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EFFECT OF MECHANICAL CLEANING ON SEAWATER CORROSION OF CANDIDATE OTEC HEAT EXCHANGER MATERIALS.

PART 1. TESTS WITH M.A.N. BRUSHES

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ABSTRACT

Corrosion evaluations were conducted on 3003 Alclad, 5052 aluminum, C70600 copper-nickel, AL-6X stainless steel, and commercially-pure titanium in natural seawater under simulated OTEC heat exchanger conditions to investigate the erosion-corrosion effects of mechanical tube cleaning. Test conditions of M.A.N. brush cleaning and M.A.N. brush cleaning + chlorination were compared with no mechanical cleaning over a seven month period.

M.A.N. brushing significantly accelerated corrosion of 5052 aluminum and C70600 copper-nickel. Chlorination significantly accelerated erosion-corrosion of 3003 Alclad and 5052 aluminum. Chlorination somewhat decreased erosion-corrosion of C70600 copper-nickel. There was no detectable effect of M.A.N. brushing or chlorination on AL-6X stainless steel or titanium, although AL-6X exhibited crevice corrosion at tubing connections. 3003 Alclad and 5052 aluminum exhibited pitting corrosion in all 3 test environments.

INTRODUCTION

The viability of Ocean Thermal Energy Conversion (OTEC) as a source of electrical power is currently being reviewed by the U.S. Department of Energy. Conceptual OTEC designs would be deployed in tropical and sub-tropical open ocean locations. Warm surface waters in cold deep waters would be utilized to expand and condense a working fluid in a "closed" loop Rankine thermodynamic cycle. The expanding fluid would drive a turbine generator to produce electrical power.

The tremendous quantity of warm and cold water available in the open ocean makes OTEC an economically attractive concept. Technical problems exist, however, that affect the potential success or failure of OTEC. Economic justification requires long-term compatibility between materials of construction in both seawater and working fluid environments. Also, the inherently low thermal efficiency of an operating OTEC plant requires maintenance of heat transfer efficiency unique in the power industry.

To maintain high heat exchanger efficiency, it may be necessary to perform periodic cleaning operations of the OTEC heat exchangers. This paper summarizes studies by the LaQue Center for Corrosion Technology, Inc. (Argonne National Laboratory Contract No. 31-109-38-4979) on the effects of a mechanical brush cleaning technique on the corrosion resistance of five candidate OTEC heat exchanger tubing materials in a simulated OTEC heat exchanger environment.

EXPERIMENTAL

Materials

The five materials evaluated were 3003 Alclad, 5052 aluminum, C70600 copper-nickel, AL-6X stainless steel, and commercially-pure titanium. The nominal alloy compositions are given in Table I. All materials were obtained as 25.4 mm (1 in) O.D. tubing with 0.89 mm (0.035 in) wall thickness for C70600, AL-6X, and Ti and 1.65 mm (0.065 in) wall thickness for 3003 Alclad and 5052 Al. All tubing was obtained from commercial suppliers and represents typical commercial quality. The C70600, Ti, and AL-6X tubing was welded while the aluminum tubing was seamless.

Equipment

Figure 1 shows a schematic diagram of the test facility. All piping, pumps, and other equipment in contact with the seawater environment were nonmetallic or titanium (e.g., primary pump impeller) to avoid metal ion contamination.

Figure 2 shows a photograph of a M.A.N. brush catcher assembly located at either end of a test section. The plastic catcher basket was attached to a short length of tubing of each respective material in a given loop so that no specimen would be subjected to possible end effects arising from the catcher basket. Over the catcher basket, a section of clear PVC (polyvinyl chloride) was used for containment and allowed visual inspection of the operation of the brushes during flow reversal.

As indicated in Figure 1, the test specimens were connected end to end to allow passage of the flowing seawater and the M.A.N. brush in series for each test loop. Figure 3 shows the details of specimen tube connections. A PVC spacer ring, machined to the approximate I.D. and O.D. size of the test specimens, was used to eliminate galvanic contact between test specimens. The spacer also provided for a smooth transition for the action of the M.A.N. brush from specimen to specimen minimizing the inevitable I.D. discontinuities at connection points.

The M.A.N. brushes and catcher baskets were obtained from Water Services of America, Inc. according to their recommendations of a 22.81 mm (0.898 in) diameter brush (Model No. 0049) for the 3003 Alclad and 5052 Al and a 24.33 mm (0.958 in) diameter brush (Model No. 0049) for the C70600, AL-6X, and Ti. The same catcher basket (Model No. 0001), mounting on the tube O.D., was used for all materials.

Environmental

All tests were conducted in clean, natural, unpolluted seawater. Table II gives the seawater hydrology for the test period. The recirculated test volume of 30 liters was refreshed at a rate of 1.0 L/min with fresh seawater. The seawater temperature was controlled at 30C with immersion heaters.

The seawater velocity through the tubes was 1.8 m/s (6 ft/s). The resulting flow rate was adjusted by relating the pressure drop of the system (using a throttling valve) to the measured flow rate versus pressure drop curve for the recirculating pumps.

The M.A.N. brush cleaning cycle was one round trip (two passes of the brush) per eight hours - or three round trips per day. Automatic, timer-controlled flow reversal through the test section, to operate the M.A.N. brushes, was achieved by pneumatic-actuated three-way valves as indicated in Figure 1. All three-way valves were operated by a common timer-controlled air supply.

Chlorination at a continuous level of 0.1 mg/L was achieved by a single electrolysis cell at the seawater refreshment source for the five chlorinated test loops. Residual chlorine levels were checked daily at test loop overflows, with minor adjustments of current and/or flow rate through the electrolytic chlorinator, to maintain a 0.1 mg/L chlorine level. Table III gives the statistical variation for residual chlorine.

Test Procedure

Eight specimens of tubing, 150 mm (6 in) long, were prepared for each of the fifteen material/environment combinations (five materials each in three environments). Six specimens provided replicates for removal after 3 and 7 months. The remaining two specimens were exposed for 7 months as a galvanic couple, as shown in Figure 1, with an external galvanic connection to allow study of the galvanic action between M.A.N. brushed and nonbrushed specimens in each of the M.A.N. brushed environments.

Additionally, for 3003 Alclad in the control environment (no cleaning) and M.A.N. brush cleaned (without chlorination), seven specimens, 75 mm (3 in) long, were exposed to provide short term corrosion data after 1, 2, 4, 8, 16, 32, and 64 days exposure.

All specimens were machined to provide square, burr-free ends. Specimens were degreased in acetone, weighed (± 1 mg), and coated on the O.D. with paraffin to avoid any atmospheric corrosion. The specimens were assembled end to end and fastened to a wooden support, with vinyl-covered wire, to maintain alignment.

After removal from test, one specimen of each duplicate pair was split longitudinally. One half was examined in the as-exposed condition, and the other half after acid cleaning. Acid cleaning , according to ASTM G1-72, served to remove corrosion products and organic debris. The loss of wall thickness and the type and extent of corrosion attack was then determined. The remaining intact tube specimen was acid cleaned and weighed to determine weight loss. In the case of the 3003 Alclad short term exposures (1 to 64 days), the single specimens were acid cleaned, weighed, and then split longitudinally for I.D. surface observation. The M.A.N. brushes were examined for wear and dimensional stability, etc.

Corrosion data was recorded by two methods - weight change and thickness loss/depth of attack. Weight changes provided comparative data with respect to the total extent of corrosion - without regard to morphology of the corrosion attack. Weight change data was obtained for each material/environment combination. The data are presented as weight loss per unit surface area (of the I.D. surface).

Localized corrosion (e.g., pitting or crevice corrosion) is often represented by penetration measurements. These data are presented as maximum depth of attack.

RESULTS AND DISCUSSION

3003 Alclad

Figures 4 and 5 show the I.D. surface appearance of 3003 Alclad tubing exposed in the control (no cleaning) environment and exposed to M.A.N. brush cleaning for 1 to 64 days. In both cases, the normal direction of flow through the tubes was from top to bottom in the photographs. In Figure 4, the specimens show a discoloration which is consistent with the normal growth of a corrosion film on aluminum alloys in flowing seawater. No localized corrosion was observed.

In Figure 5, the specimens show the erosion-corrosion effects of M.A.N. brushing. Starting at 8 days exposure, streaks in the corrosion product film and a lighter color at the inlet (top) end began to appear. After 32 to 64 days a significant amount of localized corrosion had occurred at the inlet ends.

Table IV summarizes the weight loss data from the short term specimens. Figure 6 gives the weight loss per unit surface area as a function of exposure time. In contrast with the surface appearances in Figures 4 and 5, the weight losses in the two environments converge after 32 days exposure. Based on overall weight loss for exposures up to 64 days, there is very little difference in the corrosion of 3003 Alclad in seawater with or without M.A.N. brush cleaning. Observation of the I.D. surface, however, revealed that the bulk of the corrosion attack in the M.A.N. brushed environment was localized corrosion at the inlet end, while corrosion in the control environment, without M.A.N. brushing, was uniform, general corrosion.

The longer term 3 and 7 months exposures, however, showed more attack in the brushed environment than in the control. Table V summarizes the weight loss data obtained in these exposures. Even with rather high variability of the data the corrosion weight loss for Alclad is somewhat higher for both 3 and 7 months exposures in the M.A.N. brushed environment than in the control with no cleaning. This increased weight loss is indicative of some acceleration of the corrosion process by the erosive effects of the brushes. Addition of 0.1 mg/L residual chlorine brought about a significant further increase in weight loss.

