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Corrosion of Stainless Steel and Aluminum Alloys in Fuming Nitric Acid

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approved by John S. Amneus

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I. INTRODUCTION AND SUMMARY

This investigation was prompted by corrosion problems which arose in rocket motor test installations during the course of propulsion research under Army Air Forces Contract W33-038-ac-14222. A laboratory study of the corrosion of various stainless steel and aluminum alloys by fuming nitric acid has been carried out, together with a critical survey of the literature on this subject. The degree to which actual field experience will substantiate the results of laboratory tests is always questionable; however, the conclusions summarized here should provide at least a starting point for the selection of alloys for fuming nitric acid service.

Laboratory corrosion tests of three months duration were conducted on types 303 (cold-rolled), 316 (cold-rolled), and 347 (forged billet) stainless steels, and on types 2S-0, 3S-0, 17S-T, and 24S-T aluminum alloys. In five series of tests corrosion rates were determined for each alloy under the following conditions, designed to duplicate these encountered at the rocket test facility: continuous exposure to commercial 6 1/2% red fuming nitric acid (RFNA); continuous exposure to both RFNA and its vapor; alternate exposure to RFNA and to dilute acid; alternate exposure to RFNA and to the atmosphere; alternate exposure to RFNA and to the atmosphere after water rinsing.

The results of these experiments, correlated with the best literature data, lead to the following conclusions:

1. Aluminum alloys are definitely superior to stainless steels for long-term continuous exposure or for intermittent exposure at ambient temperature to fuming nitric acid and its vapor. The corrosion rates of aluminum alloys in fuming nitric acid remain fairly constant with time, while those for stainless steels increase.

2. The aluminum alloys 2S-0, 3S-0, 17S-T, 24S-T, Alclad 24S-T, 53S, 61S-T, and 75S-T are practically equivalent in their resistance to fuming nitric acids.

3. Aluminum alloys should never be exposed to dilute nitric acid for any appreciable time, e.g., by draining of fuming nitric acid and leaving in water or air without very thorough rinsing, since aluminum is readily attacked by dilute acid.

4. Types 304 and 347 are the most resistant of the stainless steels to fuming nitric acid. Low carbon 304 is recommended as the better choice in view of current restrictions on columbium needed for 347.

5. Stainless steel for which only intermittent contact with fuming nitric acid is required should be drained and rinsed between exposures.

6. The corrosion resistance of aluminum alloys is practically independent of heat treatment before or after welding. Unwelded stainless steel in contact with fuming nitric acid should be from hot-rolled, fully annealed stock, while welded samples should be heat-treated at 2000° F. and rapidly cooled for maximum corrosion resistance.

7. Red fuming nitric acid is more corrosive than white fuming nitric acid to stainless steel and aluminum alloys. Traces of chlorides, salts of heavy metals, and sulfuric acid promote the attack on these alloys.

II. EXPERIMENTAL

A. Alloys Investigated

Stainless steel types 304, 316 and 347, and aluminum alloys 2S-0, 3S-0, 17S-T, and 24S-T were studied. The 347 sample was cut from a forged billet, while the 303 and 316 were from cold-rolled stock. Samples of 303 and 316 and of 17S-T and 24S-T were cut from round bar stock and given a smooth machine finish. Samples of 2S-0 and 3S-0 were cut from 1/8" sheet. None of the samples received further surface treatment.

Commercial 6 1/2% RFNA was used in all tests.

B. Testing Procedures

Five series of tests were conducted for a period of three months. Series I and II simulated conditions in drums or other containers totally or partially filled with RFNA. The cycles in Series III, IV, and V were designed to show whether parts of the rocket motor facility which must be exposed intermittently to RFNA should be drained and left in air or drained, rinsed and left in air or water during the periods between exposures to acid.

Series I: The samples were immersed continuously in RFNA.

Series II: Approximately half the surface area of each sample was immersed in RFNA, the remainder being exposed to the acid vapor.

Series III: The samples were immersed in RFNA during the first phase of each cycle. After determining weight loss, the samples were immersed momentarily in RFNA, dipped quickly into water, and all placed together but not touching each other, in 100 ml. water (actually dilute acid because of incomplete rinsing of samples). The samples were reweighed at the end of each phase. Eleven cycles involving phase times of one to ten days were completed.

Series IV: The samples were immersed in RFNA during the first phase of each cycle. After weighing, the samples were redipped in RFNA, incompletely rinsed by a quick dip in water, and left in air. Eleven cycles were completed.

shiny appearance for about four days. At the end of twelve days all three samples were covered with a shiny black film. After thirty-three days, the surfaces of 303 and 347 were becoming slightly rough, while 316 was already very rough. After 50 days the weight loss of the 316 sample amounted to nearly 50%, and it could not be dried without rubbing large particles from the surface; hence the test on this sample was discontinued. At the end of three months, the 303 sample had lost 30% of its original weight, and the surface showed very serious attack.

After one day in RFNA the aluminum samples bore vari-colored tarnishes, the colors changing and darkening with time. After three months the 2S-O and 3S-O were a dull grey, while the 17S-T and 24S-T were dull black. Slight pitting was apparent.

Series II: After twelve days exposure to RFNA and its vapor, each steel sample had darkened slightly and uniformly, and a week later all were black. The surfaces were noticeably rough after thirty-six days, the roughness increasing thereafter and becoming particularly bad in the case of the 316 sample.

The aluminum samples bore vari-colored tarnishes after one day. The colors deepened and at some weighing periods were darker on that part of a sample immersed in the acid. At the end of three months, the 2S-O, and 3S-O were dull grey, the 17S-T and 24S-T dull black. During the first few days of the tests, white crystals assumed to be $Al(NO_3)_3 \cdot 9H_2O$ formed on the vapor-exposed surface of each sample. Slight pitting occurred. No preferential attack at liquid-vapor interfaces was apparent on either the steel or aluminum samples.

Series III: The steel samples were still clean after one cycle, but started to darken after the second exposure to RFNA and were completely black after the fourth exposure to the acid. All had rough surfaces after thirty-six days, the 316 sample deteriorating most rapidly so that the test on it was discontinued after seventy-five days.

As in all the other series, the aluminum samples were tarnished after one day in RFNA and heavily tarnished after three months. During exposure to dilute acid in one of the later cycles, Series V: The samples were immersed in RFNA during the first phase of each cycle. After weighing, they were redipped in RFNA and left in air. They were reweighed at the end of this phase. Eleven cycles were completed.

At the start of the tests the samples, measuring 1/2" x 1/2" x 1/8", were washed with acetone, dried, and weighed. One sample of each alloy was included in each series. During the first ten days of testing, individual samples were immersed continuously or at intervals, as described above, in 7-8 ml. RFNA contained in 30 ml. test tubes. The test tubes were closed with rubber stoppers protected by aluminum foil. Thereafter, all samples of a given test series were immersed together, continuously or at intervals, in 75 ml. RFNA in a 250 ml. glass-stoppered Erlenmeyer flask, taking care that the samples did not touch each other. The acid was changed at approximately weekly intervals. No effort was made to control the temperature, ambient temperature varying in the range 50° - 100° F. and averaging about 80° F.

Weight losses of the samples in Series I and II were determined at intervals of one to ten days. Each sample was rinsed quickly and thoroughly with water and dried and rubbed with a chamois before weighing.

C. Experimental Results

1. Calculations

Average corrosion rates for the three months period were calculated in inches per month (ipm) for the samples in Series I and II. Average corrosion rates were calculated for each phase of the testing cycle for samples in Series III-V. These rates are given in Table I. Corrosion rates in ipm calculated for the intervals between weighings (i.e., the phase times in Series III-V) are plotted for the five series in Figures 1-10.

2. Physical Appearance of Test Samples.

Series I: The sample of 316 steel had started to blacken after one day in RFNA, while 303 and 347 retained their original the 3S-0 sample was deeply but smoothly corroded at one corner (see Figure 11), suggesting that electrochemical action had resulted from its accidently touching another sample.

Series IV: The appearance of both the steel and aluminum samples was essentially the same as in Series III. The 316 sample was removed from the test after seventy-five days. In many cases, the tarnish on the aluminum samples lightened during exposure to air and darkened again in acid.

Series V: The appearance of the steel samples was similar to that in Series III. The 316 sample was removed from the test after seventy-five days. The aluminum samples were tarnished after exposures to acid, but in general regained silvery satin finishes during exposure to air. Crystals like those observed in Series II formed on the surfaces of the 2S-0 and 3S-0 samples during exposure to air.

The appearance of all the steel and aluminum samples at the beginning and at the end of the test period is shown in Figure 11.

3. Comparison of Alloys Tested.

a. Steels. The 303, 316, and 347 stainless steel samples showed no significant differences in corrosion resistance for about the first two weeks. Thereafter until the conclusion of three months testing, the 347 samples were definitely superior to the other two types under all test conditions. Samples of each steel exhibited considerably smaller corrosion rates when exposed simultaneously to both liquid RFNA and its vapor (Series II) than when exposed to liquid RFNA alone. There was a general tendency in both the continuous exposure and the cyclic tests for corrosion rates in RFNA and its vapor to increase with time, this tendency being least pronounced with the 347 and most serious with the 316 samples.

The corrosion rates of the steel samples during the RFNA phases of the cycling tests were of the same order of magnitude as those of samples exposed continuously to RFNA. Corrosion rates in the alternate phases, i.e., water after rinsing in Series III, air after rinsing in Series IV, and air without rinsing in Series V, were much smaller than in RFNA. The cycle RFNA-rinse-water of Series III was least corrosive for the 303 and 316 samples, while for the 347 samples the RFNA-air cycle of Series V was just as good as RFNA-rinse-water.

b. Aluminum Alloys. The 2S-0, 3S-0, 17S-T, and 24S-T alloys investigated were considerably superior to the stainless steels in their resistance to RFNA and its vapor. The corrosion rates of samples exposed simultaneously to both liquid and vapor were higher by 4-6% than those of samples exposed to liquid RFNA only. Differences among the four alloys in the various tests were small, the 17S-T being slightly more resistant to liquid RFNA than the others while the 24S-T suffered the greatest attack.

