INTERNATIONAL SUMMER SCHOOL
on Direct Application of Geothermal Energy

Under the auspice of:
Division of Earth Sciences

Chapter 3.4

An Integrated Geosciences and Engineering Approach to put low Permeability Aquifers to use

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Figure 1: Hydrothermal resources in Germany

Keywords: hydraulic stimulation, North German Basin, ORC, down-hole laboratory

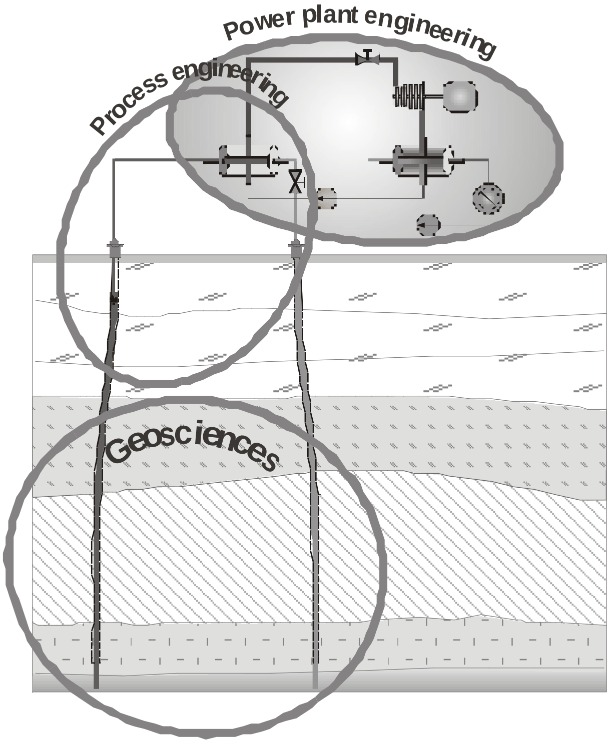

Figure 2: Multidisciplinary approach to geothermal electricity generation

Abstract

A multidisciplinary approach to make the generation of geothermal electricity available in the region of the North German Basin was launched in 2000. The goal is to learn how to stimulate a variety of rock types to improve flow rates in low permeability geothermal reservoirs. An in-situ down-hole laboratory was established by opening and deepening the former gas

Introduction

Most geothermal plants, power plants as well as heating stations, are located at geothermal anomalies, where an aquifer with sufficient porosity (fluid amount) and permeability provides the medium for heat extraction. Temperatures required for geothermal applications can usually be attained by drilling deeper. Although drilling is an important cost factor, it is generally the flow rate from the reservoir that determines the technical feasibility of exploitation. Flow rates depend on the permeability distribution in the geothermal reservoir. Even if temperature is high enough in a reservoir of sufficient porosity and fluid content, exploitation may be precluded by low permeability, unless it can be enhanced with appropriate stimulation procedures.

In the North German Basin a number of geothermal heating stations exists (Figure 1). All these installations use highly permeable porous sandstone reservoirs at depths of 1000 – 2500 m. Temperatures range from 62°C (Waren, 1500 m deep) up to 98°C (Neustadt-Glewe, 2250 m deep) (Schellschmidt et al., 2000; Erbas et al., 1999).

Geothermal electricity generation becomes attractive at temperatures above 100 ºC and flow rates of at least 50 m3/h. Such temperatures are found at depths of the order of 3000-4000 m in much of the North German Basin and large areas worldwide. Permeability to accommodate high flow rates, however, occurs less frequently in this depth range unless it can be created.

The GeoForschungsZentrum (GFZ) initiated a multidisciplinary approach towards geothermal electricity generation at locations devoid of geothermal anomalies and with low permeability. The purpose of the project is to develop technology to increase permeability of deep aquifers by enhancing or creating secondary porosity and flow paths by hydraulic fracturing. The long term goal is to control the stimulation of a variety of rocks so that geothermal energy can be exploited from any kind of reservoir where it is needed. In addition to *geoscientific* aspects, *process engineering studies* and issues regarding the design of *geothermal power plants* to operate in environments similar to the North German Basin are addressed as there is no relevant experience in these fields in Germany yet (Figure 2). In the following we describe briefly the various aspects of the project and report on the status of our work after the first year.

