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Monitoring of Hydrogeothermal Plants in Germany – an Overview

Peter Seibt*, Frank Kabus*, Markus Wolfgramm*, Jörn Bartels*, Andrea Seibt**

* Geothermie Neubrandenburg GmbH, Postfach 11 01 20, D-17041 Neubrandenburg
gtn@gtn-online.de

** BWG – Geochemische Beratung GbR, Seestrasse 7A, D-17033 Neubrandenburg
bwg-a.seibt@t-online.de

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ABSTRACT

New plants are put in operation in Germany every year based on a series of national programmes supporting geothermal energy use. The three most important geothermal regions – Molasse Basin, Upper Rhine Graben, North German Basin – differ essentially by the hydraulic and geochemical behaviour of the exploited aquifers.

The high production flow rates and temperatures required especially for the generation of electricity and aquifer energy storage systems are a challenge to the operators. The operation of geothermal plants in the above regions are accompanied by monitoring programmes focusing on the long-term behaviour of the geothermal reservoir – geothermal plant system.

Topical results of investigations are presented for individual exemplary geothermal plants.

1. INTRODUCTION

Geothermal heat and power generation plants are to be distinguished from conventional energy plants by the integration of the geothermal reservoir – geothermal plant system. As the plants being commissioned now are constructed at sites with different geological conditions, also the applied modes of operation and gathered experience will be very different. Solely continuous monitoring will help to recognise failures of the system very early and to take relevant countermeasures. Monitoring focuses on the following:

- Geochemical and microbiological investigations of the thermal waters (incl. gas content/ex-solving) to create conditions which avoid precipitations to the maximum possible extent;

- geohydro- and thermodynamic behaviour of the exploited aquifer.

2. GEOTHERMAL REGIONS IN GERMANY

Three large sedimentary basin systems exist in Germany, forming also the main geothermal regions (Fig. 1).

(1) The geothermal aquifers in the North German Basin (NGB) which originated in the Permian Carboniferous are basically composed of Mesozoic, rarely even Rotliegend porous and fractured-porous sandstones (Feldrappe et al. 2007, 2008).

(2) In the Upper Rhine Graben (URG) - a sedimentary graben system originating in the Tertiary - the main aquifers (Buntsandstein, Rotliegend: fractured-porous sandstones, basement: granite) are situated below the filling of the graben.

(3) The Molasse Basin (MB) was also formed in the Tertiary, along with the alpidic mountains. The main aquifer – Malm – (fractured or fractured-carstified carbonates) is situated too below the sedimentary filling of the basin.

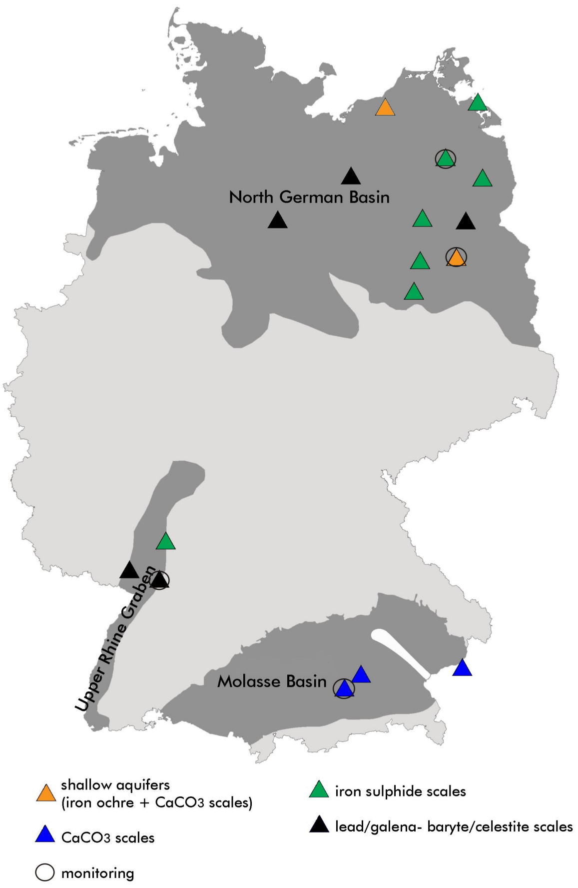

Figure 1: Main geothermal regions and sites in Germany where monitoring is done or which are serviced by the AQUISCREEN project (triangles)

For better characterisation of the aquifers and the waters in particular, totally around 4,100 water samples were analysed which were taken from wells at depths of more than 2,000 m. The data generation and quality differ quite a lot. More data were taken from the technical literature (among others, Naumann 2000, He 1998, Wedewardt 1995, Otto 1992, Klinge 1991, Langguth & Plum 1984, Lehmann 1974).