When the aluminum alloy samples were taken from RFNA and left in air or rinsed and left in water or air, their corrosion rates increased on the average about five-fold. This was to be expected, since it is well known that aluminum is attacked by dilute nitric acid.

III. DISCUSSION OF LITERATURE DATA

A. Selection of Data

Published data concerning the corrosion resistance of steel and aluminum alloys to red and white fuming nitric acids are scattered and incomplete. Those tabulated in Tables II to XX in the Appendix of this report have been critically selected from the chemical literature, from classified reports available to us, and from private communications from several steel and aluminum companies.

Comparison of data from different sources is difficult because of the large number of factors which influence experimentally determined corrosion rates. One of the most important considerations in the evaluation of data was the length of test periods. Tests covering a few hours or a few days may be necessary and valid in certain cases, e.g., in tests conducted at high temperatures. However, the present investigation has shown that in the case of the corrosion of stainless steels by RFNA at ambient temperature, the corrosion rates suddenly start to climb after about two weeks exposure and increase with time thereafter up to ninety days. Furthermore, tests of 32 months duration conducted by the Allegheny Ludlum Steel Corporation revealed several definite breaks in the corrosion rate vs. time curves for types 304 and 347 stainless steel[1]. For this reason corrosion rates for steels in RFNA calculated from the results of e.g. forty-eight hour tests at ambient temperature have significance for that period only and cannot be used validly for predictions about longer periods. Other factors which must be considered in interpreting corrosion data include heat treatment of the sample, presence of welds and treatment after welding, stresses in the sample, preparation of the test surface, ratio of edge length to surface area of the sample, presence of impurities in the corroding agent, and the temperature at which the tests are conducted.

B. Effect of Heat Treatment and Welding on Corrosion Resistance

There seems to be almost general agreement that both welded and non-welded stainless steels, except perhaps for the columbium stabilized type 347, require "proper" heat treatment in order to exhibit maximum corrosion resistance to fuming nitric acid. Apparently this conviction is based mainly on practical experience, since it is not borne out in some cases by the meager data available from laboratory studies. The following results summarize various laboratory tests lasting from three to eight months:

Corrosion rates in 95% and 99% WFNA of type 430 steel which, after welding, had been heated two hours at 1425° F., furnace-cooled to 1200° F., and then air cooled, were lower by 3-35% than those of welded, non-heat treated 430. (Sands[2], Table X.)

Corrosion rates in 99% WFNA of welded samples of type 304 steel which had been heated fifteen minutes at 1925° F. and air cooled were lower by 15% than those of welded, non-heat treated samples, but in 93% WFNA this heat treatment was of no advantage. (Sands[2], Table II.)

Welded, non-heat treated type 304 steel did not exhibit significantly higher corrosion rates than non-welded, annealed (conditions unspecified) 304 in either RFNA or WFNA at ambient temperature or at 120° F. However, the average corrosion rates of welded type 304 which had been held at 1650° F. for twenty-four hours and air cooled were about six times higher than those of welded, non-annealed 304 in RFNA and WFNA at ambient temperature, and about twice as high at 120° F. (M. W. Kellogg Company[3], Tables IV and V). Several other stabilizing treatments at 1650° for shorter periods with various methods of cooling were no more successful in reducing corrosion (Carnegie-Illinois Steel Corporation[4]).

Heating type 347 steel for 15 minutes at 1925° F. and air cooling resulted in an average 7% increase in corrosion rates in 95-99% WFNA at 130°, as compared with welded, non-heat treated 347 (Sands[2], Table VII).

The corrosion rate of welded, non-annealed type 347 in RFNA at ambient temperature was slightly higher than that of annealed (conditions unspecified) 347 containing no weld. However, the rates for welded, non-annealed samples were lower in WFNA at ambient temperature and in RFNA and WFNA at 120° F. than the rates for non-welded samples (M. W. Kellogg Company[3], Tables VIII and IX).

The M. W. Kellogg Company[3] found that cold-working of stainless steel caused a serious increase in corrosion rates in fuming nitric acid, particularly if some heat was required as in bending stainless steel pipe. In such a case, solution treatment for fifteen minutes at 2000° F. was recommended.

On the basis of these scattered data and the experience of the Carnegie-Illinois Steel Corporation[4], heat treatment of stainless steels after welding appears more likely to cause a decrease rather than an increase in corrosion resistance, unless the heat treating is done at about 2000° F., followed by rapid cooling. In the latter case the chances of increasing corrosion resistance seem to be considerably better. Unwelded stainless steel in contact with fuming nitric acid should be from hot-rolled, fully annealed stock.

According to Sands[2], corrosion of heat-treated steel samples is largely confined to the edges. He suggests that this may account for some variation between plant and laboratory experience, since drums and welded containers do not have edges exposed to attack. Excessive corrosion at edges and corners was not observed in the present tests on types 303 and 316 steel cut from cold-rolled bar stock, or on type 347 cut from a forged billet.

Aluminum alloys, welded or non-welded, appear not to require heat treatment before exposure to fuming nitric acid. Heat treatment is not particularly detrimental to corrosion resistance, however. These conclusions follow from the data for 2S, 3S, and Alclad 24S-T alloys in Tables XII-XIV and XVI-XVIII. Localized corrosion around welds in aluminum alloys has not been observed.

C. Effect of Acid Composition on Corrosion Resistance

Few data have been found in the literature which will permit reliable direct comparison of the corrosive action of 6.5% RFNA, 16% RFNA, and WFNA on stainless steel and aluminum alloys. Kaplan and Andrus[5] state that corrosion rates are not significantly different in these acids, although other sources indicate, without furnishing data, that WFNA is less corrosive than the red fuming acids.

The M. W. Kellogg Company[3] reports the following: For types 304 and 347 steel, WFNA and RFNA (of unspecified compositions) are about equally corrosive at ambient temperature (Tables IV and V, VIII and IX). At 120° F. corrosion rates of these steels are about two to four times as high in RFNA as in WFNA, depending on the presence of welds and heat treatment of the samples. For 2S-O and Alclad 24S-T aluminum, corrosion rates in RFNA are about 1.5 times those in WFNA at ambient temperature. At 120° F. the rates in RFNA are usually slightly smaller than those in WFNA (Tables XIII and XIV, XVII and XVIII).

Sands[2] shows that stainless steels (Tables II, III, VI, VII, and X) are generally more susceptible to attack by 97-99% WFNA than by 93-95% WFNA, while aluminum (Tables XII and XVI) is slightly more resistant to attack by the more concentrated acid. It is also apparent from these tables that the vapor phase of WFNA is generally more corrosive to both stainless and aluminum alloys than is the liquid phase. In the present investigation, the aluminum alloys were more severely attacked by the vapor of RFNA than by the liquid acid; however the liquid RFNA was more corrosive than the vapor to the stainless steel samples.

Little is known concerning the accelerating or decelerating effects of impurities in fuming nitric acids on corrosion rates. According to Seligman and Williams[6], up to 0.05% chloride in the acid has no effect on the corrosion of aluminum, while traces of sulfuric acid promote the attack. Chlorides and salts of heavy metals in fuming nitric acids have been mentioned as harmful to aluminum[7] as well as to stainless steel, while traces of sulfuric acid also increase the corrosion of stainless steel[4]. Kaplan and Andrus found in 3-7 hour tests, however, that at 250-300° F. both aluminum and stainless steel are attacked much less severely by an 88-12 mixture of WFNA and fuming sulfuric acid ("mixed acid") than by RFNA[5,8].

D. Effect of Temperature on Corrosion Resistance.

The corrosion rates of both stainless steel and aluminum alloys in fuming nitric acid increase with increasing temperature, but few quantitative data concerning the temperature effect are available. Results of the M. W. Kellogg Company[3], summarized in Tables IV and V, VIII and IX, indicate that increasing the temperature from ambient to 120° F. causes the corrosion rates of types 304 and 347 steel to increase about twice as much in RFNA as in WFNA. On the other hand, the corrosion rates of 2S-0 and Alclad 24S-T aluminum increase about equally in RFNA and WFNA for the same temperature increase (Tables XIII and XIV, XVII and XVIII).

Corrosion rates for type 304 stainless steel and 2S and 3S aluminum alloys kept in 93% and 99% WFNA for ninety days at 90°, 110° and 130° F. are given in Tables III, XII and XVI as reported by Sands. The rates show an average two-fold increase for each 10° rise in temperature over this range. If this rate of increase were assumed to hold with RFNA up to e.g. 270° F., corrosion rates of the order of 10-100 ipm might be expected at this higher temperature. However, rates amounting to only 0.06-0.6 ipm were obtained by Kaplan and Andrus[5,8] for 304 and other stainless and aluminum alloys from tests in RFNA lasting three to seven hours at 250-300° F. (Table XI). Moreover, there is evidence that at this temperature corrosion is most severe during the first few hours of exposure, so that longer test periods would show lower average corrosion rates: Kaplan and Andrus calculated rates of 0.1 and 0.06 ipm for 304 stainless steel from tests of 3.3 and 6.6 hours respectively.

E. Recommended Alloys

The quantitative experimental data which are collected in the Appendix of this report, together with actual field experience reported by various handlers of fuming nitric acids; e.g., E. I. duPont de Nemours and Company[9], indicate that types 304 and 347 are the most resistant of the stainless steels to these acids. Low carbon 304 (carbon 0.03% maximum instead of 0.08% maximum) has been reported[4] to be more corrosion resistant than ordinary type 304 and is recommended[4,7] as the best choice for fuming nitric acid service, particularly in view of current restrictions on the columbium needed for 347.