Geosciences: increasing production rates

Research on developing methods to improve the performance of low permeability geothermal aquifers involves experiments in boreholes as well as investigations of rock and fluid samples in the laboratory. The area of the North German Basin was chosen to focus this study because it contains widespread low permeability rocks that attain temperatures necessary for geothermal power generation, it is fairly well known due to gas exploration activities and it hosts a large consumer population.

The North German Basin

The North German Basin is part of a large basin system extending across Europe from the North Sea into Poland. It is filled with up to 10 km of Phanerozoic sediments. An initial rifting phase (Late Carboniferous - Early Permian) is responsible for extrusive rocks covering large areas of the basin and attaining locally up to 2000 m thickness. These 307-277 Ma old volcanic rocks consist of rhyolites, ignimbrites, andesites and, to a lesser extent, basalts (Breitkreuz et al, 1999; Benek et al., 1996). This igneous event was followed by long-lasting (> 250 Ma) subsidence (Scheck et. al., 1999) and sediment accumulation. A clastic sequence (Early Permian Rotliegend) of aeolian sandstones, fluvial fans as well as playa deposits covered the volcanic rocks. Then thick (up to 4000 m) cyclic evaporites and carbonates were deposited (Late Permian Zechstein). Salt diapirism took place mainly during Late Cretaceous and thereafter causing large lateral variations in salt thickness. This affects strongly the temperature distribution around salt structures because the thermal conductivity of salt is a factor of two to three times larger than that of other sediments.

Selection of a site for stimulation experiments in a borehole

Conditions imposed on geologic formations suitable for our studies were: (1) temperature above 120°C, which implied a formation at depths greater than 3000 m; (2) large regional extent so that results from this project may be extrapolated to other similar areas, and (3) a variety of lithologies available for investigation. The widespread Rotliegend formation was chosen. It is a gas reservoir and has been extensively drilled so that it is very well known. The Rotliegend rocks comprise clastic siltstones and sandstone layers as well as extrusive andesites at the base.

Geological and technical drilling information on more than 100 deep former oil and gas exploration wells in northeast Germany were examined in detail to find a site for an in-situ laboratory for hydraulic experiments in the Rotliegend formation. Technical feasibility of renewed access and the existence of low-permeability rocks at temperatures of 130-140ºC were the criteria used to scrutinize these oil and gas wells. The 4240 m deep well Groß Schönebeck 3/90 was selected. This well, drilled in 1990, was cased down to 3880 m depth with the remaining 360 m left open. As insufficient gas was found, the well was closed practically immediately after com-

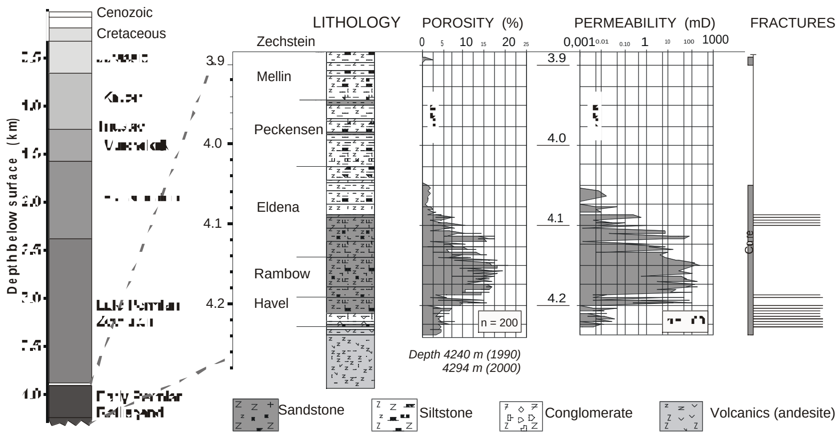

Figure 3: Stratigraphy, porosity and permeability of Rotliegend rocks in Groß Schönebeck

pletion. To gain access to the openhole section it would only be necessary to drill through a few hundred meters of cement. The remaining sections were filled with drilling mud. The reopening of the well required only a fraction of the costs of a new borehole.