The maximum depth of attack (0.12 —> 0.24 mm maximum depth) in all three environments as shown in Table VI. The maximum depth of attack of approximately 0.2 mm was apparently attained within the 3 month exposure. No significant increase in maximum depth of attack or in weight loss was observed between 3 and 7 months exposure. This suggests that pitting is limited to the depth of the I.D. 3003 cladding (nominally 10% of the wall, or 0.16 mm) and does not penetrate into the substrate 7072 alloy.

Figures 7, 8 and 9 show the I.D. appearance of Alclad specimens from the three environments. Note the pitting corrosion in all environments and extensive erosion-corrosion in the brushed environments. Localized corrosion of 3003 Alclad in natural seawater is well documented.[1-4] The limited depths of pitting of 3003 Alclad tubing has also been observed in shipboard cooling system experiments.[4]

5052 Aluminum

The corrosion data in Tables V and VI show a good correlation between weight loss and maximum depth of attack for 5052 aluminum. Similar to, but even more pronounced than in the case of Alclad, corrosion of 5052 in natural seawater is accelerated by brush cleaning and further accelerated by chlorination.

5052 showed localized attack similar to Alclad. Figures 10, 11, and 12 show the I.D. appearance of 5052 specimens from the three environments. Pitting corrosion is evident in all environments. In the brushed environments, the pitting morphology is more elongated, or striated, showing the erosion-corrosion influence of the brush cleaning. Pitting of 5052 aluminum has also been documented in the literature.[1,2,5] The effect of various seawater variables on pitting of 5052 has been reported by Dexter.[5]

Figure 13 shows crevice corrosion of 5052 on the O.D. under the flexible vinyl tubing connector to a maximum depth of over 20% of the wall thickness. Only one case of crevice corrosion was observed, but like pitting corrosion, crevice corrosion of 5052 is also well documented.[1,2]

C70600 Cu-Ni

Widespread experience is documented for C70600 in seawater in condensers and heat exchangers aboard merchant and naval vessels, coastal power generating stations and desalination plants.[1,6] The weight loss and depth of attack data in the control environment (Tables V and VI, respectively) reflect the general corrosion behavior of C70600 in flowing seawater. There is rapid corrosion weight loss initially, but little further attack between 3 and 7 months exposure.

Brush cleaning, however, produces substantial acceleration of the corrosion weight loss - with no apparent leveling off up to 7 months exposure. Also, as noted in Table VII, the morphology of attack changes from general uniform corrosion in the non-cleaned controls to localized corrosion in the cleaned environments.

Figures 14, 15, and 16 provide a comparison of the I.D. surface appearances after test exposure in the three environments. As in the case of aluminum alloys, the erosive effects of the brush cleaning are evidenced in the surface attack morphology as elongated, or striated pits.

It has been found by some manufacturers in the copper industry that on-line automatic cleaning of copper-nickel condenser tubes using brushes can be detrimental by "overcleaning" the tube. This "overcleaning" erodes the protective film and prevents its reformation.[7] The erosion then allows the initial rapid corrosion to continue with no protection from a corrosion product film.

Tables V and VI also suggest that, on the basis of both weight loss and maximum depth of attack, chlorination can offer some limited protection from these erosion-corrosion effects of brush cleaning - as evidenced by a decrease in weight loss and maximum depth of attack with the addition of 0.1 mg/L residual chlorine.

LCCT has performed other corrosion tests of C70600 in flowing (1.5 m/s), chlorinated (2.0 mg/L residual Cl_2) seawater as shown in Table VII. In these tests, chlorination reduced the corrosion rate by 35%. It should be pointed out that caution should be exercised in interpreting the appparent beneficial effects of chlorination on erosion-corrosion resistance of C70600. Other work has shown that, while chlorination can provide some inhibition of corrosion of copper-nickel alloys in flowing seawater, under conditions of impinging flow (likely to be experienced at obstructions, 90° bends, etc.) chlorination can result in a significant acceleration of corrosion.[8]

AL-6X Stainless Steel

As indicated in Tables V and VI, AL-6X showed only slight pitting on the tube I.D. Figure 17 shows the typical appearance of this very limited pitting. This attack was observed in all three environments and is, therefore, not related to the brush cleaning.

Like 5052 aluminum, discussed earlier, AL-6X was subject to extensive crevice corrosion on the O.D. The crevice was created by the flexible vinyl tubing connection. This crevice, with a very small gap and a large depth, can create local conditions of low oxygen and low pH that can result in a corrosion attack. Figure 18 shows the most severe case of crevice corrosion observed of which perforated the tube wall. It should be pointed out that this crevice geometry represents a very severe condition may not be encountered in a heat exchanger. Crevice corrosion, to some extent, was observed on the O.D. surfaces of all six specimens of AL-6X exposed for 7 months. The other crevice sites were much less severely attacked than that shown in Figure 18. Figure 19 is representative of these less severely attacked sites.

Titanium

As indicated in Tables V and VI, titanium showed minimal weight loss and no detectable loss in thickness in all three environments. Figure 20 shows a typical titanium specimen after test exposure.

Galvanic Exposures

Table VII shows the weight loss data from the galvanic couple experiments with non-brushed specimens coupled to M.A.N. brushed specimens in the same flow stream. Data from freely corroding specimens (discussed earlier and presented in Table VI) is given for comparison to illustrate the effects of galvanic coupling.

These galvanic tests were intended to provide some insight into possible galvanic acceleration of corrosion of brushed tubes by non-brushed tubes. It was surmised that non-brushed tubes could be cathodic to brushed tubes and thereby galvanically accelerate erosion-corrosion of brushed tubes.

The data in Table VII does not reveal any significant galvanic acceleration of corrosion of brushed tubes by non-brushed tubes.

In fact for 5052 aluminum this galvanic coupling appears to bring about a decrease in weight loss of specimens brush cleaned in natural seawater and an increase in weight loss of specimens brush cleaned in chlorinated seawater. At present, the significance of these observations are not clear.

Appearance of M.A.N. Brushes

Several M.A.N. brushes were briefly examined after three months of service. Figures 21 and 22 show the brush from the 3003 Alclad loop (without chlorination) compared with a similar size unused brush. (Figure 8 shows the I.D. surface of a tube specimen through which this brush passed during the test.) Although precise measurements of bristle length and overall brush diameter could not be made, Figure 21 shows that some bristle wear may have occurred. Note that the lengths of the bristles appear to be more uneven in the exposed brush. Also, the overall diameter seems to have decreased somewhat as determined by the length of bristle which is visible outside the end plate of the brush.

Figure 23 shows the brush from the C70600 loop (without chlorination) compared with a similar size unused brush. In contrast with the 3003 Alclad brush in Figure 21 and 22, the brush in Figure 23 appears to have grown in overall diameter during the test. This increase in overall diameter is apparently due to the bristles being pulled from the spiral wire core by excessive mechanical/frictional forces imposed upon the brush bristles by the very rough tubing I.D. surfaces. As shown in Figure 15, the I.D. surface of the tube specimens contacted by this brush have been roughened by erosion-corrosion.

CONCLUSIONS

3003 Alclad

1. 3003 Alclad is susceptible to pitting in both seawater with no cleaning and under M.A.N. brushed conditions.

2. Chlorination, at the 0.1 mg/L level, in combination with M.A.N. brush cleaning, greatly increases the extent of corrosion (based on weight loss).

5052 Aluminum

1. 5052 aluminum is susceptible to pitting in both seawater with no cleaning and under M.A.N. brushed conditions.

2. M.A.N. brushing nearly doubles the extent of corrosion as compared to control specimens with no cleaning. The corrosion takes the form of extensive pitting.

3. The addition of 0.1 mg/L Cl_2 in combination with M.A.N. brush cleaning increases the extent of corrosion.

C70600 Copper-Nickel

1. M.A.N. brushing increases the extent of corrosion (more than an order of magnitude based on weight loss) as compared to specimens with no brushing.

2. Chlorination, at the 0.1 mg/L level, somewhat reduces the extent of corrosion of the M.A.N. brushed specimens.

AL-6X Stainless Steel

1. No significant I.D. corrosion was detected as a result of M.A.N. brush cleaning, although some slight pitting was observed in the chlorinated environment.

2. Crevice corrosion was observed on O.D. surfaces in the severe crevices formed between the vinyl tubing and the specimens.

Titanium

1. No corrosion was detected in any environments, irrespective of cleaning or chlorination.

M.A.N. Brushes

1. Examinations revealed that wear of the brushes could be produced by corroding surfaces.

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TABLE I

Nominal Compositions of Alloys Tested

Alloy	Nominal Composition (wt.%)
C70600	Cu-10Ni-1.4Fe
Grade 5052 Al	Al-2.5Mg-0.25Cr
3003 Alclad	7072 (Al-1.0Zn) clad 3003 (Al-1.2Mn)
Titanium, C.P.	Ti
AL-6X Stainless Steel	Fe-24Ni-20Cr-6Mo

TABLE II

Seawater Hydrology* During the 7 Month Test Period (7/7/79 to 2/9/80)

	Mean	Minimum	Maximum	No. of Observations
pH	8.1	7.9	8.1	32
Cl^-(gm/L)	19.4	18.4	20.5	32
Salinity (gm/L)	35.1	33.2	37.0	32
Dissolved Oxygen (mg/L)	6.6	4.5	9.4	30

* Seawater sampled at inlet of piping system.

