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Long term reliability of geothermal plants – Examples from Germany

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ABSTRACT

The paper presents first results of a project aiming at the improvement of the long term reliability of geothermal installations. Scaling, corrosion, thermal water and gas geochemistry and naturally occurring radioactivity are discussed. Results of corrosion experiments show that materials have to be adapted to the thermal water properties of the reservoir. Formation of scales is strongly linked to corrosion problems and degassing of the brine.

1. INTRODUCTION

The reliability of geothermal installations is essential for the profitable geothermal heat and power generation. Operating costs should be low, due to high investments for drilling and construction of the plant. Technical devices must have a high stability to keep the service intervals long and the maintenance costs low.

Seven plants with an installed heating capacity of more than 5 MW each are currently operated in Germany, more plants are under construction. Corrosion and scaling of different levels and failure of components are documented for the plants. For example, in the case of failure of the submersible pumps, pulling and work-over cause high additional costs for the plant operator.

Scaling, corrosion and processes leading to failures of technical devices are under investigation in a multi-disciplinary project. Microbiologists, geochemists, radiochemists, corrosion chemists, geologists and geothermal process engineers are working together in order to develop strategies to extend the life span of materials and devices applied in geothermal plants. Detailed analyses of geothermal brine compositions, dissolved gases and scales at the various locations form the basis of the project.

2. SCIENTIFIC PROGRAM

From a scientific point of view, four main topics are in the focus of the project: material testing, water and gas geochemistry, scale formation and naturally occurring radioactive material (NORM). All of them are closely interlinked, which has to be considered in the discussion of corrosion or scale formation in geothermal installations. Due to the wide range of geothermal reservoir types in Germany the project works together with plant operators in North and South Germany. The Neustadt-Glewe geothermal facility, where a bypass for scientific experiments was build 2005, is in the focus of the studies. Most of the work presented in the paper was done at the pilot plant.

The geothermal plant at Neustadt-Glewe (North Germany) is producing salt-rich brine from a Rhaetian sandstone aquifer located at a depth of 2300 m, production rates are around 100 m³ /h with the temperature being 97 °C at the well head. 12 years experience gathered by the operators and the geochemical conditions make the Neustadt-Glewe geothermal plant an excellent place for a project on long-term reliability.

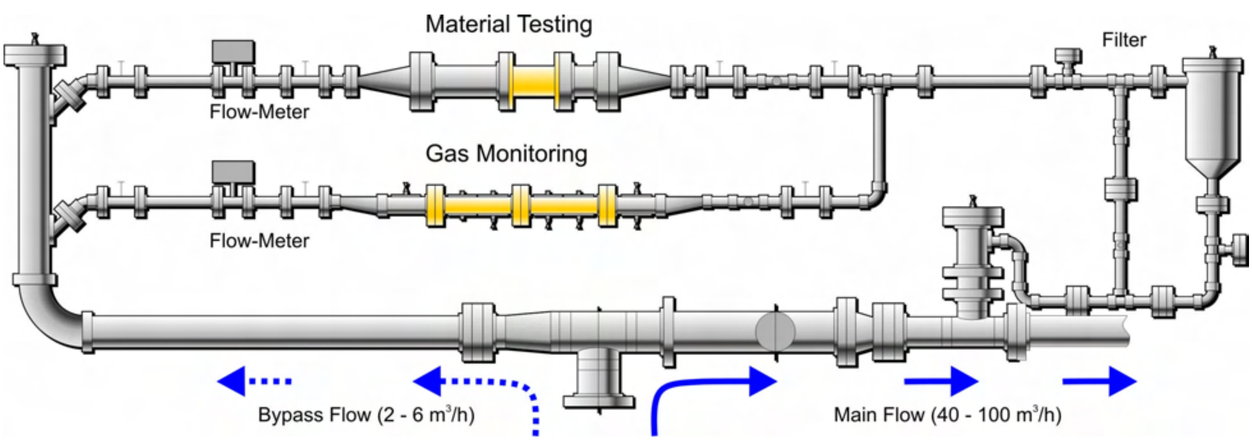

Figure 1: Thermal water bypass for material testing and gas monitoring. A flow of 2 – 6 m 3 /h which is passing sections can be regulated individually by valves, and a flow meter is installed as well. Finally the water will be filtered before re-entering the main flow.

