Technical Note N-605

PRELIMINARY EXAMINATION OF MATERIALS EXPOSED ON STU I-3 IN THE DEEP OCEAN - (5640 FEET OF DEPTH FOR 123 DAYS)

BY

Fred M. Reinhart

June 1964

U. S. NAVAL CIVIL ENGINEERING LABORATORY
Port Hueneme, California

PRELIMINARY EXAMINATION OF MATERIALS EXPOSED ON STU I-3 IN THE DEEP OCEAN - (5640 FEET OF DEPTH FOR 123 DAYS)

Y-F015-01-01-001(c)

Type C

by

Fred M. Reinhart

ABSTRACT

Preliminary results of corrosion of materials, based solely upon visual examinations, exposed in 5640 feet of water in the Pacific Ocean for 123 days showed only a few cases of deterioration different from those usually found in moving surface sea water. The Clad layers on two aluminum alloys corroded at a much faster rate than normal for surface sea water. The lace-work and undersurface types of attack on certain stainless steels appear to be similar to types of attack by stagnant surface sea water; this could be attributed to low oxygen content as well as lack of a significant movement of deep sea water. Other materials, both metallic and non-metallic, were not seriously deteriorated and some showed absolutely no evidence of deterioration.

INTRODUCTION

In July 1959, when the Naval Civil Engineering Laboratory initiated its studies to develop systems and techniques for construction in deep ocean areas, virtually nothing was known about the effects of the environment on the properties of engineering materials, particularly at some depth below the surface of the ocean. Hence, the objective of the materials testing reported herein is a basic one: to find out how the various engineering materials respond to the environments of the ocean depths. Details of background experiments to date are included in references (1), (2), (3) and (4). A detailed report[5] concerning the emplacement and retrieval of the test unit carrying the specimens discussed herein is nearing completion.

For many years man's chief interest in the oceans was in the field of oceanography; tides, waves, currents and animal life. Investigations in these areas of interest were, for the most part, conducted either at the surface or at depths not exceeding 300 feet. From such studies evolved measurements of greater ocean depths, submarine topography, and properties of sea water such as salinity, pH, temperature, and concentrations of dissolved gases. Recently, with the advent of longer-range submarines operating in greater depths, the necessity for better and longer-range detection devices developed. In support of the above and for other reasons, the desirability of deeply submerged permanent or semi-permanent structures is envisioned.

Because information about the deteriorative action of deep ocean waters on materials is practically non-existent, a program to accumulate such information was initiated.

EXPOSURE

A structure to which was attached 1324 specimens of 492 different materials, Table I, was emplanted on the floor of the Pacific Ocean 5640 feet below the surface on 4 October 1963 about 81 nautical miles west of Port Hueneme, California, at Latitude 33° 44' North, Longitude 120° 45' West.

The environmental characteristics of this site were investigated and found to include the following:

1. Firm green mud sediment and rocks.
2. Current, less than 0.5 knot, estimated from photographs.
3. Pressure, about 2500 psi.
4. Temperature, 2.76 degrees C (37 degrees F).
5. Oxygen, 0.83 milliliter/liter of sea water (1.19 parts per million).
6. pH, 7.25.
7. Salinity, 34.6 parts per thousand.
8. Alkalinity, 2.19 milliequivalents per liter of sea water.
9. Oxidation-reduction potential, +340 MV.

Other gases such as carbon dioxide and hydrogen sulfide, which can also influence the deterioration of materials, were not determined. The rates and modes of the deterioration of materials at this site could be different from those on the surface because the specific characteristics of this environment are quite different from those prevailing at the surface of the ocean. In the general area of the test site, compared to the surface, the pressure is greater by 2500 psi; the temperature is lower by approximately 10 degrees C; the oxygen concentration is much lower, 0.83 ml/l as contrasted to 5.6 ml/l at the surface; the pH is lower, 7.25 versus 7.87; the salinity is higher, 34.6 versus 33.6 parts per thousand.

The structure was retrieved on 4 February 1964 after 123 days of exposure.

RESULTS AND DISCUSSION

The results included herein are based solely upon visual examination of uncleaned specimens and are subject to changes or clarifications necessitated by results of weight loss determinations, pit depth measurements, changes in mechanical properties and metallurgical examinations. Therefore, these are only general impressions which are not suitable for design criteria.

The visual impressions will be discussed with regard to groups or types of materials.

Specimens located on the sides of the test frame were above the sea floor and entirely in a water environment. Specimens on the bottom of the test frame were located such that half their length extended below the test frame bearing plates. It was hoped that the bottom halves would be submerged in sediment; however, upon retrieval it was found that the entire structure had been supported by the ends of four or five specimen racks which had been resting on rocks. All except one specimen was exposed in a water environment; this specimen apparently had been in contact with a rock. Even though the bottom specimens were not embedded in sediment or in actual contact with the floor of the ocean, specimens of some alloys were more corroded than were their counterparts on the sides of the test structure, located a distance between 3 and 5 feet above the sea floor.

ALUMINUM ALLOYS:

Aluminum-Manganese Alloys, 3003-H14 and Clad 3003-H12:

The 3003-H14 and Clad 3003-H12 specimens in the water racks (side racks) were covered with a dark iridescent film, dotted with a few pinpoint pits and some corrosion attack at the specimen edges. There were scattered white corrosion products and pits (some 5 mils deep) and attack along all edges of the 3003-H14 specimen in the mud rack. The Clad layers on the Clad 3003-H12 specimen in the mud rack were completely corroded through to the core material in many places, as shown in Figure 1. Some of these areas were 1/2 inch in diameter and all were 14 mils deep. A typical area is shown in Figure 2.

Aluminum-Magnesium Alloys, 5083, 5086, 5454 and 5456:

These alloys were covered with iridescent films with a few areas of penetration in the form of slightly etched areas and a few isolated pits. On the 5456-H321 alloy, there was one pit 30 mils deep. There were a few scattered pits on the welded alloys of this group, some as deep as 42 mils; however, neither the welds nor the weld zones were selectively attacked.

Aluminum-Magnesium-Silicon Alloys, 6061:

The 6061-T6 alloy also had acquired a seemingly protective iridescent film with a few isolated etched areas where this film had failed. The deepest pits were 4 mils. There were some specimens of anodized 6061-T6 which were bolted together; their surfaces were free from attack of any kind except at one small area at a lap joint.

Aluminum-Copper Alloys, 2014, 2024, 2219; Clad 2024 and Clad 2219:

The manner of attack typical of the bare alloys of this group is illustrated in Figure 3. There are scattered blisters ranging up to 1/8 inch high, each surrounded by a ring of white corrosion products. An enlarged view of a blister is shown in Figure 4.

The Clad alloys were more evenly corroded, there being thinner and more even films of white, powdery corrosion products over most of the exposed surfaces. The Clad layers did not appear to have been sacrificed completely through to the core materials.

Aluminum-Zinc-Magnesium Alloys, 7075, 7079, 7178, X7039, X7002, Clad 7079, Clad 7178 and Clad X7002:

The manner of corrosion attack on this group of bare alloys was somewhat similar to that of the 2000 series alloys as shown in Figure 5. However, there were pits in addition to the blisters, some as deep as 60 mils. A pit typical of those on the 7000 series of alloys is shown in Figure 6.

The corrosion of the specimens of the Clad 7000 series was practically identical with the type of attack on the Clad 2000 series alloys. However, this type of attack did not prevail for the two Clad 7178-T6 aluminum alloy buoys submerged at depths of 200 and 500 feet respectively which were in the braided polypropylene rope mooring system.

The buoys were fabricated by bonding two hemispheres together with an epoxy adhesive. A rod with attachment eyes extended diametrically through the center of each hemisphere. The type of corrosion on one hemisphere of a buoy was different from that on the other hemisphere of the same buoy: on the lower buoy, the Clad layer on the bottom hemisphere had corroded through to the core material in numerous areas, as shown in Figure 7, while large blisters, some 2 inches in diameter and 0.75 inch high, formed on the top hemisphere. Greater detail of the corrosion of the Clad layer exposing the underlying core material is shown in Figure 8. A medium size blister on the top hemisphere is shown in Figure 9. The hole in the top of the blister indicates the origin of the failure: a pin-hole in the Cladding where the sea water gained access to the interface between the Clad alloy and the core alloy. When this blister was sectioned to inspect the corrosion underneath, the blister was found to be filled with crystalline aluminum oxide corrosion products, Figure 10. It appeared that the sea water penetrated the Clad layer at a defect, probably a pin-hole, and the corrosion was then concentrated at the interface between the two alloys. The thickness of the remaining Clad layer indicated that it was not sacrificed to protect the core material as was its function. On the other hand, the selective corrosion of the Clad layer on the bottom hemisphere and the uncorroded core material shows that, in this case, the Clad alloy was being sacrificed to protect the core material as intended.

Of this class (aluminum, zinc, magnesium) of alloys, only the X7002-T6 was welded and exposed in the "as welded" condition and as reheat treated after welding. In both cases the bead of weld metal was selectively attacked, that on the reheat treated specimen was completely penetrated and severely honeycombed as shown in Figure 11. This clearly indicated that the welding rod alloy was not compatible with the sheet alloy. The selective attack of the weld bead indicated that it was very highly anodic to the sheet material, hence the rapid rate of attack.

COPPER ALLOYS:

Copper, brass, and bronze were mostly covered with thin uniform films of corrosion products ranging in color from light blue or green to darker and brighter shades of blue and green with some brown intermixed. Figure 12 shows the heaviest and most non-uniform film of this group of alloys, aluminum bronze. The range of colors and the varying thicknesses of the films on these alloys are shown in detail in Figure 13. Most of these films were powdery and could be brushed away easily when dry. The corrosion was uniform and no measurable pits could be found on any of the alloys.

The corrosion of the copper-nickel alloys was also characterized by thin uniform films of various colors ranging from light green or blue to blue-brown to nearly black. A specimen typical of this class of alloys is shown in Figure 14. The streaks in the film seem to indicate the presence of some water current (perhaps eddy currents) arising from the ocean floor. The loose nature of these films indicates that any water current present was of low velocity but was sufficiently strong to create patterns such as is shown in Figure 14. The character of the blue and under-lying brown films on the specimen in Figure 14 is shown in greater detail in Figure 15.