Aluminum alloys in general are more satisfactory for service in fuming nitric acid than are the stainless steels. According to data available, there is little choice among the types 2S-O, 3S-O, 17S-T, 24S-T, Alclad 24S-T, 53S, 61S-T, and 75S-T as far as corrosion resistance is concerned.

ADDENDUM - JUNE, 1951

No reliable exhaustive study of corrosion by fuming nitric acid has been carried out. The conclusions reached in this report were based on our own simple laboratory tests and on the best published data available to us in January, 1951. These conclusions are not altered by the following additional information brought to our attention since that time:

1. M. W. Kellogg Company Report SPD 121, Appendix E, March 19, 1948.

2. Progress Reports 1 through 4, dated May 31, August 21, October 6, and December 11, 1950, by the Ohio State Research Foundation, Columbus, Ohio, on "Investigation of Materials for Handling Fuming Nitric Acid". It is suggested that Dr. M. G. Fontana, supervisor of this project, be contacted for possible further information.

In contrast to aluminum alloys, the corrosion resistance of stainless steels to fuming nitric acid is greatly dependent on welding and heat treatment processes. It is possible that some suitably heat-treated stainless steels may be nearly as corrosion resistant as aluminum alloys, but the fact that the heat treatment is critical cannot be over emphasized.

As stated in this report, scattered laboratory tests have shown that white fuming nitric acid is less corrosive than red fuming nitric acid. However, experience at our rocket test facility indicates the reverse to be the case. We are now duplicating with the white acid the laboratory tests which we conducted with the red acid.

The possibility of galvanic corrosion resulting from the coupling of dissimilar materials must always be given serious consideration. For instance, recent experience at our rocket test facility shows that aluminum immersed in fuming nitric acid in contact with certain stainless steels is rapidly corroded.

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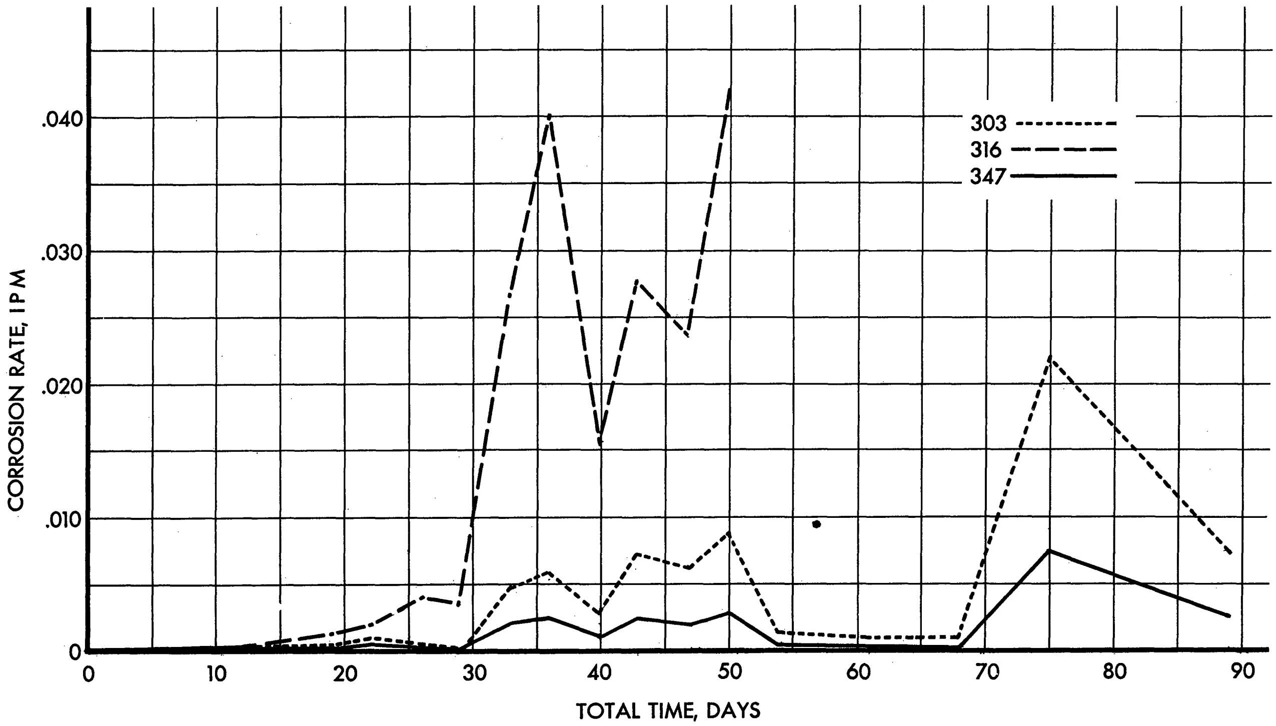

