Online Monitoring of Corrosion in Slightly Saline Geothermal Water in Iceland

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ABSTRACT

Online monitoring of corrosion is a valuable tool for heating systems to minimize risk of damage due to steel corrosion. Monitoring with weight loss coupons has the limitation that it takes a while to recognize the problem and a great damage may have already happened. A cost effective device for online monitoring, not relying on electricity or telecommunication at the production site is of great value in small heating systems or at a drill sites before harnessing. The current project, aimed at development and testing of such a device, was conducted at a well site under testing. By drilling near the farm site Keldunes in rural NE Iceland in 2006, a low temperature geothermal field was verified. The production water has a temperature of approximately 76°C. The water is slightly saline, 1-2 ‰, depending on relative mixture of the different aquifers in the well. The origin of the water is mixed, partly derived from geothermal effluent water from the Krafla high temperature geothermal field further inland and partly of more local origin. Production testing of the well revealed severe calcite scaling. Scaling tests, performed over an extended period indicated some ongoing steel corrosion but appeared negligible. Since a production testing a corrosion test has run for a six month period, both with traditional weight loss coupons and also by online monitoring with differential ER equipment from MetriCorr. The data logger was powered by solar cells connected to batteries with the data being retrieved through a mobile phone connected to the data collection system. The operation of the system went very well in spite of harsh conditions. Even though the corrosion rate was low, it showed distinct changes by lowered wellhead pressure and infinitesmal air inflow. The device proved to be a useful and cost effective tool to monitor possible changes in corrosion conditions easily assembled and operated at remote sites outside the electric grid. There are many small heating systems where such a device would be of great use and may even prevent damage due to corrosion.

Introduction

To minimize risk of damage due to steel corrosion it is important to have a functional monitoring system. Monitoring with weight loss coupons has a limitation in that it takes a while to recognize the problem. Significant amount of damage may already have happened during the time when the corrosion rate is verified and quantified. Online monitoring of corrosion is therefore much more preferable and having an applicable low-cost system would be a valuable asset for many of the small heating systems in Iceland and elsewhere. With small heating systems there is not always telecommunications at the production site. At a drill site before harnessing of the field there may not even be electricity. There is a need though to test the well before installing such costly devices. For such occurrences development and testing of practicable low-cost device is of great value. The current project, which is aimed at such development a test site with a free flowing geothermal well was used. The site, Keldunes, is located in a remote rural area in NE Iceland (Figure 1). The choice of the site was due to the fact that the sparsely populated rural area is not connected to a geothermal heating system. However a geothermal field has recently been verified at the location. The field has somewhat saline water which seems to have high scaling potential and may be corrosive. Due to the water beeing so saline, a small uptake of oxygen would induce rapid steel corrosion. Testing of production properties is ongoing and the testing of online monitoring with differential ER equipment from MetriCorr (Nielsen and Nielsen, 2003) was conducted simultaneously with testing by traditional weight loss coupons. The equipment has been tested earlier in Icelandic district heating systems with promising results were the differential ER monitoring was found to respond well to changes in dissolved oxygen which is the main corrosive factor in the systems (Richter, 2006 and Richter et al., 2006, 2007). The project was funded by the student innovation fund, the Húsavík power company, the National energy authority and the National power company. The local people have also assisted a large amount of their time in the field.