MAGNESIUM ALLOYS:

The one magnesium alloy AZ31B was selectively attacked, there being holes some 1 inch in diameter in the 0.064 inch thick specimen.

NICKEL ALLOYS:

Nickel and Ni-O-Nel 825 alloys were practically unattacked; the metallic sheen was still present when removed from exposure. However, the 70 percent nickel--30 percent copper alloy (Monel) was covered with a thin, tightly adhering mottled brown film of corrosion products.

A nickel-chromium-molybdenum-cobalt alloy (Hastelloy C) also retained its original metallic sheen, indicating its immunity to attack by sea water at this depth for the period of test.

STEELS AND IRONS:

Wrought iron, carbon steels, low alloy high-strength steels and alloy steels are corroded in the same manner and to about the same extent. A typical example of attack is shown in Figure 16. The films of rust were relatively thin and uniform, ranging in color from tan to very dark red. They were relatively fine grained, loosely adherent and they tended to flake easily. The character and different colors of the corrosion products (rust) are shown clearly in Figure 17. The speckled, grey areas are uncorroded metal from which the rust has flaked.

The 5% chromium steel was corroded in scattered areas and pitted, some pits being 20 mils deep and from 0.25 to 1 inch in diameter.

The chromium stainless steels (405, 410 and 430) exhibited the most startling types of corrosive attack-penetration in a lacework configuration and internal honeycomb attack. Figure 18 illustrates one area of attack on Type 430 stainless steel with a heavy incrustation of corrosion products along the edges of the corroded streak. This same area is shown at greater magnification in Figure 19; a row of pits extending from one side of the photograph to the other is visible. When this row of pits was pressed with the author's thumbnail, the entire surface collapsed in a line about 1/8 inch wide and 2-½ inches long exposing a honeycomb-like interior. The lacework type of attack is shown in Figure 20. This lacework attack is similar to the honeycomb attack except that the surface and interior appear to be attacked equally. These two types of attack are quite similar to the attack of these alloys in stagnant surface sea water. The water current at this site is believed to be low and practically amounts to stagnant water conditions. Another factor of this site is the low oxygen concentration, 0.83 ml/l, which is about one-seventh of that at the surface. The oxygen concentration of stagnant surface sea water is usually lower than that of moving surface sea water because air (oxygen) can only reach sub-surface stagnant waters by the diffusion process.

Specimens of Type 430 stainless steel cold rolled about 20% with a 2B finish were unaffected.

The chromium-nickel (18-8) stainless steels were not immune to the honeycomb type of attack described above. It occurred on Type 301 stainless steel as shown in Figure 21. The elongated, depressed spot in the center of the bluish area was the origin of a honeycombed undersurface area 3/8 inch by 3/4 inch. There was a thin film of uncorroded metal on each surface of the specimen with the interior being filled with tightly packed, black, magnetic iron oxide.

There was pin-hole attack on the sheared edges of Types 304 and 304L chromium nickel stainless steels.

The other chromium-nickel stainless steels (Types 302, 316, 316L, 321 and 20-CB) were not attacked by the sea water.

All the precipitation hardening stainless steels were subject to both the honeycomb and lacework types of corrosion. The types of steels were 17-7PH, annealed; 15-7 AMV, annealed; 15-7 AMV, RH950; 15-7 AMV, RH1150 and Tenelon. These materials also were susceptible to severe crevice corrosion in addition to the above mentioned types of corrosion. In order to test for crevice corrosion, a 1 inch square of an alloy was bolted to a panel of the same alloy using a plastic bolt and nut. Sea water entering the crevice between the 1 inch square and the panel will cause crevice corrosion if the alloy is susceptible to this type of attack. Such a combination is shown in Figure 22. The one inch piece bolted to the panel is shown at higher magnification in Figure 23. There was crevice corrosion of the 1 inch piece underneath the head of the plastic (nylon) bolt. The faying surfaces after disassembly are shown in Figure 24 where it is clear that intense crevice corrosion has occurred.

A stress corrosion crack was found on one specimen of 15-7 AMV, RH1150, Figure 25. The origin of the crack was in the pitted area on the edge of the specimen where it had been in contact with the polyethylene insulator.

TITANIUM ALLOYS:

All the titanium alloys (A70, 75A, 7Al-12Zr, 6Al-4V, 5Al-2.5Sn, 13V-11Cr-3Al, and 4Al-3Mo-1V) both unwelded and welded were unaffected by this environment.

DISSIMILAR COUPLES:

There was no apparent galvanic corrosion between a precipitation hardening stainless steel (17-4PH,A) coupled to an austenitic stainless steel (301, annealed).

There was slight galvanic corrosion of a 7075-T6 aluminum alloy panel to which had been riveted a Type 321 stainless steel strip.

There was excessive corrosion both galvanic and secondary of a 7075-T6 aluminum strip riveted to an AZ31B magnesium alloy panel with 5056 aluminum alloy rivets. This galvanic couple is shown in Figure 26. The excessive corrosion of the magnesium alloy panel was the result of it being sacrificed to protect the aluminum alloy strip. However, since the corrosion products from the magnesium alloy were alkaline, they in turn caused exceedingly rapid deterioration of the aluminum alloy strip. The increase in thickness of the aluminum alloy strip due to corrosion is shown more clearly in Figure 27.

FASTENERS:

Galvanized bolts and nuts with 1.5 mils of zinc had turned yellow, indicating that the pure zinc layers had corroded away exposing the zinc-iron alloy layers.

The 70 nickel-30 copper (Monel) bolts and nuts tarnished to a brown color.

The 18% chromium - 8% nickel stainless steel bolts and nuts were corroded, particularly the nuts and in the crevice between the head of the bolt and the fiberglass panel, Figure 28.

The cadmium had completely corroded from the cadmium plated bolts and nuts and they were covered with a uniform film of red rust, Figure 29.

METALLIC COATINGS:

The steel shackles used for rigging the braided polypropylene lines were electroless nickel to prevent their corrosion. The nickel coatings disappeared rapidly and caused rapid corrosion in the crevice between the shoulder of the bolt and the eye of the shackle. The nickel plate cracked circumferentially in the U part of the shackle and bled red rust to a considerable extent as shown in Figure 30.

COATINGS:

There were no failures of the coatings on low carbon steel panels given in Table 1(h)1.

The coatings (Table 1(h)2) on the nylon and dacron fabrics became dull; otherwise they appeared to be impervious to sea water.

PLASTICS:

No deterioration other than dulling was discernible on the plastic samples, Table 1(i).

ELASTOMERS:

No failures of the "O"-Rings were found from visual inspections.

CONCRETE:

There was no measurable change in the permeability of either the low or high strength concrete specimens, Table 1(k).

FOULING:

"There were no marine fouling organisms attached to the metallic test specimens. Abundant to trace amounts of bacterial slime growth were present on the surface of some plastic materials and on the electroless nickel plated shackles. Cotton and manila (hemp) fibers in rope form and jute fibers in burlap form showed degradation from microbial activity. A deep-sea organism, 1/2 inch long, was found attached securely to the cut end of a piece of polyvinyl chloride pipe".[6]

SUMMARY

A total of 492 different materials were exposed on the floor of the Pacific Ocean at a depth of 5640 feet about 81 nautical miles west of Port Hueneme, California, for 123 days.

The characteristics of this environment were:

1. Firm green mud sediment and rocks.
2. Current, estimated to be less than 0.5 knot.
3. Pressure, about 2500 psi.
4. Temperature, 2.76°C (37°F).
5. Oxygen, 0.83 milliliters per liter of sea water (1.19 parts per million).
6. pH, 7.25.
7. Salinity, 34.6 parts per thousand.
8. Alkalinity, 2.19 milliequivalents per liter of sea water.
9. Oxidation-reduction potential, +340MV.

Preliminary results based solely upon visual observations indicate:

1. The corrosion rates of aluminum alloys Clad 3003-H12 and Clad 7178-T6 were greater than those normally found in surface sea water exposures.

2. The pitting pattern was different from that of surface exposure in that there were usually fewer but deeper pits other than those above-mentioned on the aluminum alloys (30 to 60 mils).

3. The copper base alloys were corroded evenly over the surfaces of the specimens. They were covered with thin films of multicolored corrosion products - blue, green, brown and black.

4. The magnesium base alloys were penetrated in scattered areas.

5. Only one nickel alloy, Monel, was covered with a thin tenacious film of mottled brown corrosion products. The other nickel alloys were untarnished.

6. Wrought iron, carbon steels, low alloy-high strength steels and alloy steels all corroded in the same manner; uniform, relatively thin layers of red corrosion products (rust).

7. The chromium stainless steels (405, 410 and 430), a chromium-nickel stainless steel (301) and the precipitation hardening stainless steels (17-7 PH, A; 15-7 AMV, A; 15-7 AMV, RH 950; 15-7 AMV, RH 1150 and Tenelon) were attacked in either a lacework pattern or an undersurface type of attack. Both of these types of attack are found to occur in stagnant surface sea water. The attack at the 5640 foot depth could be due to the absence of any appreciable water current (essentially stagnant conditions) or to the low oxygen concentration.

8. The other chromium-nickel stainless steels (302, 316, 316L, 321 and 20-CB) were not attacked by sea water.

9. The precipitation hardening stainless steels were also subject to severe crevice corrosion.

10. None of the titanium alloys, both unwelded and welded, were attacked.

11. Both parts of the aluminum-magnesium alloy galvanic couple were excessively corroded. There was slight galvanic corrosion of the aluminum portion of the 7075-T6 aluminum alloy - 321, stainless steel galvanic couple. There was no apparent galvanic corrosion of a 17-4 PH, A, precipitation hardening stainless steel - 301, A, chromium-nickel stainless steel couple.

12. Monel fasteners were not attacked, stainless steel (300 series), fasteners rusted, galvanized steel fasteners turned yellow, and cadmium plated steel fasteners rusted in the deep sea water.