A bypass (Fig. 1) which has recently been installed in the Neustadt-Glewe geothermal plant supplies hot thermal water for in-situ corrosion experiments, material testing and online gas monitoring. Preliminary results from these investigations show a correlation of free gas and the appearance of scales in the Neustadt-Glewe plant.

The release of dissolved gas due to flow turbulences changes the chemistry of the thermal water which affects scaling processes. To predict scaling and corrosion problems in future geothermal facilities, interactions between gas concentrations, variations of the chemical composition of the thermal waters and the behaviour of the construction materials, further investigation is needed.

2.1 Material testing

The thermal water bypass provides very good conditions for material testing and scale formation experiments. Material samples are exposed to the brine as individual samples and in combination, e.g., high-grade stainless steel and red bronze. So, the electrochemical behaviour of the material in the hot thermal brine can observed in-situ. After four-week exposure, the scales formed at the surfaces and the material itself are analyzed. The composition of the scales provides information about the corrosion and scale formation processes and can be compared with scales precipitated at different places in the plant. Experience from the experiment will be applied to prevent corrosion and scaling in the future.

2.2 Gas monitoring

Dissolved gas in the thermal water has been identified as one source for scale formation. At the boiling point or pressure drops, scales form quickly (Arnórsson 1989). Degassing processes, especially when the CO_2 content is high, induce changes of the water chemistry which promote the precipitation of metal sulphides by a rising pH (Hardardóttir et al. 2005). So, it is important to know the gas content and the gas composition for the operation of a geothermal plant. Furthermore, it is fundamental to monitor the long-term development of the gas composition and content.

In Neustadt-Glewe, a gas separation system is installed at the thermal water bypass which provides dry gas for real-time analyses of the gas composition. The analyses are done by a quadruple mass spectrometer with a high temporal resolution of less than 5 minutes; so, changes in the thermal water loop could be detected very quickly. In addition, the d^{13}C and d^{18}O ratios of methane and CO_2 are determined for selected gas samples. By now, the gas monitoring has been carried out only at Neustadt-Glewe. It is planned to perform additional measurements at other geothermal sites.

2.3 Water sampling and analyses

Pressurized hot thermal water has to be sampled with care. An inline cooling unit reduces the temperature of the water to 20°C where pH and Eh could be determined more easily than at temperatures of more than 90 °C. Due to the high gas content and temperatures some volatile components are stripped when the pressure is reduced by opening the tap for sampling (see Fig. 2). So, some components usually analyzed in water have to be detected by different methods in the gas phase.

The water composition is analyzed by ICP-OES, IC and ICP-MS in the laboratory. pH, Eh and acid capacity are analyzed directly after recovery of the samples. In the beginning of the project it turned out that the variability of the water composition in Neustadt-Glewe over time is low, so the sampling intervals are chosen to be small, one sample every 3 to 6 months.

2.4 Thermal circuit inspection

During downtimes, when the thermal loop is stopped, scale samples have been taken for further analyses. Material has been sampled from tubes, valves, filters and heat exchangers. By now, more than 40 samples were taken from different points in Neustadt-Glewe geothermal plant. The different mineral phases are detected by X-Ray diffraction (XRD) and scanning electron microscope (SEM). The chemical composition is determined by ICP-OES and C/S-Analyzer. The mineralogical and chemical compositions of scales in a geothermal loop give important information about the formation processes, thus completing the experiments done at the thermal water bypass.

