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EVALUATION OF CANDIDATE ALLOYS FOR THE CONSTRUCTION OF METAL FLEX HOSES IN THE STS LAUNCH ENVIRONMENT

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ABSTRACT

Various vacuum jacketed cryogenic supply lines at the Shuttle launch site use convoluted flexible expansion joints. The atmosphere at the launch site has a very high salt content, and during a launch, fuel combustion products include hydrochloric acid. This extremely corrosive environment has caused pitting corrosion failure in the flex hoses, which were made out of 304L stainless steel. A search was done to find a more corrosion resistant replacement material. This study focused on 19 metal alloys. Tests which were performed include electrochemical corrosion testing, accelerated corrosion testing in a salt fog chamber, long term exposure at the beach corrosion testing site, and pitting corrosion tests in ferric chloride solution. Based on the results of these tests, the most corrosion resistant alloys were found to be, in order, Hastelloy C-22, Inconel 625, Hastelloy C-276, Hastelloy C-4, and Inco Alloy G-3. Of these top five alloys, the Hastelloy C-22 stands out as being the best of the alloys tested, for this application.

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1.0 INTRODUCTION

1.1 Flexible hoses are used in various supply lines that service the Orbiter at the launch pad. These convoluted flexible hoses were originally made out of 304L stainless steel. The extremely corrosive environment of the launch site has caused pitting corrosion in many of these flex hose lines. In the case of vacuum jacketed cryogenic lines, failure of the flex hose by pitting causes a loss of vacuum and subsequent loss of insulation.

1.2 The atmosphere at the launch site has a very high chloride content caused by the proximity of the ocean. During a launch, the products from the fuel combustion reaction include concentrated hydrochloric acid. This combination of chloride and acid leads to a very corrosive environment. This type of environment causes severe pitting in some of the common stainless steel alloys.

1.3 A search was undertaken to find an alternative material for the flex hoses, to reduce the problems associated with pitting corrosion. An experimental study was carried out on 19 candidate alloys, including 304L stainless steel for comparison. These alloys were chosen on the basis of their reported resistance to chloride environments.

1.4 Data is available in the literature on the corrosion resistance of several of the alloys being considered in this study. The data generally is for seawater (1-3), chloride solutions (3-13), or acids (8,10,12,14,15) individually. Some information is available on combinations of these (8,10,11,13,16), but experimental results were not found for all of the alloys under the specific conditions of the environment of interest -- NaCl combined with HCl.

1.5 Tests to determine which of the candidate alloys would have the best corrosion resistance include electrochemical corrosion testing, accelerated corrosion testing in a salt fog chamber, long term exposure at the beach corrosion testing site, and pitting corrosion tests in ferric chloride solution. The results of the electrochemical testing and preliminary results from the ferric chloride immersion test were reported previously (17,18). The electrochemical results are summarized here in Appendix A, for convenience. KSC personnel have been completing the ferric chloride immersion test and carrying out the salt fog chamber and beach exposure tests during the year since last summer. This report presents the results of these tests for all 19 of the candidate alloys.

2.0 MATERIALS AND EQUIPMENT

2.1 CANDIDATE ALLOYS

2.1.1 Nineteen alloys were chosen for testing as possible replacement material for the 304L stainless steel flex hoses. 304L stainless steel was included for comparison purposes. The 19 candidate alloys and their nominal compositions are shown in Table 1. These alloys were chosen for consideration based on their reported resistance to corrosion.

2.1.2 In addition to corrosion resistance, mechanical properties are also important to consider when selecting a new material. Some physical and mechanical properties for the candidate alloys are listed in Table 2.

2.2 SALT FOG CHAMBER/ACID DIP

2.2.1 Accelerated testing of the candidate alloys was performed in an Atlas Corrosive Fog Exposure System Model SF-2000. The solution used was the standard 5% sodium chloride mixture prepared as needed. The dipping solution used in the process was a 1.0N (about 9 vol%) hydrochloric acid/alumina (Al_2O_3) mixture. The particle size of the alumina was 0.3 micron. The solution was thoroughly stirred prior to dipping due to the settling of the alumina powder.

2.2.2 Flat test specimens exposed to these solutions were 1" x 2" samples of the identified alloys and were approximately 1/8" thick. One set of samples were base metals with an autogenous weld on one end as identified in Table 3. Another set of specimens were the candidate alloys welded to 304L stainless steel for galvanic studies and are identified in Table 4. All flat specimens had a 3/8" hole drilled in the center for mounting purposes. Stress corrosion cracking specimens were standard U-bend samples prepared with a weld in the center of the bend, using the same materials as given in Table 3. The specimens were obtained commercially from Metal Samples Company, RT. 1, Box 152, Munford, AL.

2.3 BEACH EXPOSURE/ACID SPRAY

2.3.1 All exposure in this test was carried out at the KSC Beach Corrosion Test Site which is approximately 100 feet from the high tide line. The site is located on the Atlantic Ocean approximately 1 mile south of Launch Complex 39A.

2.3.2 The acid solution used in the spray operation was 10% hydrochloric acid by volume (about 1.0N) mixed with the 0.3 micron alumina powder to form a slurry. The specimens used in this testing were duplicate specimens as described in the salt fog/acid dip tests.

2.4 FERRIC CHLORIDE IMMERSION

2.4.1 Large glass beakers (600 - 1000 ml) were used to hold the test solution. Specimens were suspended in the solution by a glass cradle. Test specimens were 1" x 2" flat samples as described in the salt fog/acid dip tests.

3.0 TEST PROCEDURES

3.1 SALT FOG CHAMBER/ACID DIP

3.1.1 Before mounting, the new corrosion specimens were visually checked and weighed to the nearest 0.1 milligram on a properly calibrated Mettler AE160 electronic balance. The specimens were then mounted on insulated rods and set in the salt fog chamber at about 15-20 degrees off the vertical.

3.1.2 The specimens were exposed to one week (168 hours) of salt fog per ASTM B117 (19). The temperature of the chamber was controlled at 95°F (35°C) ± 2°F. After the one week exposure, the specimens were removed and dipped in the hydrochloric acid/alumina mixture to simulate the booster effluent created during launch of the Space Shuttle. After one minute of immersion, the specimens were allowed to drain and dry overnight. Following this dipping procedure, the samples were installed in the salt fog chamber for the next one week cycle.

3.1.3 After a four week/four dip period, the specimens were removed from the mounting rod and inspected. The inspection procedure included cleaning, weighing, and visual characterization of the corrosion taking place. The corroded specimens were first cleaned using a nonabrasive pad and soapy water to remove heavy deposits of alumina. This was followed by chemical cleaning per ASTM G1 (20) to remove tightly adhering corrosion products. After cleaning, the specimens were allowed to dry overnight before weighing. The specimens were weighed to the nearest 0.1 milligram on the Mettler electronic balance. The coupons were visually inspected with the naked eye and under 40x magnification. All observations were recorded in terms of appearance, sheen, pit severity/density, and stress cracking phenomena. After the inspection, the specimens were remounted and returned to the chamber for the next four week/four dip cycle of testing.

3.2 BEACH EXPOSURE/ACID SPRAY

3.2.1 The beach exposure test procedure was based on ASTM G50 (21), with the addition of an acid spray. The new duplicate specimens were first visually inspected and weighed to the nearest 0.1 milligram as was stated before. The coupons were mounted on short insulated rods that were attached to a plexiglas sheet. The orientation of the specimens was face side up and boldly exposed to the environment to receive the full extent of sun, rain, and sea spray. The U-bend specimens were mounted on 36" long insulated rods and secured with nylon tie wraps. Both the plexiglas sheet and the insulated rods were mounted on test stands at the beach corrosion test site using nylon tie wraps. The specimens were mounted facing east towards the ocean at a 45 degree angle.

3.2.2 Approximately every two weeks, the specimens received an acid spray with the solution described. The acid spray thoroughly wet the entire surface and was allowed to remain on the surface of the specimens until it dried or was rinsed off by rain.

3.2.3 After the first exposure period of 60 days, the specimens were brought to the laboratory for inspection. The inspection procedure was the same as that for the salt fog testing. The samples were remounted and returned to the beach site for continued exposure testing.

3.3 FERRIC CHLORIDE IMMERSION

3.3.1 The ferric chloride immersion test procedure was based on ASTM G48, Method A (22). The test solution was made by dissolving 100 grams of reagent grade ferric chloride ($FeCl_3 \cdot 6H_2O$) in 900 ml of distilled water. The solution was then filtered to remove insoluble particles and allowed to cool to room temperature.

3.3.2 Samples were measured to calculate exposed surface area, cleaned, rinsed, and weighed before immersion in the test solution. Each sample was placed in a glass cradle and lowered into the test solution. The beaker was covered with a watch glass and left for 72 hours.

3.3.3 After 72 hours, the samples were removed and rinsed with water. Corrosion products were removed, and the samples were then dipped in acetone or alcohol and allowed to air dry. Each specimen was weighed and examined visually for signs of pitting and weld decay. Specimens were also examined at low magnification and photographed.

3.3.4 Some of the samples that showed no sign of corrosion were put back into the test solution. These samples were periodically inspected and re-immersed for a total exposure time of 912 hours.

