Chemical Technology Division
Chemical Technology Division
Chemical Technology Division
Chemical Technology Division
Chemical Technology Division
Chemical Technology Division
Chemical Technology Division
Chemical Technology Division
Chemical Technology Division
Chemical Technology Division
Chemical Technology Division
Chemical Technology Division
Chemical Technology Division
Chemical Technology Division
Chemical Technology Division
Chemical Technology Division
Chemical Technology Division

ANL-97/2

Mobile Evaporator Corrosion Test Results

by A. Rozeveld and D. B. Chamberlain

MASTER

Argonne National Laboratory, Argonne, Illinois 60439
operated by The University of Chicago
for the United States Department of Energy under Contract W-31-109-Eng-38

Chemical Technology Division
Chemical Technology Division
Chemical Technology Division
Chemical Technology Division

Argonne National Laboratory, with facilities in the states of Illinois and Idaho, is owned by the United States government, and operated by The University of Chicago under the provisions of a contract with the Department of Energy.

Reproduced from the best available copy.

Available to DOE and DOE contractors from the
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831
Prices available from (423) 576-8401

Available to the public from the
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161

Distribution Category:
Radioactive Waste Tank
Remediation
(UC-2030)

ANL-97/2

ARGONNE NATIONAL LABORATORY
9700 South Cass Avenue
Argonne, IL 60439

MOBILE EVAPORATOR CORROSION TEST RESULTS

by

A. Rozeveld and D. B. Chamberlain

Chemical Technology Division

May 1997

TABLE OF CONTENTS

Page

ACRONYMS vii

ABSTRACT 1

INTRODUCTION 1

CORROSION TEST PLAN 2

ACCEPTANCE CRITERIA 2

TEST SOLUTIONS 4

SELECTION OF CANDIDATE ALLOYS 5

TEST SETUP 7

CORROSION TEST RESULTS 9

1. Alkaline Test Results 9

   a. Stainless Steels 9
   b. Nickel-Based Alloys 11
   c. Titanium--Grade 2 13

2. Nitric Acid Results 14

   a. Type 304L Stainless Steel 14
   b. Type 316L Stainless Steel 15
   c. Type AL-6XN Stainless Steel 17
   d. Incoloy 825 18
   e. Inconel 625 19
   f. Inconel 690 20
   g. Hastelloy G-30 21
   h. Titanium--Grade 2 22

3. Electrochemical Testing 23

   a. Linear Polarization Resistance Data 23
   b. Cyclic Potentiodynamic Polarization Data 23

DISCUSSION 23

TABLE OF CONTENTS (contd)

Page

REFERENCES 24

APPENDIX A 25

APPENDIX B 37

APPENDIX C 46

LIST OF FIGURES

Page

1. Corrosion Test Matrix 3
2. Schematic Diagram of Standard Coupon 7
3. Schematic Diagram of Welded Coupon 7
4. Corrosion Test Kettle 8
5. Schematic of the Multiple Crevice Assembly That Was Bolted to Corrosion Coupons for the Crevice Corrosion Experiments 9
6. Type 304L Stainless Steel with Severe, Uniform Intergranular Attack and Uniform Grain Loss 15
7. Type 316L Stainless Steel with Severe, Uniform Intergranular Attack and Uniform Grain Loss 16
8. Type Al-6XN Stainless Steel with Uniform Intergranular Attack and Intermittent Grain Loss 17
9. Incoloy 825 Nickel-Based Alloy Exhibiting Uniform Intergranular Attack with Some Grain Loss 18
10. Inconel 625 Nickel-Based Alloy with Uniform Intergranular Attack 19
11. Inconel 690 Nickel-Based Alloy Showing Light Intergranular Attack with Slight Grain Loss 20
12. Hastelloy G-30 Nickel-Based Alloy with Light Etching 21
13. Grade 2 Titanium Exhibiting No Etching or Intergranular Attack 22

LIST OF TABLES

Page

1. Nitric Acid Test Solution Composition 4
2. Sodium Hydroxide Test Solution Composition 4
3. Selected Alloys for Corrosion Testing 5
4. Chemical Composition of Selected Alloys 6
5. Type 304L Stainless Steel Corrosion Rates--Alkaline Solution 10
6. Type 316L Stainless Steel Corrosion Rates--Alkaline Solution 10
7. Type AL-6XN Stainless Steel Corrosion Rates--Alkaline Solution 11
8. Incoloy 825 Corrosion Rates--Alkaline Solution 11
9. Inconel 625 Corrosion Rates--Alkaline Solution 12
10. Inconel 690 Corrosion Rates--Alkaline Solution 12
11. Hastelloy G-30 Corrosion Rates--Alkaline Solution 13
12. Titanium Grade 2 Corrosion Rates--Alkaline Solution 13
13. Type 304L Stainless Steel Corrosion Rates--Acidic Solution 14
14. Type 316L Stainless Steel Corrosion Rates--Acidic Solution 16
15. AL-6XN Stainless Steel Corrosion Rates--Acidic Solution 17
16. Incoloy 825 Corrosion Rates--Acidic Solution 18
17. Inconel 625 Corrosion Rates--Acidic Solution 19
18. Inconel 690 Corrosion Rates--Acidic Solution 20
19. Hastelloy G-30 Corrosion Rates--Acidic Solution 21
20. Titanium Grade 2 Corrosion Rates--Acidic Solution 22
21. Combined Nickel+Chromium Content of Selected Nickel-Based Alloys 24

ACRONYMS

ANL	Argonne National Laboratory
ASTM	American Society for Testing and Materials
CPU	Compact Processing Unit
DOE	Department of Energy
HAZ	Heat Affected Zone
mm/y	millimeters/year
mpy	mils per year (i.e., 0.001 inches/year)
NACE	National Association of Corrosion Engineers
ORNL	Oak Ridge National Laboratory
SCC	Stress Corrosion Cracking
SRS	Savannah River Site
TWRS	Tank Waste Remediation System
UST-ID	Underground Storage Tank - Integrated Demonstration

MOBILE EVAPORATOR
CORROSION TEST RESULTS

by

A. Rozeveld and D. B. Chamberlain

ABSTRACT

Laboratory corrosion tests were conducted on eight candidates to select a durable and cost-effective alloy for use in mobile evaporators to process radioactive waste solutions. Based on an extensive literature survey of corrosion data, three stainless steel alloys (304L, 316L, AL-6XN), four nickel-based alloys (825, 625, 690, G-30), and titanium were selected for testing. The corrosion tests included vapor phase, liquid junction (interface), liquid immersion, and crevice corrosion tests on plain and welded samples of candidate materials. Tests were conducted at 80°C for 45 days in two different test solutions: a nitric acid solution to simulate evaporator conditions during the processing of the cesium ion-exchange eluant and a highly alkaline sodium hydroxide solution to simulate the composition of Tank 241-AW-101 during evaporation.

All of the alloys exhibited excellent corrosion resistance in the alkaline test solution. Corrosion rates were very low and localized corrosion was not observed. Results from the nitric acid tests showed that only 316L stainless steel did not meet our performance criteria. The 316L welded interface and crevice specimens had rates of 22.2 mpy and 21.8 mpy, respectively, which exceeds the maximum corrosion rate of 20 mpy. The other welded samples had about the same corrosion resistance as the plain samples. None of the welded samples showed preferential weld or heat-affected zone (HAZ) attack. Vapor corrosion was negligible for all alloys. All of the alloys except 316L exhibited either "satisfactory" (2-20 mpy) or "excellent" (<2 mpy) corrosion resistance as defined by National Association of Corrosion Engineers. However, many of the alloys experienced intergranular corrosion in the nitric acid test solution, which could indicate a susceptibility to stress corrosion cracking (SCC) in this environment.

INTRODUCTION

The program titled "UST-ID: Mobile Evaporator/Concentrator Technology Development" was funded by the Department of Energy (DOE) to develop a mobile evaporator/concentrator compact processing unit (CPU) originally intended for processing wastes from underground storage tanks at Hanford and potentially four other DOE sites. Changes in the project's mission were introduced when Westinghouse Hanford and DOE decided against the installation and testing of CPU-based processes. Because of this decision, the focus on evaporator CPU usage has shifted to the general DOE complex. As part of the development process, a durable and cost-effective alloy must be selected as the material of construction for the CPU. This report describes the selection and corrosion testing of eight candidate alloys and presents the test results from Stage 1 of the corrosion test plan.

CORROSION TEST PLAN

Corrosion testing was carried out at CC Technologies in Columbus, OH, under American Society for Testing and Materials (ASTM) standards and guidelines. This company is a fully equipped, corrosion testing and research laboratory specializing in the evaluation of material properties, materials selection, corrosion, and corrosion control. The corrosion test plan is described briefly below.

The corrosion test plan consists of two stages. Stage 1, which is the subject of this report, included vapor phase, liquid junction (interface), liquid immersion, and crevice corrosion tests on plain and welded samples of candidate materials. Additional testing required includes tests for stress corrosion cracking (SCC) with specimens prepared per ASTM G30-90. Alloys that had corrosion rates of 20 mpy or less in Stage 1 should be tested for SCC. Stage 1 tests were completed at 80°C for 45 days in two different test solutions (described below). A slight vacuum (pressure of 660 mmHg) was maintained to simulate the conditions inside an evaporator. Figure 1 illustrates the test matrix for Stage 1. Tests on abraded specimens are being considered to evaluate the effect of the feed solids content on the corrosion resistance. Tests using irradiated specimens will not be conducted because the maximum concentration of radionuclides in the evaporator will be 2 Ci/L, which will not affect corrosion rates [HARRISON].

ACCEPTANCE CRITERIA

Based upon the Stage 1 test results, acceptable alloys should have a general corrosion rate less than 0.53 mm/y (20 mpy). The National Association of Corrosion Engineers (NACE) defines "excellent" corrosion resistance to be less than 0.053 mm/y (2 mpy) and "satisfactory" performance to be less than 0.53 mm/y (20 mpy); we have adopted these guidelines. If intergranular corrosion is evident in the samples, then SCC tests should be completed. These tests, however, are beyond the scope of this study.

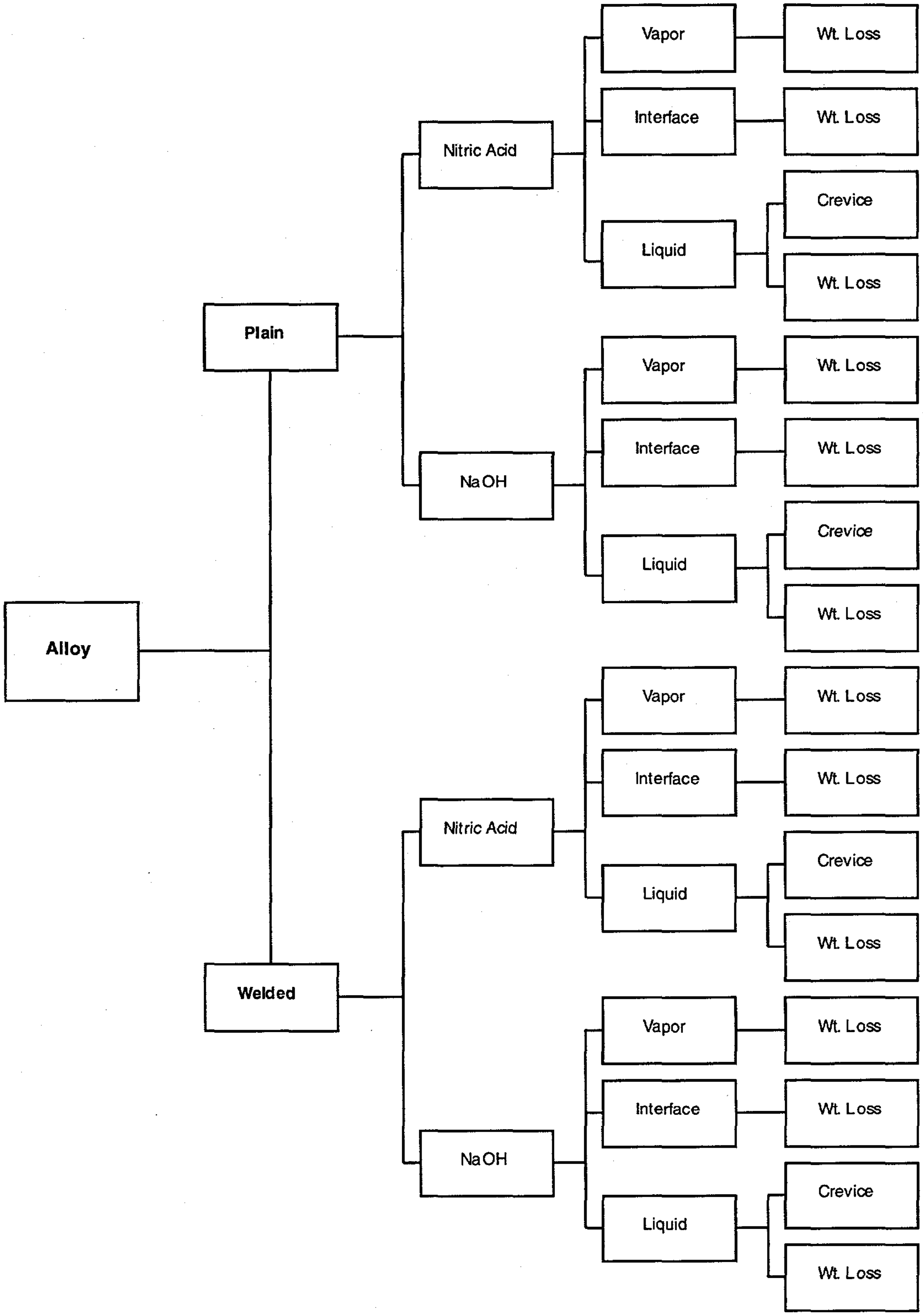

Fig. 1. Corrosion Test Matrix

TEST SOLUTIONS

The evaporator CPU was originally intended to process (1) cesium-free tank waste from Hanford Tank 241-AW-101 and (2) cesium ion-exchange eluant. Although CPUs will no longer be installed and tested at Hanford, the recommended test solutions for the corrosion test plan were not changed for two reasons. First, the Tank Waste Remediation System (TWRS) program still includes a number of evaporators in their Case BETA Prime flowsheet [ORME]. These data will assist them to select materials for these units. Second, the simulated waste solutions being evaluated in this study are more corrosive than what we can expect at other sites. Thus, materials that pass our acceptance criteria would be appropriate for those sites. If SCC tests are done, solution compositions more specific to other sites may be evaluated.

Two solutions were selected for testing: (1) a nitric acid solution to simulate evaporator conditions during the processing of the cesium ion-exchange eluant and (2) a highly alkaline sodium hydroxide solution to simulate the composition of Tank 241-AW-101 during evaporation. The compositions of these solutions are shown in Tables 1 and 2, respectively [RICHMOND]. Since corrosion rates increase with increasing concentration and temperature for both nitric acid and sodium hydroxide solutions, the most concentrated compositions expected in the evaporator were chosen as test solutions.

Table 1. Nitric Acid Test Solution Composition

Constituent	Concentration, M
H^+	15.9
Na^+	2.5
NO_3^-	18.4

Table 2. Sodium Hydroxide Test Solution Composition

Cation Constituent	Concentration, M	Anion Constituent	Concentration, M
Aluminum	9.5 E-01	Chloride	1.5 E-01
Chromium	3.1 E-03	Hydroxide	5.7 E+00
Iron	7.9 E-04	Fluoride	4.0 E-03
Magnesium	2.0 E-03	Nitrite	2.8 E+00
Potassium	1.1 E+00	Nitrate	3.8 E+00
Sodium	9.0 E+00	Phosphate	2.2 E-02
Ammonia	1.5 E-02	Sulfate	1.1 E-02
		Carbonate	2.1 E-01

During the processing of waste solutions containing fluoride and calcium ions, a CaF_2-containing scale may form on surfaces. If the system is flushed with nitric acid to remove the scale, a highly corrosive HNO_3-HF solution may form. The material of construction selected for the system must have acceptable corrosion resistance to this acid mixture. Alternatively, it may be possible to reduce or eliminate the corrosivity of the fluoride solution by adding a complexant such as Zr or Al to the solution [CHEN]. We recommend that those alloys which exhibit acceptable corrosion resistance in Stage 1 be tested in an HNO_3-HF environment.

SELECTION OF CANDIDATE ALLOYS

Based on an extensive literature survey of corrosion data, eight alloys were selected for corrosion testing in the two environments described above (15.9 M HNO_3 and 5 M NaOH). The selection process will be discussed briefly here; a more detailed description can be found in Appendix A.

Three stainless steel (SS) alloys, four nickel-based alloys, and titanium were selected for testing; they are listed in Table 3. The chemical composition of each of the alloys is given in Table 4. Type 304L is a common evaporator construction material; 316L, 825 and 625 are also used [ANTHONY]. We included several alloys in our testing program to provide alternative materials for the CPU in case the stainless steels prove to be inadequate.

Table 3. Selected Alloys for Corrosion Testing

Alloy Type	Alloy Name
Stainless steel	304L, 316L, AL-6XN
Nickel-based alloy	825, 625, 690, G-30
Titanium	Grade 2

The 304L and 316L alloys are Ni-Cr low-carbon stainless steels; 316L SS also has 2.5% Mo for pitting resistance. The alloy AL-6XN is a "6-moly stainless." It contains higher levels of Ni and Cr than 304 or 316L plus ~6% Mo. In general, the higher the nickel and chromium content, the more corrosion resistant the alloy, so AL-6XN should be fairly resistant to our test solutions.

The nickel-based alloys 825, 625, 690 and G-30 also have higher Ni and Cr contents and are expected to perform as well as or better than the stainless steels in the acidic and alkaline test solutions. These four alloys have Ni+Cr contents ranging from 63.5% to 87%. Grade 2 titanium is commercially pure and is often used for heat-exchanger tubes in evaporators.

Table 4. Chemical Composition of Selected Alloys

Alloy	Chemical Composition, wt%														
	Al	C	Cb[a]+Ta	Co	Cr	Cu	Fe	Mn	Mo	N	Ni	P	S	Si	Ti	Other
304L SS		0.020			18.26	0.30	Bal.	1.86	0.30	0.090	8.11	0.032	0.0020	0.56		
316L SS		0.020			16.33	0.23	Bal.	1.84	2.12	0.030	10.17	0.028	0.0003	0.52		
AL-6XN		0.015			20.48	0.24	Bal.	0.34	6.23	0.240	23.90	0.021	0.0003	0.38		
825	0.009	0.010			22.07	1.72	29.69	0.40	3.49		41.22		<.0010	0.29	1.02	
625	0.230	0.020	3.42		21.89		3.34	0.05	8.97		61.68	0.007	<.0010	0.13	0.25	
690	0.220	0.010			29.10		10.26	0.42			59.40		0.0030	0.30	0.29	
G-30		0.010	0.88	2.20	29.10	1.90	14.60	1.10	5.00		Bal.	0.008	<.0020	0.26		W-2.80
Ti (Grade 2)		0.100								0.009					Bal.	O=0.12, H=7 ppm

[a]Archaic usage for niobium (Nb) is columbium (Cb).

TEST SETUP

Two plain and two welded specimens of each candidate alloy were tested in each solution at every condition. Samples of each alloy were from the same heat[1] and oriented parallel to the rolling direction. They were prepared according to ASTM G1-90; the batch (or heat) sample surface finish was polished to 120 grit. Schematic diagrams of the standard and welded coupons are given in Figs. 2 and 3, respectively.

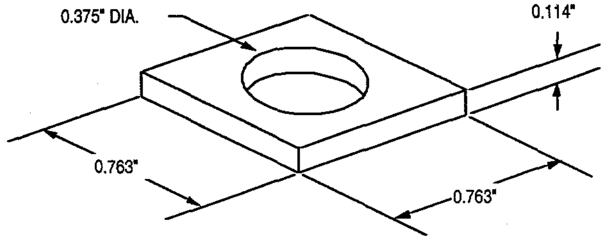

Fig. 2. Schematic Diagram of Standard Coupon

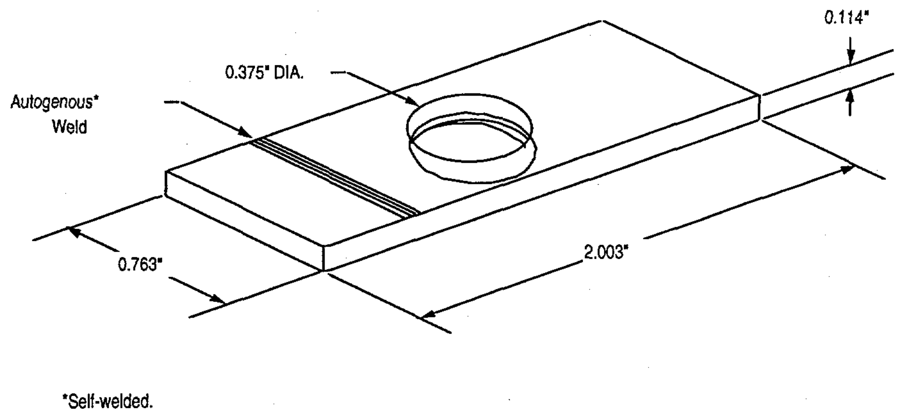

Fig. 3. Schematic Diagram of Welded Coupon

Tests were performed in four-liter resin kettles equipped with a heating mantle and thermocouple (see Fig. 4). Samples were supported in the kettles by a rigid Teflon "tree" which has Hastelloy C276 hardware isolated from the samples by Teflon washers and tubes. Coupons were placed in three areas of the kettle: the vapor phase, the interface, and the liquid phase. The testing apparatus was adapted to allow for sampling of the test solutions, and thus for monitoring compositional variations, during the tests. Such variations could indicate a sudden change in the corrosion rate of the test specimen. Monitoring was completed by conducting periodic linear polarization resistance measurements. Changes in these readings would indicate a change in the solution chemistry. No change was seen during testing. Funding constraints prevented us from completing any solution analyses.

[1]Heat is defined as a batch of steel prepared and poured at the same time.

