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Preliminary Corrosion Testing of Nickel Alloys in Simulated High Temperature Geothermal Environment

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ABSTRACT

To explore the potential of obtaining more energy output per geothermal well, deep drilling (~5000 m depth) of geothermal wells was started in Iceland few years ago, within the Iceland Deep Drilling Project (IDDP). The first IDDP well produced superheated steam at high temperatures and pressures during its lifetime. The geothermal steam contained acidic gas components including H_2S, HCl and CO_2, which upon condensation became extremely corrosive with pH level of 2.5-3.

To gain more understanding of the corrosion behavior of several alloys at saturation and superheated conditions in deep geothermal wells, preliminary testing of highly corrosion resistant nickel alloys, UNS N06625 and N10276, was done in simulated geothermal environment. The UNS N10276 and UNS N06625 were tested 350°C in flow through reactor with a pressure of 10 bar for a 1 and 3 week exposures. The UNS N06625 was additionally tested at 180°C with same pressure and exposure time conditions. The simulated environment was composed of a generated steam containing H_2S, HCl and CO_2 gases at the given temperature and pressure with a pH level of 3 upon condensation.

The UNS N06625 performed very well at 180°C where corrosion rate was measured insignificant at 1 week exposure but very low at 3 weeks exposure. At 350°C the corrosion rate of UNS N06625 was lower than UNS N10275, but corrosion rate for both alloys were though higher than generally accepted. Microstructural and chemical analysis revealed localized corrosion damage and corrosion products cracks in UNS N06625 but no localized damage in UNS N10276. High molybdenum content in UNS N10275 is possible the reason for better localized corrosion resistance

The future work is to develop the tests and the testing facility further i.e. test more alloys at higher temperature and pressure levels and investigate the effect of SiO_2 scaling on under deposit and localized corrosion of the alloys.

1. INTRODUCTION

During Icelandic Deep Drilling Project no.1 (IDDP-1) in situ weight loss experiment was conducted from exhaust pipe from wellhead of the borehole for several alloys. The geothermal fluid was at 450°C and 140 bars at wellhead but the weight loss experiments were done in exhaust pipe with throttled steam from wellhead where the temperature was 350°C and pressure 12-13 bars (Karlsdottir, 2015). The geothermal fluid from IDDP-1 contained HCl and HF in addition to the conventional corrosive species such as CO_2 and H_2S (Ármannsson, 2014)

Due to pressure loss in steam pipelines (exhaust) connected to the wellhead, large amount of silica deposited in the exhaust and hence silica accumulated and covered the corrosion samples during the test trials. The IDDP-1 well had to be shut off by injecting cold water due to malfunctioning of the master valves when it had to be shut of due to leakage in the flow line due to corrosion (Ingason, 2014). Materials tested in the IDDP-1 steam on site had very low corrosion rates low, both for the carbon steel and the corrosion resistant alloys (CRA) samples. Despite this all the samples were subject to localized corrosion i.e. pitting and/or cracking. Apparently, the silica scaling seemed to prevent general corrosion but promote under deposit corrosion (Karlsdóttir, 2015).

In order to simulate the corrosion of several alloys at IDDP-1 conditions, lab equipment was setup with prepared fluid in order to gain more understanding on the corrosion behavior of the alloys without the silica scaling. The main discussion of this paper will cast a light on the lab setup and the results of the preliminary corrosion experiments done in simulated IDDP-1 conditions.

2. EXPERIMENTAL

2.1 Experimental Design

The corrosion experiments were done in a 300 mm long and 11.7 mm wide flow through reactors in laboratory. Figure 1 shows a photograph of the reactor and Figure 2 of flow diagram of the system. The reactor material was UNS N06625 able to withstand 170 bars at 450°C. MACOR ceramic insulation material was placed between the samples and later, alumina, to prevent electrical contact between metal samples and possible galvanic corrosion between the two metals.

UNS N10276 and UNS N06625 were tested at 350°C in the flow through reactor with a pressure of 10 bar for 1 and 3-week exposure time. Additionally, the UNS N06625 was tested at 180°C with same pressure and exposure time. Solution of Na_2S and Na_2CO_3 were mixed with HCl solution to have obtain steam with CO_2, H_2S and HCl gases in the reactor, which upon condensation was measured to be of pH = 3. The chemical composition of the solutions as well as the mixed solution is given in Table 1.

Table 1: Chemical composition of the solutions used in the testing.

	Solution 1	**Solution 2**	**Mixed Solution**
Flow rate	0.5 ml/min	0.5 ml/min	1 ml/min
Na_2S (mmol/kg)	10	0	5
Na_2CO_3 (mmol/kg)	10	0	5
HCl (mmol/kg)	0	42	21
H_2O	Bal.	Bal.	Bal.

For chemical testing the pH of the outlet solution was measured using a digital pH meter. H_2S and CO_2 concentration was measured using titration method (Jónsson, 2015).

Pressure in the system was regulated by a backpressure regulator. The reactive solution were condensed and HCl and H_2S captured by NaOH and zinc acetate trap. The fluid was then collected and neutralized in drums.

