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FINAL REPORT

DEVELOPMENT OF IMPROVED CORROSION
RESISTANT STAINLESS STEEL

PROJECT 9170-4037
CONTRACT DDR-124
GENERAL ELECTRIC COMPANY, HANFORD

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ALLEGHENY LUDLUM STEEL CORPORATION
Brackenridge, Pennsylvania

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Introduction:

The General Electric Company, Hanford Works, has encountered difficulties with present materials used for storage tanks and concentrators for reactive waste and reactor vessels for dissolving fuel elements. Since the chemical solutions involved in the processing must be highly corrosive to accomplish their purpose, corrosion problems for handling equipment become serious as well. Type 304L has been employed in such equipment, but leaves much to be desired because of high corrosion rates; the problems associated with failure and disposal of failed equipment are obvious. There is need for alloys with improved corrosion resistance. Types 309L and 309Cb stainless steel have been investigated at General Electric Company and while an improvement, they do not fulfill all the desired characteristics needed.

The use of nitric-hydrofluoric mixtures more recently as a preferred chemical processing solution poses a much more serious difficulty, because unlike other mineral acids, hydrofluoric is not easily or readily inhibited in its corrosiveness and nitric provides little, if any, benefit toward inhibition.

The purpose of this investigation has been to develop new or improved alloys which might be employed in processing equipment, and especially equipment handling nitric-hydrofluoric acid mixtures.

Summary:

Special modifications of Types 309 and 310 and also higher chromium and nickel alloys have been evaluated for their ability to meet corrosion requirements.

Tests have been conducted on welded and unwelded samples from 15 special laboratory

melted compositions in boiling 65% nitric acid, in boiling 13 molar HNO_3 with additions of .075M, 0.25M and 0.50M HF, in 0.5 molar sulfuric acid, in 6% ferric chloride and in a boiling mixture containing 6M HNO_3 + .4M H_2SO_4 + .4M NaNO_3 + .3M $\text{Fe}_2(\text{SO}_4)_3$ + .01M Cr + .01M Hg + .01M PO_4 . Welds have been examined after corrosion tests, and sensitized specimens from all compositions have been tested in boiling 65% nitric acid.

Successful laboratory melting and processing of these compositions to plate and sheet has been accomplished on small scale equipment. Multipass welding by the manual tungsten inert gas method using filler strips cut from sheet was successful in sample preparation with no evidence of cracking or other difficulties.

It may be concluded that, in both the nitric-hydrofluoric mixtures and the complex mixture, a much improved general corrosion resistance over Type 309 can be obtained with .02% carbon Type 310 Cb, with .02% carbon Type 310, and with all of the high chromium nickel alloys. In regard to attack in weld heat affected zones, these results show the .02% carbon Type 310 Cb to be outstanding. While the .02% carbon Type 310 shows some trace evidence of discontinuous precipitate at grain boundaries, it suffered no intergranular attack adjacent to the weld even in the boiling nitric-hydrofluoric solutions, but did exhibit a slight etch in this area. The austenitic 30% Cr - 25% Ni alloy which was very excellent in general corrosion resistance, unfortunately suffered intergranular attack in the heat affected zone but this may be attributed to the high nitrogen content (.084%).

There is considerable variation in sensitivity of the 65% nitric acid, the HNO_3 -HF, and the complex mixture to grain boundary precipitates or other structural conditions. In the course of sample examination it was discovered that the complex solution can cause austenite grain boundary etching even in the absence of a visible precipitate. Similarly the nitric-hydrofluoric solutions severely attack the Type 309 Cb weld structure but are very mild toward Type 310 or Type 310Cb. Much is not understood about why these solutions behave as they do.

Recommendation:

Based on the specific compositions included in this investigation, the .02% carbon Type 310 Cb (Heat GD-44) appears most promising as an improvement over Type 309L and Type 309Cb. It possesses improved general corrosion resistance in boiling HNO_3 -HF solutions and in the boiling complex mixture and, furthermore, shows no intergranular susceptibility or accelerated attack in heat affected weld zones nor does the weld suffer severe disintegration in either solution. A second alloy possessing nearly as good properties (Heat FV-19A) is a .02% carbon Type 310. On a laboratory scale it has also been demonstrated that these Type 310 compositions can be successfully melted and processed to plate and sheet, and welded with no cracking. Provided the improvements in corrosion resistance are attractive to General Electric Company, Manford, the second phase consisting of the development of production methods for mill sized heats in sheet, plate and tubing should be undertaken.

Should even a greater improvement in corrosion resistance be desired the higher chromium and nickel alloys warrant additional investigation. Since each of the four different Cr-Ni compositions were restricted to a specific carbon and nitrogen content, a program to study the influence of these latter two elements would be necessary before they could be recommended. The fully austenitic Heat FV11, a 30 Cr - 25 Ni alloy, would have deserved recommendation were it not for its susceptibility to intergranular corrosion.

Additional study of the peculiar effects of sensitizing on corrosion by the HNO_3 -HF and complex solution is indicated. The unusual austenite grain boundary etch by the complex solution even in the absence of visible precipitated carbides is unexplained, and equally mysterious is the slight acceleration of HNO_3 -HF attack at areas where only a trace discontinuous grain boundary precipitate is present.

Alloy Composition Selection:

In a development program of the type involved here it was necessary to consider seriously the problem of intergranular susceptibility in the as welded condition since

the nature and size of the equipment involved does not permit a post-annealing operation. For this reason all heats were melted with this in mind and low carbon or columbium stabilization was employed to accomplish this. Vacuum melting of very low carbon variations of the Type 309 composition below .03% was offered as one special variation. The addition of columbium to low carbon Type 310 was another.

The purity of materials was considered as possibly affecting the general corrosion resistance in these environments and the use of high and low silicon modifications of Type 310 as well as high and low manganese content in Type 310 was proposed as worthy of investigating.

Finally the selection of higher chromium and nickel alloys above the standard stainless steel ranges would be expected to provide better corrosion resistance because of their alloy content. These alloys could, therefore, serve a two fold purpose because it is generally known that precipitation of harmful intergranular carbides is frequently retarded appreciably in a duplex austenitic ferritic structure.

Table I covers the composition aims which were selected to be melted in the program. These were 100 pound air induction and 50 pound vacuum induction laboratory heats. The required method of melting is designated in the table, since those materials with very low carbon necessitated vacuum melting. Vacuum melting would have to be considered as a production method if it were found that these compositions had the best performance in the corrosion tests.

TABLE I

COMPOSITION OF LABORATORY HEATS

Item #	Size of Heat	Method of Melting	AIM							
			C	Mn	Si	Cr	Ni	P	S	Cb
1	100#	Air Ind.	.03 max	.75	.35	35	20	.045 max	.03 max	-
2	100#	Air Ind.	.03 max	.75	.35	30	20	.045 max	.03 max	-
3	100#	Air Ind.	.03 max	.75	.35	30	25	.045 max	.03 max	-

TABLE I (contd)

Item #	Size of Heat	Method of Melting	C	Mn	Si	Cr	Ni	P	S	Cb
4	100#	Air Ind.	.03 max	.75	.35	30	15	.045 max	.03 max	-
5	50#	Air Ind.	.03 max	.10	.35	25	20	.045 max	.03 max	-
	50#	(a)	.03 max	1.00	.35	25	20	.045 max	.03 max	-
6	50#	Air Ind.	.03 max	.75	.30	25	20	.045 max	.03 max	-
	50#	(b)	.03 max	.75	1.00	25	20	.045 max	.03 max	-
7	100#	Air-50#	.03 max	.75	0	25	20	.045 max	.03 max	-
8	100#	Air-50#	.03 max	.75	.15	25	20	.045 max	.03 max	-
9	100#	Air Ind.	.03 max	1.50	.40	22.25	14.50	-	-	-
10	50#	Vacuum	.01 max	1.50	.40	22.25	14.50	-	-	-
11	50#	Vacuum	.005 max	1.50	.40	22.25	14.50	-	-	-
12	50#	Vacuum	.001 max	1.50	.40	22.25	14.50	-	-	-
13	50#	Vacuum	.01 max	.50	.40	22.25	15.25	-	-	-
14	100#	Air Ind.	.05 max	1.50	.40	22.50	14.50	-	-	.50 or 10 x C
15	100#	Air Ind.	.02 max	.75	.35	25	20	-	-	.20

(a) Pour 50 lb. ingot and then add 1% Mn to remaining 50# portion

(b) Pour 50 lb. ingot and then add 1% Si to remaining 50# portion

In respect to structure, the proposed compositions were classified into two groups: duplex structure austenitic-ferritic heats and fully austenitic heats.

Heat numbers 1, 2, 3, and 4 (Table I) show the composition of the proposed duplex structure materials. The main advantage of these heats is their resistance to intergranular corrosion. In highly alloyed austenitic stainless steels the solubility for carbon decreases, and even holding to .03% max carbon content does not seem to be sufficient to insure good resistance to intergranular attack. While lower carbon content below .03% would be helpful, this requires special melting procedures which are more expensive and there is also a limitation in the size of such heats. In contrast the duplex structure materials are resistant to intergranular attack at .03% carbon or even higher. These ferrite-austenite compositions have, in general, higher mechanical properties, though this might not be an important factor in the selection of a material. Since chromium is the most important element in conferring corrosion resistance in the media involved here, increasing the chromium content thus produced these duplex structures. The presence of delta ferrite, per se, does not adversely

affect corrosion resistance except in cases where it might lead to the formation of sigma phase. Sigma phase may be hazardous to nitric acid corrosion resistance. The nickel content of the duplex phase was varied in order to establish its influence in these strong nitric acid solutions, and also to establish if it can control embrittlement in the weld.

The austenitic heats were designed to investigate several corrosion problems.

Heat number 5 (Table I) was a 25% chromium, 20% nickel heat which was divided into two 50-pound ingots of identical composition with the exception of manganese which was aimed at .10% in one ingot and 1% in the other. The object of this was to investigate the influence of manganese in the corrosion problems. There are no data in the literature to reveal the influence of manganese at this level, and it is generally assumed that it does not affect corrosion resistance in this low range. We earlier established experimentally in our laboratory that variation of manganese content in this range had noticeable influence on the oxidation properties. While oxidation and corrosion resistance are not necessarily related, oxidation during annealing might influence the base metal adjacent to the oxidized surface and was subsequently, for this reason, considered necessary to investigate.

Heat numbers 6, 7, and 8 represented 25% chromium and 20% nickel steels with various silicon contents. Heat number 6 was divided into two ingots with identical composition except silicon content. Numbers 7 and 8 are 50-pound heats of 25% chromium - 20% nickel with 0 and .15% silicon. This information was only of academic interest since it is impossible presently to produce a commercial air melted heat with silicon content lower than .20%. It has been established that silicon has an influence on the corrosion resistance of austenitic stainless steels. This was reported by Brown, DeLong and Myers*, as well as by Burrat.

Heat numbers 9, 10, 11, 12, and 13 were Type 309L in which the carbon content was decreased from .03 to .001 in order to establish the limit of solubility for carbon and carbon level necessary to prevent intergranular corrosion.

*ASTM Special Technical Publication No. 165

Heat number 14 was Type 309Cb, included for comparison with other materials and for the study of knife-line attack.

Heat number 15 was selected because based on existing published information and general consideration of the corrosion and metallurgical problems this was the optimum anticipated composition.

Melting and Actual Compositions Attained:

In general, with a few exceptions, it was possible to attain the desired composition as shown in Table II. The composition designated item 12 was cancelled, however, because it was impossible to attain the desired .001% carbon by vacuum induction melting. Heats FV71-15 and FV70-15 were remade heats using Grainal 79,⁽¹⁾ since the original heats cracked during hot rolling. Both these heats have the highest delta ferrite structure. In the case of Heat FV56-15, the silicon content was held as low as possible to .033%, but in order to do this the raw materials were of such purity that carbon content became unusually low, .0039%, considering the .03% maximum carbon aim. In the following heat, FV57-15, the silicon content of .28% is somewhat higher than the aim of .15%. The fact that it lies between 0 and the usual .4% average pointed to our decision to test this anyhow, since it could fill the gap and maintain a reasonable carbon content.

(1) Grainal 79 is an addition for ferrous melts which can impart the following properties: Improves hot working characteristics of wrought stainless steels and reduces heat checking of castings. The chief advantage of the use of Grainal 79 in our work here has been to avoid cracking of these high alloy content stainless steels during hot rolling. Grainal 79 is manufactured by Vanadium Corporation of America and has the following chemical composition:

<u>C</u>	<u>Mn</u>	<u>Zr</u>	<u>Si</u>	<u>Al</u>	<u>Ti</u>	<u>B</u>	<u>Cu</u>
.17	7.67	2.87	3.24	12.49	21.67	.50	.22

TABLE II

ACTUAL COMPOSITIONS

Item #	Heat No.	Method of Melting	C	Mn	Si	Cr	Ni	P	S	Cb	Ti	Cu	Co	Al	N
*1	FV71-15	Air Ind.	.030	.86	.39	34.74	19.70	.024	.017	-	.025	.070	.028	.0042	.066
2	FV20-15	Air Ind.	.022	.87	.51	30.28	19.83	.008	.010	-	.018	.040	.044	.0031	.060
3	FV11-A	Air Ind.	.030	.83	.56	30.32	24.48	.015	.011	-	.011	.050	.056	.0017	.084
*4	FV70-15	Air Ind.	.024	.75	.42	29.96	15.14	.025	.019	-	.025	.070	.053	.0030	.037
5	FV17-15A	Air Ind.	.017	.33	.52	25.48	20.28	.020	.016	-	.018	.080	.058	.0022	.048
	FV17-15B	Air Ind.	.018	1.24	.48	25.36	20.13	.015	.016	-	.011	.082	.052	.0026	.046
6	FV19-15A	Air Ind.	.020	.85	.47	25.62	20.30	.015	.008	-	.014	.082	.062	.0013	.047
	FV19-15B	Air Ind.	.017	.82	1.07	25.18	20.21	.015	.018	-	.011	.080	.062	.0071	.046
7	FV56-15	Air Ind.	.0039	.77	.033	24.40	19.99	.006	.014	-	.014	.030	.045	.0025	.040
8	FV57-15	Air Ind.	.021	.90	.28	24.80	19.61	.008	.014	-	.011	.030	.069	.0039	.045
9	FY78-14	Air Ind.	.026	1.59	.45	22.25	14.25	.022	.015	-	.014	.035	.039	.0031	.030
10	RV296-4	Vacuum	.0086	1.51	.42	22.34	14.51	.008	.010	-	.022	.030	.034	.0027	.0028
11	RV294-4	Vacuum	.0041	1.57	.46	22.71	14.32	.008	.008	-	.011	.035	.057	.0029	.0044
13	RV297-4	Vacuum	.0081	.59	.45	22.30	15.03	.008	.008	-	.014	.030	.031	.0024	.0038
14	FY79-14	Air Ind.	.043	1.53	.47	22.48	14.25	.015	.013	.40	.014	.042	.034	.0015	.044
15	GD-44	Air Ind.	.015	.84	.40	24.76	20.00	.014	.015	.22	.014	.057	.035	.0022	.043

*These two heats were melted with 4#/ton ratio of Grainal 79. Original heats cracked severely and had to be remade.

It is significant to note that, although no aim was made on nitrogen content, the vacuum melted heats, RV-294, RV296, and RV297, have very low nitrogen compared to the usual normal content of about .04%. On the other hand, three of the very high Cr-Ni alloys had slightly higher than normal nitrogen, due to the fact that it is added as a part of the ferrochrome addition. This was of some concern, since nitrogen may appear in a grain boundary nitride precipitate similar to carbide when high nitrogen stainless steels are sensitized. This is discussed later in the instance of Heat FV-11 with .084% N.