4.0 TEST RESULTS AND DISCUSSION

4.1 SALT FOG CHAMBER/ACID DIP

4.1.1 After four weeks of salt fog exposure and 4 dipping processes, the coupons were brought to the laboratory for analysis. After the cleaning procedure, the specimens were weighed to determine weight loss caused by the four week exposure. Using the weight loss results and the measured area of the coupons, corrosion rate calculations were made to compare the alloys' resistance to the salt fog/acid dip environment. The formula used to calculate the corrosion rate is

$$\text{CORROSION RATE (MILS PER YEAR)} = \frac{534w}{dAt}$$

where w is the weight loss in milligrams, d is the metal density in grams per cubic centimeter (g/cm^3), A is the area of exposure in square inches (in^2), and t is the exposure time in hours. This expression calculates the uniform corrosion rate over the entire surface and gives no indication of the severity of any localized attack (pitting) that could be occurring on the surface. To determine the severity of this localized attack, the coupons were examined visually with the naked eye and under 40 power magnification. The measured weight loss, the resulting calculated corrosion rate, and the visual observations for each of the alloys for the four week cycle are presented in Table 5. As can be seen from the table, several materials clearly separated from the rest and displayed superior corrosion resistance. These materials included three Hastelloy alloys (C-22, C-4, and C-276), Zirconium 702, Inconel 625, and Inco Alloy G-3. The

Inco Alloy G-3 marked the point at which the corrosion rates accelerated rapidly for the many stainless steel alloys included in the testing. The visual observations confirmed the corrosion resistance of the top alloys with no visual deterioration at 40x. These results were considered important but premature, and the specimens were returned to the salt fog chamber for further exposure.

4.1.2 Following another four week cycle, the specimens were brought to the laboratory for the eight week analysis. The same procedures were conducted to clean, weigh, calculate, and observe the specimens. The eight week data is shown in Table 6. As can be seen from the table, not much changed in the ranking of the alloys, with the top six materials clearly superior to the rest. However, the Inco Alloy G-3 started showing signs of pitting at 40x, but these pits were small. The corrosion rates did not change much since the relationship between weight loss and time should stay fairly constant. However, some materials display a slight reduction in corrosion rate, and this is probably due to a slight slowing of the pitting after an initial accelerated attack. In comparison to the electrochemical data (17), two materials changed their relative positions in the rankings. The cyclic polarization in 1.0N HCl/3.55% NaCl showed the Zirconium 702 material to be a poor performer, but in the salt fog/acid dip testing, this material displayed excellent corrosion resistance. On the other hand, the electrochemical testing in the 1.0N HCl/3.55% NaCl showed the Ferralium 255 to perform well, but in the salt fog/acid dip testing, this material corroded rapidly and pitted badly. The reasons for this behavior are unclear, but continued testing confirmed this result.

4.1.3 Following another four week cycle, the specimens were brought to the laboratory for the 12 week analysis. The results of the 12 week testing are shown in Table 7. After 12 weeks in the salt fog chamber and 12 dips in the acid slurry, a clear trend started to emerge. The corrosion rates were remaining fairly constant with a slight reduction still being displayed by some materials. The alloys were settling into their positions for the ranking of corrosion resistance in this accelerated environment. The Inco Alloy G-3 lost its sheen and continued to display pitting attack and some deterioration of the weld. The observation of very small pits developing on the three Hastelloy materials and one Inconel material were barely detectable and were considered insignificant since the weight loss remained very low.

4.1.4 Following another four week cycle, the specimens were brought to the laboratory for the 16 week analysis. The 16 week data is presented in Table 8. As can be seen from the table, several materials displayed increased attack and fell lower in the rankings. Most notable were the 304L, 316L, and 317L stainless steels. This allowed several materials to move up in the rankings, most notably the Inconel 600, Inconel 825, and the Ferralium 255. The visual observations continued to be helpful in characterizing the alloy surface and type of corrosive attack. The top materials did not display any increase in pitting, and the weight loss data confirms this fact.

4.1.5 At the completion of another four week cycle, the specimens were brought to the laboratory for the 20 week analysis. The 20 week data is presented in Table 9. As can be seen from the table, the materials generally remained in their respective positions when compared to the 16 week data. The 304L stainless steel dropped slightly in the rankings due to severe weld attack. When the corrosion rate data is graphed, as in Figure 1, the great differences in performance can easily be seen. The level of performance of the top alloys is much higher than that of the lower materials. The cutoff line between the Incoloy G-3 and the Hastelloy B-2 shows a 15 fold increase in the corrosion rate. The corrosion rate of 304L stainless steel is approximately 260 times higher than that of Hastelloy C-22 in the salt fog/acid dip exposure test.

4.1.6 In conjunction with the standard alloy coupons, specimens were tested in the composite welded configuration. These specimens were produced by joining dissimilar metals by welding the candidate alloys to 304L stainless steel. The resulting composite coupons were exposed to the same conditions as the standard specimens to determine any undesirable galvanic effects at the weld area. This was considered necessary since the successful new alloy would be installed in an existing 304L stainless steel piping system, and galvanic corrosion in the weld area could become a source of system failure. The composite welded coupons were cleaned prior to examination in the same manner as described earlier. The 16 week observations are presented in Table 10. As can be seen from the table, most of the specimens suffered some type of weld decay. For the alloys under consideration from a corrosion resistance standpoint (Hastelloy C-22 and Inconel 625), the deterioration was mostly on the 304L surfaces adjacent to the weld. Since 304L stainless steel is anodic to these two alloys, this result was expected. The 304L is corroding preferentially and cathodically protecting the more corrosion resistant alloy. Since the particular application of the corrosion resistant alloy is to form thin wall convolutes welded to a heavy wall 304L stainless steel pipe, the galvanic effect will be minimal. The effects can be further lessened by welding using the corrosion resistant alloy as the weld filler and coating the weld area with AR-7 to block any electrolyte from reaching the galvanic couple. The AR-7 material is readily available from KSC stock and is described fully in KSC-STD-C-0001B.

4.1.7 Further testing was conducted during the study to determine if any of the alloys under consideration would be susceptible to stress corrosion cracking in the Shuttle launch environment. This was considered important due to the forming operations used in fabricating flexible convoluted bellows. The convolutes are severely deformed during manufacture, and high residual tensile stresses could be present. This situation combined with a corrosive environment created concern to properly define the stress corrosion behavior of the candidate alloys. For this testing, standard U-bend specimens were exposed to the same set of conditions as the corrosion coupons. These U-bend specimens were welded in the middle of the bend to create the worst case condition. As of the time of this report, only two of the stress corrosion specimens have failed. The 304L stainless steel specimen cracked after eight weeks and eight acid dips. The Ferralium 255 specimen cracked after 12 weeks and 12 acid dips. All other materials are continuing to display stress corrosion cracking resistance in the salt fog/acid dip environment.

4.2 BEACH EXPOSURE/ACID SPRAY

4.2.1 After 60 days of beach exposure and 5 sprays with the acid slurry, the coupons were brought to the laboratory for analysis. After the cleaning procedure, the specimens were weighed, corrosion rate calculations were made, and visual examinations were conducted as described for the salt fog/acid dip process. The results of these analyses for each of the alloys for the 60 day/5 spray cycle are presented in Table 11. As can be seen from the table, several materials clearly separated from the rest and displayed excellent corrosion resistance. The Hastelloy C-22 and Inconel 625 showed no detectable weight loss while the Hastelloy C-4 and C-276 were on the limits of measurement. The calculated corrosion rates for these materials are considered insignificant, and any one should be considered acceptable. The observations confirmed the resistance of these alloys with no visual deterioration at 40x. These results were considered important but premature, and the specimens were returned to the beach for further exposure.

4.2.2 After 251 days of beach exposure with 13 acid sprays, the specimens were brought to the laboratory for analysis. The same procedures as before were conducted to clean, weigh, calculate, and observe the coupons. The 251 day data is shown in Table 12. A graphical presentation of the corrosion rate data is shown in Figure 2. Following the 251 day exposure cycle, the same four materials displayed excellent corrosion resistance and were clearly superior to the remainder of the alloys. The same reduction in corrosion rate phenomenon was experienced as in the salt fog testing. This is probably due to a reduction in pitting rates over time as explained previously. The corrosion rates shown in Figure 2 display the same cutoff as for the salt fog data, except that the increase in corrosion rate is not as pronounced. Between the Incoloy G-3 and the Ferralium 255, there is only a 5 fold increase in corrosion rate. Since the corrosion rates of Hastelloy C-22 and Inconel 625 were not measurable, no numerical comparison factor can be found with respect to the other alloys. However, these two alloys are clearly superior to the stainless steel alloys in the beach exposure/acid spray testing.