13. Electroless nickel plating on steel cracked and bled red rust during the exposure.

14. There were no failures of organic coatings applied on low carbon steel or on fabrics.

15. All the plastic materials and elastomers became dull.

16. The permeability of concrete was not affected.

17. Bacterial slimes were found on some plastic materials and on electroless nickel plated shackles.

18. Cotton, manila and jute fibers showed degradation from microbial activity.

19. More definite conclusions will be forthcoming after the corrosion evaluations such as weight losses, pit depths, changes in mechanical properties and metallographic examinations have been completed.

REFERENCES

1. U. S. Naval Civil Engineering Laboratory. Technical Note N-380, Properties of Materials in Deep Ocean Environment - A Progress Report, by Kenneth O. Gray. Port Hueneme, 23 March 1960.

2. U. S. Naval Civil Engineering Laboratory. Technical Note N-446, Effects of the Deep Ocean Environment on Materials - A Progress Report, by Kenneth O. Gray. Port Hueneme, 30 July 1962.

3. U. S. Naval Civil Engineering Laboratory. Technical Report R-182, The Effects of Marine Organisms on Engineering Materials for Deep Ocean Use, by J. S. Muraoka. Port Hueneme, 7 March 1962.

4. U. S. Naval Civil Engineering Laboratory. Technical Note N-458, Emplacement of the First Submersible Test Unit on the Sea Floor - One Mile Deep, by Ronald E. Jones. Port Hueneme, 18 February 1963.

5. U. S. Naval Civil Engineering Laboratory. Technical Report R- The Techniques Employed in the Design, Emplacement and Retrieval of Submersible Test Units, by Ronald E. Jones. Port Hueneme (In preparation).

6. U. S. Naval Civil Engineering Laboratory. Technical Report R- Deep Ocean Deterioration Study - Part I, Four Months Exposure at Test Site I, by J. S. Muraoka. Port Hueneme (In preparation).

TABLE I - LIST OF MATERIALS SUBMERGED IN 5640 FEE

Material	Size Inches	Unstress.	Stress.	Fe	Si
(a) Aluminum Alloys					
3003-H14	6 x 12	X		0.7	0.6
Clad 3003-H14 Core 3003	6 x 12	X		0.7	0.6
Cladding 7072				Fe+Si	0.7 Max
5052-H34, Plain, Bolted Cd & Zn Hdwe.	6 x 12	X		Fe+Si	0.45 Max
5083-H113 Plain & butt welded	6 x 12	X		0.40	0.40
5086-H34 Plain & butt welded	6 x 12	X		0.50	0.40
5454-H32 Plain & butt welded	6 x 12	X		Fe+Si	0.40 Max
5456-H343, H34 Plain & butt welded	6 x 12	X		Fe+Si	0.40 Max
6061-T6, Plain lap weld, Bolted Cd & Zn Hdwe., Butt weld 4043 rod, AS welded & re-heat treated after welding	6 x 12	X		0.7	0.40-0.8
2014-T6 & T3	6 x 12	X		1.0	0.50-1.2
2024-T81	6 x 12	X		0.50	0.50
Clad 2024-T3 Core 2024	6 x 12	X		0.50	0.50
Cladding 1230				Fe+Si	0.7 Max.
2219-T6 & T81 Plain & butt welded 2319 rod	6 x 12	X			
X7002-T6, Butt welded as welded and re-heat treated after welding	6 x 12	X		0.40	0.20
7075-T73	6 x 12	X		0.7	0.50
Clad 7075-T6 Core 7075	6 x 12	X		0.7	0.50
Cladding 7072				Fe+Si	0.7 Max.
X7039-T6	6 x 12	X		0.17	0.11
7079-T6	6 x 12	X		0.12	0.14
7178-T6	6 x 12	X		0.7	0.50

TABLE I - LIST OF MATERIALS SUBMERGED IN 5640 FEET OF WATER IN THE PACIFIC OCEAN FOR 123 DAYS

	Size			Chemical Composition, Per Cent by Weigh						
1	Inches	Unstress.	Stress.	Fe	Si	Cu	Mn	Mg	Cr	Zn
Alloys										
	6 x 12	X		0.7	0.6	0.20	1.0-1.5			0.1
003	6 x 12	X		0.7	0.6	0.20	1.0-1.5			0.1
072				Fe+Si	0.7 Max.	0.10	0.10	0.10		0.8-1
Cd & Zn Hdwe.	6 x 12	X		Fe+Si	0.45 Max.	0.10	0.10	2.2-2.8	0.15-0.35	0.2
t welded	6 x 12	X		0.40	0.40	0.10	0.30-1.0	4.0-4.9	0.05-0.25	0.2
t welded	6 x 12	X		0.50	0.40	0.10	0.20-0.7	3.5-4.5	0.05-0.25	0.2
t welded	6 x 12	X		Fe+Si	0.40 Max.	0.10	0.7	2.7	.1	0.2
butt welded	6 x 12	X		Fe+Si	0.40 Max.	0.20	0.50-1.0	4.7-5.5	0.05-0.20	0.2
ld,Bolted Cd & t weld 4043 rod, re-heat treated	6 x 12	X		0.7	0.40-0.8	0.15-0.40	0.15	0.8-1.2	0.15-0.35	0.2
8										
	6 x 12	X		1.0	0.50-1.2	3.9-5.0	0.40-1.2	0.20-0.8	0.10	0.2
	6 x 12	X		0.50	0.50	3.8-4.9	0.30-0.9	1.2-1.8	0.10	0.2
024	6 x 12	X		0.50	0.50	3.8-4.9	0.30-0.9	1.2-1.8	0.10	0.2
230				Fe+Si	0.7 Max.	0.10	0.05			0.1
butt welded	6 x 12	X				6.3	0.30			
as welded and ated after welding	6 x 12	X		0.40	0.20	0.75	0.15	2.50	0.15	3.5
	6 x 12	X		0.7	0.50	1.2-2.0	0.30	2.1-2.9	0.18-0.40	5.1-6
7075	6 x 12	X		0.7	0.50	1.2-2.0	0.30	2.1-2.9	0.18-0.40	5.1-6
7072				Fe+Si	0.7 Max.	0.10	0.10	0.10		0.8-1
	6 x 12	X		0.17	0.11	Trace	0.22	2.8	0.21	4.
	6 x 12	X		0.12	0.14	0.64	0.20	3.5	0.16	4.
	6 x 12	X		0.7	0.50	1.6-2.4	0.30	2.4-3.1	0.18-.40	6.7-7

EET OF WATER IN THE PACIFIC OCEAN FOR 123 DAYS

	Chemical Composition, Per Cent by Weight							
	Cu	Mn	Mg	Cr	Zn	Ti	Other	Al
6	0.20	1.0-1.5			0.10			Remainder
6	0.20	1.0-1.5			0.10			Remainder
Max.	0.10	0.10	0.10		0.8-1.3			Remainder
Max.	0.10	0.10	2.2-2.8	0.15-0.35	0.20			Remainder
	0.10	0.30-1.0	4.0-4.9	0.05-0.25	0.25	0.15		Remainder
	0.10	0.20-0.7	3.5-4.5	0.05-0.25	0.25	0.15		Remainder
Max.	0.10	0.7	2.7	.1	0.25	0.20	Be	Remainder
Max.	0.20	0.50-1.0	4.7-5.5	0.05-0.20	0.25	0.20	0.0005	Remainder
.8	0.15-0.40	0.15	0.8-1.2	0.15-0.35	0.25	0.15		Remainder
1.2	3.9-5.0	0.40-1.2	0.20-0.8	0.10	0.25	0.15		Remainder
	3.8-4.9	0.30-0.9	1.2-1.8	0.10	0.25			Remainder
	3.8-4.9	0.30-0.9	1.2-1.8	0.10	0.25			Remainder
ax.	0.10	0.05			0.10			Remainder
	6.3	0.30				0.06		Remainder
	0.75	0.15	2.50	0.15	3.5			Remainder
	1.2-2.0	0.30	2.1-2.9	0.18-0.40	5.1-6.1	0.20		Remainder
	1.2-2.0	0.30	2.1-2.9	0.18-0.40	5.1-6.1	0.20		Remainder
x.	0.10	0.10	0.10		0.8-1.3			Remainder
	Trace	0.22	2.8	0.21	4.0	0.02		Remainder
	0.64	0.20	3.5	0.16	4.3	0.03		Remainder
	1.6-2.4	0.30	2.4-3.1	0.18-.40	6.7-7.3	0.20		Remainder

TABLE I - (

Material	Size Inches	Unstress.	Stress.	Fe
(b) Copper Alloys				
Copper-Electrolytic Tough Pitch	6 x 12	X		
Nickel-Manganese Bronze (Casting)	1 x 6	X		1.6
Phosphorous Bronze A	6 x 12	X		<0.0
Phosphorous Bronze D	6 x 12	X		<0.0
Silicon Bronze	6 x 12	X		<0.0
Arsenical Admiralty Bronze	6 x 12	X		0.0
Muntz Metal	6 x 12	X		<0.0
Nickel-Aluminum Bronze	2 x 12	X		2.5
Nickel-Manganese-Aluminum Bronze	2 x 12	X		
High Tensile Brass	2 x 12	X		2-
Red Brass	2 x 12	X		
Naval Brass	2 x 12	X		
Cupro-Nickel 95-5	6 x 12	X		1.2
Cupro-Nickel 90-10	6 x 12	X		1.1
Cupro-Nickel 80-20	6 x 12	X		0.6
Cupro-Nickel 70-30 Low Fe	6 x 12	X		0.5
Cupro-Nickel 70-30 High Fe	6 x 12	X		5.27
Beryllium-Copper (Brylco #10)	6 x 12	X		
Beryllium-Copper (Brylco #25)	6 x 12	X		
Beryllium-Copper (Brylco #165)	6 x 12	X		