Unlike commercial heats, impurities and non-metallic inclusions are more common in small research heats. This fact is often evidenced as end grain attack on heavy gage corrosion test samples; thin gage sheet is not subject to end grain attack. Thus sheet samples are preferred to establish corrosion rates.

Processing to Gage:

Material from all heats was conditioned, forged to sheet bar and then hot rolled to 1/4" plate (for weld test samples). Enough material was selected at this stage for the purpose of providing welds, and the remaining approximate 40% of each heat was further processed either by hot rolling to .100" or .060" or by hot rolling to .100" and subsequent cold rolling to .060".

No difficulties were encountered in processing any of the heats at any stages. The two heats mentioned previously, which were remelted using Grainal 79, also processed satisfactorily with no cracking. The forging and hot rolling temperatures for all heats are reported in Table III.

It is pointed out that laboratory processing on this small scale cannot duplicate commercial hot finishing practices. Since the starting commercial ingot is many times larger than a laboratory ingot, much greater reductions are necessary to reach the gages involved in this program. Thus grain refinement and uniformity of structure in our 1/4" plate test samples is much less than would be attained in an

actual mill product. However, the information gained from our processing methods is highly significant, for it indicates that with development of suitable mill processing procedures all of the compositions are probably capable of satisfactory production on a large scale.

TABLE III

PROCESSING DATA

Item #	Heat No.	Forged to Sheet	Hot Rolled to	Hot Rolled to		Cold Rolled
		Bar at	.25" at *	Gage	Temp.	
1	FV71	2200°F	2100°F	.060"	2100°F	-
2	FV20	2200°F	2100°F	.060"	2100°F	-
3	FV11	2200°F	2100°F	.060"	2100°F	-
4	FV70	2200°F	2100°F	.060"	2100°F	-
5	FV17-15A	2200°F	2100°F	.060"	2100°F	-
	FV17-15B	2200°F	2100°F	used for		-
				weld filler		
6	FV19-15A	2200°F	2100°F	.060"	2100°F	-
	FV19-15B	2200°F	2100°F	.060"	2100°F	-
7	FV56	2200°F	2100°F	-	-	.060"
8	FV57	2200°F	2100°F	-	-	.060"
9	FY78	2200°F	2150°F	.100"	2150°F	.060"
10	RV296	2200°F	2150°F	.100"	2150°F	.060"
11	RV294	2200°F	2150°F	.100"	2150°F	.060"
13	RV297	2200°F	2150°F	.100"	2150°F	.060"
14	FY79	2200°F	2150°F	.100"	2150°F	.060"
15	GD44	2200°F	2100°F	.100"	2100°F	.060"

* Material taken at this gage subsequently was annealed at 2050°F and used for weld tests. Samples tested as welded only, except for a few special samples reannealed and then sensitized at 1200°F.

Annealing and Descaling:

The plate material at 1/4" received an anneal at 2050°F for 20 minutes, air cooled, followed by descaling in 15% HNO₃ + 3% HF solution. This material was subsequently welded and corrosion tested in the as welded condition.

The portions of each heat that were hot rolled to lighter gages were descaled in 15% HNO₃ + 3% HF at various stages and before cold rolling. After cold rolling all materials were degreased in 10% alkaline cleaner of the sodium orthosilicate type and then annealed at three temperatures (2050°F, 2150°F and 2300°F) since it was felt that annealing temperature might have an influence on corrosion rates, especially where

duplex austenitic-ferritic structures are present in the base material. This information would also be invaluable for subsequent mill processing assistance. All .060" sheet materials received an anneal of 15 minutes, air cool, followed by pickling in 15% HNO₃ - 3% HF at 140°F to descale them in preparation for corrosion tests.

Strips .060" x 3/16" were sheared from Heats FV17B, GD44, FY78, RV294, RV296, RV297, and FY79 for filler metal in welding.

Welding:

The 1/4" plate sections which were annealed at 2050°F were cut into 24" long strips and machined to a single V-groove preparation with a 60° included angle. Multi-pass welding by the manual tungsten inert gas method was employed, using filler metal of sheared strips of sheet. Multipass welding which involves higher heat input provides typical structural effects in the base metal and weld that would exist in process vessels and equipment. A surface cross weld pass was subsequently applied to permit evaluation of the condition which would occur in actual fabricated structures.

Filler metals employed in welding were strips cut from sheet as follows:

- (a) All Type 309 compositions were welded with filler strips cut from each individual heat. This was also true for Heat GD44, the .02% carbon Type 310 plus Cb composition.
- (b) All remaining heats used filler metal from Heat FV17B, a .02% carbon Type 310.

Table IV shows the results of magne-gage readings for the base metal, a fusion cross weld, and of the weld with filler added. This is a measure of ferrite content, and reveals an interesting observation that the expected duplex structure for Heat FV11 (a 30 Cr-25 Ni heat) did not materialize. This may be due to the fact this heat contained .084% nitrogen, a strong austenitizer. The three vacuum Type 309 heats with very low carbon and nitrogen showed some ferrite in the base metal as annealed at 2050°F and some increase after welding. None of the 25-20 heats were affected from the ferrite standpoint upon welding. As expected, the high chromium-nickel alloys show high delta ferrite contents, increasing when they are fusion welded.

TABLE IV
MAGNE-GAGE READINGS

% MAGNETIC PHASE

Annealed @ 2050°F + Welded

<u>Heat No.</u>	<u>Base Metal Analysis</u>	<u>Base Metal</u>	<u>Fusion Weld</u>	<u>FV17B Filler Metal</u>
FV71	35-20	18%	27%	11%
FV20	30-20	12	12	8
FV11	30-25	0	0	0
FV70	30-15	22	40	18
FV17A	25-20 + .33 Mn	0	0	0
FV17B	25-20 with .018 C	0	0	0
FV19A	25-20 with .020 C	0	0	0
FV19B	25-20 + 1 Si	0	0	0
FV56	25-20 with .03 Si	0	0	0
FV57	25-20 with .28 Si	0	0	0
GD44	25-20 Cb	0	0	0 (GD44)
FY78	Type 309L	1	2	3 (FY78)
RV294	Type 309-very low C	4	7	7 (RV294)
RV296	Type 309-very low C	3	6	5 (RV296)
RV297	Type 309-very low C	2	3	3 (RV297)
FY79	Type 309 Cb	5%	5%	5% (FY79)

After welding, all samples were mechanically abraded with a leaf grinder abrasive belt wheel to remove scale and oxides, then lightly pickled in a dilute hydrochloric acid solution (chosen because it avoids intergranular attack). The welds were not ground flush with the surface, and instead the light preparation described above left the normal contour of the weld untouched. Subsequently these samples were sawed to a rough size and edges machined to dimensions for corrosion tests. A 1/4" hole was drilled at one end to suspend the samples intended for boiling test solutions. Examination of samples after corrosion testing is discussed later.

Sample Preparation:

The weld samples were prepared as described above and the edges ground with 120 grit emery prior to testing. These were then thoroughly degreased in a hot 10% alkaline solution of the sodium orthosilicate type, rinsed with hot dilute nitric then distilled water and dried before weighing.

The unwelded samples were cut to size after annealing, and a 1/4" hole drilled in one end of the 1" x 2" size. After deburring each sample was ground on the surface and edges with 120 grit emery, degreased and then passivated in warm 20% HNO₃ solution to clean and passivate them before weighing.

The special sensitized samples prepared for the boiling 65% nitric acid test were heated 1 hour at 1200°F and then lightly ground and pickled in dilute (20%) HCl solution to remove all oxide scale before weighing and testing.

The standard size samples for each environment are shown below:

- (b) HNO₃-HF solution - 1" x 2" with 1/4 hole at one end
- (c) Complex mixture - 1" x 2" with 1/4 hole at one end
- (d) 65% HNO₃ - 1" x 2" with 1/4 hole at one end
- (e) .5M H₂SO₄ - 2" x 2"
- (f) 6% FeCl₃ - 4" x 4"

Corrosion Tests:(a) General Nature of Corrosion Test Environments

In most corrosion test programs for new alloys, selection of proper and representative solutions is often very difficult. However, in this program, we were benefited by previous experience and knowledge of certain process solutions that could be adapted directly to the program. Two of these solutions are described in (b) and (c) below. The three additional solutions (d), (e) and (f), are commonly used to establish general knowledge of corrosion properties of the stainless steels.

- (b) 13M HNO₃ + .075M HF at boiling
13M HNO₃ + .25M HF at boiling
13M HNO₃ + .50M HF at boiling

Nitric acid cannot inhibit HF except to a minor extent. The ratio of HNO₃ to HF is 40:1 on a molar basis, but should represent very severe conditions where alloy composition can be significant. This solution can develop knife-line and intergranular attack especially well if these susceptible conditions exist in the metal.

Increased chromium and nickel offer some advantage to resist attack of the metal (fully annealed or in the absence of precipitated carbides). End grain attack may often be expected in this environment.

These tests must be conducted in special equipment because of the HF content. Figure I is a photograph of the test equipment. A polyethylene reflux tube surrounded by a glass jacket was inserted in the top of the Kel-F bottle. Cooling water was circulated through the jacket. The samples were suspended by means of knotted Teflon tape. The vessel was heated to boiling by immersion in a hot oil bath. Kel-F vessels were used in this case. Length of the test was six 24 hour periods at boiling temperature.

Specimens 1" x 2" of unwelded material were employed for weight loss determinations after various heat treatments at 2050, 2150 and 2300°F. Welded samples are examined visually and microscopically after the test to determine extent of intergranular corrosion. Samples were stopped before six periods if corrosion attack penetrated cross section.

Film G920

Approx. 1/2 Size

FIGURE 1

Kel-F Vessel and Polyethylene Reflux
Condenser Used for Boiling Tests in
13M HNO₃ + .075, 0.25 and 0.50 M HF

- (c) 6M HNO₃ + .4M H₂SO₄ + .4M NaNO₃ + .3M Fe₂(SO₄)₃ + .01M Cr⁺⁶ + .01M Hg + .01M PO₄ at boiling (108°C) - Complex Solution

There are certain characteristics of this solution which can be described.

Although there are other acids and salts added, this is primarily still a strong oxidizing environment because of the high (6M) nitric acid content. The sulfuric acid is approximately 4% by weight, but fortunately its effect is nullified by the strong inhibiting action of both the nitric acid and ferric sulfate. Similarly, phosphate ion will have no corrosive effect under such strongly oxidizing conditions. Sodium nitrate per se does not cause or inhibit corrosion to stainless steels. While the influence of mercury has never been defined, it is definitely known that hexavalent Cr ion is strongly accelerating to nitric acid attack especially in the range named (.01M).

It is concluded that this test is primarily a boiling 6M nitric acid test strongly affected by the accelerating Cr⁺⁶ ion. For alloys to resist this environment, higher chromium content is a beneficial constituent.

The tests were conducted in cold finger reflux condensers at boiling temperature. Time period for this test was 240 hours, with specimens weighed and losses calculated (inches penetration per month) each 24 hours. This is desirable since the accelerating effect of accumulating chromium Cr⁺⁶ ion can be studied. It must be remembered that the ratio of solution volume to specimen area (approximately 150 ml/sq inch) in our test would not exist in actual equipment in service, especially never in heat exchanger tubes.

Weld samples were examined visually and microscopically after tests for evidence of intergranular or other localized attack.

- (d) Boiling 65% Nitric Acid

Nitric acid is strongly oxidizing, so much so that it does not even attack mild steel at low temperatures. At boiling, 18-8 stainless steel may show corrosion rates of perhaps .7 to 1 mil/month, while Type 309 Cb shows about .3 to .5 mils/month.

Higher chromium content offers the most benefit to improve corrosion resistance while fringe advantages of low silicon, low manganese and low carbon in this environment are less known.

The test offers some value because it represents strong nitric conditions as in the application, and also because it is a standard well recognized test for stainless steels.

This test was conducted under reflux conditions with cold finger condensers for five 48-hour periods in boiling acid. All samples were preboiled 3 hours and weighed before regular tests were started. New acid was used for each period. Corrosion rates were calculated in inches penetration per month. Welded specimens were examined for knife-line and intergranular corrosion. Unwelded samples were tested in the three annealed conditions and also after sensitizing 1 hour at 1200°F.

(e) Pitting Test - 6% Ferric Chloride

The information provided is often helpful since the presence of chloride ion as a contaminant in processes can cause hazardous rapid penetration of vessel walls by pinhole pitting. Higher nickel contents are known to be helpful.

This test represents pitting under strongly depolarizing conditions. Specimens were totally immersed at room temperature and examined periodically for evidence of pitting. Freedom from pits after 300 hours indicates a high degree of corrosion resistance to localized attack by halogens. No weight losses were calculated for pitting tests.

(f) 0.5M Sulfuric Acid at 200°F

No present stainless steels will resist this solution. In the absence of nitric acid or ferric sulfate as inhibitors, attack due to .5M sulfuric is severe. It presents some indication of the stability of the passive condition of the alloys involved in the program.

The tests were conducted for 2 hours at the specified concentration and temperature. The tests were maintained at 200°F $\pm$ 1°F in a constant temperature water bath.

Activation in 150°F dilute 10% HCl was employed prior to testing in sulfuric acid. Specimens were immersed until the development of hydrogen bubbles on the surface, rinsed in hot water and immediately placed in the sulfuric acid solution.

Results of Corrosion Tests:

The tables presenting results of corrosion tests on sheet material are shown in their entirety at the end of the report in tables prefixed A, figures prefixed C.

Tables dealing with welded samples are prefixed B in the same manner.

For purposes of discussion, various pertinent summaries will be used in the text to illustrate and compare results.

General Corrosion Resistance of Various Compositions:

A. Effect of Annealing Temperature on Sheet

In the development of new alloys some knowledge of proper annealing temperature for best corrosion properties is needed. Previous experience with unbalanced, low nickel Type 316, for example, indicated that annealing at 2050°F was too high and corrosion rates in boiling nitric acid were excessive because of delta ferrite. An anneal at 1800°F corrected this situation. Similar reasoning applies to the duplex Cr-Ni alloys and even the very low carbon Type 309 with small amounts of ferrite. Corrosion rates in various environments for sheet samples annealed at 2050°F, 2150°F, and 2300°F are compared in Table V. This table also provides a very good summary of results for other comparisons later.

In general, variation in annealing temperature from 2050°F to 2300°F has relatively minor effects; while alloy composition has a greater influence in environments such as HNO₃-HF, the complex mixture and even in ferric chloride. However, there are some significant results which should be pointed out regarding annealing.

(a) There seems to be a slight general trend for decreasing corrosion rates in the boiling HNO₃-HF solutions as annealing temperature is raised from 2050°F to 2300°F although in a few cases the reverse may be true.

(b) In all but two cases, increasing anneal temperature from 2050°F to 2150°F increased corrosion rates in the boiling complex mixture. Rather drastic increases were observed with the three very low carbon and nitrogen vacuum melted heats, RV294, RV296 and RV297, and these show excessive rates of 8.8, 8.0 and 7.9 mils/month when annealed at 2150°F. They show severe intergranular surface attack in this environment and this unusual phenomenon will be discussed later.

(c) Annealing temperature has relatively little effect on boiling 65% nitric acid corrosion rates except again on two of the vacuum melted heats, RV294 and RV297, as well as Type 309L and Type 310, all of which increase in rate with increasing temperature.

(d) The rather erratic nature of the sulfuric acid corrosion attack does not permit any evaluation as to whether higher annealing temperature is hazardous or beneficial, but there appears to be some effect, varying with compositions.

