Corrosion of Candidate Materials in Lake Rotokawa Geothermal Exposure

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Corrosion of Candidate Materials in Lake Rotokawa Geothermal Exposure

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Abstract

Corrosion rates were determined for CDA 613, CDA 715, A-36 carbon steel, 1020 carbon steel, and Alloy 825 flat coupons which were exposed to geothermal spring water at Paraiki site number 9 near Lake Rotokawa, New Zealand. Qualitative observations of the corrosion performance of Type 304L stainless steel and CDA 102 exposed to the same environment were noted.

CDA 715, Alloy 825, 1020 carbon steel, and other alloys are being considered for the materials of construction for high-level radioactive waste containers for the United States civilian radioactive waste disposal program. Alloys CDA 613 and CDA 102 were tested to provide copper-based materials for corrosion performance comparison purposes. A36 was tested to provide a carbon steel baseline material for comparison purposes, and alloy 304L stainless steel was tested to provide an austenitic stainless steel baseline material for comparison purposes.

In an effort to gather corrosion data from an environment that is rooted in natural sources of water and rock, samples of some of the proposed container materials were exposed to a geothermal spring environment. At the proposed site at Yucca Mountain, Nevada, currently under consideration for high-level nuclear waste disposal, transient groundwater may come in contact with waste containers over the course of a 10,000-year disposal period. The geothermal springs environment, while extremely more aggressive than the anticipated general environment at Yucca Mountain, Nevada, could have similarities to the environment that arises at selected local sites on a container as a result of crevice corrosion, pitting corrosion, microbiologically influenced corrosion (MIC), or the concentration of the ionic species due to repetitive evaporation or boiling of the groundwater near the containers.

The corrosion rates were based on weight loss data obtained after six weeks exposure in a 90 °C, low-pH spring with relatively high concentrations of SO_4^{2-} and Cl^- .

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Introduction

Three alloys being considered for high-level radioactive waste containment were part of a broader group of alloys exposed to a geothermal spring environment at Lake Rotokawa, New Zealand to evaluate their relative corrosion resistance. The geothermal field, located at Paraiki Site Number 9, provides a naturally produced aggressive environment of high temperature, low pH, and corrosive ionic species.¹ The environment in the hot springs is of particular interest because of its similarities with conditions which may present themselves at local corrosion sites on the waste containers during the 10,000-year controlled-release period of waste disposal. The hot spring has a temperature near 90 °C, acidic conditions (pH 2), and high concentrations of SO_4^{2-} and Cl^- ions, as well as silica and other inorganics.

The site under consideration for the potential United States civilian high-level radioactive waste repository is located at Yucca Mountain, Nevada. As a result of the radioactive decay of materials that would be contained within the waste containers at Yucca Mountain, the temperature of the near-field environment surrounding the containers might be as high as 250 °C initially and decline to 90 °C or less as the thermal output in the near-field decreased. Naturally or thermally driven vadose groundwater flows may enter the elevated-temperature, near-field environment and produce high-humidity conditions. Thus, the container could be exposed to corrosive conditions as a result of the vadose water interaction with the container. Concentration of ionic species in the bulk water, including SO_4^{2-} and Cl^- , could rise to the saturation point due to repetitive evaporation effects or reflux of water in the near field. Yucca Mountain groundwater

contains only small amounts of SO_4^{2-} and Cl^- in the bulk environment.² However, hydrological and geochemical processes over thousands of years could bring about large increases in the concentration of these anions near the containers. Low-pH conditions are not uncommon locally as a result of differential oxygen concentrations such as would occur at favorable crevice sites on the waste containers.³ The resulting oxygen concentration cell in a crevice could drive down the pH and create a much more aggressive local environment. Low-pH conditions might also be present as a result of MIC. Microbial metabolic products tend to produce low-pH chemistry; an example is hydrogen sulfide, produced by sulfate reducing bacteria.⁴

Alloy 825, CDA 715, and 1020 carbon steel are three of the alloys on the current list of candidate materials for high-level radioactive waste containment.⁵ One of the container designs envisions a relatively thick carbon steel outer container and a reduced thickness corrosion-resistant inner container. Another proposed design incorporates an equally thick copper-nickel alloy outer container and a corrosion-resistant alloy inner container. Alloy 825 is one of the candidate corrosion-resistant materials, CDA 715 one of the copper-nickel materials, and 1020 steel is a carbon steel material. CDA 102 copper, A36 carbon steel, and 304L stainless steel were tested for comparison purposes.