TABLE III

Statistical Variation of Residual Chlorine (All Chlorinated Environments)

Mean (mg/L)	Maximum (mg/L)	Minimum (mg/L)	Std. Deviation (mg/L)	No. of Observations
0.12	0.20	0.05	0.04	140

TABLE IV

Weight Loss and Depth of Attack for Short Term Tests of 3003 Alclad

Spec No.	Environment	Exposure Duration (days)	Weight Loss (mg/cm^2)	Maximum Depth of Attack (mm)
AC-36	Control(No Cleaning)	1	0.38	<0.01
AC-35	"	2	0.64	<0.01
AC-34	"	4	1.13	<0.01
AC-33	"	8	1.78	<0.01
AC-32	"	16	2.50	<0.01
AC-31	"	32	4.01	0.01
AC-30	"	64	5.26	0.02
AC-23	M.A.N. Brushed	1	0.57	<0.01
AC-24	"	2	1.08	<0.01
AC-25	"	4	2.23	<0.01
AC-26	"	8	3.27	0.01*
AC-27	"	16	3.59	0.04*
AC-28	"	32	4.31	0.11*
AC-29	"	64	5.44	0.21*

TABLE V

Weight Loss Data for Specimens Exposed to Seawater

Material	Environment	Weight Loss Per Unit Area (mg/cm^2) 3 Month Exposure	7 Month Exposure+
3003 Alclad	Control	4.45	4.20,4.23,4.27
	M.A.N. brushed	4.57	5.99,6.83,6.46
	M.A.N. brushed and 0.1 mg/L Cl_2	34.29	19.62,24.67,4.95
5052 Al	Control	2.81	1.81,4.23,2.16
	M.A.N. brushed	4.84	13.56,9.50,9.77
	M.A.N. brushed and 0.1 mg/L Cl_2	10.13	14.27,14.38,14.38
C70600 Cu-Ni	Control	7.53	6.90,7.04,6.34
	M.A.N. brushed	87.46	36.41,144.64,128.08
	M.A.N. brushed and 0.1 mg/L Cl_2	48.54	74.03,84.07,83.77
AL-6X	Control	0.22*	9.81*,0.23*,0.10*
	M.A.N. brushed	0.02	0.06,0.16*,0.16*
	M.A.N. brushed and 0.1 mg/L Cl_2	0.01	0.04,0.12,0.08*
Titanium, C.P.	Control	<0.01	0.02,0.05,0.05
	M.A.N. brushed	<0.01	0.02,0.02,0.04
	M.A.N. brushed and 0.1 mg/L Cl_2	<0.01	<0.01,0.03,0.02

+ Numbers are for replicate specimens.

* Extensive crevice corrosion noted on specimen O.D.

TABLE VI

Maximum Depth of Attack Data for Specimens Exposed to Seawater

Material	Environment	3 Month Exposure: Max. Depth of Attack(mm)	3 Month Exposure: Type of Attack	7 Month Exposure: Max. Depth of Attack(mm)	7 Month Exposure: Type of Attack
3003 Alclad	Control	0.12	P	0.02	-
	M.A.N. brushed	0.24	P,I	0.20	P,I
	M.A.N. brushed and 0.1 mg/L Cl_2	0.20	P	0.17	P,I
5052 Al	Control	<0.01	-	0.17	P,I
	M.A.N. brushed	0.09	P	0.32	P,C
	M.A.N. brushed and 0.1 mg/L Cl_2	0.19	P	0.35	P,I
C70600 Cu-Ni	Control	<0.01	-	<0.01	-
	M.A.N. brushed	0.13	P	0.47	P
	M.A.N. brushed and 0.1 mg/L Cl_2	0.05	P	0.26	P,I
AL-6X	Control	0.01	C	0.01	P,C
	M.A.N. brushed	0.01	C	0.01	P,C
	M.A.N. brushed and 0.1 mg/L Cl_2	0.01	C	0.01	P,C
Titanium, C.P.	Control	<0.01	-	<0.01	-
	M.A.N. brushed	<0.01	-	<0.01	-
	M.A.N. brushed and 0.1 mg/L Cl_2	<0.01	-	<0.01	-

Code

P: Pitting corrosion.
I: Accelerated corrosion at inlet end.
C: Crevice corrosion on O.D. surface at connectors.

TABLE VII

Corrosion of C70600 in Chlorinated Seawater
After 30 Days

Environment	Corrosion Rate (µm/yr)
Natural Seawater @ 1.5 m/s	93.9
Natural Seawater @ 1.5 m/s	84.9
Natural Seawater + 2.0 mg/L Cl_2 @ 1.5 m/s	48.6
Natural Seawater + 2.0 mg/L Cl_2 @ 1.5 m/s	51.9

TABLE VIII

Weight Loss of 7-Month Galvanic Coupling Exposures

Specimen No.	Material	Loop Environment	Specimen Environment	Wt. Loss (mg/cm)	Freely Corroding*** Weight Loss (mg/cm)
AC-8	3003 Alclad	Seawater	Non-brushed	3.58	4.20-->4.27
Coupled To:					
AC-7	"	"	M.A.N. brushed	6.72	5.99-->6.83
AC-16	"	Seawater + 0.1 mg/L Cl	Non-brushed	4.95	-
Coupled To:					
AC-15	"	"	M.A.N. brushed	24.67	4.95-->24.67
A -8	5052 Al	Seawater	Non-brushed	1.90	1.81-->4.23
Coupled To:					
A -7	"	"	M.A.N. brushed	3.02	9.50-->13.56
A -16	"	Seawater + 0.1 mg/L Cl	Non-brushed	2.48	-
Coupled To:					
A -15	"	"	M.A.N. brushed	25.64	14.27-->14.38
CA-8	C70600	Seawater	Non-brushed	7.52	6.23-->7.04
Coupled To:					
CA-7	"	"	M.A.N. brushed	132.63	36.41-->144.64
CA-16	"	Seawater + 0.1 mg/L Cl	Non-brushed	13.15	-
Coupled To:					
CA-15	"	"	M.A.N. brushed	87.99	74.03-->84.07
6X-8	AL-6X	Seawater	Non-brushed	0.05*,**	0.10*-->9.81*
Coupled To:					
6X-7	"	"	M.A.N. brushed	0.05*	0.06-->0.16*
6X-16	"	Seawater + 0.1 mg/L Cl	Non-brushed	0.01*,**	-
Coupled To:					
6X-15	"	"	M.A.N. brushed	0.04*	0.02-->0.05
Ti-8	Titanium	Seawater	Non-brushed	0.02	0.02-->0.04
Coupled To:					
Ti-7	"	"	M.A.N. brushed	<0.01	0.01-->0.04
Ti-16	"	Seawater + 0.1 mg/L Cl	Non-brushed	0.04	-
Coupled To:					
Ti-15	"	"	M.A.N. brushed	<0.01	<0.01-->0.03

* Crevice corrosion on O.D.
** Pitting on I.D.
*** Range of weight loss on 3 specimens.

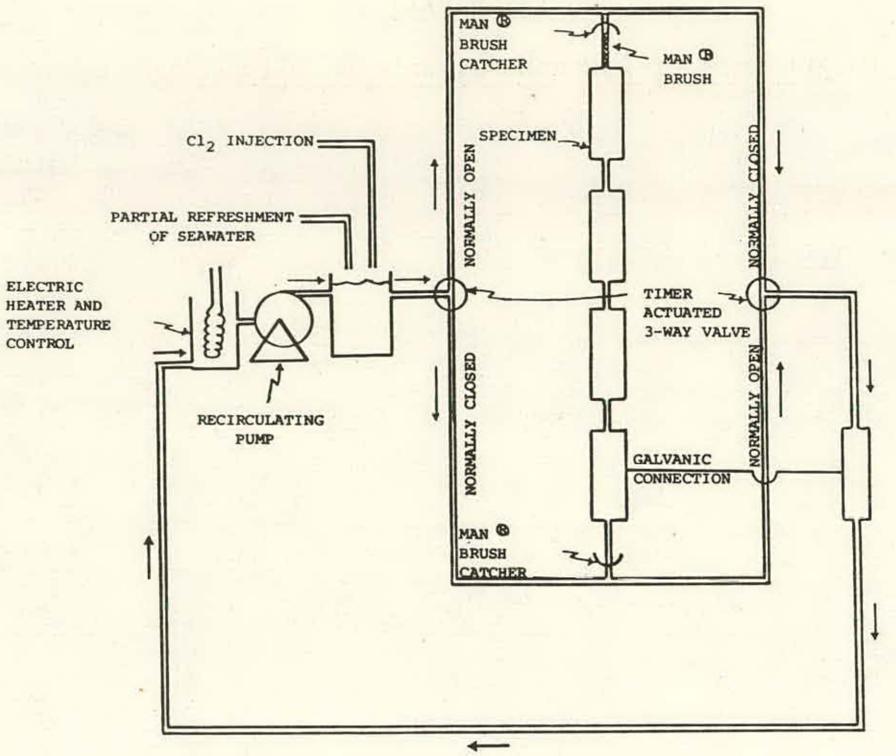


Figure 1. Schematic of M.A.N. brush cleaning system with partial seawater refreshment, chlorination, and temperature control. Neg. No. S-1836