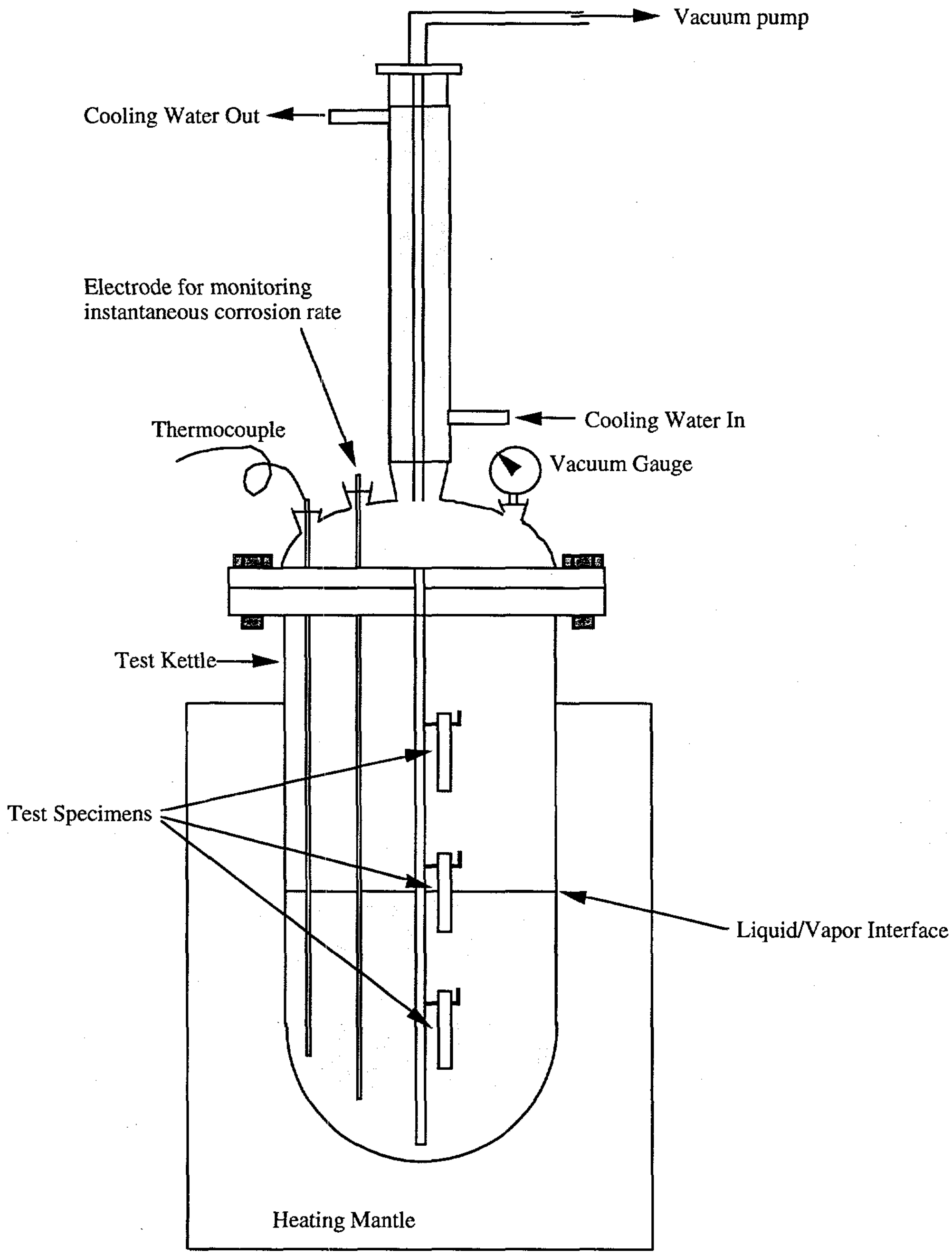

Fig. 4. Corrosion Test Kettle

The crevice corrosion samples were prepared according to standard procedure ASTM G78, with radically grooved Teflon crevice-formers bolted to either side of the test sample. A schematic of this assembly is shown in Fig. 5. These samples were located in the liquid phase in each kettle.

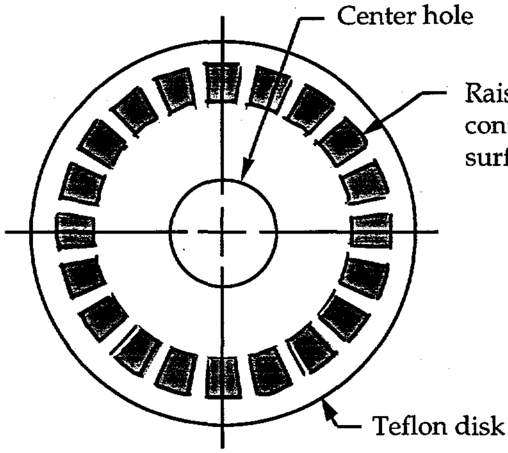

Fig. 5. Schematic of the Multiple Crevice Assembly That Was Bolted to Corrosion Coupons for the Crevice Corrosion Experiments

Tests were conducted at 80°C (176°F) and 660 mmHg for 45 days. Evaluation of the samples after testing included mass loss measurements for corrosion rate calculations and examination for pitting, intergranular corrosion, weld attack, and crevice corrosion. Visual observations before cleaning included notation of staining, deposits, or corrosion products. Those samples which required it were mechanically cleaned to remove loose deposits by brushing the samples with a soft nylon brush under running warm water, then rinsing with deionized water and acetone. A weighed blank specimen of each material was included in the chemical cleaning operations to ensure that any weight loss associated with the cleaning process was accounted for in the weight-loss calculations.

Some problems associated with applying a vacuum to the test kettles were encountered during testing. The standard test kettles were not designed for operation with a vacuum, so they were modified during the setup for the alkaline solution tests to maintain a slight vacuum. However, the nitric acid test solution attacked some components of the modified kettles, contaminating the test solution. Rather than compromise the test results, the samples were cleaned (according to ASTM G1-90) and reweighed, a new nitric acid test solution was prepared, and the tests were restarted. Twice during the subsequent 45-day exposure, the vacuum was lost for a short time (<24 hr) when the vacuum line was blocked by debris. These short-term deviations from vacuum should not affect the test results.

CORROSION TEST RESULTS

The corrosion rate data presented in this section are averages of the two specimens for each alloy and condition. The complete data set, including the weight measurements, is reported in Appendices B and C.

1. Alkaline Test Results

a. Stainless Steels

All of the stainless steel samples had very low corrosion rates (≤0.06 mpy, ≤0.0015 mm/y) in the alkaline solution (see Tables 5-7). Although some corrosion rate differences were seen in the liquid, vapor, and interface samples, the rates were very low and differences are probably not significant. No pitting, crevice, or preferential weld attack was found on any of the stainless steel samples. The 304L and 316L samples had some slight discoloration on the liquid phase and interface specimens beneath the crevice formers and the sample mounting hardware; no discoloration was observed on the AL-6XN samples.

Table 5. Type 304L Stainless Steel Corrosion Rates--Alkaline Solution[a]

Condition	Average Corrosion Rate	
	mm/y	mpy
Liquid--Wt. Loss	0.0015	0.06
Liquid--Crevice	0.0008	0.03
Interface--Wt. Loss	0.0008	0.03
Vapor--Wt. Loss	0.0008	0.03
Weld--Liquid--Wt. Loss	0.0005	0.02
Weld--Liquid--Crevice	0.0005	0.02
Weld--Interface--Wt. Loss	0.0003	0.01
Weld--Wt. Loss--Vapor	0.00[b]	0.00[b]

[a]Test was completed at 80°C and 660 mmHg for 45 days.

[b]An average corrosion rate of 0.00 indicates that the sample experienced no weight loss during testing.

Table 6. Type 316L Stainless Steel Corrosion Rates--Alkaline Solution[a]

Condition	Average Corrosion Rate	
	mpy	mm/y
Liquid--Wt. Loss	0.0008	0.03
Liquid--Crevice	0.0010	0.04
Interface--Wt. Loss	0.0005	0.02
Vapor--Wt. Loss	0.0005	0.02
Weld--Liquid--Wt. Loss	0.0008	0.03
Weld--Liquid--Crevice	0.0008	0.03
Weld--Interface--Wt. Loss	0.00[b]	0.00[b]
Weld--Wt. Loss--Vapor	0.0003	0.01

[a]Test was completed at 80°C and 660 mmHg for 45 days.

[b]An average corrosion rate of 0.00 indicates that the sample experienced no weight loss during testing.

Table 7. Type AL-6XN Stainless Steel Corrosion Rates--Alkaline Solution[a]

Condition	Average Corrosion Rate	
	mm/y	mpy
Liquid--Wt. Loss	0.0013	0.05
Liquid--Crevice	0.0010	0.04
Interface--Wt. Loss	0.0013	0.05
Vapor--Wt. Loss	0.0010	0.04
Weld--Liquid--Wt. Loss	0.0015	0.06
Weld--Liquid--Crevice	0.0010	0.04
Weld--Interface--Wt. Loss	0.0010	0.04
Weld--Wt. Loss--Vapor	0.0005	0.02

[a]Test was completed at 80°C and 660 mmHg for 45 days.

b. Nickel-Based Alloys

None of the nickel-based alloys experienced pitting, crevice, or preferential weld attack. The 825 sample exhibited a very light etching during the visual inspection before cleaning, but the observed corrosion rates for all conditions of the alloy were quite low (see Tables 8-11). All of the nickel-based alloys had very low corrosion rates [≤0.0008 mm/y (≤0.07 mpy)] in the alkaline solution.

Table 8. Incoloy 825 Corrosion Rates--Alkaline Solution[a]

Condition	Average Corrosion Rate	
	mm/y	mpy
Liquid--Wt. Loss	0.0005	0.02
Liquid--Crevice	0.0008	0.03
Interface--Wt. Loss	0.0005	0.02
Vapor--Wt. Loss	0.0005	0.02
Weld--Liquid--Wt. Loss	0.0003	0.01
Weld--Liquid--Crevice	0.0003	0.01
Weld--Interface--Wt. Loss	0.00[b]	0.00[b]
Weld--Wt. Loss--Vapor	0.00[b]	0.00[b]

[a]Test was completed at 80°C and 660 mmHg for 45 days.
[b]An average corrosion rate of 0.00 indicates that the sample experienced no weight loss during testing.

Table 9. Inconel 625 Corrosion Rates--Alkaline Solution[a]

Condition	Average Corrosion Rate	
	mm/y	mpy
Liquid--Wt. Loss	0.0008	0.03
Liquid--Crevice	0.0010	0.04
Interface--Wt. Loss	0.0008	0.03
Vapor--Wt. Loss	0.0008	0.03
Weld--Liquid--Wt. Loss	0.0003	0.01
Weld--Liquid--Crevice	0.0003	0.01
Weld--Interface--Wt. Loss	0.0003	0.01
Weld--Wt. Loss--Vapor	0.0003	0.01

[a]Test was completed at 80°C and 660 mmHg for 45 days.

Table 10. Inconel 690 Corrosion Rates--Alkaline Solution[a]

Condition	Average Corrosion Rate	
	mm/y	mpy
Liquid--Wt. Loss	0.0018	0.07
Liquid--Crevice	0.0015	0.06
Interface--Wt. Loss	0.0008	0.03
Vapor--Wt. Loss	0.0018	0.07
Weld--Liquid--Wt. Loss	0.0003	0.01
Weld--Liquid--Crevice	0.00[b]	0.00[b]
Weld--Interface--Wt. Loss	0.00[b]	0.00[b]
Weld--Wt. Loss--Vapor	0.00[b]	0.00[b]

[a]Test was completed at 80°C and 660 mmHg for 45 days.
[b]An average corrosion rate of 0.00 indicates that the sample experienced no weight loss during testing.

Table 11. Hastelloy G-30 Corrosion Rates--Alkaline Solution[a]

Condition	Average Corrosion Rate	
	mm/y	mpy
Liquid--Wt. Loss	0.0003	0.01
Liquid--Crevice	0.0005	0.02
Interface--Wt. Loss	0.0003	0.01
Vapor--Wt. Loss	0.0003	0.01
Weld--Liquid--Wt. Loss	0.00[b]	0.00[b]
Weld--Liquid--Crevice	0.00[b]	0.00[b]
Weld--Interface--Wt. Loss	0.00[b]	0.00[b]
Weld--Wt. Loss--Vapor	0.00[b]	0.00[b]

[a]Test was completed at 80°C and 660 mmHg for 45 days.
[b]An average corrosion rate of 0.00 indicates that the sample experienced no weight loss during testing.

c. Titanium--Grade 2

No pitting, crevice, or preferential weld attack was observed on the titanium samples. They were discolored with a blue-brown tint, which was darker on the liquid phase samples. The corrosion rates (see Table 12) for all of the titanium samples were very low ≤0.0038 mm/y (≤0.15 mpy).

Table 12. Titanium Grade 2 Corrosion Rates--Alkaline Solution[a]

Condition	Average Corrosion Rate	
	mm/y	mpy
Liquid--Wt. Loss	0.0023	0.09
Liquid--Crevice	0.0023	0.09
Interface--Wt. Loss	0.0031	0.12
Vapor--Wt. Loss	0.0018	0.07
Weld--Liquid--Wt. Loss	0.0026	0.10
Weld--Liquid--Crevice	0.0031	0.12
Weld--Interface--Wt. Loss	0.0038	0.15
Weld--Wt. Loss--Vapor	0.0015	0.06

[a]Test was completed at 80°C and 660 mmHg for 45 days.

2. Nitric Acid Results

a. Type 304L Stainless Steel

Corrosion rates for the 304L stainless steel coupons are reported in Table 13. No pitting or crevice attack was observed for any of the samples. The samples exhibited a deep blue-black tinting that was impervious to standard cleaning methods. However, the luminescent appearance of the tinting indicated that it was a very thin film and would not affect the corrosion rate calculation. The tinting was heavier on samples exposed to the liquid phase and interface conditions. The 304L samples experienced severe uniform intergranular attack with uniform grain loss. In the welded coupons, the weld structures were revealed and exhibited intergranular attack, but no preferential attack of the weld or heat-affected zone (HAZ) was found. The average corrosion rate for the liquid-phase samples was 0.138 mm/y (5.4 mpy). A micrograph of the coupon surface, showing severe, uniform intergranular attack and uniform grain loss, is shown in Fig. 6.

Table 13. Type 304L Stainless Steel Corrosion Rates--Acidic Solution[a]

Condition	Average Corrosion Rate	
	mm/y	mpy
Liquid--Wt. Loss	0.148	5.77
Liquid--Crevice	0.0842	3.29
Interface--Wt. Loss	0.119	4.65
Vapor--Wt. Loss	0.0026	0.10
Weld--Liquid--Wt. Loss	0.132	5.16
Weld--Liquid--Crevice	0.139	5.43
Weld--Interface--Wt. Loss	0.113	4.43
Weld--Wt. Loss--Vapor	0.0018	0.07

[a]Test was completed at 80°C and 660 mmHg for 45 days.

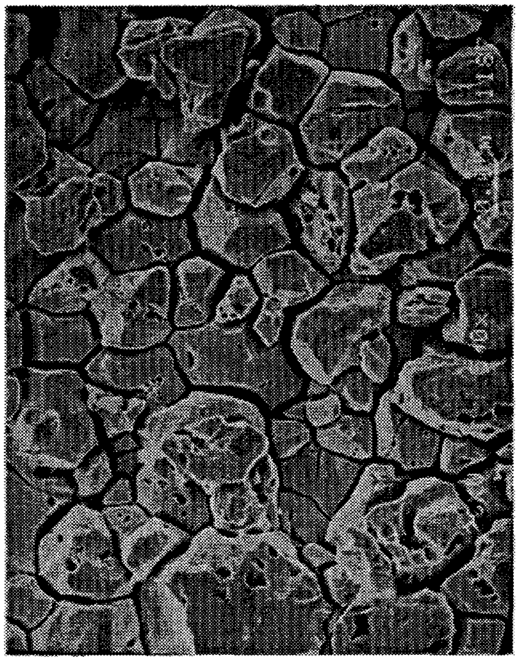

Fig. 6. Type 304L Stainless Steel with Severe, Uniform Intergranular Attack and Uniform Grain Loss. Micrograph of base metal at 500X. Coupon shown is a liquid-phase sample following 45-day immersion testing at 80°C and 660 mmHg.

b. Type 316L Stainless Steel

Results for the 316L samples were similar to those for the 304L samples (see Table 14). Blue-brown tinting was observed on the samples; there was no evidence of pitting or crevice attack. The attack was again characterized as severe uniform intergranular corrosion with uniform grain loss. Weld structures were revealed, but no preferential attack occurred. The average corrosion rate for the 316L liquid-phase samples was 0.443 mm/y (17.3 mpy). A micrograph of the coupon surface, showing severe, uniform intergranular attack and uniform grain loss, is shown in Fig. 7.

Table 14. Type 316L Stainless Steel Corrosion Rates--Acidic Solution[a]

Condition	Average Corrosion Rate	
	mm/y	mpy
Liquid--Wt. Loss	0.369	14.42
Liquid--Crevice	0.418	16.32
Interface--Wt. Loss	0.301	11.77
Vapor--Wt. Loss	0.0038	0.15
Weld--Liquid--Wt. Loss	0.426	16.65
Weld--Liquid--Crevice	0.557	21.75
Weld--Interface--Wt. Loss	0.569	22.24
Weld--Wt. Loss--Vapor	0.0023	0.09

[a]Test was completed at 80°C and 660 mmHg for 45 days.

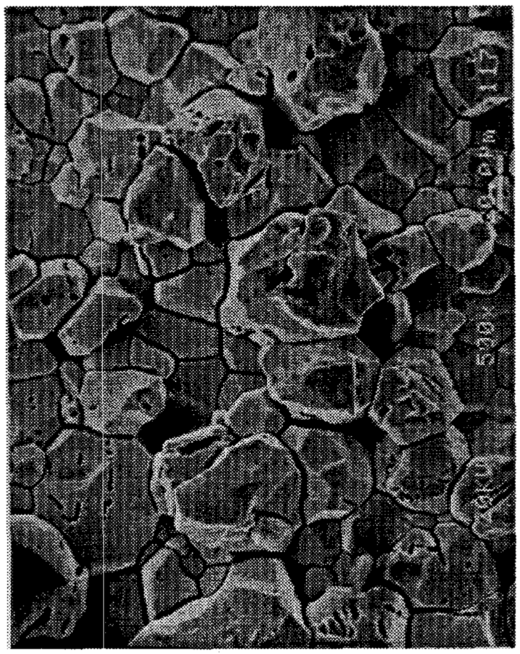

Fig. 7. Type 316L Stainless Steel with Severe, Uniform Intergranular Attack and Uniform Grain Loss. Micrograph of base metal at 500X. Coupon shown is a liquid-phase sample following 45-day immersion testing at 80°C and 660 mmHg.

c. Type AL-6XN Stainless Steel

No discoloration, pitting, or crevice attack was visible on the AL-6XN samples. The samples exhibited uniform intergranular attack with intermittent grain loss, but was not as severe as that on 304L and 316L. The weld structure was clearly revealed on the AL-6XN liquid phase and interface samples but just barely visible on the vapor-phase samples. No preferential weld attack was observed. The average corrosion rate for the AL-6XN liquid phase samples was 0.033 mm/y (1.3 mpy) (see Table 15). A micrograph of the coupon surface showing uniform intergranular attack and intermittent grain loss is shown in Fig. 8.

Table 15. Type AL-6XN Stainless Steel Corrosion Rates--Acidic Solution[a]

Condition	Average Corrosion Rate	
	mpy	mm/y
Liquid--Wt. Loss	0.032	1.26
Liquid--Crevice	0.053	2.05
Interface--Wt. Loss	0.054	2.13
Vapor--Wt. Loss	0.0026	0.10
Weld--Liquid--Wt. Loss	0.0276	1.08
Weld--Liquid--Crevice	0.0218	0.85
Weld--Interface--Wt. Loss	0.067	2.63
Weld--Wt. Loss--Vapor	0.0018	0.07

[a]Test was completed at 80°C and 660 mmHg for 45 days.

Fig. 8. Type Al-6XN Stainless Steel with Uniform Intergranular Attack and Intermittent Grain Loss. The horizontal scratches are from polishing during coupon preparation. Micrograph of base metal at 500X. Coupon shown is a liquid-phase sample following 45-day immersion testing at 80°C and 660 mmHg.

d. Incoloy 825

No pitting, crevice, or preferential weld attack was observed on any of the samples, but they experienced uniform intergranular attack with some grain loss; the weld structures were revealed on the liquid-phase and interface samples. The average corrosion rate for the liquid-phase samples was 0.0009 mm/y (3.6 mpy) (see Table 16). A micrograph of the coupon surface, showing uniform intergranular attack with some grain loss, is shown in Fig. 9.

Table 16. Incoloy 825 Corrosion Rates--Acidic Solution[a]

Condition	Average Corrosion Rate	
	mm/y	mpy
Liquid--Wt. Loss	0.115	4.48
Liquid--Crevice	0.117	4.58
Interface--Wt. Loss	0.047	1.84
Vapor--Wt. Loss	0.0008	0.03
Weld--Liquid--Wt. Loss	0.069	2.69
Weld--Liquid--Crevice	0.063	2.47
Weld--Interface--Wt. Loss	0.030	1.17
Weld--Wt. Loss--Vapor	0.0003	0.01

[a]Test was completed at 80°C and 660 mmHg for 45 days.

Fig. 9. Incoloy 825 Nickel-Based Alloy Exhibiting Uniform Intergranular Attack with Some Grain Loss. Micrograph of base metal at 460X. Coupon shown is a liquid-phase sample following 45-day immersion testing at 80°C and 660 mmHg.

e. Inconel 625

No pitting, crevice, or preferential weld attack was observed on the samples. However, the weld structure was clearly revealed on the liquid phase and interface samples. The observed attack was uniform and intergranular with no grain loss. The corrosion rate for the liquid-phase specimens averaged 0.069 mm/y (2.7 mpy) (see Table 17). A micrograph of the coupon surface, showing uniform intergranular attack, is shown in Fig. 10.

Table 17. Inconel 625 Corrosion Rates--Acidic Solution[a]

Condition	Average Corrosion Rate	
	mm/y	mpy
Liquid--Wt. Loss	0.082	3.20
Liquid--Crevice	0.095	3.70
Interface--Wt. Loss	0.071	2.76
Vapor--Wt. Loss	0.0018	0.07
Weld--Liquid--Wt. Loss	0.056	2.18
Weld--Liquid--Crevice	0.039	1.52
Weld--Interface--Wt. Loss	0.068	2.65
Weld--Wt. Loss--Vapor	0.0018	0.07

[a]Test was completed at 80°C and 660 mmHg for 45 days.