The Paraiki site, with elevated levels of SO_4^{2-} and Cl^- , low-pH chemistry, and 90 °C temperature presents a very aggressive environment that one might expect to be repository-relevant only on a reduced scale, i.e., at crevice sites and MIC sites where the rock and waste container interact. Although the bulk environment at Yucca Mountain is significantly more benign than that of Paraiki Site Number 9 spring water, the geothermal spring water may serve as a worst case environment of crevice, pitting, or MIC sites on a

container. Therefore, the corrosion rates are not indicative of the rates that may result by emplacing coupons in the Yucca Mountain site, but rather, are simply a gauge for judging the relative corrosion resistance of alloys in an extremely aggressive naturally evolved environment; an environment that may be relevant only to local corrosion sites on a container and not on the greater part of the container. The observed corrosion rates and the physical examination of the coupons are summarized in this report.

Data from this exposure will aid in the material selection decision for nuclear waste containers by supplementing the data derived from the program of long-term testing of candidate materials currently underway at Lawrence Livermore National Laboratory (LLNL).

Materials

Seven alloys were tested, including materials from the austenitic stainless steels, carbon steels, copper-based, and nickel-based austenitic systems. As already mentioned, three of the alloys, CDA 715, Alloy 825, and 1020 carbon steel are included in the current candidate list for materials under consideration for high-level radioactive waste containment for the United States civilian radioactive waste program. The remaining five alloys are similar to other materials in the current candidate list. The alloys and their compositions are shown in Table 1.

Table 1. Alloys Exposed to Geothermal Conditions

<u>Alloy</u>	<u>UNS Number</u>	<u>Nominal Composition</u>
A-36 Carbon Steel	K02600	C 0.26 max; Mn 0.80-1.20; P 0.04 max ; S 0.05 max .
1020 Carbon Steel	G10200	C 0.22 max; Mn 0.6-1.20; P 0.035 max; S 0.040 max; Si 0.15-0.40; Fe remainder.
CDA 613 (Copper-Based)	C61300	Al 6.0-7.5; Fe 2.0-3.0 ; Mn 0.2 max; Ni 0.15 max; P .015 max ; Pb 0.01 max ; Si 0.10 max; Sn 0.2-0.5 ; Zn 0.10 max.
CDA 102 (Copper-Based)	C10200	Oxygen Free 99.95 Cu min ;.
CDA 715 (Copper-Based)	C71500	Ni 29.0-33.0; Cu balance; Mn 1.0 max; Pb 0.02 max; Fe 0.4-1.0; Zn 0.5 max; C 0.05 max; P 0.02 max; S 0.02 max
304L Austenitic Stainless Steel	S30403	C 0.03 max; Cr 18.0-20.0; Mn 2.0 max; Ni 8.0-12.0; P 0.045 max; S 0.030 max; Si 1.00 max.
Alloy 825 (Nickel-Based)	N08825	Ni 38.0-46.0 ; Cr 19.5-23.5 ; Mo 2.5-3.5 ; Fe balance ; Cu 1.5-3.0 ; Ti 0.6-1.2 ; Mn 1.0 max ; C 0.05 max ; Si 0.5 max ; S 0.03 max ; Al 0.2 max.

Experimental

Test Specimens

Samples of U-bends (nominal thickness 1-mm) prepared according to the general requirements of ASTM G46 were used to evaluate stress corrosion resistance.⁶ A pair of 50-mm by 50-mm by 3-mm panels, bolted together to form a crevice contact, were used in the evaluation of crevice corrosion resistance. 25-mm by 50-mm flat coupons (1.8-mm nominal thickness) were used to measure weight loss for use in the calculation of corrosion rates as well as characterization of general corrosion.