Material	Size Inches	Unstress.	Stress.	Mg	Al	
(c) Magnesium Alloys						
AZ31B	6 x 12	X		Remainder	3.0	0
(d) Nickel Alloys						
Ni - 200	6 x 12	X				0
70 Ni - 30 Cu, 400	6 x 12	X				0
Ni-O-Nel, 825	6 x 12	X			0.14	0
K-Monel	6 x 12	X			2.80	0
Hastelloy C	6 x 12	X	X			0

(Continued)

Chemical Composition, Per Cent by Weight

Fe	Sn	Mn	Zn	Ni	Si	Al	Other	Cu+Ag
								99.95
.66	0.70	3.06	Bal	3.77		1.73	Pb 0.02	54.58
.05	4.94		<0.10				P 0.26	94.64
.05	9.23		<0.10				P 0.17	90.60
.02		1.18			3.28			95.49
.01	1.00		27.77				As 0.027	71.19
.02			39.29					60.69
.50		1.00		5.00		9.50		82.00
2-4		3-4.5	Bal			4-7.5	Pb 0.01	60-68
			15					85
	0.75		39.25					60
.24		0.53		6.25				91.98
.16		0.38		9.42				89.04
.62		0.35		20.41				78.62
.53		0.33		30.53				68.61
.27	<0.05	0.75	<0.05	29.95				64.02
	Be 1.8-2.05			0.05	Co 0.20-0.30			Balance
	Be 1.6-1.8			0.20	Co 0.20-0.30			Balance

Mn	Zn	Si	Cu	Ni	Fe	Ca	C	S	Cr	Ti	Mo	Other
0.20	1.0	0.10	0.05	0.005	0.005	0.04						0.30
0.23		0.03	0.02	99.58	0.07		0.04	0.005				
0.92		0.13	33.35	65.70	0.75		0.12	0.007				
0.82		0.31	1.61	41.12	30.86		0.05	0.011	21.12	1.00	2.94	W3.70
0.60		0.15	29.50	65.00	1.00		0.15	0.0005		0.50		Co 1.30
0.38		0.50		Bal.	6.08		0.06	0.007	15.80		16.04	W 0.22

TABLE I - (Co

Material	Size Inches	Unstress.	Stress.	C	Mn
(e) Steels and Irons					
1. Wrought Iron	1 x 6	X		0.02	0.06
2. Carbon Steels					
C1010, Hot Rolled & Pickled	6 x 12	X		0.11	.52
A36, Hot Rolled & Pickled	6 x 12	X		.24	.70
A387, Grade D, Hot Rolled & Pick.	6 x 12	X		.06	.49
Copper Steel, 0.2 % Cu	1 x 6		X		
Improved Plow Steel Wire Rope	1" dia. 7 x 19				
Anchor Chain, Dilok	3/4"	X			
Anchor Chain, Stud Link Welded	3/4"	X			
C1015, Polyvinyl chloride cladding	6 x 12	X		.14	.37
3. Low Alloy high strength steels					
COR-TEN	1 x 6	X		.07	.38
HY-80, Blast Cleaned	6 x 12	X		.17	.28
T-1, Blast Cleaned	6 x 12	X		.14	.78
T-1A, Blast Cleaned	6 x 12	X		.18	.86
4. Alloy Steels					
4130	6 x 12	X		.30	.65
4340, Heat treated to 200,000 psi and 150,000 psi Yield Strengths	6 x 12	X	X	.43	.73
502, Annealed & Pickled, #1 Finish	6 x 12	X		.06	.48
4. Stainless Steels					
Chromium Types					
405, #2B Finish, Annealed & pickled	6 x 12	X		.05	.62
410, #2D Finish	6 x 12	X		.13	.43
430, #2B Finish, Anealed & pickled	6 x 12	X		.07	.47
Chromium-Nickel Types					
201	1 x 6	X		.15	6.5
202	1 x 6	X		.15	8.7
301, Annealed, pickled, cold-rolled, 22% reduction; annealed	6 x 12	X	X	.11	1.17
302, #2B Finish	6 x 12	X		.06	1.05
304, #1 Finish	6 x 12	X		.06	1.74
304L, #2B Finish	6 x 12	X	X	.03	1.24
316, #1 Finish	6 x 12	X		.06	1.61
316L, #2B Finish	6 x 12	X	X	.03	1.29
321, #1 Finish	6 x 12	X		.08	
347	6 x 12	X		.08	

ontinued)

Chemical Composition, Per Cent by Weight

Si	Cu	Cr	Ni	Mo	V	B	Ti	Al	S	P	Other	Fe
0.13									0.01	0.13	Slag2.5	Rem.
.048									.024	.016		Rem.
.055									.027	.011		Rem.
.24		2.20		1.02					.021	.013		Rem.
	0.20											Rem.
	.13											Rem.
.54	.28	.88	.31						.025	0.11		Rem.
.20		1.76	2.96	.40					.018	.020		Rem.
.23	.22	.56	.74	.42	.036	.0041			.025	.020		Rem.
.28		.64	.05	.18	.047	.0028	.020		.023	.014		Rem.
		.65		.20					.050	.040		Rem.
.27		.82	1.77	.24					.014	.013		Rem.
.33		4.75		.55					.010	.020		Rem.
.27		14.5						.27	.011	.014		Rem.
.45		12.3	.10						.005	.019		Rem.
.36		16.4							.011	.029		Rem.
		17.0	4.5									Rem.
		18.0	5.0									Rem.
.34		17.4	6.73				5XC		.021	.025		Rem.
.60		18.21	9.33						.013	.020		Rem.
.43		18.8	10.00						.013	.024		Rem.
.68		18.7	10.20						.023	.028		Rem.
.40		18.3	13.60	2.41					.016	.021		Rem.
.51		17.5	13.10	2.32					.019	.015		
		18.0	10.5				5XC					Rem.
		18.0	11.0								Cb+Ta, 10XC	Rem.

TABLE I - (Conti

Material	Size Inches	Unstress.	Stress.	C	Mn	S
(e) Steels and Irons (Cont'd)						
4. Stainless Steels, cont'd.						
Chromium-Nickel Types (cont'd)						
Tenelon, #2B Finish				.07	14.3	.
Precipitation Hardening Types						
17-4 PH, TH1050	1 x 6		X	.07		
17-7 PH	6 x 12	X		.09		
PH 15-7 Mo, RH950	1 x 6		X			
15-7 AMV, Annealed RH950 & RH1150	6 x 12	X	X	.27	.67	.84
AM 350	2 x 12	X		.10	.80	.25
AM 355 CRT	1 x 6	X		.12	.77	.34
W Pickled	6 x 12	X		.05	.56	.74
Special Steels						
Carpenter 20-CB	6 x 12	X	X	.04	.79	.67
18% Ni, Maraging	1 x 6		X	.02		

(f) Titanium Alloys				C	N_2
A70	2 x 12	X		.15	.07
75A	6 x 12	X		.08	.05
C120AV	2 x 12	X		.10	.03
6Al - 4V	6 x 12	X	X	.023	.015
6Al - 4V Circular and Butt welds, as welded	6 x 12	X	X	.025	.015
5Al - 2.5 Sn, Circular and Butt welds, as welded	6 x 12	X	X	.025	.014
13V-11Cr-3Al, Unwelded, Circular and Butt welds, as welded	6 x 12	X	X	.027	.027
4Al-3Mo-1V	6 x 12	X		.08	.05
7Al-12Zr	6 x 12	X		.04	.03

(g) Dissimilar Couples

Fiberglass - 6061-T6 aluminum alloy, bolted with galvanized fasteners
Beryllium copper strips spot welded to beryllium copper
17-4 PH annealed bolted to 301 stainless steel panel with stainless fasteners
321 stainless steel riveted to 7075-T6 aluminum alloy panel with Monel rivets
7075-T6 aluminum alloy riveted to AZ31 magnesium alloy with 5056 aluminum alloy ri
Zinc anode on low carbon steel

tinued)

Chemical Composition, Per Cent by Weight

Si	Cu	Cr	Ni	Mo	V	B	Ti	Al	S	P	Other	Fe
.67		18.4	.27						.003	.021	N_2,.48	Rem.
	4.0	16.5	4.0									Rem.
		17.0	7.2					1.0				Rem.
		15.0	7.2	2.5				1.1				Rem.
.84		15.0	7.40	2.42	.16			1.55	.012	.020		Rem.
.25		16.5	4.3	2.75							N_2,.10	Rem.
.34		15.35	4.62	2.73					.009	.021	N_2,.095	Rem.
.74		16.8	6.80				.79	.09	.009	.026		Rem.
.67	3.11	19.80	28.38	2.06					.004	.018	Co/Ta.77	Rem
			18.0	5.0			.4	.1			Co 7.0	Rem.

2	H_2	Fe	Al	V	Sn	Mn	Other	Ti
7	.015							Remainder
5	.015	.25						Remainder
3			6.0	4.0			0.6	Remainder
15	.006-.007	.15	6.0	3.9				Remainder
[illegible]	.007	.13	5.9	4.0				Remainder
14	.011	.34	5.1		2.2	.007		Remainder
27	.008	.17	3.1	13.4			Cr 11.4	Remainder
	.015	.25	4.25	1.0			Mo 3.0	Remainder
	.010	.015	7.0				O .10 Zr 12.0	Remainder

rivets

TABLE I - (Contin

(h) Coatings

1. On low carbon steel
   Epoxy-Tar-Carbomastic #3
   Coal Tar Enamel
   Vinyl-Alkyd
   Saran White over Orange
   Vinyl Mastic with Zinc Inorganic Silicate
   Phenolic-Phenoline 300 Mica Filled
   Epoxy-Phenolic Plastic 7122
   Asphalt-Mica Filled Emulsion
   Epoxy-Devran 202/203
   Urethane-Laminar X500

2. Fabrics
   Hypalon coated nylon, 5.25 and 14.25 oz per sq yd
   Hypalon coated nylon, 8.25 and 4.25 oz per sq yd
   Hypalon coated dacron, 8.25 and 18.75 oz per sq yd
   Chemigum coated nylon, 24.3 and 24.3 oz per sq yd
   Chemigum coated nylon, 21.82 and 21.82 oz per sq yd
   Neoprene coated dacron, 12.15 and 12.15 oz per sq yd
   Neoprene coated nylon, 12.85 and 12.85 oz per sq yd
   Crude rubber coated nylon, 14 and 14 oz per sq yd