Geothermal Conditions at Test Site

At the of Bay of Öxarfjördur in NE Iceland (Figure 1) the active zone of rifting and volcanism in Iceland intersects the Tjörnes transverse fracture zone which offsets the plate boundary towards the west (Georgsson et al. 2000, Saemundsson, 1974). There is extensive geothermal activity in the Öxarfjördur area, all of which is mostly confined to three fissure swarms transecting the NE volcanic zone. There are only low-temperature geothermal systems (reservoir temperatures below 150°C) encountered in the Öxarfjördur area, but further to the south within the fissure swarms, there are several powerful high-temperature geothermal systems (Björnsson et al., 2007, Georgsson et al., 1989, 1993, 2000, Kristmannsdóttir et al., 2006, 2007). Effluent water from the high-temperature geothermal systems in the south flows towards north along the fissure swarms. Volcanic episodes in fissure swarms greatly influence the groundwater system in the Öxarfjördur area by increasing amount of geothermal effluent water heating up the water flow in the fissure swarms (Björnsson, 1985, Sigurdsson, 1980). In addition to the high temperature water flowing from south, there is a massive flow of fresh water from the highlands mixing with sea water which has an easy access into the fractured young rock formations, further complicating the groundwater system in the area. The salinity of the geothermal water may partly be derived from local sediments building up the Jökulsá river delta.

Studies of the groundwater systems as well as the geothermal waters have been carried out by several scientists during the last twenty years (Hafstad, 1989, Georgssson et al., 1989, 1993, 2000, Kristmannsdóttir and Ólafsson, 1989, Kristmannsdóttir and Klemensson, 2007, Kristmannsdóttir et al., 2006, 2007). One of the low-temperature geothermal fields is located at Bakkahlaup near Keldunes, which was verified by drilling in 2006 (Fridleifsson et al., 2007).

The test well is in this geothermal field. It is located at the bank of the glacial river Jökulsá, sometimes surrounded by the river in floods (Figure 2). The depth of the well is 610 m and it was assumed to be very successful as it yielded almost 20 L/s of 76°C hot water at the completion of drilling.

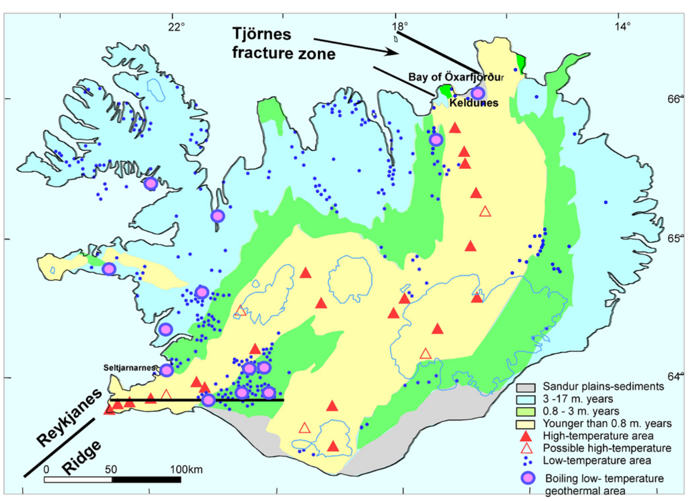

Figure 1. A geothermal map showing the location of Keldunes. Based on data from Björnsson et al., 1990.

The sparsely populated rural area near to the geothermal field is heated by electricity and the potential for a geothermal heating system, *hitaveita,* is greatly anticipated, but means to build it and harness the field are limited.

Two aquifers were intersected within the well, one at 380 m depth and the main one at 560 m depth. The first aquifer at 380 m depth had a temperature of about 64 °C and salinity of 0.9 ‰ (Kristmannsdóttir, 2006). The main aquifer at about 560 m depth was 78 °C (Fridleifson et al., 2007). The bottom temperature of the well was 86 °C. When the drilling was concluded the temperature of the free flowing water was 76.5 °C and the salinity of the water after a one month´s flow test was 1.3 ‰ (Kristmannsdóttir, 2006). After conclusion of the well a corrosion and scaling test was performed which concluded in January 2008 (Kristmannsdóttir and Björnsson, 2008). At present, the closing pressure of the well is about 0.6 bar_g. When fully open the flow is nearly 10 L/s. In figure 3 a pressure/flow curve for the well is shown. By increased flow and decreased pressure there seem to be a change in relative mixing of different aquifers displayed by slight changes in salinity. When the well is fully open, there seems to be a slight inflow of atmospheric air at the wellhead with the present setup.