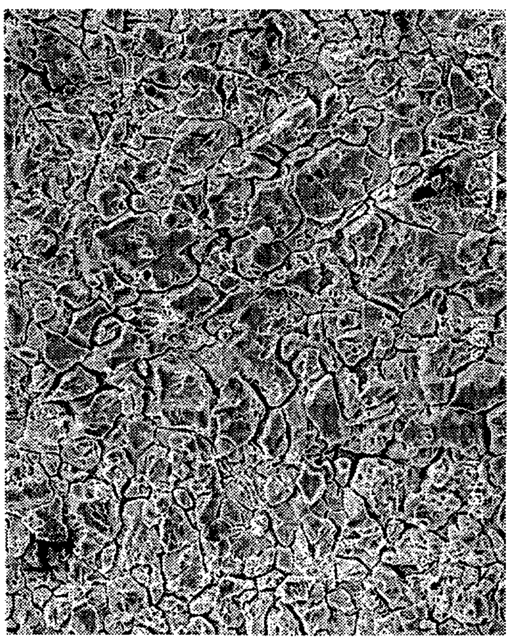

Fig. 10. Inconel 625 Nickel-Based Alloy with Uniform Intergranular Attack. Micrograph of base metal at 500X. Coupon shown is a liquid-phase sample following 45-day immersion testing at 80°C and 660 mmHg.

f. Inconel 690

No pitting, crevice, or preferential weld attack was observed on the samples. The attack was characterized as light intergranular attack with slight grain loss. The weld structures were revealed on the liquid-phase and interface samples. These samples also showed a very light brown tinting and very slight etching on all exposed areas. The liquid-phase samples had an average corrosion rate of 0.038 mm/y (1.5 mpy) (see Table 18). A micrograph of the coupon surface, showing light intergranular attack with slight grain loss, is shown in Fig. 11.

Table 18. Inconel 690 Corrosion Rates--Acidic Solution[a]

Condition	Average Corrosion Rate	
	mm/y	mpy
Liquid--Wt. Loss	0.043	1.67
Liquid--Crevice	0.039	1.51
Interface--Wt. Loss	0.017	0.65
Vapor--Wt. Loss	0.0008	0.03
Weld--Liquid--Wt. Loss	0.038	1.50
Weld--Liquid--Crevice	0.035	1.38
Weld--Interface--Wt. Loss	0.013	0.51
Weld--Wt. Loss--Vapor	0.0003	0.01

[a]Test was completed at 80°C and 660 mmHg for 45 days.

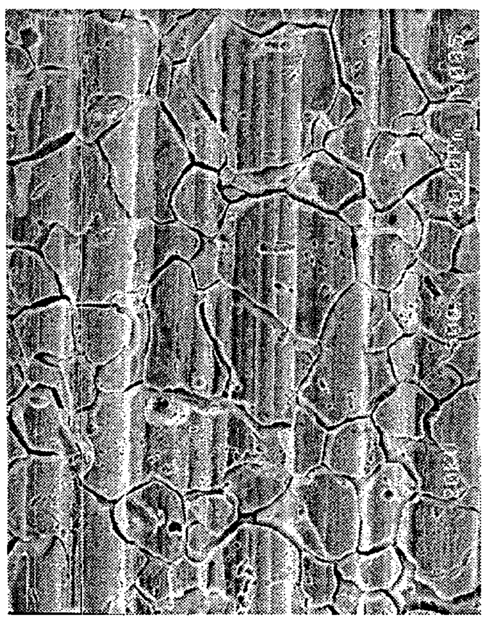

Fig. 11. Inconel 690 Nickel-Based Alloy Showing Light Intergranular Attack with Slight Grain Loss. The vertical scratches are from polishing during coupon preparation. Micrograph of base metal at 500X. Coupon shown is a liquid-phase sample following 45-day immersion testing at 80°C and 660 mmHg.

g. Hastelloy G-30

No pitting, crevice, or preferential weld attack was observed on the G-30 samples. They experienced light etching, which revealed the alloy's microstructure, but no significant intergranular attack was observed. Weld structures were visible on the liquid-phase and interface specimens. These specimens also had very light brown tinting on the exposed surfaces. The average corrosion rate for the liquid-phase samples was 0.019 mm/y (0.76 mpy) (see Table 19). A micrograph of the coupon surface, showing light etching of the surface, is shown in Fig. 12.

Table 19. Hastelloy G-30 Corrosion Rates--Acidic Solution[a]

Condition	Average Corrosion Rate	
	mm/y	mpy
Liquid--Wt. Loss	0.020	0.78
Liquid--Crevice	0.026	1.03
Interface--Wt. Loss	0.023	0.90
Vapor--Wt. Loss	0.001	0.04
Weld--Liquid--Wt. Loss	0.014	0.55
Weld--Liquid--Crevice	0.018	0.69
Weld--Interface--Wt. Loss	0.015	0.60
Weld--Wt. Loss--Vapor	0.0008	0.03

[a]Test was completed at 80°C and 660 mmHg for 45 days.

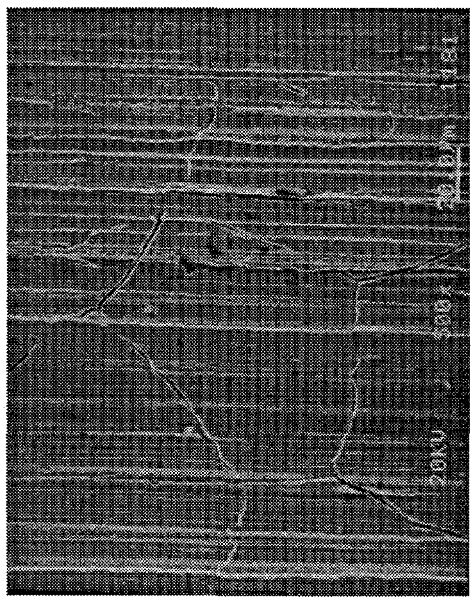

Fig. 12. Hastelloy G-30 Nickel-Based Alloy with Light Etching. Micrograph of base metal at 500X. The horizontal scratches are from polishing during coupon preparation. Coupon shown is a liquid-phase sample following 45-day immersion testing at 80°C and 660 mmHg.

h. Titanium--Grade 2

No pitting, crevice, or preferential weld attack was observed. The liquid-phase and interface samples were tinted a very light blue-brown. No etching or intergranular attack was observed. The average corrosion rate for the liquid-phase samples was 0.0028 mm/y (0.11 mpy) (see Table 20). A micrograph of the coupon surface, which exhibits no etching or intergranular attack, is shown in Fig. 13.

Table 20. Titanium Grade 2 Corrosion Rates--Acidic Solution[a]

Condition	Average Corrosion Rate	
	mm/y	mpy
Liquid--Wt. Loss	0.010	0.40
Liquid--Crevice	0.0005	0.02
Interface--Wt. Loss	0.0005	0.02
Vapor--Wt. Loss	0.0008	0.03
Weld--Liquid--Wt. Loss	0.0005	0.02
Weld--Liquid--Crevice	0.0005	0.02
Weld--Interface--Wt. Loss	0.0013	0.05
Weld--Wt. Loss--Vapor	0.0008	0.03

[a]Test was completed at 80°C and 660 mmHg for 45 days.

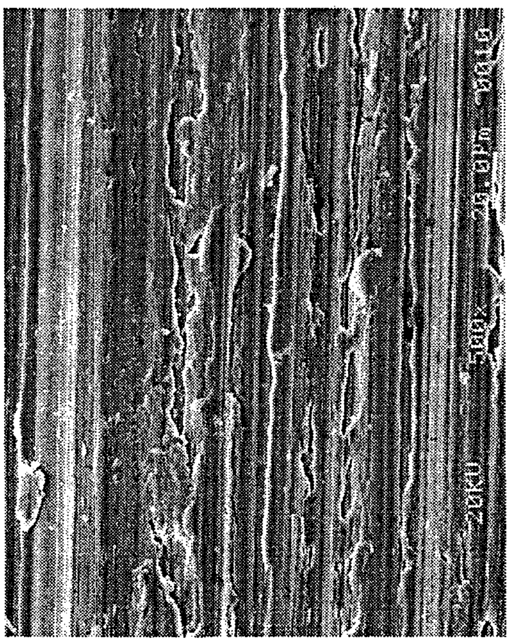

Fig. 13. Grade 2 Titanium Exhibiting No Etching or Intergranular Attack. Micrograph of base metal at 500X. The vertical scratches are from polishing during coupon preparation. Coupon shown is a liquid-phase sample following 45-day immersion testing at 80°C and 660 mmHg.

3. Electrochemical Testing

a. Linear Polarization Resistance Data

The corrosion rate of 304L in nitric acid solution did not exceed 0.11 mm/y (4.2 mpy) after 96 hours of exposure, although initial rates were observed in excess of 1.28 mm/y (50 mpy). (Stainless steels initially experience higher rates of corrosion before passivation occurs.) No effect of the vacuum losses was seen in the measured corrosion rate during the 45-day exposure. No effect of solution additions to the kettle (to maintain solution levels) was observed in the measured corrosion rates once the system returned to 80°C following the addition. The corrosion rate of 304L in the alkaline test solution did not exceed 0.07 mpy after 48 hours of exposure. No effect on the rate was observed upon application of vacuum to the test kettle. Likewise, solution additions did not affect the measured corrosion rate once the temperature of the system returned to 80°C following the addition.

b. Cyclic Potentiodynamic Polarization Data

Cyclic potentiodynamic polarization (CPP) tests were performed by CC Technologies on the candidate alloys soon after the long-term exposure tests were started. They were conducted at 80°C. The results were expected to predict those of the long-term tests, that is, whether the alloys would undergo pitting in the test solution. In this technique, the polarity and magnitude of the current flow between a specimen of the alloy and an inert counter electrode are measured as a function of electrochemical potential. The potential is scanned to a value that exceeds the pitting potential, then reversed and returned to the corrosion potential. The occurrence of hysteresis between the forward and reverse scans is generally indicative of pitting or crevice corrosion on the specimen during the test. These results are given in Appendix B. The results showed no pitting or crevice attack on any of the samples.

DISCUSSION

All of the alloys exhibited excellent corrosion resistance in the sodium hydroxide test solution. Corrosion rates were very low and localized corrosion was not observed.

Results for the nitric acid test solution showed that only 316L stainless steel did not meet our acceptance criteria. The 316L welded interface and crevice specimens had rates of 0.59 mm/y (22.2 mpy) and 0.58 mm/y (21.8 mpy), respectively, which exceeds the maximum corrosion rate of 0.53 mm/y (20 mpy). Except for 316L welded samples had about the same corrosion resistance as the plain samples. None of the welded samples showed preferential weld or HAZ attack. Vapor corrosion was negligible for all alloys. All of the alloys except 316L exhibited either "satisfactory" (0.053-0.53 mm/y, 2-20 mpy) or "excellent" (<0.053 mm/y, 2 mpy) corrosion resistance as defined by National Association of Corrosion Engineers (NACE). However, many of the alloys experienced intergranular corrosion in the nitric acid test solution, which could indicate a susceptibility to SCC in this environment. Any of these alloys under consideration for use in a nitric acid solution should be tested for SCC beforehand in that solution.

The nickel-based alloys we tested have (Ni+Cr) contents ranging from 63.5% to 87% (see Table 21). Surprisingly, Hastelloy G-30 performed as well as or better than the rest of the nickel-based alloys, even though it has a (Ni+Cr) content of only 67%. This behavior may reflect the presence of cobalt in the alloy, which is believed to increase the corrosion resistance of nickel-based alloys [BARKER]. In addition, only G-30 and titanium experienced no intergranular attack. As expected, the corrosion resistance of titanium in the nitric acid solution was excellent.

The results indicate that all of the alloys should undergo further testing for SCC in the sodium hydroxide solution. All of the alloys except 316L should be tested for SCC in the nitric acid test solution. The 316L stainless steel should not be considered for service in a nitric acid environment similar to the test solution.

Table 21. Combined Nickel+Chromium Content of Selected Nickel-Based Alloys

	Alloy			
	825	625	690	G-30
General Type	Ni-Cr-Fe-Mo	Ni-Cr-Mo-Fe	Ni-Cr-Fe	Ni-Cr-Fe-Mo-Co-W
Ni+Cr wt%	63.5	81	87	67.5

REFERENCES

ANTHONY
D. Anthony, "Improved Evaporators for Radioactive Wastes," Chem. Eng. Progress, p. 58-63, July 1993.

BARKER
S. A. Barker and E. B. Schwenk, "Materials Evaluation for a Transuranic Processing Facility," WHC-SA-0963-FP (November 1990).

CHEN
L. Chen, personal communication (1994).

HARRISON
R. J. Harrison, AECL, Chalk River Laboratories, Chalk River, ON (Canada), personal communication (1994).

NACE
Corrosion Data Survey, Metals Section, NACE, 6th ed., p. 11, 1985.

ORME
R. Orme, Westinghouse Hanford Company, personal communication (1994).

RICHMOND
W. Richmond, "Conceptual Design Report: Cesium Demonstration Unit," EBASCO/BNFL Report E/B-SD-W236B-RPT-008-Rev 0B (1994).

APPENDIX A

MATERIALS SELECTION

A. Selection of Process Solutions

The evaporator/concentrator compact processing unit (CPU) was originally intended to process cesium-free tank waste from Hanford Tank 241-AW-101 and cesium ion-exchange eluant. Changes in the project's mission occurred when Westinghouse Hanford and DOE decided against installation and testing of CPU-based processes. Because of this decision, the focus on evaporator CPUs shifted to the Savannah River Site (SRS) and Oak Ridge National Laboratory (ORNL). However, the focus of materials selection and the recommended test solutions were not changed for several reasons. First, the Tank Waste Remediation System (TWRS) program still includes a number of evaporators in their Case BETA Prime flowsheet [ORME]. These corrosion data will assist in selecting materials for these units. Second, the waste solutions being evaluated generally appear to be more corrosive than what we can expect at other sites. Therefore, by testing various materials in both acidic and alkaline environments, corrosion data applicable to these sites is obtained.

The composition of the two waste solutions being evaluated for evaporation are reported in Tables A-1 and A-2. The test solutions will contain the major components of these process streams (see Tables A-3 and A-4). Since corrosion rates increase with concentration and temperature for both nitric acid and sodium hydroxide, the most concentrated compositions expected in the evaporator were chosen as test solutions. One criterion for a CPU-based process is to be able to process both acidic and alkaline solutions. Therefore, the material of construction must be resistant to corrosion in both environments. If a dedicated evaporator is used for one process stream, then this restrictive requirement can be relaxed.

Table A-1. Chemical Composition of Tank 241-AW-101[a, b]

Constituent	Avg. Conc., M	Constituent	Avg. Conc., M
Aluminum	1.03 E+00	Sodium	1.00 E+01
Arsenic	<1.33 E-07	Titanium	<9.88 E-05
Barium	<6.80 E-05	Uranium	9.39 E-04
Bismuth	<5.79 E-04	Zinc	<4.84 E-03
Cadmium	<1.08 E-05	Zirconium	<5.54 E-04
Calcium	8.26 E-04	Ammonia	1.45 E-02
Chromium	3.08 E-03	Carbonate	2.05 E-01
Copper	<3.81 E-04	Chloride	1.46 E-01
Iron	<7.86 E-04	Cyanide	1.03 E-03
Lead	<1.46 E-03	Hydroxide	5.07 E+00
Magnesium	2.15 E-03	Fluoride	<4.02 E-03
Manganese	4.76 E-04	Nitrite	2.19 E+00
Mercury	<7.8E-6	Nitrate	3.46 E+00
Molybdenum	6.00 E-04	Phosphate	2.22 E-02
Potassium	1.07 E+00	Sulfate	1.07 E-02
Selenium	4.20 E-07	TOC[c]	0.205
Silicon	<4.36 E-03		
Silver	<3.10 E-04		

[a]Composition from [RICHMOND].
[b]Density = 1.56 g/cm^3; 43.6 wt% water.
[c]TOC = Total Organic (oxidizable) Carbon, in mol/L.

Table A-2. HLW Stream Composition of the Cesium-Removal Ion-Exchange Eluant[a,b]

Constituent	Concentration, M
Ca^{+2}	1.56 E-04
Cs^{+}	2.77 E-05
H^{+}	2.47 E-01
Na^{+}	4.30 E-02
NO_3^{-}	2.91 E-01
Sr^{+2}	1.46 E-07

[a]98.1 wt% water.
[b]Aspen Model Prediction.

Table A-3. Sodium Hydroxide Test Solution Composition

Constituent	Concentration, M	Constituent	Concentration, M
Aluminum	9.5 E-01	Chloride	1.5 E-01
Chromium	3.1 E-03	Hydroxide	5.7 E+00
Iron	7.9 E-04	Fluoride	4.0 E-03
Magnesium	2.0 E-03	Nitrite	2.8 E+00
Potassium	1.1 E+00	Nitrate	3.8 E+00
Sodium	9.0 E+00	Phosphate	2.2 E-02
Ammonia	1.5 E-02	Sulfate	1.1 E-02
		Carbonate	2.1 E-01

Table A-4. Nitric Acid Test Solution Composition

Constituent	Concentration, M
H^+	15.9
Na^+	2.5
NO_3^-	18.4

During the processing of waste solutions such as the one given in Table A-1, scale containing CaF_2 may form in the evaporator/concentrator CPU. If the CPU is flushed with nitric acid to remove the scale, a highly corrosive HNO_3-HF solution may form. Thus, the material of construction which is selected must have acceptable corrosion resistance to the nitric-hydrofluoric acid mixture to which it may be exposed. Alternatively, complexing agents such as zirconium or aluminum can be added to the nitric acid cleaning solutions to complex the fluoride, reducing the corrosivity of the solution. Those alloys which exhibit acceptable corrosion resistance in Stage 1 should be tested in a nitric-hydrofluoric acid environment.

Acceptable corrosion rates have been suggested by the National Association of Corrosion Engineers for various applications [NACE]. They are listed in Table A-5.

Table A-5. NACE Corrosion Ratings

Corrosion Rate, mm/y (mpy)	Rating	Applications
0.051 (<2)	excellent	very critical
0.051-0.51 (2-20)	satisfactory	critical
0.51-1.28 (20-50)	useful	non-critical
1.28 (>50)	poor	none

In industry, the "excellent" rating may extend up to 0.128 mm/y (5 mpy) [ALLEGHENY CORP]. Meyer [MEYER] considered a rate of 0.51 mm/y (20 mpy) to be the maximum allowable corrosion rate for nitric acid concentrators (evaporators). We considered alloys for testing that had rates of up to 1.28 mm/y (50 mpy) in various standard test solutions.

C. Selection of Candidate Materials

Some general comments can be made concerning suitable alloys for nitric acid and sodium hydroxide environments; the following information was condensed from the Handbook of Corrosion Data [CRAIG]:

Nitric Acid

In nitric acid environments, most AISI 300-series stainless steels (annealed) exhibit good or excellent corrosion resistance up to 65% HNO_3 and 100°C. Molybdenum alloying additions tend to decrease resistance to nitric acid; thus, 316L (2.5 wt% Mo) is less resistant to nitric acid than 304L. Sensitization (precipitation of corrosion-inhibiting alloying elements as carbides at grain boundaries, which removes them from the bulk alloy) reduces corrosion resistance and can be avoided by using low or extra-low carbon alloys when welding is necessary and by using the alloy in the solution heat-treated condition.

Nickel alloys are extensively used in the production of nitric acid. Because chromium forms a passive film, higher Cr-Ni alloys are more corrosion resistant than higher Mo-Ni alloys (recall the effect of Mo additions in stainless steel as mentioned above).

Commercially pure titanium is often used in nitric acid applications where stainless steels are not suitable. Titanium exhibits excellent corrosion resistance at all concentrations up to 80°C. Above 80°C, resistance depends on nitric acid purity; hot, very pure solutions or vapor condensates may cause significant uniform corrosion. Impurities such as Si^{+4}, Cr^{+6}, Fe^{+3}, or Ti^{+4} can inhibit this high-temperature corrosion. Thus, in recirculating process streams where a steady-state level of Ti^{+4} is achieved, titanium can exhibit excellent corrosion resistance.

Sodium Hydroxide

All stainless steels resist corrosion by sodium hydroxide in all concentrations up to about 65°C. Types 304 and 316 exhibit low rates of corrosion in boiling NaOH up to ~20% concentration; stress corrosion cracking (SCC) can occur at about 100°C. The presence of chlorides in an alkaline solution does not appear to have a deleterious effect on the austenitic stainless steels, as long as the solution remains alkaline; a solution of 0.5 g/l NaOH (~0.0125 M) with a pH of 12 is sufficient. Type 316L performs better overall in caustic environments than type 304L due to its greater pitting resistance.

Nickel and its alloys exhibit very low corrosion rates in sodium hydroxide. Increasing the nickel content of nickel-base alloys increases resistance to general corrosion and SCC.

Titanium exhibits low corrosion rates in sodium hydroxide at temperatures below boiling; corrosion increases significantly with increasing concentration and temperature. For alpha and near-alpha alloys hydrogen embrittlement can occur at temperatures greater than 80°C and pH≥12. Oxidizing species such as chlorate, hypochlorite or nitrate compounds can extend resistance to hydrogen uptake to slightly higher temperatures.

Very little information exists on the corrosion resistance of metals in nitric-hydrofluoric acid mixtures. The data used in Table A-6 of this report indicate that stainless steels are of limited use in such solutions. Nickel-base alloys exhibit considerably better resistance. There are some data which show that increasing (Ni+Cr) content increases resistance to HNO_3-HF solutions. Cobalt alloying additions (along with Ni+Cr) could also be helpful in such an environment, since cobalt alloys become more noble with additions of chromium [SMITH]. Titanium is not resistant to dilute hydrofluoric acid solutions.

In general, chromium additions lend improved resistance to oxidizing acids, such as HNO_3, while Mo additions do the same for reducing acids. Molybdenum also improves pitting resistance. Carbon, phosphorus, and sulfur levels should be kept as low as possible to prevent precipitation of carbides, phosphides, or sulfides, which could remove corrosion-resistant alloying additions such as chromium from solution.

Materials originally under consideration for corrosion testing included the following: 304L, 316L, AL-6XN, alloys 800, 825, 617, 625, 686, 690, C-276, C-22, G-30, and titanium (Grade 2). Tables A-6 to A-8 lists corrosion rates for the various alloys in HNO_3, NaOH, and HNO_3-HF environments. Alloy compositions (major components) are given in Table A-9.