(i) Plastics

Fiberglass, bolted with Monel and 18-8 hardware
Acrylic, Plexiglass G
Vinyl, rigid C
Cellulose Acetate B
Polystyrene, rigid A
Polyethylene
Glass cloth 181 epoxy impregnated type 2 WS 1070 A
Glass cloth 143 epoxy empregnated, type 2, WS 1070 A
"E" Glass HTS, filament wound, epoxy impregnated, type 1, W
ME-1 Bisphenol-A epoxide, anhydride cure
ME-25 Bisphenol-A epoxide long chain amine cure
ME-118 Cyclic diepoxide dimer acid cure
ME-144 Epoxidized polyolefin, anhydride and peroxide cure
ME-159 Epoxy novolac anhydride cure
ME-160 Bisphenol-A epoxide with reactive dilutent amine cur
ME-172 Polyester
ME206 High functionality epoxide
ME-300 Epoxy

lnued)

	Size Inches	Unstressed
	6 x 12	X
	6 x 12	X
	6 x 12	X
	6 x 12	X
	6 x 12	X
	6 x 12	X
	6 x 12	X
	6 x 12	X
	6 x 12	X
	6 x 12	X
	15 x 15	X
	15 x 15	X
	15 x 15	X
	15 x 15	X
	15 x 15	X
	15 x 15	X
	15 x 15	X
	15 x 15	X
	6 x 12	X
	6 x 12	X
	6 x 12	X
	6 x 12	X
	6 x 12	X
	6 x 12	X
	6 x 12	X
	6 x 12	X
WS 1028 A Amend 1	6 x 12	X
	6 x 12	X
	6 x 12	X
	6 x 12	X
	6 x 12	X
	6 x 12	X
ure	6 x 12	X
	6 x 12	X
	6 x 12	X
	6 x 12	X

(i) Plastics (Continued)

Aerotactic Foams

IA -	Aerotactic 70 (Butene-vinyl-toluene-styrene copolymer fille
IB -	" " "
IC	" " "
IIA -	Aerotactic 70-P (Aerotactic 70 polyethylene filled plus SI
IIB -	" " " 60 lb
IIIA -	Aerotactic No. ESI B15 (Epoxy filled with SI microballons)
IIIB -	" " "
IIIC -	" " "
IVA -	Aerotactic No. ESI 3144 (Epoxy filled with SI microballons)
IVB -	" " "
IVC -	" " "

High density polyethylene, Dupont Alathon 7020, molding condition D
High density polyethylene, Dupont Alathon 7050, molding condition
Polyvinyl chloride pipe, black
Polyvinyl chloride pipe, dark gray, Type I
Polyvinyl chloride pipe, light gray, Type II

Glass filament wound rings impregnated with plastic
- K645
- K646
- K647
- K648
- K651
- K659
- K660
- K664
- K676
- K677

Glass filament wound cylinders, 994 glass roving impregnated with S
- Coated with L-70
- Coated with modified polyester

Glass reinforced polyester laminate, Pleogen 1321GRA
Glass reinforced phenolic laminate, EC200, type II, Class I
Glass reinforced phenolic-silicone laminate, Plyophen 98-573, Type
Glass reinforced phenolic-epoxy laminate, Plyophene 98-583, Type II,
Glass reinforced epoxy laminate, Trevarno F161, Types I & II, Class

TABLE I - (Continued)

Continued)		
ic Foams		
rotactic 70 (Butene-vinyl-toluene-styrene copolymer filled with SI microballons)	35 lb density	
" " " "	45 lb density	
" " " "	60 lb density	
rotactic 70-P (Aerotactic 70 polyethylene filled plus SI microballons)	35 lb density	
" " "	60 lb density (polyethylene filled only)	
rotactic No. ESI B15 (Epoxy filled with SI microballons)	25 lb density	
" " "	35 lb density	
" " "	45 lb density	
rotactic No. ESI 3144 (Epoxy filled with SI microballons)	25 lb density	
" " "	35 lb density	
" " "	45 lb density	
ity polyethylene, Dupont Alathon 7020, molding condition D		1/8
ity polyethylene, Dupont Alathon 7050, molding condition D		1/8
chloride pipe, black		
chloride pipe, dark gray, Type I		
chloride pipe, light gray, Type II		(
ament wound rings impregnated with plastic		
ament wound cylinders, 994 glass roving impregnated with S-58-68 resin		7" d
with L-70		
with modified polyester		
nforced polyester laminate, Pleogen 1321GRA		
nforced phenolic laminate, EC200, type II, Class I		
nforced phenolic-silicone laminate, Plyophen 98-573, Type II, Class 2		
nforced phenolic-epoxy laminate, Plyophene 98-583, Type II, Class 2		
nforced epoxy laminate, Trevarno F161, Types I & II, Classes 1, 2 & 3		

1)

		Size Inches	Unstressed
led with SI microballons)	35 lb density	1 x 1 x 1	X
"	45 lb density	1 x 1 x 1	X
"	60 lb density	1 x 1 x 1	X
I microballons)	35 lb density	1 x 1 x 1	X
lb density (polyethylene filled only)		1 x 1 x 1	X
)	25 lb density	1 x 1 x 1	X
	35 lb density	1 x 1 x 1	X
	45 lb density	1 x 1 x 1	X
s)	25 lb density	1 x 1 x 1	X
	35 lb density	1 x 1 x 1	X
	45 lb density	1 x 1 x 1	X
D		1/8 x 2½ x ¼	X
a D		1/8 x 2½ x ¼	X
		1 dia x 6	X
		Union	X
		Coupling	X
		6" dia	X
		6" dia	X
		6" dia	X
		6" dia	X
		6" dia	X
		6" dia	X
		6" dia	X
		6" dia	X
		6" dia	X
		6" dia	X
S-58-68 resin		7" dia by 12"long	X
		6 x 12	X
		6 x 12	X
II, Class 2		6 x 12	X
I, Class 2		6 x 12	X
ses 1, 2 & 3		6 x 12	X

TABLE I - (Continue

(j) Elastomers
  O-Rings 1" ID x 1/4" cross-section
    Polyblend, AML #1714
    Seal compound, MIL-R-6855, Class II, 80 hardness
    Nitrile compound, AML #1739B
    Neoprene compound, AML #1764F
    Natural rubber compound, AML #1777D

(k) Concrete
  High strength - San Gabriel aggregate w/c = 0.44 by weight
  Low strength - " " " w/c = 0.70 by weight

nued)

Size Inches	Unstressed
4" dia x 8"	X
4" dia x 8"	X

Figure 1. Scattered white corrosion products and attack on Clad 3003-H12, aluminum-manganese alloy.

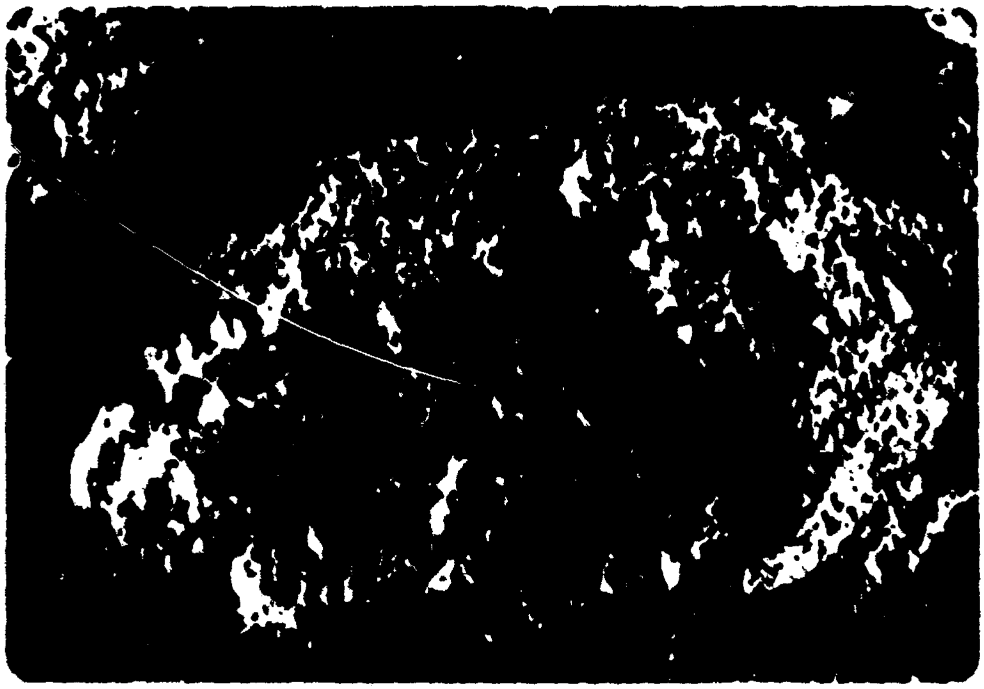

Figure 2. A portion of Figure 1 enlarged to show (a) the white corrosion products, (b) the dark grey disintegrated cladding material and (c) the lighter grey core material.