To minimize space occupied in the geothermal spring not all specimen types from each alloy were represented in the test matrix. Flat coupons of Alloys A36 and 1020 carbon steel, CDA 613, CDA 715, and 825 were exposed for weight loss determinations. U-bend samples from Alloys CDA 102, CDA 613, and 304L were evaluated for stress corrosion resistance, and a crevice assembly from Alloy CDA 613 was evaluated for crevice corrosion resistance.

The samples were tested in a surface-polished 120-grit condition to eliminate the effects of differences in mill finish of the various alloys. The samples were cleaned in isopropyl alcohol prior to shipment to the Lake Rotokawa area.

Geothermal Environment

The volume of the spring water at Paraiki Site Number 9 was approximately 400 liters, and the pool was about 0.6 m deep. The natural gas flow rate through the spring was relatively low and the release was described as a gentle bubbling process.⁷ The

temperature of the spring was 89 °C, and the pH was 2.07. Elemental concentrations in the spring water are given below:

Paraiki Site Number 9 Elemental Concentration mg/L

Cl	SO ₄	Br	Si O ₂
431	1130	1.26	324

Using a polyester string, the specimens were suspended vertically near the bottom of the spring and were exposed for six weeks. After the specimens were removed from the spring, they were dried, packaged in plastic bags, and returned to LLNL for analysis.

Results and Discussion

Upon arrival at LLNL the samples were visually examined before and after cleaning. Selected cross sections were obtained for metallographic examination. Weight loss determinations of the flat 25-mm by 50-mm specimens were made after chemical cleaning with appropriate agents.

As-Received Examination

A visual examination of each specimen was made after carefully removing the coupons from the plastic shipping bags. The results of this examination are presented in Table 2. All of the carbon steel and Type 304L stainless steel specimens had completely dissolved in the geothermal spring during the six-week exposure. The severe general corrosion attack on the remaining alloys produced large quantities of corrosion product and masked any attack due to crevice corrosion or stress corrosion cracking. The base

metal surface was impossible to observe because of the excessive corrosion products present on all alloys. Therefore, the as-received examination was simply observation of the corrosion products.

Although the corrosion attack is severe on all samples, the morphology of the corrosion product is distinct between alloys. Surface features on the Alloy 825 specimens consisted of substantial amounts of large flakes of corrosion product that appeared to be the result of an exfoliated-mode attack. The corrosion product morphology suggests complete surface layer removal as general corrosion proceeds.

The CDA 613 and CDA 102 corrosion products had very fine consistencies, granular morphologies with uniform size distribution. Although the corrosion products of the CDA 613 and CDA 102 are similar, the extents of attack are markedly different. Since no weight-loss coupons were tested for alloy CDA 102, comparisons are based on qualitative observations of the alloys. The size of the CDA 102 U-bend sample, as a result of more severe general corrosion attack, is noticeably smaller than that of the CDA 613 U-bend. Although weight loss data were not obtained for CDA 102, the comparative general corrosion attack of CDA 102 and CDA 613 U-bends suggests a higher corrosion rate for CDA 102. The CDA 715 corrosion product exhibits a mix between very fine granular and flaky morphology. The flaky corrosion product appears to be similar to the Alloy 825 corrosion product. Perhaps the thirty-percent nickel content in CDA 715 contributes to the similarity in corrosion product morphology with that of the nickel-rich Alloy 825.