Table A-6. Corrosion Rates in HNO_3 Solutions

Alloy	Corrosion Rate mm/y	Corrosion Rate mpy	Test Conditions	Reference
304L	0.25	9.6	65% HNO_3 boiling	CRAIG
316L	0.9	34.3	65% HNO_3 boiling	CRAIG
AL-6XN	0.7	28.9	Huey test	ALLEGHENY CORP
Alloy 800	0.2	8.4	Huey test, 65% boiling	INCO-1985A
Alloy 625	0.51	20	65% HNO_3 boiling	INCO-1994
	0.8	30	65% HNO_3 boiling	INCO-1985B
	0.3	12.0	65% HNO_3 boiling	INCO-1985A
Inconel 686	5.9	231	65% HNO_3 boiling	INCO-1985A
Inconel 690	0.08	3.0	65% HNO_3 boiling	INCO-1985A
Inconel 617	0.5	20	65% HNO_3 boiling	INCO-1979
Hastelloy C-276	22.6	888	65% HNO_3 boiling	HAYNES-1987
Hastelloy C-22	3.4	134	65% HNO_3 boiling	HAYNES-1991
Hastelloy G-30	0.1	5	65% HNO_3 boiling	HAYNES-1989
Ti[a]	0.08	3.1	70% boiling	CRAIG[b]
	0.04	1.56	70%, 70°C, aerated	TIMET
	0.06-0.9	2.5-37	70% boiling, non-aerated	SMITH

[a]Commercially pure.
[b]Grade 1.

Table A-7. Corrosion Rates in NaOH Solutions

Alloy	Corrosion Rate		Test Conditions	Reference
	mm/y	mpy		
304L	0.003	0.1	20%,[a] 97°C	CARLOS
	0.04	1.4	20%, 60°C	CRAIG
	1.4-4.7	53-183	50% boiling	ALLEGHENY TECH
316	0.09	3.6	20%, 60°C, rapid agitation, 20% suspended crystalline salt	CRAIG
316L	2.0	77.7	50% boiling	ALLEGHENY CORP
	3.1	123	50% boiling	CRAIG
AL-6XN	0.4	16.0	50% boiling	ALLEGHENY CORP
	0.4	17.2	50% boiling, welded	CRAIG
Alloy 800	0.005	0.2	23%, 93°C, NaCl~7-8%	CRAIG
Alloy 625	0.01	0.5	50% boiling	CRAIG
Alloy 825	0.5	18.0[b]	15%, 100°C, + 2% Cl-saturated monochlorotoluene, 2% HCl,	CRAIG
	0.008	0.3	74%, 129°C	INCO-1989
Inconel 686	--	--	--	--
Inconel 690		c	20%, 320°C,	INCO-1980
		d	≥30% and T > 260°C	INCO-1980
Inconel 617	0.01	0.4	20% boiling	INCO-1979
	0.3	11	48% boiling	INCO-1979
Hastelloy C-276	--	--	--	--
Hastelloy C-22	--	--	--	--
Hastelloy G-30	0.05	1.8	50% boiling	HAYNES-1994
Ti (commercially pure)[e]	0.05	2.0	50% boiling	CRAIG

[a]6M OH^-, 0.20M Cl^-, 0.01M F^-, 1.00M NO_2^-, 2.00M NO_3^-; similar composition to Tank 241-AW-101 waste listed in Table 1.
[b]Severe pitting (10 mil depth), crevice attack.
[c]No SCC in 1000 h.
[d]Severe general corrosion.
[e]Grade not specified.

Table A-8. Corrosion Rates in HNO_3-HF Solutions

Alloy	Corrosion Rate mm/y	Corrosion Rate mpy	Test Conditions	Reference
304L	94.3	3699.0	2M HNO_3-2M NaF, 60°C	SMITH
316L	224.4-1586.1	8800-62,200	Type 316, 10% HNO_3, 3% HF, 80°C, rapid agitation	CLIMAX MOLY
AL-6XN	3.1	120	10% HNO_3, 3% HF, 70°C	ALLEGHENY CORP
Alloy 800	--	--	--	--
Alloy 625	0.4	15.6	2M HNO_3-2M NaF, 60°C	SMITH
	0.7	28.0	10% HNO_3, 3% HF, 60°C	INCO-1989
Alloy 825	0.5	19.9	2M HNO_3-2M NaF, 60°C	SMITH
Inconel 686	--	--	--	--
Inconel 690	4.1	160	2M HNO_3-2M NaF, 60°C	SMITH
	0.2	6	10% HNO_3, 3% HF, 60°C	INCO-1985A
Inconel 617	1.2	49.0	2M HNO_3-2M NaF, 60°C	SMITH
Hastelloy C-276	0.9	34.6	2M HNO_3-2M NaF, 60°C	SMITH
Hastelloy C-22	0.2	6.1	2M HNO_3-2M NaF, 60°C	SMITH
Hastelloy G-30	0.2	5.7	2M HNO_3-2M NaF, 60°C	SMITH
Ti (commercially pure)	--	a		TIMET
		b	1% HF, 15% HNO_3, 25°C	SMITH

[a]"Rapidly attacked...by even very dilute concentration" of HF. "Not recommended" for HF- or F-containing solutions with pH<7. Complexing (i.e., with Al^{+3} or Cr^{+6}) "may effectively inhibit corrosion in dilute fluoride solutions."

[b]"Rapid" attack.

Table A-9. Alloy Compositions--Major Components[a]

Alloy	Fe	Ni	Cr	Mo	Co	W	Ti	Cu	Other
304L SS	71	10	19						
316L SS	68.5	12	17	2.5					
AL-6XN	48	24	21	6				0.1	N--0.22
800	43	33	21			0.37	0.75	0.37	
825	29	42	21.5	3			0.9	2.2	
617	3	50	22	9	12.5		0.6	0.5	B--0.006
625	5	59.5	21.5	9	1		0.4		Nb+Ta--3.15-4.15
686	5	59	21	16		3.7	0.13		
690	9	60	29					0.50	
C-276	5.5	55	15.5	16	2.5	3.75			V--0.35
C-22	3	56	22	13	2.5	3			V--0.35
G-30	15	37.5	30	5	5	2.75		1.7	Nb+Ta--0.3-1.5
Ti (Grade 2)	0.3						99		

[a]Selected alloys in bold type.

Inconel 686 and Hastelloy C-276 and C-22 are eliminated from consideration based on their poor performance in boiling concentrated nitric acid. Of the stainless steels (304L, 316L, AL-6XN), 304L exhibits the lowest corrosion rate in HNO_3 and is comparable to 316L in NaOH. However, 316L is more resistant to pitting than 304L. AL-6XN performs better than 316L in HNO_3 and better in 50% boiling NaOH than either of the others. Type 304L is often used in nitric acid environments, while 316L is preferred for caustic environments; AL-6XN could be a compromise between the two. AL-6XN is a "6-Mo stainless"--a high-Ni, high-Cr stainless steel with ~6 wt% Mo. It is described by the manufacturer as "...fill(ing) the gap between the corrosion performance of conventional 316 stainless steel and nickel-based 625 or Alloy 276" [ALLEGHENY CORP]. Westinghouse Hanford Company has specified 6-Mo alloys for the inner shell construction of new double-shell waste tanks [FRANSON]. Its corrosion resistance is good in NaOH and HNO_3-HF, and is acceptable (for inclusion in our test program) in nitric acid. Therefore, all three stainless steels will be tested. Alloy 800 is similar to AL-6XN in composition; the Mo in Al-6XN is replaced with additional Ni and various trace alloying elements (W, Ti, Cu) in alloy 800. Its corrosion resistance is comparable to that of stainless steels; since we are already testing three stainless alloys, testing of alloy 800 would be redundant.

The Ni-base alloys under consideration (825, 625, 690, 617, G-30) perform acceptably in all three environments (except possibly 690 in NaOH, where the only information available simply lists conditions beyond which the alloy does not perform well). The compositional difference between 617 and 625 is due mainly to the replacement of ~ 10 wt% Ni with Co in 617; the Co provides solid-solution strengthening and oxidation resistance at temperatures greater than 980°C. Since the evaporator/concentrator CPU will not approach that temperature, we will test 625 but not 617. Alloys 825, 625, 690 and G-30 are all various types of Ni-Cr alloys, with a range of (Ni+Cr) contents and additional alloying elements (see Table A-10). We will test all of these alloys to determine if one of them is clearly superior to the rest in our test environments.

Table A-10. (Nickel+Chromium) Content of Selected Ni-Base Alloys

	Alloy			
	825	625	690	G-30
General Type	Ni-Cr-Fe-Mo	Ni-Cr-Mo-Fe	Ni-Cr-Fe	Ni-Cr-Fe-Mo-Co-W
(Ni+Cr) wt%	63.5	81	87	67.5

Titanium is available in a variety of grades, or compositions. Grades 1-4 are considered commercially pure, Grade 1 being the most pure. Grades 5-12 contain various amounts of intentionally added alloying elements. Grade 2 titanium is currently used for heat exchanger tubes in evaporators and in other industrial applications where good corrosion resistance is required. Titanium is extremely susceptible to corrosion by HNO_3-HF solutions. However, it is expected to have excellent corrosion resistance in the HNO_3 and NaOH test solutions. Since it may be very well suited to the majority of our processing needs, it ought to be considered as a candidate material. Actual flushing conditions have not yet been determined; it may be possible to adjust the composition of the flushing solution to provide a less corrosive environment for the evaporator.

D. Candidate Materials

The alloys which have been selected for corrosion testing are the following:

- Stainless steels: 304L, 316L, AL-6XN
- Nickel-base alloys: 825, 625, 690, Hastelloy G-30
- Titanium: Grade 2

These materials range from the workhorse 304L stainless steel to the more exotic G-30. Obtaining information about a variety of alloys will give us greater flexibility in materials selection for the CPU should the usual stainless alloys prove to be inadequate.

REFERENCES

ALLEGHENY CORP
"AL-6XN Alloy," Allegheny Ludlum Corporation, Pittsburgh, PA, 1991.

ALLEGHENY TECH
"General Corrosion of T304 in Acids, Bases and Salts," Allegheny Ludlum Technical Center, 1992.

CARLOS
W. C. Carlos, Multi-Function Waste Tank Facility Corrosion Test Report (Phase 1), (WHC-SD-W236A-TRP-001, Rev. 0), December 27, 1993.

CLIMAX MOLY
A Guide to Corrosion Resistance, Climax Molybdenum, 1961.

CRAIG
Handbook of Corrosion Data, B. Craig, ed., ASM International, 1989.

FRANSON
I. Franson, Allegheny Ludlum Technical Center, Personal communication (January 31, 1994).

HAYNES-1987
"Alloy C-276," Publication H-2002B, Haynes International, 1987.

HAYNES-1989
"Alloy G-30," Publication H-2028C, Haynes International, 1989.

HAYNES-1991
"Alloy C-22," Publication H-2019D, Haynes International, 1991.

HAYNES-1994
M. L. Caruso, Haynes International, unpublished data (April 19, 1994).

INCO-1979
"Alloy 617," Huntington Alloys (now Inco Alloys International), 1979.

INCO-1980
"Alloy 690," Huntington Alloys (now Inco Alloys International), 1980.

INCO-1985A
"Resistance to Corrosion," p. 29, Inco Alloys International, 4th ed., 1985.

INCO-1985B
"Alloy 625," Inco Alloys International, 5th ed., 1985.

INCO-1989
"Alloy 622," (Publication IAI-61), Inco Alloys International, 1989.

INCO-1994
L. Shoemaker, Inco Alloys International, unpublished data (March 18, 1994).

MEYER
F. H. Meyer, Jr., Corrosion in a Nitric Acid Concentrator, AECD-3735, 1956.

NACE
Corrosion Data Survey, Metals Section, NACE, 6th ed., p. 11, 1985.

ORME
R. Orme, Westinghouse Hanford Company, personal communication (1994).

RICHMOND
W. Richmond, "Conceptual Design Report: Cesium Demonstration Unit," EBASCO/BNFL Report E/B-SD-W236B-RPT-008-Rev 0B (1994).

SMITH
H. D. Smith et al., Corrosion Resistance of Stainless Steels and High Ni-Cr Alloys to Acid-Fluoride Wastes, (PNL-SA-20408), April 1992.

TIMET-1991
"Corrosion Resistance of Titanium," Timet Corp., 1991.

APPENDIX B

ELECTROCHEMICAL TESTING

Cyclic potentiodynamic polarization (CPP) tests were performed by CC Technologies on the candidate alloys soon after the long-term exposure tests were started. They were conducted at 80°C. The results were expected to predict those of the long-term tests, that is, whether the alloys would undergo pitting in the test solution. In this technique, the polarity and magnitude of the current flow between a specimen of the alloy and an inert counter electrode are measured as a function of electrochemical potential. The potential is scanned to a value that exceeds the pitting potential, then reversed and returned to the corrosion potential. The occurrence of hysteresis between the forward and reverse scans is generally indicative of pitting or crevice corrosion on the specimen during the test. The results (see Table B-1 and Figs. B-1 through B-14 b) showed no pitting or crevice attack on any of the samples.

Table B-1. Results from Cyclic Potentiodynamic Polarization Tests

Alloy	Environment	Free-Corrosion Potential, volts vs. SCE	Free-Corrosion Current Density, A/cm^2	Passive Current Density, A/cm^2	Anodic Tafel Slope, mV/dec.	Cathodic Tafel Slope, mV/dec.	Corrosion Rate, mpy
304L[a]	Alkaline Waste	-0.275	7.00E-07	8.00E-05	75	52	0.30
316L[a]	Alkaline Waste	-0.310	4.50E-07	2.00E-04	52	56	0.19
AL6XN[a]	Alkaline Waste	-0.315	8.00E-07	4.00E-05	33	102	0.34
625[b]	Alkaline Waste	-0.560	1.50E-07	4.00E-05	67	67	0.06
825[c]	Alkaline Waste	-0.308	1.80E-07	4.00E-05	53	85	0.08
690[b]	Alkaline Waste						
G30[d]	Alkaline Waste	-0.487	1.00E-07	4.00E-05	83	104	0.04
Ti Gr2[e]	Alkaline Waste	-0.885	9.00E-07	3.50E-05	65	62	0.31
304L	Acid Waste	0.915	8.00E-06		75	63	3.33
316L	Acid Waste	0.880	1.70E-05	1.60E-04	54	44	7.25
AL6XN	Acid Waste	0.902	2.00E-06		47	36	0.85
625	Acid Waste	0.886	4.00E-06		67	42	1.64
825	Acid Waste	0.692	7.00E-06	1.20E-04	33	43	2.93
690	Acid Waste						
G30	Acid Waste	0.785	2.00E-06	2.00E-05	47	52	0.83
TiGr2	Acid Waste	0.738	1.00E-05	6.90E-05	67	55	3.46

[a]Stainless steel alloys.

[b]Inconel nickel-based alloys.

[c]Incoloy nickel-based alloy.

[d]Hastelloy nickel-based alloy.

[e]Titanium Grade 2.

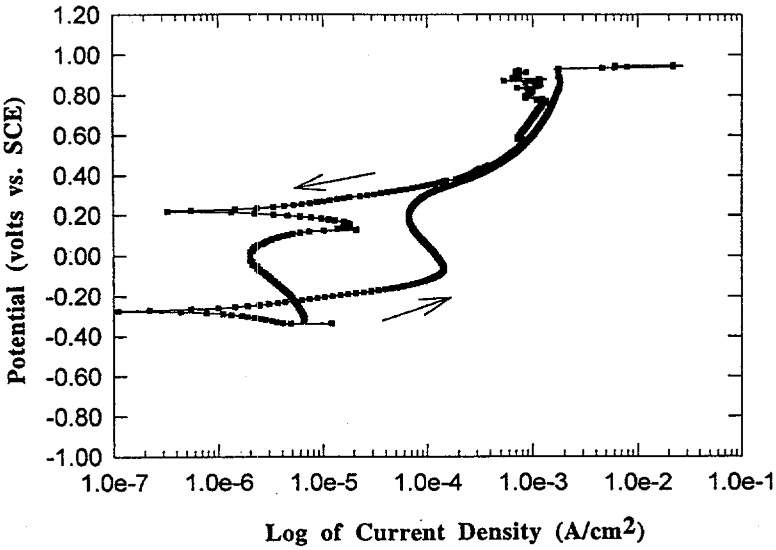

Fig. B-1. Cyclic Potentiodynamic Polarization Test Results of 304L Stainless Steel in Alkaline Solution

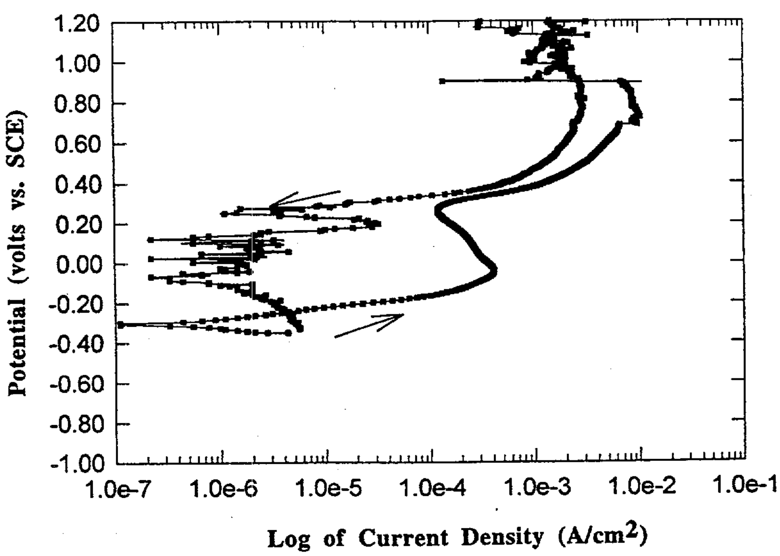

Fig. B-2. Cyclic Potentiodynamic Polarization Test Results of 316L Stainless Steel in Alkaline Solution

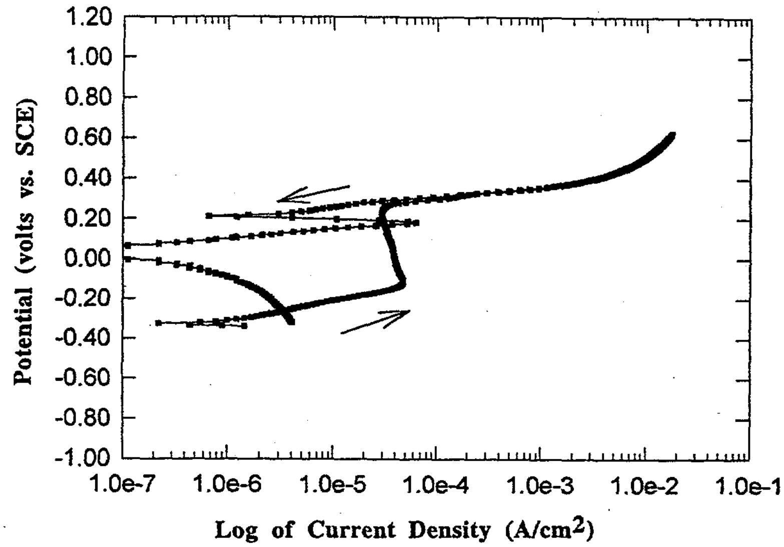

Fig. B-3. Cyclic Potentiodynamic Polarization Test Results of AL-6XN Stainless Steel in Alkaline Solution

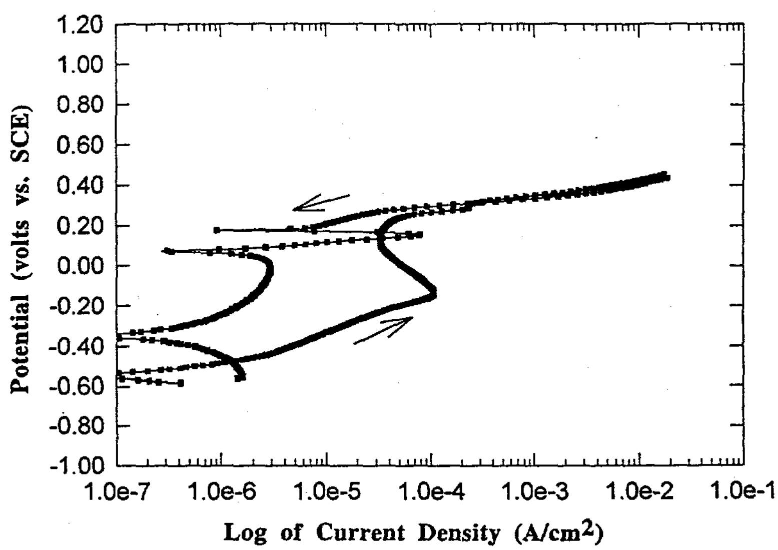

Fig. B-4. Cyclic Potentiodynamic Polarization Test Results of Inconel 625 in Alkaline Solution

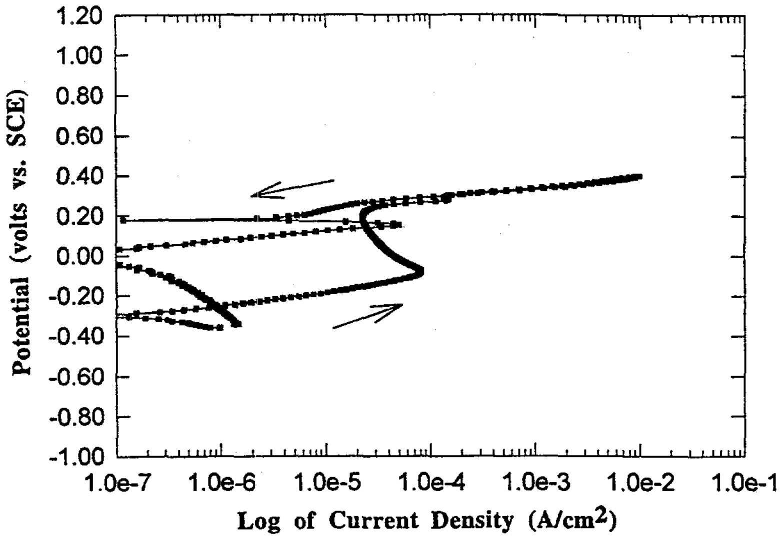

Fig. B-5. **Cyclic Potentiodynamic Polarization Test Results of Incoloy 825 in Alkaline Solution**