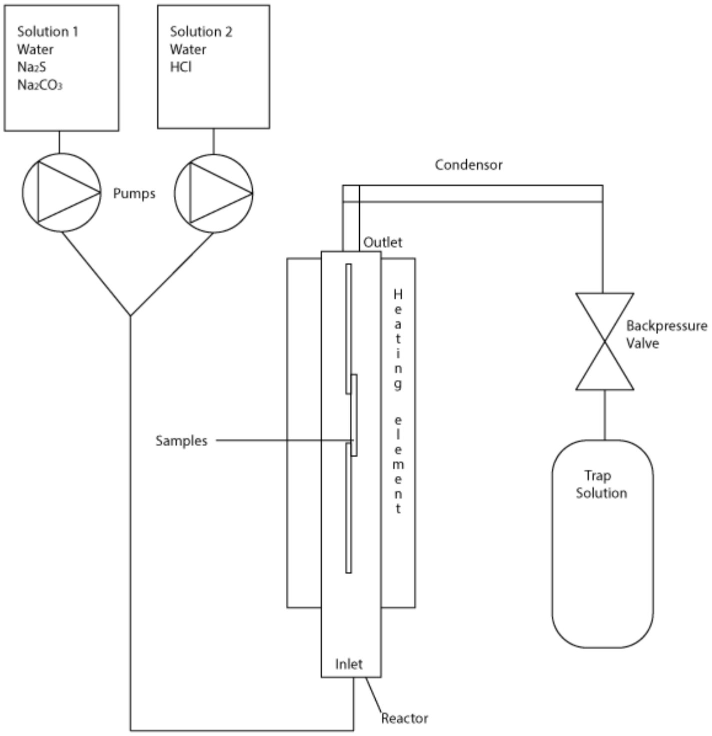

Figure 1: Experimental flow sheet diagram

The corrosion coupons tested had the following dimensions (100 mm x 7 mm x 2mm) (length x width x thickness) and 50 mm x 7 mm x 2 mm. The 100 mm long coupons were used for weight loss analysis but the 50 mm long coupons for SEM and XEDS analysis. To prevent contact between the metal coupons and the fasteners or sample holders, MACOR ceramic washers were machined from

MACOR ceramic material and put between the coupons and the fasteners/holders. The chemical composition of the MACOR material is given in Table 2.

Table 1. Chemical composition of MACOR ceramic by weight (Corning, 2015):

SiO_2	MgO	Al_2O_3	K_2O	B_2O_3	F
46%	17%	16%	10%	7%	4%

In addition, alumina insulators were used for one test setup. The test sample assembly can be seen in figure 2. The samples were all polished with SiC abrasive paper (down to 200 grit) prior to the tests. Each sample was measured and weighed according to ASTM G1 (ASTM G1-90, 1999) before and after the exposure in the reactor for weight loss analysis.

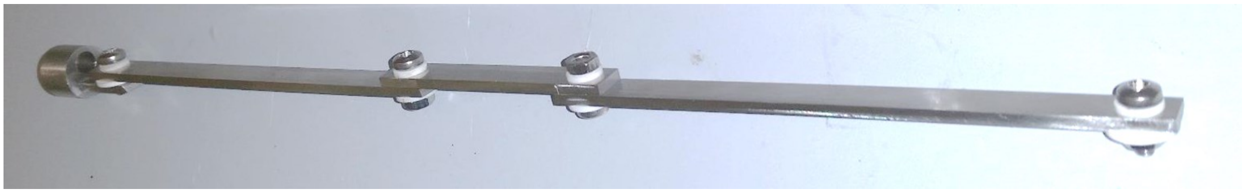

Figure 2: Corrosion samples assembled for testing. Three samples were in each test in the reactor.

2.2 Materials

UNS N06625 is a highly alloyed nickel alloy with min. 58% nickel (Ni), 21,5% chromium (Cr), 9% molybdenum (Mo) and 3.75% niobium (Nb) plus tantalum (Ta) (% by weight) and several other elements. The UNS N06625 has excellent strength, fabricability, corrosion resistance and high temperature service temperature.

UNS N10276 is also a highly alloyed nickel alloy with 57% Ni, 16% Cr, 16% Mo, 4% Tungsten (W) (% by weight) and several other alloying elements in minor amount. It is ductile, form- and weldable and has excellent corrosion resistance in harsh environment.

2.3 Post-Exposure Analysis

The weight loss coupons were cleaned and weighted before and after corrosion testing according to the ASTM standard G1-90 “Standard Practice for Preparing, Cleaning, and Evaluating Corrosion Test Specimens” (ASTM G1, 1999). The 50 mm long surface samples were cut and mounted in electrical conducting bakelite, then ground and polished with SiC paper (down to 2400 grit) for microstructural analysis in SEM (Scanning Electron Microscope) and chemical analysis of the surface and corrosion products in XEDS (X-ray Energy Dispersive Spectroscopy).

3. RESULTS

3.1 UNS N06625

3.1.1 Testing at 180°C, 1 week exposure

After cleaning and weighing of the samples the samples had gained a slight amount of mass or 2.85 and 2.54 mg for the 180°C test for 1 week. This is due to slight amount of surface staining which could not be removed during cleaning. The corrosion rate measured is thus negligible but the corrosion seemed to be some on the surface. Aluminum was analyzed in the deposits, implying contamination from dissolution of MACOR ceramic material.

I n the microstructural analysis with the SEM of the surface of the N06625 small formations or deposits are evident, as shown in Figure 3 mostly of sulfur corrosion products. Aluminum on the surface was probably due to dissolved alumina from the MACOR ceramic washers but most of the corrosion products were FeS indicating that some corrosion has taken place on the surface. The high amount of sulfur corrosion deposits were unexpected at 180°C as less sulfur was detected on surface of UNS N06625 at 350°C.

3.1.2 Testing at 180°C, 3-week exposure

After a 3-week exposure, there were more visible deposits on the sample. The measured corrosion rate was very low, the average of the two samples tested was 0.0035 mm/yr.

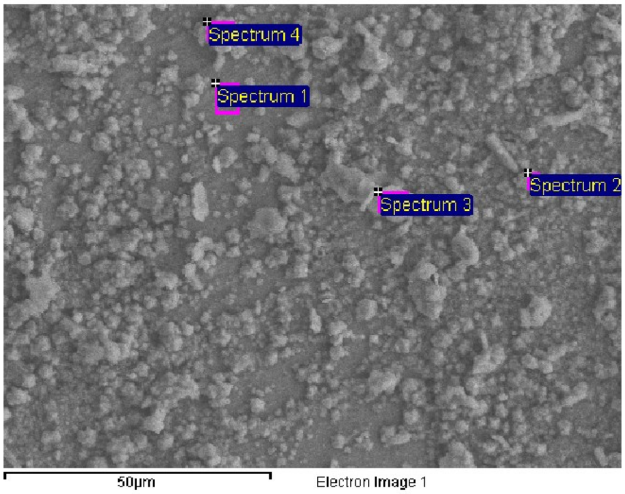

Figure 3: Surface of UNS N06625 after 3 weeks at 180°C.