FIG. 1 SERIES I: CORROSION OF STAINLESS STEELS
Continuous exposure to 6.5% RFNA

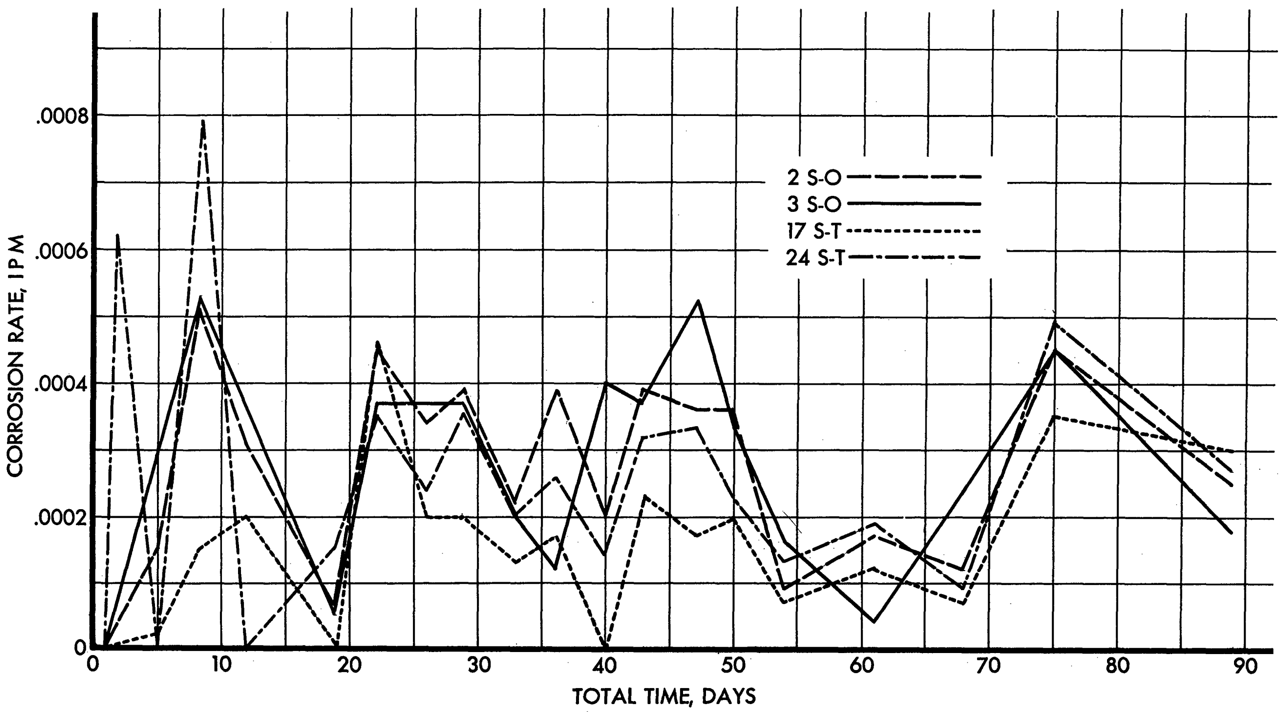

FIG. 2 SERIES I: CORROSION OF ALUMINUM ALLOYS
Continuous exposure to 6.5% RFNA

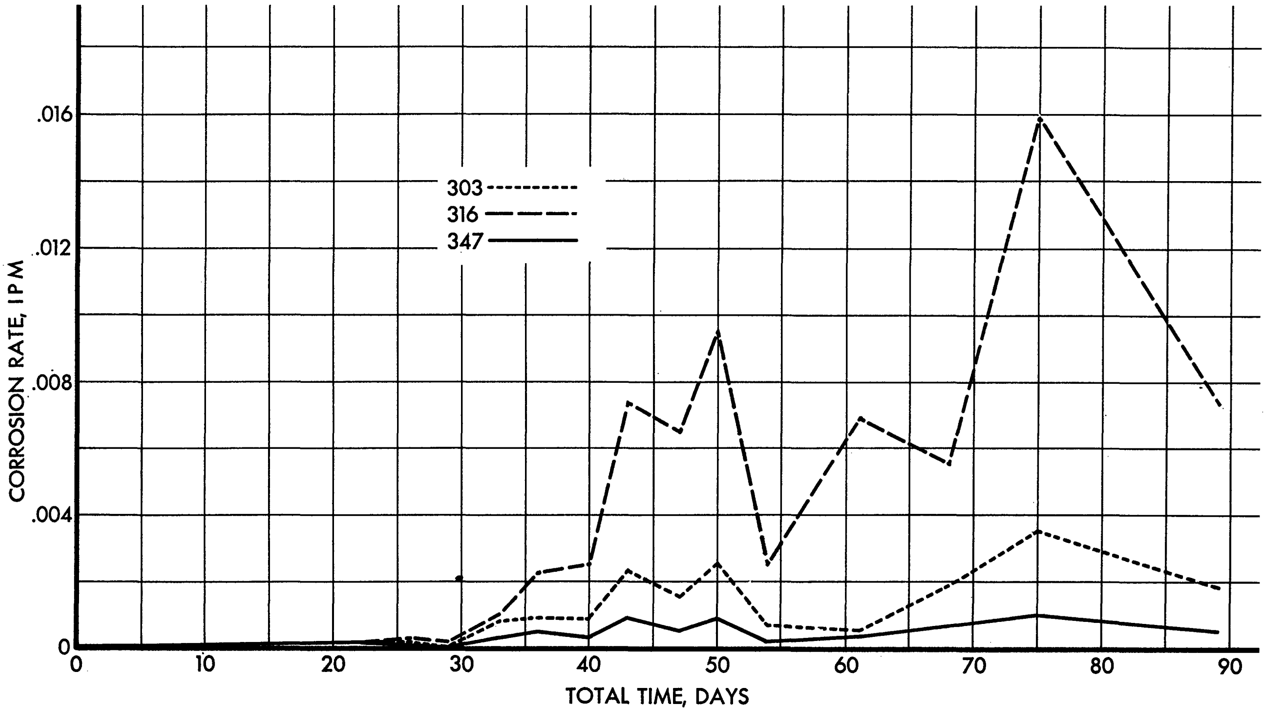

FIG- 3 SERIES II: CORROSION OF STAINLESS STEELS
Continuous exposure to both liquid and fumes of 6.5% RFNA

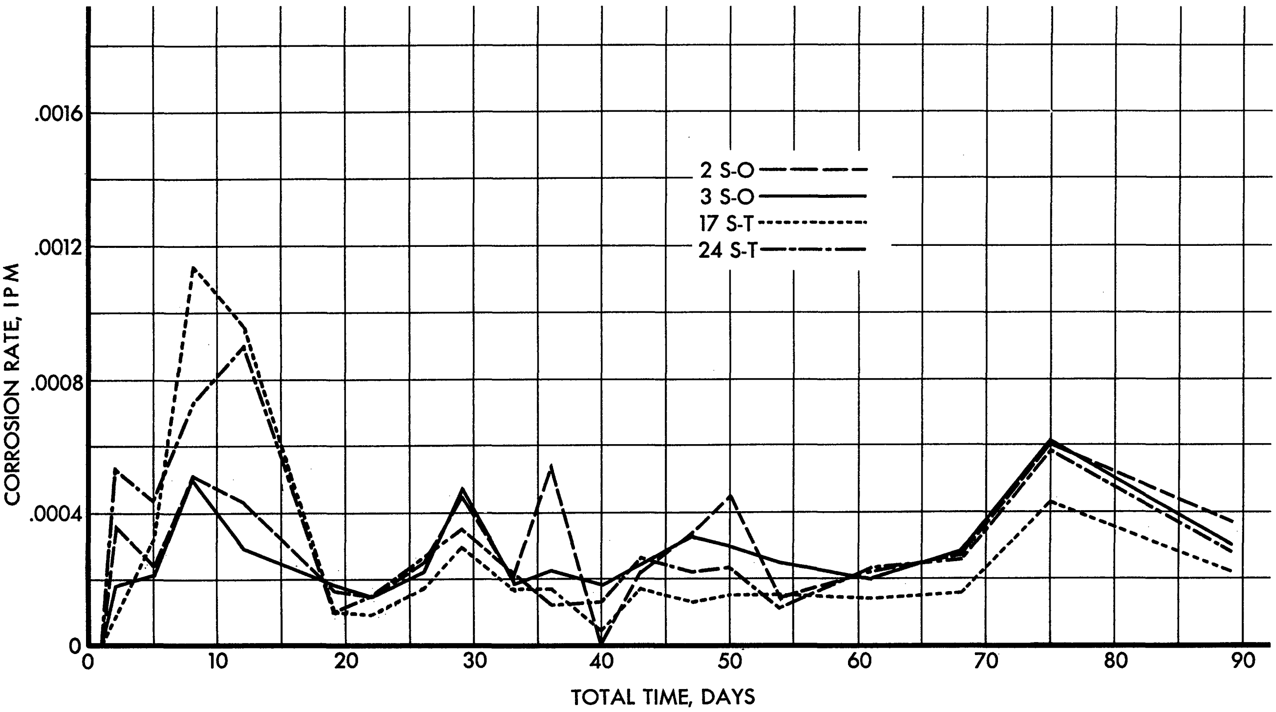

FIG. 4 SERIES II: CORROSION OF ALUMINUM ALLOYS
Continuous exposure to both liquid and fumes of 6.5% RFNA

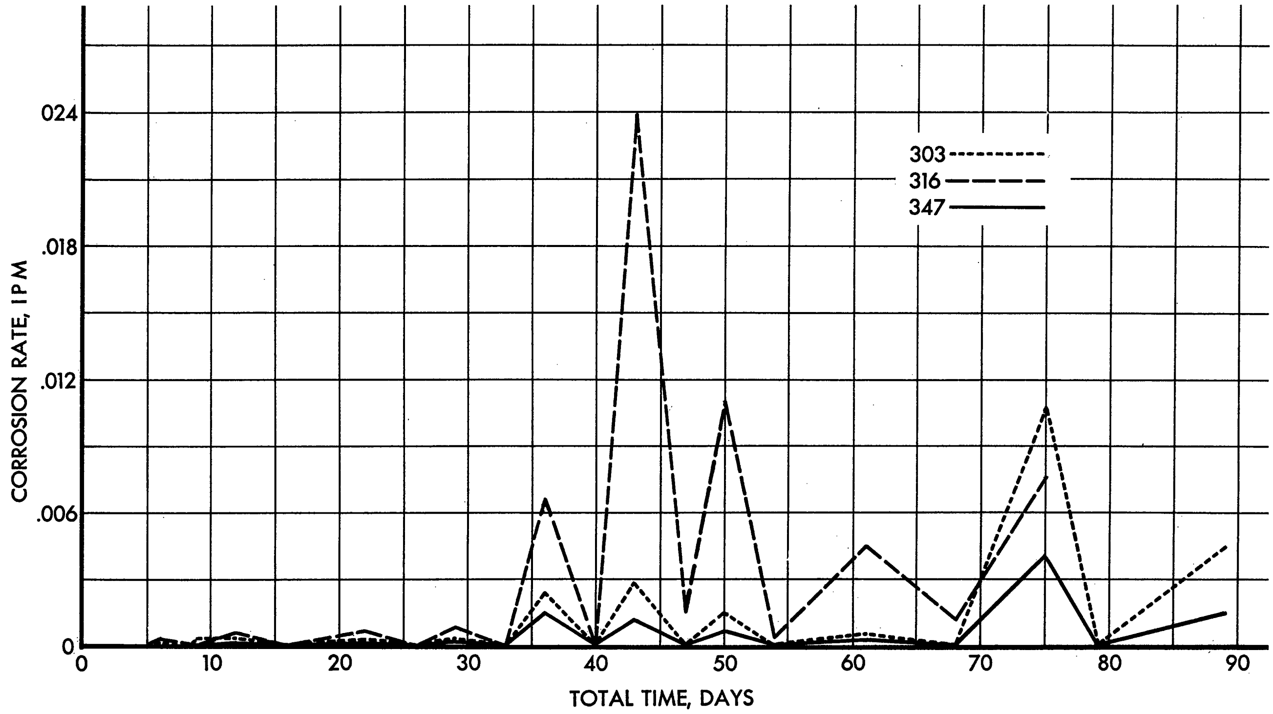

FIG. 5 SERIES III: CORROSION OF STAINLESS STEELS
Alternate exposure to 6.5% RFNA and
dilute HNO_3 (Higher rates in RFNA)

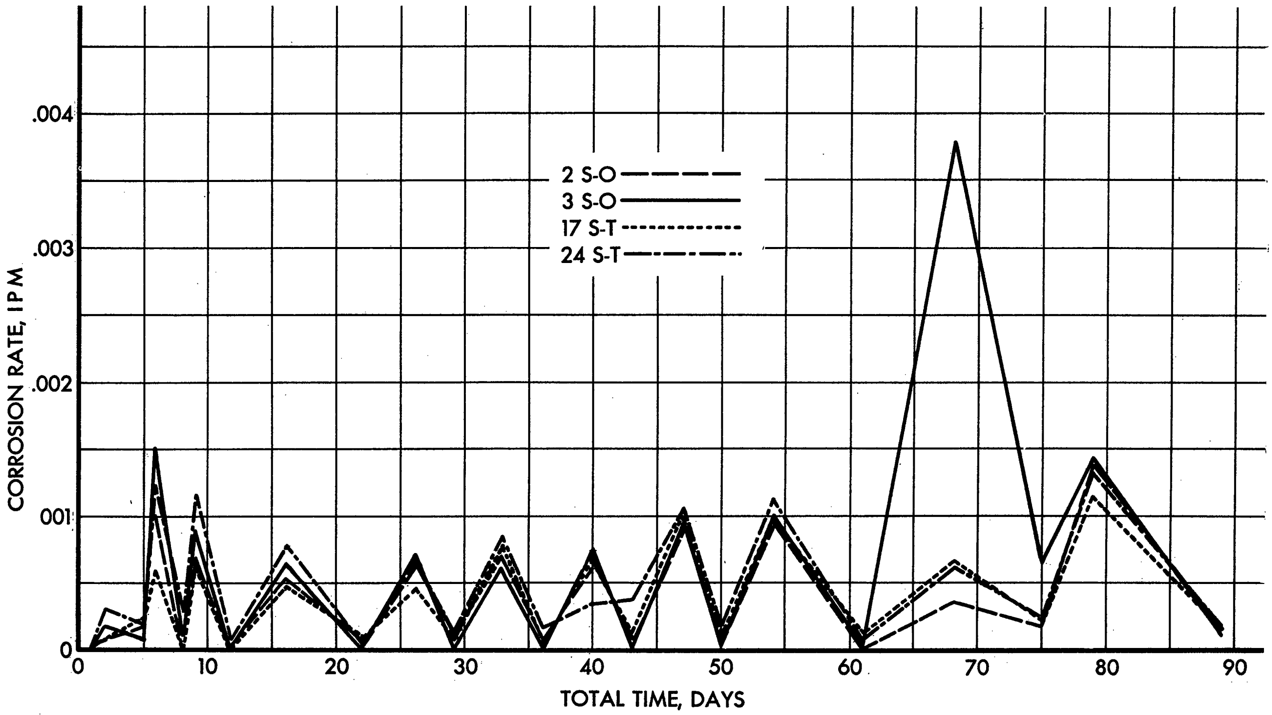

FIG. 6 SERIES III: CORROSION OF ALUMINUM ALLOYS
Alternate exposure to 6.5% RFNA and
dilute HNO_3 (Higher rates in dilute acid.)