The collected data allow for a basic typification and characterisation of the waters in Germany (Wolfgramm &

Seibt 2008). Local deviations from the trends presented in the following have to be considered.

The analysis of 2,700 water samples taken in the NGB shows a relatively uniform composition. The salinity increases by 10 g/L (Tertiary – Keuper) up to approx. 15 g/L (Buntsandstein) per 100 m depth. The concentration of individual ions increases evenly mainly. Na-Cl waters occur down to depths of 2,000 m, Ca-Na-Cl waters are located deeper. Also the gas contents increase from 0.005 to approx. 2 L/L of fluid. (2) The main aquifer waters in the URG (Buntsandstein/basement) are highly saliferous as well. Salinities between 95 and 140 g/L were determined for depths ranging from 1,500 to 3,500 m. These are also Na-(Ca)-Cl waters which are characterised by high gas (0.005 – 4 L/L of fluid) and CO_2 contents. Relatively high concentrations of fluoride (up to 35 mg/L), arsenic (up to 15 mg/L), H_4SiO_4 and iron (up to 200 mg/L, respectively) are typical. Both the NGB and the main aquifer waters in the URG are mainly basinal and evaporitic. The high salt and chloride contents produce corrosive conditions and a high risk of electrochemical corrosion. Due to the degassing of CO_2, carbonate precipitation has to be considered; temperature changes lead to the precipitation of SiO_2 and sulphate minerals. (3) Other than the above, the young Malm infiltration waters in the MB show low salinities up to approx. 1 g/L which may increase up to 5 g/L due to inflowing Tertiary waters. CH_4 and CO_2 dominate the gas contents with 0 to 0.5 L/L of fluid. There is a high risk of carbonate precipitation resulting from degassing. The H_2S content of up to approx. 25 mg/L must be particularly considered due to its corrosive impact.

Quite a number of geothermal plants was installed in the three main geothermal regions. A good overview is provided by the geo-information system GeoTIS (www.geotis.de). Four geothermal plants were selected for a comprehensive monitoring programme (Fig. 1). In addition, more selected sites are investigated regularly for the water and gas chemism, the solid contents, microbial inventory and organogenic components under the AQUISCREEN research project.

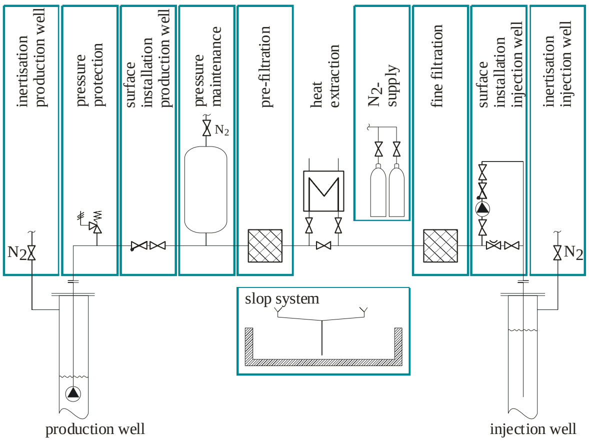

Figure 2: Elements of the surface thermal water loop

3. PLANT CONFIGURATION

Hydrogeothermal surface loops can be combined by the elements presented in Figure 2 for the known cases of application in the above geothermal regions in Germany. Numerous components required to guarantee the safe operation are integrated along with the pipelines for the transport of the thermal water to the place of its thermic use in recuperators for heat production and/or evaporators for power generation in binary cycle processes. Their necessity and shaping depend on the geothermal region where the plant is installed on the one side, and on the production flow rate – even more on the production temperature and the cooling of the thermal water prior to injection - on the other side.