2.5 Microbiology

Microbially induced corrosion (MIC) is known as a major cause of problems, such as the build-up of scalings, local corrosion, plugging, etc.., especially in oil industry, but also in geothermal plants. MIC showed to occur within a wide range of environmental conditions, including high temperatures of more than 100°C and extreme pH values (Alfaro et al. 2006). Corrosion by microorganisms may proceed either indirectly, via the formation of toxic and aggressive metabolic end products, such as H_2S or sulphuric acid, which then degrade the materials applied in the plants. Recent findings also confirm that microorganisms are also capable of directly retrieving electrons for their metabolism from iron surfaces, leading very rapidly to local corrosion phenomena (Dinh et al. 2004). A third phenomenon often associated with MIC is the formation of extensive and resistant biofilms leading to significant decrease in passage capacities.

Figure 2: Thermal water sampling equipment Degassing processes after release of pressure are responsible for bubble formation in the flow cell.

2.6 Naturally occurring radioactive material (NORM)

Water from high-saline geothermal reservoirs contains naturally occurring radionuclides that may range from background to levels at which radiation protection measures have to be considered.

These radionuclides are accumulated in the geothermal installations in pipes, filters and heat exchangers. Even at low deposition rates, but extracted from large volumes over long periods of time, significant amounts of radioactivity will be measured.

To understand in more detail the processes of radionuclide mobilisation in the aquifer and the deposition processes in the technical installation above ground, a continuous monitoring program regarding primordial radionuclides was implemented. The composition of the aquifer, the geothermal water and the scales were analyzed mainly by γ–ray spectrometry and, additionally, by ICP-MS (^{238}U, ^{234}U, ^{232}Th) and α-particle spectrometry (^{230}Th, ^{210}Po) after radiochemical separation.

3 RESULTS AND DISCUSSION

3.1 Water and gas geochemistry

Analyses of the geochemistry of the water exist since the beginning of the thermal water production in 1995. Data published by Naumann in 2000 and compared to those obtained from the analyses of samples taken recently show no remarkable differences concerning the main ions. The water can be described as brine of the Na-Cl type with a total salt content of 220 g/L. The pH is 5.5 and the temperature at the well head varies from 95°C to 97°C depending on the flow rate.

Data from the online gas monitoring and the analyses of the water data show only small variations over longer periods. The total content of dissolved gas in the thermal water of Neustadt-Glewe is 10 %. The concentration of the components in the separated gas are CO_2 with 73 %, CH_4 - 15 %, N_2 - 10 %, C_2H_4 - 0.7 %, and traces of Ar, H_2, and He. No remarkable changes were measured since the gas monitoring was started at the bypass in 2005.

Table 1: Thermal water composition of the Neustadt-Glewe geothermal plant. The sample was taken in May 2006 at the well head.

Cations [mg/l]		Anions [mg/l]	
K^+	782	Cl^-	128600
Na^+	74000	SO_4^{2-}	647
Mg^{2+}	1410	HCO_3^-	153
Ca^{2+}	8330	BO_2^-	187
Fe^{2+}	71.4	Br^-	400
Mn^{2+}	12.8		
Sr^{2+}	421		
Zn^{2+}	3.29		
Trace elements [µg/l]			
Ag	3.01	Ba	5470
Cu^{2+}	<20.0	Pb^{2+}	526
As	<150	U	0.122
Ni^{2+}	<10.0		

The composition of the brine is typical for Rhaetian aquifers in North Germany (Naumann 2000). Shallower aquifers in the north German basin might have a lower salinity (Hoth et al. 1997). The Strontium content, which is high in Neustadt-Glewe, plays an important role when discussing the formation of Celestine and the NORM potential of geothermal heat and power generation.

3.2 Scaling and Corrosion

The main components of the scales found in the Neustadt-Glewe geothermal plant are lead, galena and barium-rich celestine. The lead concentration in thermal water is surprisingly low with 0.5 mg/L; so, Pb^{2+} was not seen as the source of remarkable scale deposits in the beginning of the project.

Celestine and barite are slightly undersaturated in the circulated thermal water. We found those minerals only at places where the temperature is reduced. Due to the temperature dependency of the solubility product, barite and celestine might be supersaturated at places where the temperature is lowered by, e.g., measuring probes.

In some areas, mainly on rubber-coated steel tubes, the scales consist of lead sulphide only forming small crystals with 100 µm in diameter. Those crystals cover the tube surface with a thin film; the influence on the operation of the plant is small.