4.2.3 When the beach results are compared to the salt fog results, many materials change positions relative to each other. In general, the materials at the top (Hastelloy C-22 and Inconel 625) and at the bottom (20Cb-3 and Monel 400) of each list remained in their respective positions. However, the standard stainless steel alloys such as 304L, 304LN, 316L, and 317L declined in relative performance while the duplex stainless alloys such as Ferralium 255 and ES 2205 improved in the rankings. This was an interesting occurrence and could be explained as follows. The main difference between the two tests is oxygen availability. While the specimens are in the salt fog chamber, the surfaces are continually wet, and this film of water could reduce the oxygen available to the metal surface. Since most corrosion resistant alloys depend on oxide films on their surface for protection, the suspicion is that the salt fog conditions could be hindering the formation of these protective oxide films on the duplex stainless steels, allowing accelerated corrosion to take place. The beach data, in contrast to the salt fog data, supports the electrochemical findings in regard to the Ferralium 255. The reasons for this are unknown but could be due to the formation of the protective oxide films.

4.2.4 For reasons stated earlier, composite welded coupons were tested in conjunction with the standard specimens to determine any undesirable effects of the galvanic couple.

The composite specimens were cleaned in the same manner prior to the examination. The 251 day beach exposure observations are shown in Table 13. As can be seen from the table, most specimens were suffering from weld decay. The severity was generally less than that observed in the salt fog testing, but the results are similar in nature with most of the attack concentrated on the 304L stainless steel surfaces. As stated before, coating of the weld area with the AR-7 material should reduce the galvanic effects to a minimum.

4.2.5 In conjunction with the salt fog testing, duplicate U-bend stress corrosion cracking specimens were exposed at the beach corrosion test site to determine the stress corrosion cracking susceptibility of the candidate alloys. As of the time of this report, none of the specimens exposed to the naturally occurring conditions at the beach site have experienced failure. Exposure of these specimens will continue, to determine if any specimens will crack in the future.

4.2.6 By comparing results from the salt fog to the beach testing, many differences have been noted. The beach testing is considered the best judge of an alloy's performance since it has naturally occurring conditions that reflect the conditions experienced at Launch Complex 39. However, the accelerated testing does give us insight into which materials have a good chance of performing well. In all the testing, by electrochemical methods, salt fog/acid dip, beach exposure/acid spray, and ferric chloride immersion, the same materials are at the top of the list. The Hastelloy C-22 has displayed superior corrosion resistance during all the testing, and coupled with its mechanical properties, it is the logical first choice for a replacement material for convoluted flex hose/bellows fabrication. Other materials may be selected by using the data presented, but caution should be exercised to properly determine the environment in which the materials will be used. This work concentrated on one specific environment that contains sodium chloride and hydrochloric acid. Since all these alloys are very environment specific, altering that environment even slightly may produce extreme changes in alloy performance. Other chemical environments such as high pH, stronger acids, other corrosives, or high temperatures may cause failure of the materials identified in this study. When dealing with high performance corrosion resistant alloys, thorough testing is an absolute requirement for choosing the right material for the job. The long term history received from the continued beach testing will be invaluable to completely characterize alloy behavior.

4.3 FERRIC CHLORIDE IMMERSION

4.3.1 Results for the samples with an autogenous weld are summarized in Table 14. Some samples showed no signs of corrosion. Others showed uniform corrosion, pitting corrosion, weld decay, or corrosive attack in the heat affected zone. Some representative photos, all at 2.2x, are shown in Figure 3. Figure 3a, of Inconel 625, shows no corrosion. The 316L in Figure 3b shows severe pitting corrosion. Hastelloy B-2, seen in Figure 3c, suffered uniform corrosion, and the Inconel 825 sample of Figure 3d shows severe pitting attack at the weld and in the heat affected zone.

4.3.2 Results for the samples welded to 304L stainless steel are given in Table 15. It was not possible to obtain a sample of Zirconium 702 welded to 304L; so Zirconium 702 does not appear in Table 15. The effect of galvanic corrosion can be seen clearly by noticing that the 304L part of each sample suffered severe pitting corrosion. This can be seen visually in Figure 4. Some additional discussion of the ferric chloride immersion results may be found in reference 18.

5.0 CONCLUSIONS

5.1 Several alloys were found that have superior resistance to pitting and crevice corrosion, compared to the 304L stainless steel that was originally used for construction of convoluted flexible joints.

5.2 Good agreement was found between all 4 of the corrosion tests. In particular, the cyclic polarization technique was found to give excellent agreement with the beach exposure and salt fog chamber results. So this electrochemical method may be used as a very quick way to evaluate alloys before performing long term field exposure tests.

5.3 Using the conditions found at the Space Shuttle launch site (high chloride content plus hydrochloric acid), the most resistant alloys were found to be, in order, Hastelloy C-22, Inconel 625, Hastelloy C-276, Hastelloy C-4, and Inco Alloy G-3.

5.4 On the basis of corrosion resistance, combined with weld and mechanical properties, Hastelloy C-22 was determined to be the best material for construction of flex hoses for use at the Space Shuttle launch site.

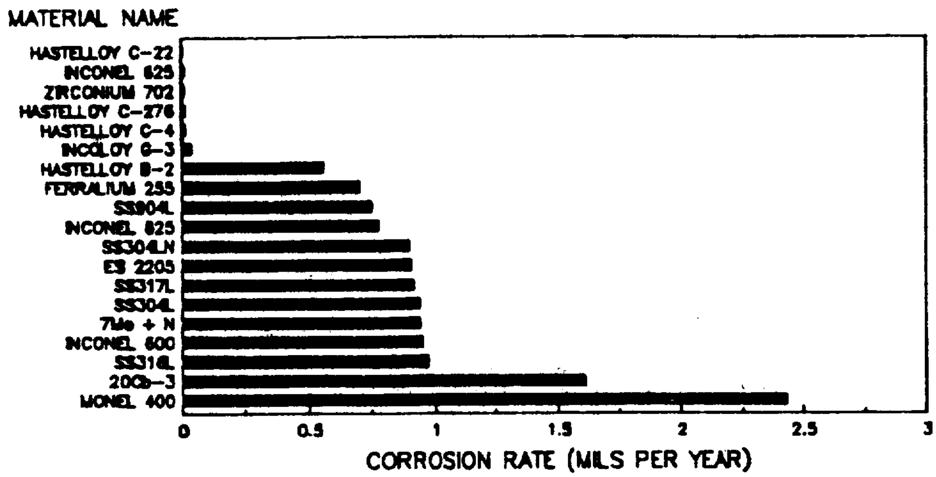

Figure 1 Salt Fog/Acid Dip Results
After 20 Weeks/20 Acid Dips

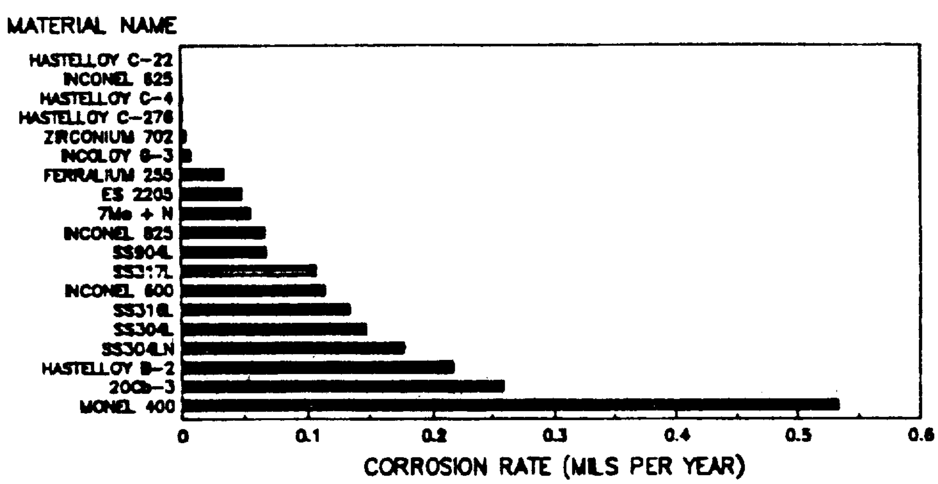

Figure 2 Beach Corrosion Data
251 Days/13 Acid Sprays

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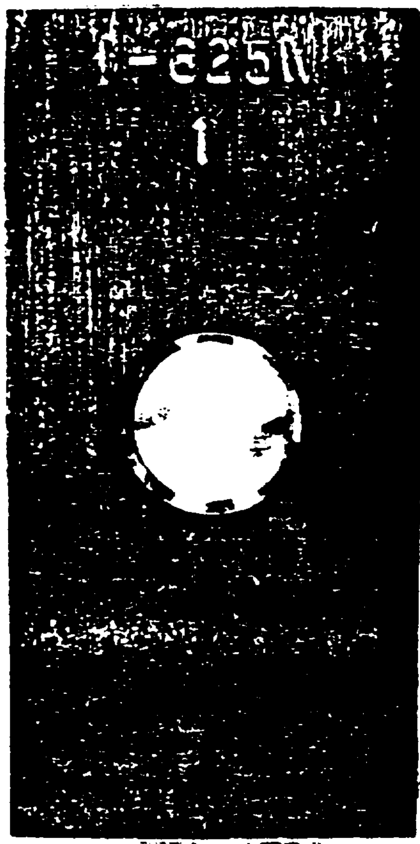
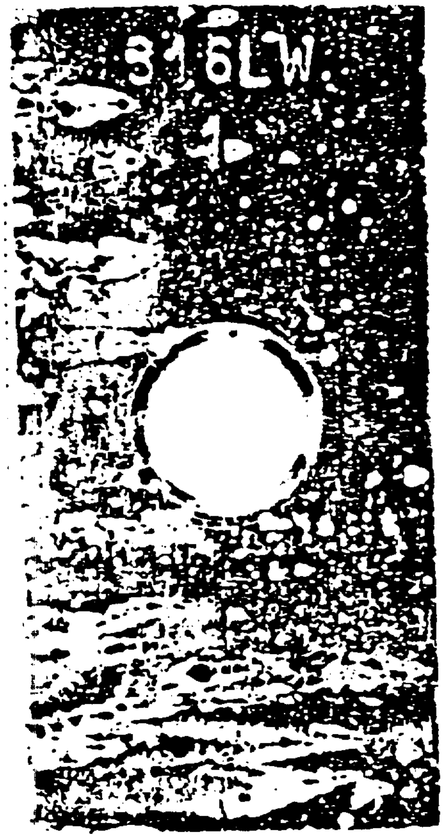
Figure 3 Photos After Ferric Chloride Immersion, 2.2x