Independently of the site, it can always be assumed that

- the overall loop has to be kept under a specific overpressure. The ex-solving of gases and of CO_2 in particular must be avoided due to the risk of lime precipitations. Moreover, two-phase flows imply other problems in general, reaching from the impact on the sensor technology (flow rate) to cavitation and erosion. It is inevitable to have the pressure maintained in operation by means of a valve installed at the injection well, but also by means of a nitrogen-filled buffer tank when non-operative for compensation of the thermal water volume contraction while cooling, and of the water level changes in the wells while closing the well head fittings.
- the contact of atmospheric oxygen with the water must be excluded which would lead to corrosion and the release of particles. Along with diffusion-tight casings, there must be provided nitrogen admission to all interphases in the loop, i.e. in the annular spaces of both wells and the buffer tanks. When using Palaeozoic waters in the NGB, their – as a rule – high N_2 content allows for self-inertisation.

The positioning and shaping of the thermal water filtration units depend mainly on the specific conditions of the injection horizon.

In any case, the coarse particles (50 … 100 µm) must be separated after production to avoid in particular erosion of the downstream equipment and sedimentation in static water sections. The injection water quality achievable in this way in the Bavarian Molasse Basin and in the Upper Rhine Graben is mostly sufficient already. Filtration must be much finer in the North German Basin where there are no karstified or fractured aquifers, but porous reservoirs. A second fine filtration unit has to be installed immediately before the injection well which must be adapted to the pore space geometry.

Due to the salinity of the thermal waters and the related environmental impact when discharged into surface water bodies, exclusively automatic changeover filters with filter elements (bags, cartridges) are applied for filling of the geothermal loop systems in the NGB and the URG. The Malm waters allow for automatic backwashable filters.

A separate slop system is required for the reception of leakage and flushing water in the case of saliferous thermal waters. But, such a tank has to be provided mostly even in the Malm karst serving for cooling of the waters exclusively, followed by proper discharging.

Conventional deep drilling technologies applied in the oil and gas industry are used for the installation of the underground system.

The well is completed after successful drilling. Two variants are possible for the final installation of a geothermal plant directly in the reservoir section: Open-hole and cased-hole completion.

Open-hole completions of production and injection wells have been favoured in the recent years due to generally better hydraulic conditions.

When the reservoir rock is little consolidated (e.g., sandstone reservoirs tending to sand out in the case of hydraulic strain), special additional completion measures have to be taken. For the gravel pack – the variant of completion which is applied typically for geothermal wells in the NGB – the annular space remaining after extension of the well in the reservoir section and installation of a wired screen is filled with filter gravel adapted to the grain size of the reservoir sand. Such additional sand control measures can be abstained from when the reservoir is very stable.

In the Bavarian MB, the open reservoir section is protected by slotted liners.

4. MONITORING

4.1 Thermal water analysis

The thermal water is regularly analysed within the framework of the monitoring programme. The extent of the analyses and the frequency of sampling vary depending on the kind and mode of operation of the plant concerned. In principle, full water analyses are done in major intervals, and relevant site-specific parameters are analysed in minor intervals. Especially SiO_2 and heavy metals are investigated periodically in the Neubrandenburg heat store installation (Kabus et al. 2009).

Generally, the basic parameters such as pH, Eh values and conductivity are determined by means of measurements in a flow cell. All important main components (Na^+, K^+, Ca^{2+}, Cl^-, SO_4^{2-}, HCO_3^-) and the most important secondary components (e.g., Fe^{2+}, Mn^{2+}, Br^-, J^-, SiO_2) are subjected to full analyses. The programme for the analysis of the trace elements varies depending on the site.

4.2 Analysis of particles in the thermal water flow

Along with water samples, solid samples are taken as well in the geothermal plants, mainly from the filters. Moreover, a special filtration method was developed for the very fast separation of the solids from the thermal water flow within the system. Solid samples were taken from the well sump or plant components during bottom-hole sampling or repair, respectively. By now, more than 200 solid samples have been taken and investigated by means of microscopic methods (reflected light microscopy, SEM investigations combined with EDX analysis).