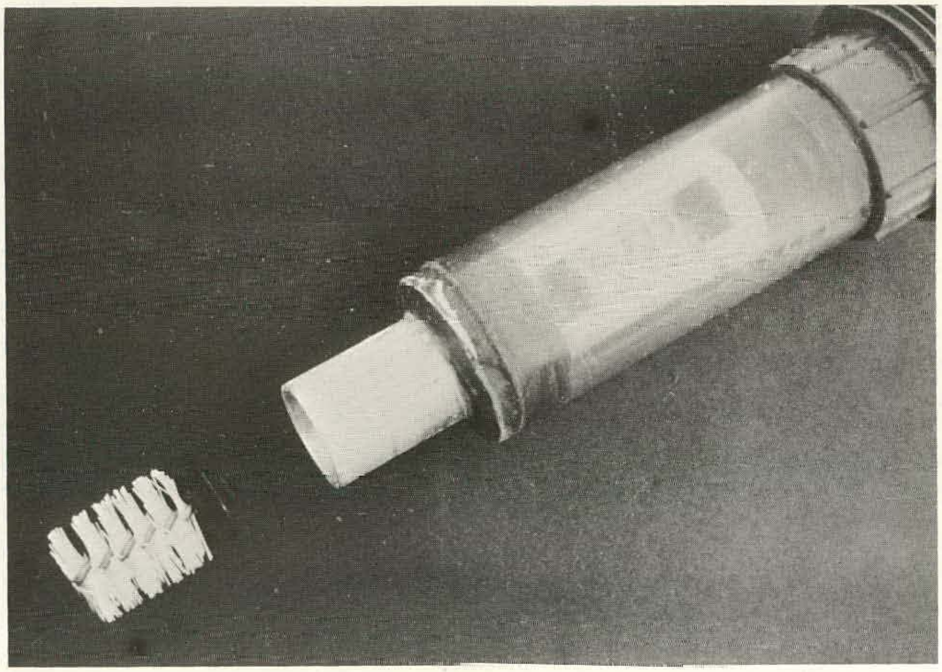


Figure 2. M.A.N. brush catcher assembly and M.A.N. brush. 0.6X Magnification. Neg. No. S-1837

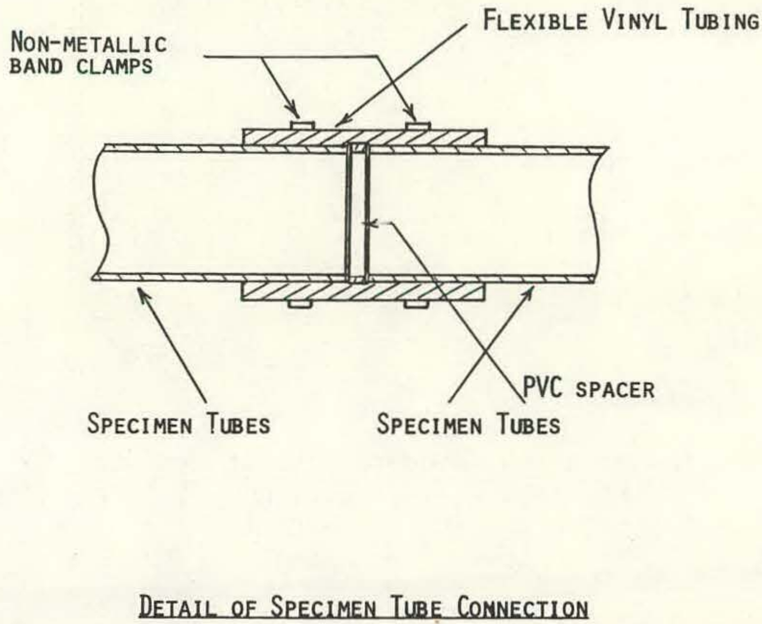


Figure 3. Detail of specimen tube connection.
Neg. No. S-1838

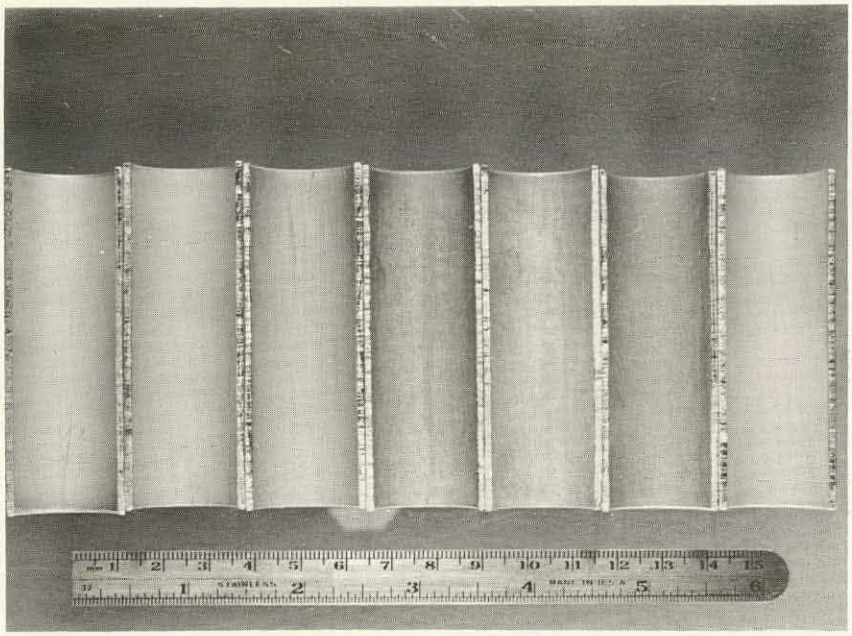


Figure 4. 3003 Alclad after exposure without cleaning for (left to right) 1,2,4,8,16,32, and 64 days. Normal flow direction was top to bottom.
0.6X Magnification. Neg. No. 79158-6

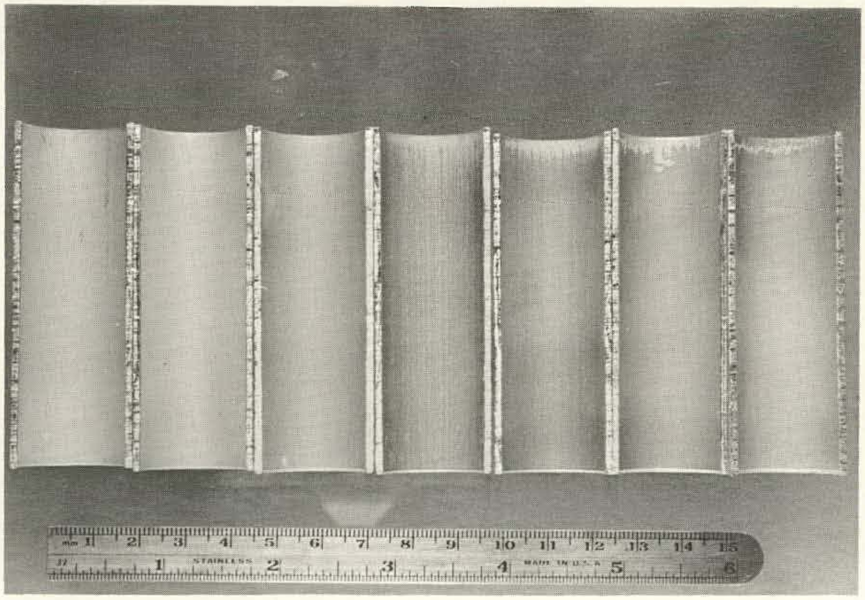
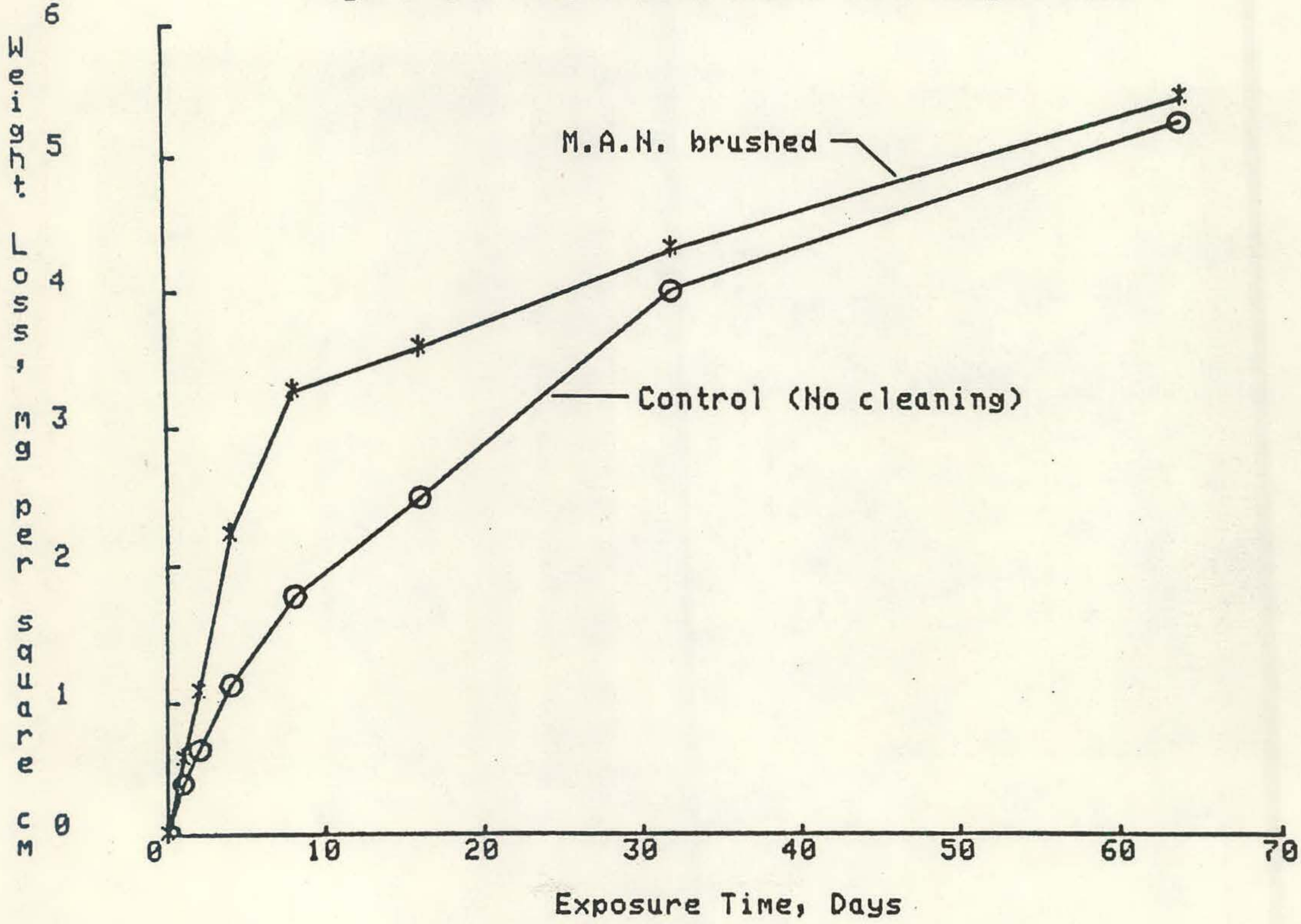