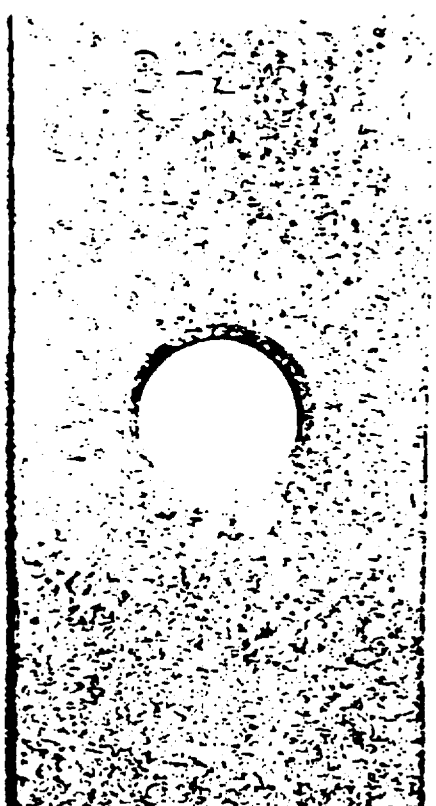
a) Inconel 625



b) 316L

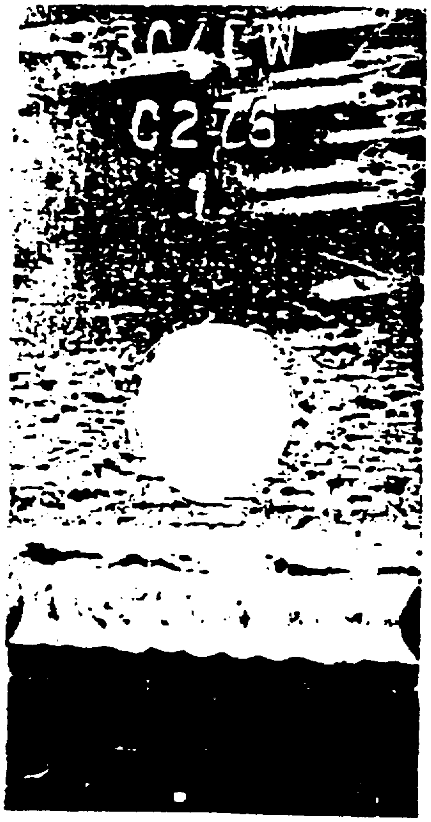


c) Hastelloy B-2



d) Inconel 825

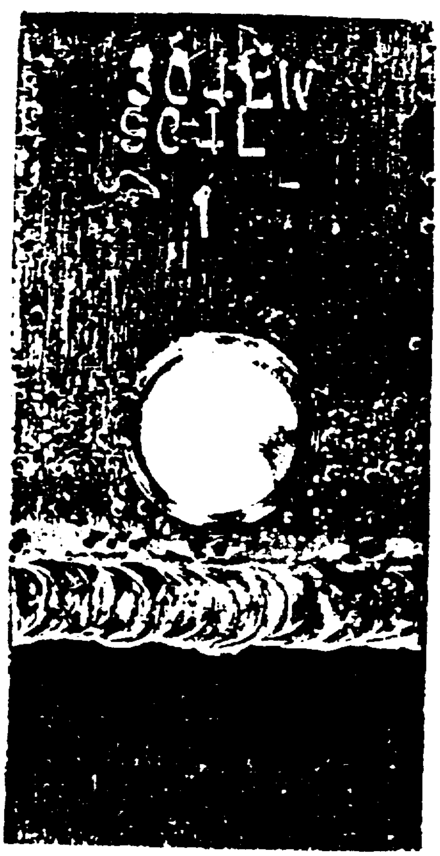
Figure 4 Ferric Chloride Immersion - Galvanic Samples



a) 304L Welded to Hastelloy C-276

<--- 304L Severe Pitting

<--- Hastelloy C-276 No Corrosion



b) 304L Welded to 904L

<--- 304L Severe Pitting

<--- 904L No Corrosion

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Table 1 Candidate Alloys and Their Nominal Compositions (wt%)

ALLOY	Ni	Fe	Cr	Mo	Mn*	Co*	Cu	C*	Si*	P*	S*	Other
HASTELLOY C-4	Bal.	3.0	18	17	1.0	2.0		0.01	0.08	0.02	0.01	Ti 0.7
HASTELLOY C-22	Bal.	3.0	22	13	0.5	2.5		0.01	0.08	0.02	0.01	V 0.3, W 3
HASTELLOY C-276	Bal.	7.0	17	17	1.0	2.5		0.01	0.08	0.02	0.01	V 0.3, W 4.5
HASTELLOY B-2	Bal.	2.0	1	28	1.0	1.0		0.01	0.1	0.02	0.01	
INCONEL 600	Bal.	8.0	16		1.0		0.5	0.15	0.5		0.01	
INCONEL 625	Bal.	5.0	23	10	0.5	1.0		0.10	0.5	0.01	0.01	Cb 4.1
INCONEL 825	Bal.	22.0	21	3	1.0		2.5	0.05	0.5		0.03	
INCO G-3	Bal.	20.0	22	7	1.0	5.0	2.0	0.02	1.0	0.04	0.03	Cb 0.5, W 1.5
MONEL 400	Bal.	2.5			2.0		31	0.30	0.5		0.02	
ZIRCONIUM 702												Zr 99.2, Hf 4.5
SS 304L	10	Bal.	19		2.0			0.03	1.0			
SS 304LN	10	Bal.	19		2.0			0.03	1.0	0.04	0.03	N 0.13
SS 316L	12	Bal.	17	2.5	2.0			0.03	1.0	0.04	0.03	
SS 317L	13	Bal.	19	3.5	2.0			0.03	1.0			
SS 904L	25	Bal.	21	4.5	2.0		1.5	0.02	1.0	0.04	0.03	
20 Cb-3	35	Bal.	20	2.5	2.0		3.5	0.07	1.0			
7Mo + N	4	Bal.	28	2	2.0			0.03	0.6	0.03	0.01	N 0.25
ES 2205	5	Bal.	22	3	2.0			0.03	1.0	0.03	0.02	N 0.14
FERRALIUM 255	5	Bal.	26	3	1.5		2.0	0.04	1.0	0.04	0.03	N 0.17

* Values are max.

Table 2 Physical and Mechanical Properties of the Candidate Alloys

ALLOY	Density (g/cm3)	Tensile Strength (ksi)	Yield Strength (ksi)	Modulus of Elasticity (psi)	Hardness	Impact Strength at -320F (ft lb)	Coeff. of Thermal Expansion (in/in F)
HASTELLOY C-4	8.64	111	60	31E+06	90 Rb	270	6.0E-06
HASTELLOY C-22	8.69	116	59	30E+06	93 Rb	260	6.9E-06
HASTELLOY C-276	8.89	115	52	30E+06	90 Rb	263	6.2E-06
HASTELLOY B-2	9.22	139	76	31E+06	92 Rb	53	5.6E-06
INCONEL 600	8.43	90	37	30E+06	88 Rb	61	7.4E-06
INCONEL 625	8.44	120	60	30E+06	79 Rb	35	7.1E-06
INCONEL 825	8.14	112	64	30E+06	80 Rb	67	7.8E-06
INCO G-3	8.31	90	35	29E+06	85 Rb	263	8.1E-06
MONEL 400	8.82	77	37	26E+06	72 Rb	200	7.7E-06
ZIRCONIUM 702	6.50	36	16	11E+06	77 HB	*	2.9E-06
SS 304L	8.02	79	33	28E+06	70 Rb	71	9.2E-06
SS 304LN	8.02	79	33	28E+06	70 Rb	*	9.2E-06
SS 316L	8.02	81	34	28E+06	75 Rb	51	9.2E-06
SS 317L	8.02	85	35	28E+06	88 Rb	*	8.9E-06
SS 904L	8.00	71	31	28E+06	84 Rb	*	8.5E-06
20 Cb-3	8.08	98	53	28E+06	90 Rb	*	8.3E-06
7Mo + N	7.75	110	81	29E+06	99 Rb	0	6.4E-06
ES 2205	7.80	100	70	28E+06	30 Rc	0	7.5E-06
FERRALIUM 255	7.75	130	100	31E+06	26 Rc	0	6.6E-06