Figure 2. At wellhead of BA-04 in Keldunes. The Jökulsá river is seen in the background.

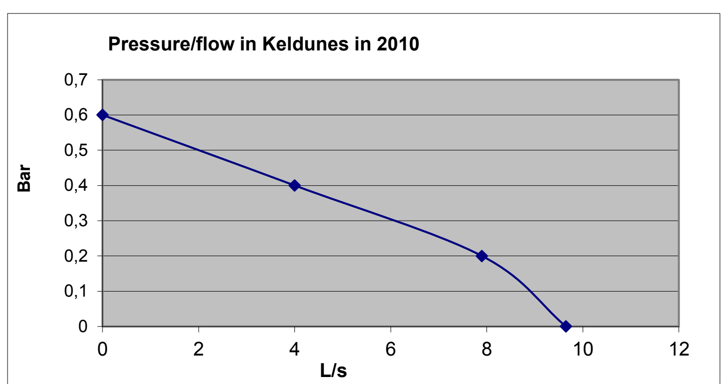

Figure 3. A pressure/flow curve for the well BA-04 at Keldunes

Geochemistry and Production Properties of the Water

The chemical composition of the geothermal water from the well at Keldunes (BA-04) is shown in Table 1. The geothermal water is classified as sodium chloride water, but the chloride concentration may vary slightly according to wellhead pressure and flow. The salinity of the water changed from 1.3 ‰ to about 2 ‰ during the first production test lasting for 20 months, but has stayed more or less constant since. There seems to be some variation in salinity depending on the pressure/flow conditions, indicating that different aquifers have slightly different salinity. The salinity is not excessively high as compared to water in many geothermal heating systems in Iceland. In table 1 water chemistry from one of the Icelandic heating systems using low-temperature saline geothermal water in their production, at the low-temperature field Seltjarnarnes (see Figure 1 for location) in SW Iceland is shown for comparison. There the water is almost twice as saline as at Keldunes, but has been operated without any major problems for about 40 years. The pH of the geothermal water is about 8.5 and lowers subsequently with increased salinity. There is no dissolved oxygen in the Keldunes water and a trace concentration of sulphide (H_2S). The water is depleted in magnesium as are all geothermal waters, but the magnesium content increases rapidly by increase in salinity and is two orders of magnitude higher than in non saline geothermal waters of similar temperature (Kristmannsdóttir, 2004). Fluoride is on the high side, but lowers with increasing salinity. The concentration of aluminum is very low as is common in saline geothermal waters. The concentration of iron and manganese is low, along with zinc and mercury as well as the concentration of all other analyzed trace elements. The composition of stable isotopes (δ^2H= -80‰ and $\delta^{18}O$ = -11‰) indicates a mixture of three components; groundwater from the southern highlands, seawater and local groundwater (Kristmannsdóttir et al. 2007). Further, very low pMC values (% ^{14}C) for Keldunes indicate that the water represents a mixture of geothermal effluent water from the Krafla high temperature geothermal field and more local water (Kristmannsdóttir et al. 2007).

Table 1. Composition of water from well BA-04 in Keldunes. Water from the heating system in Seltjarnarnes SW Iceland is shown for comparison.

Place Sample no. Date	Keldunes 2008-001 08.02.08	Seltjarnarnes HK-10-073 22.10.10
T °C	75.9	107.2
pH/°C	8.46/20	8.37/23
SiO_2 mg/L	157.5	114.9
B µg/L	739	240
Na mg/L	632	726
K mg/L	28.6	14.1
Ca mg/L	57.2	634
Mg mg/L	0.269	0.400
Sr mg/L	0.10	2.87
Al µg/L	23	24
Fe µg/L	4.1	10
Mn µg/L	1.5	13
CO_2 mg/L	37.6	5.5
Hg µg/L	0.020	6,7
H_2S mg/L	0.015	0.18
SO_4 mg/L	145	345
Cl mg/L	1020	1940
F mg/L	0.93	0.50
Cond. mS/cm at 25°C	3300	6135
TDS mg/L	1915	3777

The reservoir temperature indicated by geothermometers is 130-150°C (Fournier, 1977, Arnórsson et al., 1983). Calculated mineral equilibria for many common alteration minerals in basaltic rocks indicate mixing of waters at reservoir temperatures of 110-140°C, but has a considerable scatter in the results (Kristmannsdóttir et al. 2007).