Examination of the materials surface in the SEM shows a crystalline deposit rather uniformly distributed over the sample surface. The elemental analysis shows it consists of a mix of sulfides and oxides of indicated by the detected O, Ni, Fe and Cr. Viewing the sample in cross section very little could be seen even at rather high magnifications. Almost no corrosion layer could be seen and no indication of cracking.

Table 3: Chemical analysis of areas scanned in Figure 3.

Area	Fe	O	S	Al	Nb	Mo	Ni	Cr	Mn	Cl
Spectrum 1	5.3	19.9	0	1.2	2.7	8.8	41.8	18.9	0.6	0.9
Spectrum 2	4.3	21.1	21.9	0.9	0	3.6	42.2	4.7	0	1.4
Spectrum 3	10.0	15.8	30.4	0.5	0	0	36.1	5.7	0	1.5
Spectrum 4	9.9	17.1	17.6	0	0	0	43.6	5.8	0	5.9

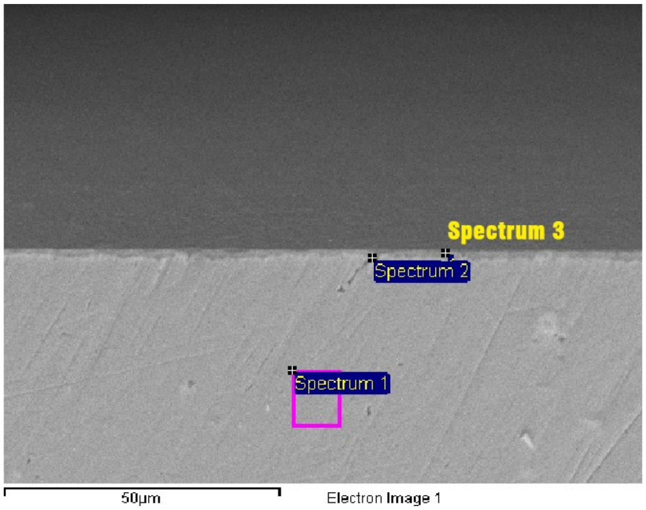

Figure 4: SEM micrograph of UNS N06625 after 3-weeks exposure at 180°C. Very thin corrosion layer is observed

3.1.3 Testing at 350°C, 1 week exposure

After a 1 week exposure at 350 °C the UNS N06625 samples were mostly covered with a thin black deposit but no visible damage from corrosion was apparent with visual inspection. After cleaning and weighing average corrosion rate of the samples was 0.026 mm/yr.

The center sample was inspected with SEM for microstructural examination of the surface and cross-section. XEDS analysis was also performed for chemical composition analysis of the surface and the cross-section.

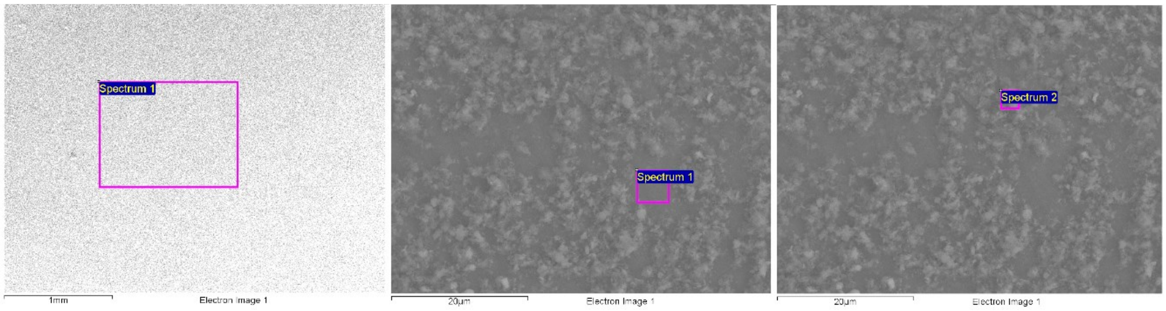

Figure 5: Areas selected for XEDS analysis a) low magnification of surface b) smooth surface at high magnification c) surface deposits at high magnification.

At low magnification, the surface of the sample looks quite uniform as is seen in Figure 5 a). On closer view an unclear deposit is visible which can be seen in Figure 5 b) and c). High amount of aluminum was analyzed at the smooth surface but less aluminum deposits seems to be on the fuzzy deposits on the surface. Small amount of sulfur and higher amount of oxygen was analyzed in the deposits comparing to the smooth surface. The chemical analysis indicates that the surface deposits are most likely corrosion products rich in sulfur (S) and oxygen (O).

Table 4: Chemical analysis (%wt) of surface areas for Inconel 625 after 1 week at 350°C

Area	C	O	Al	Si	Ti	Cr	Fe	Ni	Nb	Mo	S
a	0	28.3	2.4	0.8	0	26.6	6.0	23.7	5.1	7.0	0
b	6.0	28.2	10.2	0.6	0	24.5	5.6	13.3	4.7	6.7	0
c	0	38.2	3.0	0.7	0.2	31.3	7.0	6.6	4.0	7.4	1.7

3.1.4 Testing at 350°C, 3-week exposure

For the 3-week exposure at 350°C there was visible damage the sample at the exit of the reactor. A large crack had developed through the center of the upper sample and is shown in Figure . Some scaling was present on all of the samples but only the top sample showed visible corrosion damage.

Figure 6: Crack on the surface of UNS N06625 sample

The average corrosion rate was 0.15 mm/yr for the UNS N06625 sample tested for 3 weeks at 350°C. The presence of a deep crack on the surface of the UNS N06625 sample was not expected after 3-week exposure as the material is known to be very corrosion resistant The crack was analyzed with XEDS to identify the corrosion products.