* Data not available

Table 3 Autogenous Weld Samples

BASE ALLOY	FILLER	BASE ALLOY	FILLER
HASTELLOY C-4	C-4	SS 304L	ER 308L
HASTELLOY C-22	C-22	SS 304LN	ER 308L
HASTELLOY C-276	C-276	SS 316L	ER 316L
HASTELLOY B-2	B-2	SS 317L	ER 317
INCONEL 600	ERNiCr-3	SS 904L	904L
INCONEL 625	ERNiCrMo-3	20 Cb-3	ER 320
INCONEL 825	ERNiFeCr-1	7Mo + N	ER312Mo
INCO G-3	Hastelloy G3	ES 2205	ER22.8.3L
MONEL 400	ERNiCo-7	FERRALIUM 255	F 255
ZIRCONIUM 702	ERZr2		

Table 4 Samples Welded to 304L Stainless Steel

BASE ALLOY	FILLER	BASE ALLOY	FILLER
HASTELLOY C-4	ERNiCrMo-7	SS 304LN	ER 308L
HASTELLOY C-22	ERNiCrMo-10	SS 316L	ER 316L
HASTELLOY C-276	ERNiCrMo-4	SS 317L	ER 317
HASTELLOY B-2	ERNiMo-7	SS 904L	ER 904L
INCONEL 600	ERNiCr-3	20 Cb-3	ER 320
INCONEL 625	ERNiCr-3	7Mo + N	ER312Mo
INCONEL 825	ERNiCr-3	ES 2205	ER22.8.3L
INCO G-3	Hastelloy G3	FERRALIUM 255	F 255
MONEL 400	ERNiCr-3		

NOTE: It was not possible to obtain a sample of Zirconium 702 welded to 304L stainless steel

Table 5 Results of 4 Week Exposure in 5% Salt Fog and 4 Dips in 1.0N HCl - Alumina

MATERIAL NAME	WGT LOSS(g)	CORR. RATE(MPY)	REMARKS - OBSERVATIONS AT 1X AND 40X
HASTELLOY C-22	0.0007	0.0140	NO PITTING AT 1X - NO PITTING AT 40X
ZIRCONIUM 702	0.0008	0.0210	NO PITTING, BRIGHT SHEEN AT 1X - NO PITTING AT 40X
HASTELLOY C-4	0.0015	0.0290	NO PITTING AT 1X - NO PITTING AT 40X
HASTELLOY C-276	0.0018	0.0340	NO PITTING AT 1X - NO PITTING AT 40X
INCONEL 625	0.0020	0.0400	NO PITTING, BRIGHT SHEEN AT 1X - NO PITTING AT 40X
INCOLOY G-3	0.0059	0.1210	NO PITTING AT 1X - SLIGHT PITTING AT 40X
HASTELLOY B-2	0.0228	0.4150	NO PITTING AT 1X - UNIFORM CORROSION AT 40X
SS904L	0.0300	0.6200	VISIBLE PITTING, NO SHEEN AT 1X - MODERATE PITTING AT 40X
SS304LN	0.0324	0.6320	VISIBLE PITTING, NO SHEEN AT 1X - MODERATE PITTING AT 40X
SS316L	0.0301	0.6400	VISIBLE PITTING, NO SHEEN AT 1X - MODERATE PITTING AT 40X
SS317L	0.0324	0.6370	VISIBLE PITTING, NO SHEEN AT 1X - MODERATE PITTING AT 40X
SS304L	0.0359	0.7300	VISIBLE PITTING, NO SHEEN AT 1X - MODERATE PITTING AT 40X
INCONEL 825	0.0386	0.8080	VISIBLE PITTING, NO SHEEN AT 1X - MODERATE PITTING AT 40X
INCONEL 600	0.0420	0.8770	NO SHEEN AT 1X - NUMEROUS SMALL PITS AT 40X
7Mo + N	0.0469	1.0600	NO PITTING, NO SHEEN AT 1X - VERY SLIGHT PITTING AT 40X
FERRALIUM 255	0.0476	1.0600	VISIBLE PITTING, SLIGHT SHEEN AT 1X - NUMEROUS SLIGHT PITS AT 40X
ES 2205	0.0675	1.2060	NO PITTING, NO SHEEN AT 1X - VERY SLIGHT PITTING AT 40X
MONEL 400	0.0893	1.7550	SLIGHT SHEEN AT 1X - SLIGHT PITTING, ETCHED AT 40X
20Cb-3	0.0945	2.0300	VERY VISIBLE CORROSION AT 1X - NUMEROUS LARGE PITS, SOME DEEP AT 40X

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Table 6 Results of 8 Week Exposure in 5% Salt Fog and 8 Dips in 1.0N HCl - Alumina

MATERIAL NAME	WGT LOSS(g)	CORR. RATE(MPY)	REMARKS - OBSERVATIONS AT 1X AND 40X
HASTELLOY C-22	0.0015	0.0150	NO PITTING, BRIGHT SHEEN AT 1X - NO PITTING, NO WELD DECAY AT 40X
ZIRCONIUM 702	0.0012	0.0160	SOME STAINING, BRIGHT SHEEN AT 1X - NO PITTING, NO WELD DECAY AT 40X
HASTELLOY C-276	0.0028	0.0260	NO PITTING, BRIGHT SHEEN AT 1X - NO PITTING, NO WELD DECAY AT 40X
INCONEL 625	0.0027	0.0270	NO PITTING, BRIGHT SHEEN AT 1X - NO PITTING, NO WELD DECAY AT 40X
HASTELLOY C-4	0.0029	0.0280	NO PITTING, BRIGHT SHEEN AT 1X - NO PITTING, NO WELD DECAY AT 40X
INCOLOY G-3	0.0071	0.0730	NO PITTING, SLIGHT SHEEN AT 1X - MODERATE SHALLOW PITTING, SOME PITTING OF WELD AT 40X
HASTELLOY B-2	0.0420	0.3820	NO PITTING, NO SHEEN AT 1X - UNIFORM CORROSION WITH LOCALIZED ATTACK AT 40X
SS304LN	0.0620	0.6050	VISIBLE PITTING, NO SHEEN AT 1X - NUMEROUS PITS, SOME LARGE, NO WELD DECAY AT 40X
SS316L	0.0631	0.6730	VISIBLE PITTING, NO SHEEN AT 1X - NUMEROUS SHALLOW PITS, SOME WELD DECAY AT 40X
SS304L	0.0672	0.6900	VISIBLE PITTING , NO SHEEN AT 1X - NUMEROUS PITS, SOME LARGE, NO WELD DECAY AT 40X
SS904L	0.0695	0.7280	VISIBLE PITTING, NO SHEEN AT 1X - NUMEROUS LARGE SHALLOW PITS, PITTING OF WELD AT 40X
SS317L	0.0699	0.7520	VISIBLE PITTING , NO SHEEN AT 1X - MODERATE PITTING, SOME WELD DECAY AT 40X
INCONEL 825	0.0854	0.8930	VISIBLE PITTING, NO SHEEN AT 1X - VERY NUMEROUS PITS, PITTING OF WELD AT 40X
INCONEL 600	0.0915	0.9420	NO SHEEN AT 1X - UNIFORM ATTACK, NO WELD DECAY AT 40X
7Mo + N	0.0916	1.0350	NO PITTING, NO SHEEN AT 1X - UNIFORM CORROSION, MODERATE WELD DECAY AT 40X
FERRALIUM 255	0.0939	1.0450	VISIBLE PITTING, NO SHEEN AT 1X - UNIFORM ATTACK WITH NUMEROUS PITS, PITTING OF WELD AT 40X
ES 2205	0.1286	1.1500	VISIBLE PITTING, NO SHEEN AT 1X - SLIGHT PITTING WITH CREVICE CORROSION, PITTING OF WELD AT 40X
20Cb-3	0.1705	1.8300	VISIBLE PITTING, NO SHEEN AT 1X - HEAVY PITTING, MANY LARGE AND DEEP, SEVERE PITTING OF WELD AT 40X
MONEL 400	0.1908	1.8750	NO SHEEN AT 1X - UNIFORM CORROSION, SOME PITTING OF WELD AT 40X

Table 7 Results of 12 Week Exposure in 5% Salt Fog and 12 Dips in 1.0N HCl - Alumina