The chloride concentration of the waters in all samples is too high for direct use in *hitaveitas* without heat exchangers (Kristmannsdóttir and Björnsson, 2008). If the salinity exceeds 0.4-0.5 ‰, the use of heat exchangers is considered necessary (Kristmannsdóttir, 2004). Increased chloride concentration acts as a catalyst for all reactions, including corrosion and scaling, so one has to be very careful with the utilization of even slightly saline water. The concentration of H_2S in the geothermal water in Keldunes is very low so it gives very little corrosion protection in the case of oxygen uptake. Depending on flow rate and wellhead pressure the calculated saturation with respect to calcite in the Keldunes water varies from slight to high supersaturation (Kristmannsdóttir and Björnsson, 2008). Increased flow rate and lower pressure increses the supersaturation, whereas lower flow rate and higher pressure decreases it. Most Icelandic geothermal waters are nearly within equilibrium with calcite at reservoir temperatures and contain no free CO_2.

Scaling and Corrosion

The results from a 20 month flow test after completion of drilling the well indicated negligible steel corrosion, but considerable calcite scaling (Kristmannsdóttir and Björnsson, 2008). The scaling was more aggressive than is known anywhere else by the use of water from Icelandic low-temperature geothermal fields. Later a two month scaling test was performed at higher wellhead pressure resulting in much lower scaling rate, but still had worrying levels. Several later tests were made of 1-4 months duration with both low carbon steel and stainless steel and the water cooled by about 5 °C to see if that had an effect on the scaling rate (Tucker, 2010). A rather low rate of scaling was observed during that test, but some slow steel corrosion attacks were detected, especially on the low carbon steel (Tucker, 2010). The main reason for this corrosion is suspected to be the inflow of atmospheric air at low wellhead pressure, but this hypothesis has not been verified. It was watched out for, especially in the later tests that there was minimal possibility of inflow of atmospheric air into the system.

Online Corrosion Test 2010-2011

Setup of the Test

As there was some slow manifested steel corrosion at the Keldunes site in the test in 2009 the site was considered suitable for testing with online corrosion monitoring equipment and comparing with conventional test by weight loss coupons for normalizing the output. The site is also typical for the small remote sites where the online monitoring would be a very useful tool if it were customized for Icelandic conditions. The equipment used for online testing is based on differential electrical resistance-technology (ER) previously tested in Icelandic heating systems together with other on-line methods (Richter, 2006, Richter et al 2006 and Richter et al 2007). A simplified graph of the ER monitoring circuit is shown in Figure 4. The equipment consists of a probe, datalogger and a GPRS Modem. The datalogger and the modem are from Metri-corr in Denmark, while the probe is produced by Alabama Specialty Products Inc (Metri-corr, e.d. & Alabama Special Products Inc, e.d.).

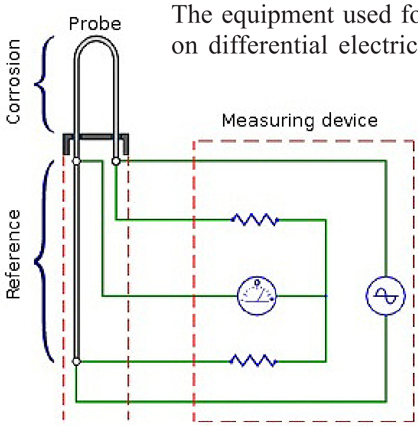

Figure 4. A simplified graph of the ER- monitoring circuit.