(e) Among those few heats susceptible to attack in ferric chloride it can be said that vacuum melted compositions become worse with a higher anneal whereas all others improve.

(f) Since there may be increasing or decreasing corrosion rates in various solutions the choice of annealing temperature may be best governed by the type of environment. The attack by each solution is apparently different, depending upon structure of the alloy material involved.

For purposes of the later investigation, samples annealed at 2050°F were employed in the weld tests because of material limitations. The facts presented above must later be recalled in discussion of weld tests.

B. Effect of Composition

To avoid confusion and simplify presentation of data for easier comparison, subsequent discussion of the effects of composition will refer only to the 2050°F anneal condition since it applies to both sheet and welded plate tests.

TABLE V

INFLUENCE OF ANNEALING TEMPERATURE ON AVERAGE CORROSION RATES

SHEET SAMPLES

Heat No.	Type	Annealed at	13M HNO ₃ .25M HF mils/mo	13M HNO ₃ .50M HF mils/mo	Complex Mixture mils/mo Avg.	65% HNO ₃ in/mo Avg.	.5M H ₂ SO ₄ in/mo Avg.	FeCl ₃ Hours to Pit
FV71	35 Cr-20 Ni	2050°F	35	37	3.3	.0018	.33	100
		2150	30	42	3.5	.00020	.32	100
		2300	25	*	*	.00021	.24	300
FV11	30 Cr-25 Ni	2050°F	29	44	3.1	.00024	.22	No pits
		2150	26	39	2.6	.00020	.30	No pits
		2300	28	*	*	.00018	.32	No pits
FV20	30 Cr-20 Ni	2050°F	32	42	3.1	.00020	.14	100
		2150	34	*	3.8	.00018	.26	100
		2300	29	*	*	.00018	.25	100
FV70	30 Cr-15 Ni	2050°F	37	51	3.8	.00017	.42	24
		2150	34	48	4.0	.00023	.023	24
		2300	42	*	*	.00023	.71	24
FV19B	310 + 1 Si	2050°F	52	62	3.3	.00034	.20	No pits
		2150	47	58	2.9	.00017	.10	No pits
		2300	46	*	*	.00022	.28	No pits
FV56	310 + .03 Si + .004C	2050°F	44	71	2.8	.00024	.16	No pits
		2150	49	61	3.1	.00024	.08	24
		2300	50	*	*	.00023	.18	100
FV57	310 + .28 Si	2050°F	44	75	2.8	.00020	.23	No pits
		2150	42	70	3.0	.00023	.30	No pits
		2300	34	*	*	.00023	.23	No pits
FV17A	310 + .33 Mn	2050°F	61	72	3.1	.00027	.10	No pits
		2150	75	98	3.2	.00026	.17	No pits
		2300	62	*	*	.00023	.17	No pits
FV19A	310 + .02 C	2050°F	38	53	2.9	.00019	.23	No pits
		2150	43	*	3.4	.00031	.26	No pits
		2300	45	*	*	.00032	.26	No pits
GD44	310 + Cb	2050°F	45	64	3.5	.00024	.27	No pits
		2150	44	75	3.8	.00024	.29	No pits
		2300	38	*	*	.00027	.14	No pits
RV296	309 + .008 C	2050°F	57	93	7.8	.00024	.25	168
		2150	52	90	8.8	.00028	.24	144
		2300	47	*	*	.00032	.23	24
RV294	309 + .004 C	2050°F	58	87	6.2	.00027	.38	144
		2150	70	89	8.0	.00027	.28	144
		2300	57	*	*	.00028	.45	48

TABLE V (contd)

<u>Heat No.</u>	<u>Type</u>	<u>Annealed at</u>	<u>13M HNO₃ .25M HF mils/mo</u>	<u>13M HNO₃ .50M HF mils/mo</u>	<u>Complex Mixture mils/mo Avg.</u>	<u>65% HNO₃ in/mo Avg.</u>	<u>.5M H₂SO₄ in/mo Avg.</u>	<u>FeCl₃ Hours to Pit</u>
RV297	309 + .008 C	2050°F	59	85	6.6	.00023	.16	168
		2150	55	90	7.9	.00028	.21	144
		2300	54	*	*	.00033	.25	24
FY78	309 + .026 C	2050°F	77	105	5.7	.00022	.35	56
		2150	54	102	5.9	.00026	.34	168
		2300	51	*	*	.00030	.37	144
FY79	309 + Cb	2050°F	69	126	5.3	.00028	.27	No pits
		2150	60	94	5.4	.00029	.26	No pits
		2300	62	*	*	.00028	.29	No pits

* Not Tested

Table VI is a condensed version of results for 2050°F annealed sheet in the three HNO₃-HF solutions, the complex mixture and the boiling 65% HNO₃ test. Sulfuric acid and ferric chloride results, which show little relation to the other tests will be discussed separately.

It is immediately apparent upon inspection of the table that there are drastic differences in corrosion rates among the five different solutions, varying as much as 300 fold between boiling nitric acid and the strongest HNO₃-HF mixture. A second significant observation is that there is no relationship among the tests, and good corrosion resistance in one environment does not permit a prediction that proportionally good performance of an alloy can be expected in one of the others. A slight exception exists for the three HNO₃-HF solutions which show reasonable good relationship to each other and rates increase proportionately with HF content. For example, a comparison of three heats will be shown below to illustrate this better. All have practically the same nitric acid corrosion rates but vastly different behavior in other environments.

<u>Heat No.</u>	<u>Type</u>	<u>Boiling 65% HNO₃</u>	<u>Complex Mixture</u>	<u>13M HNO₃ + .50M HF</u>
FV11	30 Cr-25 Ni	.00024 in/mo	3.1 mils/mo	44 mils/mo
GD44	310 Cb	.00024 in/mo	3.5 mils/mo	64 mils/mo
FY79	309L	.00022 in/mo	5.7 mils/mo	105 mils/mo

It is necessary, therefore, to evaluate all three type environments at the same time to have any significance. Individual discussion of different compositions or groups of compositions will follow.

(a) High Chromium Nickel Alloys

Taking first the four high chromium nickel alloys, these show definitely the lowest corrosion rates in the HNO₃-HF solutions of all the materials tested. They do not, however, show any different corrosion rates than Type 310 or its modifications in the complex mixtures and, in fact, may even show slightly greater attack. Furthermore, their performance in nitric acid is about the same as the other materials in the program though perhaps a little lower than the Type 309 group. Comparing with Type 310

TABLE VI

EFFECT OF COMPOSITION ON CORROSION RATES

SHEET SAMPLES ANNEALED 2050°F

Heat No.	Type	13M HNO ₃ + .075M HF mils/mo	13M HNO ₃ + .25M HF mils/mo	13M HNO ₃ + .50M HF mils/mo	Complex Mix mils/mo	65% HNO ₃ in/mo
FV71	35 Cr-20 Ni	11.3	35	37	3.3	.00018
FV11	30 Cr-25 Ni	10	28	44	3.1	.00024
FV20	30 Cr-20 Ni	11.3	32	42	3.1	.00019
FV70	30 Cr-15 Ni	17.6	36.4	51	3.8	.00017
FV19B	310 + 1.0 Si	16.8	52	62	3.3	.00034
FV56	310 + .03 Si*	17.5	44	73	2.8	.00024
FV57	310 + .28 Si	14.5	44	73	2.8	.00020
FV17A	310 + .33 Mn	22.3	61	72.5	3.1	.00027
FV19A	310 + .020 C	15	39	73	2.9	.00019
GD44	310 + Cb	13	45.5	64	3.5	.00024
RV296	309 + .008 C	20	57	93	7.8	.00024
RV294	309 + .004 C	19.2	57.5	87	6.2	.00027
RV297	309 + .008 C	19	58.5	82	7.6	.00023
FY78	309 + .026 C	25.8	76.5	105	5.7	.00022
FY79	309 + Cb	22.5	69	126	5.3	.00028

* .004% C

materials in the HNO_3 -HF solutions, there is indication that increasing chromium content to 30% in Heat FV20 and to 35% in Heat FV71 with a 20% nickel level has provided added corrosion resistance. Similarly a comparison of Heat FV70 containing 30% Cr and 15% Ni with the Type 309 steels shows even more drastic improvement for an increase of 8% chromium content. All of these four special chromium nickel alloys are a considerable improvement over Type 309 materials in the complex mixture. The effect of nickel is less pronounced than chromium, at least at the higher chromium levels, and a change of 10% nickel does not affect rates to any great extent.

The fully austenitic 25 Cr-20 Ni Heat FV11 appears promising in this group, showing good corrosion resistance and offering certain advantages of a single phase structure.

(b) Type 310 Group

As a whole, this group offers a marked improvement over the Type 309 series in the complex mixture solution and HNO_3 -HF solutions. There is variation in this group, since several composition factors were investigated. The very high silicon content Heat FV19B showed interesting good performance in the HNO_3 -HF solutions, but did appear slightly inferior to all other heats in boiling 65% nitric acid. No outstanding corrosion resistance was realized with the very low silicon (and very low .004% carbon) Heat FV56 or with the low .33% manganese Heat FV17A, which may actually be somewhat inferior in HNO_3 -HF solutions. From the more practical standpoint either a .02% carbon Type 310 or a .02% carbon Type 310 Cb, Heats FV19A and GD44 respectively, appear promising in this group. These latter two show superiority to Types 309L and 309 Cb in both HNO_3 -HF and complex solution tests.

(c) Type 309 Group

In this series the most paradoxical behavior is exhibited. Somewhat better corrosion rates of the three very low carbon vacuum melted heats over 309L and 309 Cb in HNO_3 -HF solutions is nullified by their poorer resistance to the complex solution.

Regardless, however, the group as an entirety is poorer than all other materials included in the program. Very low carbon and nitrogen content of the vacuum melted Type 309 heats does appear a benefit in HNO_3 -HF.

As a consequence of the comparison above, certain conclusions can be reached regarding the preferred compositions for best corrosion resistance.

Using the regular Type 309L (Heat FY78) and Type 309 Cb (Heat FY79) as a base for comparison it is quite evident that Type 310L (actually .020 C in Heat FV19A) and Type 310 Cb (Heat GD44) offer much superior resistance to both the HNO_3 -HF solutions as well as the complex mixture. Relatively little significance of composition is noted in the 65% boiling nitric acid tests. Apparently the 65% boiling nitric test is most useful for evaluation of sensitization and intergranular susceptibility; more of this will be discussed later.

In addition for the ultimate in corrosion resistance to the HNO_3 -HF solutions, it is apparent that the higher chromium and nickel alloys offer the greatest benefit. Among these heats, FV11, a 30 Cr-25 Ni alloy which is fully austenitic in structure, shows the best corrosion resistance. None of the high Cr-Ni alloys, however, offer any better corrosion properties than the Type 310 alloys in the complex mixture or in boiling 65% HNO_3 . Both Type 310 and the high Cr-Ni alloys are, however, much better than any of the Type 309 alloys in the complex mixture.

Figure 2 is a bar graph which compares performance of .026% carbon Type 309; Type 309 Cb; .020% carbon Type 310; Type 310 Cb; and 30% Cr-25% Ni alloy in the 13 Molar HNO_3 + .25 Molar HF and in the complex mixture. It is evident that an improvement in corrosion resistance has been obtained.

C. Sulfuric Acid and Ferric Chloride Pitting Tests

The results of both these tests have no relationship to the other environments and will be discussed separately here.

There is no relationship observed between sulfuric acid corrosion rates and any composition primarily because corrosion in sulfuric acid under these test

13 Molar HNO_3 +
0.25 Molar HF

Complex Mixture
6M HNO_3 + .4M H_2SO_4 + .4M NaNO_3
+ .3M $\text{Fe}_2(\text{SO}_4)_3$ + .01M Cr + .01M Hg
+ .01M PO_4

FIGURE 2

conditions is taking place in the active state, and rates are known to be erratic in such cases. It was hoped that some higher alloy compositions might show passivity in this test. Some interesting information was learned from these tests on welded plate samples. These are summarized in the following short table, covering visual examination of the machined edges for unusual attack. End grain attack, a form of very deep lines of corrosion attack usually associated with the presence of non-metallic inclusions was observed on some materials:

<u>Heat No.</u>	<u>Description of Sulfuric Acid Test (Welded) Specimens</u>
FV70	Heavy end grain attack. Heavier band of etching starting at weld and extending out about 3/16" into base metal.
FV71	Same as FV70
FV20	Light etch
FV11	Light etch
FV17A	Appreciable end grain attack
FV19A	Light etch only
FV19B	Light etch only
FV56	Trace end grain attack
FY78	Severe end grain attack
RV296	Severe end grain attack
RV294	Severe end grain attack
RV297	Severe end grain attack
FY79	Severe end grain attack

Heats FV70 and FV71 contain the highest amounts of delta ferrite. Apparently the heat affected zone susceptible to slightly more rapid sulfuric attack in these areas is not a case of precipitated carbides, but more likely delta ferrite.

The ferric chloride test results are also of interest, since resistance to chloride pitting is valuable in chemical processing equipment. Failure due to rapid

penetration of a tank wall can be hazardous. The typical appearance of a deeply pitted material is illustrated by Figure 3 for one of the welded plate specimens.

Certain materials showed very good resistance to pitting in 300 hours exposure. It is significant to note that this environment was found to be rather sensitive to delta ferrite. Those heats which failed by pitting were in every instance compositions containing delta ferrite even in small amounts of 2% or 3%. There is no relationship between ferrite content and time to pitting, however.

Effect of Welding or Sensitizing on Corrosion Resistance:

A. Welding

The results of corrosion tests on as welded samples appear in Tables B-1 to B-5 inclusive at the end of the report. While the corrosion rates are of great interest, they are influenced by certain factors more critical which demand visual or microscopic inspection, namely end grain attack, weld attack or pitting and possibly intergranular attack.

Figure 4 is a photograph of selected samples after tests in the boiling complex solution of nitric acid and sulfuric acid plus certain salts. These were cut for microscopic examination before photographing. In general, the extent of attack is much less than in the nitric-hydrofluoric solutions shown later. No severe weld attack or pitting has occurred. However, certain heats show faint evidence of attack in heat affected zones in this solution. Although it is somewhat difficult to note from the photograph, all the samples show slightly different attack in the heat affected zone than the base metal. Heats RV294, RV296 and RV297 show apparent bands of attack extending out from the weld to about $3/16$ " or $1/4$ ". Heats FY78, FY79, FV17A, and FV17B show apparent narrower bands of attack very close to the weld. FV11 shows a broad band of attack which starts beyond $1/8$ " from the weld. All other heats show no accelerated localized attack in this corrosive medium.