MATERIAL NAME	WGT LOSS(g)	CORR. RATE(MPY)	REMARKS - OBSERVATIONS AT 1X AND 40X
HASTELLOY C-22	0.0013	0.0120	NO PITTING, BRIGHT SHEEN AT 1X - A FEW SMALL PITS AT 40X
ZIRCONIUM 702	0.0015	0.0130	NO PITTING, BRIGHT SHEEN AT 1X - SLIGHT UNIFORM CORROSION, NO PITTING AT 40X
INCONEL 625	0.0029	0.0190	NO PITTING, BRIGHT SHEEN AT 1X - FEW VERY SMALL PITS AT 40X
HASTELLOY C-276	0.0031	0.0190	NO PITTING, BRIGHT SHEEN AT 1X - FEW VERY SMALL PITS AT 40X
HASTELLOY C-4	0.0036	0.0230	NO PITTING, BRIGHT SHEEN AT 1X - FEW PITS AT 40X
INCOLOY G-3	0.0080	0.0550	SLIGHT PITTING, NO SHEEN AT 1X - FEW SMALL PITS, UNIFORM CORROSION AT 40X
HASTELLOY B-2	0.0662	0.4010	NO PITTING, NO SHEEN/STAINED AT 1X - FEW PITS, UNIFORM CORROSION AT 40X
SS304LN	0.1081	0.7030	SOME PITTING, NO SHEEN, VISIBLE RUST AT 1X - NUMEROUS PITS AT 40X
SS904L	0.1031	0.7200	VISIBLE PITTING, NO SHEEN AT 1X - NUMEROUS SMALL PITS, SOME LARGE AND DEEP AT 40X
SS304L	0.1094	0.7490	VISIBLE PITTING, NO SHEEN AT 1X - NUMEROUS LARGE PITS AT 40X
SS316L	0.1071	0.7610	VISIBLE PITTING, NO SHEEN AT 1X - LARGE DEEP PITS, UNIFORM CORROSION AT 40X
SS317L	0.1124	0.8060	SOME LARGE PITS, NO SHEEN AT 1X - LARGE DEEP PITS AT 40X
INCONEL 825	0.1250	0.8720	VISIBLE PITTING, NO SHEEN AT 1X - NUMEROUS LARGE PITS, FAIRLY DEEP AT 40X
FERRALIUM 255	0.1294	0.9600	NUMEROUS PITS, NO SHEEN AT 1X - SEVERAL LARGE PITS AT 40X
INCONEL 600	0.1417	0.9730	NO PITTING, NO SHEEN AT 1X - UNIFORM CORROSION AT 40X
ES 2205	0.1326	1.1470	VISIBLE PITTING, NO SHEEN AT 1X - SOME LARGE PITS AT 40X
7Mo + N	0.1547	1.1653	NO PITTING, NO SHEEN AT 1X - FEW LARGE DEEP PITS, UNIFORM CORROSION AT 40X
20Cb-3	0.2430	1.7420	LARGE VISIBLE PITS, NO SHEEN AT 1X - VERY LARGE PITS, SEVERE CORROSION AT 40X
MONEL 400	0.3233	2.1180	NO PITTING, NO SHEEN AT 1X - NUMEROUS PITS, SEVERE UNIFORM CORROSION AT 40X

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Table 8 Results of 16 Week Exposure in 5% Salt Fog and 16 Dips in 1.0N HCl - Alumina

MATERIAL NAME	WGT LOSS(g)	CORR. RATE(MPY)	REMARKS - OBSERVATIONS AT 1X AND 40X
HASTELLOY C-22	0.0014	0.0068	NO PITTING, BRIGHT SHEEN AT 1X - SOME VERY SMALL PITS, NO DEPOSITS AT 40X
INCONEL 625	0.0022	0.0110	NO PITTING, BRIGHT SHEEN AT 1X - FEW MEDIUM SIZED PITS AT 40X
ZIRCONIUM 702	0.0018	0.0119	SLIGHT PITTING, SEMI BRIGHT SHEEN AT 1X - NO PITS, PATCHES OF CORROSION AT 40X
HASTELLOY C-276	0.0032	0.0151	NO PITTING, BRIGHT SHEEN AT 1X - SOME VERY SMALL PITS, NO DEPOSITS AT 40X
HASTELLOY C-4	0.0035	0.0170	NO PITTING, BRIGHT SHEEN AT 1X - SOME VERY SMALL PITS, NO DEPOSITS AT 40X
INCOLOY G-3	0.0086	0.0442	NO PITTING, BRIGHT SHEEN AT 1X - FEW SMALL PITS, NO DEPOSITS AT 40X
HASTELLOY B-2	0.1186	0.5390	NO PITTING, DISCOLORATION, NO SHEEN AT 1X - SHALLOW LARGE PITS, UNIFORM CORROSION AT 40X
FERRALIUM 255	0.1506	0.8381	VISIBLE PITTING, NO SHEEN AT 1X - NUMEROUS LARGE AND SMALL PITS, NO DEPOSITS AT 40X
SS304L	0.1672	0.8761	VISIBLE PITTING, NO SHEEN AT 1X - NUMEROUS LARGE AND DEEP PITS AT 40X
INCONEL 825	0.1684	0.8819	NUMEROUS PITS, NO SHEEN AT 1X - NUMEROUS LARGE AND DEEP PITS, WELD DECAY AT 40X
SS304LN	0.1801	0.9176	SMALL PITS, DISCOLORED, NO SHEEN AT 1X - NUMEROUS PITS, SOME DEPOSITS AT 40X
SS304L	0.1864	0.9573	VISIBLE PITTING, NO SHEEN AT 1X - MANY PITS, SOME WELD DECAY AT 40X
INCONEL 600	0.1931	0.9942	NO PITTING, DISCOLORATION, NO SHEEN AT 1X - UNIFORM CORROSION, SMALL PITS AT 40X
SS317L	0.1962	1.0018	VISIBLE PITTING, NO SHEEN AT 1X - NUMEROUS LARGE AND DEEP PITS AT 40X
SS316L	0.1915	1.0210	VISIBLE PITTING, NO SHEEN AT 1X - NUMEROUS LARGE AND DEEP PITS AT 40X
7Mo + N	0.1863	1.0526	FEW PITS, DISCOLORATION, NO SHEEN AT 1X - FEW LARGE PITS WELD DECAY, UNIFORM CORROSION AT 40X
ES 2205	0.2309	1.2228	VISIBLE PITTING, DARK COLOR, NO SHEEN AT 1X - SOME LARGE AND MANY SMALL PITS AT 40X
20Cb-3	0.3352	1.9022	EXTENSIVE PITTING, NO SHEEN AT 1X - EXTENSIVE LARGE, DEEP PITS, NO DEPOSITS AT 40X
MONEL 400	0.4864	2.4009	NO PITTING, NO SHEEN AT 1X - UNIFORM CORROSION, PITS IN WELD, NO DEPOSITS AT 40X

Table 9 Results of 20 Week Exposure in 5% Salt Fog and 20 Dips in 1.0N HCl - Alumina

MATERIAL NAME	WGT LOSS(g)	CORR. RATE(MPY)	REMARKS - OBSERVATIONS AT 1X AND 40X
HASTELLOY C-22	0.0009	0.0035	NO PITTING, BRIGHT SHEEN AT 1X - VERY FEW TINY PITS, NO DEPOSITS AT 40X
INCONEL 625	0.0025	0.0100	NO PITTING, BRIGHT SHEEN AT 1X - VERY FEW SMALL PITS AT 40X
ZIRCONIUM 702	0.0020	0.0136	SLIGHT PITTING, SEMI BRIGHT SHEEN AT 1X - NO PITS, SURFACE CORROSION PATCHES AT 40X
HASTELLOY C-276	0.0035	0.0132	NO PITTING, BRIGHT SHEEN AT 1X - VERY FEW TINY PITS AT 40X
HASTELLOY C-4	0.0037	0.0143	NO PITTING, BRIGHT SHEEN AT 1X - FEW VERY SMALL PITS, NO DEPOSITS AT 40X
INCOLOY G-3	0.0093	0.0383	NO PITTING, BRIGHT SHEEN AT 1X - SOME SHALLOW PITTING AT 40X
HASTELLOY B-2	0.1547	0.5625	NO PITTING, DISCOLORATION, DULL SHEEN AT 1X - SHALLOW LARGE PITS, UNIFORM CORROSION AT 40X
FERRALIUM 255	0.1584	0.7039	NUMEROUS PITS, NO SHEEN AT 1X - NUMEROUS SHALLOW PITTING AT 40X
SS304L	0.1735	0.7525	VISIBLE PITTING, DISCOLORED, NO SHEEN AT 1X - MANY WIDE SHALLOW AND SMALL DEEP PITS AT 40X
INCONEL 825	0.1858	0.7775	VISIBLE HEAVY PITTING, NO SHEEN AT 1X - MANY DEEP PITS, SEVERE WELD ATTACK AT 40X
SS304LN	0.2258	0.8329	VISIBLE SMALL PITS, DISCOLORED, NO SHEEN AT 1X - NUMEROUS PITS, MANY DEEP AT 40X
ES 2205	0.2518	0.9001	VISIBLE PITTING, NO SHEEN AT 1X - SOME MEDIUM PITTING, UNIFORM CORROSION AT 40X
SS317L	0.2132	0.9088	VISIBLE PITTING, DISCOLORED, NO SHEEN AT 1X - MANY WIDE SHALLOW AND SMALL DEEP PITS AT 40X
SS304L	0.2269	0.9323	VISIBLE SMALL PITS, DISCOLORED, NO SHEEN AT 1X - NUMEROUS PITS, SOME DEEP IN WELD AT 40X
7Mo + N	0.2072	0.9365	VISIBLE PITTING IN WELD, NO SHEEN AT 1X - NUMEROUS PITS, SOME DEEP, WELD ATTACK AT 40X
INCONEL 600	0.2298	0.9465	NO PITTING, NO SHEEN AT 1X - TINY PITS, UNIFORM CORROSION AT 40X
SS316L	0.2276	0.9708	VISIBLE HEAVY PITTING, DISCOLORED, NO SHEEN AT 1X - MANY WIDE SHALLOW AND SMALL DEEP PITS AT 40X
20Cb-3	0.3746	1.6112	VISIBLE VERY HEAVY PITTING, NO SHEEN AT 1X - EXTREME PITTING, MANY VERY DEEP AT 40X
MONEL 400	0.6195	2.4358	NO PITTING, DISCOLORED, NO SHEEN AT 1X - TINY PITS WITH UNIFORM CORROSION AT 40X