The test equipment was housed in a shed that was brought to the test site with solar cells mounted on the walls of the shed as well as the antenna for the mobile phone used to send the data through the GPRS modem (Figure 5).

As inflow of atmospheric air at low wellhead pressure was suspected to be at least partly causing corrosion at the wellhead in the 2009 test. It was carefully checked in the beginning of the online test that inflow of atmospheric air into the system was excluded. The equipment was mounted within a steel canister and within in a similar steel canister connected parallel to the first one there were two mounted two stainless steel test plates (standard weight loss coupons). The flow rate through the two steel canisters was carefully adjusted so it was exactly the same. The setup of the equipment is displayed in Figure 6.

Before the equipment was installed, it was tested and further developed by the engineering company Vista. The equipment was configured in such a way that the datalogger collected the data continously and every 6 hours the data were sent through a GPRS modem to an e-mail address at the Vista engineering company.

The Python programming language was used to write a sentry guarding the e-mail address, detecting an e-mail and writing the data in a DAT file, Vista Data Vision (VDV). The VDV software is used for monitoring of a variety of different parameters like motor traffic, weather, energy usage, water level in wells to mention a few. The VDV automatically scales the change of thickness in the test plate over time by a “Rate of Change” adjustment in the software. Thus a time related measurement of the thickness of the plate is provided as one of the output.

Figure 5a. The shed used to house the test equipment.

Figue 5b. Finish of the solar cells used to power the test.

Figure 6. Setup of the testing and datalogger equipment inside the shed at the Keldunes location.

Concurrently running the first two months of the test, the chemistry of the geothermal water was monitored by regular sampling and measurements of selected parameters (Sveinbjörnsson and Sigurðsson, 2010).

Run of the Test

The test was started on July 22nd 2010 and concluded January 30th 2011. The first lot of test plates for comparison was inserted on July 22nd 2010 and removed on August 29th 2010 and were thus exposed for about 900 hours to the geothermal water. The second lot was inserted on August 29th 2010 and removed on January 30th 2011 and were exposed for nearly 3700 hours to the geothermal water. On the 12th of October 2010 the valve at the wellhead was opened more to lower the wellhead pressure, but the flow was adjusted to be the same as before. The reason was to see if a small inflow of atmospheric air might occur and change the corrosion rate. The plates were cleaned carefully and weighed by an analytical balance at University of Akureyri before insertion. When the plates were removed they were dried onsite and kept in a plastic bag during transport to the lab where they were weighed with the same precision as before insertion. The plates were inspected carefully by microscope, but there was not considered any reason to analyze them by SEM or other devices as the corrosion products were negligible.

Samples for chemical analysis of the geothermal water at Keldunes were collected weekly through the first two months of the test time to make sure that the chemical composition was stable and possible changes in corrosion could not be related to chemical fluctuations or changes (Sveinbjörnsson and Sigurðsson, 2010). The parameters measured were, conductivity, pH, total carbonate, calcium, magnesium and chloride.

Results

Test Plates / Standard Weight Loss Coupons

The first lot of test plates were kept in the flow of geothermal water for about 900 hours whereas the second lot was immersed for almost 3700 hours. The plates in the first run looked quite uncorroded, but the color had changed and they looked a bit darker after immersion than before (Figure 7). In the second run the plates showed a rather slight corrosion, but the drying of the plates on site was incomplete and some rust was formed on the surface (Figure 8). The plates were gently cleaned with concentrated alcohol (spiritus fortis) before weighing.