One interesting observation is the variation in the attack on the Type 316 stainless steel loading bolts used in the U-bend and crevice specimens. The bolt/nut assembly used for stressing the CDA 102 U-bend, isolated from the specimen with ceramic washers, was

nearly pristine and did not suffer any corrosion damage. The isolated Type 316 stainless steel bolts used in loading the CDA 613 U-bend coupon, however, did suffer some minor corrosion attack. The attack was relatively cosmetic and the surfaces of the threads were intact with some staining and minor pitting. Interestingly, only one nut appeared to be corroded (the bolted assembly contains two nuts butted up against each other), while the other was pristine. The isolated bolt/nut assembly on the CDA 613 crevice coupon suffered more severe corrosion attack, and the bolts and nuts were corroded to the extent that the integrity of a tight crevice assembly was compromised. This anomaly of varying degrees of attack on Type 316 stainless steel loading bolts from one specimen to another may be explained if we examine corrosion product accumulation on a specimen. Perhaps the bolt/nuts were electrically coupled to the metal sample via the excessive corrosion product in contact with the specimen and the bolts. This may have caused galvanic coupling between the bolt and specimen, leading to varying results.

Post-Cleaning Examination

Following the as-received specimen examination, the specimens were cleaned in acidified solutions that are described in the requirements of ASTM G1.⁸ The acid cleaning procedures from one alloy to another differ only in the acid used. All samples were cleaned at room temperature for three minutes in the appropriate acidified solution, rinsed in distilled water while scrubbing with a nylon brush, and air dried. CDA 613 and CDA 715 specimens were cleaned in a 10-percent by volume concentrated sulfuric acid solution, and Alloy 825 specimens were cleaned in a 15-percent by volume concentrated

hydrochloric acid solution. The visual examination of each specimen was performed after the prescribed cleaning, and results are presented in Table 3.

The corrosion attack on all three Alloy 825 flat weight-loss specimens was severe. The surfaces of two of the three specimens reveal a random pattern of variable depths of attack. The surfaces of these specimens are not flat, but instead appear very rough. These two specimens have discolored metal (brown and black) islands which are peppered about the surface and below which lies a shiny silver-colored base metal layer, which is relatively smooth in texture. The third specimen has a very shiny surface with a wavy morphology. The depth of attack varies on this specimen, and the surface appears to be filled with large blisters. The shiny color is not the same as is observed before testing. A gray color is typical of the surface prior to testing. Weight loss data indicate that the specimen with the shiny, wavy surface is the one that experienced the most severe attack. The dark-colored islands of metal described above may be systematically dissolved as corrosion attack proceeds, leaving a shiny surface behind as the islands of metal go into solution.

The CDA 613 samples suffered less corrosion attack than any of the other alloys. The surfaces of the U-bend, crevice, and weight-loss coupon are all very similar, appearing clean and smooth, with only mottled staining present. The U-bend sample was the most severely attacked, showing some minor pitting; however, the pitting was very shallow. No stress-corrosion cracking or crevice corrosion attack was observed. The corrosion attack was characterized as uniform, general corrosion attack with no significant surface defects resulting from the exposure.

Two weight-loss specimens of Alloy CDA 715 suffered corrosion attack that is characterized in intensity as between the corrosion attack of Alloy CDA 613 and 825, but more closely paralleling the performance of Alloy 825. The surface of the CDA 715 looks like that of a specimen that experienced erosion-corrosion attack. However, discussions with staff at the Paraiki site, and their observation of a rather gentle bubbling of the spring water, would seem to discount this possibility. Nonetheless, the surface looks as though it melted, with flowing features about the surface, and is typical of the appearance of a specimen that has experienced erosion-corrosion attack. The depth of attack varies slightly across the specimen, the varying depth corresponding to the melted appearance of the surface. There are no islands of metal present as there were on Alloy 825; rather, there is just a uniform melted appearance about the samples. Both CDA 715 specimens have similar surface attack features and cannot be distinguished from one another.

Optical Metallography

As-Polished

Cross sections of Alloys CDA 613, CDA 715, and 825 are presented in Figures 1, 2, and 3, respectively. The samples are sectioned across the 25-mm width of the flat weight-loss coupons. The cross section examinations are as-polished to a one-micron finish. For comparison purposes a witness specimen, that has not been tested, was placed in the same metallographic mount to provide a visual contrast of the extent of attack through the thickness. The cross sections suggest different depths of attack among these three alloys.

The Alloy CDA 613 specimen shows the least amount of attack and is uniform in depth of corrosion attack throughout the cross section (see Figure 1). No localized attack is observed that penetrates preferentially into the depth of the specimen.