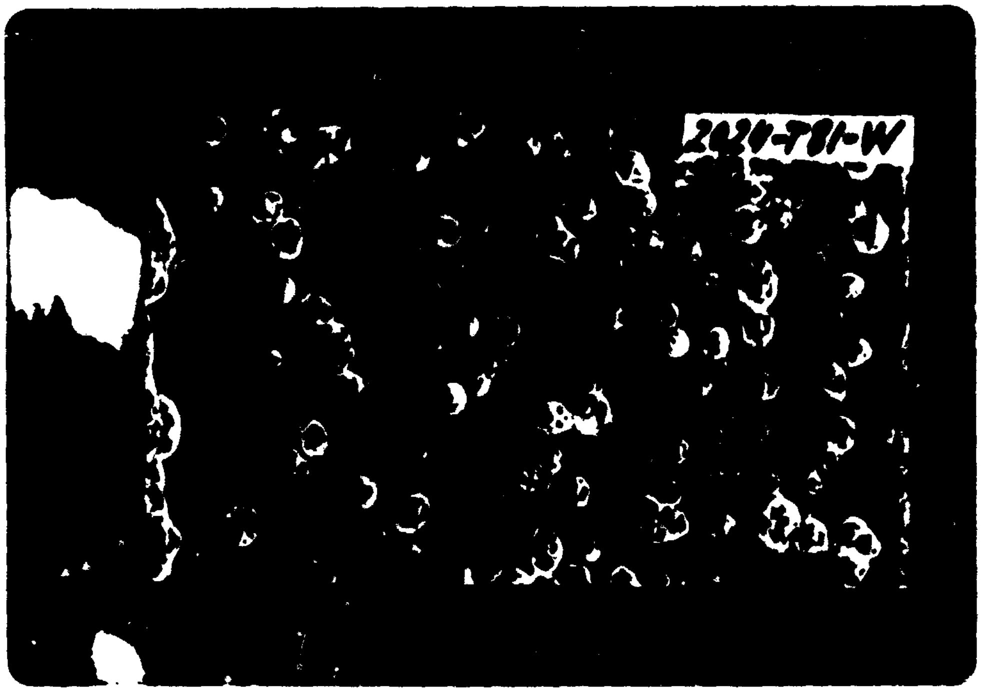

Figure 3. Scattered corrosion blisters on 2024-T81, typical of the attack on all the 2000 series (aluminum-copper) alloys.

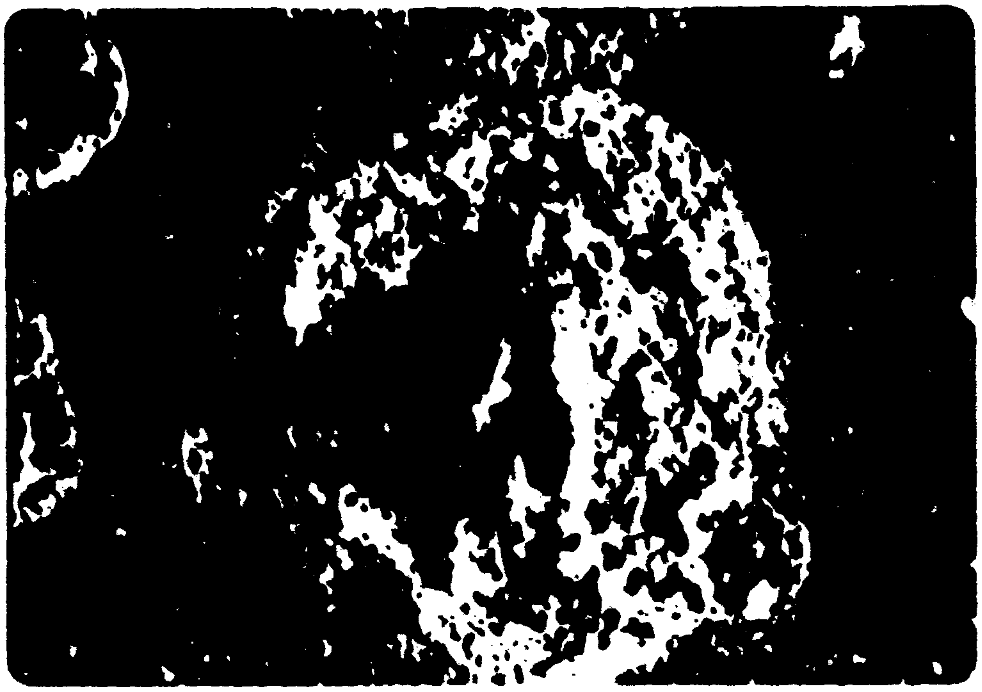

Figure 4. An area of Figure 3 at higher magnification showing a broken blister with its surrounding white, powdery corrosion products.

Figure 5. Scattered blisters and pits on 7079-T6 alloy which are typical of the attack on all the bare 7000 Series (aluminum-zinc-magnesium) alloys.

Figure 6. A pit typical of those in the bare 7000 Series alloys, above.

Figure 7. Junction of the two hemispheres of a Clad 7178-T6 aluminum alloy buoy. The Clad layer on the top hemisphere has corroded through exposing the underlying core material.

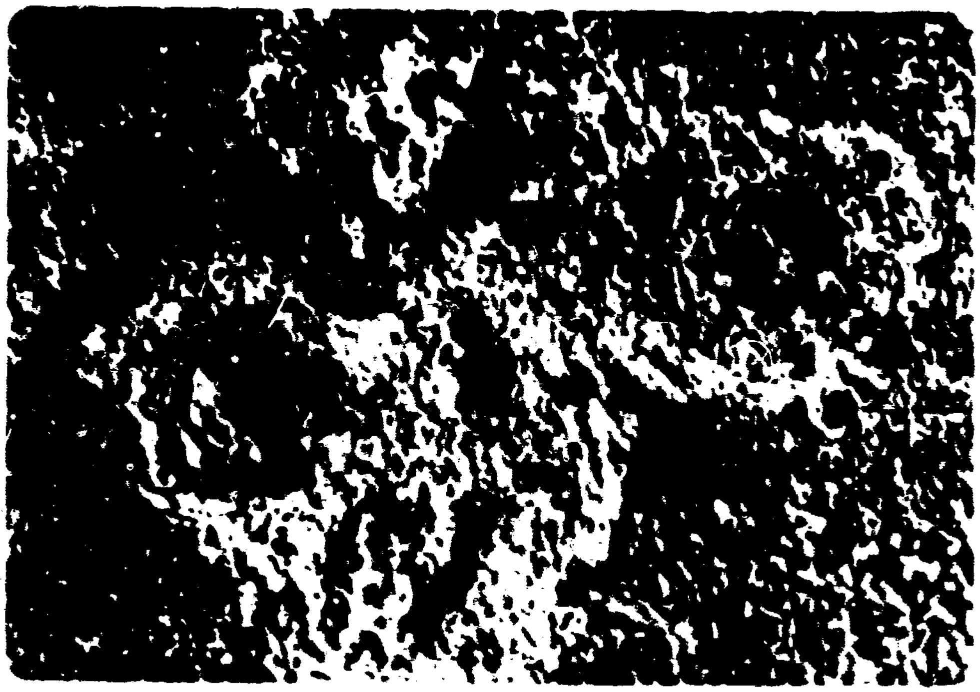

Figure 8. An area of the corroded Clad layer of the buoy in Figure 7 at greater magnification.

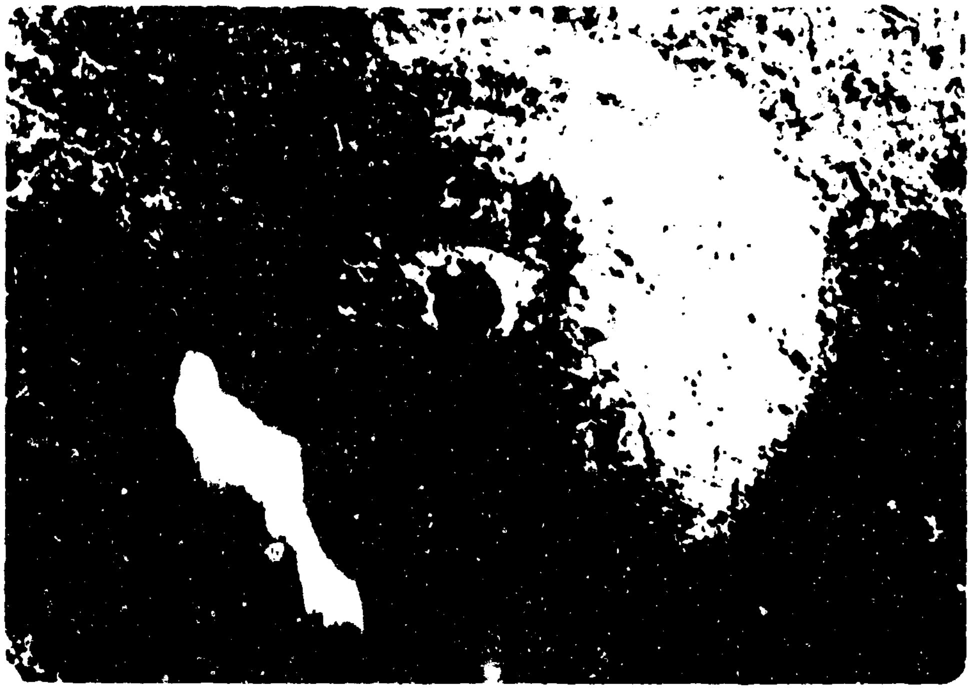

Figure 9. A medium size blister on the bottom hemisphere shown in Figure 7. The hole in the top of the blister is the origin of attack.

Figure 10. The blister shown in Figure 9 after sectioning to expose the core material and the crystallized aluminum oxide corrosion products. The uncorroded layer of Cladding alloy is relatively thick.

Figure 11. Selective attack of weld bead on welded X7002-T6 reheat treated after welding. Weld bead was considerably anodic to the sheet alloy.

Figure 12. Aluminum bronze specimen showing the type of corrosion film and the range of colors on the copper, brass and bronze alloys.