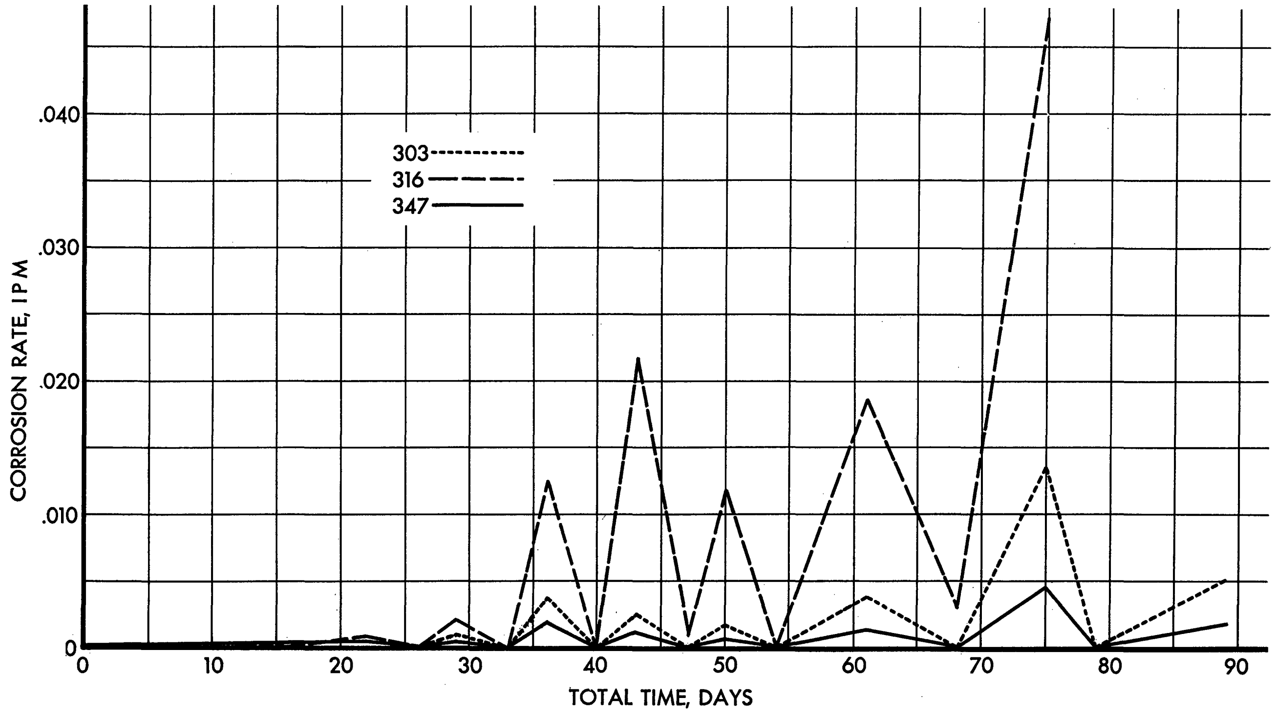

FIG. 7 SERIES IV: CORROSION OF STAINLESS STEELS
Alternate exposure to 6.5 RFNA and to air
after water rinse (Higher rates in RFNA.)

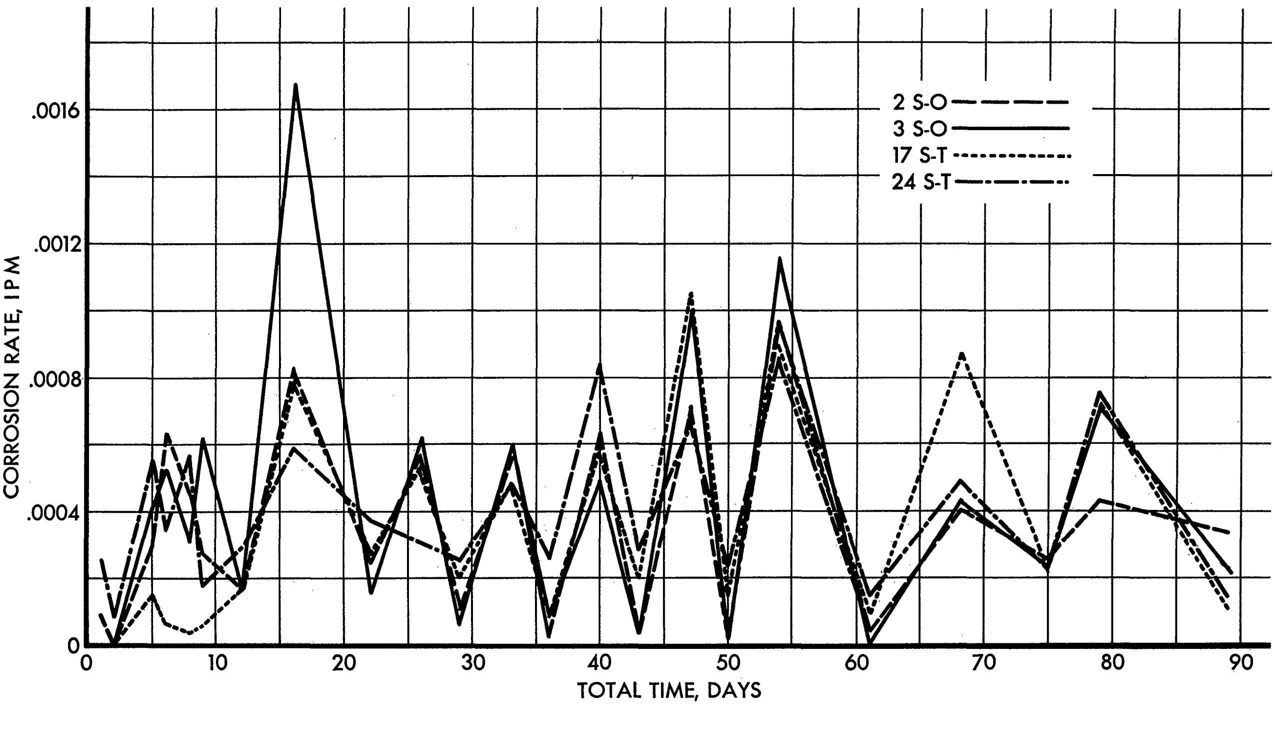

FIG. 8 SERIES IV: CORROSION OF ALUMINUM ALLOYS
Alternate exposure to 6.5% RFNA and to air
after water rinse. (Higher rates in air)

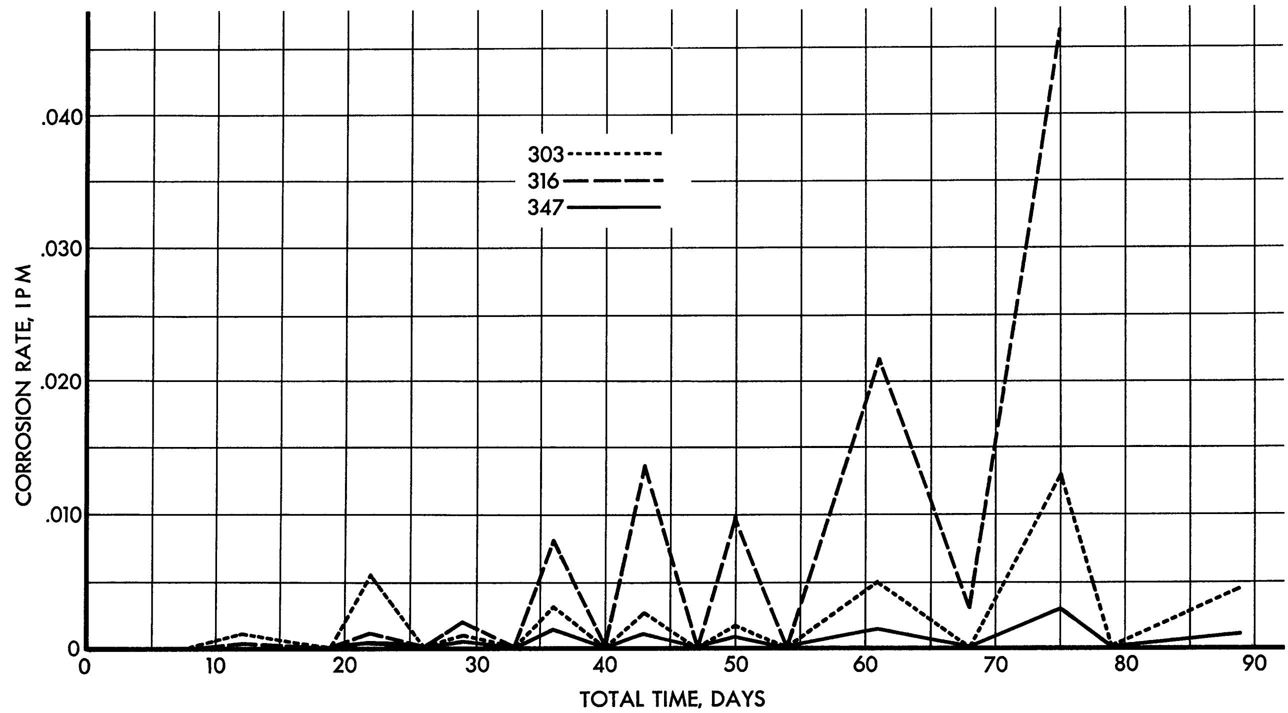

FIG. 9 SERIES V: CORROSION OF STAINLESS STEELS
Alternate exposure to 6.5% RFNA and to air
without rinsing or drying. (Higher rates in RFNA)