In Figure 5 we have shown all the weld specimens after they have been tested in the boiling 13 molar nitric + 0.25 molar hydrofluoric solution. Intergranular

6% FERRIC CHLORIDE PITTING TEST

HEAT FV-20

PITTED 20 HRS BASE METAL
PITTED 96 HRS IN WELD

Film G994

FIGURE 3

As Welded Samples after testing ten 24 hour periods
in boiling 6M HNO₃ + .4M H₂SO₄ + .4M NaNO₃
+ .3M Fe₂ (SO₄)₃ + .01M Cr + .01M Hg + .01M PO₄

FV-11
3.7 mils/mo

FV-17B
3.5 mils/mo

FV-17A
3.5 mils/mo

FY-78
4.9 mils/mo

RV-296
5.1 mils/mo

RV-294
4.9 mils/mo

RV-297
5.2 mils/mo

FY-79
4.6 mils/mo

Film G995

FIGURE 4

HIGH CR-NI

TYPE 310 GROUP

TYPE 309 GROUP

FV-71
42 mils/mo

FV-19B
56 mils/mo

RV-296
82 mils/mo

FV-11
45 mils/mo

FV-56
59 mils/mo

RV-294
68 mils/mo

FV-20
35 mils/mo

FV-57
50 mils/mo

RV-297
60 mils/mo

FV-70
54 mils/mo

FV-17A
71 mils/mo

FY-78
72 mils/mo

FV-19A
39 mils/mo

FY-79
118 mils/mo *

AS WELDED SAMPLES

AFTER SIX-24 HOUR PERIODS

IN BOILING 13M HNO₃ + .25M HF

GD-44
49 mils/mo

*Tested one
24 hr. period

Film G996

FIGURE 5

attack is very evident on Heat FV11, and some apparent slight accelerated attack adjacent to the weld can be faintly seen on Heats FV19B, FV56, FV71, FV19A and FY78. It is also obvious that severe weld deterioration has occurred on Heat FY79, the Type 309 Cb with filler metal of the same composition. There was appreciable pitting of the weld and base metal adjacent to the weld on Heat FV17A, a .33% manganese Type 310.

The appearance of samples in the boiling 13 molar HNO_3 + .50 molar HF solution is similar to this photograph with the exception of more severe attack of FV11 and FY79. Samples FV19B, FV56, FV19A and FY78 likewise appear the same in all three HNO_3 -HF solutions, with a faint line of attack adjacent to the weld but which is not intergranular. The depth of attack is not more than .001" on any of these four latter samples in any of the three solutions.

To better report the results of attack in the weld and the heat affected zones, the following Figure 6 and Table VII have been employed to help describe the areas in question. A visual rating of the intensity of attack in both environments is given in Table VII. Numerical ratings used are described as follows:

- 1 - Negligible attack with respect to adjacent areas
- 2 - Slight accelerated attack less than .004" with respect to adjacent areas
- 3 - Accelerated attack up to .020" with respect to adjacent areas
- 4 - Very severe attack
- P - Pitting
- X - Definite intergranular
- E - End grain attack

The average corrosion rates for all three HNO_3 -HF solutions and the complex solution also appear in Table VII.

FIGURE 6

WELD SAMPLE DESCRIPTION

- A = weld deposit
- B = heat affected zone due to cross weld
- C = machined end of weld
- D = machined base metal
- E = base metal 1/8" from weld
- F = area on surface 1/32" from weld
- G = area on surface 1/8" to 1/4" from weld
- H = surface of base metal 1/2" from weld

TABLE VII

VISUAL RATING OF WELDED SAMPLES AFTER CORROSION TESTS IN 13 MOLAR HNO_3 + .50 MOLAR HF

AND IN COMPLEX MIXTURE

Heat No.	Type	Welded With	HNO ₃ - .50 Molar HF								Corrosion Rates in 13M HNO ₃ +			Complex Mixture								Rate mils/mo	Surface Grain Boundary Etch
			A	B	C	D	E	F	G	H	.075M	.25M	.50M	A	B	C	D	E	F	G	H		
FV71	35 Cr-20 Ni	310	1	1	1	2	3	2	3	2	26	42	85	1	1	1	1E	1	1	1	1	3.8	No
FV11	30 Cr-25 Ni	310	1	1P	1	2	3X	1	4X	2	17	45	71	1	1	1	1	2	1	2X	1	3.7	Yes
FV20	30 Cr-20 Ni	310	1	1	1	2	2	1	1	1	14	35	76	1	1	1	1	1	1	1	1	3.4	No
FV70	30 Cr-15 Ni	310	1	1	1	E	E	1	2	1	25	54	83	1	1	1	1	1	1	1	1	4.6	No
FV19B	310 + 1 Si	310	1	1	3P	3E	3E	1	2	1	23	59	94	1	1	1	1	1	1	1	1	3.8	Yes
FV56	310 + .03 Si	310	1	3P	3P	1E	1E	1	2	1	30	59	91	1	1	1	1	1	1	1	1	2.8	Yes
FV57	310 + .28 Si	310	1	2P	2P	1	1	1	1	1	27	50	92	1	1	1	1	2X	1	1	1	2.9	Yes
FV17A	310 + .33 Mn	310	4P	4P	4P	1E	1E	4P	1	1	30	71	115	1	1	1	1	1	1	1	1	3.5	Yes
FV19A	310 + .020 C	310	3P	3P	4P	2E	2E	1	2	1	22	39	87	1	1	1	1	1	1	1	1	3.2	Yes
FV17B	310 + .018 C	310	1	1	3P	1	1	1	1	1	23	59	122	1	1	1	1	1	2	1	1	3.5	Yes
GD44	310 Cb	GD44	1	1	2P	1	1	1	1	1	27	46	92	1	1	1	1	1	1	1	1	3.7	Yes
RV296	309 + .008 C	RV296	2	2	2	1	1	1	1	1	36	82	133	1	1	1	1	1	2	2	1	5.1	Yes
RV294	309 + .004 C	RV294	3	3	3	1	1	1	1	1	38	68	149	1	1	1	1	3X	2	2	1	4.9	Yes
RV297	309 + .008 C	RV297	2	2	2	1	1	1	1	1	34	70	122	1	1	1	1	3X	2	2	1	5.2	Trace
FY78	309 + .026 C	FY78	1	1	1	2E	2E	1	1	2	38	72	122	1	1	1	1	1	2X	1	1	4.9	Yes
FY79	309 + Cb	FY79	4	4	4	1	1	1	1	1	70	118	193	1	1	1	1	3X	3X	1	1	4.6	Yes

No definite accelerated attack could be observed on any of the boiling 65% nitric acid weld test specimens, even under 30X magnification. The occasional slightly higher rates on welded plate was attributed to somewhat rougher surfaces and slight traces of end grain attack (often common to laboratory size heats). There was no acceleration of corrosion rates from period to period, a phenomenon observed when intergranular attack occurs.

However, to more carefully examine any compositions suspected of intergranular attack, sheet samples of each composition and special selected plates were reannealed at 2050°F and then sensitized for one hour at 1200°F and tested in boiling 65% nitric acid. Results of sensitized sheet appear in Table A-7 and sensitized plate in Table B-6 at end of the report. In both cases some increase of corrosion rate was observed, but surprisingly these samples showed no intergranular surface attack nor did they show increasing corrosion rates from period to period, which would tend to further confirm that no intergranular attack had occurred.

If we refer to the five heats we compared previously in the bar graphs in Figure 2 as the most promising compositions, and select them for further study as in Table VIII, we will note all have increased rates as sensitized.

TABLE VIII

EFFECT OF SENSITIZATION

NITRIC ACID CORROSION RATES IPM

<u>Heat No.</u>	<u>Type</u>	<u>Annealed 2050°F</u>	<u>Sensitized 1200°F</u>	<u>Ratio</u>
FV11	30 Cr-25 Ni	.00024	.00034	1.4
FV19A	Type 310 + .020 C	.00019	.00041	2.2
GD44	Type 310 Cb + .02 C	.00024	.00029	1.2
FY78	Type 309 + .026 C	.00022	.00046	2.1
FY79	Type 309 Cb	.00028	.00039	1.4

If the increased rates (even without intergranular attack) have any significance, then there again appears to be a high degree of promise for Heat GD44, the Type 310 with .02% carbon and .22% columbium.

Based on the corrosion test results and visual studies reported in Tables VII, A-7, B-6 and VIII, certain observations can now be made:

(a) The nitric-HF solution is far more severe in its effect to produce visual localized attack.

(b) End grain attack is a problem with heavy sections where edge to surface area ratio is appreciable. Laboratory heats are more prone to show this than commercial production material. In actual equipment, this would not be the serious factor it is here.

(c) Pitting of the weld surface and especially ends can have a serious influence on corrosion rate in HNO_3 -HF tests.

(d) No visual end grain attack is observed in the complex mixture, nor severe weld attack.

(e) In spite of mild pitting on the ends of the weld (area C) on GD44, results indicate that .020% carbon Type 310 Cb presents the best corrosion resisting as-welded surface for the HNO_3 -HF solutions. Heat FV20, a 30 Cr-20 Ni alloy is also good. Neither show localized surface attack. FV19A, a .020 carbon Type 310 also showed a gray etch in the heat affected zone, but corrosion rates were high due to a combination of weld pitting and end grain attack.

(f) Regardless of localized attack effects, the Type 310 compositions and the high Cr-Ni alloys are superior to Type 309 in both media.

(g) Heats RV294, RV297, FY78 and FY79, the Type 309 series, all show attack immediately adjacent to the weld (area F on drawing Figure 6) in the complex solution, but none in this area when subjected to HNO_3 -HF tests.

Metallographic Examination:

Samples of welded plate were all subjected first to examination at 30X magnification to examine the surface, welds and heat affected zones more critically and then each was cut, metallographically polished, etched with oxalic etchant and examined at 250X. The examination at 30X was quite surprising.

A. 30X Study

As earlier reported, no intergranular attack could be seen on the boiling 65% nitric acid samples. It appears that the nitric acid tests is not as sensitive as the other two solutions for detecting intergranular susceptibility. An examination of weld samples after testing in HNO_3 -HF solutions and the complex mixture revealed the observations reported in Table IX. Tests in 13M HNO_3 -.075M HF and 13M HNO_3 -.25M HF showed the same results as in the table but to somewhat lesser degree.

TABLE IX30X STUDIES FOR SURFACE ATTACK BY HNO_3 -HF AND COMPLEX SOLUTIONS

Heat No.	Type	13M HNO_3 + .50M HF	Complex
FV71	35 Cr-20 Ni	Line 1/8" from weld. No IG	End grain attack. No IG
FV11	30 Cr-25 Ni	IG adjacent to weld	Deep grain boundary etch-also in weld
FV20	30 Cr-20 Ni	No IG	No IG
FV70	30 Cr-15 Ni	No IG	No IG
FV19B	310 + 1 Si	Etch 1/4" from weld	Deep grain boundary etch-also in weld
FV56	310 + .03 Si	No IG	No IG
FV57	310 + .28 Si	No IG	Deep grain boundary etch-also in weld
FV17A	310 + .33 Mn	Pits adjacent to weld	Deep grain boundary etch-also in weld
FV19A	310 + .02 C	Etch 1/4" from weld	Deep grain boundary etch-also in weld
GD44	310 + Cb	No IG	Deep grain boundary etch-also in weld
RV296	309 + .008 C	Undercut weld. No IG	Very rough IG surface
RV296	309 + .004 C	Undercut weld. No IG	Very rough IG surface. IG at edge of weld
RV297	309 + .008 C	Undercut weld. No IG	Very rough IG surface. IG at edge of weld

TABLE IX (contd)

<u>Heat No.</u>	<u>Type</u>	<u>13M HNO₃ + .50M HF</u>	<u>Complex</u>
FY78	309L	Etch 1/4" from weld	Deep grain boundary etch. Also IG
FY79	309 C	Severe attack of weld	Rough IG surface. Deep IG at edge of weld

The condition observed on the complex solution samples was startling since it occurs in base metal completely unheated by welding. The unusual deep grain boundary etch or perhaps intergranular surface attack is pictured in Figure 7 taken at 30X on sample FV19A. Note that the attack occurs also along grain boundaries in the weld. This condition is not the commonly observed intergranular surface attack sometimes encountered after annealing and pickling. It was also quite evident on machined and polished edges; such edges were prepared as a final step before corrosion testing and, therefore, never had any anneal scale on them. Based on subsequent 250X microscopic examination, this intergranular etch occurs in the absence of visible grain boundary precipitate. At the present time this phenomenon is not understood but points to a possible invisible precipitate of some type that is sensitive to attack in this specific complex solution environment. In contrast the more severely corrosive HNO₃-HF solutions did not produce it in any instance.

Another interesting facet of this unusual grain boundary etch effect is that it does not occur with the duplex structures in Heats FV70, FV71 and FV20. The surface attack can occur far from any weld; it does not penetrate a full grain deep, and as a matter of fact could not be seen in a 250X microscopic examination of the cross section. Because of our concern about this serious condition, we examined all sheet samples which had been tested in the complex solution; here we had an opportunity to view samples with a 2050°F anneal and a 2150°F anneal. The results are tabulated in Table X.

Film G993

30X

FIGURE 7

Sample FV19A

Showing Deep Grain Boundary Etch in
Base Metal and Weld After Tests in
Complex Mixture

TABLE X

30X EXAMINATION OF SHEET SAMPLES AFTER COMPLEX SOLUTION TEST
FOR GRAIN BOUNDARY ETCH

<u>Heat No.</u>	<u>Type</u>	<u>2050°F</u>	<u>2150°F</u>
FV71	35 Cr-20 Ni	No	No
FV11	30 Cr-25 Ni	No	Yes
FV20	30 Cr-20 Ni	No	No
FV70	30 Cr-15 Ni	No	No
FV19B	310 + 1.0 Si	Trace	Heavy
FV56	310 + .03 Si	Yes	No
FV17A	310 + .33 Mn	Yes-mild	Yes-mild
FV19A	310 + .02 C	Yes	Yes-severe
GD44	310 Cb	Yes-severe	Yes
RV296	309 + .008 C	Yes-severe	Yes-severe
RV294	309 + .004 C	Yes-severe	Yes-severe
RV297	309 + .008 C	Yes-severe	Yes-severe
FY78	309L	Yes-severe	Yes-severe
FY79	309 Cb	Trace	Yes-heavy

It may be concluded that there probably is a susceptible precipitate of some type that is in most cases formed at higher temperatures. We have been unable to see any precipitate microscopically. It could explain the existence of heavier or grain boundary attack on Type 309 materials commencing immediately at the edge of the weld and extending a short distance into the base metal, for this area has reached very high temperatures (above 2050°F) next to the fusion zone. While the attack may be too superficial to be detected in corrosion rates, nevertheless it should be of concern and deserves much further investigation beyond the scope of this alloy development program.

B. Metallographic Studies

All the samples were examined metallographically to establish structures and presence of grain boundary precipitates. In addition they were examined for evidence of surface attack. The results are summarized in Tables XI and XII and illustrated with a series of photomicrographs that follow.

TABLE XI

METALLOGRAPHIC EXAMINATION OF WELD HEAT AFFECTED ZONE
AFTER TESTS IN COMPLEX MIXTURE

<u>Heat No.</u>	<u>Type</u>	<u>Weld</u>	<u>Delta Ferrite</u>	<u>Grain Boundary Carbides in Heat Affected Zone</u>	<u>Surface Attack</u>	<u>Weld Attack</u>
FV71	35 Cr-20 Ni	310	Yes	Very slight precipitation	None	None
FV11	30 Cr-25 Ni	310	None	Continuous	Some IG attack	None
FV20	30 Cr-20 Ni	310	Yes	None	None	None
FV70	30 Cr-15 Ni	310	Yes	None	None	None
FV19B	310 + 1 Si	310	None	Some discontinuous precipitation	Trace	None
FV56	310 + .03 Si	310	None	None	None	None
FV57	310 + .28 Si	310	None	Very light precipitation	None	None
FV17A	310 + .33 Mn	310	None	None	None	None
FV19A	310 + .020 C	310	None	Very light precipitation	None	None
FV17B	310 + .018 C	310	None	Light precipitation	None	None
GD44	310 + Cb	GD44	None	Very light	None	None
RV296	309 + .008 C	RV296	Trace	None	None	None
RV294	309 + .004 C	RV294	Trace	Very light precipitation	None	None
RV297	309 + .008 C	RV297	Trace	Very light precipitation	None	None
FY78	309 + .026 C	FY78	Trace	Light precipitation	None	None
FY79	309 + Cb	FY79	None	None	None	None

There was no microscopic evidence of intergranular attack adjacent to the weld on any of the Type 310 materials. Among the high Cr-Ni alloys only the 35 Cr-20 Ni composition showed any evidence of attack adjacent to the weld. These results are

encouraging since the Type 310 Cb and the .020 C Type 310 which are promising have shown no intergranular susceptibility in this environment, and in addition the weld deposit of .018% carbon Type 310 (from Heat FV17B) shows no susceptibility. Even the heats, RV294, RV297, and FY79, which showed indication of a heavier line of attack at the heat affected zone visible on the edges of welded plate specimens, do not show serious intergranular penetration or graininess when examined metallographically at 250X.