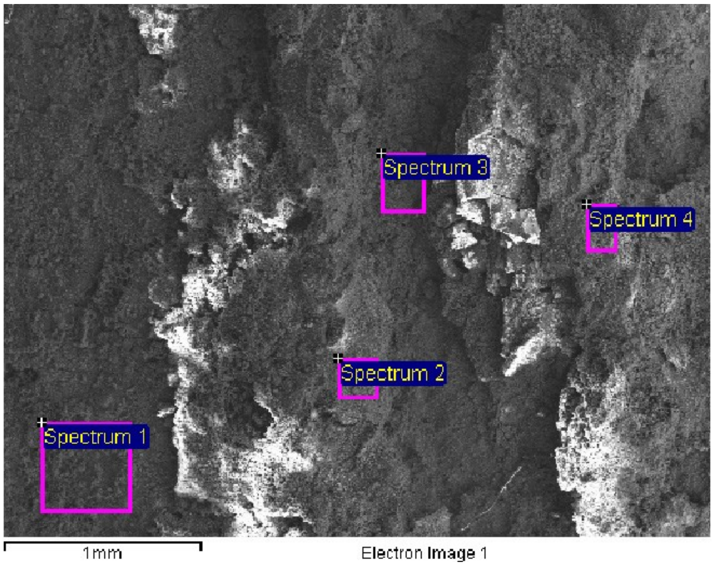

Figure 7: Surface of the area around the crack

The surface deposit along the crack seen in Figure 7 shows traces of Cl in all areas except one, and all areas contain large amounts of Cr and O as seen in Table 5 indicating these are corrosion products. Some Al is also present around the crack indicating deposits of dissolved MACOR ceramic washer. The MACOR material includes alumina but the UNS N06625 includes only maximum 0.4% Al. relatively higher Al content than 0.4% was analyzed adjacent to the crack

Table 5: Chemical analysis (%wt) of the surface area around the crack in the areas shown in Figure 7

Area	O	Al	S	Cl	Cr	Fe	Ni	Mo	Nb
Spectrum 1	32.7	3.2	3.5	0.8	45.4	4.4	6.2	3.8	0
Spectrum 2	44.5	3.2	5.0	0.7	29.7	4.5	6.3	6.2	0
Spectrum 3	21.5	2.2	11.8	0	46.3	6.0	12.3	0	0
Spectrum 4	44.3	1.9	2.6	0.6	40.8	2.3	2.9	6.2	0

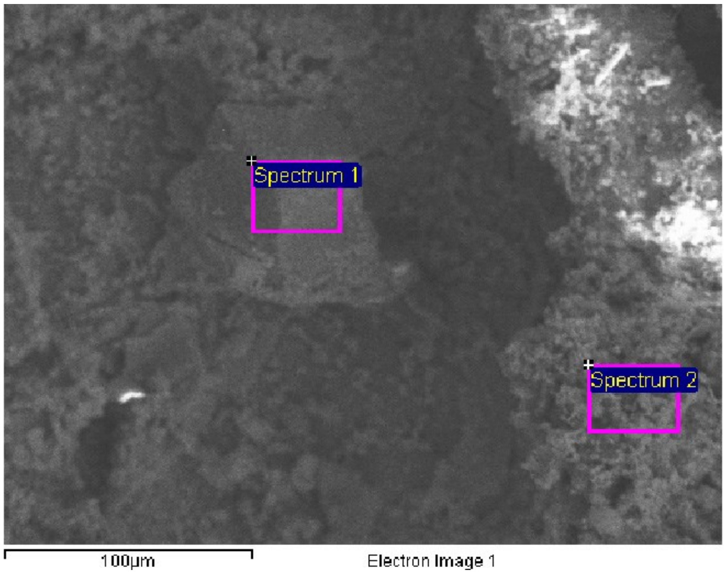

Figure 8: Area inside crack on UNS N06625 after 3-week exposure in 350°C

Looking into the area at the center of the crack in Figure 8 a crystal-like deposit was seen and analysis in Table 6 shows this deposit contains a rather high amount of Cl and S.

Table 6: Chemical analysis of the area seen in Figure 8

Area	Fe	O	Al	S	Si	Cl	Ni	Cr	Mo
Spectrum 1	2.3	31.5	0.7	5.9	0.8	8.8	26.0	24.1	0
Spectrum 2	6.4	12.9	0.9	17.1	0	0	27.6	25.3	9.8

Surface examination of the center sample showed no significant damage.

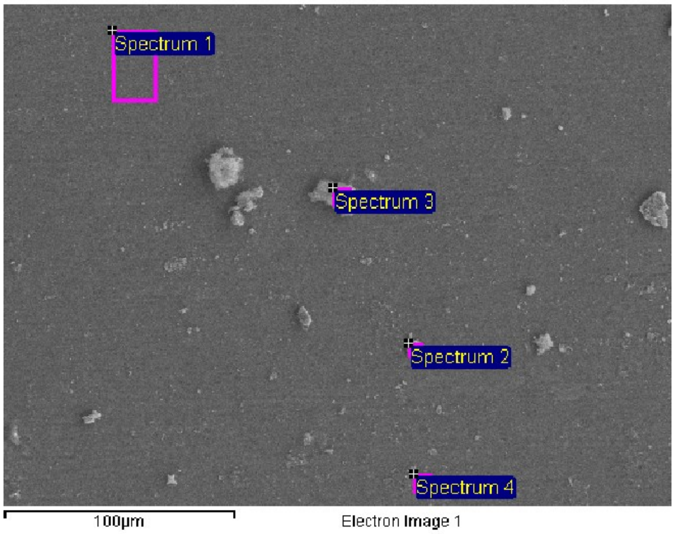

Figure 9: Surface of undamaged center sample of UNS N06625 after 3-week exposure

The deposits analyzed by XEDS appear to be loosely adherent to the surface one is high in Ni and S while the other two are mainly Cr and O. An unusually high level of Ti and Nb was detected in the area marked as Spectrum 4 in Figure 9 as shown in Table 7.

Table 7: Chemical analysis (%wt) of the areas shown in Figure

Area	Fe	O	Al	Ti	S	Nb	Cl	Ni	Cr	Tl	Mo
Spectrum 1	5.4	30.5	1.9	0.3	0	4.7	0	16.6	32.6	8.0	0
Spectrum 2	3.6	16.8	1.0	0	22.7	3.9	0	43.2	8.8	0	0
Spectrum 3	2.3	50.3	6.1	0	0	1.5	0.8	2.2	30.1	0	5.9
Spectrum 4	4.9	36.8	1.7	4.4	0	18.7	0	7.6	20.7	0	5.3

Little damage or corrosion products were visible in the cross section of the sample. Only a thin layer of corrosion product was available for chemical analysis using XEDS. No evidence of pitting or cracking was visible on this sample. However it should be kept in mind that one of the weight loss samples from this exposure experienced severe cracking as mentioned before at the outlet of the reactor, possibly due to condensation of steam and liquid droplets falling down from the exhaust pipe down to the outlet of the reactor.