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Table 10 Results of 16 Week Exposure in 5% Salt Fog and 16 Dips in 1.0N HCl - Alumina

Composite Galvanic Weld Specimens

MATERIAL NAME	REMARKS - OBSERVATIONS AT 1X AND 40X
SS304L - C-276	SOME WELD DECAY ON BOTH SIDES AT 1X - LARGE PITS ALONG 304L SIDE AT 40X
SS304L - B-2	SOME DECAY ON 304L SIDE AT 1X - 304L SIDE HAS SOME WELD DECAY AT 40X
SS304L - C-4	SOME WELD DECAY AT 1X - LARGE PITS AND DECAY ON 304L SIDE AT 40X
SS304L - C-22	SOME WELD DECAY ON 304L SIDE AT 1X - LARGE PITTING ALONG 304L SIDE AT 40X
SS304L - M400	EXTREME WELD DECAY ON 304L SIDE AT 1X - WELD DECAY ON BOTH SIDES AT 40X
SS304L - 304LN	SLIGHT WELD PITTING AT 1X - SMALL PITS AND DEPOSITS ON WELD AT 40X
SS304L - 316L	SOME DECAY ON 304L SIDE AT 1X - SMALL PITS ON WELD AT 40X
SS304L - 317L	SOME PITTING OF WELD AT 1X - WELD DECAY AND PITTING AT 40X
SS304L - 904L	SLIGHT WELD DECAY ON 304L SIDE AT 1X - SMALL PITS ON WELD AT 40X
SS304L - I-600	WELD DECAY ON 304L SIDE AT 1X - 304L SIDE WELD DECAY AT 40X
SS304L - I-625	WELD PITTING AT 1X - 304L SIDE WELD DECAY AND PITTING AT 40X
SS304L - I-825	WELD PITTING AT 1X - WELD PITTING ON BOTH SIDES AT 40X
SS304L - G-3	SOME PITTING ON WELD AT 1X - PITS ON G-3 SIDE OF WELD AT 40X
SS304L - 20Cb-3	SOME PITTING, 304L SIDE WELD DECAY AT 1X - LARGE PITS AND DECAY ON BOTH SIDES AT 40X
SS304L - 7Mo+N	VISIBLE WELD PITTING AT 1X - LARGE PITS AND WELD DECAY ON BOTH SIDES AT 40X
SS304L - ES 2205	VISIBLE WELD PITTING AT 1X - PITTING AND DECAY OF WELD ON BOTH SIDES AT 40X
SS304L - F-255	WELD DECAY ON 304L SIDE AT 1X - PITTING AND DECAY OF WELD ON BOTH SIDES AT 40X

Table 11 Results of 60 Day Exposure to Beach Corrosion Site and 5 Sprays with 10 vol% HCl - Alumina

MATERIAL NAME	WGT LOSS(g)	CORR. RATE(MPY)	REMARKS - OBSERVATIONS AT 1X AND 40X
HASTELLOY C-22	0.0000	0.0000	NO PITTING, BRIGHT SHEEN AT 1X - NO PITTING, NO WELD DECAY AT 40X
INCONEL 625	0.0000	0.0000	NO PITTING, BRIGHT SHEEN AT 1X - NO PITTING, NO WELD DECAY AT 40X
HASTELLOY C-276	0.0001	0.0009	NO PITTING, BRIGHT SHEEN AT 1X - NO PITTING, NO WELD DECAY AT 40X
HASTELLOY C-4	0.0001	0.0009	NO PITTING, BRIGHT SHEEN AT 1X - NO PITTING, NO WELD DECAY AT 40X
ZIRCONIUM 702	0.0007	0.0080	STAINED, NO SHEEN AT 1X - UNIFORM CORROSION, NO PITTING AT 40X
INCOLOY G-3	0.0015	0.0140	NO PITTING, BRIGHT SHEEN AT 1X - MINOR PITTING, UNIFORM CORROSION OF WELD AT 40X
ES 2205	0.0121	0.0990	NO PITTING, NO SHEEN AT 1X - MODERATE SHALLOW PITTING AT 40X
FERRALIUM 255	0.0105	0.1100	NO PITTING, BRIGHT SHEEN AT 1X - UNIFORM CORROSION, PITTING AT WELD AT 40X
INCONEL 825	0.0124	0.1200	VISIBLE PITTING, SLIGHT SHEEN AT 1X - SLIGHT PITTING, MINOR PITTING OF WELD AT 40X
7Mo + N	0.0130	0.1387	NO PITTING, NO SHEEN AT 1X - UNIFORM CORROSION, SEVERE PITTING OF WELD AT 40X
SS304L	0.0147	0.1440	VISIBLE PITTING, SLIGHT SHEEN AT 1X - SHALLOW PITTING, UNIFORM DECAY OF WELD AT 40X
SS317L	0.0188	0.1870	VISIBLE PITTING, SLIGHT SHEEN AT 1X - SLIGHT PITTING/SOME DEEP, NO WELD DECAY AT 40X
INCONEL 600	0.0203	0.1350	VISIBLE PITTING, NO SHEEN AT 1X - SHALLOW PITTING, NO WELD DECAY AT 40X
SS316L	0.0247	0.2450	VISIBLE PITTING, NO SHEEN AT 1X - MODERATE PITTING, SLIGHT PITTING OF WELD AT 40X
SS304L	0.0277	0.2780	VISIBLE PITTING, NO SHEEN AT 1X - MODERATE PITTING, SOME PITTING OF WELD AT 40X
HASTELLOY B-2	0.0329	0.2800	NO PITTING AT 1X - FEW PITS WITH UNIFORM CORROSION, SOME WELD DECAY AT 40X
SS304LN	0.0348	0.3200	VISIBLE PITTING, NO SHEEN AT 1X - SLIGHT PITTING, SOME PITTING OF WELD AT 40X
20Cb-3	0.0431	0.4350	VISIBLE PITTING, SLIGHT SHEEN AT 1X - HEAVY PITTING/SOME DEEP, SEVERE PITTING OF WELD AT 40X
MONEL 400	0.0954	0.8710	NO PITTING, NO SHEEN AT 1X - UNIFORM CORROSION, NO PITTING AT 40X

Table 12 Results of 251 Day Exposure to Beach Corrosion Site and 13 Sprays with 10 vol% HCl - Alumina

MATERIAL NAME	WT LOSS(g)	CORR. RATE(MPY)	REMARKS - OBSERVATIONS AT 1X AND 40X
HASTELLOY C-22	[illegible]	[illegible]	NO PITTING, BRIGHT SHEEN AT 1X - NO PITTING, NO CORROSION AT 40X
INCONEL 625	0.0000	0.0000	NO PITTING, BRIGHT SHEEN AT 1X - NO PITTING, NO WELD DECAY AT 40X
HASTELLOY C-4	0.0001	0.0009	NO PITTING, BRIGHT SHEEN AT 1X - NO PITTING AT 40X
HASTELLOY C-276	0.0001	0.0009	NO PITTING, BRIGHT SHEEN AT 1X - VERY FEW SMALL PITS, NO WELD DECAY AT 40X
ZIRCONIUM 702	0.0014	0.0040	SLIGHT PITTING, SLIGHT SHEEN AT 1X - UNIFORM CORROSION, NO PITTING AT 40X
INCOLOY G-3	0.0034	0.0077	NO PITTING, BRIGHT SHEEN AT 1X - FEW SMALL PITS, UNIFORM WELD DECAY AT 40X
FERRALIUM 255	0.0139	0.0343	SLIGHT PITTING, MEDIUM SHEEN AT 1X - UNIFORM CORROSION, WELD DECAY AT 40X
ES 2205	0.0251	0.0490	SLIGHT PITTING, NO SHEEN AT 1X - SMALL PITS, UNIFORM CORROSION SEVERE WELD DECAY AT 40X
7Mo + N	0.0220	0.0561	SLIGHT PITTING, NO SHEEN AT 1X - UNIFORM CORROSION, LARGE DEEP PITS ON WELD AT 40X
INCONEL 825	0.0288	0.0680	VISIBLE PITTING, SLIGHT SHEEN AT 1X - MANY SMALL SHALLOW PITS, PITS ON WELD AT 40X
SS904L	0.0293	0.0685	VISIBLE PITTING, LOW SHEEN AT 1X - MANY SMALL PITS, WELD PITTING AT 40X
SS317L	0.0450	0.1069	VISIBLE PITTING, NO SHEEN AT 1X - SOME SMALL PITS, SURFACE CORROSION, WELD PITTING AT 40X
INCONEL 600	0.0497	0.1140	SLIGHT PITTING, NO SHEEN AT 1X - UNIFORM SMALL PITS, NO WELD DECAY AT 40X
SS316L	0.0566	0.1344	NUMEROUS PITS, NO SHEEN AT 1X - MANY SMALL PITS, SOME WELD PITTING AT 40X
SS304L	0.0612	0.1467	VISIBLE PITTING, NO SHEEN AT 1X - LARGE AND SMALL SHALLOW PITS, WELD DECAY AT 40X
SS304LN	0.0816	0.1768	VISIBLE PITTING, NO SHEEN AT 1X - SOME PITTING WITH DEPOSITS, WELD DECAY AT 40X
HASTELLOY B-2	0.1364	0.2177	NO PITTING, NO SHEEN AT 1X - FEW PITS, UNIFORM CORROSION, NO WELD DECAY AT 40X
20Cb-3	0.1074	0.2590	EXTENSIVE PITTING, NO SHEEN AT 1X - EXTENSIVE PITTING, SOME LARGE, UNIFORM WELD DECAY AT 40X
MONEL 400	0.2447	0.5340	NO PITTING, NO SHEEN AT 1X - NO PITTING, UNIFORM CORROSION AT 40X