Alloy CDA 715 shows significant depth of attack considering the short exposure time; however, the attack is fairly uniform and rises and falls gently across the width of the specimens (Figure 2).

The Alloy 825 specimen (1 of 3 specimens tested) selected for sectioning had the most severe corrosion attack. Weight-loss data suggest the corrosion attack on this specimen was more than twice that on the other two Alloy 825 specimens. Therefore, this cross section is representative of the worst-case corrosion attack. The corrosion attack is extensive across the width of the specimen. Depth of attack varies across the width of the specimen and is approximately two-thirds to three-fourths the original thickness of the specimen. The depth of attack appears to rise and fall like standing waves (Figure 3). No localized attack was observed that penetrates preferentially into depth; however, general corrosion attack produces a significant range in depth of attack. Although the other two weight-loss coupons of this alloy were not cross sectioned, we could expect somewhat less depth of attack because of the substantially reduced weight loss of these specimens (about one half the weight-loss of the first one).

Etched Cross Sections

Chemically etched cross sections of alloys CDA 613, CDA 715, and Alloy 825 are presented in Figures 4, 5, and 6, respectively. In order to understand the substantial differences in the morphology of the corrosion product among the three alloys,

representative cross sections were chemically etched to reveal the grain structures. The cross sections are the same as those previously examined in the as-polished condition. The photographs were obtained from the cross sections of the tested samples.

The CDA 613 cross section was etched in a solution of 75-percent lactic acid and 25-percent concentrated nitric acid. The etchant revealed an equiaxed grain structure with extremely small grains (Figure 4). There are no apparent cold-work etch-pit lines present as was observed in some of the other alloys. The grain structure was homogeneous with no significant change in size of grains through the thickness of the specimen.

The CDA 715 cross section was etched in a solution containing forty two grams of copper chloride, ninety-eight ml of concentrated hydrochloric acid, and two ml of concentrated nitric acid. Nomarski Interference Contrast (NIC) was used to enhance the grain structure image (Figure 5). The etchant revealed an equiaxed grain structure; however, longitudinal roll lines suggest a cold-worked grain structure. In addition, the typical grain size present in the CDA 715 structure is significantly larger than that in the CDA 613.

The Alloy 825 cross section was etched in a solution containing 42 grams of copper chloride, 98 ml of concentrated hydrochloric acid, and 2 ml of concentrated nitric acid. NIC was used to enhance the grain structure image (Figure 6). The etchant revealed an equiaxed grain structure with some longitudinal cold-work lines present, probably as a result of rolling. The cold-work lines are not as apparent as those present in the CDA 715. The grain size is nearly the same as in the CDA 715, but much larger than the grain size of the CDA 613. Overall, the Alloy 825 cross section is very similar to the CDA 715 cross section, having comparable grain size and longitudinal cold-work lines.

Corrosion Rate Calculations

Weight loss of specimens from alloys Alloy 825, CDA 613, and CDA 715 were used to calculate corrosion rates using the relation given in ASTM G1,

$$\frac{K \times W}{A \times T \times D} = \text{Corrosion Rate (mm/year)}$$

where:

K = a dimension dependent constant, 8.76×10^4 ,

W = mass loss in grams,

A = area in mm^2 ,

T = exposure time in years

D = density in g/mm^3 .

Samples of Alloys of 1020 and A-36 carbon steel were also exposed for weight-loss determinations; however, the specimens dissolved in the hot spring environment. Therefore, the corrosion rates for the carbon steel samples are denoted as minimum corrosion rate values and for the sake of calculation assumed to be completely dissolved at precisely the time they are removed from the hot spring (six weeks). The carbon steel samples may very well have dissolved much sooner, but there is no way to verify this. The compilation of corrosion rates for the tested alloys is presented in Table 4.

As expected, the carbon steel alloys of 1020 and A-36 steel showed the highest corrosion rates. As stated earlier, these are minimum values, because of the unknown time for complete dissolution of the samples.