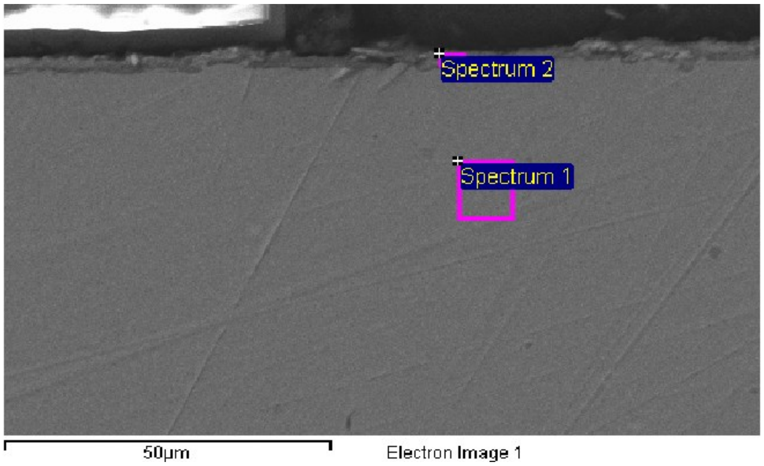

Figure 10: Cross section of UNS N06625 after 3 weeks at 350°C.

3.2 UNS N10276

UNS N10276 is a well-known high corrosion resistant material. The corrosion experiments for UNS N10276 were only done at 350°C. MACOR ceramic washers were used to insulate the UNS N10276 from the sample holders and fasteners to prevent galvanic effect between material and fasteners.

3.2.1 Testing at 350°C, 1-week exposure

After a 1 week exposure at 350°C the samples were covered with a dark black coating with some golden colored deposits toward the top end of the samples. The measured corrosion rate was 0.26 mm/yr. This corrosion rate is much higher than what would be expected from such a high corrosion resistant alloy.

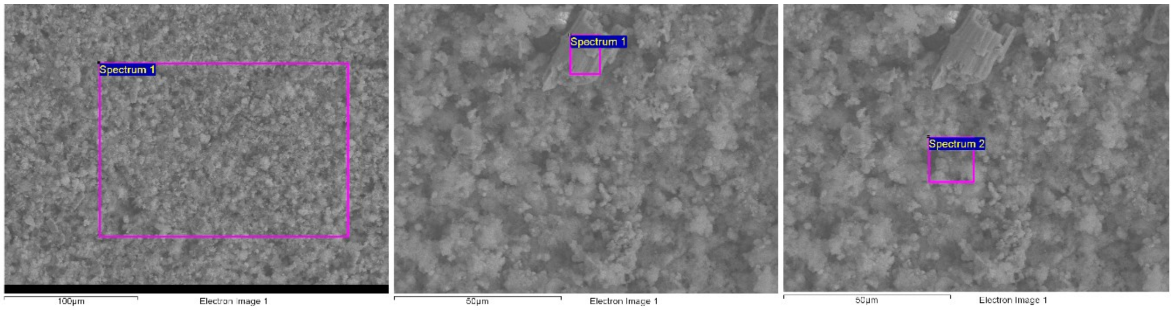

Figure 11: Micrographs from the SEM showing surface areas selected for XEDS analysis a) bulk surface at low magnification and b) surface deposit crystal at higher magnification and c) surface deposit at higher magnification.

Analysis of the surface deposits seen in Figure 11 shows a large amount of S and significant but smaller quantity of O indicating sulfur rich corrosion products covering the surface. Also the presence of Al and O can indicated the presence of deposits from the MACOR washers. An interesting feature is the crystal shown in b), where high concentration of S and Ni (see Table 8) and the morphology indicates that it is NiS crystals have formed.

Table 8: Chemical analysis (%wt) of surface areas for UNS N10275 after 1 week at 350°C from Figure 11.

Area	O	Al	S	P	Cr	Fe	Ni	W
a	16.9	11.7	51.7	1.0	10.9	1.2	5.5	1.2
b	1.6	0	34.5	0	1.1	0	62.8	0
c	18.4	10.7	46.3	0.9	16.5	1.2	4.7	1.4

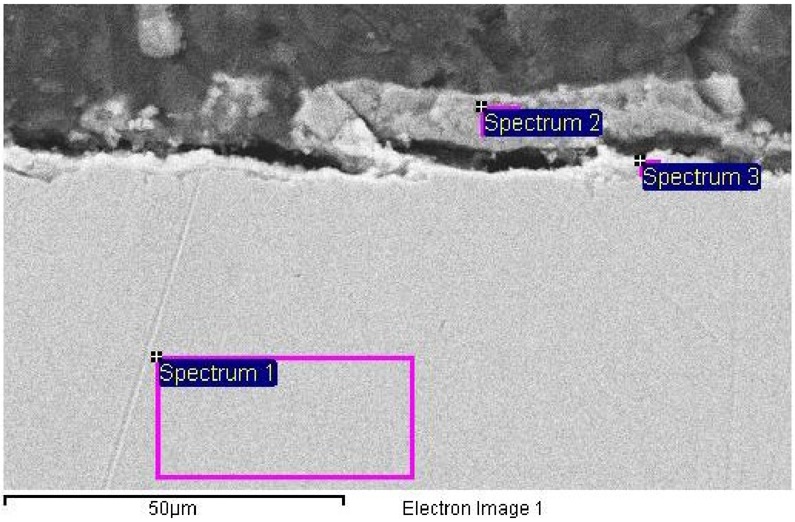

Figure 12: SEM Micrograph of the cross-section of UNS N10276 after 1 week at 350°C

Table 9: Chemical analysis (%wt) of cross section areas for Hastelloy C276 after 1 week at 350°C

Area	Fe	O	S	W	Mo	Ni	Mg	Al	Cl	Mn	Ca	Cr
Spectrum 1	6.2	0	0	3.3	16.8	57.1	0	0	0	0.8	0	15.8
Spectrum 2	2.7	31.7	1.2	5.8	20.2	5.0	0.5	1.2	1.1	0	1.1	29.7
Spectrum 3	1.9	31.5	1.2	6.3	17.0	4.8	0.7	1.2	1.8	0	1.7	31.8

Cross section of the surface showed no indication of localized damage on UNS N10276. Film has though formed on the surface that is evident in Figure 15 on the surface. The XEDS analysis of the film shows the presence of mainly, Ni, O, Mo, Cr, and S, indicating it being rich in corrosion products consisting of metal oxides and sulfides.