Table 13 Results of 251 Day Exposure to Beach Corrosion Site and 13 Sprays with 10 vol% HCl - Alumina

Composite Galvanic Weld Specimens

MATERIAL NAME	REMARKS - OBSERVATIONS AT 1X AND 40X
SS304L - C-276	PITING ON 304L SIDE AT 1X - SEVERE WELD DECAY ON 304L SIDE AT 40X
SS304L - B-2	NO VISIBLE DECAY AT 1X - SLIGHT WELD DECAY ALONG 304L SIDE AT 40X
SS304L - C-4	NO VISIBLE DECAY AT 1X - SLIGHT WELD DECAY ON 304L SIDE AT 40X
SS304L - C-22	SLIGHT WELD DECAY ON 304L SIDE AT 1X - SLIGHT WELD DECAY ON 304L SIDE AT 40X
SS304L - M400	SLIGHT WELD DECAY ON 304L SIDE AT 1X - WELD DECAY ON 304L SIDE AT 40X
SS304L - 304LN	NO VISIBLE DECAY AT 1X - PITTING OF WELD ON BOTH SIDES AT 40X
SS304L - 316L	NO VISIBLE DECAY AT 1X - PITTING AND WELD DECAY ON BOTH SIDES AT 40X
SS304L - 317L	NO VISIBLE DECAY AT 1X - WELD DECAY AND PITTING ON 304L SIDE, PITTING ONLY ON 317L SIDE AT 40X
SS304L - 904L	NO VISIBLE DECAY AT 1X - UNIFORM WELD DECAY ON 304L SIDE AT 40X
SS304L - I-600	NO VISIBLE DECAY AT 1X - WELD DECAY ON 304L SIDE, SLIGHT DECAY ON I-600 SIDE AT 40X
SS304L - I-625	NO VISIBLE DECAY AT 1X - WELD DECAY AND PITTING ON 304L SIDE AT 40X
SS304L - I-825	NO VISIBLE DECAY AT 1X - WELD DECAY AND PITTING ON 304L SIDE, SLIGHT DECAY ON I-825 SIDE AT 40X
SS304L - G-3	NO VISIBLE DECAY AT 1X - WELD DECAY AND PITTING ON 304L SIDE, SLIGHT DECAY ON G-3 SIDE AT 40X
SS304L - 20Cb-3	VISIBLE PITTING ON WELD AT 1X - WELD DECAY AND PITTING ON BOTH SIDES AT 40X
SS304L - 7Mo+N	VISIBLE PITTING ON WELD AT 1X - HEAVY PITTING ALONG WELD AT 40X
SS304L - ES 2205	WELD DECAY ON 304L SIDE AT 1X - SEVERE WELD DECAY ON 304L SIDE, PITTING ON ES-2205 SIDE AT 40X
SS304L - F-255	WELD DECAY ON 304L SIDE AT 1X - SEVERE WELD DECAY ON 304L SIDE, SLIGHT PITTING ON F-255 SIDE AT 40X

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Table 14 Ferric Chloride Immersion Results
Autogenous Weld Samples

ALLOY	HOURS IMMERSED	RESULTS
HASTELLOY C-4	912	NO CORROSION
HASTELLOY C-22	72	NO CORROSION
HASTELLOY C-276	912	NO CORROSION
HASTELLOY B-2	72	UNIFORM CORROSION
INCONEL 600	72	MODERATE PITTING
INCONEL 625	912	NO CORROSION
INCONEL 825	72	SEVERE PITTING IN HEAT AFFECTED ZONE
INCO G-3	912	NO CORROSION
MONEL 400	72	UNIFORM CORROSION
ZIRCONIUM 702	72	MODERATE PITTING
SS 304L	72	SEVERE PITTING
SS 304LN	72	SEVERE PITTING
SS 316L	72	SEVERE PITTING
SS 317L	72	MILD PITTING AND WELD DECAY
SS 904L	72	NO CORROSION
20 Cb-3	72	SEVERE PITTING IN HEAT AFFECTED ZONE
7Mo + N	72	WELD DECAY
ES 2205	72	WELD DECAY
FERRALIUM 255	72	NO CORROSION

Table 15 Ferric Chloride Immersion Results
Samples Welded to 304L Stainless Steel

ALLOY	OBSERVATIONS ON CANDIDATE ALLOY	ALLOY	OBSERVATIONS ON CANDIDATE ALLOY
HASTELLOY C-4	NO CORROSION	SS 304LN	SEVERE PITTING
HASTELLOY C-22	NO CORROSION	SS 316L	SOME PITTING
HASTELLOY C-276	NO CORROSION	SS 317L	NO CORROSION
HASTELLOY B-2	UNIFORM CORROSION	SS 904L	NO CORROSION
INCONEL 600	UNIFORM CORROSION	20Cb 3	SLIGHT PITTING
INCONEL 625	NO CORROSION	7 Mo + N	NO CORROSION
INCONEL 825	NO CORROSION	ES 2205	NO CORROSION
INCO G-3	NO CORROSION	FERRALIUM 255	NO CORROSION
MONEL 400	UNIFORM CORROSION		

NOTE: All samples were immersed for 72 hours.
In each case, the 304L portion of the sample suffered severe pitting.

APPENDIX A

Table A1 Summary of Electrochemical Results

ALLOY	3.55% NaCl + 0.1N HCl	3.55% NaCl + 1.0N HCl
HASTELLOY C-4	Stable,Noble Ecorr Very Small Hysteresis Area Excellent Pitting Resistance	Stable,Noble Ecorr Very Small Hysteresis Area Excellent Pitting Resistance
HASTELLOY C-22	Stable,Noble Ecorr Very Small Hysteresis Area Excellent Pitting Resistance	Stable,Noble Ecorr Very Small Hysteresis Area Excellent Pitting Resistance
HASTELLOY C-276	Stable,Fairly Noble Ecorr Very Small Hysteresis Area Excellent Pitting Resistance	Stable,Fairly Noble Ecorr Very Small Hysteresis Area Excellent Pitting Resistance
HASTELLOY B-2	Stable,Slightly Active Ecorr Uniform Corrosion	
INCONEL 600	Unstable,Fairly Active Ecorr Uniform Corrosion & Pitting	
INCONEL 625	Stable,Very Noble Ecorr Small Hysteresis Area Very Good Pitting Resistance	Stable,Very Noble Ecorr Very Small Hysteresis Area Excellent Pitting Resistance
INCONEL 825	Stable,Noble Ecorr Large Area,Low Pitting Resistance	
INCO G-3	Stable,Noble Ecorr Excellent Pitting Resistance	Very Noble Ecorr Excellent Pitting Resistance
MONEL 400	Stable,Slightly Active Ecorr Uniform Corrosion	
ZIRCONIUM 702	Stable,Fairly Active Ecorr Low Resistance To Pitting	
SS 304L	Fairly Stable,Active Ecorr Poor Resistance To Pitting	Fairly Stable,Active Ecorr Uniform Corrosion
SS 304LN	Unstable,Active Ecorr Large Hysteresis Area Poor Pitting Resistance	
SS 316L	Fairly Stable,Slightly Active Ecorr Large Hysteresis Area Very Poor Pitting Resistance	
SS 317L	Stable,Slightly Active Ecorr Large Hysteresis Area Very Poor Pitting Resistance	
SS 904L	Stable,Noble Ecorr Some Pitting Resistance	Fairly Stable,Active Ecorr Poor Pitting Resistance
20 Cb-3	Fairly Stable,Slightly Active Ecorr Extremely Poor Resistance To Pitting	
7Mo + N	Stable,Noble Ecorr Moderate Pitting and Uniform Corrosion	Stable,Active Ecorr Some Pitting and Uniform Corrosion
ES 2205	Stable,Noble Ecorr Moderate Pitting	Active,Fairly Stable Ecorr Some Pitting,Uniform Corrosion
FERRALIUM 255	Stable,Noble Ecorr Small Hysteresis Area Very Good Pitting Resistance	Stable,Active Ecorr Good Pitting Resistance

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