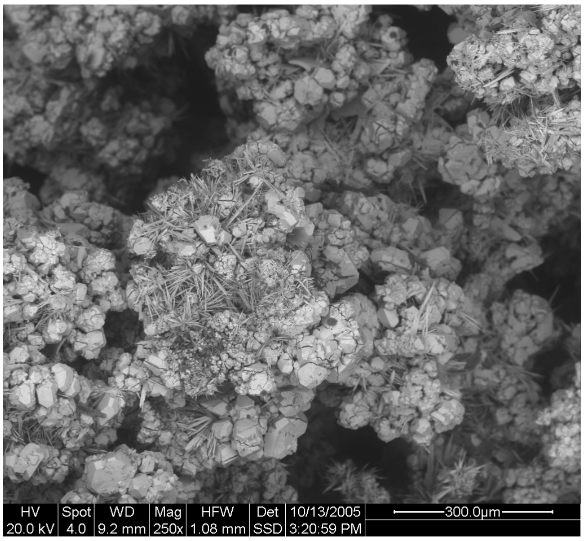

Figure 3: SEM photograph of galena crystals forming massive scales on flanges.

At places where corrosion processes were observed and/or turbulences are induced, much thicker deposits were detected (Fig. 3). One example was found at the well head where a carbon steel tube was installed over a period of less than one year. Up to 2 cm thick Scales formed directly at the tubes flanges. The scale samples consist mainly of lead and lead sulphide. Due to electrochemical steel corrosion elemental lead is formed while iron is oxidized and dissolved as Fe^{2+} in the thermal water (see Fig. 4).

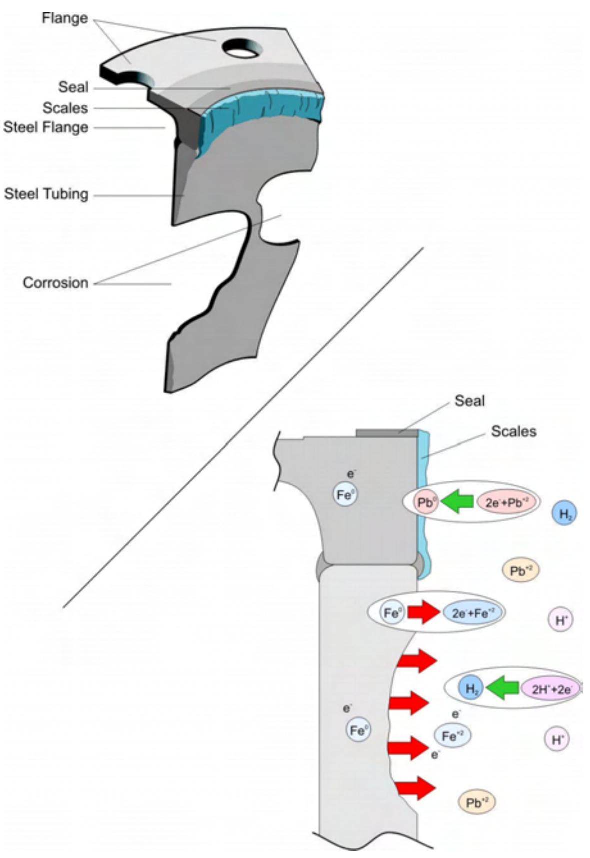

Figure 4: Simplified electrochemical steel corrosion; while iron is oxidized lead precipitates at the flanges. The deposits observed form up to 2 cm thick scales.

Dissolved sulphide in the thermal water is negligible. So, processes that form sulphide to promote the precipitation of lead sulphide have to be proven (eq. 1). Steel corrosion as shown in Fig. 4 reduces the redox potential which promotes the reduction of sulphate to sulphide. But also microbial activity has to be taken into account as a source of sulphide.

$$SO_4^{2-} + 4\,H_2 \;\rightarrow\; S^{2-} + 4\,H_2O$$

$$Pb^{2+} + S^{2-} \;\rightarrow\; PbS \qquad (1)$$

Living and active microbes were identified even in nearly 100°C hot geothermal water at Neustadt-Glewe, using molecular techniques such as fluorescence in-situ hybridisation (FISH) and quantitative PCR. Significant numbers of corrosive groups, such as sulphate-reducing or methanogenic microorganisms were detected in water samples and on scaling from plant material. The chemical analysis of the water revealed the presence of a rich variety of nutrients and electron acceptors. For valuation of the impact of microbial activity on the formation of scales, the sulphate reduction rates have to be measured.