3.2.2 Testing at 350°C, 3-week exposure

After three weeks a rather large amount of loose blackish deposit was uniformly distributed over the surface of the UNS N10276. The corrosion rate for the three week test was comparable to the one seen in the 1 week exposure with the average being 0.29 mm/yr.

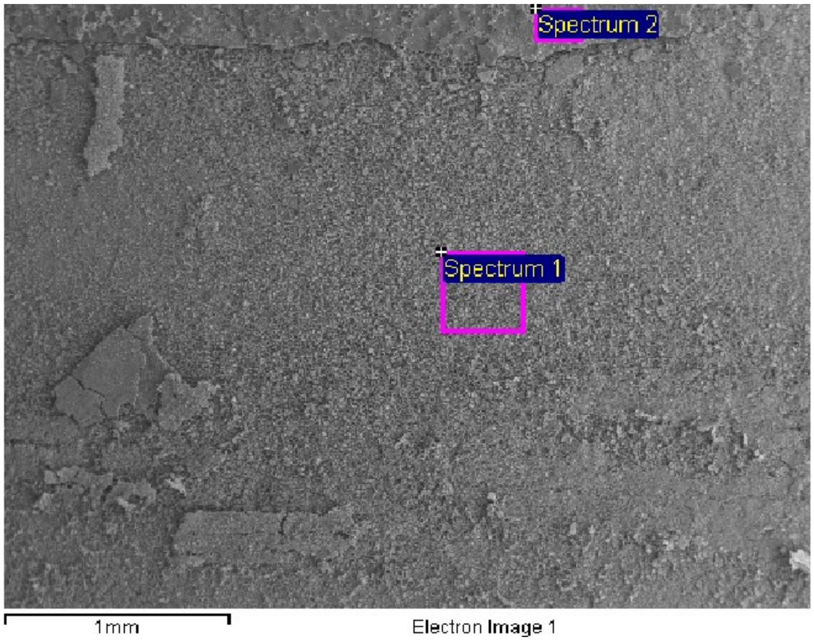

Figure 13: Surface deposits on UNS N10276 after 3 weeks at 350°C at low magnification in the SEM

SEM analysis of the surface of sample shows both flakes and fuzzy deposit. Both the flake like deposit and the fuzzy deposit were analyzed using XEDS and the composition is given in Table 10. Both deposits contain large amounts of corrosion products including either Ni, Cr and Mo while the fuzzy deposit in Spectrum 1 is more sulfur based. The flake like deposit has a higher amount of oxygen and Cr comparing the fuzzy one. The Al detected suggests precipitated material due to the dissolution of the MACOR ceramic washer material.

Table 10: Chemical analysis of the areas shown in Figure

Area	Fe	O	Al	W	Mo	Ni	Cr	Mn	S
Spectrum 1	4.6	6.4	0.3	0.7	11.6	42.9	8.2	0	25.2
Spectrum 2	5.3	31.0	1.5	3.2	7.9	13.3	27.0	0.3	10.6

SEM analysis of the cross section of the UNS N10276 alloy after 3 weeks at 350°C showed a corrosion film at the surface. No signs of significant localized damage were seen on the UNS N10276 sample despite the fact that uniform corrosion was significant and obvious on the surface of the sample, as can be seen in Figure 14.

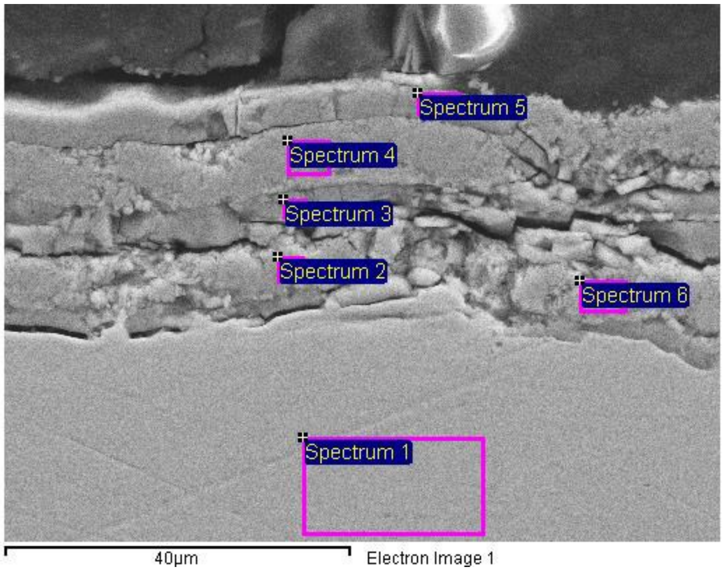

Figure 14: Cross section analysis of UNS N10276 after 3 weeks at 350°C

The surface layer is multi layered as can be seen in Figure 14. The layers are separated and have diversified amount of Ni, Cr, O and S in the layers as can be seen in Table 11.

Table 11. Elemental composition of the areas shown in Figure 14

Area	Fe	O	Al	Na	Ca	W	Si	Mo	Ni	Cr	Mn	Cl	S	C
Spectrum 1	6.5	0	0	0	0	4.0	0	16.5	56.3	15.8	0.9	0	0	0
Spectrum 2	0.7	1.5	0	0	0	0	0	6.6	56.8	1.4	0	0	33.1	0
Spectrum 3	13.6	32.0	0.5	0.6	0.5	5.3	0	6.9	3.1	33.3	0	0.8	3.5	0
Spectrum 4	1.2	0	0	0	0	0	0	15.2	49.9	1.1	0	0	32.7	0
Spectrum 5	17.0	33.8	0.7	0	0.5	4.3	0.5	4.8	3.3	31.5	0	0.7	2.9	0
Spectrum 6	1.4	6.1	0	0	0	0	0	10.1	47.0	2.5	0	0	31.1	1.7

3.3 UNS N06625, 1-week test with no MACOR ceramic washers

As a result of the rather large amount of deposit seen on many of the samples being tested at 350°C and 10 bars, and the presence of elements contained in the MACOR ceramic in the deposits, the one week test of UNS N06625 was repeated. Material was chosen as it is the material of the surrounding reactor. Instead of MACOR ceramic insulating material, an alumina washers were applied instead.