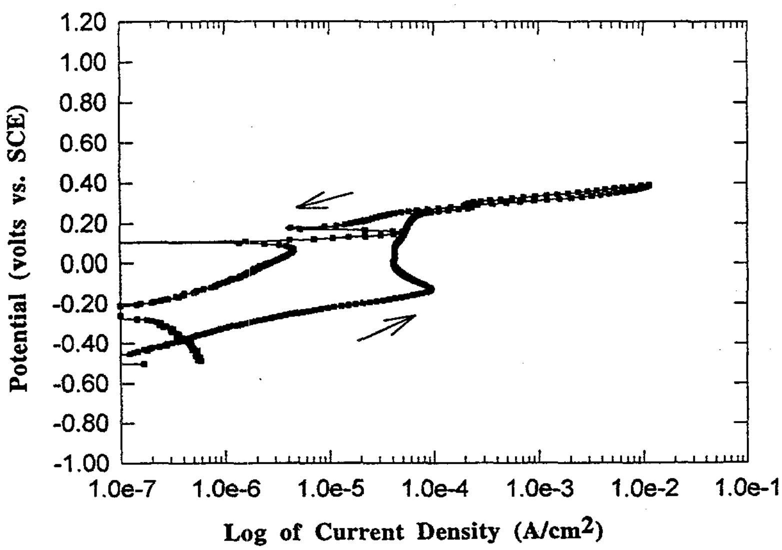

Fig. B-6. **Cyclic Potentiodynamic Polarization Test Results of Hastelloy G-30 in Alkaline Solution**

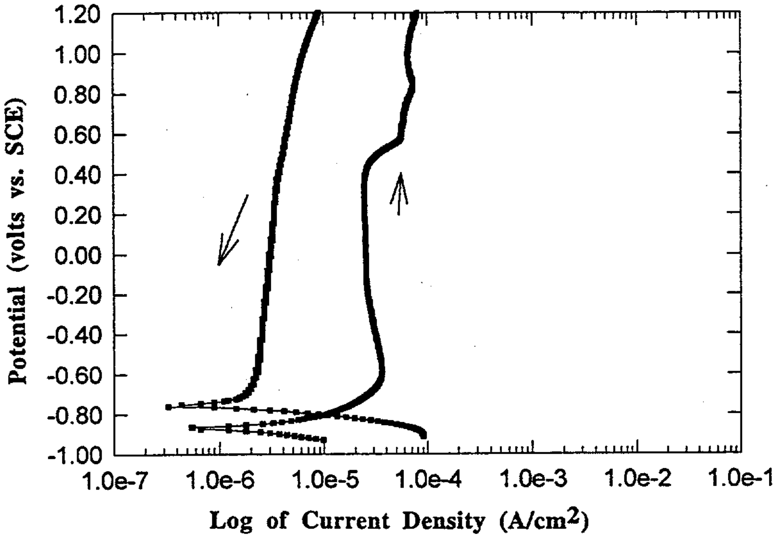

Fig. B-7a. Cyclic Potentiodynamic Polarization Test Results of Titanium Grade 2 in Alkaline Solution at Regular Scale

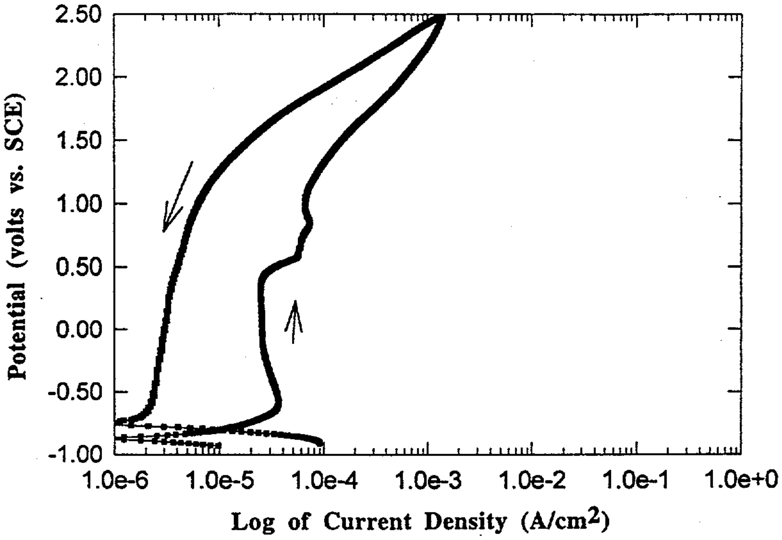

Fig. B-7b. Cyclic Potentiodynamic Polarization Test Results of Titanium Grade 2 in Alkaline Solution at Expanded Scale

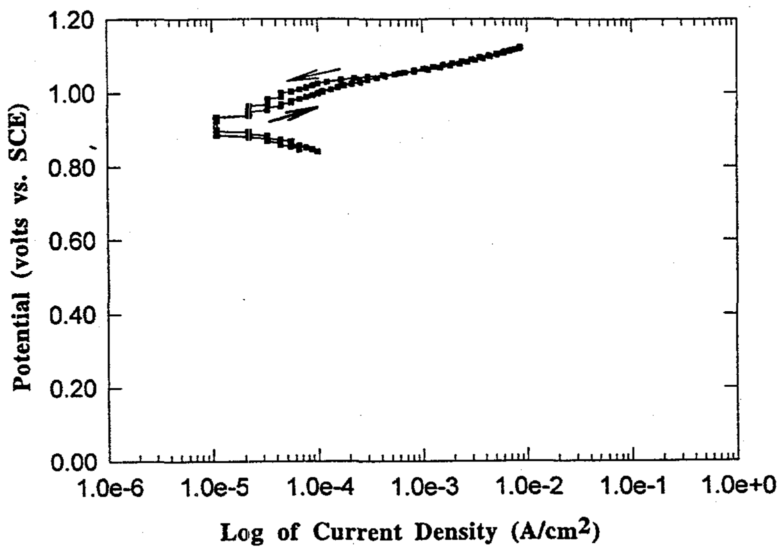

Fig. B-8. Cyclic Potentiodynamic Polarization Test Results of 304L Stainless Steel in Nitric Acid Solution

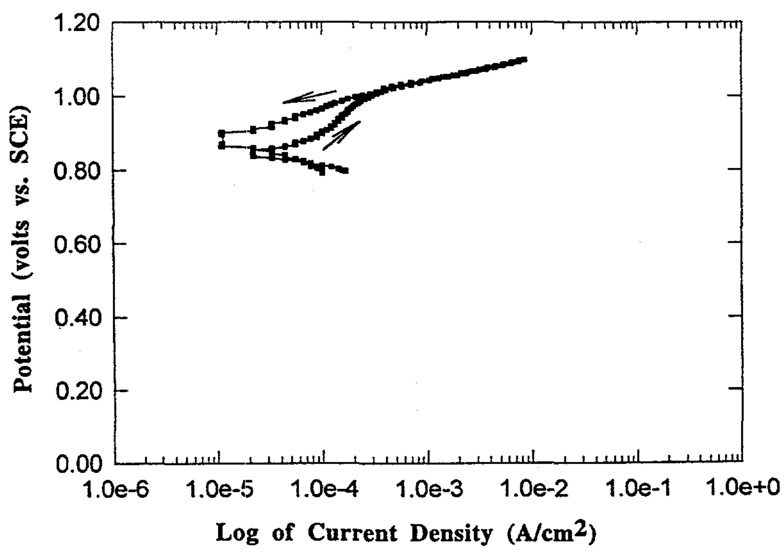

Fig. B-9. Cyclic Potentiodynamic Polarization Test Results of 316L Stainless Steel in Nitric Acid Solution

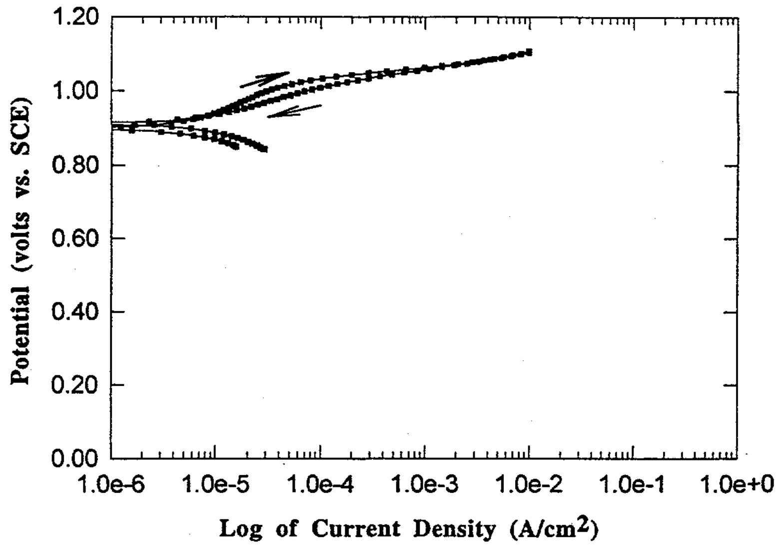

Fig. B-10. Cyclic Potentiodynamic Polarization Test Results of AL-6XN Stainless Steel in Nitric Acid Solution

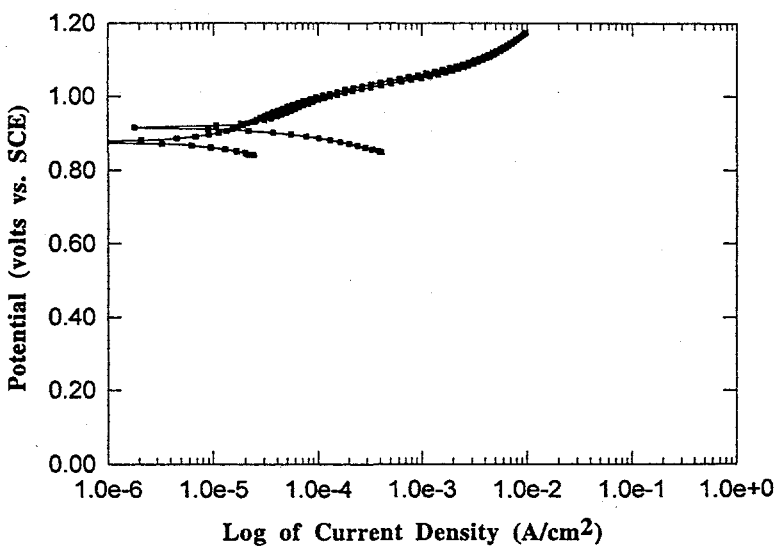

Fig. B-11. Cyclic Potentiodynamic Polarization Test Results of Inconel 625 in Nitric Acid Solution

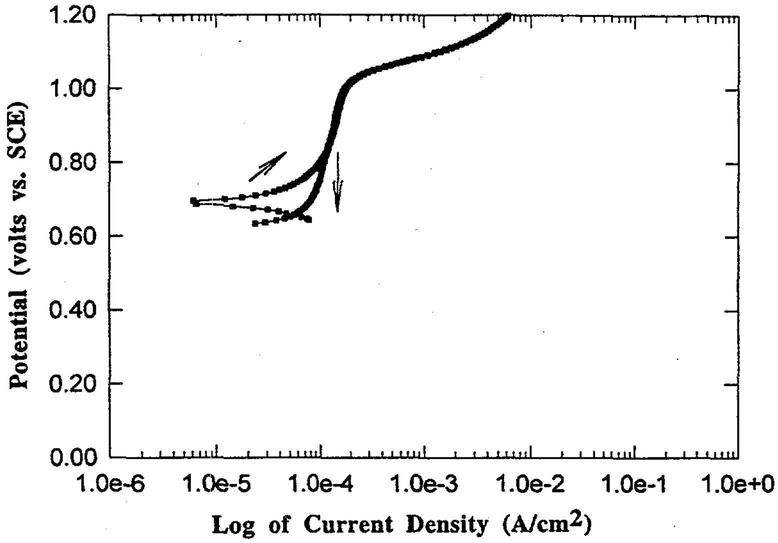

Fig. B-12. Cyclic Potentiodynamic Polarization Test Results of Incoloy 825 in Nitric Acid Solution

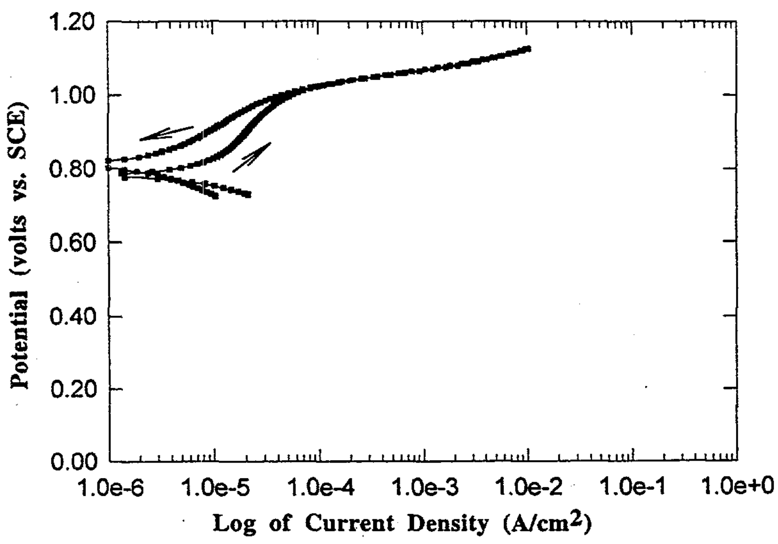

Fig. B-13. Cyclic Potentiodynamic Polarization Test Results of Hastelloy G-30 in Nitric Acid Solution

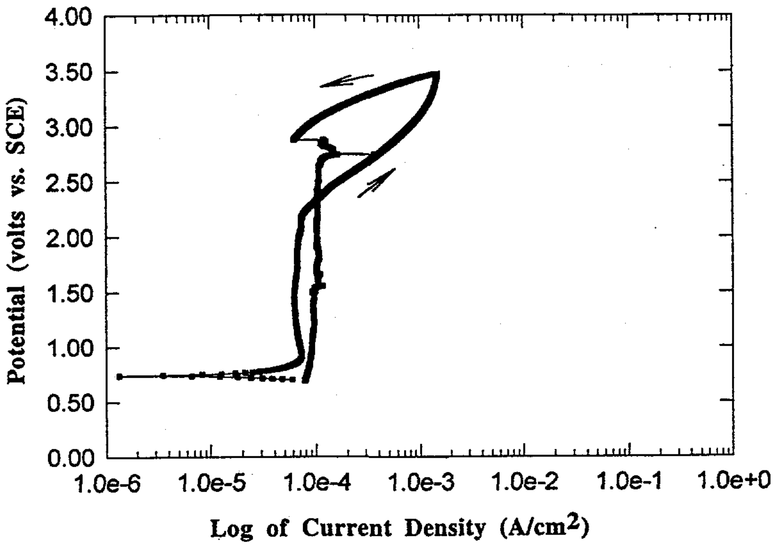

Fig. B-14a. Cyclic Potentiodynamic Polarization Test Results of Titanium Grade 2 in Nitric Acid Solution at Regular Scale

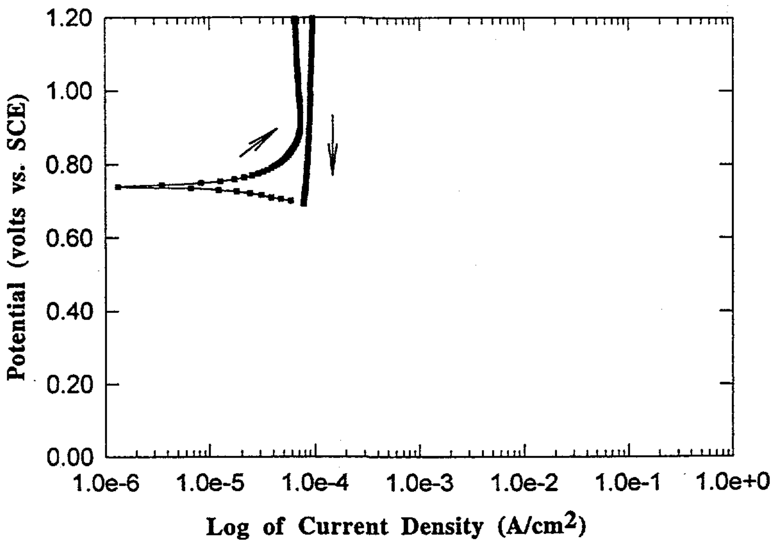

Fig. B-14b. Cyclic Potentiodynamic Polarization Test Results of Titanium Grade 2 in Nitric Acid Solution at Expanded Scale

APPENDIX C

FINAL REPORT T 004-01
CC TECHNOLOGIES

MOBILE EVAPORATOR/CONCENTRATOR
CANDIDATE ALLOY CORROSION EVALUATION

CC technologies

CORTEST COLUMBUS

FINAL REPORT

T 004-01

MOBILE EVAPORATOR / CONCENTRATOR CANDIDATE ALLOY CORROSION EVALUATION

PRESENTED TO

ARGONNE NATIONAL LABORATORY

FINAL REPORT

T 004-01

MOBILE EVAPORATOR / CONCENTRATOR CANDIDATE ALLOY CORROSION EVALUATION

TO

ARGONNE NATIONAL LABORATORY

BY

KURT M. LAWSON

CC TECHNOLOGIES LABORATORIES, INC.
2704 SAWBURY BOULEVARD
COLUMBUS, OHIO 43235

JANUARY 26, 1995

DISCLAIMER

This report documents the work performed by *CC Technologies Laboratories, Inc.* for Argonne National Laboratory. Neither *CC Technologies Laboratories, Inc.* or any person acting on behalf of *CC Technologies Laboratories, Inc.*:

(1) assumes any liabilities with respect to the use of any information contained in this report or that the use of any information, apparatus, method, or process disclosed in this report, and

(2) makes any warranty or representations that the use of any information, apparatus, method, or process disclosed in this report may not infringe on privately-owned rights.

EXECUTIVE SUMMARY

This report summarizes the results of a laboratory corrosion testing program performed by *CC Technologies Laboratories, Inc.* for Argonne National Laboratory. The objective of the project was to screen possible materials of construction for the mobile evaporator/concentrator Compact Processing Unit for processing wastes removed from underground storage tanks at Department of Energy (DOE) sites. The unit is designed to recover water from alkaline wastes and nitric acid from acidic wastes. Therefore, the materials of construction must be corrosion resistant to both the acidic and alkaline environments at the units operating temperature of 80°C.

The following eight alloys were included in the testing: 304L, 316L, and AL-6XN stainless steels; Incoloy 825, Inconel 625, Inconel 690, and Hastelloy G-30 nickel-base alloys; and titanium – Grade 2. The testing included exposure of standard weight-loss samples as well as welded samples to the liquid, vapor, and liquid/vapor interface of the simulated environments. In addition, standard and welded samples with crevice-forming washers were evaluated in the liquid phase of the environments.

The solution compositions and mixing instructions were supplied by Argonne and consisted of a fuming nitric acid solution and a sodium hydroxide alkaline waste solution. The testing was conducted in four-liter resin kettles at a temperature of 80°C, under a slight vacuum (100 Torr), for forty-five days. Solution level changes due to loss of solution from evaporation were adjusted by the addition of additional test solution. Corrosion rates within the test solutions were monitored using the linear polarization resistance (LPR) method to determine if dramatic solution compositional changes were occurring.

The results of the testing indicated that none of the alloys tested showed significant corrosion in the alkaline environment. The stainless steels (304L, 316L, and AL-6XN) exposed to the nitric acid environment showed the highest corrosion rates (up to 23 mils per year), predominantly in the liquid and vapor/liquid interface phase of the solution. These rates were accompanied by a very thin, tenacious deposit (similar to bluing) on the samples. No localized attack (pitting or crevice) was observed in either solution for any of the materials. Some of the samples exposed to the liquid phase of the nitric acid solution showed obvious etching of the base metal and the weld, although no preferential attack of the welds or heat affected zones was observed. The attack observed in the nitric acid test solution was characterized as intergranular attack with varying degrees of grain loss.

TABLE OF CONTENTS

	Page
BACKGROUND	1
APPROACH	1
Task 1 – Sample Selection, Acquisition, And Preparation	1
Task 2 – Immersion Testing	2
Task 3 – Specimen Evaluation	3
RESULTS	3
Stainless Steels	5
304L Stainless Steel	5
Alkaline Waste	5
Nitric Acid	5
316L Stainless Steel	6
Alkaline Waste	6
Nitric Acid	6
AL-6XN Stainless Steel	7
Alkaline Waste	7
Nitric Acid	7
Nickel-Base Alloys	7
Incoloy Alloy 825	7
Alkaline Waste	7
Nitric Acid	8
Inconel Alloy 625	8
Alkaline Waste	8
Nitric Acid	8
Inconel Alloy 690	9
Alkaline Waste	9
Nitric Acid	9
Hastelloy Alloy G-30	9
Alkaline Waste	9
Nitric Acid	10
Titanium	10
Titanium Grade – 2	10
Alkaline Waste	10
Nitric Acid	10
CONCLUSIONS	11
Alkaline Waste	11
Nitric Acid Waste	11

APPENDIX A Mixing Instructions For The Alkaline Waste Test Solution
APPENDIX B Corrosion Rate Data

LIST OF FIGURES

		Page
Figure 1a.	Schematic Diagram Of Standard Sample	12
Figure 1b.	Schematic Diagram Of Welded Sample.	12
Figure 2.	Resin Kettle And Associated Test Apparatus	13
Figure 3.	Corrosion Test Matrix	14
Figure 4a.	Sample "Tree."	15
Figure 4b.	Resin Kettles	15

LIST OF TABLES

Table 1.	Chemical Composition Of Alloys Used In Testing	16
Table 2.	Composition Of Test Solutions (a) Nitric Acid Test Solution Composition (b) Alkaline Waste Test Solution Composition	17

BACKGROUND

This report summarizes the results of a laboratory corrosion testing program performed by *CC Technologies Laboratories, Inc.* for Argonne National Laboratory. The objective of the project was to screen possible materials of construction for the mobile evaporator/concentrator Compact Processing Unit for processing wastes removed from underground storage tanks at Department of Energy (DOE) sites. The unit is designed to recover water from alkaline wastes and nitric acid from acidic wastes. Therefore, the materials of construction must be corrosion resistant to both the acidic and alkaline environments at the units operating conditions of a temperature of 80°C and a slight (100 Torr) vacuum.

APPROACH

The corrosion testing of a selection of alloys was necessary to determine which alloys were capable of handling the extreme environments present in the Compact Processing Unit (CPU). For the initial phase of testing, the work was divided into three tasks: *Task 1 – Sample Selection, Acquisition, and Preparation*; *Task 2 – Immersion Testing*; and *Task 3 – Specimen Evaluation.* The details of each task are given below.