Figure 5. 3003 Alclad after exposure to M.A.N. brush cleaning for (left to right) 1,2,4,8,16,32, and 64 days. Normal flow direction was top to bottom.
0.6X Magnification. Neg. No. 79158-11

Figure 6. Alclad-3003 Short Term Weight Loss



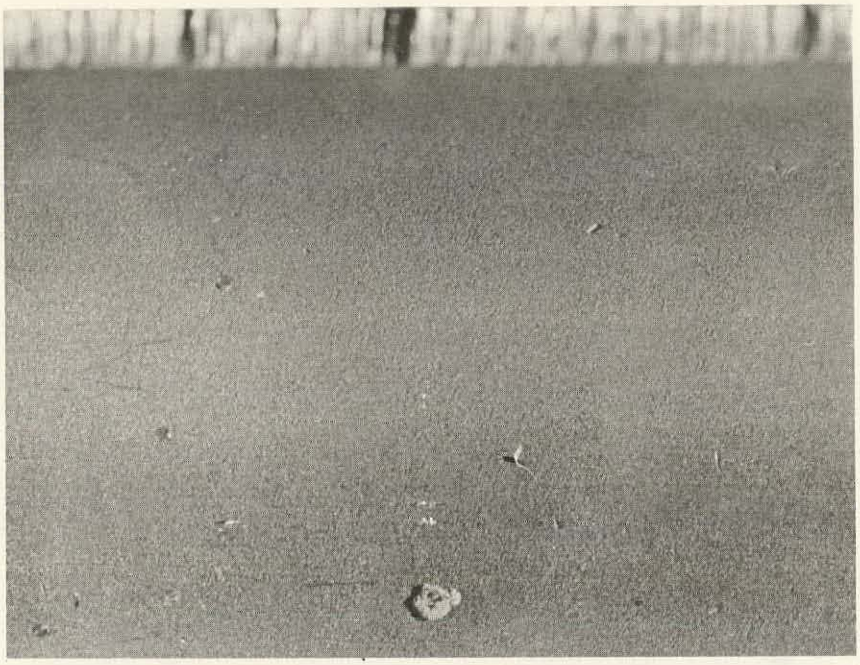


Figure 7. I.D. surface of 3003 Alclad control specimen (no cleaning) after a 3-month exposure. Note pitting corrosion.
4X Magnification. Neg. No. 79196-14

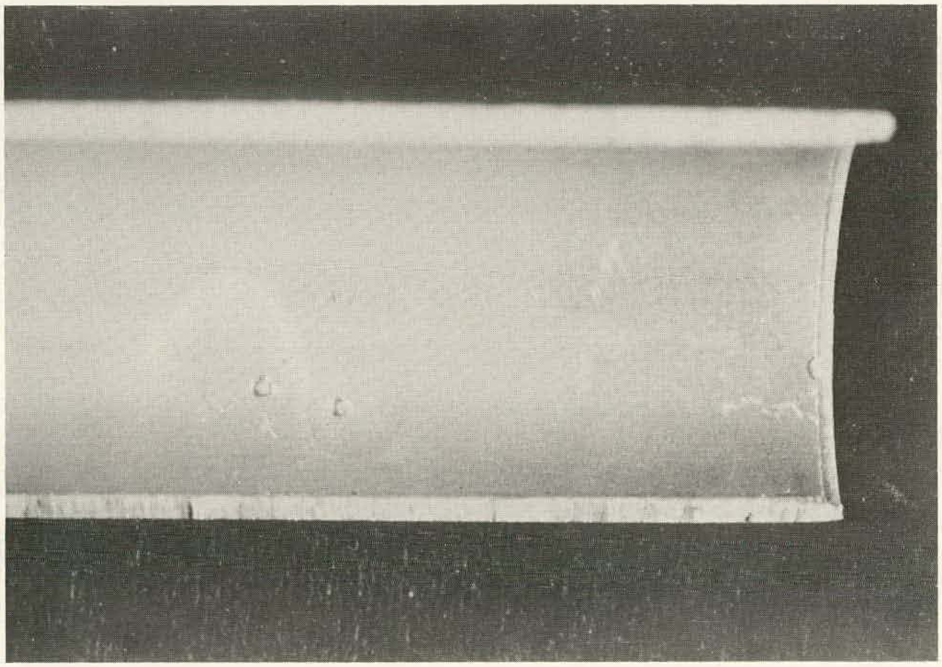


Figure 8. I.D. surface of 3003 Alclad M.A.N. brush cleaned specimen after a 7-month exposure.
2.7X Magnification. Neg. No. S-1840

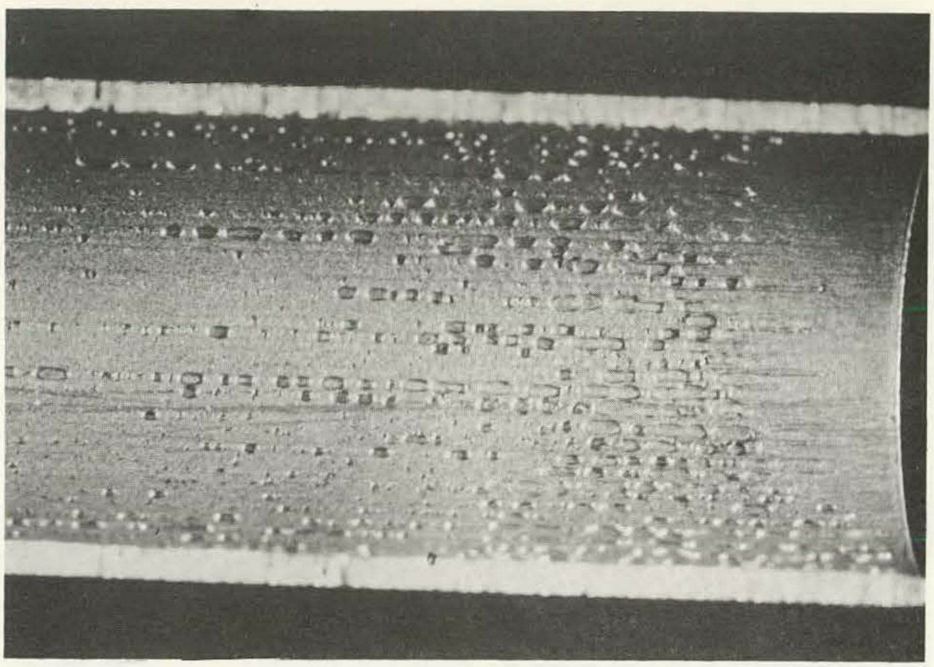


Figure 9. I.D. surface of 3003 Alclad M.A.N. brush cleaned + 0.1 mg/L chlorination specimen after a 7-month exposure. Note erosion-corrosion attack. 2.7X Magnification. Neg. No. S-1842

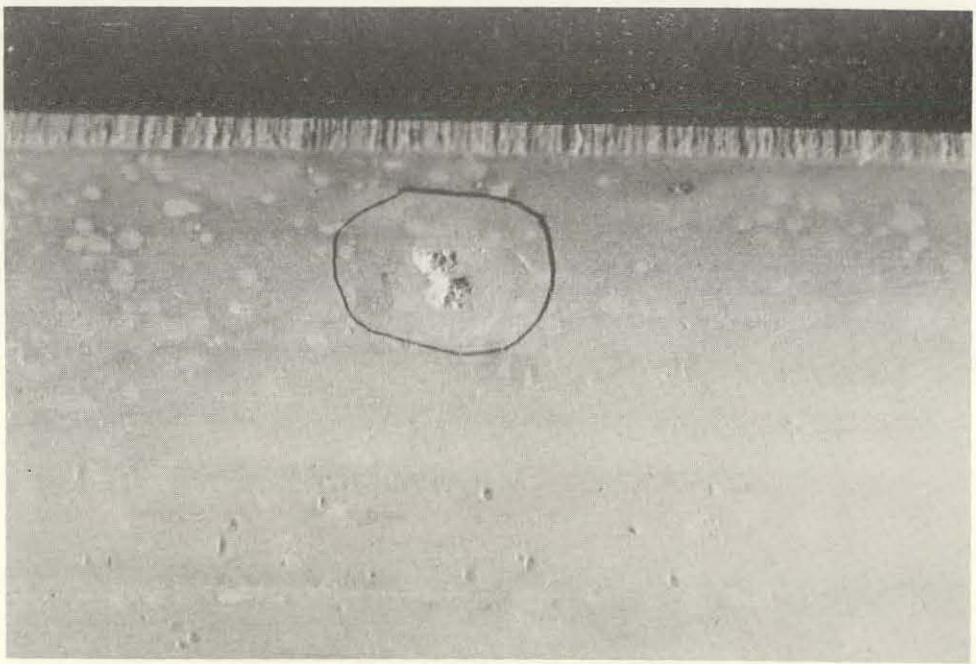


Figure 10. I.D. surface of 5052 aluminum control specimen (no cleaning) after a 7-month exposure. Note pitting corrosion.
3X Magnification. Neg. No. 80166-7