Down-hole laboratory Groß Schönebeck

The Groß Schönebeck 3/90 gas exploration well cuts through 2370 m of Quaternary to Permian sediments followed by 1492 m of the Zechstein evaporite formation reaching the Rotliegend at 3881.8 m and bottoming in andesites at a depth of 4240 m. The Rotliegend at this location can be divided into 3 major sections from the top down: siltstones (203 m), sandstones (209 m including 19 m of basal conglomerate) and two thin andesitic flows (9.5 m). In addition to geophysical logs (caliper, gamma-ray, resistivity, induction, density, spectral-gamma, sonic, dipmeter), abundant porosity (290 samples) and permeability (109 samples) measurements on cores are available.

In November 2000 the well Groß Schönebeck was re-opened and deepened to 4294 m. A first production test in December 2000 provided new information on the hydraulic properties of the open-hole section. About 300 m^3 of fluid were extracted at a rate of 2 l/s. A flowmeter log showed that most fluid came from the transition from conglomerates to volcanic rock. It was surprising that the more permeable (Rambow) sandstones did not exhibit any flow. This suggests that some damage to this interval must have occurred between 1990 and 2001. Permeability reduction could be due to precipitation of minerals in the pores and/or clogging of fluid paths by infiltration of solid particles. Repeated temperature logging shows that the temperature is still disturbed, although in the cased section of the borehole the changes in gradient can be related to stratigraphic boundaries, suggesting, that in this part, the temperature is very close to equilibrium and reflects a conductive regime. The maximum temperature measured at the bottom of the deepened section is 148.8 °C. This is much lower than that at comparable depths in e.g. Larderello (Italy) and Soultz-sous-Forêts (France), a classical high enthalpy reservoir and the present European Hot-Dry-Rock project site, respectively. However, the temperature is higher than at the German Deep Drilling site (KTB at Windischeschenbach) located in metamorphic basement in southern Germany.

Other geophysical logs were obtained in January 2001 such as, spontaneous potential, gamma-ray, spectral-gamma, laterolog, dual induction, sonic, and a high temperature borehole televiewer. Most of this new data is presently being processed, compared with previous logs interpreted.

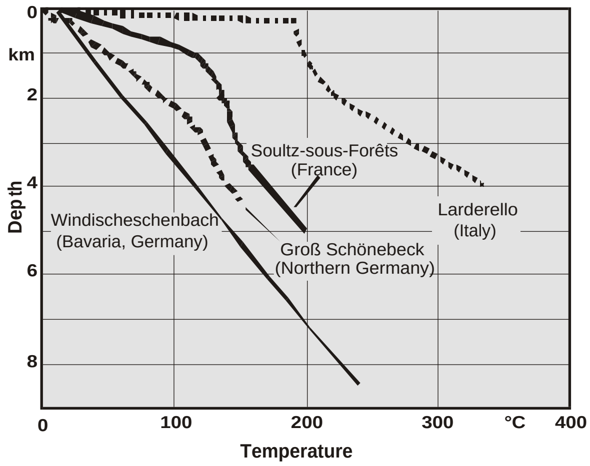

Figure 4: Temperature at Windischeschenbach (KTB), Soultz, Larderello and in the North German Basin

The focus is the identification of structures, principal stress directions and fractured intervals. The closest determinations of the maximum compressive horizontal stress direction are at a distance of 30-50 km to the north, north-east and east of the target well (Roth et al., 1998). Directions are N13E, N41E, and N45E, respectively. The last value is closest. The maximum horizontal compressive stress direction in western Europe is on average N145º ± 26º rotating from NE-SW direction in western Europe to approximately NS in the North German Basin towards the east to NNE-SSW (Müller et al., 1992; Grünthal et al., 1992; Grote 1998). In Poland the main direction is NE-SW.