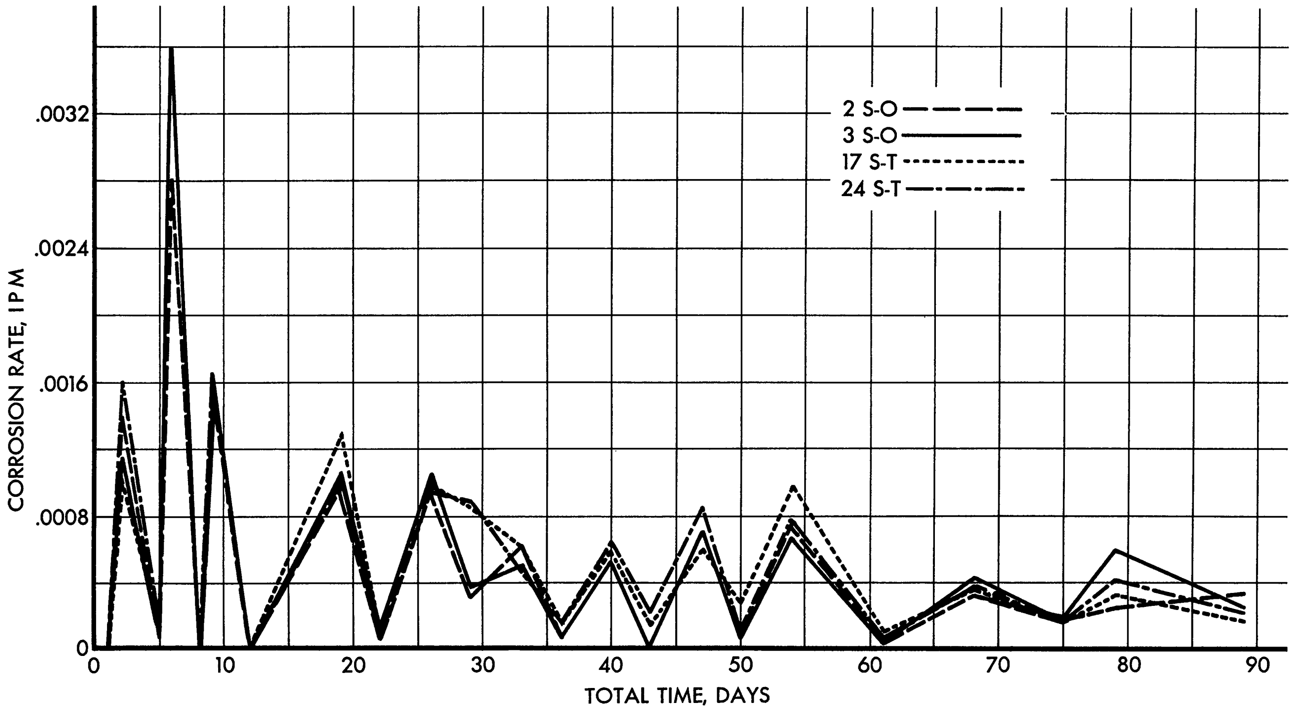

FIG. 10 SERIES V: CORROSION OF ALUMINUM ALLOYS
Alternate exposure to 6.5% RFNA and to air
without rinsing or drying. (Higher rates in air)

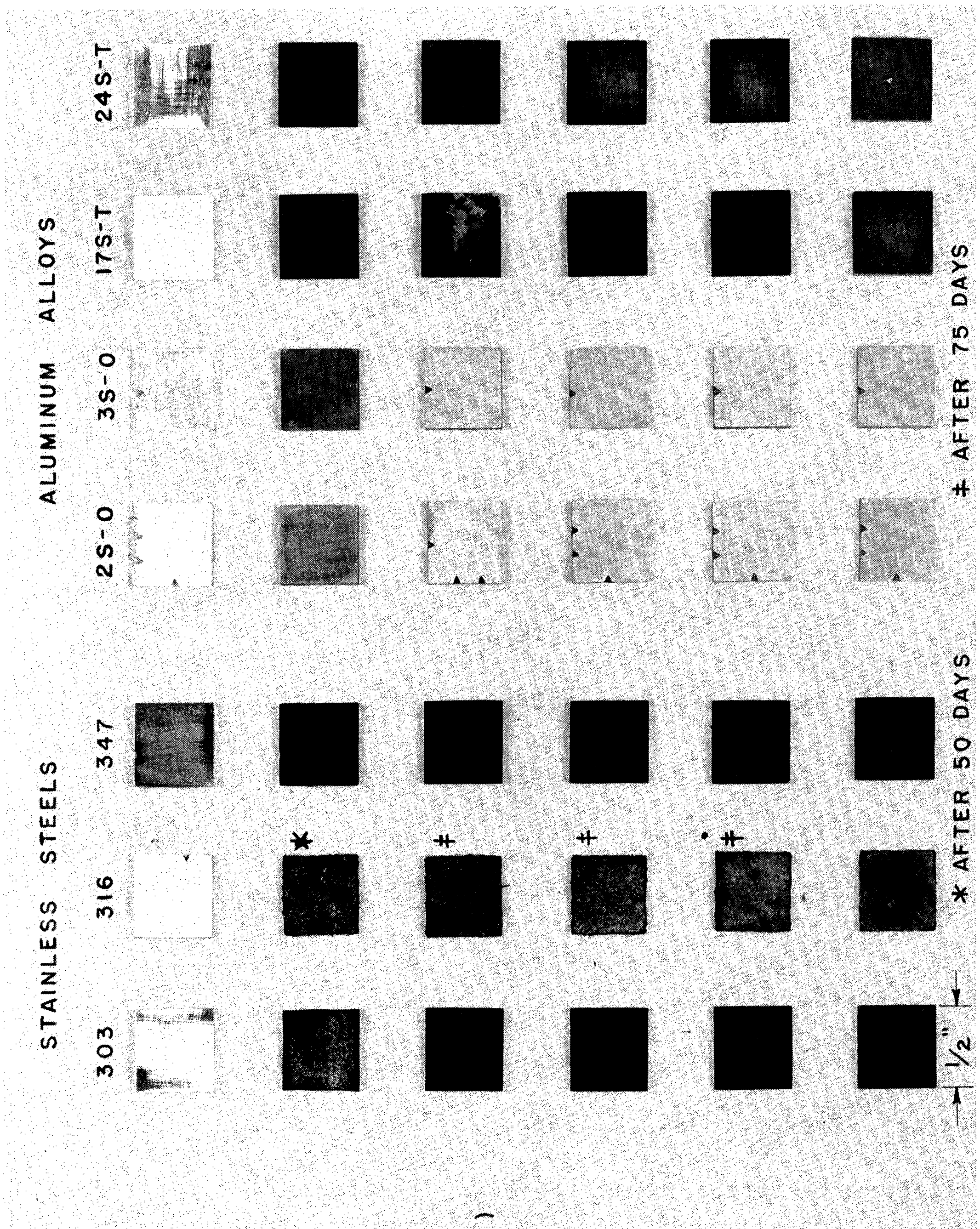

FIG. 11 STEEL & ALUMINUM SAMPLES AFTER NINETY-DAY CORROSION TESTS

TABLE I: AVERAGE CORROSION RATES IN IPM OF STAINLESS STEEL AND ALUMINUM ALLOYS IN RFNA

RFNA: Comm. 6 1/2%   Temperature: Ambient   Test Period: 90 days

Series		Stainless Steels			Aluminum Alloys			
		303	316	347	2S-0	3S-0	17S-T	24S-T
I	RFNA liq.	.00455	.01280*	.00156	.00026	.00027	.00015	.00026
II	RFNA liq. and vap.	.00113	.00461**	.00036	.00031	.00028	.00025	.00030
III (eleven cycles)	RFNA (rinse)	.00276	.00505**	.00106	.00009	.00015	.00013	.00015
	Water	.00002	.00043**	.00001	.00070	.00085	.00073	.00081
IV (eleven cycles)	RFNA (rinse)	.00395	.01490**	.00139	.00020	.00016	.00017	.00027
	Air	.00002	.00076**	.00001	.00060	.00077	.00073	.00058
V (eleven cycles)	RFNA	.00398	.01480	.00109	.00015	.00013	.00019	.00020
	Air	.00001	.00063	.00005	.00075	.00081	.00084	.00082

*After 50 days.
**After 75 days total.