Task 1 – Sample Selection, Acquisition, And Preparation

The purpose of Task 1 was to obtain the required samples of the materials identified by Argonne as being candidate materials for CPU construction. The alloys identified as such were the following:

- Stainless Steels: 304L, 316L, AL-6XN,
- Nickel-base Alloys: Incoloy alloy 825, Inconel alloy 625, Inconel alloy 690, and Hastelloy alloy G-30, and
- Titanium: Grade 2.

Sixteen plain samples and sixteen welded samples of each alloy were obtained. The sample configurations and dimensions of each sample type are shown in Figure 1. All samples of each alloy were from the same heat and oriented parallel to the rolling direction. The chemical composition of each of the alloys are given in Table 1. Surface finish on all samples was 120 grit. Once received, the samples were cleaned, degreased, and weighed.

Task 2 – Immersion Testing

The purpose of Task 2 was to perform the actual corrosion exposures under the environmental conditions supplied by Argonne. The exposures were performed in four-liter resin kettles designed to maintain the environmental conditions required. Figure 2 shows the resin kettle test apparatus. The kettles incorporate a heating mantle and thermocouple controlled by a proportion temperature controller. The reflux condenser was used to help minimize evaporation of the solutions while a slight (100 Torr) vacuum was pulled through the kettles. Also, as shown in Figure 2, samples were exposed to the liquid, the vapor, and the liquid/vapor interface portions of the test solutions.

Figure 3 shows the actual corrosion test matrix for a single alloy. Duplicate samples of each condition shown in the matrix were tested. A single kettle included two similar alloys for a total of 32 specimens. The samples were supported within the kettle by a rigid Teflon 'tree' which incorporated Hastelloy C276 hardware isolated from the samples by Teflon washers and tubes. The crevice samples indicated in the test matrix were formed by standard (ASTM G78) radially grooved Teflon crevice formers bolted to either side of the test sample. A typical sample 'tree' and kettle are shown in Figure 4. One alkaline waste kettle and one nitric acid kettle also included a cylindrical test probe incorporating a 304L stainless steel probe and two platinum wires for conducting periodic linear polarization resistance (LPR) measurements to assure that the corrosiveness of the solutions did not undergo any significant changes (which may have indicated a dramatic change in the chemistry of the test solution) over the course of the testing.

Once the sample 'trees' were assembled and placed in the kettles, the tops were seated and sealed with Teflon tape. Solutions were then added to the kettles to the level required to immerse one half of the samples exposed at the vapor/liquid interface. The temperature was then adjusted to 80°C and cooling water to the condensers and the vacuum source were started. Throughout the forty-five day exposure period, the solution level was carefully monitored and adjustments were made by the addition of test solution when required. Deviations or upset conditions to the normal operation of the test kettles are outlined in detail in the *Results Section* below.

The solution chemistries for the nitric acid test solution and the sodium hydroxide test solution were supplied by Argonne and are given in Tables 2 and 3. In addition, the mixing instructions for the alkaline waste test solution were supplied by Argonne and is reproduced in Appendix A. All chemicals used in the preparation of the test solutions were reagent grade and the water used was deionized water with a conductivity of greater than 5 Mega-Ohms.

Task 3 – Specimen Evaluation

Following the forty-five day exposure, the samples were removed from the test apparatus, rinsed, dried, and evaluated as per ASTM G1-90 and ASTM G31-72. The evaluation included visual evaluation prior to sample cleaning, mechanical and chemical cleaning, visual evaluation after cleaning, and weight-loss measurements and calculations.

Visual observations prior to sample cleaning included notation of staining, deposits, or corrosion products. Mechanical cleaning to remove loose deposits (on those samples which required it) consisted of brushing the samples with a soft bristled nylon brush under running warm water followed by DI water and acetone rinse. The nature and extent of the chemical cleaning (again, of those samples which required it) was dependent upon the alloy being cleaned and tenacity of the corrosion/chemical deposits. A weighed blank (unexposed) specimen of each material being cleaned was included in the cleaning operations to assure any weight loss associated with the cleaning process was accounted for in the weight-loss calculations. Following the cleaning, the samples were weighed and visually evaluated for pitting, crevice attack, or weld/heat affected zone (HAZ) attack. The weight loss was converted to a general corrosion rate, in mils per year. The results of these evaluations and calculations are presented in the Results section below.

RESULTS

The results of the testing conducted are organized by alloy and environment in the paragraphs following the brief general comments below. Tables B-1 through B-16 discussed in association with each alloy and environment can be found in Appendix B.

Several problems associated with the application of the vacuum to the test cells were encountered during the course of the testing. The original design of the test kettles did not incorporate facilities to apply, maintain and monitor the vacuum. During the set-up of the alkaline waste kettles, several attempts were made at sealing the kettles and various vacuum sources were tried. The final system design for the alkaline waste kettles consisted of sealing the various orifices of the resin kettles with rubber or ground glass stoppers sealed with Teflon tape. The lid of the kettles were sealed with a neoprene o-ring. Various vacuum sources were explored and an aspirator attached to a faucet was found to be the most suitable and cost effective means of generating and controlling the 100 Torr vacuum level. Each of the four alkaline test kettles were plumbed to a common manifold which was plumbed to a trap designed to condense and collect any vapor pulled through the manifold. The trap was then evacuated and the vacuum maintained via the aspirator. The vacuum level was monitored by a vacuum gauge which was installed at the trap. These vacuum design and implementation problems resulted in variations in the vacuum level for the initial eleven days of exposure for the alkaline waste samples.

During the testing, the alkaline waste kettles were observed to be lightly boiling under the temperature and vacuum conditions (80°C, 100 Torr). Following the testing, some etching and attack of the glass resin kettles exposed to the liquid phase of the alkaline waste was observed. It is not believed that the condition variations noted in the paragraphs above (vacuum deviations and glass attack) effected the results of the alkaline waste tests.

Following the initiation of the alkaline waste tests, a similar kettle/vacuum set-up was attempted for the nitric acid tests. The concentrated/fuming nitric acid, however, attacked the rubber stoppers and the neoprene o-rings of the kettles. The resulting attack contaminated the test solution in the kettles overnight and the tests were shut down for a two day period (weekend). Rather than possibly compromise the test results (due to the sample contamination and solution) the samples were removed from the kettles, cleaned, and re-weighed. New solutions were also prepared. The kettles were also thoroughly cleaned and re-designed with the wetted portions of the system being either glass or Teflon. The new system materials and vacuum system performed adequately, although twice during the forty-five day exposures the vacuum was lost for a short period (<24 hours) due to the vacuum line becoming blocked by debris. It is not believed that these excursions from the desired test conditions effected the results of the nitric acid tests.

Corrosion rates monitored during the course of the testing by the LPR technique for 304L material did not exceed 0.07 mpy for the alkaline solution after approximately forty-eight hours of exposure. No effect on the rate was observed when the vacuum was applied to the test kettle. No effect of solution additions (to maintain solution level) were observed in the measured corrosion rates once the temperature of the system had returned to 80°C following the addition. The rate was relatively stable in the alkaline solution, although rates that low are often difficult to accurately measure. Corrosion rates monitored in the nitric acid solution for 304L material did not exceed 4.2 mpy after approximately ninety-six hours of exposure, although the initial rates observed were in excess of 50.0 mpy. Individual measurements of the corrosion rate within the nitric acid solutions did vary up to +/- 2 mpy on measurements repeated during a single day; however, the rates averaged for that day never differed from the previous average by more than twenty percent. No effect of the vacuum was seen in the measured corrosion rate during the vacuum losses over the course of the forty-five day exposure. No effect of solution additions (to maintain solution level) were observed in the measured corrosion rates once the temperature of the system had returned to 80°C following the addition.

Stainless Steels

304L Stainless Steel

Alkaline Waste

The results for the 304L stainless steel exposed to the alkaline waste environment can be found in Table B-1. No pitting, crevice, or preferential attack of the welds was observed on any of the samples. Some slight discoloration (tinting) was observed beneath the crevice formers and sample mounting hardware of the liquid and vapor/liquid exposed samples. An average corrosion rate of 0.03 mpy was observed for all samples exposed to the liquid phase. An average corrosion rate of 0.02 mpy was observed for the samples exposed to the vapor/liquid interface. An average corrosion rate of 0.02 mpy was observed for the samples exposed to the vapor phase.

Nitric Acid

The results for the 304L stainless steel exposed to the nitric acid environment can be found in Table B-2. No pitting or crevice attack was observed on any of the samples. All of the samples exhibited a deep blue/black tinting (bluing) which was impervious to standard cleaning methods. The luminescent appearance of the tinting indicates that it is a very thin film and its presence will not effect the corrosion rate calculation. The observed films were heavier for the samples exposed to the liquid and vapor/liquid interface regions than those observed for the vapor phase. The nature of the attack was characterized as severe uniform intergranular attack with uniform grain loss. Although the weld structures were revealed (and also exhibited intergranular attack) on those samples exposed to the liquid and vapor liquid interface regions, no preferential attack of the weld metal or HAZ was observed. An average corrosion rate of 5.37 mpy was observed for all samples exposed to the liquid phase. An average corrosion rate of 4.54 mpy was observed for the samples exposed to the vapor/liquid interface. An average corrosion rate of 0.09 mpy was observed for the samples exposed to the vapor phase.

316L Stainless Steel

Alkaline Waste

The results for the 316L stainless steel exposed to the alkaline waste environment can be found in Table B-3. No pitting, crevice, or preferential attack of the welds was observed on any of the samples. Some slight discoloration (tinting) was observed beneath the crevice formers and sample mounting hardware of the liquid and vapor/liquid exposed samples. Tinting was also observed on the vapor side of the liquid/vapor exposed samples. An average corrosion rate of 0.03 mpy was observed for all samples exposed to the liquid phase. An average corrosion rate of 0.01 mpy was observed for the samples exposed to the vapor/liquid interface. An average corrosion rate of 0.02 mpy was observed for the samples exposed to the vapor phase.

Nitric Acid

The results for the 316L stainless steel exposed to the nitric acid environment can be found in Table B-4. No pitting or crevice attack was observed on any of the samples. Those samples exposed to the liquid and vapor/liquid interface region were heavily etched. All of the samples exhibited a deep blue/brown tinting (bluing) which was impervious to standard cleaning methods. The luminescent appearance of the tinting indicates that it is a very thin film and its presence will not effect the corrosion rate calculation. The observed films were heavier for the samples exposed to the liquid and vapor/liquid interface regions. The nature of the attack was characterized as severe uniform intergranular corrosion with uniform grain loss. The weld structures were also revealed on those samples exposed to the liquid and vapor liquid interface regions, but no preferential attack was observed. An average corrosion rate of 17.28 mpy was observed for all samples exposed to the liquid phase. An average corrosion rate of 17.00 mpy was observed for the samples exposed to the vapor/liquid interface. An average corrosion rate of 0.06 mpy was observed for the samples exposed to the vapor phase.

AL-6XN Stainless Steel

Alkaline Waste

The results for the AL-6XN stainless steel exposed to the alkaline waste environment can be found in Table B-5. No pitting, crevice, or preferential attack of the welds was observed on any of the samples. An average corrosion rate of 0.05 mpy was observed for all samples exposed to the liquid phase. An average corrosion rate of 0.04 mpy was observed for the samples exposed to the vapor/liquid interface. An average corrosion rate of 0.03 mpy was observed for the samples exposed to the vapor phase.

Nitric Acid

The results for the AL-6XN stainless steel exposed to the nitric acid environment can be found in Table B-6. No pitting or crevice attack was observed on any of the samples. The nature of the attack observed on those samples exposed to the liquid and vapor/liquid interface regions was characterized as uniform intergranular attack with some intermittent grain loss. The extent of the attack was not as severe as that observed on the 04L and 316L. The weld structures were clearly revealed on those samples exposed to the liquid and vapor liquid interface regions, but no preferential attack was observed. The welds were just barely visible on the samples exposed to the vapor phase. The sample exposed to the interface region showed a very light etching resulting from the intergranular attack. An average corrosion rate of 1.31 mpy was observed for all samples exposed to the liquid phase. An average corrosion rate of 2.38 mpy was observed for the samples exposed to the vapor/liquid interface. An average corrosion rate of 0.09 mpy was observed for the samples exposed to the vapor phase.

Nickel-Base Alloys

Incoloy Alloy 825

Alkaline Waste

The results for the Incoloy Alloy 825 (I825) samples exposed to the alkaline waste environment can be found in Table B-7. No pitting, crevice, or preferential attack of the welds was observed on any of the samples. Although the pre-clean visual evaluation indicated a possibility of light etching, the observed corrosion rates were all quite low. An average corrosion rate of 0.02 mpy was observed for all samples exposed to the liquid phase. The average corrosion rate for the samples exposed to the interface region was 0.01 mpy. The average corrosion rate for those samples exposed to the vapor phase was also 0.01 mpy.

Nitric Acid

The results for the I825 samples exposed to the nitric acid environment can be found in Table B-8. No pitting or crevice attack was observed on any of the samples. The attack was characterized as uniform intergranular attack with some grain loss. The weld structures were revealed on those samples exposed to the liquid and vapor liquid interface regions, but no preferential attack was observed. An average corrosion rate of 3.55 mpy was observed for all samples exposed to the liquid phase. An average corrosion rate of 1.51 mpy was observed for the samples exposed to the vapor/liquid interface. An average corrosion rate of 0.02 mpy was observed for the samples exposed to the vapor phase.

Inconel Alloy 625

Alkaline Waste

The results for the Inconel Alloy 625 (I625) samples exposed to the alkaline waste environment can be found in Table B-9. No pitting, crevice, or preferential attack of the welds was observed on any of the samples. An average corrosion rate of 0.02 mpy was observed for all samples exposed to the liquid phase. The average corrosion rate for the samples exposed to the interface region was 0.02 mpy. The average corrosion rate for those samples exposed to the vapor phase was also 0.02 mpy.

Nitric Acid

The results for the I625 samples exposed to the nitric acid environment can be found in Table B-10. No pitting or crevice attack was observed on any of the samples. The attack was characterized as uniform intergranular attack with no grain loss. The weld structures were clearly revealed on both sides of the samples exposed to the liquid and vapor liquid interface regions, but no preferential attack was observed. An average corrosion rate of 2.65 mpy was observed for all samples exposed to the liquid phase. An average corrosion rate of 2.71 mpy was observed for the samples exposed to the vapor/liquid interface. An average corrosion rate of 0.07 mpy was observed for the samples exposed to the vapor phase.

Inconel Alloy 690

Alkaline Waste

The results for the Inconel Alloy 690 (I690) samples exposed to the alkaline waste environment can be found in Table B-11. No pitting, crevice, or preferential attack of the welds was observed on any of the samples. An average corrosion rate of 0.03 mpy was observed for all samples exposed to the liquid phase. The average corrosion rate for the samples exposed to the interface region was 0.02 mpy. The average corrosion rate for those samples exposed to the vapor phase was also 0.04 mpy.

Nitric Acid

The results for the I690 samples exposed to the nitric acid environment can be found in Table B-12. No pitting or crevice attack was observed on any of the samples. The attack was characterized as light intergranular attack with some slight grain loss. The weld structures were revealed on the samples exposed to the liquid and vapor liquid interface regions, but no preferential attack was observed. All samples exposed to the liquid or the interface regions showed very light tinting (brown) and very slight etching. An average corrosion rate of 1.52 mpy was observed for all samples exposed to the liquid phase. An average corrosion rate of 0.58 mpy was observed for the samples exposed to the vapor/liquid interface. An average corrosion rate of 0.02 mpy was observed for the samples exposed to the vapor phase.

Hastelloy Alloy G-30

Alkaline Waste

The results for the Hastelloy Alloy G-30 samples exposed to the alkaline waste environment can be found in Table B-13. No pitting, crevice, or preferential attack of the welds was observed on any of the samples. An average corrosion rate of 0.01 mpy was observed for all samples exposed to the liquid phase. The average corrosion rate for the samples exposed to the interface region was 0.01 mpy. The average corrosion rate for those samples exposed to the vapor phase was also 0.01 mpy.

Nitric Acid

The results for the Hastelloy Alloy G-30 samples exposed to the nitric acid environment can be found in Table B-14. No pitting or crevice attack was observed on any of the samples. The attack was characterized as light etching which revealed the microstructure of the alloy, however, no significant intergranular attack was noted. The weld structures were revealed on the samples exposed to the liquid and vapor liquid interface regions, but no preferential attack was observed. All samples exposed to the liquid or the interface regions showed very light tinting (brown). An average corrosion rate of 0.76 mpy was observed for all samples exposed to the liquid phase. An average corrosion rate of 0.75 mpy was observed for the samples exposed to the vapor/liquid interface. An average corrosion rate of 0.03 mpy was observed for the samples exposed to the vapor phase.

Titanium

Titanium Grade – 2

Alkaline Waste

The results for the Titanium Grade – 2 (Ti-2) samples exposed to the alkaline waste environment can be found in Table B-15. No pitting, crevice, or preferential attack of the welds was observed on any of the samples. All samples were discolored/tinted (blue/brown). The discoloration/tinting was darker in the liquid phase exposures. An average corrosion rate of 0.09 mils per year (mpy) was observed for all samples exposed to the liquid phase. The average corrosion rate for the samples exposed to the interface region was 0.14 mpy. The average corrosion rate for those samples exposed to the vapor phase was also 0.07 mpy.

Nitric Acid

The results for the Ti-2 samples exposed to the nitric acid environment can be found in Table B-16. No pitting or crevice attack was observed on any of the samples. All samples exposed to the liquid or the interface regions showed very light tinting (blue/brown). An average corrosion rate of 0.11 mpy was observed for all samples exposed to the liquid phase. An average corrosion rate of 0.03 mpy was observed for the samples exposed to the vapor/liquid interface. An average corrosion rate of 0.03 mpy was observed for the samples exposed to the vapor phase.

CONCLUSIONS

Alkaline Waste

The results of the exposures performed indicate that from both a general and localized corrosion standpoint any of the alloys evaluated would be acceptable in the alkaline waste environment under the conditions of these tests. However, other concerns not addressed in this study may dramatically effect the performance of these alloys in this environment. Some of these concerns include the effect of solution flow or velocity and the effect of solution chemical changes/concentration during the recovery process. Also, acceptable corrosion resistance in the alkaline waste environment does not preclude the potential for other failure modes such as stress corrosion cracking (SCC).

Nitric Acid Waste

The results of the nitric acid exposures performed indicate that the lower stainless steels (304L and 316L) evaluated showed the highest general corrosion rates (up to 23 mpy). The rates observed on the other alloys were on the average all less than 3 mpy. Corrosion rates of this magnitude can be managed through proper design; however, as was the case with the alkaline waste tests, other concerns not addressed by this study (flow, chemistry, etc.) need to be carefully considered. No evidence of localized corrosion (pitting or crevice) or preferential attack of the welds was observed for any of the alloys. However, intergranular corrosion was observed on many of the alloys. The extent of the intergranular attack could be well characterized and reported through the metallographic examination of representative samples of each alloy. The susceptibility of an alloy to intergranular corrosion is often an indication of the alloys susceptibility to SCC (particularly in stainless steels and copper alloys). This possibility should be thoroughly explored before an alloy is chosen for use.

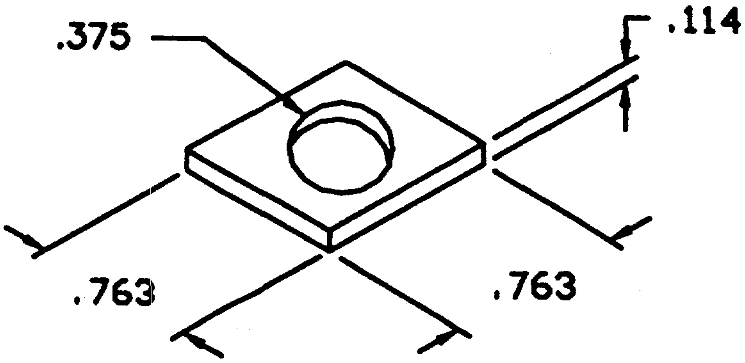

Figure 1a. Schematic Diagram Of Standard Sample.

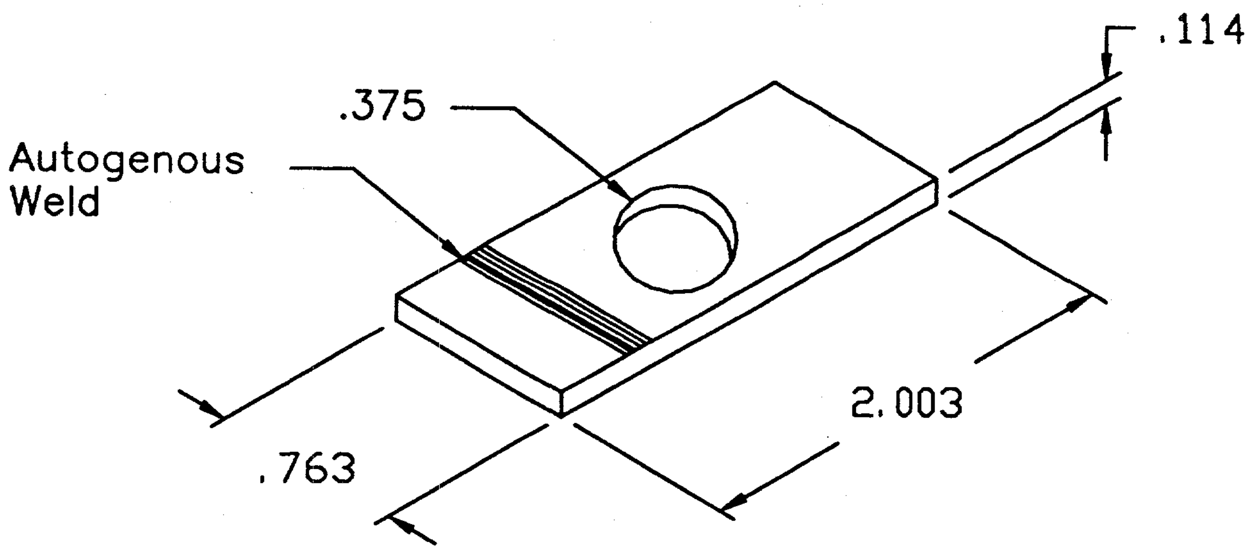

Figure 1b. Schematic Diagram Of Welded Sample.