The results of the bypass and corrosion experiments show that the formation rates are high for lead and lead sulphide. E.g., precipitations rates of 190 mg/(m^2 d) were measured in an experiment with construction steel being tested in combination with stainless steel in the bypass. It is unlikely that bacteria are responsible for those high rates. Most probably electrochemical processes have the biggest impact on corrosion and scaling in the geothermal plant of Neustadt-Glewe.

Minerals which precipitate due to supersaturation such as barite and celestine play a minor role in the thermal loop. The impact of degassing processes and its influence on the pH promote the precipitation of metal sulphides (Hardardóttir et al. 2005). There might be additional overlaying processes, because lead scales with minor amounts of sulphide formed at locations where turbulences in thermal water are induced, e.g., by bent tubes.

3.2 NORM

Along with the above mentioned high salinity the thermal water at Neustadt-Glewe contains 7,4 Bq/L ^{226}Ra, 0,3 Bq/L ^{210}Pb, 8,6 Bq/L ^{228}Ra, 4,8 Bq/L ^{224}Ra respectively. The sources of these radionuclides are the radioactive decay chains ^{238}U and ^{232}Th in the aquifer, where all radionuclides have reached secular equilibrium with concentrations for both decay chains in the range from 5 to 50 Bq/kg, which is equivalent to 0.4 – 4 ppm U and 1.2 until 12 ppm Th. The geochemical conditions in the aquifer cause mainly a transport of the radium isotopes ^{226}Ra ($T_{1/2}$ = 1600 a), ^{223}Ra ($T_{1/2}$ = 11,4 d), ^{228}Ra ($T_{1/2}$ = 5,7 a) and ^{224}Ra ($T_{1/2}$ = 3,6 d) without support of the predecessor in the decay chain. The activity concentration of ^{226}Ra, ^{228}Ra and ^{224}Ra is high enough that these nuclides are detectable after the period between the solution in the aquifer and the sampling at surface. The observed ratio ^{226}Ra/^{228}Ra of 1.0 ± 0.2 in the geothermal water represents the ^{226}Ra/^{228}Ra ratio in the aquifer.

The activity concentration in the geothermal loop long-life ^{238}U and ^{232}Th was at least 3 orders of magnitude lower than the concentration of the Ra isotopes. ^{226}Ra, ^{210}Pb and ^{228}Ra are accumulated in the filters and scales and can reach specific activities of up to 10^2 Bq/g. The origin of ^{228}Th ($T_{1/2}$ = 1.9 a), which is only analyzed in the scales is the radioactive decay of the mother nuclide ^{228}Ra ($T_{1/2}$ = 5.7 a).

Due to the high specific activities, the contaminated technical materials are classified as radioactive residues and must be supervised permanently. A release from regulatory control is possible if the radiation exposure for a population member is lower than 1 mSv/a.

4 CONCLUSIONS

The project is now in the third year and some results are understood well by now. So the following points can finally be figured out: 1. Corrosion in the geothermal plant Neustadt-Glewe is mostly electrochemically driven. Bacteria which are present may play a minor role. 2. The thermal water composition did not change throughout the recent decade. 3. Degassing processes promote the formation of scales. 4. Radionuclides from the geothermal water are accumulated to an extent at which radiation protection measures are recommended.

A proper material selection and plant design adapted to the water geochemistry will help to increase the long-term stability of geothermal installations. E.g., using45° bent tubes reduces degassing processes. The prevention of scaling decreases the formation potential of NORM. It is important to regard those points and the water and gas geochemistry in an early stage when constructing geothermal plants.

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