Proper sampling and immediate preparation of the samples are very important, since in many cases the minerals transform quickly due to the impact of atmospheric oxygen (e.g., oxidation of iron sulphides).

Generally, detrital particles from the aquifer, technical particles from the plant and newly formed minerals can be distinguished (cf. Wolfgramm & Seibt 2006). In particular, samples taken at different points of the plant (before and after the heat exchanger, etc.) give – duly considering the mode of operation of the plant and the results of the analysis of the water and microbial samples – significant markers for the thermal water behaviour during the operation of the geothermal plant.

4.3 Determination of the gas content and composition

The composition of the free gases and of those which are dissolved in the water as well as the gas:water ratio are very important for the smooth operation of a geothermal heating plant as the gases dissolved in the water under formation conditions ex-solve when the pressure is relieved which may lead to major technological problems.

Basically, the aquifer conditions are responsible for the maximum limitation of the amount of the dissolved gases. Those gases which occur in geothermal sources can be subdivided in two groups – 1) the reactive gases CO_2, H_2S, NH_3, H_2, and hydrocarbons (such as CH_4) forming together with the inactive N_2 the main components of the gas phase and taking part in chemically balanced reactions, and 2) the inert gases such as the noble gases. In particular, the so called reactive gases should not degas in order to avoid scaling.

For gas measurement, thermal water samples are taken continuously from the thermal water loop via a by-pass and supplied to a mobile degasser (cf. Figure 3). According to experience, a temperature of approx. 95 °C must be adjusted by regulation of the cooling water for the almost complete degassing even of the freely soluble gases. Constant temperature of the fluid and stable relations among the inflow and outflow of the fluid must be adjusted as a prerequisite of proper degassing.

The gas flow is registered by means of a drum gas meter and related then to the degassed water.

Gas samples for laboratory investigations are taken when determining the gas:water ratio. As a rule, Ar, O_2, N_2, CO_2, CH_4, H_2, as well as higher hydrocarbons (ethane, propane, butane, pentane, hexane, propylene, etc.) and hydrogen sulphide are analysed.

The share of the freely soluble gases such as of carbon monoxide in the degassed fluid is determined in-situ via the base capacity (KB value up to pH = 8.2).

The degassing pressure is determined based on the gas:water ratio established in this way and the gas and water composition.

Figure 3: Set-up of measuring instruments for gas sampling

4.4 Microbiological monitoring

The AQUISCREEN project includes, among others, microbiological monitoring of geothermal plants in Germany (Fig. 1, Würdemann et al. 2006, 2008). For that the molecular-biological "fingerprinting" method (polymerase chain reaction - single-strand-conformation polymorphism-based genetic profiles of small-subunit rRNA genes, PCR SSCP) is applied for the identification of the microbial biocenosis. The phylogenetic classification of the found microorganisms is done based on their 16S rDNA allowing for conclusions regarding the metabolic processes dominating in the geothermal plants. The detailed investigation of the organogenic components of the waters and filter residues indicate microbial activities as well (Vetter et al., WGC 2010 Proceedings).

Microbial activities in geothermal wells and plants have been underestimated before, but they are particularly important at temperatures < 100 °C, as it could be demonstrated already by means of the microscopic investigations of the solids (cf. Figure 4).

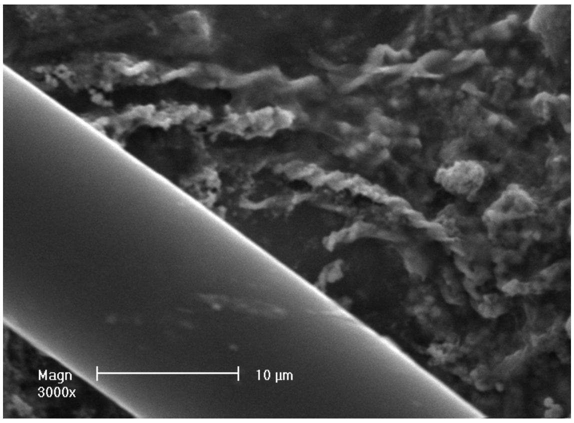

Figure 4: SEM photo – cold store for the Berlin Reichstag building: spiral iron hydroxide formed by Gallionella sp.