The corrosion rate of the test performed without washers was less than the previous test at 350°C with the MACOR washers, with the average corrosion rate being 0.01 mm/yr which is about 2.5 times lower than the rate seen with the washers. It is though not a significant difference since the actual weight loss is small, test period relatively short and variations in the running of the reactors could also affect the corrosion rate.

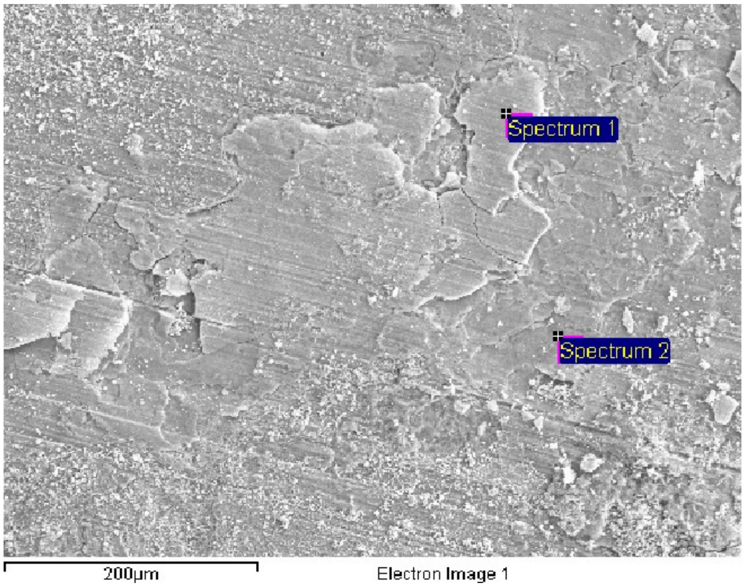

Figure 15: Surface deposits on UNS N06625 after 1 week at 350°C with no MACOR washers

The deposits seen in Figure 15 are a mix of mainly O and some S based corrosion products as seen by the high Cr, Mo, Nb and Ni as can be seen in Table 12. A small amount of Cl was detected in deposit along with some Na suggesting maybe some NaCl formation. High levels of Nb are present in both Spectrums especially number 1. Why there is local enrichment of Nb in some areas is not known, and will be examined further in future corrosion experiments that are planned with updated version of the reactor setup. Less aluminum was observed on surface than on samples connected with MACOR ceramic washers

Table 12: Chemical analysis of the corrosion deposits seen in Figure 15

Area	Fe	O	Al	Na	Ti	Nb	Mo	Ni	Cr	Mn	Cl	S
Spectrum 1	1.6	28.6	0	0.6	0.8	17	13.8	2.8	24.0	0.3	0	10.5
Spectrum 2	3.3	27.3	1.0	0.6	0.4	8.2	6.6	13.7	34.2	0.4	0.3	4.0

4. DISCUSSION

During the running of the reactor system some issues were encountered that likely affected the outcome of the experiment. The major ones are listed below:

- Blockage of the outlet resulting in a buildup of pressure
- Blockage of the inlet resulting in the loss of flow
- Dissolution of the MACOR ceramic and deposition of the material on the samples
- Likely boiling of the solution on the sample closest to the inlet
- Possible separation of the steam components along the length of the reactor due to gravitational forces.
- Condensation in piping and liquid dropping due to gravity back into the outlet of reactor.

The blockage of the outlet had different causes although the most frequent one was due to the backpressure regulator. The regulator had a very narrow flow path which easily was blocked by the corrosion products in the outlet stream. On a few occasions the inlet was blocked by elemental sulfur clogging the tubing leading to the reactor. This blockage was easily removed by blocking of the inlet valve and clearing the tube. In future it would be advisable to use a larger diameter tube leading to and from the reactors.

In the case of the MACOR ceramic it turned out to be unsuitable for testing in these conditions. In future testing other methods of electrical insulation would be needed for the sample to prevent sample contamination.

Short distance from the inlet of the reactor to the bottom sample may have affected the corrosion rate and corrosion form in the testing. This may have resulted in liquid droplets being sprayed onto the bottom sample and creating boiling conditions on the sample surface.

UNS N06625 was expected to perform very well in this test as it had performed well in the on-site IDDP-1 testing for dry steam (Karlsdottir, 2015) and wet scrubbing (Karlsdottir, Thorbjornsson, & Sigmarsson, 2013). However some slight damage was seen in heat exchanger testing at IDDP-1 (Ragnarsdóttir, 2013). In the IDDP-1 testing, amorphous SiO_2 scaling on the corrosion coupons probably effected the corrosion rate and corrosion form of the alloys tested (Karlsdottir, 2015). In these preliminary experiments, no SiO_2 scaling occurred and was not part of the experiments scope. Future corrosion testing with improved lab setup will though simulate the SiO2 scaling to gain more understanding on the effect of SiO_2 scaling on corrosion rate and corrosion form in high temperature deep geothermal environment.

UNS N10276 showed no evidence of localized corrosion. The corrosion rate was higher than UNS N06625 for 1 week testing but similar to UNS N06255 for the 3-week tests. The high Mo content (16%) is likely a major factor in protecting the alloy from localized corrosion. Uniform corrosion of the UNS N10276 alloy was considered high for such an expensive alloy in engineering application.

5. CONCLUSION AND FUTURE WORK

This experiment has shown that damage can be seen on even high end corrosion resistant alloys in the simulated high temperature acidic geothermal steam environment. The nickel alloy UNS N06625 showed localized damage at the higher temperature although they performed very well for the lower temperature test. UNS N10276 showed no signs of localized damage although the corrosion rate was higher than acceptable (>0.1 mm/yr). The high content of molybdenum in UNS N10276 has likely prevented the alloy from localized corrosion.