Three Alloy 825 specimens showed corrosion rates ranging from 1.33 to 4.56 mm per year. One of the specimens produced markedly higher weight loss than the other two specimens, which may suggest a more aggressive local environment in the hot spring. The overall performance of this material is rather poor, considering the short exposure time.

A single specimen of Alloy CDA 613 exhibited a corrosion rate of 0.77 mm per year, the smallest corrosion rates of all alloys tested. Although replicate specimens of this alloy were not tested, the weight-loss result is consistent with the superior corrosion performance of the CDA 613 U-bend specimen versus the CDA 102 U-bend.

Two specimens of Alloy CDA 715 had corrosion rates of 2.32 and 2.34 mm per year, respectively. The resistance to general corrosion for alloy CDA 715 is found to be between those of Alloy CDA 613 and Alloy 825 and its performance is closer to the performance of Alloy 825. The high corrosion rate of this material in the Paraiki hot spring environment would not be considered satisfactory. The material performance is that of a freely corroding specimen.

Conclusions

The corrosion performance of Alloy CDA 613 is superior to that of the other alloys tested in the geothermal spring environment at Lake Rotokawa, Paraiki Site Number 9. However, the 0.77-mm/year corrosion rate is still significant, and is not trivial. The corrosion attack on Alloy CDA 613, which was masked under the fine, granular corrosion product, produced a rather smooth specimen surface, much like it was before the exposure. The fine corrosion product is consistent with the extremely small grain size predominant in the grain structure. There is little evidence of severe degradation of the

surface as was present in all the other alloys. The worst of the attack appears to be some minor pitting on the U-bend sample and mottled staining of the crevice and weight loss coupons. Longer exposure may well have produced a declining corrosion rate, and for this reason, a second set of tests should be conducted with extended exposure times in order to determine the corrosion rate as a function of time. Since the mode of attack is driven by general corrosion, there is no need to test crevice or U-bend specimens in the future.

Alloys 825 and CDA 715 performed so poorly that further testing of these alloys, in the present metallurgical condition, is not warranted in this environment. Results from weight loss determinations for Alloys 825 and CDA 715 indicated accelerated corrosion rates. The surfaces of both alloys were severely attacked, and the result was permanent alteration, causing them to appear much different from the initial surfaces. The similar grain structures of these two materials may have been a factor in producing the similar attack. Both alloys appear to have a longitudinal cold-worked grain structure that may have provided the impetus for exfoliation-type attack. The resulting surfaces are attacked to such an extent that significant differences in depth of attack occurred across the width of a 25-mm sample. The integrity of the materials is questionable after only six weeks of exposure.

Samples of Type 304L stainless steel and carbon steel dissolved before the end of the six week exposure period. The performance of these alloys is so poor that further testing in this environment is certainly not warranted.

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Tested

Untested

Figure 1. After cleaning. As-polished CDA 613 exposed to Paraiki hot spring for six weeks. 15X

Tested

Untested

Figure 2. After cleaning. As-polished CDA 715 exposed to Paraiki hot spring for six weeks. 15X

Figure 3. After cleaning. As-polished Alloy 825 exposed to Paraiki hot spring for six weeks. 15X

Figure 4. Etched CDA 613 exposed to Paraiki hot spring for six weeks. 500x

Figure 5. Etched CDA 715 exposed to Paraiki hot spring for six weeks. 500x

Figure 6. Etched Alloy 825 exposed to Paraiki hot spring for six weeks. 500x

Table 2. Corrosion Evaluation of As-Received Samples After Six Weeks Exposure to Lake Rotokawa Hot Springs Paraki Site 9