4.5 Injectivity monitoring

The knowledge of the topical and future hydraulic and thermic state of the underground installation of the geothermal part is the key to the understanding of the dynamic behaviour of the overall system and the long-term safe and stable operation of the entire plant.

The numerical simulation of the hydraulic and thermic processes in the underground allow for the calculation of the development of the aquifer state in terms of space and time jointly with the operational data of the plant. The condition is the adequate preparation of the operational data for the injection and production.

The considerations focus on the injectivity of the reinjection well – along with the prognosis of the thermic service life of the plant (limited by the thermal breakthrough of the reinjected water at the production well).

The beginning of a deterioration of the injectivity must be recognised early enough for countermeasures. For that it is necessary to distinguish extraordinary behaviour and normal trend when evaluating the measured injectivity values. In a geothermal doublet, the normal trend originates from the increasing cold water share in the underground around the near injection well zone and the related increasing viscosity contribution to the injection pressure. A beginning well damage and its nature may be concluded only from the pressure shares which changed beyond.

GTN applies the reservoir simulator FEFLOW (DHI-WASY 2008) for the calculation of this normal trend based on the continuously registered operational data. In particular, these are flow rate, temperature and pressure at the production and injection wellheads. It would be best to include also downhole pressure measurement as a part of the monitoring system – however, this has not been done by now anywhere. Extension and temperature of the cold water zone around the reinjection well depend on the overall injection history which must be put in the model completely with a time resolution of 1 to 15 days. For heat store wells with annually repeating cycles it is possible to generate standard curves of the injectivity drop without modeling. Deviations from that – usually similar - mode of operation indicate extraordinary processes in the injection well (Figure 5).

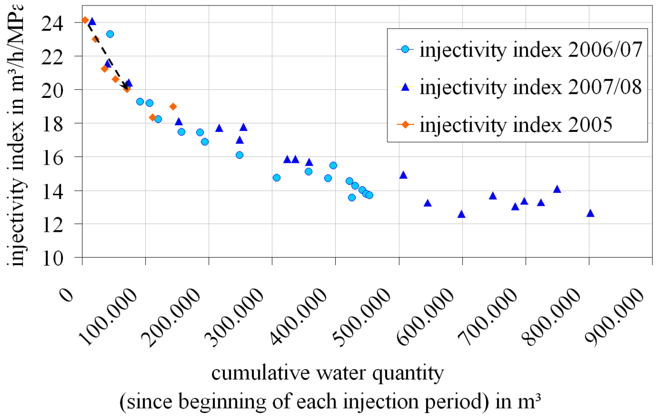

Figure 5: Temperature-corrected injectivity-quantity relation of a heat store well (cold side): standard curve of the temperature-dependent injectivity drop based on operational data of several years for early detection of deviations

When relating the injectivity of a well to the wellhead pressure, then the real injection temperature will affect the real value. The weight of the water column in the well changes with the injection temperature, and the share of the injection pressure to be contributed by the additional wellhead pressure will vary accordingly. That is why the injectivity value with its observed trend applied for the monitoring refers to the wellhead pressure plus the pressure share of the water column in the well, thus being independent of the temperature.

The temperature-corrected value of the injectivity index (II_{corr}) is calculated with respect to a reservoir "overpressure" (denominator in eq. (1)) as follows

$$II_{corr}\left[\frac{m^3/h}{bar}\right] = \frac{Q_{circ}[m^3/h]}{(\Delta p_{head} + \Delta p_{column} - p_{reservoir})[bar]} \quad (1)$$

with

$$\Delta p_{column}[bar] = \frac{\rho_{reservoir,temp}(T_{inj})[kg/m^3] * 9.81[m/s^2] * Z_{reservoir}[m]}{100.000} \quad (2)$$

p_{head} wellhead pressure

p_{column} pressure contribution of the water column

$p_{reservoir}$	undisturbed reservoir pressure
$\rho_{reservoir,temp}$	density of the thermal water, temperature-dependent
$Z_{reservoir}$	well depth
T_{inj}	injection temperature
Q_{circ}	circulation rate

Here, the pressure losses due to friction in the well are not considered. However, they do not depend on any trend or temperature-related variations and can thus be considered as a constant contribution to the injectivity.