TABLE II: AVERAGE CORROSION RATES OF TYPE 304 STEEL IN WFNA

Steel	%WFNA	Temp. °F.	Time, Days	Corrosion Rate, ipm	Reference
304, welded, annealed (conditions unspecified)	95, liquid	80-90	0-120	.00009**	Allegheny Ludlum (1)
			120-240	.00003	
			240-375	.00001	
			375-495	.00015	
			495-615	.00006	
			615-960	.00001	
			0-960	.00005	
304, welded, annealed (conditions unspecified)	95, vapor	80-90	0-255	.00004**	"
			255-420	.0001	
			420-510	.0008	
			510-960	.00003	
			0-960	.00012	
304, welded	93, liquid	90	90	.00005	Sands (2)
" "	93, vapor	"	"	.00003	
304, welded, heat treated *	93, liquid	"	"	.00005	
" " " "	93, vapor	"	"	.00003	
304, welded	99, liquid	90	90	.00220	"
" "	99, vapor	"	"	.00397	
304, welded, heat treated *	99, liquid	"	"	.00191	
" " " "	99, vapor	"	"	.00333	

* 10 minutes at 1925° F., air cooled.
** Calculated from graphs of total penetration vs. time.

TABLE III: AVERAGE CORROSION RATES OF TYPE 304 STEEL IN WFNA

Steel	% WFNA	Temp. °F.	Time, Days	Corrosion Rate, ipm	Reference
304, welded, heat treated*	93, liquid	90	90	.00005	Sands (2)
" " " "	" "	110	"	.00017	
" " " "	" "	130	"	.00070	
304, welded, heat treated*	93, vapor	90	90	.00003	"
" " " "	" "	110	"	.00019	
" " " "	" "	130	"	.00045	
304, welded, heat treated*	99, liquid	90	90	.00191	"
" " " "	" "	110	"	.00339	
" " " "	" "	130	"	.00410	
304, welded, heat treated*	99, vapor	90	90	.00333	"
" " " "	" "	110	"	.00553	
" " " "	" "	130	"	.00485	

*10 minutes at 1925° F., air cooled.

TABLE IV: AVERAGE CORROSION RATES OF TYPE 304 STEEL IN WFNA

Steel	Acid	Temp. ° F.	Time, Days	Corrosion Rate, ipm*	Reference
304, annealed (conditions unspecified)	WFNA	ambient	63-128 128-189 189-217 217-236 236-327	.00001 .00001 .00004 .00008 .00010	M. W. Kellogg (3)
304, welded	WFNA	ambient	63-156 156-217 217-235 235-326	.00001 .00002 .00004 .00007	"
304, welded, annealed (24 hours at 1650° F., air cooled)	WFNA	ambient	45-77 77-108 108-170 170-200 200-217 217-248	.00002 .00013 .00018 .00035 .00049 .00053	"
304, annealed (conditions unspecified)	WFNA	120	23-50 50-79 79-110 110-141 141-181	.00018 .00028 .00047 .00063 .00067	"
304, welded	WFNA	120	23-50 50-79 79-110 110-141 141-181	.00025 .00035 .00042 .00057 .00080	"

TABLE IV: AVERAGE CORROSION RATES OF TYPE 304 STEEL IN WFNA (CONT'D)

Steel	Acid	Temp. °F.	Time, Days	Corrosion Rate, ipm*	Reference
304, welded, annealed (24 hours at 1650° F. air cooled)	WFNA	120	23-50	.00025	M. W. Kellogg (3)
			50-79	.00038	
			79-110	.00057	
			110-141	.00104	
			141-181	.00150	

* Calculated from graphs of corrosion rates in inches per year (ipy) vs. time.

TABLE V: AVERAGE CORROSION RATES OF TYPE 304 STEEL IN RFNA

Steel	Acid	Temp. °F.	Time, Days	Corrosion Rate, ipm**	Reference
304, annealed (conditions unspecified)	RFNA	Ambient	54-137 137-165 165-196 196-225 225-300	.00001 .00003 .00006 .00010 .00012	M. W. Kellogg (3)
304, welded	RFNA	Ambient	54-137 137-165 165-196 196-225 225-247	.00001 .00003 .00004 .00006 .00009	"
304, welded, annealed *(24 hours at 1650° F. air cooled)	RFNA	Ambient	46-128 128-157 157-190 190-217 217-240	.00001 .00005 .00022 .00049 .00054	"
304, annealed (conditions unspecified)	RFNA	120	23-50 50-140 140-182 182-242	.0013 .0010 .0016 .0010	"
304, welded	RFNA	120	23-50 50-140 140-182 182-242	.0020 .0015 .0017 .0014	"
304, welded, annealed See above *	RFNA	120	24-50 50-79 79-240	.0040 .0030 .0025	"

** Calculated from graphs of corrosion rates in ipy vs. time.

TABLE VI: AVERAGE CORROSION RATES OF TYPES 309 AND 310 STEEL IN WFNA

Steel	% WFNA	Temp. °F.	Time, Days	Corrosion Rate, ipm	Reference
309, flash weld " " "	95, liquid 95, vapor	130 "	90 "	.00006 .00105	Sands (2)
309, flash weld " " "	97, liquid 97, vapor	130 "	90 "	.0027 .0046	"
310, flash weld " " "	95, liquid 95, vapor	130 "	90 "	.00008 .00024	"
310, flash weld " " "	97, liquid 97, vapor	130 "	90 "	.0008 excessive	"
310, welded, annealed (conditions unspecified)	95, liquid	80-90	0-180 180-375 375-960 0-960	.00003* .00000 .00001 .00004	Allegheny Ludlum (1)
310, welded, annealed (conditions unspecified)	95, vapor	80-90	0-255 255-375 375-510 510-960 0-960	.00002 * .0003 .0005 .0002 .00025	"

* Calculated from graphs of total penetration vs. time.

TABLE VII: AVERAGE CORROSION RATES OF TYPE 347 STEEL IN WFNA

Steel	%WFNA	Temp. °F.	Time, Days	Corrosion Rate, ipm	Reference
347, flash weld	95, liquid	130	90	.00004	Sands(2)
" " " , heat treated*	" "	"	"	.00004	
347, flash weld	95, vapor	130	90	.00186	"
" " " , heat treated*	" "	"	"	.00200	
347, flash weld	97, liquid	130	90	.0027	"
" " " , heat treated*	" "	"	"	.0031	
347, flash weld	97, vapor	130	90	.0053	"
" " " , heat treated*	" "	"	"	.0059	
347, flash weld	99, liquid	130	90	.0050	"
" " " , heat treated*	" "	"	"	.0053	
347, flash weld	99, vapor	130	90	.0059	"
" " " , heat treated*	" "	"	"	.0065	
347 welded	95, liquid	80-90	0-90	.00004 **	Allegheny Ludlum (1)
			90-135	.00008	
			135-375	.00002	
			375-465	.00022	
			465-675	.00007	
			675-960	.00000	
			0-960	.00005	
347, welded	95, vapor	80-90	0-255	.00000 **	"
			255-540	.0004	
			540-960	.0001	
			0-960	.00018	

*15 min. at 1925° F., air cooled
**Calculated from graphs of total penetration vs. time.

TABLE VIII: AVERAGE CORROSION RATES OF TYPE 347 STEEL IN WFNA

Steel	Acid	Temp. °F.	Time, Days	Corrosion Rate, ipm*	Reference
347, annealed (conditions unspecified)	WFNA	ambient	23-54 54-86 86-118 118-149 149-234	.00007 .00014 .00017 .00028 .00047	M. W. Kellogg (3)
347, welded	WFNA	ambient	31-60 60-86 86-118 118-149 149-244	.00004 .00010 .00017 .00028 .00042	"
347, annealed (conditions unspecified)	WFNA	120	23-49 49-78 78-110 110-141 141-182 182-244	.00032 .00040 .00044 .00087 .00113 .00152	"
347, welded	WFNA	120	23-49 49-78 78-110 110-141 141-182	.00015 .00018 .00022 .00033 .00045	"

*Calculated from graphs of corrosion rates in ipy vs. time.

TABLE IX: AVERAGE CORROSION RATES OF TYPE 347 STEEL IN RFNA

Steel	Acid	Temp. °F.	Time, Days	Corrosion Rate, ipm	Reference
347, annealed (conditions unspecified)	RFNA	ambient	28-100 100-132 132-160 160-243	.00010* .00017 .00025 .00030	M. W. Kellogg (3)
347, welded	RFNA	ambient	28-88 88-150 150-244	.00026* .00032 .00034	"
347, annealed (conditions unspecified)	RFNA	120	23-49 49-79 79-140 140-181 181-242	.0015 * .0013 .0012 .0013 .0014	"
347, welded	RFNA	120	23-79 79-140 140-181 181-242	.0010 * .0009 .0010 .0012	"
347	RFNA	ambient	29	.00025	Bethlehem Steel (10)

* Calculated from graphs of corrosion rates in ipy vs. time.