In the first test run with 900 hours immersion the measured corrosion rate by weight loss was 2.1 μm and in the second test with 3700 hours immersion the measured corrosion rate was 0.5 μm. These numbers are in the same range as measured in oxygen free district heating systems in Reykjavik. In systems with even low oxygen content (<100ppb) the corrosion rate of steel has been found considerably higher or 20-60 μm (Richter et al. 2006). In the second test at Keldunes going over longer period of time the corrosion rate was considerably slower, even though there was possibly some uptake of atmospheric air during most part of the testing time. Thus, a protective layer seems to be formed passivating the metal.

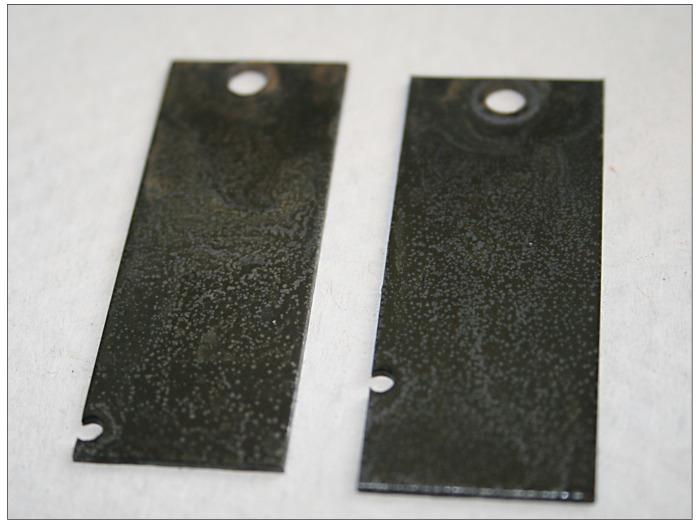

Figure 7. Plates from the first test.

Figure 8. The plates from the second test.

Online Monitoring

As found by weight loss measurements very low corrosion rates were found at the Keldunes site, confirming that the water is free of dissolved oxygen. In Figure 9 output of the VDV data during the whole run of the testing time is shown. There were no changes observed in the measured corrosion rate until on October 12th when the valve on the well was opened more and the wellhead pressure lowered. The flow rate through the equipment was kept unchanged. It is possible that by lowering the pressure at the wellhead there have been some minimal uptake of atmospheric air into the water. It may also induce degassing of the water, thereby changing the pH. Change in pH may affect the resistivity and thereby the corrosion rate. Just that day, there was observed much more scatter in the data, even though the mean corrosion rate was still as low as before. This scatter was displayed from then on