4.6 Monitoring of the production temperature

Changes of the inflow conditions, horizontal temperature differences, e.g., in inclined aquifers, and the thermal breakthrough of the cold water front may lead to the change of the production temperature.

In order to be able to recognise potential trends resulting from the described causes, the temperature loss in the production well must be calculated and the production temperature at the wellhead be corrected by this value.

When producing thermal water from deeper reservoirs, heat losses will occur in the well due to the heat exchange among the thermal water and the surrounding rock. Along with the material parameters of the thermal water, the well and the surrounding rock, these losses depend on the production flow rate.

For that, a cylinder-symmetric numerical model of the well and the surrounding rock is applied, and the time history of the wellhead temperature is calculated based on the adequate mean history of the production flow rates. SHEMAT is applied as simulator (Clauser et al. 2003). The bottom hole temperature is adapted until the measured and the calculated well head temperature will comply. Then, the bottom hole inflow temperature trend can be evaluated. But it is best practice to evaluate and adapt phases of continuous production as long-lasting as possible.

5. SELECTED MONITORING EXAMPLES

5.1 Thermal water chemistry (Neubrandenburg heat store)

For three years now, the approx. 1,200 m deep Postera sandstone is used as a heat store in Neubrandenburg (Kabus et al. 2009). In summer, cold water is produced from the well Gt N4 at flow rates of 100 m^3/h, heated up above ground by means of the waste heat arising from the local gas and steam cogeneration plant and injected in the “warm” well Gt N1. In winter, the direction of flow is reversed: The water is produced from the well Gt N1 at temperatures of approx. 70 – 80 °C, the heat is absorbed by a heat exchanger and used for heating, and the cooled water (approx. 45 °C) is injected in the “cold” well Gt N4. Geochemical reactions are to be expected due to this seasonal operation and the cyclic variation of the temperature conditions. It is planned to increase the maximum charging conditions from 80 °C to 90 °C which is possible according to geochemical modeling and laboratory tests. Nevertheless, both the operation and the increase of the temperature will be accompanied by monitoring. In the course of the store operation, the heavy metal contents in the fluid have increased, in particular zinc, but also copper, etc. Also heavy metal sulphides (e.g., copper sulphide) can be proven in the aquifer since the commissioning of the system. Other precipitations could not be observed. However, the microbial activity increased on the cold side (Gt N4) resulting mainly in iron sulphide formation and viscous fermentation in the well. In winter 2008/spring 2009, it resulted in a heavy decrease of the injectivity of the well. In spring 2009, soft acidising was done, thus eliminating the damages.

5.2 Analysis of particles in the thermal water flow (Unterhaching geothermal plant)

Under the monitoring programme in the Unterhaching Geothermal Plant, solids have been collected and analysed regularly which showed that these consist by approx. 50 % of aragonite/calcite, and 40 % of iron and copper sulphide which formed newly. Minor quantities of aquifer dolomites, technical particles (plastic residues, etc.) and clay minerals were observed.

Mainly, the sulphides showed grain sizes ranging from 10 to 50 µm intergrown in crusts of 100 – 1000 µm (Figure 6). 85 % of the carbonates show grain sizes > 200 µm. It could be demonstrated by monitoring that the solids filtration unit before the heat exchanger is dimensioned sufficiently.