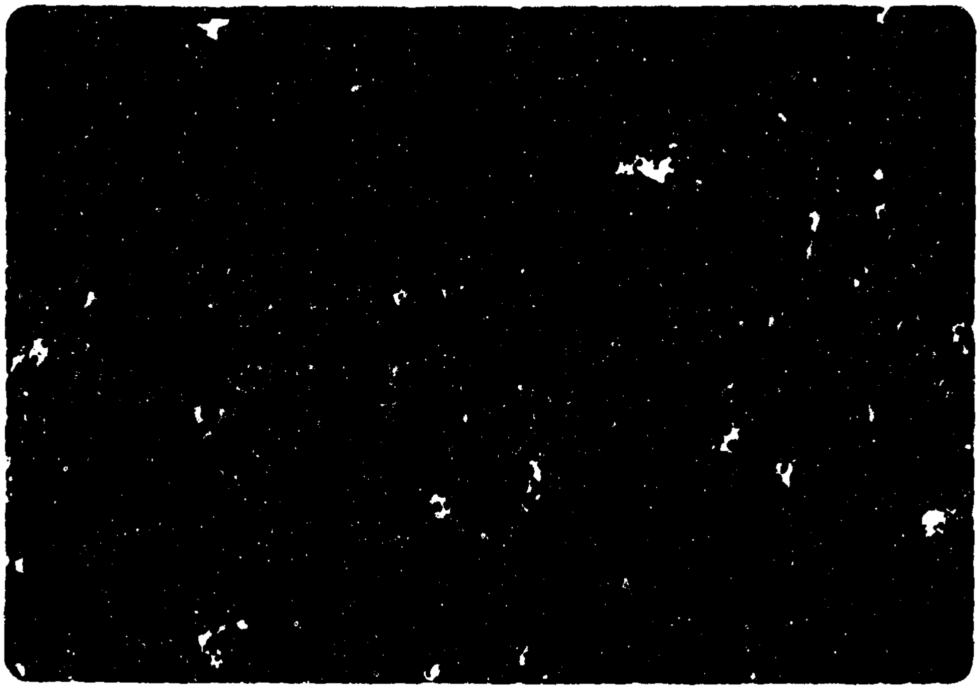

Figure 13. A small area of the specimen in Figure 12 at greater magnification showing the corrosion film thickness in more detail.

Figure 14. Patterned film of vari-colored corrosion products on 95% copper-5% nickel alloy.

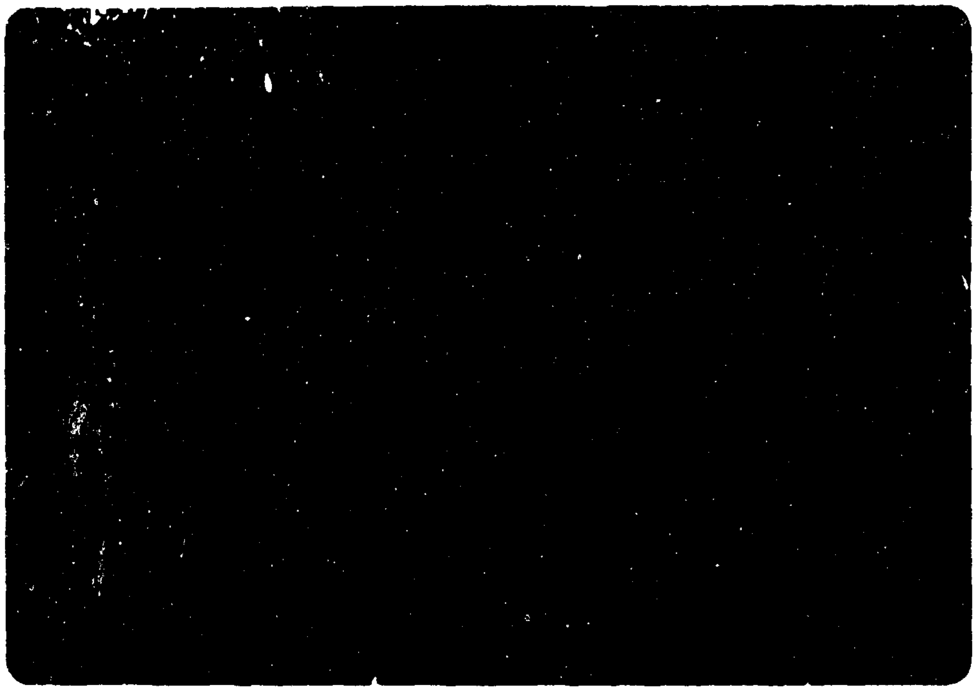

Figure 15. An area of the specimen in Figure 14 at greater magnification showing the details of both the blue and dark brown corrosion product films.

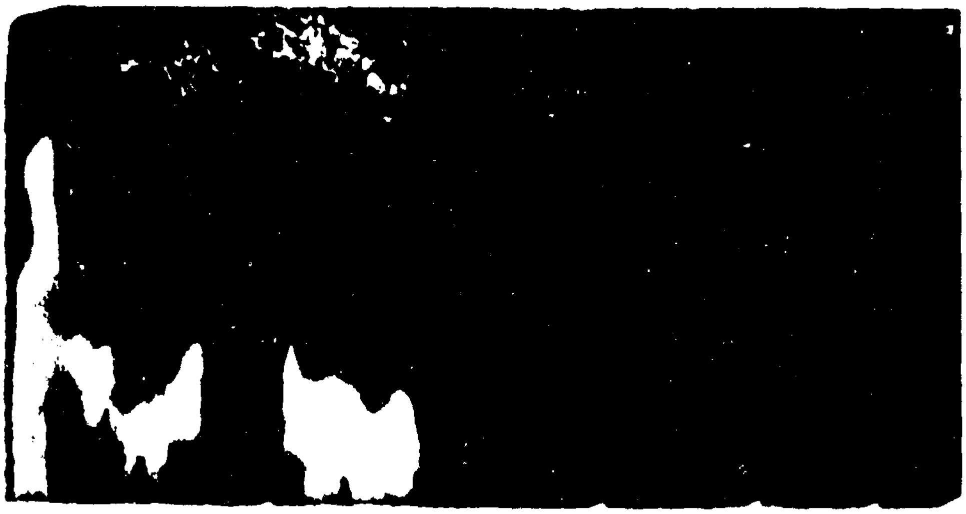

Figure 16. Layer of corrosion products typical of those on wrought iron, carbon steels, low alloy high-strength steels and alloy steels. The corrosion products had flaked in some areas exposing the underlying steel.

Figure 17. Corrosion products of steels and irons showing the shades of red of the rust and their flakiness in greater detail.

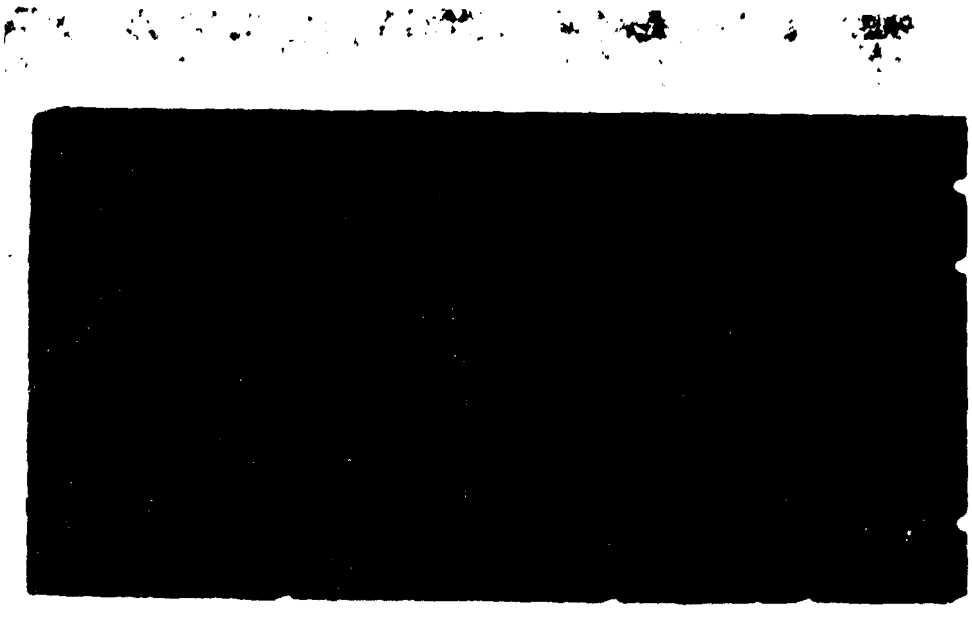

Figure 18. Type 430 stainless steel with one area of attack and heavy deposit of corrosion products.

Figure 19. Corroded area of Figure 18 at higher magnification showing the row of pits with corrosion products on both sides.

Figure 20. Lacework type of attack on the chromium stainless steels.

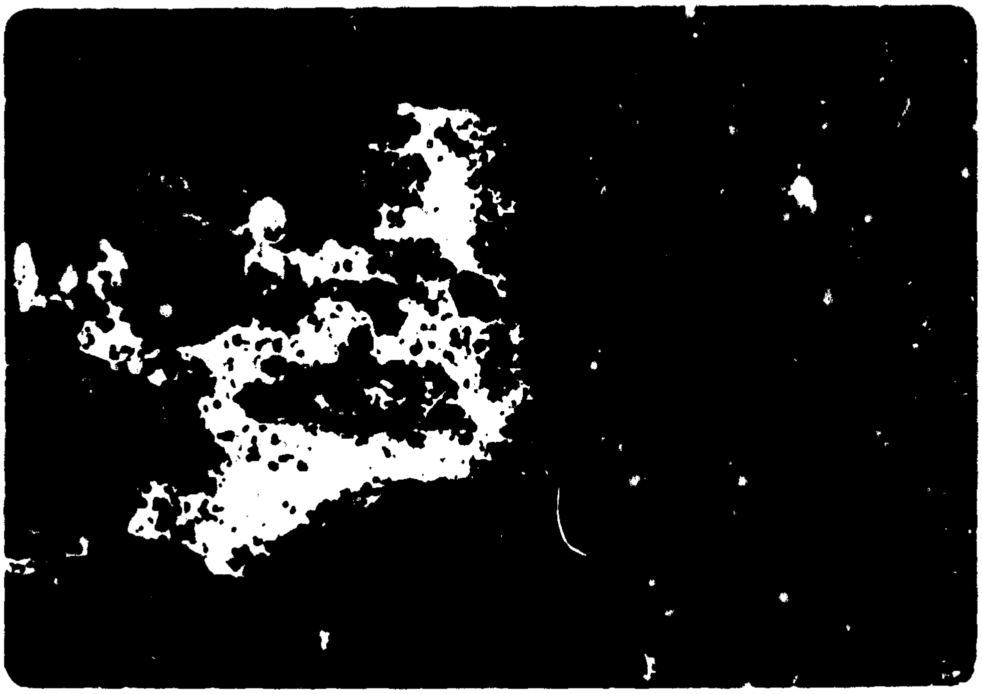

Figure 21. Small pit in center of clear area on Type 301 stainless steel which was the origin of the honeycomb or undersurface type of attack.