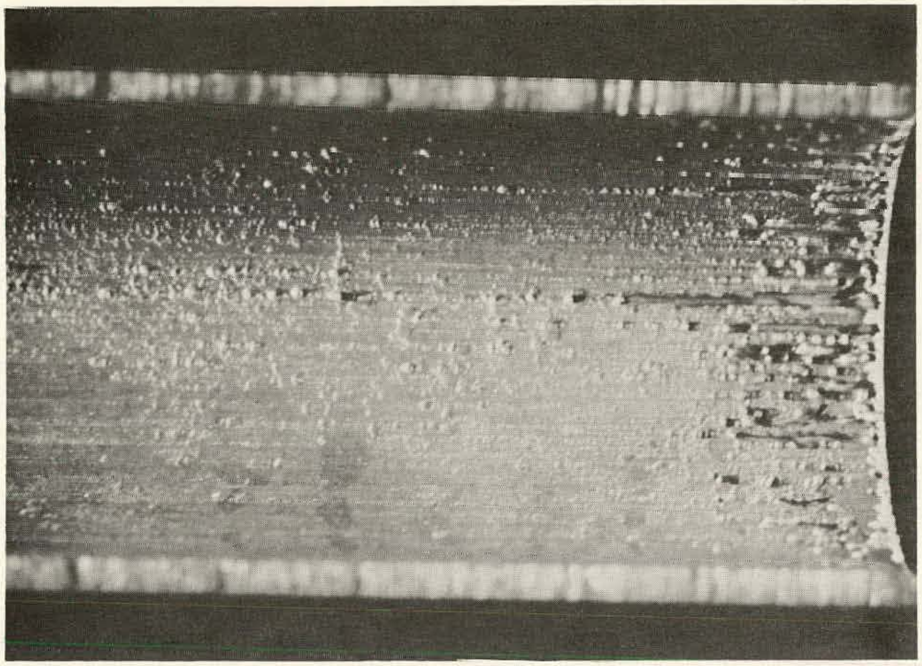


Figure 11. I.D. surface of 5052 aluminum M.A.N. brush cleaned specimen after a 7-month exposure. Note erosion-corrosion attack.
2.7X Magnification. Neg. No. S-1845

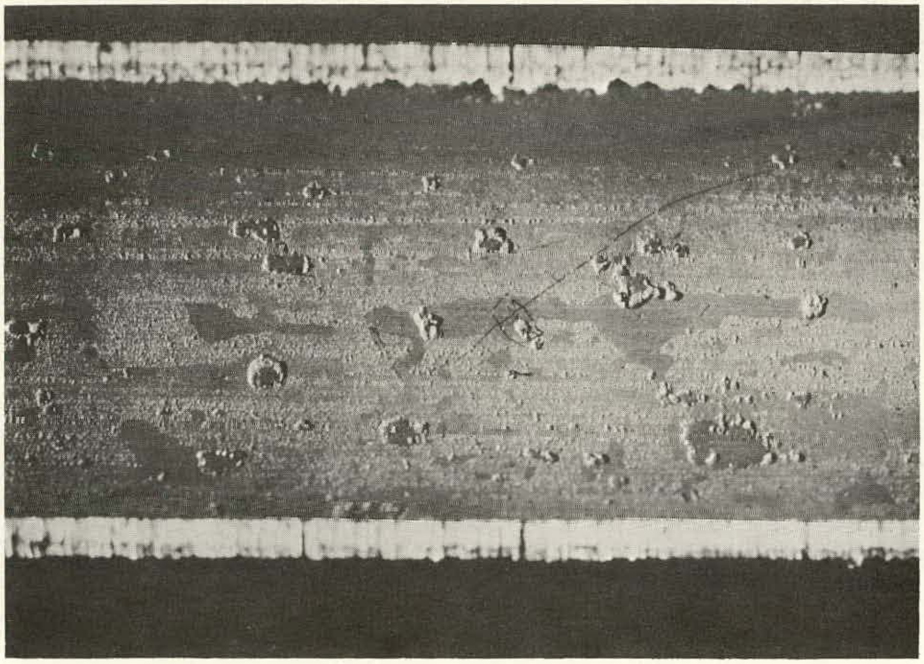


Figure 12. I.D. surface of 5052 aluminum M.A.N. brush cleaned + 0.1 mg/L chlorination specimen after a 7-month exposure. Note erosion-corrosion and pitting attack.
2.7X Magnification. Neg. No. S-1847

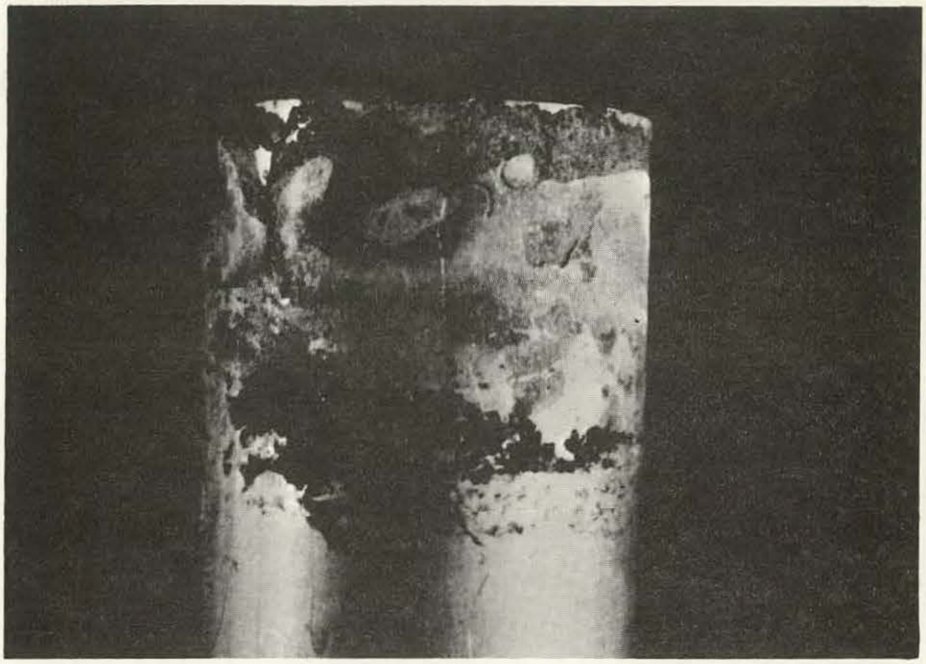


Figure 13. O.D. surface of 5052 aluminum control specimen (no cleaning) after a 7-month exposure, showing crevice corrosion under flexible connector.
2.4X Magnification. Neg. No. S-1844

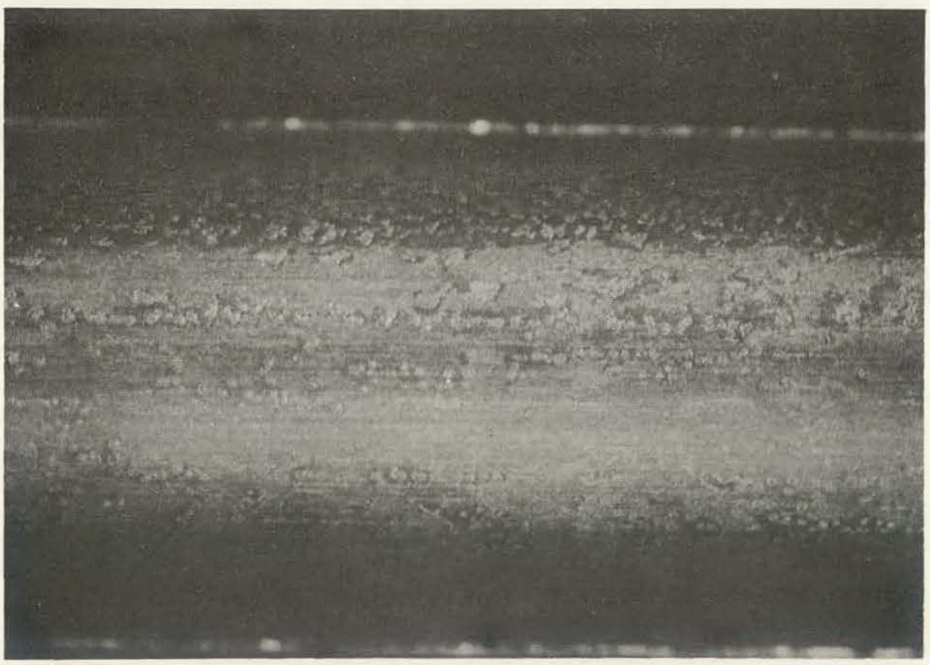


Figure 14. I.D. surface of C70600 control specimen (no cleaning) after a 7-month exposure.
2.8X Magnification. Neg. No. S-1848