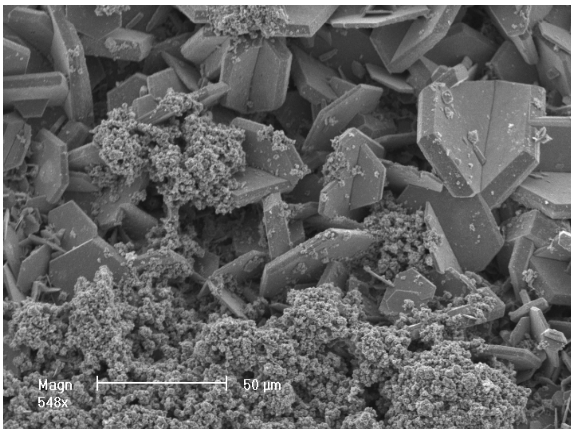

Figure 6: Thin-shaly iron sulphides in the Unterhaching geothermal plant (SEM photo of a filter sample)

5.3 Determination of the gas content and composition (Unterhaching geothermal plant)

Degassing tests were done at three different measuring points in the thermal water loop of the Unterhaching geothermal plant in the Bavarian Molasse Basin in order to record the impact of structural components and, thus, different flow conditions. The measuring points A and B were arranged directly on the production well side, measuring point A (fluid temperature = 64 °C) and measuring point B (fluid temperature approx. 93 °C) after the heat exchanger, and measuring point C at the injection well with the aim to measure over a longer period of time in order to qualify the variations of the gas:water ratio. At the sampling point A = 145 cm³, B = 110 cm³, and C = 105 cm³ of gas were dissolved in 1,000 ml of fluid under the described conditions and converted into STP "Standard temperature and pressure“ (T = 298.15 K, p = 1.01325 hPa).

The gas collecting pipes were slightly air-contaminated. The gas compositions given in Table 1 result from the relevant correction.

Table 1: Gas composition of the samples at the measuring points A, B, and C (MP – Measuring Points)

MP	T_{Fluid}	Gas contents (STP)	Gas composition [vol.-%]					
	[°C]	[dm/dm³]	N_2	CH_4	$\sum C_nH_{2n+2}$	CO_2	H_2S
A	91-94	0.15	20.7	40.3	3.3	34.4	0,4
B	64	0.11	22.7	50.8	3.9	22.4	0,1
C	63	0.11	13.1	49.1	3.9	33.5	0,2

As expected, more freely soluble gases are degassed by means of the degasser at a thermal water temperature of approx. 93 °C (A) compared to approx. 63 °C (B). Comparing the results it becomes clear that the degassing temperature decides on the gas composition. That is why the carbon dioxide dissolved in the water was determined after degassing via the base capacity (KB value up to pH = 8.2). Solute sulphide was also proven in the degassed fluid at all measuring points. Duly considering the solute carbon dioxide and the solute sulphide concentration, the gas contents and compositions were corrected. These results are shown in Table 2.

Table 2: Gas contents and composition (MP – Measuring Point, KB – KB value)

MP	KB	H_2S diss.	Total gas content (STP)	Gas composition with solute CO_2 [vol.-%]			
	[mmol/L]		[dm/dm³]	N_2	CH_4	CO_2	H_2S
A	**1.25**	**1.76**	**0.21**	**14.3**	**30.1**	**36.9**	**18.7**
B	2.55	1.05	0.19	13.0	31.4	43.1	12.4
C	2.22	0.69	0.17	8.2	33.1	49.1	8.9

Sample A is affected least by the operation. The gas mixture consists mainly of carbon dioxide and hydrogen sulphide (56 vol.-%), methane, ethane and other hydrocarbons (approx. 30 vol.-%) as well as of nitrogen (14 vol.-%), secondarily. The total gas content amounts to 210 cm³/L. These results form the basis for the determination of the degassing pressure.

The investigations show that obviously a very small share of gas is released in the heat exchangers, predominantly of nitrogen. Another slight decrease of the gas share in the fluid is observed towards the injection well. These results must be verified by continuous monitoring.

5.4 Monitoring of the injectivity (Neustadt-Glewe geothermal plant)

Since 1997, the operational data of the geothermal plant are evaluated regularly for the determination of the injectivity, applying only operating states with sufficiently long-lasting constant mode of operation in order to eliminate the effect of the start-up and shut-down processes. If required, such operating states are realised at a constant rate and in manual operation particularly for the determination of the injectivity. However, the constancy of the temperature cannot be influenced as it depends on the heat consumers.

