	[d] .505	95.37	4.37	-----	-----	.26	----
AZM [e]	Hot pressed	.22	91.80	7.04	0.85	-----	.31	----
Dowmetal J	Extruded, machined	[d] .505	92.40	6.15	1.14	-----	.31	----
Dowmetal H	Sand cast, sand blasted	[d] .505	90.04	6.44	3.21	-----	.31	----
Dowmetal "S"	Sheet, wire brushed	.053	96.01	-----	.97	-----	-----	3.02
AM764-T6 [c]	Cast	.29	91.66	-----	3.44	4.63	.27	----
XAM65S [f]	Forged	.26	89.57	4.28	-----	5.18	.97	----
AM61S	Forged	.32	92.49	-----	-----	6.42	1.09	----
	Rolled	.18						
AM3S [g]	Rolled	.20	98.5	-----	-----	-----	1.5	----

[a] Analyses by the cooperating manufacturers, the American Magnesium Corporation and the Dow Chemical Co.
[b] By difference.
[c] Alloys no longer manufactured.
[d] Value of diameter.
[e] Now designated AM57S.
[f] Now designated AM65S.
[g] Nominal composition.

TABLE XIII.—APPROXIMATE NUMBER AND AREAS OF CORROSION OR BLISTERING RESULTING FROM EXPOSURE ON MAGNESIUM ALLOYS GIVEN THE SURFACE TREATMENTS INDICATED AND PAINTED WITH FOUR COATS OF ALUMINUM PIGMENTED VARNISH

Material	Surface treatment	Exposed 5 years at Coco Solo				Exposed 5 years at Washington [a]	
		Corroded areas [b]		Blisters on paint		Blisters on paint	
		Number	Total area	Number	Total area	Number	Total area
			Sq. in.		*Sq. in.*		*Sq. in.*
AM3S, rolled	Phosphoric acid	0	0	8	0.06	1	0.01
	Chrome-pickle	9	0.08	8	[c] 2.6	0	0
XAM65S, forged	Phosphoric acid	1	.01	0	0	0	0
	Chrome-pickle	13	.17	0	0	0	0
AM764, cast	Phosphoric acid	4	.03	22	1.3	0	0
	Chrome-pickle	9	.10	30	.59	0	0
AM61S, rolled	Phosphoric acid	8	.03	0	0	0	0
	Chrome-pickle	12	.53	5	.45	1	.01
AM61S, forged	Phosphoric acid	5	.01	3	.05	1	.01
	Chrome-pickle	10	.21	28	1.91	4	.02
AM7.4, cast	Phosphoric acid	9	.20	[d] 5	.06	0	0
	Chrome-pickle	26	1.34	[d] 94	1.57	6	.22
AZM, hot pressed	Phosphoric acid	3	.02	0	0	0	0
	Chrome-pickle	66	.85	393	3.0	51	.26
AM240, cast	Phosphoric acid	10	15.9	[d] 2	.39	0	0
	Chrome-pickle	49	18.8	[d] 300	1.5	41	.33

[a] No corroded areas were visible on material exposed at Washington, D. C., the paint being intact on all samples.
[b] The entire surface area of each panel exposed to the weather was approximately 85 square inches.
[c] One blister had an area of 2.5 square inches, but no corrosion was visible beneath it.
[d] Corrosion product was present in appreciable amounts under these blisters.

TABLE XIV.—TENSILE PROPERTIES AND DEPTH OF PENETRATION OF CORROSIVE ATTACK ON MAGNESIUM ALLOYS EXPOSED 1 YEAR AT HAMPTON ROADS, VA.

Dowmetal materials	Surface finish	Average tensile properties [a]				Maximum depth of penetration
		Ultimate tensile strength	Elongation in 2 inches	Yield strength [b]	Reduction of area	
		Lb./sq. in.	*Percent*	*Lb./sq. in.*	*Percent*	*Thousandths inch*
E, Sheet	Paint	43,600	13.0	34,300	18.6	0
	Chrome-pickle	39,600	3.0	33,200	5.8	10
S, Sheet	Paint	33,000	15.0	25,100	17.9	0
	Chrome-pickle	30,700	11.0	23,600	13.1	6
A, Cast	Paint	26,600	6.0	11,600	8.6	0
	Chrome-pickle	26,200	6.0	11,500	9.4	12
H, Cast	Paint	28,000	5.5	13,100	8.3	0
	Chrome-pickle	27,200	5.0	12,500	8.2	3
F, Extruded	Paint	40,700	17.5	30,100	35.9	0
	Chrome-pickle	40,600	14.0	30,200	14.0	12
J, Extruded	Paint	46,200	17.0	32,700	20.8	0
	Chrome-pickle	45,800	15.0	32,700	17.8	[c] 6