Figures 8 to 14 inclusive were structures at the surface of various samples after testing in the complex solutions. These have been selected to illustrate various representative structures and what they show after corrosion tests in this environment.

Figure 8 is a photograph of Heat FV11, the austenitic 30% Cr-25 % Ni steel in the weld heat affected zone. Note the presence of a continuous carbide precipitate and definite intergranular attack at the surface.

Figure 9 is a duplex austenitic-ferritic structure of Heat FV71, a 30 Cr-15 Ni alloy in the weld heat affected zone. There was no visual evidence of accelerated attack at weld heat affected zones and this is confirmed by a microscopic examination.

Figures 10 and 11 represent Type 310 heats without a grain boundary precipitate in the weld heat affected zone. Note the very rough surface in Figure 10; this was present all over the surface of the base metal even in areas remote from weld heat affected zones. This could be the surface etch described above and shown in Figure 7, but note that this is a material which has no visible grain boundary precipitate. In Figure 11 some discontinuous precipitate is visible in the heat affected zone, and there is some slight evidence of attack of a pitting nature but not necessarily at the grain boundaries.

Figure 12 is the vacuum melted Heat RV296 with very low carbon which shows delta ferrite. The area shown is immediately beside the edge of the weld. There is

no grain boundary carbide precipitate, yet some traces of surface etch are apparent. The surface appears the same in base metal areas remote from the weld heat affected zone.

Figure 13 represents .02% carbon Type 310 Cb in the weld heat affected zone. The trace amounts of discontinuous grain boundary precipitate have not promoted any intergranular corrosion. The surface showed the unusual grain boundary etch when examined at 30X but the condition existed all over the surface and not confined to weld heat affected zones.

Figure 14, the Type 309 Cb weld, showed no evidence of attack in the complex boiling mixture. This is in surprising contrast to the performance of the same weld in boiling HNO_3 -HF solution pictured in Figure 19 later.

Table XII deals with microscopic examination at 250X of samples that showed any suspicion of possible intergranular corrosion in the boiling HNO_3 -HF solutions. Again it was seen that no intergranular corrosion had occurred in this solution other than the one instance of FV11, the austenitic 30 Cr-25 Ni alloy which also was attacked in the complex solution.

The attack in HNO_3 -HF solutions on the all austenitic samples is severe and appears as in Figure 15. No attack is evident at grain boundaries in spite of the discontinuous precipitate.

Figure 16 dealing with Heat FV-11 shows intergranular attack as expected. Figure 17 is the duplex structure 35 Cr-20 Ni heat at the heat affected zone. The same structure and surface attack is also seen at areas remote from the heat affected zone.

The final two figures, 18 and 19, show the Type 309 Cb base metal and weld. Although Figure 18 shows no surface attack in the heat affected zone beside the weld, there is serious deterioration of the weld itself (Figure 19). There is no evidence from metallographic examination to explain the rapid corrosion of the Type 309 Cb in HNO_3 -HF solution. The Type 310 Cb weld in this program is not subject to this type of deterioration.

FIGURE 8

Plate 200E8

250X Oxalic

Heat FV11

Weld Heat Affected Zone After
Test in Complex Solution

FIGURE 9

Plate 200E9

250X Oxalic

Heat FV71

Weld Heat Affected Zone After
Test in Complex Solution

FIGURE 10

Plate 200E10

250X Oxalic

Heat FV17A

Weld Heat Affected Zone After
Test in Complex Solution

FIGURE 11

Plate 200E7

250X Oxalic

Heat FV19B

Weld Heat Affected Zone After
Test in Complex Solution

FIGURE 12

Plate 201E3

250X Oxalic

Heat RV296

Weld Heat Affected Zone After
Test in Complex Solution

FIGURE 13

Plate 201E1

250X Oxalic

Heat GD44

Weld Heat Affected Zone After
Test in Complex Solution

FIGURE 14

Plate 201E2

250X Oxalic

Heat FV79

Weld in Heat FV79 Type 309Cb

After Test in Complex Mixture

FIGURE 15

Plate 201E7

250X Oxalic

Heat FV19B

Weld Heat Affected Zone After

Test in 13M HNO₃ - .50M HF

FIGURE 16

Plate 201E8

250X Oxalic

Heat FV11

Weld Heat Affected Zone After

Test in 13M HNO_3 - .50M HF

FIGURE 17

Plate 201E4

250X Oxalic

Heat FV71

Weld Heat Affected Zone After

Test in 13M HNO_3 - .50M HF

FIGURE 18

Plate 201E5

250X Oxalic

Heat FV79

Weld Heat Affected Zone After

Test in 13M HNO₃ - .50M HF

FIGURE 19

Plate 201E6

250X Oxalic

Weld in Heat FV79 After

Test in 13M HNO₃ - .50M HF

TABLE XII

METALLOGRAPHIC EXAMINATION OF WELDED 1/4" PLATE SAMPLES

HNO₃-HF TESTS

Heat No.	Weld Metal	Heat Affected Zone	
		Area Next to Weld	Area ~1/8" from Weld
FV19B	All austenitic	No precipitation carbides	Some discontinuous precipitation
FV11	Possible trace of ferrite	No precipitation	Continuous precipitation carbides- intergranular attack
FV19A	All austenite	No precipitation	Slight amount discontinuous precipitation
FV71	Considerable ferrite	~30% ferrite in base metal	~30% ferrite, probably precipita- tion along ferrite austenite
FV56	All austenite	No precipitation	No precipitation
FY79	~5% ferrite	Trace of ferrite with precipitation along ferrite-austenite boundaries	Trace of ferrite with precipitation along ferrite-austenite boundaries

The microexamination of weld corrosion test specimens has revealed the following significant conclusions.

1. Although the HNO_3 -HF solutions are highly corrosive in nature they do not produce intergranular attack except where a continuous grain boundary precipitate is present.

2. In contrast the complex solution appears capable of causing intergranular etching (of a superficial nature less than a grain deep) of the austenite structures even in the absence of a visible grain boundary precipitate; it does not do this with duplex structures. The invisible precipitate or grain boundary condition appears to be more severe with higher annealing temperatures. This could explain the location of appreciable intergranular attack immediately at the edge of weld fusion zones in Type 309L or 309 Cb materials which extends an appreciable distance into the base metal, diminishing in intensity as the distance increases. Such attack does not occur in a sharp, deep line, like the so-called knife-line attack seen with welded and sensitized Type 347 or Type 309 Cb. This appreciable band attack next to the fusion zone does not occur on any of the Type 310 compositions included in this program.

3. With the exception of the 30 Cr-25 Ni Heat FV11 that had continuous grain boundary precipitate, microscopic examination after the HNO_3 -HF tests at 250X was not able to reveal any intergranular corrosion or grain fall-out at the surface of any compositions included in the program. Even the FV vacuum melted heats showed no attack at the edge of the fusion zone in HNO_3 -HF, although they definitely were attacked in the complex solution, visible on the machined ends.

4. Heat GD44, Type 310 Cb, showed no intergranular attack in any of the solutions, either in the as welded condition or after sensitizing. It is subject, however, to the mild surface intergranular etch similar to all the other austenitic compositions, but which is not serious.

5. There is no explanation (no structural peculiarity) why Type 309 Cb welds are subject to severe deterioration in boiling HNO_3 -HF solutions but unaffected by the complex solution. The Type 310 Cb weld was unaffected by either solution.

6. In those instances where the HNO_3 -HF solution produces an apparent gray etch in heat affected zones, with trace grain boundary precipitate, this attack is superficial (not more than .001" deep) and is not intergranular or graying in nature.

Conclusions of Investigation:

1. Results of the investigation indicate that .02% carbon Type 310 Cb or .02% carbon Type 310 both are an improvement over Type 309L and Type 309 Cb in the nitric-hydrofluoric and complex solutions from the standpoint of general corrosion rates. All of the high Cr-Ni alloys show improved corrosion rates over both Types 309 and 310 compositions in HNO_3 -HF solutions, but the high Cr-Ni alloys are about comparable to Type 310 materials in the complex mixture.

2. All of the Type 310 alloys, as well as Heat FV11, a 30 Cr-25 Ni alloy, are fully austenitic. Corrosion rates in any of the environments does not appear to be affected by the presence or absence of ferrite; rather instead their alloy content has a dominant influence, with chromium being strongest and nickel less. Only in 6% FeCl_3 does ferrite appear to have an influence in promoting pitting.

3. Silicon and manganese variations have perhaps slight effect on corrosion in the various environments, but not sufficient to consider such variables as sufficient to improve corrosion resistance to the point desired. High silicon may be a disadvantage in 65% HNO_3 .

4. In weld tests on plate, corrosion tests in HNO_3 -HF and the complex mixture are the only ones capable of developing intergranular attack on the alloys in this program. The HNO_3 -HF solution caused definite intergranular attack of FV11 the austenitic 30 Cr-25 Ni alloy (with .084% N) in the heat affected zone. The complex solution showed severe intergranular attack of the same Heat FV11 and accelerated

attack at the edge of the fusion zone on Heats RV294, RV297, FY79, all Type 309 or 309 Cb heats.

5. Light gray etching by HNO_3 -HF solutions in heat affected zones of Heats FY78 (.02% carbon Type 309), and the following Type 310 heats, FV17A, FV19A, FV19B, and FV56, was very superficial and definitely not intergranular in nature.

6. Severe weld attack of Type 309 Cb occurs in HNO_3 -HF but not the complex solution.

7. The complex mixture produces a superficial intergranular etch at grain boundaries in austenitic structures visible at 30X even in the fully annealed condition when no grain boundary precipitate can be seen. The attack appears to be worse with higher annealing temperatures. The mechanisms are not understood and would be an interesting phenomenon to investigate.

8. It has been demonstrated that an improved corrosion resistant alloy over Type 309L and Type 309 Cb has been attained in this investigation. Heat GD44, the .02% carbon Type 310 Cb, offers the best promise among the Type 310 compositions. It shows much better corrosion rates in boiling HNO_3 -HF and complex solutions than Types 309L or 309 Cb, and is not subject to intergranular attack in weld heat affected zones in any of the environments. This alloy is fully austenitic and demonstrated it could, on a laboratory scale, be hot finished and cold finished satisfactorily to plate and sheet. It welded satisfactorily with filler of the same composition, and, unlike Type 309 Cb, showed no accelerated corrosion of the weld deposit.

9. Because of their even better corrosion resistance, the high Cr-Ni alloys offer possible future promise. They are duplex structures (except for Heat FV11, a 30 Cr-25 Ni alloy with .084% N) and as such would be very difficult to process into various wrought forms. The encouragement provided by heat FV11 is overshadowed by its intergranular susceptibility. More should be learned about the effects of carbon and nitrogen in these higher alloys in regard to single phase structure and inter-

granular susceptibility, in view of their very low corrosion rates.

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TABLE A-1

CORROSION RESULTS IN BOILING SOLUTIONS

OF 13M HNO₃ + .075M HF

ON SHEET (SIX 24 HOUR PERIODS)

Heat No.	Annealed at	Corrosion Rate IPM						Avg.
		1	2	3	4	5	6	
FV-70	2050°F	.0187	.0165	.0182	.0168	.0179	.0163	.0174
"	2050	.0182	.0165	.0185	.0170	.0181	.0164	.0175
"	2150	.0190	.0176	.0159	.0168	.0172	.0176	.0174
"	2150	.0193	.0179	.0164	.0172	.0178	.0182	.0178
FV-19B	2050°F	.0212	.0182	.0174	.0173	.0166	.0124	.0172
"	2050	.0202	.0171	.0163	.0163	.0156	.0116	.0162
"	2150	.0241	.0147	.0150	.0182	.0181	.0168	.0178
"	2150	.0241	.0148	.0152	.0184	.0181	.0168	.0179
FV-11	2050°F	.0127	.0117	.0107	.0083	.0108	.0073	.0103
"	2050	.0124	.0115	.0109	.0076	.0105	.0072	.0100
"	2150	.0072	.0103	.0086	.0108	.0079	.0075	.0087
"	2150	.0226	.0102	.0084	.0107	.0079	.0070	.0111
FV-19A	2050°F	.0211	.0148	.0181	.0130	.0120	.0094	.0147
"	2050	.0215	.0149	.0184	.0134	.0122	.0096	.0150
"	2150	.0245	.0075	.0144	.0129	.0153	.0135	.0164
"	2150	.0242	.0176	.0144	.0129	.0153	.0139	.0164
FV-20	2050°F	.0141	.0134	.0135	.0096	.0120	.0063	.0115
"	2050	.0136	.0134	.0134	.0096	.0117	.0062	.0113
"	2150	.0184	.0134	.0130	.0132	.0115	.0093	.0131
"	2150	.0190	.0131	.0132	.0126	.0114	.0091	.0131
FV-17A	2050°F	.0237	.0237	.0244	.0186	.0255	.0174	.0222
"	2050	.0239	.0246	.0245	.0241	.0219	.0187	.0230
"	2150	.0359	.0301	.0284	.0286	.0266	.0296	.0299
"	2150	.0360	.0301	.0284	.0287	.0266	.0301	.0300
FV-71	2050°F	.0133	.0074	.0117	.0110	.0103	.0086	.0104
"	2050	.0163	.0088	.0138	.0130	.0122	.0103	.0124
"	2150	.0150	.0128	.0131	.0134	.0115	.0105	.0127
"	2150	.0145	.0122	.0125	.0128	.0109	.0100	.0122
FV-56	2050°F	.0244	.0185	.0220	.0204	.0186	.0150	.0198
"	2050	.0192	.0146	.0173	.0160	.0124	.0118	.0152
"	2150	.0264	.0187	.0208	.0187	.0136	.0136	.0186
"	2150	.0247	.0172	.0192	.0173	.0126	.0125	.0173
FV-57	2050°F	.0183	.0151	.0169	.0148	.0156	.0077	.0147
"	2050	.0177	.0141	.0157	.0138	.0144	.0113	.0145
"	2150	.0206	.0105	.0161	.0159	.0145	.0195	.0162
"	2150	.0220	.0113	.0174	.0172	.0157	.0212	.0175

TABLE A-1 (contd)