Figure 22. Crevice corrosion on precipitation hardened stainless steel specimens assembled for determining this type of attack.

Figure 23. One inch square piece and bolt in Figure 22 showing crevice corrosion at bolt head and at edges of piece.

Figure 24. Faying surfaces after disassembly of combination in Figure 23 showing that intense crevice corrosion had occurred.

Figure 25. Stress corrosion crack in 15-7 AMV, RH1150. Origin of crack was at pitted area where specimen was in contact with the polyethylene insulator. (Precipitation hardened stainless steel.)

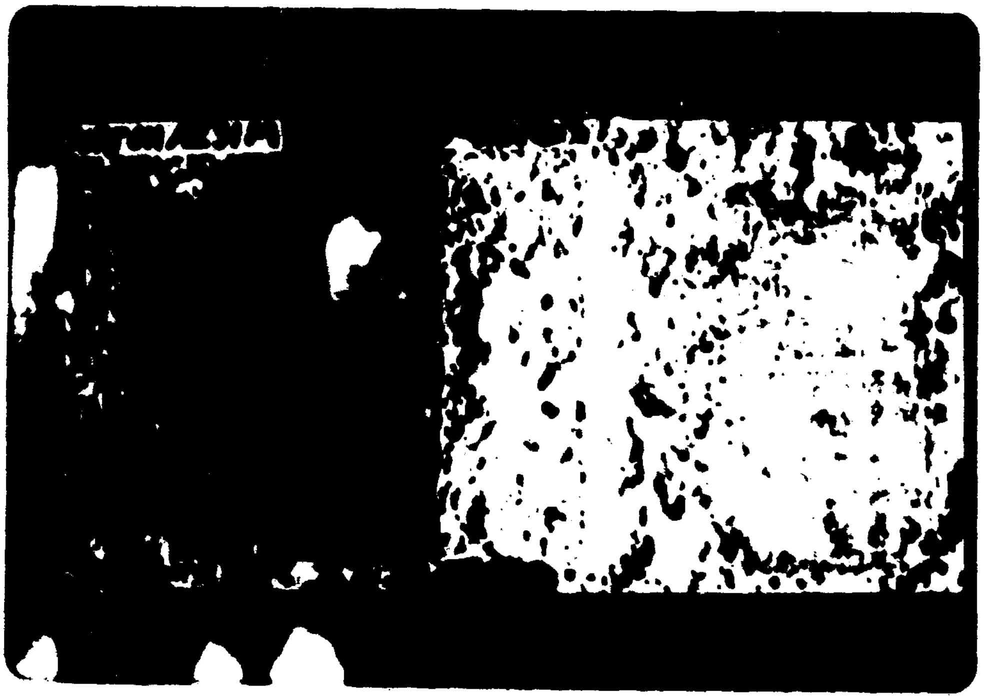

Figure 26. Galvanic couple, 7075-T6 aluminum alloy strip riveted to AZ31B magnesium alloy panel.

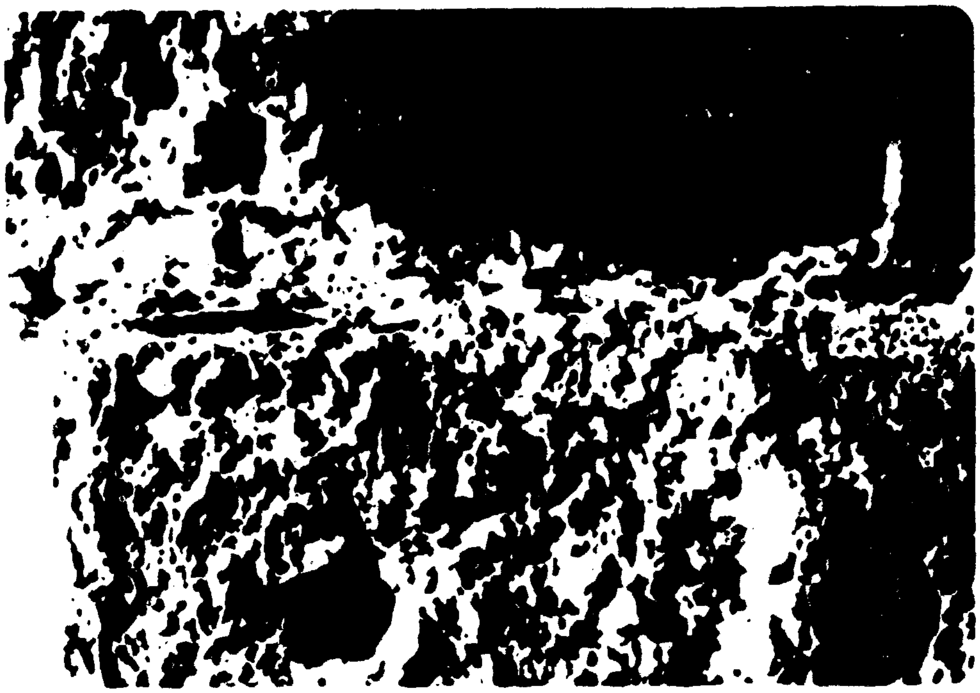

Figure 27. End of 7075-T6 aluminum alloy strip showing that it has been almost entirely converted to white and grey corrosion products.

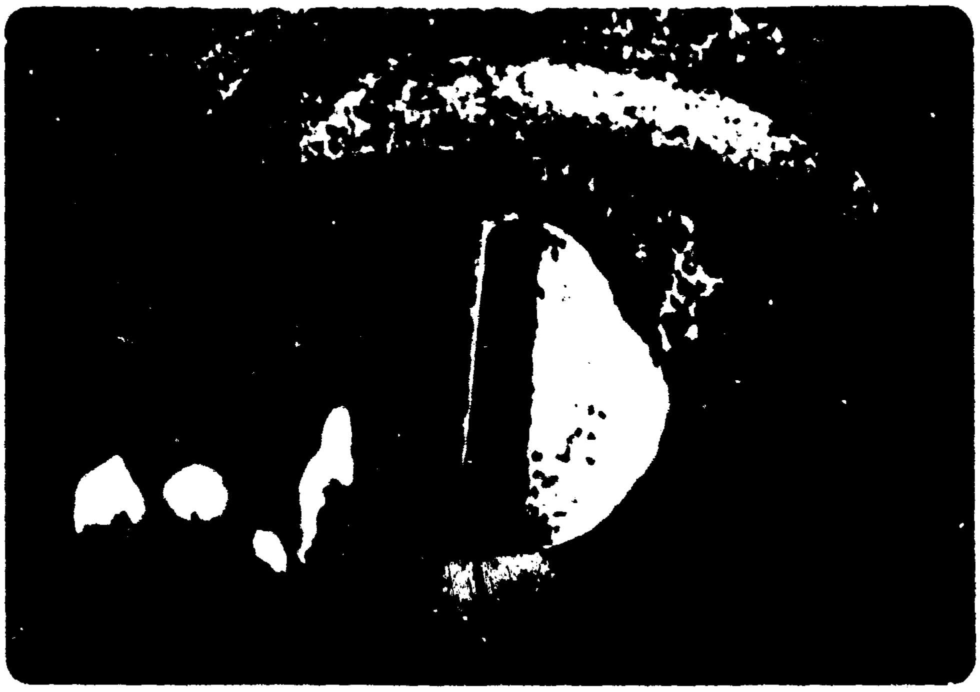

Figure 28. Corrosion originating in the crevice between the head of an 18% chromium-8% nickel stainless steel machine screw.

Figure 29. Cadmium plated bold and nut from which the cadmium had corroded and the underlying steel had rusted.

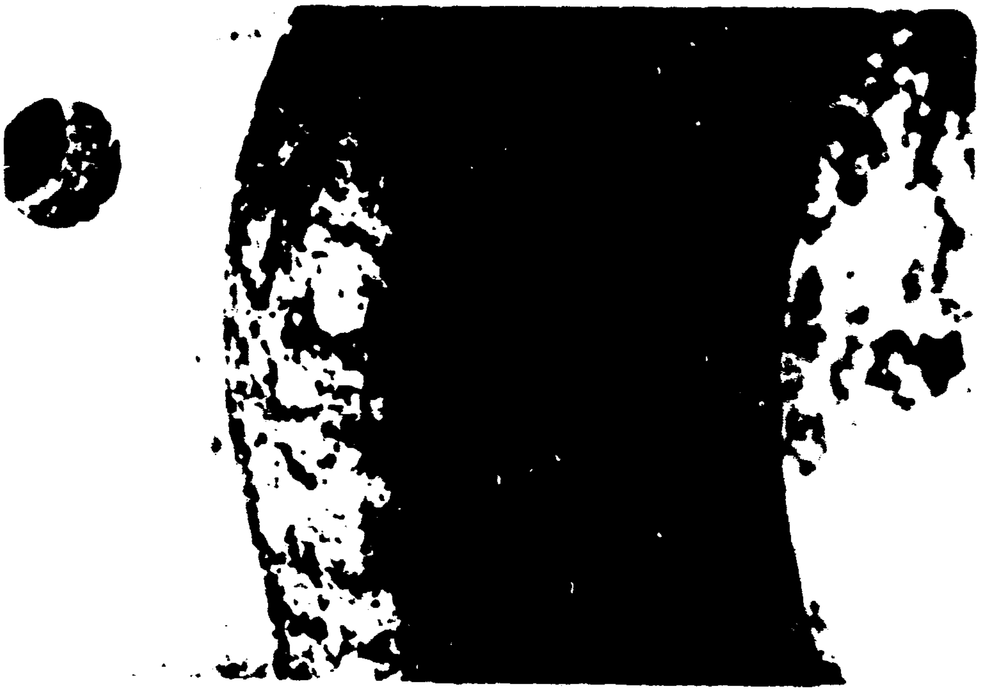

Figure 30. Cracks in electroless nickel plating and bleeding rust on a plated steel shackle.