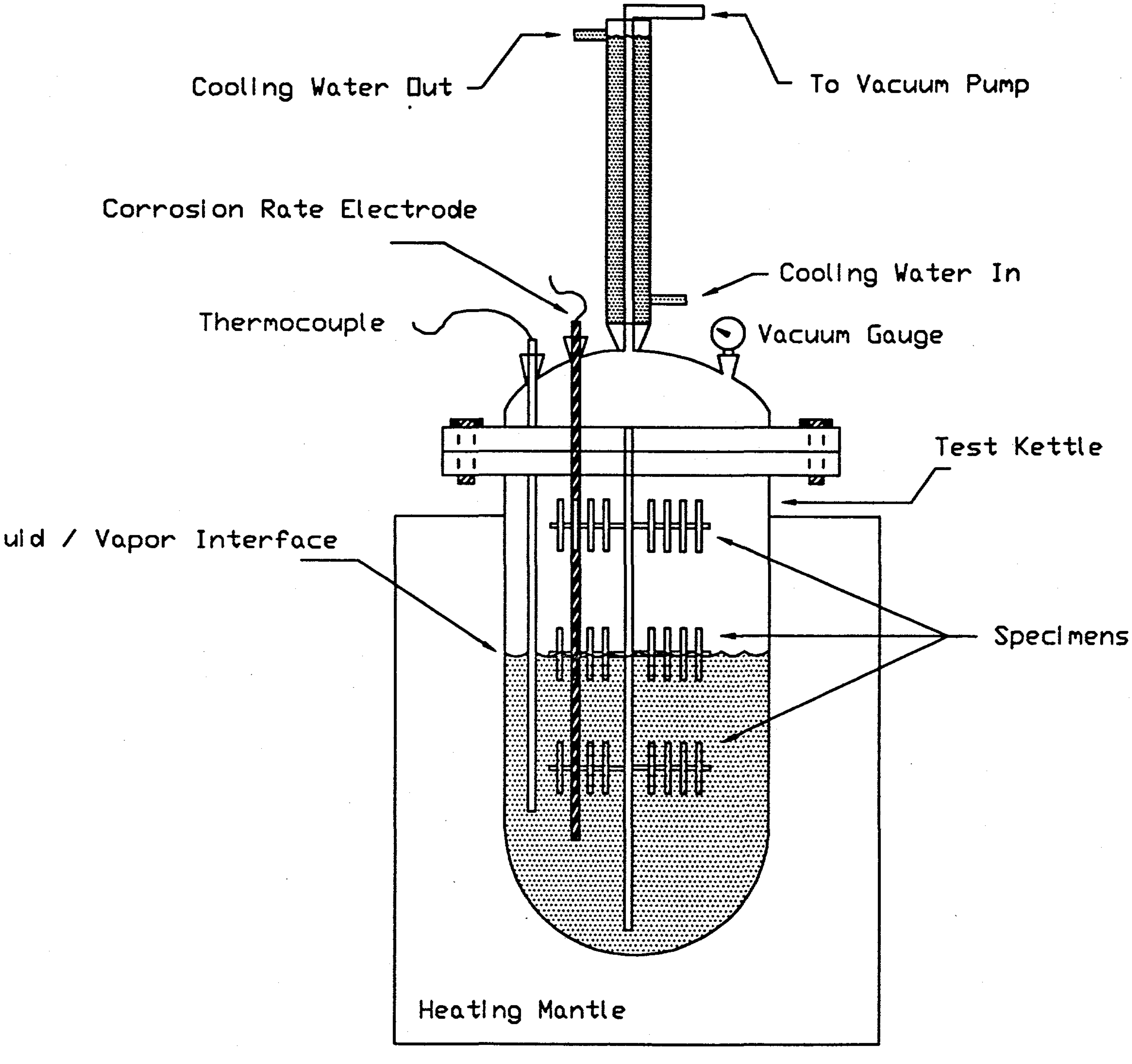

Figure 2. Resin Kettle And Associated Test Apparatus.

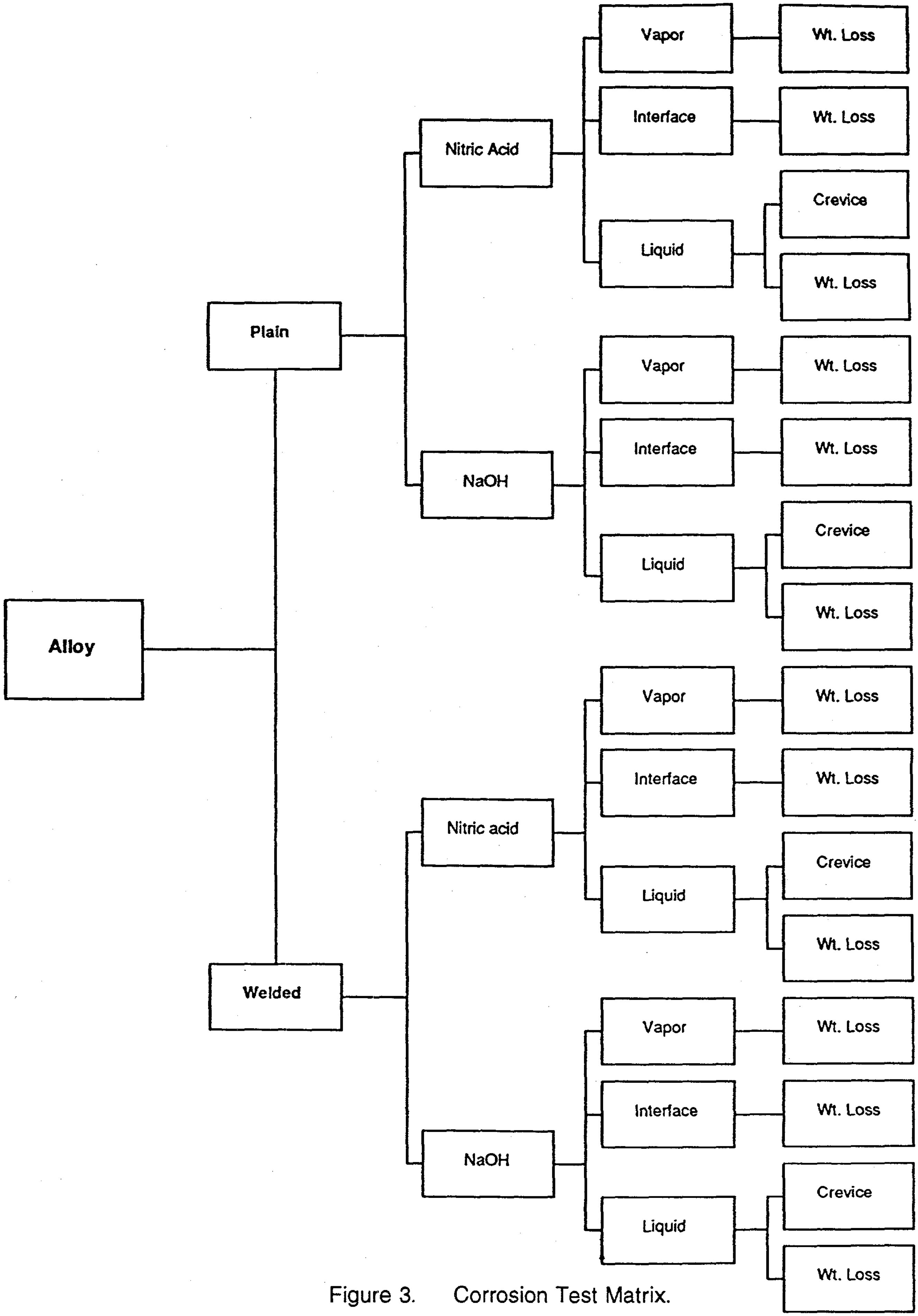

Figure 3. Corrosion Test Matrix.

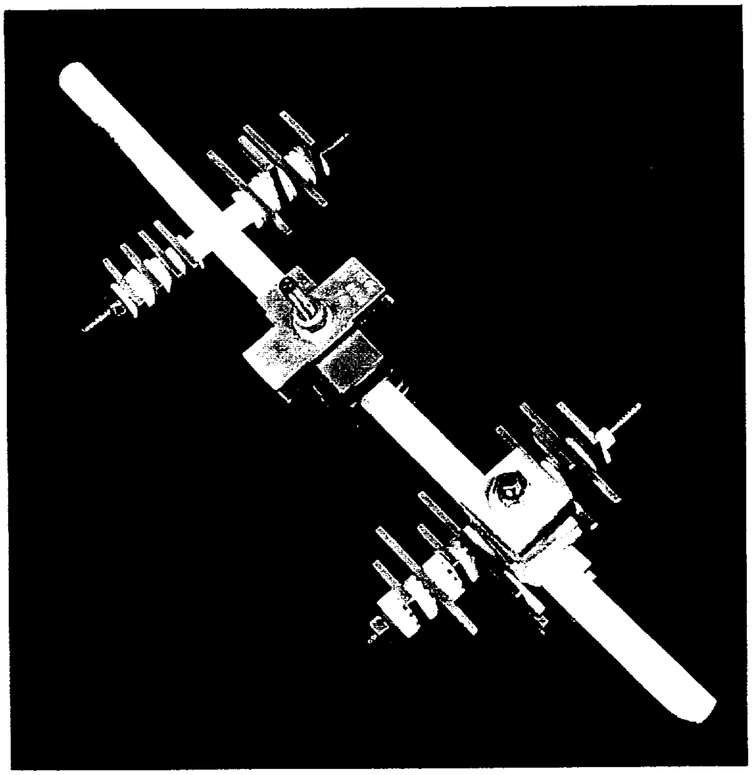

Figure 4a. Sample "Tree."

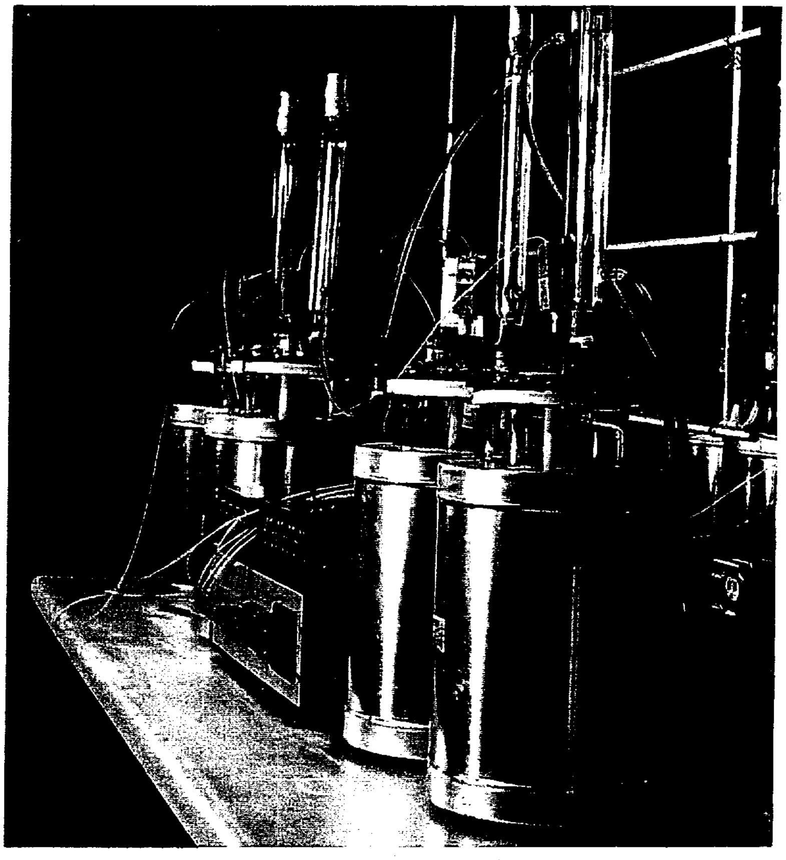

Figure 4b. Resin Kettles.

Table 1. Chemical Composition Of Alloys Used In Testing.

Alloy	Chemical Composition														
	Al	C	Cb+Ta	Co	Cr	Cu	Fe	Mn	Mo	N	Ni	P	S	Si	Ti	Other
304 L		0.020			18.26	0.30	Bal.	1.86	0.30	0.090	8.11	0.032	0.0020	0.56		
316 L		0.020			16.33	0.23	Bal.	1.84	2.12	0.030	10.17	0.028	0.0003	0.52		
AL6-XN		0.015			20.48	0.24	Bal.	0.34	6.23	0.240	23.90	0.021	0.0003	0.38		
Incoloy 825	0.009	0.010			22.07	1.72	29.69	0.40	3.49		41.22		<0.0010	0.29	1.02	
Inconel 625	0.230	0.020	3.42		21.89		3.34	0.05	8.97		61.68	0.007	<.0010	0.13	0.25	
Inconel 690	0.220	0.010			29.10		10.26	0.42			59.40		0.0030	0.30	0.29	
Hastelloy G-30		0.010	0.88	2.20	29.10	1.90	14.60	1.10	5.00		Bal.	0.008	<.0020	0.26		W - 2.80
Titanium Gr. 2		0.100			0.30					0.009					Bal.	O - 0.12, H - 7ppm

Table 2. Composition of Test Solutions.

a. Nitric Acid Test Solution Composition.

Constituent	Concentration (M)
H^+	15.9
Na^+	2.5
NO_3^-	18.4

b. Alkaline Waste Test Solution Composition

Constituent	Concentration (M)
Aluminum	9.5 E-01
Ammonia	1.5 E-02
Bicarbonate	2.1 E-01
Chloride	1.5 E-01
Chromium	3.1 E-03
Hydroxide	5.7 E+00
Iron	7.9 E-04
Fluoride	4.0 E-03
Manganese	2.0 E-03
Nitrate	3.8 E+00
Nitrite	2.8 E+00
Phosphate	2.2 E-02
Potassium	1.1 E+00
Sodium	9.0 E+00
Sulfate	1.1 E-02

APPENDIX A

MIXING INSTRUCTIONS FOR THE ALKALINE WASTE TEST SOLUTION

ARGONNE NATIONAL LABORATORY
Chemical Technology Division Building 205
9700 South Cass Avenue, Argonne, Illinois 60439-4837

Telephone: 708/252-4777
Fax: 708/252-5246

June 21, 1994

Mr. Kurt Lawson
Cortest Columbus Technologies, Inc.
2704 Sawbury Boulevard
Columbus, OH 43235

Dear Kurt:

Regarding our conversation on June 9, 1994 concerning the recipe for the sodium hydroxide test solution--I have outlined the compound amounts and proper mixing sequence below.

Compound	g/L
Na_2CO_3	22.26
Na_2SO_4	1.56
NaCl	8.77
NaF	0.1680
$NaNO_2$	193.21
$NaNO_3$	78.97
NaOH	184.03
$Al(NO_3)_3 \cdot 9H_2O$	356.35
$Mg(NO_3)_2 \cdot 6H_2O$	0.5126
$Fe(NO_3)_3 \cdot 9H_2O$	0.3192
Na_2CrO_4	0.5022
$Na_3PO_4 \cdot 10H_2O$	8.36
KOH	61.72
NH_4NO_3	1.200

1. Dissolve KOH and NaOH in H_2O. Start with about 50% of the required volume. Add more as necessary.

2. After KOH and NaOH have dissolved, add $Al(NO_3)_3 \cdot 9H_2O$ slowly until all has dissolved.

3. Add Na_2CrO_4 after Al has dissolved.

4. Add other salts at random except NH_4NO_3 and $NaNO_2$.

5. Add NH_4NO_3 and $NaNO_2$ last.

6. Dilute to final volume.

This recipe will produce a test solution with the following concentrations:

Constituent	Concentration (M)	Constituent	Concentration (M)
Aluminum	9.5 E-01	Chloride	1.5 E-01
Dichromate	3.1 E-03	Hydroxide	5.7 E+00
Iron	7.9 E-04	Fluoride	4.0 E-03
Magnesium[a]	2.0 E-03	Nitrite	2.8 E+00
Potassium	1.1 E+00	Nitrate	3.8 E+00
Sodium	9.0 E+00	Phosphate	2.2 E-02
Ammonia	1.5 E-02	Sulfate	1.1 E-02
		Carbonate	2.1 E-01

[a]In the original Statement of Work, this element was incorrectly labeled as "Manganese".

I hope this is helpful. If you have any other questions, please give me a call.

Sincerely,

Ann E. V. Rozeveld
Separation Science and Technology Section
Chemical Technology Division

AEVR/dkt

APPENDIX B

CORROSION RATE DATA

Table B-1. Exposure Results - 304L Stainless Steel - Alkaline Waste, 80 C, 45 Days

Sample ID	Condition	Initial Weight (g)	Final Weight (g)	Weight Loss (g)	Corrosion Rate (mpy)	Average Corrosion Rate (mpy)
1	Wt. Loss - Liquid	12.4311	12.4299	0.0012	0.04	
2	Wt. Loss - Liquid	12.3566	12.3545	0.0021	0.07	0.06
7	Crevice - Liquid	12.4646	12.4639	0.0007	0.02	
8	Crevice - Liquid	12.5774	12.5765	0.0009	0.03	0.03
9	Wt. Loss - Interface	12.5131	12.5123	0.0008	0.03	
10	Wt. Loss - Interface	12.3460	12.3452	0.0008	0.03	0.03
13	Wt. Loss - Vapor	12.2619	12.2611	0.0008	0.03	
14	Wt. Loss - Vapor	12.5741	12.5733	0.0008	0.03	0.03
631	Weld - Wt. Loss - Liquid	18.1673	18.1663	0.0010	0.02	
632	Weld - Wt. Loss - Liquid	18.4738	18.4730	0.0008	0.01	0.02
637	Weld - Crevice - Liquid	17.7660	17.7651	0.0009	0.02	
638	Weld - Crevice - Liquid	17.5638	17.5628	0.0010	0.02	0.02
639	Weld - Wt. Loss - Interface	17.2323	17.2320	0.0003	0.01	
640	Weld - Wt. Loss - Interface	17.7362	17.7359	0.0003	0.01	0.01
673	Weld - Wt. Loss - Vapor	17.5033	17.5031	0.0002	0.00	
674	Weld - Wt. Loss - Vapor	17.9803	17.9800	0.0003	0.01	0.00

Average:	0.02
Standard Deviation:	0.02

Table B-2. Exposure Results - 304L Stainless Steel - Nitric Acid, 80 C, 45 Days

Sample ID	Condition	Initial Weight (g)	Final Weight (g)	Weight Loss (g)	Corrosion Rate (mpy)	Average Corrosion Rate (mpy)
3	Wt. Loss - Liquid	12.4053	12.2250	0.1803	6.35	
4	Wt. Loss - Liquid	12.3422	12.1948	0.1474	5.19	5.77
5	Crevice - Liquid	12.5159	12.3643	0.1516	5.34	
6	Crevice - Liquid	12.4635	12.3245	0.1390	4.90	3.29
11	Wt. Loss - Interface	12.4611	12.3283	0.1328	4.68	
12	Wt. Loss - Interface	12.5189	12.3880	0.1309	4.61	4.65
15	Wt. Loss - Vapor	12.5331	12.5297	0.0034	0.12	0.10
16	Wt. Loss - Vapor	12.4360	12.4336	0.0024	0.08	~~3.04~~
633	Weld - Wt. Loss - Liquid	17.2816	16.9540	0.3276	5.77	
634	Weld - Wt. Loss - Liquid	18.7333	18.4750	0.2583	4.55	5.16
635	Weld - Crevice - Liquid	17.4758	17.1780	0.2978	5.25	
636	Weld - Crevice - Liquid	16.8980	16.5801	0.3179	5.60	5.43
671	Weld - Wt. Loss - Interface	17.6361	17.3767	0.2594	4.57	
672	Weld - Wt. Loss - Interface	17.8265	17.5833	0.2432	4.29	4.43
675	Weld - Wt. Loss - Vapor	16.0238	16.0190	0.0048	0.08	
676	Weld - Wt. Loss - Vapor	17.5240	17.5203	0.0037	0.07	0.07

Average: 3.84

Standard Deviation: 2.30

Table B-3. Exposure Results - 316L Stainless Steel - Alkaline Waste, 80 C, 45 Days

Sample ID	Condition	Initial Weight (g)	Final Weight (g)	Weight Loss (g)	Corrosion Rate (mpy)	Average Corrosion Rate (mpy)
1	Wt. Loss - Liquid	12.7285	12.7275	0.0010	0.04	
2	Wt. Loss - Liquid	12.6590	12.6582	0.0008	0.03	0.03
7	Crevice - Liquid	12.7124	12.7115	0.0009	0.03	
8	Crevice - Liquid	12.7147	12.7134	0.0013	0.05	0.04
9	Wt. Loss - Interface	12.6205	12.6204	0.0001	0.00	
10	Wt. Loss - Interface	12.4933	12.4922	0.0011	0.04	0.02
13	Wt. Loss - Vapor	12.3405	12.3400	0.0005	0.02	
14	Wt. Loss - Vapor	12.6700	12.6694	0.0006	0.02	0.02
9	Weld - Wt. Loss - Liquid	20.2809	20.2790	0.0019	0.03	
10	Weld - Wt. Loss - Liquid	20.3018	20.3005	0.0013	0.02	0.03
11	Weld - Crevice - Liquid	20.2740	20.2723	0.0017	0.03	
12	Weld - Crevice - Liquid	20.3798	20.3785	0.0013	0.02	0.03
13	Weld - Wt. Loss - Interface	20.4488	20.4499	-0.0011	0.00	
14	Weld - Wt. Loss - Interface	20.2992	20.2992	0.0000	0.00	0.00
15	Weld - Wt. Loss - Vapor	20.0904	20.0900	0.0004	0.01	
16	Weld - Wt. Loss - Vapor	20.3734	20.3723	0.0011	0.02	0.01