TABLE X: AVERAGE CORROSION RATES OF TYPE 430 STEEL IN RFNA

Steel	%WFNA	Temp. °F.	Time Days	Corrosion Rate, ipm	Reference
430, flash weld, " " " , heat treated	95, liquid " "	130 "	90 "	.00036 .00035	Sands (2)
430, flash weld " " " , heat treated	95, vapor " "	130 "	90 "	.00075 .00067	"
430, flash weld " " " , heat treated	99, liquid " "	130 "	90 "	.0068 .0044	"
430, flash weld " " " , heat treated	99, vapor " "	130 "	90 "	.0063 .0053	"

TABLE XI: AVERAGE CORROSION RATES OF STAINLESS STEELS IN RFNA AT ELEVATED TEMPERATURE

Steel	Acid	Temp. °F.	Time, Hours	Corrosion Rate, ipm	Reference
304	6.5% RFNA	250-300	3.3	0.1	Kaplan and Andrus (5,8)
304	"	"	6.6	0.06	"
316	"	"	7	0.2	"
410, heat treated (conditions unspecified)	"	"	7	0.4	"
414	"	"	7	0.3	"
416	"	"	7	0.25	"
420	16% RFNA	"	7	0.3	"
440	"	"	7	0.2	"
446	"	"	7	0.25	"

TABLE XII: AVERAGE CORROSION RATES OF 2S ALUMINUM IN WFNA

Aluminum	% WFNA	Temp. °F.	Time, Days	Corrosion Rate, ipm	Reference
2S, welded, heat treated *	93, liquid	90	90	.00016	Sands (2)
" " " "	" "	110	"	.00088	
" " " "	" "	130	"	.00061	
2S, welded, heat treated *	93, vapor	90	90	.00008	"
" " " "	" "	110	"	.00009	
" " " "	" "	130	"	.00014	
2S, welded, heat treated *	99, liquid	90	90	.00002	"
" " " "	" "	110	"	.00008	
" " " "	" "	130	"	.00053	
2S, welded, heat treated *	99, vapor	90	90	.00010	"
" " " "	" "	110	"	.00023	
" " " "	" "	130	"	.00023	
2S, welded	95, liquid	90	90	.00001	"
" "	95, vapor	"	"	.00008	
2S, welded, heat treated *	95, liquid	"	"	.00001	
" " " "	95, vapor	"	"	.00007	
2S, welded	99, liquid	90	90	.00002	"
" "	99, vapor	"	"	.00007	
2S, welded, heat treated *	99, liquid	"	"	.00001	
" " " "	99, vapor	"	"	.00010	

* 5 hours at 940° F., air cooled

TABLE XIII: AVERAGE CORROSION RATES OF 2S-O ALUMINUM IN WFNA

Aluminum	Acid	Temp. °F.	Time Days	Corrosion Rate, ipm*	Reference
2S-O, annealed (conditions unspecified)	WFNA	ambient	31-49 49-149 149-183	.00016 .00025 .00020	M. W. Kellogg (3)
2S-O, welded	WFNA	ambient	32-62 62-123 123-153 153-189	.00027 .00031 .00028 .00036	"
2S-O, annealed (conditions unspecified)	WFNA	120	24-49 49-181	.00052 .00035	"
2S-O, welded	WFNA	120	24-49 49-80 80-110 110-141 141-181	.00058 .00043 .00038 .00041 .00045	"

* Calculated from graphs of corrosion rates in ipy vs. time.

TABLE XIV: AVERAGE CORROSION RATES OF 2S-0 ALUMINUM IN RFNA

Aluminum	Acid	Temp. °F.	Time, Days	Corrosion Rate, ipm*	Reference
2S-0 annealed (conditions unspecified)	RFNA	ambient	28-59 59-88 88-149 149-183	.00031 .00034 .00036 .00030	M. W. Kellogg (3)
2S-0, welded	RFNA	ambient	33-186	.00027	"
2S-0, annealed (conditions unspecified)	RFNA	120	24-50 50-79 79-139 139-180	.00051 .00042 .00040 .00044	"
2S-0, welded	RFNA	120	24-48 48-140 140-180	.00067 .00051 .00054	"

* Calculated from graphs of corrosion rates in ipy vs. time.

TABLE XV: AVERAGE CORROSION RATES OF 2S ALUMINUM IN RFNA

Aluminum	Acid	Temp. °F.	Time, Days	Corrosion Rate, ipm	Reference
2S-0	RFNA	ambient	2	.00001	Bethlehem Steel (10)
			4	.00005	
			6	.00004	
			8	.00005	
			10	.00008	
			12	.00004	
			14	.00002	
			16	.00002	
2S, as machined	RFNA	ambient	15	.00007	"
			29	.00004	
2S, polished	RFNA	ambient	15	.00007	"
			29	.00003	
2S, rolled	RFNA	ambient	15	.00004	"
			29	.00002	
2S, fine tool finish	RFNA *	ambient	18	.00009	"
2S, fine tool finish	RFNA **	ambient	10	.00012	"
2S, cut from weld	RFNA	ambient	28	.00003	"
2S, adjacent to weld	RFNA	ambient	28	.00005	"

* Contaminated Acid From Stainless Steel Drum.

** Acid Contained 4% Water.

TABLE XVI: AVERAGE CORROSION RATES OF 3S ALUMINUM ALLOY IN WFNA

Aluminum	% WFNA	Temp. ^{o}F.	Time, Days	Corrosion Rate, ipm	Reference
3S, welded, heat treated *	93, liquid	90	90	.00017	Sands (2)
" " " "	" "	110	"	.00092	"
" " " "	" "	130	"	.00132	
3S, welded, heat treated *	93, vapor	90	90	.00008	"
" " " "	" "	110	"	.00012	
" " " "	" "	130	"	.00136	
3S, welded, heat treated *	99, liquid	90	90	.00002	"
" " " "	" "	110	"	.00033	
" " "	" "	130	"	.00185	
3S, welded, heat treated *	99, vapor	90	90	.00016	"
" " " "	" "	110	"	.00051	
" " " "	" "	130	"	.00089	
3S, welded	95, liquid	90	90	.00001	"
" "	95, vapor	"	"	.00009	
3S, welded, heat treated *	95, liquid	"	"	.00001	
" " " "	95, vapor	"	"	.00010	
3S, welded	99, liquid	90	90	.00002	"
" "	99, vapor	"	"	.00016	
3S, welded, heat treated *	99, liquid	"	"	.00001	
" " " "	99, vapor	"	"	.00015	

* 5 hours at 940^{o} F., air cooled

TABLE XVII: AVERAGE CORROSION RATES OF ALCLAD 24S-T ALUMINUM ALLOY IN WFNA

Aluminum	Acid	Temp. °F.	Time, Days	Corrosion Rate, ipm *	Reference
Alclad, 24S-T, annealed (conditions unspecified)	WFNA	ambient	45-76 76-108 108-138 138-198 198-250	.00017 .00012 .00010 .00008 .00010	M. W. Kellogg(3)
Alclad, 24S-T, welded	WFNA	ambient	18-45 45-77 77-107 107-167 167-226	.00021 .00024 .00018 .00014 .00016	"
Alclad 24S-T, welded, annealed (solution treated 15 min. at 920° F , water quenched)	WFNA	ambient	31-61 61-89 89-124 124-152 152-186	.00026 .00030 .00034 .00030 .00032	"
Alclad 24S-T, annealed	WFNA	120	23-49 49-79 79-182	.00082 .00074 .00081	"
Alclad 24S-T, welded, annealed (solution treated 15 min. at 920° F., water quenched)	WFNA	120	23-79 79-110 110-140 140-182	.00087 .00093 .00112 .00125	"

* Calculated from graphs of corrosion rates in ipy vs. time.

TABLE XVIII : AVERAGE CORROSION RATES OF ALCLAD 24S-T ALUMINUM ALLOY IN RFNA

Aluminum	Acid	Temp. °F.	Time, Days	Corrosion Rate, ipm *	Reference
Alclad 24S-T, annealed (conditions unspecified)	RFNA	ambient	46-109 109-138 139-199 199-250	.00031 .00019 .00015 .00018	M. W. Kellogg (3)
Alclad 24S-T, welded	RFNA	ambient	77-106 106-188 188-217	.00032 .00025 .00021	"
Alclad 24S-T, welded, annealed (solution treated 15 min. at 920° F., water quenched)	RFNA	ambient	33-59 59-88 88-119 119-149 149-183	.00042 .00049 .00041 .00038 .00044	"

*Calculated from graphs of corrosion rates in ipy vs. time.

TABLE XVIII: AVERAGE CORROSION RATES OF ALCLAD 24S-T ALUMINUM ALLOY IN RFNA (CONT'D)

Aluminum	Acid	Temp. °F.	Time, Days	Corrosion Rate, ipm*	Reference
Alclad 24S-T, annealed (conditions unspecified)	RFNA	120	23-49 49-78 78-111 111-142 142-181	.00080 .00061 .00058 .00065 .00072	M. W. Kellogg (3)
Alclad 24S-T, welded	RFNA	120	23-49 49-78 78-110 110-142 142-181	.00065 .00042 .00045 .00050 .00055	"
Alclad 24S-T, welded, annealed (solution treated 15 min. at 920° F., water quenched)	RFNA	120	23-48 48-78 78-110 110-181	.00078 .00059 .00062 .00067	"

*Calculated from graphs of corrosion rates in ipy vs. time.

TABLE XIX: AVERAGE CORROSION RATES OF ALUMINUM ALLOYS IN FUMING NITRIC ACID

Aluminum	Acid	Temp. °F.	Time Days	Corrosion Rate, ipm	Reference
3S-0	RFNA	ambient	28	.00007	Bethlehem Steel (10)
14S-T6	RFNA	ambient	50-84 84-105 105-164 164-196	.00025 * .00029 .00036 .00038	M. W. Kellogg (3)
43	RFNA	ambient	33-64 64-93 93-126 126-147 147-174	.00039 * .00043 .00047 .00051 .00047	"
43	WFNA	ambient	30-89 89-120 120-200	.00045 * .00059 .00069	"
53S	RFNA	ambient	21	.00009	Bethlehem Steel (10)
61S-T	RFNA	ambient	27	.00001	"
63S-T	RFNA	ambient	28	.00003	"
75S-T	RFNA	ambient	28	.00002	"

* Calculated from graphs of corrosion rates in ipy vs. time.

TABLE XX: AVERAGE CORROSION RATES OF ALUMINUM ALLOYS IN RFNA AT ELEVATED TEMPERATURE

Aluminum	% RFNA	Temp. °F.	Time, Hours	Corrosion Rate, ipm	Reference
17S-T	16	250-300	7	0.6	Kaplan and Andrus (5,8)
17S-T	6.5	"	7	0.3	"
24S-T	6.5	"	6	0.5	"

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