The results should though be taken with notice since the lab material and setup may have affected the corrosion rate and corrosion forms in the experiments. Before further studies will be done, improvements will be made on the lab setup.

Future work aims to improve the setup and avoid the issues from these experiments i.e. to prevent any condensation/boiling and improve the control the physical condition in the reactor with improved controls and equipment, i.e. data loggers, preheaters, horizontal setup, altered inlet flow to ensure homogeneity of mixture into reactor, apply heating cords around piping to prevent condensation etc. Ceramic fasteners for the coupons will not be used; instead fasteners made with the same alloy as the corrosion coupon will be applied. In addition, the effect of amorphous silica scaling on the corrosion rate and corrosion form of several corrosion resistant alloys will be tested at high temperature.

REFERENCES

Tindur Jónsson. Corrosion Behavior of Materials in Simulated High Temperature Geothermal Environment. Faculty of Industrial Engineering, Mechanical Engineering and Computer Science, University of Iceland, Reykjavik, Iceland, August 2015.

Karlsdottir, S. N., Ragnarsdottir, K. R., Thorbjornsson, I. O., & Einarsson, A. (2015). Corrosion testing in superheated geothermal steam in Iceland. *Geothermics, 53*, 281-290.

Ingason, K., Kristjánsson, V., Einarsson, K., 2014. Design and development of the discharge system of IDDP-1. Geotermics 49, pp. 58-65.

ASTM International. (1999). *Standard Practice for Preparing, Cleaning, and Evaluating Corrosion Test Specimens*. Retrieved from: http://www.astm.org/Standards/G1.htm

Ármannsson, H., Fridriksson, T., Gudfinnsson, G. H., Ólafsson, M., Óskarsson, F., & Thorbjörnsson, D. (2014). IDDP—The chemistry of the IDDP-01 well fluids in relation to the geochemistry of the Krafla geothermal system. *Geothermics, 49*, 66-75.

Coretest Systems Inc. (2015). *BPR-2 Dome-Loaded Back Pressure Regulator*. Retrieved from: http://www.coretest.com/product_detail.php?p_id=66

Corning Incorporated. (2015). *MACOR* Retrieved from: http://psec.uchicago.edu/ceramics/MACOR%20Data%20Sheet.pdf

Fridleifsson, G. Ó., Albertsson, A., Stefánsson, B., & Gunnlaugsson, E. (2003). *Icelandic Deep Drilling Project: Deep vision and future plans*. Paper presented at the International Geothermal Conference, Reykjavík, Iceland. http://rafhladan.is/bitstream/handle/10802/9395/S06Paper122.pdf?sequence=1

Fridleifsson, G. Ó., Pálsson, B., Albertsson, A. L., Stefansson, B., Gunnlaugsson, E., Ketilsson, J., & Gislason, T. (2015). IDDP-1 Drilled Into Magma - World´s First Magma-EGS System Created. *Proceedings World Geothermal Congress*. Retrieved from http://iddp.is/wp-content/uploads/2015/04/1-paper-1-37001-GOF-et-al.pdf

Gunnlaugsson, E., Armannsson, H., Thorhallson, S., & Steingrimsson, B. (2014). *Problems in Geothermal Operation - Scaling and Corrosion*. Paper presented at the Short Course VI on Utilization of Low- and Medium-Enthalpy Geothermal Resources and Financial Aspects of Utilization. http://www.unugtp.is/en/moya/page/sc-18

Haynes International. (2001). *HASTELLOY C-276 ALLOY* Retrieved from: http://www.haynesintl.com/pdf/h2002.pdf

Karlsdottir, S. N., Ragnarsdottir, K. R., Moller, A., Thorbjornsson, I. O., & Einarsson, A. (2014). On-site erosion–corrosion testing in superheated geothermal steam. *Geothermics, 51*, 170-181. doi:10.1016/j.geothermics.2014.01.007

Karlsdottir, S. N., & Thorbjornsson, I. O. (2013). *Corrosion Testing Down-Hole in Sour High Temperature Geothermal Well in Iceland*. Paper presented at the CORROSION 2013, Orlando, Fl. http://www.nace.org/cstm/Store/Product.aspx?id=36ab9393-8402-e311-a0ec-0050569a007e

Karlsdottir, S. N., Thorbjornsson, I. O., & Sigmarsson, T. (2013). *Corrosion and Scaling in Wet Scrubbing Equipment of the Superheated Geothermal Well IDDP-1 in Iceland*. Paper presented at the CORROSION 2013, Orlando, Fl. http://www.nace.org/cstm/Store/Product.aspx?id=39ab9393-8402-e311-a0ec-0050569a007e

Karlsdóttir, S. N. (2012). Corrosion, Scaling and Material Selection in Geothermal Power Production. In A. Sayigh (Ed.), *Comprehensive Renewable Energy* (Vol. 7, pp. 239-257). Oxford: Elsevier.

Ragnarsdóttir, K. R. (2013). *Corrosion Experiments In Dry Superheated Steam From IDDP-1*. (M.Sc), University of Iceland, Reykjavík. Retrieved from http://hdl.handle.net/1946/13893

SITEC-Sieber Engineering AG. (2008a). *Hand Driven Pump*. Retrieved from: http://www.sitec-hp.ch/2014/fileadmin/SITEC_AG/PDF_Prospekte/750_01.pdf

SITEC-Sieber Engineering AG. (2008b). *Hand Valves*. Retrieved from: http://www.sitec-hp.ch/2014/fileadmin/SITEC_AG/PDF_Prospekte/710_01.pdf

Specialmetals.com. (2013). *Inconel alloy 625*. Retrieved from: http://www.specialmetals.com/assets/documents/alloys/inconel/inconel-alloy-625.pdf

ASTM International. (1999). *Standard Practice for Preparing, Cleaning, and Evaluating Corrosion Test Specimens*. Retrieved from: http://www.astm.org/Standards/G1.htm

Corning Incorporated. (2015). *MACOR* Retrieved from: http://psec.uchicago.edu/ceramics/MACOR%20Data%20Sheet.pdf