[a] Values for the painted specimens are average obtained on 9 samples, 3 of which were kept in sealed containers (dry atmosphere). Since there was no loss on the painted specimens, these are typical of uncorroded material. Values for the chrome-pickled are the average on 3 specimens, all exposed.
[b] Stress at which stress-strain curve showed a departure of 0.2 percent from the initial modulus line.
[c] The attack, which was more or less uniform, resulted in a reduction in thickness of the sheet of between 0.003 and 0.004 inch.

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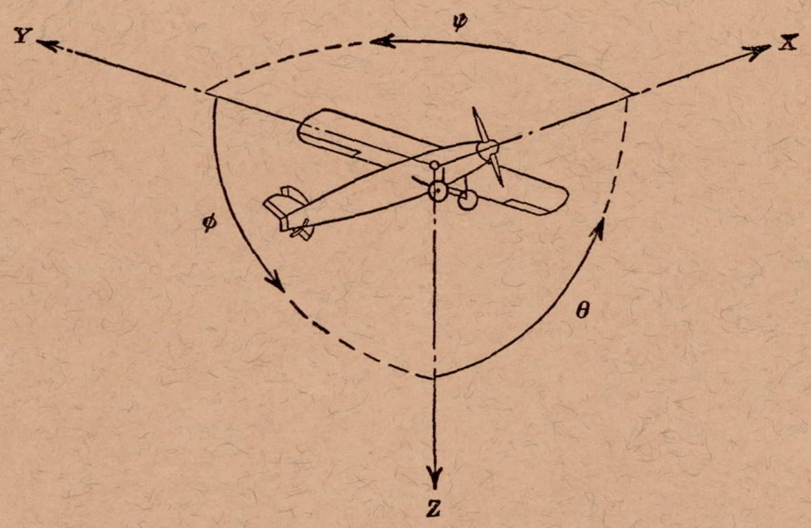

Positive directions of axes and angles (forces and moments) are shown by arrows

Axis		Force (parallel to axis) symbol	Moment about axis			Angle		Velocities	
Designation	Symbol		Designation	Symbol	Positive direction	Designation	Symbol	Linear (component along axis)	Angular
Longitudinal	X	X	Rolling	L	$Y \longrightarrow Z$	Roll	ϕ	u	p
Lateral	Y	Y	Pitching	M	$Z \longrightarrow X$	Pitch	θ	v	q
Normal	Z	Z	Yawing	N	$X \longrightarrow Y$	Yaw	ψ	w	r

Absolute coefficients of moment

$C_l=\frac{L}{qbS}$ (rolling) $\quad C_m=\frac{M}{qcS}$ (pitching) $\quad C_n=\frac{N}{qbS}$ (yawing)

Angle of set of control surface (relative to neutral position), δ. (Indicate surface by proper subscript.)

4. PROPELLER SYMBOLS

D, Diameter

p, Geometric pitch

p/D, Pitch ratio

V', Inflow velocity

V_s, Slipstream velocity

T, Thrust, absolute coefficient $C_T=\frac{T}{\rho n^2 D^4}$

Q, Torque, absolute coefficient $C_Q=\frac{Q}{\rho n^2 D^5}$

P, Power, absolute coefficient $C_P=\frac{P}{\rho n^3 D^5}$

C_s, Speed-power coefficient$=\sqrt[5]{\frac{\rho V^5}{P n^2}}$

η, Efficiency

n, Revolutions per second, r.p.s.

Φ, Effective helix angle$=\tan^{-1}\left(\frac{V}{2\pi r n}\right)$

5. NUMERICAL RELATIONS

1 hp.=76.04 kg-m/s=550 ft-lb./sec.

1 metric horsepower=1.0132 hp.

1 m.p.h.=0.4470 m.p.s.

1 m.p.s.=2.2369 m.p.h.

1 lb.=0.4536 kg.

1 kg=2.2046 lb.

1 mi.=1,609.35 m=5,280 ft.

1 m=3.2808 ft.