Heat No.	Annealed at	Corrosion Rate IPM						Avg.
		1	2	3	4	5	6	
FY-78	2050°F	.0206	.0291	.0317	.0275	.0238	.0210	.0256
"	2050	.0206	.0287	.0313	.0272	.0235	.0207	.0253
"	2150	.0304	.0300	.0248	.0202	.0153	.0143	.0225
"	2150	.0299	.0290	.0329	.0195	.0146	.0137	.0233
RV-296	2050°F	.0277	.0262	.0216	.0183	.0131	.0117	.0198
"	2050	.0285	.0270	.0224	.0189	.0136	.0121	.0204
"	2150	.0308	.0271	.0218	.0154	.0175	.0120	.0208
"	2150	.0308	.0272	.0220	.0155	.0177	.0121	.0209
RV-294	2050°F	.0277	.0251	.0167	.0158	.0168	.0122	.0191
"	2050	.0278	.0255	.0168	.0159	.0169	.0124	.0192
"	2150	.0288	.0205	.0209	.0163	.0183	.0128	.0196
"	2150	.0287	.0203	.0206	.0160	.0181	.0125	.0194
RV-297	2050°F	.0267	.0161	.0221	.0176	.0182	.0125	.0189
"	2050	.0272	.0162	.0221	.0176	.0182	.0125	.0190
"	2150	.0233	.0210	.0164	.0176	.0147	.0150	.0180
"	2150	.0240	.0209	.0164	.0146	.0171	.0174	.0184
FY-79	2050°F	.0285	.0262	.0250	.0195	.0248	.0124	.0227
"	2050	.0275	.0261	.0249	.0194	.0248	.0125	.0225
"	2150	.0236	.0230	.0358	.0184	.0224	.0122	.0226
"	2150	.0239	.0228	.0137	.0188	.0228	.0125	.0191
GD-44	2050°F	.0171	.0151	.0124	.0121	.0128	.0089	.0131
"	2050	.0177	.0153	.0126	.0123	.0129	.0090	.0133
"	2150	.0173	.0138	.0112	.0129	.0128	.0082	.0127
"	2150	.0175	.0139	.0154	.0129	.0128	.0082	.0135

TABLE A-2

CORROSION RESULTS IN BOILING SOLUTIONS

OF 13M HNO₃ + .25M HF

ON SHEET (SIX 24 HOUR PERIODS)

Heat No.	Annealed at	Corrosion Rate IPM						Avg.
		1	2	3	4	5	6	
FV-70	2050°F	.0437	.0335	.0373	.0596	.0269	.0194	.0367
"	2050	.0439	.0341	.0382	.0612	.0272	.0197	.0374
"	2150	.0328	.0376	.0335	.0294	.0405	.0281	.0337
"	2150	.0326	.0382	.0339	.0298	.0411	.0285	.0340
"	2300	.0542	.0363	.0350	.0419	.0465	.0379	.0420
"	2300	.0520	.0365	.0352	.0420	.0468	.0382	.0418
FV-19B	2050°F	.0413	.0668	.0262	.0983	.0435	.0322	.0514
"	2050	.0420	.0674	.0264	.1000	.0439	.0327	.0521
"	2150	.0468	.0743	.0301	.0816	.0286	.0279	.0466
"	2150	.0489	.0771	.0312	.0741	.0297	.0290	.0483
"	2300	.0457	.0317	.0374	.0569	.0368	.0623	.0451
"	2300	.0468	.0328	.0388	.0590	.0384	.0647	.0468
FV-11	2050°F	.0319	.0202	.0282	.0259	.0299	.0357	.0286
"	2050	.0321	.0203	.0283	.0260	.0301	.0361	.0288
"	2150	.0345	.0102	.0204	.0658	.0240	.0224	.0296
"	2150	.0352	.0103	.0205	.0254	.0242	.0226	.0230
"	2300	.0307	.0358	.0175	.0235	.0227	.0349	.0275
"	2300	.0314	.0359	.0177	.0238	.0221	.0353	.0277
FV-19A	2050°F	.0955	.0480	.0342	.0335	.0380	.0316	.0468
"	2050	.0084	.0460	.0330	.0322	.0367	.0306	.0312
"	2150	.0484	.0369	.0431	.0511	.0313	.0503	.0435
"	2150	.0477	.0361	.0422	.0429	.0378	.0491	.0426
"	2300	.0291	.0141	.0669	.0481	.0739	.0356	.0446
"	2300	.0702	.0135	.0368	.0463	.0712	.0343	.0454
FV-20	2050°F	.0144	.0557	.0199	.0231	.0437	.0338	.0318
"	2050	.0145	.0551	.0197	.0229	.0434	.0333	.0315
"	2150	.0321	.0444	.0169	.0394	.0437	.0265	.0338
"	2150	.0313	.0441	.0168	.0391	.0433	.0344	.0348
"	2300	.0296	.0263	.0194	.0295	.0380	.0367	.0299
"	2300	.0284	.0254	.0187	.0285	.0368	.0355	.0289
FV-17A	2050°F	.0608	.0599	.0370	.0746	.0689	stopped	.0602
"	2050	.0615	.0602	.0401	.0765	.0693	"	.0615
"	2150	.0626	.0712	.0947	.0613	.0876	"	.0755
"	2150	.0613	.0698	.0965	.0607	.0872	"	.0751
"	2300	.0527	.0884	.0371	.0579	.0764	"	.0625
"	2300	.0518	.0877	.0341	.0571	.0755	"	.0612

TABLE A-2 (contd)

Heat No.	Annealed at	Corrosion Rate IPM						Avg.
		1	2	3	4	5	6	
FV-71	2050°F	.0192	.0299	.0481	.0434	.0350	.0262	.0336
"	2050	.0201	.0317	.0514	.0460	.0371	.0281	.0357
"	2150	.0208	.0191	.0464	.0397	.0278	.0321	.0310
"	2150	.0194	.0181	.0443	.0378	.0264	.0305	.0294
"	2300	.0263	.0269	.0203	.0201	.0281	.0338	.0259
"	2300	.0242	.0255	.0192	.0192	.0270	.0324	.0246
FV-56	2050°F	.0472	.0343	.0687	.0292	.0410	.0482	.0448
"	2050	.0457	.0334	.0696	.0284	.0396	.0458	.0438
"	2150	.0468	.0391	.0775	.0218	.0689	.0340	.0480
"	2150	.0482	.0402	.0874	.0220	.0690	.0340	.0501
"	2300	.0511	.0468	.0358	.0458	.0452	.0435	.0447
"	2300	.0624	.0648	.0528	.0667	.0394	.0493	.0559
FV-57	2050°F	.0462	.0591	.0313	.0485	.0271	.0564	.0448
"	2050	.0431	.0589	.0299	.0472	.0263	.0550	.0434
"	2150	.0405	.0211	.0494	.0474	.0459	.0436	.0413
"	2150	.0410	.0214	.0499	.0482	.0466	.0443	.0419
"	2300	.0381	.0176	.0414	.0289	.0461	.0322	.0341
"	2300	.0389	.0177	.0414	.0289	.0463	.0323	.0343
FY-78	2050°F	.0416	.1224	.0657	stopped	stopped	stopped	.0765
"	2050	.0421	.1214	.0659	"	"	"	.0765
"	2150	.0322	.0248	.0616	.0635	.0687	.0682	.0532
"	2150	.0334	.0251	.0632	.0750	.0690	.0686	.0557
"	2300	.0361	.0249	.0481	.0637	.0693	.0680	.0517
"	2300	.0363	.0249	.0482	.0641	.0631	.0680	.0507
RV-296	2050°F	.0419	.0245	.0876	.0637	.0583	.0616	.0563
"	2050	.0429	.0246	.0892	.0648	.0592	.0622	.0572
"	2150	.0397	.0605	.0483	.0579	.0563	.0489	.0519
"	2150	.0406	.0600	.0480	.0573	.0561	.0489	.0518
"	2300	.0338	.0233	.0447	.0596	.0601	.0625	.0473
"	2300	.0341	.0233	.0452	.0599	.0603	.0626	.0476
RV-294	2050°F	.0401	.0656	.0428	.0696	.0790	.0596	.0595
"	2050	.0390	.0643	.0421	.0685	.0605	.0583	.0555
"	2150	.0788	.0591	.0738	stopped	stopped	stopped	.0706
"	2150	.0771	.0592	.0735	"	"	"	.0699
"	2300	.0352	.0584	.0651	.0645	.0573	.0541	.0558
"	2300	.0354	.0603	.0667	.0662	.0589	.0564	.0573
RV-297	2050°F	.0436	.0724	.0549	.0528	.0644	.0635	.0586
"	2050	.0441	.0725	.0544	.0526	.0641	.0632	.0585
"	2150	.0397	.0479	.0672	.0620	.0583	.0548	.0541
"	2150	.0415	.0488	.0686	.0656	.0574	.0469	.0548
"	2300	.0320	.0654	.0663	.0630	.0581	.0319	.0528
"	2300	.0322	.0653	.0662	.0632	.0582	.0406	.0543

TABLE A-3

CORROSION RESULTS IN BOILING SOLUTIONS

of 13M HNO₃ + .50M HF

ON SHEET (SIX 24 HOUR PERIODS)

Heat No.	Annealed at	Corrosion Rate IFM						Avg.
		1	2	3	4	5	6	
FV-70	2050°F	.0772	.0652	.0353	.0279	.0575	.0405	.0506
"	2050	.0694	.0668	.0438	.0285	.0589	.0415	.0515
"	2150	.0689	.0405	.0526	.0266	.0683	.0348	.0486
"	2150	.0671	.0395	.0509	.0258	.0665	.0338	.0473
FV-19B	2050°F	.1026	.0968	.0469	.0296	.0604	.0381	.0624
"	2050	.1020	.0959	.0466	.0294	.0598	.0379	.0619
"	2150	.0844	.0731	.0505	.0347	.0576	.0458	.0577
"	2150	.0852	.0738	.0505	.0349	.0582	.0467	.0582
FV-11	2050°F	.0667	.0711	.0330	.0198	.0427	.0299	.0439
"	2050	.0672	.0723	.0339	.0201	.0434	.0304	.0446
"	2150	.0532	.0257	.0373	.0298	.0540	.0320	.0387
"	2150	.0541	.0267	.0385	.0307	.0558	.0329	.0398
FV-19A	2050°F	.0407	.0355	.0512	.0453	.0575	.0810	.0519
"	2050	.0420	.0370	.0533	.0473	.0602	.0844	.0540
FV-20	2050°F	.0244	.0398	.0397	.0636	.0322	.0526	.0421
"	2050	.0236	.0388	.0387	.0615	.0317	.0515	.0410
FV-17A	2050°F	.0454	.0841	.0661	.0532	.0858	.0846	.0699
"	2050	.0513	.0844	.0671	.0619	.0936	.0918	.0750
"	2150	.0973	.0653	.1067	.1320	.0865	stopped	.0976
"	2150	.0984	.0655	.1072	.1326	.0872	"	.0982
FV-71	2050°F	.0203	.0325	.0355	.0391	.0379	.0586	.0373
"	2050	.0211	.0337	.0371	.0408	.0395	.0513	.0373
"	2150	.0286	.0288	.0424	.0628	.0477	.0516	.0437
"	2150	.0272	.0270	.0394	.0585	.0446	.0484	.0409
FV-56	2050°F	.0627	.0692	.0668	.0925	.0447	.0772	.0689
"	2050	.0899	.0687	.0659	.0911	.0440	.0758	.0726
"	2150	.0865	.0373	.0708	.0693	.0363	.0749	.0625
"	2150	.0655	.0388	.0720	.0689	.0364	.0748	.0594
FV-57	2050°F	.0911	.0732	.0844	.0765	.0805	.0496	.0759
"	2050	.0905	.0712	.0812	.0733	.0769	.0875	.0734
"	2150	.0893	.0874	.0543	.0483	.0796	.0573	.0694
"	2150	.0906	.0884	.0555	.0495	.0812	.0586	.0706
FY-78	2050°F	.1197	.1652	.0728	.0711	.0900	.1089	.1046
"	2050	.1200	.1645	.0729	.0703	.0898	.1096	.1045
"	2150	.1178	.0612	.1250	stopped	stopped	stopped	.1013
"	2150	.1212	.0624	.1259	excessive weight loss	excessive weight loss	excessive weight loss	.1032
					end grain attack	end grain attack	end grain attack	

TABLE A-3

Heat No.	Annealed at	Corrosion Rate IPM						Avg.
		1	2	3	4	5	6	
RV-296	2050°F	.1139	.1111	.0716	.0556	.1062	.1003	.0931
"	2050	.1118	.1096	.0708	.0553	.1075	.1011	.0927
"	2150	.1124	.0705	.1072	.0638	.0786	.1108	.0906
"	2150	.1125	.0698	.1050	.0631	.0773	.1106	.0897
RV-294	2050°F	.1036	.0782	.0616	.0605	.1104	.1068	.0869
"	2050	.1037	.0792	.0612	.0605	.1108	.1064	.0870
"	2150	.1105	.1548	.0764	.1063	.0874	.1039	.1066
"	2150	.1095	.1522	.0742	.1046	.0866	.1042	.1052
RV-297	2050°F	.0014	.0675	.1215	.1624	.0842	.0725	.0849
"	2050	.0016	.0685	.1219	.1645	.0859	.0735	.0860
"	2150	.0991	.0727	.1339	.0661	.0885	.0761	.0894
"	2150	.0991	.0724	.1348	.0666	.0889	.0762	.0897
FY-79	2050°F	.1265	.1299	.1206	stopped	stopped	stopped	.1257
"	2050	.1257	.1305	.1209	"	"	"	.1257
"	2150	.0968	.1139	.0693	.0893	.1004	.0916	.0936
"	2150	.0974	.1154	.0692	.0903	.1007	.0917	.0941
GD-44	2050°F	.0943	.0555	.0593	.0470	.0555	.0730	.0641
"	2050	.0937	.0554	.0592	.0467	.0554	.0729	.0639
"	2150	.0716	.0735	.0910	.0789	.0623	.0679	.0742
"	2150	.0725	.0755	.0933	.0809	.0635	.0693	.0758

TABLE A-4

CORROSION RATES IN BOILING COMPLEX MIXTURE

OF 6M HNO₃ + .4M H₂SO₄ + .4M NaNO₃+ .3M Fe₂(SO₄)₃ + .01M Cr + .01M Hg + .01M PO₄

ON SHEET ANNEALED 2050°F

Rates in Inches per Month

Heat No.	1st	2nd	3rd	4th	5th	6th	7th	8th	9th	10th	Avg.
FV-70	.00412	.00282	.00368	.00339	.00401	.00350	.00458	.00359	.00401	.00439	.00380
"	.00466	.00279	.00360	.00329	.00390	.00341	.00396	.00396	.00387	.00434	.00377
FV-19B	.00513	.00300	.00309	.00267	.00322	.00287	.00328	.00326	.00336	.00349	.00333
"	.00465	.00296	.00308	.00271	.00326	.00293	.00336	.00340	.00345	.00353	.00333
FV-11	.00338	.00205	.00229	.00213	.00290	.00274	.00342	.00377	.00386	.00334	.00298
"	.00367	.00207	.00241	.00220	.00295	.00277	.00340	.00256	.00374	.00430	.00310
FV-19A	.00392	.00262	.00259	.00233	.00277	.00249	.00293	.00308	.00314	.00342	.00288
"	.00374	.00254	.00252	.00228	.00271	.00240	.00287	.00299	.00305	.00333	.00284
FV-20	.00350	.00211	.00278	.00260	.00311	.00292	.00343	.00354	.00353	.00390	.00314
"	.00347	.00210	.00272	.00263	.00317	.00296	.00342	.00358	.00355	.00394	.00315
FV-17A	.00459	.00252	.00288	.00245	.00293	.00271	.00308	.00323	.00316	.00361	.00311
"	.00446	.00254	.00287	.00246	.00295	.00274	.00285	.00351	.00321	.00365	.00312
FV-71	.00292	.00209	.00302	.00286	.00345	.00319	.00363	.00368	.00370	.00389	.00324
"	.00268	.00203	.00318	.00304	.00372	.00346	.00395	.00401	.00403	.00423	.00343
FV-56	.00430	.00253	.00263	.00224	.00256	.00241	.00264	.00278	.00288	.00309	.00280
"	.00367	.00261	.00282	.00242	.00275	.00253	.00268	.00275	.00282	.00289	.00279
FV-57	.00310	.00258	.00274	.00233	.00278	.00249	.00220	.00280	.00302	.00315	.00271
"	.00374	.00304	.00310	.00257	.00297	.00257	.00221	.00267	.00273	.00276	.00283
FY-78	.00060	.00333	.00443	.00500	.00486	.00580	.00637	.00865	.00817	.00885	.00560
"	.00048	.00318	.00449	.00530	.00522	.00629	.00685	.00923	.00845	.00936	.00588
RV-296	.00446	.00566	.00737	.00722	.00722	.00859	.00927	.00892	.00971	.00914	.00775
"	.00432	.00584	.00762	.00736	.00736	.00867	.00923	.00877	.00964	.00894	.00777
RV-294	.00089	.00376	.00577	.00678	.00611	.00566	.00755	.00957	.00892	.00927	.00642
"	.00089	.00370	.00579	.00679	.00622	.00590	.00784	.00434	.00909	.00974	.00603
RV-297	.00380	.00610	.00658	.00807	.00780	.00780	.00938	.00994	.00681	.00954	.00758
"	.00376	.00658	.00709	.00863	.00521	.00825	.00969	.00015	.00694	.00961	.00563
FY-79	.00330	.00406	.00509	.00481	.00481	.00569	.00592	.00585	.00619	.00581	.00515
"	.00406	.00439	.00552	.00512	.00512	.00602	.00628	.00623	.00624	.00604	.00550
GD-44	.00059	.00292	.00331	.00368	.00302	.00331	.00375	.00493	.00470	.00518	.00353
"	.00058	.00292	.00330	.00375	.00319	.00339	.00254	.00513	.00483	.00539	.00350