<u>Alloy</u>	<u>Identification</u>	<u>Specimen Type</u>	<u>Description of Corrosion Attack</u>
Alloy 825	I-825S 262	25-mm x 50-mm Flat Weight Loss	Severe corrosion attack; appears to be exfoliation-type attack with substantial depth. Fairly uniform attack.
Alloy 825	I-825S 263	25-mm x 50-mm Flat Weight Loss	Severe corrosion attack; appears to be exfoliation-type attack with substantial depth. Fairly uniform attack.
Alloy 825	I-825S 266	25-mm x 50-mm Flat Weight Loss	Most severe corrosion attack with only remnants of exfoliation-type attack, much of the exfoliated surface dissolved away. Fairly uniform attack.
CDA 613	CDA 613-19	25-mm x 50-mm Flat Weight Loss	Very fine, granular type corrosion product with significant amount of corrosion product. Uniform attack.
CDA 613	CDA 613 46-22	U-Bend	Very fine, granular type corrosion product with significant amount of corrosion product. Uniform attack. No evidence of SCC. Minor pitting attack and dark staining on 316 SS loading bolt.
CDA613	CDA 613 19/ CDA 613 20	Dual specimen; bolted 50-mm x 50-mm Crevice	Very fine, granular type corrosion product with significant amount of corrosion product; very uniform attack. No crevice corrosion observed. 316 stainless assembly bolts severely corroded.
CDA 715	CDA 715-35	25-mm x 50-mm Flat Weight Loss	Mixed corrosion product. Both granular and flaky, exfoliation-type corrosion. Substantial depth of attack at exfoliated areas, somewhat less at granular areas.
CDA 715	CDA 715-34	25-mm x 50-mm Flat Weight Loss	Mixed corrosion product. Both granular and flaky, exfoliation-type corrosion. Substantial depth of attack at exfoliated areas, somewhat less at granular areas.
CDA 102	CDA 102 46-24	U-Bend	Very fine, granular corrosion product with significant amount of corrosion product. Very uniform attack. No evidence of SCC on U-bend. No significant attack on isolated 316 SS loading bolt.
304L	304L 46-8	U-Bend	Sample dissolved. Nothing to examine.
A-36 Steel	A-36 622	25-mm x 50-mm Flat Weight Loss	Sample dissolved. Nothing to examine.
1020 Steel	1020 740	25-mm x 50-mm Flat Weight Loss	Sample dissolved. Nothing to examine.
1020 Steel	1020 743	25-mm x 50-mm Flat Weight Loss	Sample dissolved. Nothing to examine.
1020 Steel	1020 744	25-mm x 50-mm Flat Weight Loss	Sample dissolved. Nothing to examine.
1020 Steel	1020 74- ⁽¹⁾	25-mm x 50-mm Flat Weight Loss	Sample dissolved. Nothing to examine.

(1) - Unknown last digit

Table 3. Corrosion Evaluation of Post-Test Cleaned Samples After Six Week Exposure to Lake Rotokawa Hot Springs Paraiki Site 9