Average:	0.02
Standard Deviation:	0.01

Table B-4. Exposure Results - 316L Stainless Steel - Nitric Acid, 80 C, 45 Days

Sample ID	Condition	Initial Weight (g)	Final Weight (g)	Weight Loss (g)	Corrosion Rate (mpy)	Average Corrosion Rate (mpy)
3	Wt. Loss - Liquid	10.6853	10.2901	0.3952	13.93	
4	Wt. Loss - Liquid	12.7403	12.3171	0.4232	14.91	14.42
5	Crevice - Liquid	12.5270	12.0689	0.4581	16.14	
6	Crevice - Liquid	12.5154	12.0472	0.4682	16.50	16.32
11	Wt. Loss - Interface	12.6331	12.3192	0.3139	11.06	
12	Wt. Loss - Interface	12.4620	12.1077	0.3543	12.48	11.77
15	Wt. Loss - Vapor	12.5574	12.5534	0.0040	0.14	
16	Wt. Loss - Vapor	11.8711	11.8664	0.0047	0.17	0.15
1	Weld - Wt. Loss - Liquid	20.1985	19.2662	0.9323	16.43	
2	Weld - Wt. Loss - Liquid	20.6226	19.6660	0.9566	16.86	16.65
3	Weld - Crevice - Liquid	20.2954	19.0792	1.2162	21.44	
4	Weld - Crevice - Liquid	20.4636	19.2117	1.2519	22.07	21.75
5	Weld - Wt. Loss - Interface	20.4969	19.3309	1.1660	20.55	
6	Weld - Wt. Loss - Interface	19.7417	18.3842	1.3575	23.93	22.24
7	Weld - Wt. Loss - Vapor	20.2433	20.2377	0.0056	0.10	
8	Weld - Wt. Loss - Vapor	20.1558	20.1511	0.0047	0.08	0.09

Average:	12.92
Standard Deviation:	8.37

Table B-5. Exposure Results - AL6XN Stainless Steel - Alkaline Waste, 80 C, 45 Days

Sample ID	Condition	Initial Weight (g)	Final Weight (g)	Weight Loss (g)	Corrosion Rate (mpy)	Average Corrosion Rate (mpy)
9	Wt. Loss - Liquid	12.5306	12.5294	0.0012	0.04	
10	Wt. Loss - Liquid	12.8889	12.8872	0.0017	0.06	0.05
11	Crevice - Liquid	12.7853	12.7842	0.0011	0.04	
12	Crevice - Liquid	11.8396	11.8386	0.0010	0.03	0.04
13	Wt. Loss - Interface	12.9104	12.9086	0.0018	0.06	
14	Wt. Loss - Interface	12.5320	12.5310	0.0010	0.03	0.05
15	Wt. Loss - Vapor	12.9423	12.9409	0.0014	0.05	
16	Wt. Loss - Vapor	13.3706	13.3698	0.0008	0.03	0.04
9	Weld - Wt. Loss - Liquid	21.3128	21.3104	0.0024	0.04	
10	Weld - Wt. Loss - Liquid	21.5713	21.5664	0.0049	0.08	0.06
11	Weld - Crevice - Liquid	21.7320	21.7289	0.0031	0.05	
12	Weld - Crevice - Liquid	21.7030	21.7016	0.0014	0.02	0.04
13	Weld - Wt. Loss - Interface	21.5300	21.5281	0.0019	0.03	
14	Weld - Wt. Loss - Interface	21.6392	21.6361	0.0031	0.05	0.04
15	Weld - Wt. Loss - Vapor	20.9858	20.9845	0.0013	0.02	
16	Weld - Wt. Loss - Vapor	21.2347	21.2340	0.0007	0.01	0.02

Average:	0.04
Standard Deviation:	0.02

Table B-6. Exposure Results - AL6XN Stainless Steel - Nitric Acid, 80 C, 45 Days

Sample ID	Condition	Initial Weight (g)	Final Weight (g)	Weight Loss (g)	Corrosion Rate (mpy)	Average Corrosion Rate (mpy)
1	Wt. Loss - Liquid	12.7376	12.6996	0.0380	1.31	
2	Wt. Loss - Liquid	12.6770	12.6414	0.0356	1.22	1.26
3	Crevice - Liquid	12.6904	12.6185	0.0719	2.47	
4	Crevice - Liquid	12.9028	12.8552	0.0476	1.64	2.05
5	Wt. Loss - Interface	12.9360	12.8520	0.0840	2.89	
6	Wt. Loss - Interface	12.8665	12.8265	0.0400	1.37	2.13
7	Wt. Loss - Vapor	12.8663	12.8629	0.0034	0.12	
8	Wt. Loss - Vapor	12.8371	12.8345	0.0026	0.09	0.10
1	Weld - Wt. Loss - Liquid	21.6136	21.5368	0.0768	1.32	
2	Weld - Wt. Loss - Liquid	21.7366	21.6879	0.0487	0.84	1.08
3	Weld - Crevice - Liquid	21.8340	21.7819	0.0521	0.90	
4	Weld - Crevice - Liquid	21.5543	21.5071	0.0472	0.81	0.85
5	Weld - Wt. Loss - Interface	21.6803	21.5137	0.1666	2.86	
6	Weld - Wt. Loss - Interface	21.6155	21.4760	0.1395	2.40	2.63
7	Weld - Wt. Loss - Vapor	21.4596	21.4554	0.0042	0.07	
8	Weld - Wt. Loss - Vapor	21.5115	21.5071	0.0044	0.08	0.07

Average:	1.27
Standard Deviation:	0.97

Table B-7. Exposure Results - Incoloy 825 - Alkaline Waste, 80 C, 45 Days

Sample ID	Condition	Initial Weight (g)	Final Weight (g)	Weight Loss (g)	Corrosion Rate (mpy)	Average Corrosion Rate (mpy)
9	Wt. Loss - Liquid	13.2024	13.2020	0.0004	0.01	
10	Wt. Loss - Liquid	12.8122	12.8117	0.0005	0.02	0.02
11	Crevice - Liquid	13.3003	13.2992	0.0011	0.04	
12	Crevice - Liquid	13.2837	13.2832	0.0005	0.02	0.03
13	Wt. Loss - Interface	13.2264	13.2255	0.0009	0.03	
14	Wt. Loss - Interface	13.3308	13.3305	0.0003	0.01	0.02
15	Wt. Loss - Vapor	13.1913	13.1910	0.0003	0.01	
16	Wt. Loss - Vapor	13.0744	13.0738	0.0006	0.02	0.02
109	Weld - Wt. Loss - Liquid	21.8268	21.8263	0.0005	0.01	
110	Weld - Wt. Loss - Liquid	19.9539	19.9533	0.0006	0.01	0.01
111	Weld - Crevice - Liquid	21.1550	21.1545	0.0005	0.01	
112	Weld - Crevice - Liquid	21.3082	21.3076	0.0006	0.01	0.01
113	Weld - Wt. Loss - Interface	20.7956	20.7955	0.0001	0.00	
114	Weld - Wt. Loss - Interface	21.1859	21.1860	-0.0001	0.00	0.00
115	Weld - Wt. Loss - Vapor	21.2805	21.2805	0.0000	0.00	
116	Weld - Wt. Loss - Vapor	20.9935	20.9935	0.0000	0.00	0.00

Average:	0.01
Standard Deviation:	0.01

Table B-8. Exposure Results - Incoloy 825 - Nitric Acid, 80 C, 45 Days

Sample ID	Condition	Initial Weight (g)	Final Weight (g)	Weight Loss (g)	Corrosion Rate (mpy)	Average Corrosion Rate (mpy)
1	Wt. Loss - Liquid	13.3319	13.2160	0.1159	3.96	
2	Wt. Loss - Liquid	13.4186	13.2723	0.1463	5.00	4.48
3	Crevice - Liquid	13.0887	12.9485	0.1402	4.79	
4	Crevice - Liquid	13.2610	13.1331	0.1279	4.37	4.58
5	Wt. Loss - Interface	12.9922	12.9362	0.0560	1.92	
6	Wt. Loss - Interface	13.2345	13.1828	0.0517	1.77	1.84
7	Wt. Loss - Vapor	13.1588	13.1580	0.0008	0.03	
8	Wt. Loss - Vapor	12.9519	12.9508	0.0011	0.04	0.03
101	Weld - Wt. Loss - Liquid	21.0876	20.9474	0.1402	2.40	
102	Weld - Wt. Loss - Liquid	21.0159	20.8421	0.1738	2.97	2.69
103	Weld - Crevice - Liquid	21.1230	21.0137	0.1093	1.87	
104	Weld - Crevice - Liquid	21.2443	21.0649	0.1794	3.07	2.47
105	Weld - Wt. Loss - Interface	21.4018	21.3337	0.0681	1.16	
106	Weld - Wt. Loss - Interface	21.1333	21.0648	0.0685	1.17	1.17
107	Weld - Wt. Loss - Vapor	19.5562	19.5554	0.0008	0.01	
108	Weld - Wt. Loss - Vapor	21.0260	21.0252	0.0008	0.01	0.01

Average:	2.16
Standard Deviation:	1.74

Table B-9. Exposure Results - Inconel 625 - Alkaline Waste, 80 C, 45 Days

Sample ID	Condition	Initial Weight (g)	Final Weight (g)	Weight Loss (g)	Corrosion Rate (mpy)	Average Corrosion Rate (mpy)
9	Wt. Loss - Liquid	14.5993	14.5984	0.0009	0.03	
10	Wt. Loss - Liquid	14.7592	14.7582	0.0010	0.03	0.03
11	Crevice - Liquid	14.6116	14.6107	0.0009	0.03	
12	Crevice - Liquid	14.4641	14.4628	0.0013	0.04	0.04
13	Wt. Loss - Interface	14.7749	14.7739	0.0010	0.03	
14	Wt. Loss - Interface	14.5583	14.5572	0.0011	0.04	0.03
15	Wt. Loss - Vapor	14.6107	14.6096	0.0011	0.04	
16	Wt. Loss - Vapor	14.6560	14.6553	0.0007	0.02	0.03
9	Weld - Wt. Loss - Liquid	22.1036	22.1027	0.0009	0.01	
10	Weld - Wt. Loss - Liquid	22.1837	22.1832	0.0005	0.01	0.01
11	Weld - Crevice - Liquid	22.1328	22.1323	0.0005	0.01	
12	Weld - Crevice - Liquid	21.4931	21.4926	0.0005	0.01	0.01
13	Weld - Wt. Loss - Interface	21.5755	21.5749	0.0006	0.01	
14	Weld - Wt. Loss - Interface	22.0848	22.0843	0.0005	0.01	0.01
15	Weld - Wt. Loss - Vapor	21.7762	21.7755	0.0007	0.01	
16	Weld - Wt. Loss - Vapor	22.1780	22.1775	0.0005	0.01	0.01

Average:	0.02
Standard Deviation:	0.01

Table B-10. Exposure Results - Inconel 625 - Nitric Acid, 80 C, 45 Days

Sample ID	Condition	Initial Weight (g)	Final Weight (g)	Weight Loss (g)	Corrosion Rate (mpy)	Average Corrosion Rate (mpy)
1	Wt. Loss - Liquid	14.5689	14.4845	0.0844	2.78	
2	Wt. Loss - Liquid	14.6193	14.5099	0.1094	3.61	3.20
3	Crevice - Liquid	14.6357	14.5270	0.1087	3.59	
4	Crevice - Liquid	14.5411	14.4256	0.1155	3.81	3.70
5	Wt. Loss - Interface	14.4630	14.3684	0.0946	3.12	
6	Wt. Loss - Interface	14.4717	14.3987	0.0730	2.41	2.76
7	Wt. Loss - Vapor	14.6685	14.6664	0.0021	0.07	
8	Wt. Loss - Vapor	14.7600	14.7576	0.0024	0.08	0.07
1	Weld - Wt. Loss - Liquid	21.8308	21.6932	0.1376	2.27	
2	Weld - Wt. Loss - Liquid	21.8507	21.7245	0.1262	2.08	2.18
3	Weld - Crevice - Liquid	22.2019	22.0973	0.1046	1.73	
4	Weld - Crevice - Liquid	21.7327	21.6532	0.0795	1.31	1.52
5	Weld - Wt. Loss - Interface	22.1684	22.0106	0.1578	2.60	
6	Weld - Wt. Loss - Interface	22.2569	22.0936	0.1633	2.69	2.65
7	Weld - Wt. Loss - Vapor	22.0491	22.0443	0.0048	0.08	
8	Weld - Wt. Loss - Vapor	22.2296	22.2259	0.0037	0.06	0.07

Average: 2.02

Standard Deviation: 1.34

Table B-11. Exposure Results - Inconel 690 - Alkaline Waste, 80 C, 45 Days

Sample ID	Condition	Initial Weight (g)	Final Weight (g)	Weight Loss (g)	Corrosion Rate (mpy)	Average Corrosion Rate (mpy)
9	Wt. Loss - Liquid	14.0474	14.0446	0.0028	0.10	
10	Wt. Loss - Liquid	14.1820	14.1807	0.0013	0.04	0.07
11	Crevice - Liquid	13.9978	13.9959	0.0019	0.06	
12	Crevice - Liquid	14.1568	14.1550	0.0018	0.06	0.06
13	Wt. Loss - Interface	14.2447	14.2439	0.0008	0.03	
14	Wt. Loss - Interface	13.9695	13.9688	0.0007	0.02	0.03
15	Wt. Loss - Vapor	14.2477	14.2458	0.0019	0.06	
16	Wt. Loss - Vapor	13.2145	13.2123	0.0022	0.07	0.07
9	Weld - Wt. Loss - Liquid	21.7252	21.7248	0.0004	0.01	
10	Weld - Wt. Loss - Liquid	21.6447	21.6441	0.0006	0.01	0.01
11	Weld - Crevice - Liquid	21.8455	21.8453	0.0002	0.00	
12	Weld - Crevice - Liquid	22.0687	22.0686	0.0001	0.00	0.00
13	Weld - Wt. Loss - Interface	22.1099	22.1096	0.0003	0.01	
14	Weld - Wt. Loss - Interface	22.1055	22.1059	-0.0004	-0.01	0.00
15	Weld - Wt. Loss - Vapor	22.1788	22.1784	0.0004	0.01	
16	Weld - Wt. Loss - Vapor	22.2409	22.2409	0.0000	0.00	0.00

Average:	0.03
Standard Deviation:	0.03

Table B-12. Exposure Results - Inconel 690 - Nitric Acid, 80 C, 45 Days

Sample ID	Condition	Initial Weight (g)	Final Weight (g)	Weight Loss (g)	Corrosion Rate (mpy)	Average Corrosion Rate (mpy)
1	Wt. Loss - Liquid	14.0705	14.0229	0.0476	1.62	
2	Wt. Loss - Liquid	14.1730	14.1221	0.0509	1.73	1.67
3	Crevice - Liquid	13.3507	13.3069	0.0438	1.49	
4	Crevice - Liquid	13.0137	12.9687	0.0450	1.53	1.51
5	Wt. Loss - Interface	13.6287	13.6049	0.0238	0.81	
6	Wt. Loss - Interface	14.0710	14.0567	0.0143	0.49	0.65
7	Wt. Loss - Vapor	13.9528	13.9520	0.0008	0.03	
8	Wt. Loss - Vapor	13.5860	13.5852	0.0008	0.03	0.03
1	Weld - Wt. Loss - Liquid	21.4776	21.3971	0.0805	1.37	
2	Weld - Wt. Loss - Liquid	21.7257	21.6295	0.0962	1.64	1.50
3	Weld - Crevice - Liquid	22.2794	22.2062	0.0732	1.24	
4	Weld - Crevice - Liquid	21.9229	21.8342	0.0887	1.51	1.38
5	Weld - Wt. Loss - Interface	21.9297	21.8994	0.0303	0.52	
6	Weld - Wt. Loss - Interface	21.9927	21.9634	0.0293	0.50	0.51
7	Weld - Wt. Loss - Vapor	22.0750	22.0746	0.0004	0.01	
8	Weld - Wt. Loss - Vapor	22.0857	22.0846	0.0011	0.02	0.01

Average: 0.91

Standard Deviation: 0.67

Table B-13. Exposure Results - Hastelloy G-30 - Alkaline Waste, 80 C, 45 Days

Sample ID	Condition	Initial Weight (g)	Final Weight (g)	Weight Loss (g)	Corrosion Rate (mpy)	Average Corrosion Rate (mpy)
1	Wt. Loss - Liquid	14.4937	14.4936	0.0001	0.00	
2	Wt. Loss - Liquid	14.4341	14.4337	0.0004	0.01	0.01
3	Crevice - Liquid	14.4916	14.4914	0.0002	0.01	
4	Crevice - Liquid	14.5846	14.5837	0.0009	0.03	0.02
5	Wt. Loss - Interface	14.2514	14.2510	0.0004	0.01	
6	Wt. Loss - Interface	14.5476	14.5474	0.0002	0.01	0.01
7	Wt. Loss - Vapor	14.3813	14.3811	0.0002	0.01	
8	Wt. Loss - Vapor	14.5407	14.5404	0.0003	0.01	0.01
101	Weld - Wt. Loss - Liquid	20.7638	20.7633	0.0005	0.01	
102	Weld - Wt. Loss - Liquid	20.2044	20.2047	-0.0003	0.00	0.00
103	Weld - Crevice - Liquid	21.4097	21.4103	-0.0006	0.00	
104	Weld - Crevice - Liquid	21.6047	21.6052	-0.0005	0.00	0.00
105	Weld - Wt. Loss - Interface	21.2474	21.2482	-0.0008	0.00	
106	Weld - Wt. Loss - Interface	21.5521	21.5524	-0.0003	0.00	0.00
107	Weld - Wt. Loss - Vapor	21.3956	21.3960	-0.0004	0.00	
108	Weld - Wt. Loss - Vapor	21.4382	21.4390	-0.0008	0.00	0.00

Average:	0.01
Standard Deviation:	0.01

Table B-14. Exposure Results - Hastelloy G-30 - Nitric Acid, 80 C, 45 Days

Sample ID	Condition	Initial Weight (g)	Final Weight (g)	Weight Loss (g)	Corrosion Rate (mpy)	Average Corrosion Rate (mpy)
9	Wt. Loss - Liquid	14.2112	14.1896	0.0216	0.72	
10	Wt. Loss - Liquid	14.3810	14.3560	0.0250	0.84	0.78
11	Crevice - Liquid	14.4856	14.4577	0.0279	0.93	
12	Crevice - Liquid	14.6124	14.5787	0.0337	1.13	1.03
13	Wt. Loss - Interface	14.4856	14.4607	0.0249	0.83	
14	Wt. Loss - Interface	14.3135	14.2848	0.0287	0.96	0.90
15	Wt. Loss - Vapor	14.6053	14.6040	0.0013	0.04	
16	Wt. Loss - Vapor	14.6308	14.6299	0.0009	0.03	0.04
109	Weld - Wt. Loss - Liquid	21.2571	21.2250	0.0321	0.54	
110	Weld - Wt. Loss - Liquid	21.6100	21.5764	0.0336	0.56	0.55
111	Weld - Crevice - Liquid	21.2915	21.2511	0.0404	0.68	
112	Weld - Crevice - Liquid	21.5520	21.5098	0.0422	0.71	0.69
113	Weld - Wt. Loss - Interface	21.3955	21.3608	0.0347	0.58	
114	Weld - Wt. Loss - Interface	21.4694	21.4330	0.0364	0.61	0.60
115	Weld - Wt. Loss - Vapor	21.4588	21.4568	0.0020	0.03	
116	Weld - Wt. Loss - Vapor	21.4183	21.4165	0.0018	0.03	0.03

Average: 0.58

Standard Deviation: 0.36

Table B-15. Exposure Results - Titanium 2 - Alkaline Waste, 80 C, 45 Days

Sample ID	Condition	Initial Weight (g)	Final Weight (g)	Weight Loss (g)	Corrosion Rate (mpy)	Average Corrosion Rate (mpy)
1	Wt. Loss - Liquid	7.3417	7.3401	0.0016	0.10	
2	Wt. Loss - Liquid	7.3750	7.3736	0.0014	0.09	0.09
3	Crevice - Liquid	7.4744	7.4729	0.0015	0.09	
4	Crevice - Liquid	7.4681	7.4668	0.0013	0.08	0.09
5	Wt. Loss - Interface	7.5158	7.5139	0.0019	0.12	
6	Wt. Loss - Interface	7.5703	7.5682	0.0021	0.13	0.12
7	Wt. Loss - Vapor	7.4863	7.4852	0.0011	0.07	
8	Wt. Loss - Vapor	7.4128	7.4116	0.0012	0.07	0.07
1	Weld - Wt. Loss - Liquid	11.6762	11.6749	0.0013	0.08	
2	Weld - Wt. Loss - Liquid	11.7261	11.7242	0.0019	0.12	0.10
3	Weld - Crevice - Liquid	11.5776	11.5758	0.0018	0.11	
4	Weld - Crevice - Liquid	11.6418	11.6398	0.0020	0.12	0.12
5	Weld - Wt. Loss - Interface	11.4370	11.4345	0.0025	0.15	
6	Weld - Wt. Loss - Interface	11.8120	11.8095	0.0025	0.15	0.15
7	Weld - Wt. Loss - Vapor	11.6877	11.6868	0.0009	0.06	
8	Weld - Wt. Loss - Vapor	11.8014	11.8002	0.0012	0.07	0.06

Average:	0.10
Standard Deviation:	0.03

Table B-16. Exposure Results - Titanium 2 - Nitric Acid, 80 C, 45 Days

Sample ID	Condition	Initial Weight (g)	Final Weight (g)	Weight Loss (g)	Corrosion Rate (mpy)	Average Corrosion Rate (mpy)
9	Wt. Loss - Liquid	7.7239	7.7115	0.0124	0.77	
10	Wt. Loss - Liquid	7.5176	7.5172	0.0004	0.02	0.40
11	Crevice - Liquid	7.5567	7.5565	0.0002	0.01	
12	Crevice - Liquid	7.6266	7.6263	0.0003	0.02	0.02
13	Wt. Loss - Interface	7.5806	7.5803	0.0003	0.02	
14	Wt. Loss - Interface	7.3855	7.3851	0.0004	0.02	0.02
15	Wt. Loss - Vapor	7.6163	7.6155	0.0008	0.05	
16	Wt. Loss - Vapor	7.3702	7.3700	0.0002	0.01	0.03
9	Weld - Wt. Loss - Liquid	11.7715	11.7711	0.0004	0.02	
10	Weld - Wt. Loss - Liquid	11.8157	11.8155	0.0002	0.01	0.02
11	Weld - Crevice - Liquid	11.7916	11.7914	0.0002	0.01	
12	Weld - Crevice - Liquid	11.5847	11.5844	0.0003	0.02	0.02
13	Weld - Wt. Loss - Interface	11.6036	11.6029	0.0007	0.04	
14	Weld - Wt. Loss - Interface	11.4668	11.4660	0.0008	0.05	0.05
15	Weld - Wt. Loss - Vapor	11.7683	11.7677	0.0006	0.04	
16	Weld - Wt. Loss - Vapor	10.7186	10.7182	0.0004	0.02	0.03

Average:	0.07
Standard Deviation:	0.19