CORROSION RATES IN BOILING COMPLEX MIXTURE

OF 6M HNO₃ + .4M H₂SO₄ + .4M NaNO₃
 + .3M Fe₂(SO₄)₃ + .01M Cr + .01M Hg + .01M PO₄

ON SHEET ANNEALED AT 2150°F

INCHES PENETRATION PER MONTH

Heat No.	1st	2nd	3rd	4th	5th	6th	7th	8th	9th	10th	Avg.
FV-70	.00444	.00368	.00338	.00455	.00371	.00443	.00346	.00421	.00387	.00404	.00398
"	.00419	.00383	.00347	.00461	.00373	.00448	.00351	.00423	.00390	.00408	.00400
FV-19B	.00435	.00306	.00260	.00311	.00250	.00289	.00230	.00278	.00271	.00276	.00291
"	.00397	.00291	.00257	.00307	.00249	.00286	.00230	.00287	.00275	.00280	.00286
FV-11	.00355	.00230	.00204	.00256	.00213	.00271	.00225	.00273	.00273	.00288	.00259
"	.00337	.00231	.00205	.00262	.00219	.00281	.00236	.00287	.00291	.00306	.00266
FV-19A	.00381	.00352	.00291	.00359	.00288	.00331	.00341	.00288	.00400	.00388	.00342
"	.00411	.00361	.00299	.00362	.00289	.00327	.00332	.00294	.00394	.00383	.00345
FV-20	.00399	.00308	.00277	.00373	.00315	.00396	.00368	.00377	.00481	.00474	.00377
"	.00354	.00292	.00274	.00391	.00339	.00411	.00386	.00402	.00524	.00500	.00387
FV-17A	.00431	.00310	.00262	.00317	.00259	.00306	.00282	.00281	.00367	.00358	.00317
"	.00388	.00314	.00271	.00324	.00268	.00320	.00298	.00298	.00388	.00382	.00325
FV-71	.00290	.00303	.00295	.00381	.00305	.00405	.00360	.00357	.00441	.00416	.00355
"	.00292	.00293	.00286	.00370	.00298	.00393	.00361	.00331	.00423	.00412	.00346
FV-56	.00449	.00341	.00288	.00335	.00274	.00289	.00268	.00252	.00317	.00313	.00313
"	.00450	.00337	.00286	.00338	.00268	.00288	.00268	.00258	.00307	.00311	.00311
FV-57	.00395	.00315	.00275	.00307	.00252	.00297	.00263	.00261	.00331	.00348	.00304
"	.00433	.00290	.00267	.00307	.00251	.00296	.00261	.00259	.00324	.00334	.00302
FV-78	.00382	.00429	.00378	.00569	.00472	.00655	.00672	.00701	.00923	.00853	.00603
"	.00410	.00437	.00385	.00558	.00451	.00628	.00639	.00671	.00876	.00783	.00584
RV-296	.00424	.00539	.00607	.00828	.00802	.00954	.01367	.01228	.01109	.01111	.00897
"	.00439	.00563	.00659	.00879	.00879	.01034	.00856	.01024	.01203	.01184	.00872
RV-294	.00452	.00559	.00591	.00812	.00750	.00912	.00881	.00898	.01105	.01061	.00802
"	.00449	.00571	.00605	.00817	.00759	.00914	.00899	.00901	.01103	.01054	.00807
RV-297	.00466	.00536	.00645	.00757	.00723	.00840	.00846	.00893	.01119	.01084	.00791
"	.00444	.00527	.00633	.00754	.00978	.00575	.00843	.00902	.01114	.01102	.00787
FV-79	.00428	.00426	.00466	.00487	.00454	.00554	.01086	.00580	.00574	.00741	.00580
"	.00407	.00405	.00439	.00454	.00420	.00513	.00492	.00533	.00691	.00682	.00504
GD-44	.00359	.00346	.00327	.00365	.00303	.00348	.00351	.00375	.00489	.00488	.00375
"	.00330	.00342	.00332	.00371	.00314	.00385	.00336	.00382	.00504	.00499	.00380

CORROSION RATES IN

(d) BOILING 65% NITRIC ACID (FIVE 48 HOUR PERIODS)

(e) .5M H₂SO₄ AT 200°F (2 HOURS)(f) 6% FeCl₃ PITTING TEST

ON SHEET

Heat No.	Temp., °F	65% HNO ₃ IPM							.5M H ₂ SO ₄ 2 hrs - 200°F	6% FeCl ₃ Room Temperature
		1st	2nd	3rd	4th	5th	Avg. of 5	Average of 2, 3, 4, 5		
FV70-15	2050	.00023	.00018	.00015	.00017	.00017	.00018	.00017	.42 in/mo	Pitted 24 hrs
		.00021	.00017	.00015	.00017	.00017	.00017	.00017		
	2150	.00046	.00026	.00021	.00022	.00021	.00027	.00023	.023 in/mo	Pitted 24 hrs
		.00045	.00025	.00021	.00022	.00020	.00027	.00022		
	2300	.00034	.00025	.00022	.00022	.00023	.00025	.00023	.71 in/mo	Pitted 24 hrs
		.00034	.00024	.00021	.00023	.00023	.00025	.00023		
FV19-15B	2050	.00043	.00025	.00036	.00037	.00035	.00037	.00033	.20 in/mo	No pits 300 hrs
		.00043	.00034	.00035	.00035	.00035	.00036	.00035		
	2150	.00027	.00019	.00014	.00018	.00018	.00019	.00017	.10 in/mo	No pits 300 hrs
		.00024	.00019	.00014	.00018	.00018	.00019	.00017		
	2300	.00031	.00020	.00020	.00023	.00025	.00023	.00022	.28 in/mo	No pits 300 hrs
		.00035	.00016	.00018	.00023	.00025	.00024	.00021		
FV11-A	2050	.00035	.00026	.00021	.00023	.00021	.00025	.00023	.22 in/mo	No pits 300 hrs
		.00038	.00027	.00021	.00024	.00023	.00027	.00024		
	2150	.00022	.00017	.00032	.00019	.00018	.00022	.00022	.30 in/mo	No pits 300 hrs
		.00023	.00017	.00015	.00019	.00019	.00019	.00017		
	2300	.00022	.00018	.00016	.00018	.00019	.00019	.00018	.32 in/mo	No pits 300 hrs
		.00021	.00017	.00017	.00018	.00019	.00018	.00018		
FV19-15A	2050	.00027	.00019	.00017	.00018	.00020	.00020	.00019	.23 in/mo	No pits 300 hrs
		.00029	.00020	.00016	.00018	.00020	.00021	.00019		
	2150	.00034	.00028	.00029	.00033	.00034	.00032	.00031	.26 in/mo	No pits 300 hrs
		.00037	.00028	.00028	.00034	.00035	.00032	.00031		
	2300	.00035	.00028	.00030	.00035	.00035	.00033	.00032	.26 in/mo	No pits 300 hrs
		.00037	.00028	.00029	.00034	.00034	.00032	.00031		
FV20-15	2050	.00035	.00021	.00016	.00018	.00015	.00021	.00018	.14 in/mo	Pitted 100 hrs
		.00041	.00022	.00018	.00019	.00017	.00023	.00021		
	2150	.00037	.00020	.00017	.00017	.00014	.00021	.00017	.26 in/mo	Pitted 100 hrs
		.00037	.00021	.00017	.00019	.00014	.00022	.00018		
	2300	.00036	.00023	.00016	.00018	.00016	.00022	.00018	.25 in/mo	Pitted 100 hrs
		.00035	.00023	.00016	.00018	.00015	.00021	.00018		
FV17-15A	2050	.00040	.00028	.00023	.00027	.00028	.00029	.00027	.10 in/mo	No pits 300 hrs
		.00045	.00028	.00023	.00028	.00030	.00031	.00027		
	2150	.00034	.00027	.00021	.00024	.00026	.00026	.00025	.17 in/mo	No pits 300 hrs
		.00038	.00030	.00023	.00026	.00027	.00029	.00027		
	2300	.00035	.00023	.00019	.00023	.00023	.00025	.00022	.17 in/mo	No pits 300 hrs
		.00034	.00023	.00020	.00025	.00024	.00025	.00023		
FV71-15	2050	.00032	.00021	.00017	.00017	.00015	.00020	.00018	.33 in/mo	Pitted 100 hrs
		.00032	.00020	.00017	.00018	.00017	.00021	.00018		
	2150	.00037	.00028	.00021	.00032	.00018	.00027	.00025	.32 in/mo	Pitted 100 hrs
		.00028	.00016	.00016	.00017	.00013	.00018	.00015		
	2300	.00038	.00026	.00017	.00019	.00015	.00023	.00019	.24 in/mo	Pitted 300 hrs
		.00039	.00029	.00021	.00024	.00015	.00026	.00022		

TABLE A-6 (contd)

Heat No.	Temp., °F	65% HNO ₃ IPM							.5M H ₂ SO ₄ 2 hrs - 200°F	6% FeCl ₃ Room Temperature
		1st	2nd	3rd	4th	5th	Avg. of 5	Average of 2, 3, 4, 5		
FV56-15	2050	.00040	.00026	.00022	.00023	.00021	.00026	.00023	.16 in/mo	No pits 300 hrs
		.00045	.00027	.00023	.00024	.00020	.00028	.00024		
	2150	.00047	.00025	.00026	.00025	.00020	.00029	.00024	.08 in/mo	Pitted 24 hrs
		.00045	.00026	.00023	.00024	.00020	.00028	.00023		
	2300	.00053	.00030	.00016	.00026	.00020	.00029	.00023	.18 in/mo	Pitted 100 hrs
		.00052	.00029	.00016	.00026	.00019	.00028	.00023		
FY57-15	2050	.00033	.00025	.00012	.00023	.00019	.00022	.00020	.23 in/mo	No pits 300 hrs
		.00031	.00022	.00014	.00023	.00019	.00022	.00020		
	2150	.00036	.00027	.00019	.00026	.00018	.00025	.00023	.30 in/mo	No pits 300 hrs
		.00038	.00027	.00019	.00024	.00021	.00026	.00023		
	2300	.00039	.00028	.00021	.00023	.00019	.00026	.00023	.23 in/mo	No pits 300 hrs
		.00040	.00027	.00022	.00024	.00020	.00027	.00023		
FY-78	2050	.00050	.00015	.00021	.00025	.00021	.00025	.00021	.35 in/mo	Pitted 56 hrs
		.00033	.00027	.00017	.00023	.00021	.00024	.00022	.34 in/mo	Pitted 144 hrs
	2150	.00048	.00028	.00025	.00024	.00025	.00030	.00026	.34 in/mo	Pitted 168 hrs
		.00042	.00028	.00026	.00024	.00025	.00029	.00026	.34 in/mo	Pitted 168 hrs
	2300	.00044	.00032	.00032	.00027	.00032	.00033	.00031	.36 in/mo	Pitted 144 hrs
		.00036	.00031	.00029	.00029	.00025	.00029	.00028	.37 in/mo	Pitted 144 hrs
RV-296	2050	.00032	.00025	.00022	.00022	.00021	.00024	.00023	.26 in/mo	Pitted 168 hrs
		.00031	.00026	.00024	.00024	.00022	.00025	.00024	.24 in/mo	Pitted 168 hrs
	2150	.00042	.00032	.00030	.00027	.00029	.00032	.00030	.23 in/mo	Pitted 144 hrs
		.00037	.00026	.00026	.00024	.00025	.00028	.00025	.25 in/mo	Pitted 192 hrs
	2300	.00041	.00035	.00033	.00030	.00029	.00034	.00032	.23 in/mo	Pitted 24 hrs
		.00042	.00034	.00034	.00030	.00030	.00034	.00032	.23 in/mo	Pitted 24 hrs
RV-294	2050	.00050	.00033	.00024	.00024	.00024	.00031	.00026	.36 in/mo	Pitted 144 hrs
		.00045	.00033	.00025	.00027	.00026	.00030	.00028	.39 in/mo	Pitted 144 hrs
	2150	.00043	.00032	.00026	.00026	.00025	.00030	.00027	.28 in/mo	Pitted 144 hrs
		.00039	.00031	.00026	.00026	.00026	.00028	.00027	.28 in/mo	Pitted 144 hrs
	2300	.00038	.00029	.00028	.00024	.00025	.00029	.00027	.48 in/mo	Pitted 48 hrs
		.00045	.00033	.00029	.00026	.00026	.00032	.00029	.42 in/mo	Pitted 48 hrs
RV-297	2050	.00034	.00027	.00020	.00022	.00024	.00025	.00023	.17 in/mo	Pitted 168 hrs
		.00036	.00026	.00019	.00023	.00023	.00025	.00023	.15 in/mo	Pitted 168 hrs
	2150	.00044	.00030	.00027	.00025	.00024	.00030	.00027	.21 in/mo	Pitted 144 hrs
		.00049	.00032	.00029	.00027	.00027	.00033	.00029	.21 in/mo	Pitted 144 hrs
	2300	.00044	.00039	.00032	.00030	.00031	.00035	.00033	.25 in/mo	Pitted 24 hrs
		.00041	.00037	.00031	.00030	.00031	.00034	.00032	.25 in/mo	Pitted 24 hrs
FY-79	2050	.00037	.00028	.00026	.00029	.00029	.00028	.00028	.26 in/mo	OK 300 hrs
		.00036	.00027	.00027	.00026	.00030	.00029	.00028	.27 in/mo	OK 300 hrs
	2150	.00048	.00029	.00027	.00028	.00029	.00030	.00028	.26 in/mo	OK 300 hrs
		.00051	.00032	.00028	.00029	.00031	.00034	.00030	.26 in/mo	OK 300 hrs
	2300	.00044	.00030	.00029	.00027	.00027	.00029	.00028	.29 in/mo	OK 300 hrs
		.00042	.00029	.00028	.00026	.00027	.00030	.00028	.28 in/mo	OK 300 hrs
CD-44	2050	.00024	.00026	.00021	.00021	.00021	.00023	.00024	.27 in/mo	OK 300 hrs
		.00029	.00024	.00023	.00024	.00024	.00025	.00024	.27 in/mo	OK 300 hrs
	2150	.00027	.00020	.00022	.00026	.00026	.00024	.00024	.29 in/mo	OK 300 hrs
		.00031	.00022	.00023	.00026	.00026	.00026	.00024	.28 in/mo	OK 300 hrs
	2300	.00031	.00026	.00024	.00029	.00029	.00028	.00027	.14 in/mo	OK 300 hrs
		.00031	.00027	.00024	.00024	.00027	.00027	.00026	.14 in/mo	OK 300 hrs