<u>Alloy</u>	<u>Identification</u>	<u>Specimen Type</u>	<u>Description of Corrosion Attack</u>
Alloy 825	I-825S 262	25-mm x 50-mm Flat Weight Loss	Combination of black, brown , and silver-colored surface. Very rough surface with varying degrees of depth of attack.
Alloy 825	I-825S 263	25-mm x 50-mm Flat Weight Loss	Combination of black, brown , and silver-colored surface; mostly silver. Very rough surface with varying degrees of depth of attack.
Alloy 825	I-825S 266	25-mm x 50-mm Flat Weight Loss	Shiny, silver color,relatively clean surface with few spotted areas of deep pits. Overall surface characteristic is not flat but rather wavy, probably some undermining degradation below the outer surface layer.
CDA 613	CDA 613-19	25-mm x 50-mm Flat Weight Loss	Fairly clean, smooth surface with little or no pitting. Color same as starting color, yellow bronze. Mottled stain appearance. No depth of attack observed in the cleaned condition.
CDA 613	CDA 613 46-22	U-Bend	Fairly clean surface, a little rough with uniform attack. Color same as starting color, yellow bronze. Mottled stain appearance. No depth of attack observed in the cleaned condition.No SCC observed but one nut on loading assembly is pitted.
CDA613	CDA 613 19/ CDA 613 20	Dual Specimen; Bolted 50-mm x 50-mm Crevice	Fairly clean, smooth surface with some pitting near the four bolt locations. Color same as starting color, yellow bronze. Mottled stain appearance. No depth of attack observed in the cleaned condition.
CDA 715	CDA 715-35	25-mm x 50-mm Flat Weight Loss	Appears to be erosion-corrosion attack. Sample almost appears to be melted, with flowing metal on surface. Mottled staining of surface. Fairly rough surface with varying degrees of depth of attack. Silvery surface color.
CDA 715	CDA 715-34	25-mm x 50-mm Flat Weight Loss	Appears to be erosion-corrosion attack. Sample almost appears to be melted, with flowing metal on surface. Mottled staining of surface. Fairly rough surface with varying degrees of depth of attack. Silvery surface color.
CDA 102	CDA 102 46-24	U-Bend	Fairly clean surface, light uniform pitting attack. Color is oxidized copper. Mottled stain appearance. No depth of attack observed in the cleaned condition.No SCC observed. No corrosion on 316 SS load bolt assembly.
304L	304L 46-8	U-Bend	Sample dissolved. Nothing to examine.
A-36 Steel	A-36 622	25-mm x 50-mm Flat Weight Loss	Sample dissolved. Nothing to examine.
1020 Steel	1020 740	25-mm x 50-mm Flat Weight Loss	Sample dissolved. Nothing to examine.
1020 Steel	1020 743	25-mm x 50-mm Flat Weight Loss	Sample dissolved. Nothing to examine.
1020 Steel	1020 744	25-mm x 50-mm Flat Weight Loss	Sample dissolved. Nothing to examine.
1020 Steel	1020 74- ⁽¹⁾	25-mm x 50-mm Flat Weight Loss	Sample dissolved. Nothing to examine.

(1)-Unknown last digit

Table 4. Corrosion Rates of Alloys Exposed to Pairiki Site 9 at Lake Rotokawa, New Zealand

Alloy	Identification	Length	Width	Thickness	Mounting Hole Diameter	Weight Initial	Weight Final	Weight Loss	Exposure Duration	Surface Area	Density	Corrosion Rate
		cm	cm	cm	cm	g	g	g	hr	sq cm	g/cm ³	mm/y
Alloy 825	I-825S 266	5.103	2.578	0.165	0.617	16.2177	4.1642	12.0535	1008	28.25	8.14	4.56
Alloy 825	I-825S 262	5.098	2.565	0.191	0.584	16.3297	12.7813	3.5484	1008	28.54	8.14	1.33
Alloy 825	I-825S 263	5.090	2.527	0.165	0.632	16.0487	10.7138	5.3349	1008	27.62	8.14	2.06
CDA 613	CDA 613-19	5.121	2.563	0.188	0.620	16.4704	14.4719	1.9985	1008	28.53	7.89	0.77
CDA 715	CDA 715-35	5.121	2.581	0.183	0.620	19.2286	12.3342	6.8944	1008	28.64	8.94	2.34
CDA 715	CDA 715-34	5.121	2.586	0.188	0.625	19.8294	12.9733	6.8561	1008	28.77	8.94	2.32
1020 Steel	1020 740 (1)	5.093	2.563	0.201	0.620	17.1542	0	17.1542	1008	28.57	7.87	6.63
1020 Steel	1020 743 (1)	5.093	2.588	0.191	0.627	17.2003	0	17.2003	1008	28.67	7.87	6.62
1020 Steel	1020 744 (1)	5.093	2.553	0.196	0.615	17.0959	0	17.0959	1008	28.40	7.87	6.65
1020 Steel	1020 74-* (1)	Unknown	Unknown	Unknown	Unknown	Unknown	0	Unknown	1008	Unknown	7.87	Unknown
A-36 Steel	A-36 622 (1)	5.110	2.540	0.183	0.625	15.9328	0	15.9328	1008	28.15	7.6	6.47

(1) - Sample dissolved and was not on the wire when removed from hot spring. Corrosion rates are minimum values due to unknown time-to-complete dissolution.

* - Sample Identification reported as 1020 74; last digit missing. Unknown specimen identification and therefore many parameters are unknown