When outlining the temperature-corrected injection pressure via the injection flow rate as in Figure 7, then all values will be on a straight line assuming constant injectivity. This straight line is given in Figure 7 for two different well states. Figure 7 shows a significant deterioration of the injectivity in October 1998 and beginning in September 2008. The evaluation of the data obtained after soft acidising shows, respectively, that the initial state after the installation of the well („initial value 11/97“) could practically be re-established (Seibt & Wolfgramm 2008). The values are again on the original straight line.

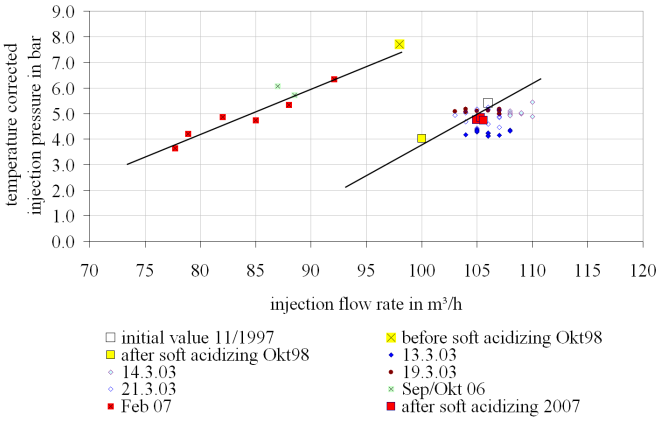

Figure 7: Temperature-corrected overpressure according to Equation (2) depending on the injection rate at different operation stages of the Neustadt-Glewe geothermal plant

5.5 Monitoring of the production temperature (Neustadt-Glewe geothermal plant)

The observed dependency of the production temperature on the production flow rate was simulated by means of a numerical model for the cooling of the produced thermal water in the production well. Thus, a decrease of the production temperature which may occur for other reasons (e.g., inclined reservoir layers or thermal breakthrough) can be separated from this effect and recognised at all. Figure 8 shows the operational data and the results of a SHEMAT simulation (Clauser et al. 2003) outlined via the production flow rate. It becomes evident that the simulation is very well able to reproduce the measured data.

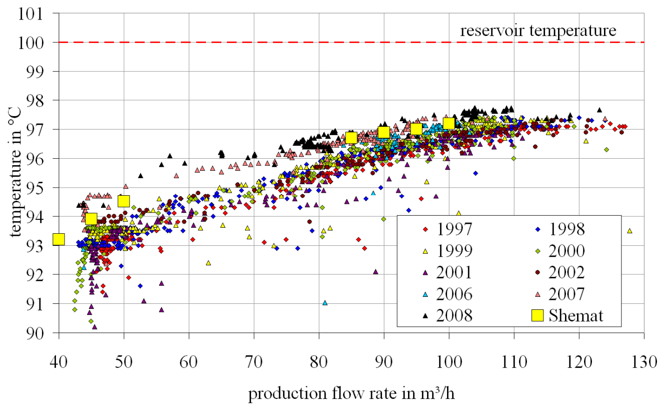

Figure 8: Maximum wellhead temperature at Gt NG 1/88 from 1997 to 2008 und values obtained from a SHEMAT simulation with a reservoir temperature of 100 °C

6. CONCLUSIONS

The continuous monitoring of the operating conditions of the geothermal reservoir – geothermal plant system is an essential prerequisite for the stable operation of geothermal plants, based on a good knowledge of the geohydraulic and geological-geochemical reservoir parameters determined during the development.

At present, cycles and methodology of measurements are optimised in a series of monitoring programmes adapted to the particularities of the geothermal regions in Germany. The experience gained from previous monitoring programmes shows that the operator can be supplied with well founded statements for the optimisation of the plant operation.

The results of the monitoring are considered in the design of new plants.

7. ACKNOWLEDGMENT

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- Monitoring and enhancement of the capacity of a geothermal cogeneration plant in the Malm karst of the Bavarian Molasse Basin – the example of Unterhaching (project no. 325041)
- Seasonal aquifer storage of surplus heat arising from a gas and steam turbine cogeneration plant - monitoring and optimisation of the operation of the Neubrandenburg aquifer heat store at increasing store temperatures (project no. 0329838B)
- Modular monitoring of the injection water quality (project no. 325102)

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