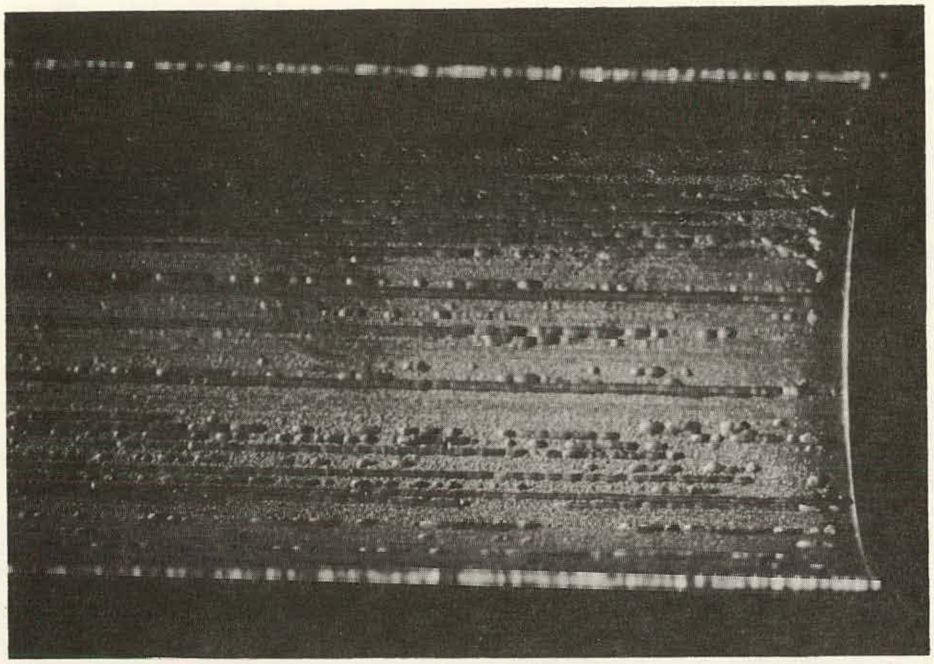


Figure 15. I.D. surface of C70600 M.A.N. brush cleaned specimen after a 7-month exposure. Note erosion-corrosion attack.
2.7X Magnification. Neg. No. S-1849

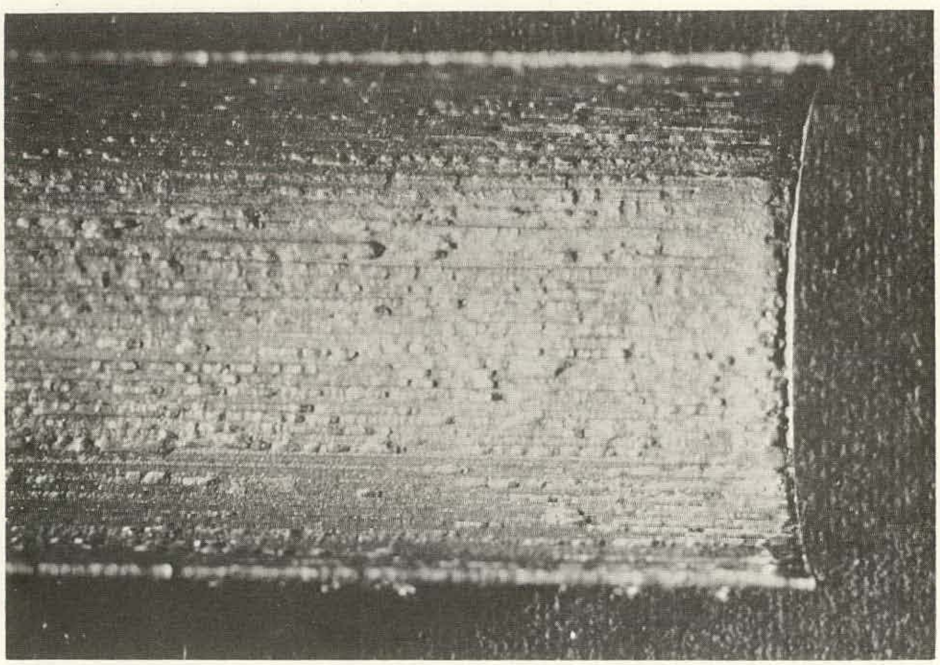


Figure 16. I.D. surface of C70600 M.A.N. brush cleaned + 0.1 mg/L chlorination specimen after a 7-month exposure. Note somewhat less attack than Figure 15.
2.7X Magnification. Neg. No. S-1850

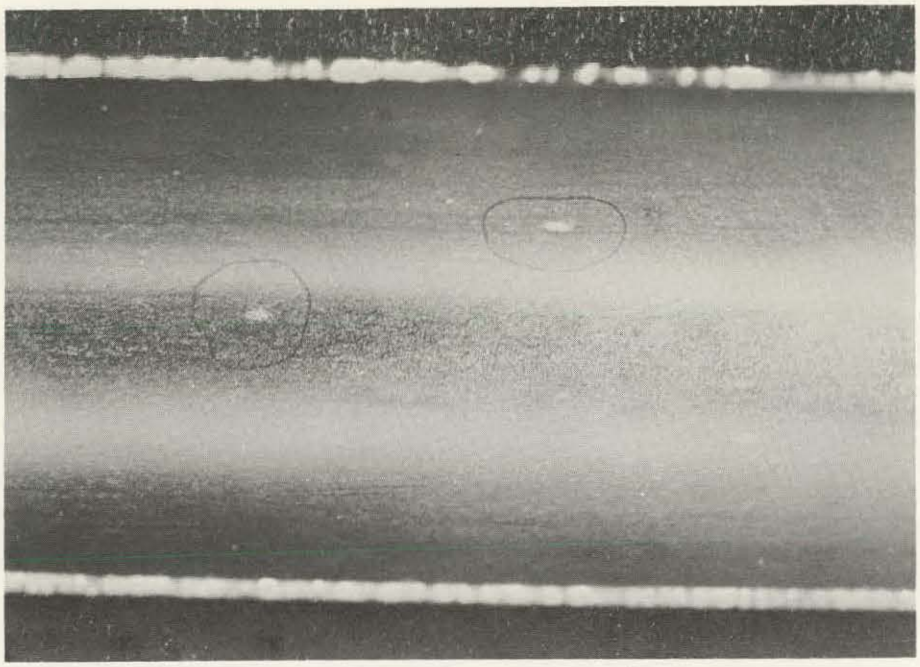


Figure 17. I.D. surface of AL-6X M.A.N. brush cleaned + 0.1 mg/L chlorination specimen after a 7-month exposure, showing typical limited pitting nucleation.
2.7X Magnification. Neg. No. S-1855

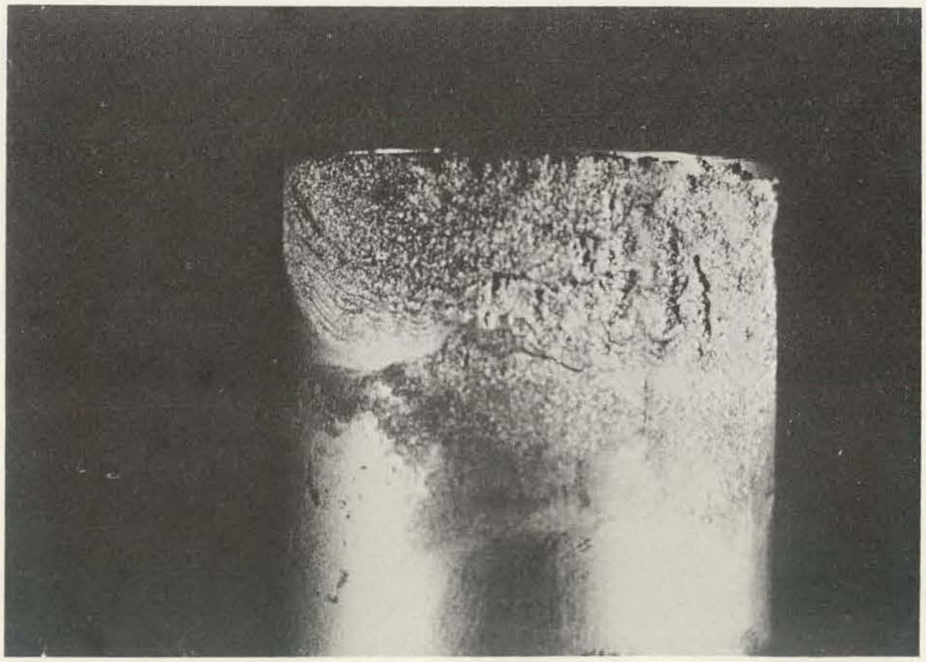


Figure 18. O.D. surface of AL-6X control specimen (no cleaning) after a 7-month exposure, showing severe crevice corrosion under flexible connector.
2.5X Magnification. Neg. No. S-1852

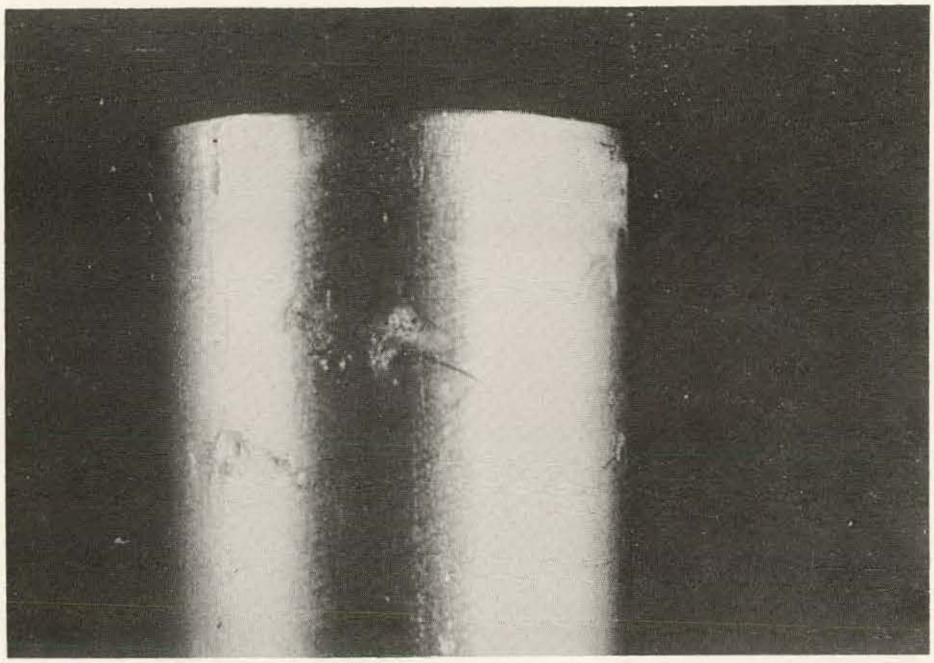


Figure 19. O.D. surface of AL-6X M.A.N. brush cleaned after a 7-month exposure, showing typical crevice corrosion under flexible connector. 2.5X Magnification. Neg. No. S-1854