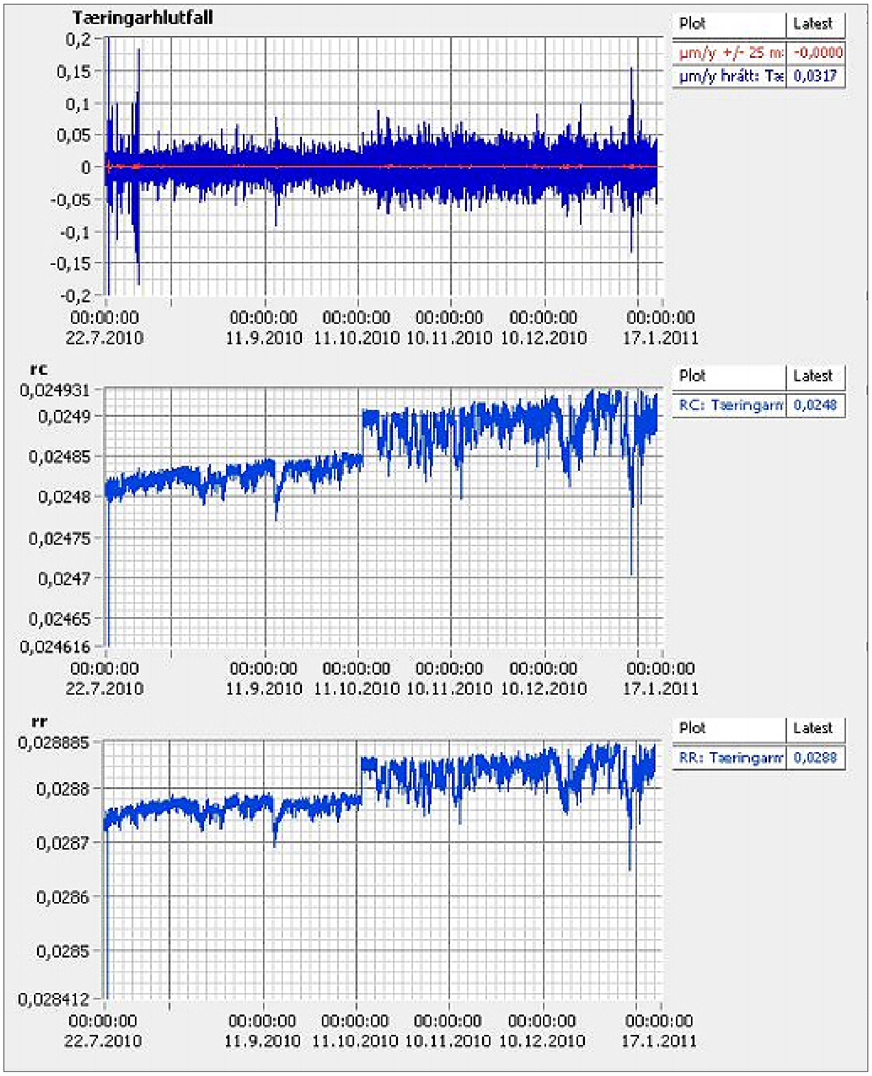

Figure 9. Online monitoring at Keldunes during the entire testing time showing the rate of corrosion.

until the completion of the test. In spite of this increased scatter the corrosion rate remained very low throughout the testing time. Still this change proves the monitoring device to be very sensitive to any change in conditions at the monitoring site.

Discussion and Conclusion

The main aim of the project was to develop and test online corrosion monitoring equipment suitable for monitoring small heating systems where telecommunication were not available at the production site and not even electricity. Secondly the aim was to develop a system to test corrosion potential at drill sites before harnessing in remote areas. For such occurrences a practible and cost effective device for online monitoring is of great value. Thirdly the aim of the project was to test the corrosion rate at the site of Keldunes, in rural NE Iceland where a low temperature geothermal field with a temperature of about 76°C has been was verified and hoped to be harnessed in a near future. Several production tests at the site have revealed severe calcite scaling and possibly some steel corrosion. The corrosion test at the Keldunes site was run during a six month period, both with traditional weight loss coupons and also by online monitoring with ER equipment from MetriCorr. The data logger was powered by solar cells connected to batteries and the data retrieved through a mobile phone connected to the data collection system.

The operation of the system came off very well in spite of harsh conditions and the data were continuously delivered via the mobile phone. The corrosion rate was indeed found to be very slow, 0.5-2.1 µm/year, but by opening the top valve of the well and thereby lowering the pressure, some infinitesmal inflow of air was probably induced, resulting in some increase in corrosion rate. These numbers are in the same range as previously measured in oxygen free district heating systems in Iceland. The corrosion rate was so insignificant however that it could not be quantitatively correlated to the changes recorded by the equipment. Still this change in recording proves the monitoring device to be very sensitive to any changes in conditions in the system.

The device proved to be a useful and cost effective tool to monitor possible changes in corrosion conditions and to be easily assembled and operated at remote sites outside the electric grid. There are many small heating systems in Iceland and in remote places elsewhere where such a device would be of great use and might prevent damage due to corrosion.

For the Keldunes site the test is found to give rather positive results as the corrosion rate is slow and will probably result in a decision to go ahead and start harnessing the field. Hopefully the new *hitaveita* will be successfully installed before the end of this year to great benefit to the rural area where heating has so far depended on expensive electricity.

Acknowledgements

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