TABLE A-7

BOILING 65% NITRIC ACID RESULTS

ON SHEET SAMPLES SENSITIZED 1 HOUR AT 1200°F

Heat No.	Inches Per Month					
	1st	2nd	3rd	4th	5th	Avg.
FV-70	.00052	.00061	.00050	.00051	.00052	.00053
	.00140	.00071	.00056	.00058	.00058	.00077
FV-19B	.00082	.00039	.00033	.00036	.00034	.00045
	.00041	.00039	.00030	.00034	.00032	.00035
FV-11	.00038	.00034	.00030	.00031	.00034	.00033
	.00040	.00036	.00032	.00031	.00036	.00035
FV-19A	.00049	.00044	.00033	.00046	.00041	.00043
	.00040	.00040	.00068	.00026	.00021	.00039
FV-20	.00037	.00037	.00030	.00030	.00031	.00033
	.00044	.00043	.00030	.00032	.00033	.00036
FV-17A	.00041	.00042	.00036	.00032	.00036	.00037
	.00048	.00044	.00035	.00033	.00036	.00039
FV-71	.00040	.00036	.00031	.00032	.00033	.00034
	.00042	.00041	.00035	.00036	.00038	.00038
FV-56	.00058	.00046	.00035	.00036	.00037	.00043
	.00072	.00049	.00039	.00037	.00039	.00047
FV-57	.00050	.00045	.00035	.00034	.00038	.00040
	.00051	.00044	.00033	.00034	.00036	.00040
FY-78	.00070	.00049	.00039	.00036	.00036	.00046
	.00066	.00050	.00041	.00037	.00037	.00046
RV-296	.00086	.00054	.00045	.00040	.00040	.00053
	.00035	.00045	.00055	.00021	.00036	.00038
RV-294	.00040	.00040	.00036	.00034	.00035	.00037
	.00044	.00044	.00036	.00037	.00037	.00040
RV-297	.00046	.00046	.00037	.00038	.00035	.00040
	.00073	.00055	.00038	.00040	.00038	.00049
FY-79	.00043	.00043	.00033	.00036	.00037	.00038
	.00045	.00045	.00033	.00037	.00037	.00039
GD-44	.00032	.00032	.00025	.00029	.00028	.00029
	.00031	.00031	.00023	.00027	.00027	.00028

TABLE B-1

CORROSION RESULTS IN BOILING SOLUTIONS

OF 13M HNO₃ + .075M HF

ON AS WELDED PLATE

Inches Penetration per Month

<u>Heat No.</u>	<u>1st</u>	<u>2nd</u>	<u>3rd</u>	<u>4th</u>	<u>5th</u>	<u>6th</u>	<u>Avg.</u>
FV-70	.0208	.0297	.0227	.0275	.0217	.0290	.0252
FV-19B	.0161	.0294	.0207	.0256	.0218	.0252	.0233
FV-11	.0113	.0211	.0144	.0161	.0211	.0169	.0168
FV-19A	.0167	.0266	.0246	.0243	.0239	.0169	.0222
FV-20	.0113	.0077	.0177	.0136	.0165	.0194	.0144
FV-17A	.0233	.0191	.0376	.0290	.0349	.0348	.0298
FV-71	.0280	.0258	.0301	.0224	.0219	.0260	.0257
FV-56	.0371	.0298	.0331	.0212	.0310	.0258	.0297
FV-57	.0303	.0282	.0241	.0295	.0236	.0231	.0265
FY-78	.0432	.0399	.0284	.0429	.0364	.0343	.0375
RV-296	.0420	.0382	.0269	.0353	.0370	.0367	.0361
RV-294	.0433	.0363	.0352	.0396	.0404	.0351	.0383
RV-297	.0383	.0322	.0316	.0353	.0332	.0342	.0341
FY-79	.0493	.0789	.0782	stopped	stopped	stopped	.0688
GD-44	.0190	.0285	.0286	.0292	.0266	.0268	.0265
FV-17B	.0160	.0233	.0257	.0260	.0231	.0264	.0235

TABLE B-2

CORROSION RESULTS IN BOILING SOLUTIONS

OF 13M HNO₃ + .25M HF

ON AS WELDED PLATE

Inches Penetration per Month

<u>Heat No.</u>	<u>1st</u>	<u>2nd</u>	<u>3rd</u>	<u>4th</u>	<u>5th</u>	<u>6th</u>	<u>Avg.</u>
FV-70	.0579	.0590	.0460	.0616	.0530	.0486	.0544
FV-19B	.0783	.0459	.0409	.0597	.0579	.0528	.0559
FV-11	.0427	.0547	.0409	.0449	.0447	.0437	.0453
FV-19A	.0419	.0352	.0420	.0436	.0342	.0390	.0393
FV-20	.0407	.0249	.0343	.0352	.0418	.0355	.0354
FV-17A	.0846	.0579	.0685	.0809	.0707	.0649	.0713
FV-71	.0492	.0408	.0390	.0356	.0438	.0435	.0420
FV-56	.0515	.0661	.0442	.0700	.0677	.0556	.0592
FV-57	.0510	.0500	.0476	.0572	.0542	.0401	.0500
FY-78	.0635	.0647	.0655	.0992	.0735	.0680	.0724
RV-296	.0901	.0919	.0605	.0949	.0756	.0780	.0818
RV-294	.0735	.0615	.0540	.0946	.0574	.0662	.0679
RV-297	.0719	.0518	.0739	.0669	.0725	.0800	.0695
FY-79	.1182	stopped - weld attack					
GD-44	.0493	.0457	.0420	.0497	.0384	.0531	.0464
FV-17B	.0416	.0720	.0465	.0580	.0788	.0570	.0590

TABLE B-3

CORROSION RESULTS IN BOILING SOLUTIONS

OF 13M HNO₃ + .50M HF

ON AS WELDED PLATE

Inches Penetration Per Month

Heat No.	1st	2nd	3rd	4th	5th	6th	Avg.
FV-71	.0845	.0958	.0945	.1040	.0513	.0787	.0848
FV-17B	.0909	.1302	.1645	.1060	stopped-severely attacked at weld end grain attack		.1229
FV-19A	.0936	.1067	.0932	.0696	.0707	.0904	.0874
GD-44	.0860	.1023	.1066	.1027	.0735	.0826	.0923
RV-294	.1579	.1609	.1686	.0973	.0996	.2095	.1490
FY-79	.1663	.2307	.1809	stopped-weld severely attacked-severe end grain attack			.1926
FV-70	.0762	.0928	.0943	.0461	.0744	.1135	.0829
FV-19B	.1025	.1068	.0954	.0593	.1042 stopped- pitting type attack on weld-attack at carbide precipitation areas- severe end grain attack		.0936
RV-297	.1256	.1308	.1394	.0766	.1239	.1364	.1221
RV-296	.1357	.1355	.2170	.0696	.1161	.1259	.1333
FV-11	.0696	.0810	.0472	.0866	stopped-pitting type attack on weld-severe attack at carbide precipi- tation areas		.0711
FY-78	.1395	.1198	.1014	.0926	.1652	.1135	.1220
FY-17A	.1269	.1305	.0900	stopped-weld attacked- spotty end grain attack			.1158
FY-57	.1030	.1000	.0699	.0972	.0855	.0931	.0915
FV-20	.0755	.0854	.0479	.0642	.0941	.0867	.0756
FV-56	.1065	.1143	.0474	.1023	.0760	.0970	.0906

TABLE B-4

CORROSION RATES IN BOILING COMPLEX MIXTURE

OF 6M HNO₃ + .4M H₂SO₄ + .4M NaNO₃+ .3M Fe₂ (SO₄)₃ + .01M Cr + .01M Hg + .01M PO₄

ON AS WELDED PLATE

Inches Penetration Per Month

<u>Heat No.</u>	<u>1st</u>	<u>2nd</u>	<u>3rd</u>	<u>4th</u>	<u>5th</u>	<u>6th</u>	<u>7th</u>	<u>8th</u>	<u>9th</u>	<u>10th</u>	<u>Avg.</u>
FV-70	.00375	.00409	.00436	.00491	.00388	.00464	.00460	.00523	.00541	.00509	.00460
FV-19B	.00371	.00360	.00367	.00376	.00322	.00377	.00361	.00418	.00418	.00415	.00379
FV-11A	.00298	.00257	.00236	.00309	.00294	.00389	.00383	.00465	.00504	.00511	.00365
FV-19A	.00323	.00321	.00298	.00308	.00271	.00314	.00307	.00351	.00361	.00364	.00322
FV-20	.00043	.00224	.00292	.00333	.00300	.00357	.00377	.00480	.00469	.00542	.00342
FV-17A	.00338	.00334	.00312	.00326	.00388	.00322	.00317	.00362	.00387	.00377	.00346
FV-71	.00052	.00261	.00353	.00366	.00351	.00330	.00413	.00538	.00516	.00567	.00375
FV-56	.00304	.00318	.00295	.00299	.00247	.00262	.00242	.00271	.00261	.00261	.00276
FV-57	.00298	.00306	.00246	.00291	.00249	.00293	.00262	.00318	.00336	.00305	.00290
FY-78	.00076	.00430	.00143	.00889	.00415	.00461	.00524	.00684	.00636	.00685	.00494
RV-296	.00074	.00387	.00468	.00526	.00430	.00513	.00600	.00740	.00662	.00710	.00511
RV-294	.00079	.00382	.00459	.00511	.00452	.00315	.00541	.00717	.00675	.00730	.00486
RV-297	.00074	.00417	.00460	.00541	.00410	.00513	.00589	.00741	.00679	.00761	.00519
FY-79	.00069	.00393	.00425	.00508	.00438	.00396	.00506	.00634	.00571	.00609	.00455
GD-44	.00391	.00383	.00340	.00350	.00323	.00342	.00351	.00413	.00413	.00405	.00371
FV-17B	.00290	.00298	.00317	.00360	.00331	.00377	.00369	.00413	.00350	.00397	.00347

CORROSION TESTS ON AS WELDED PLATE IN

- (d) Boiling 65% HNO₃ (five 48-hour periods)
 (e) .5M H₂SO₄ at 200°F (2 hour period)
 (f) 6% FeCl₃ (pitting test)

Heat No.	65% HNO ₃ IPM						Avg. Periods 2, 3, 4, + 5	.5M H ₂ SO ₄ 2 hrs - 200°F	Time to Pit 6% FeCl ₃	
	1st	2nd	3rd	4th	5th	Avg.			Surface	Weld
FV-70	.00050	.00040	.00026	.00025	.00025	.00033	.00029	.81 in/mo	96 hrs	72 hrs
	.00058	.00042	.00027	.00025	.00026	.00036	.00030			
FV-19B	.00030	.00023	.00025	.00021	.00026	.00025	.00024	.20 in/mo	72 hrs	48 hrs
	.00027	.00021	.00026	.00023	.00019	.00023	.00022			
FV-11	.00026	.00016	.00018	.00014	.00018	.00018	.00017	.31 in/mo	24 hrs	96 hrs
	.00025	.00016	.00019	.00015	.00018	.00019	.00017			
FV-19A	.00036	.00022	.00023	.00017	.00022	.00024	.00021	.22 in/mo	96 hrs	72 hrs
	.00035	.00020	.00023	.00017	.00022	.00023	.00021			
FV-20	.00036	.00027	.00028	.00021	.00029	.00028	.00026	.20 in/mo	24 hrs	96 hrs
	.00036	.00017	.00018	.00016	.00020	.00021	.00018			
FV-17A	.00034	.00022	.00023	.00024	.00022	.00025	.00023	.08 in/mo	48 hrs	72 hrs
	.00035	.00023	.00024	.00024	.00023	.00026	.00024			
FV-71	.00038	.00017	.00020	.00017	.00019	.00022	.00018	.44 in/mo	72 hrs	96 hrs
	.00036	.00016	.00022	.00022	.00019	.00023	.00020			
FV-56	.00042	.00025	.00024	.00017	.00022	.00026	.00022	.17 in/mo	72 hrs	48 hrs
	.00042	.00025	.00037	.00018	.00025	.00029	.00026			
FV-57	.00028	.00018	.00018	.00020	.00017	.00020	.00018	.22 in/mo	96 hrs	72 hrs
	.00029	.00019	.00018	.00020	.00018	.00021	.00019			
FY-78	.00046	.00036	.00036	.00032	.00030	.00036	.00034	.11 in/mo	216 hrs	24 hrs
	.00042	.00034	.00034	.00031	.00029	.00034	.00032			
RV-296	.00034	.00028	.00027	.00025	.00025	.00028	.00026	.69 in/mo	264 hrs	24 hrs
	.00039	.00031	.00029	.00028	.00027	.00031	.00029			
RV-294	.00044	.00036	.00032	.00028	.00028	.00034	.00031	.90 in/mo	300 hrs	24 hrs
	.00046	.00034	.00030	.00029	.00027	.00033	.00030			
RV-297	.00035	.00031	.00028	.00021	.00027	.00028	.00027	.62 in/mo	264 hrs	24 hrs
	.00032	.00028	.00025	.00019	.00024	.00026	.00024			
FY-79	.00053	.00036	.00034	.00032	.00033	.00038	.00034	.34 in/mo	216 hrs	24 hrs
	.00051	.00041	.00036	.00038	.00036	.00040	.00038			
GD-44	.00040	.00040	.00031	.00034	.00031	.00035	.00034	.20 in/mo	96 hrs	72 hrs
	.00041	.00041	.00033	.00035	.00032	.00036	.00035			
FV-17B	.00027	.00018	.00019	.00015	.00021	.00020	.00018	.19 in/mo	48 hrs	72 hrs
	.00024	.00017	.00019	.00014	.00020	.00019	.00018			

TABLE B-6

CORROSION RATES IN BOILING 65% HNO₃
ON WELDED PLATE WHICH WAS REANNEALED
AND THEN SENSITIZED AT 1200°F

Heat No.	Inches Per Month					
	1st	2nd	3rd	4th	5th	Avg.
FV-70	.00039	.00037	.00032	.00033	.00035	.00035
FV-11	.00032	.00031	.00032	.00031	.00036	.00032
FY-78	.00037	.00033	.00031	.00030	.00033	.00033
RV-296	.00035	.00031	.00029	.00026	.00030	.00030
RV-294	.00036	.00030	.00029	.00024	.00029	.00030
RV-297	.00044	.00036	.00032	.00028	.00031	.00034
FY-79	.00051	.00045	.00048	.00052	.00058	.00051
FV-17B	.00031	.00027	.00022	.00021	.00022	.00025

CORROSION RATES FOR SHEET ANNEALED AT 2050°F

in 13M HNO₃ + .075M HF

FIGURE C-1

FIGURE C-2
CORROSION RATES FOR SHEET ANNEALED AT 2050°F
IN 13M HNO₃ + .25M HF

FIGURE C-3

CORROSION RATES FOR SHEET ANNEALED AT 2050°F
IN 13M HNO₃ + .50M HF

FIGURE C-4

CORROSION RATES FOR SHEET SAMPLES ANNEALED AT 2050°F

TESTED IN 6M HNO₃ + .4M H₂SO₄ + .4M NaNO₃ + .3M Fe₂(SO₄)₃ +

.01M Cr + .01M Hg + .01M PO₄