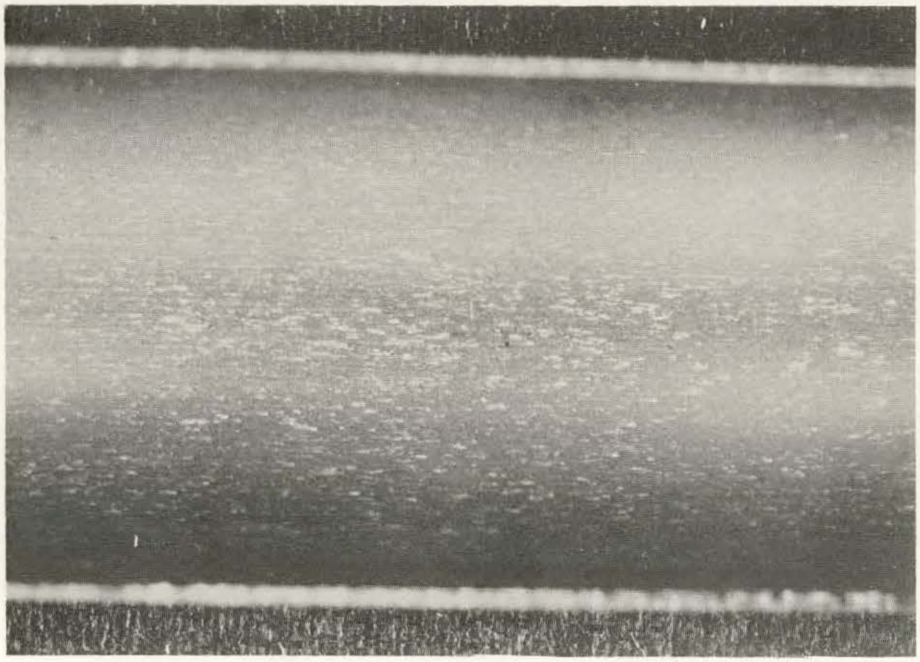


Figure 20. Typical titanium specimen after test exposure. Light areas are pre-existing artifacts and not corrosion attack. 2.8X Magnification. Neg. No. S-1856

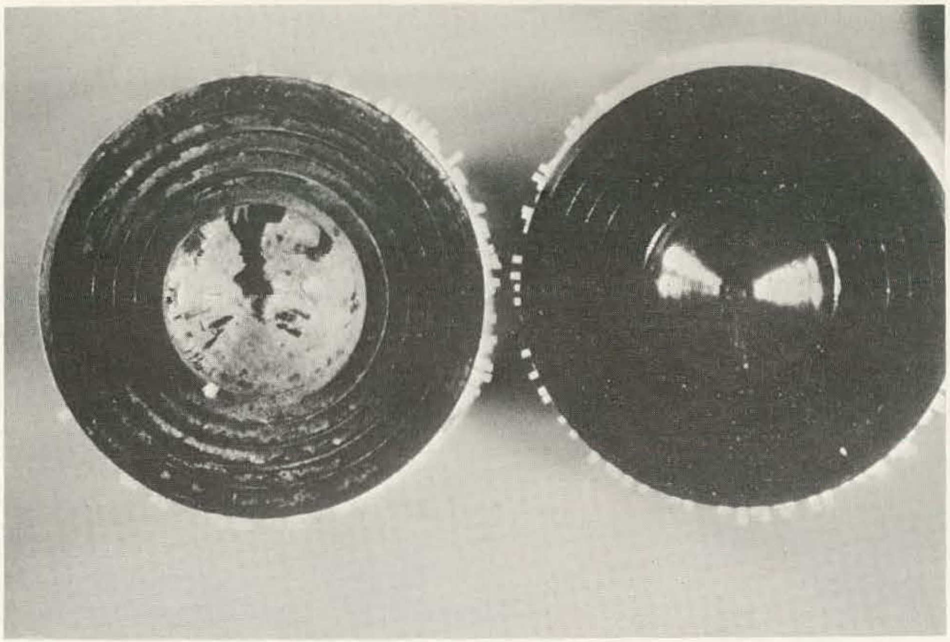


Figure 21. End view of M.A.N. brush from 3003 Alclad loop (no Cl_2) after a 3-month operation (left) and similar unused brush (right).
2.5X Magnification. Neg. No. S-1643

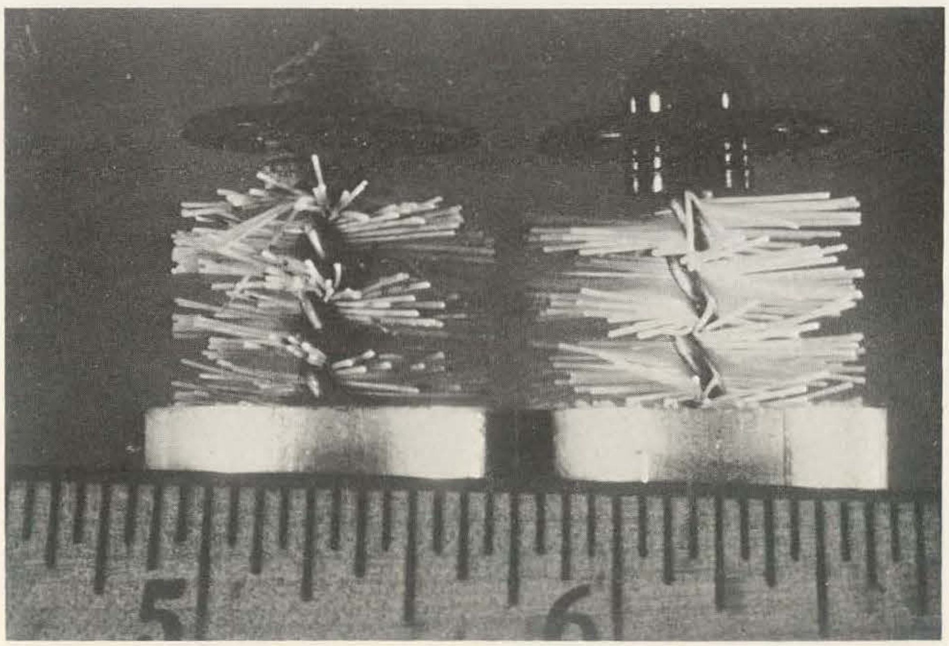


Figure 22. Same as Figure 21 but side view.
2.8X Magnification. Neg. No. S-1644

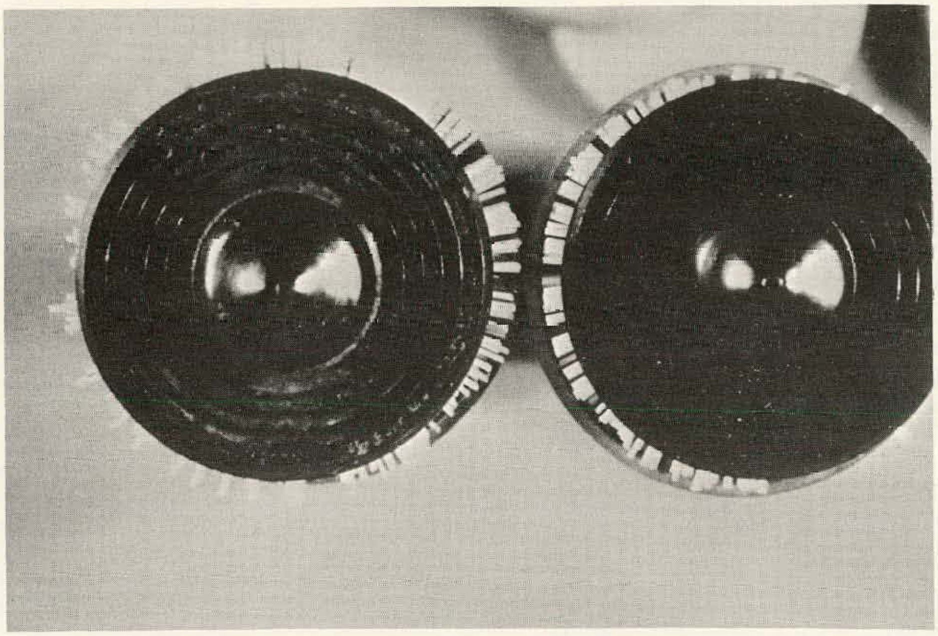


Figure 23. End view of M.A.N. brush from C70600 loop ($no Cl_2$) after 3 months operation (left) and similar unused brush (right).
2.5X Magnification Neg. No. S-1642

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