In the summer of 2001, as a preparation to the massive stimulation experiments, a first injection experiment will quantify the principal stress components. Two intervals are targeted for stimulation experiments in the fall/winter of 2001: the Rambow sandstone section and the volcanic rocks at the bottom. In the first case, experience from the oil industry forms the basis for hydraulic fracturing. In sandstone oil and gas reservoirs, hydraulic fracturing generally involves injecting high viscosity fluids through perforations and using proppants. The resulting fractures reach tens of meters into the reservoir, are constrained in height and have great widths (centimeters) propped open. Injection fluids are of small volume (< 100 m3), but have a complex design of viscosity and proppant proportion variation during the procedure. The second target, stimulation of the volcanic rock, will draw upon the experience amassed in Hot-Dry-Rock projects carried out mostly in crystalline and volcanic rock. Here massive (> 100 m3) hydraulic stimulation is performed in open hole sections with water. Fractures are only millimeters in width but reach hundreds of meters into the formation. They are kept open through a self-propping effect caused by the roughness of the fracture surface and the shear motion the rock undergoes during stimulation, impeding complete closure. The detailed design of the stimulation experiments is currently under way.

Contribution of laboratory studies

In addition to experiments in boreholes, the geological and mechanical characterristics of rocks with regard to their hydraulic behavior in the laboratory are an important part of this investigation. Sandstone and volcanic rock samples and cores studied in the laboratory complement the down-hole experiments. Equipment to perform experiments under in-situ conditions (temperature, confining and pore pressure) allows studies of mechanical behavior and measurement of physical properties (acoustic, electrical, thermal, hydraulic) under controlled environmental conditions. It is also possible to vary selected parameters systematically to gain insight into relationships between different properties. As an example, properties such as rock strength or permeability can be examined as a function of pore pressure, an experiment difficult to carry out in the borehole.

Geochemistry of the fluids and gases

At the Groß Schönebeck site and over most of the North German Basin care must be taken to pre-treat the injection fluids in order to avoid reaction with formation fluids resulting in precipitation. The Rotliegend formation fluids in Groß Schönebeck are of Ca-Na-Cl-type with Total Dissolved Solids (TDS) of 256 g/l. Gas (headspace) samples yielded 12.75 % methane (CH_4). This information was gained during the 1990 Drill Stem Test. Fluids and gases were continuously sampled at the wellhead during the production test in December 2000. Three samples were taken at the bottom of the well. Studies are in progress to set up specifications for injection fluids to be used during stimulation to avoid damaging the sandstone formation by chemical reactions between injection and formation fluids leading to precipitation. Another issue being examined is the effect of long term exploration (temperature and pressure changes in the reservoir) and re-injection of the spent fluid.

Process engineering: sustainable operation

Process engineering studies address the problems associated with the conception and operation of a geothermal power plant. The chemistry of fluids and multiphase flow (e.g. water with non condensable gases) are critical for assessing the operation pressure and other parameters of a power plant. Moreover, as seen above, the fluids in the North German basin are expected to be highly corrosive, highly mineralized brines. During exploitation, these fluids are cooled while moving through different components of the system, changing their physical and chemical characteristics before being reinjected at depth. Consequently a technology has to be developed which ensures safe long term operation of the machines and apparatuses without endangering reservoir permeability.

Geothermal power plant: a vision for the future

The passing of the german Renewable Energy Sources Act (BMU, 2000) improved general conditions for geothermal electricity generation. To demonstrate the feasibility of geothermal power production in geological settings comparable to the Northern German Basin, a geothermal power plant will be installed if the hydraulic experiments at Groß Schönebeck are successful in producing the needed flow rates.

A binary system is the only conversion technology applicable in areas devoid of geothermal temperature anomalies as is the North German Basin. Still, this technology is not in a stage of development capable of providing standard machinery. Each installation is designed for the conditions at a specific location. Optimization and modeling methods used in classic power plant design are applied to set up the cycle, dimension the components and adjust the process parameters.

During the optimization process, criteria are defined to rank the quality of a design. Here the quality of a conversion technology is assessed with the net capacity, the delivered energy and exergy as well as the conversion efficiency (energetic and exergetic) defined by:

Net capacity P_{Net} (kW):

$$P_{Net} = P_{Generator} - \left(P_{downholepump} + P_{feed\ pump} + P_{coolingwater\ pump}\right)$$

Delivered energy $\Delta\dot{Q}$ (kW):

$$\Delta\dot{Q} = \dot{Q}_{brine} - \dot{Q}_{brine,\ return}$$

Delivered exergy $\Delta\dot{E}$ (kW):

$$\Delta \dot{E} = \dot{E}_{brine} - \dot{E}_{brine,return}$$

Energetic efficiency of the cycle h:

$$\eta = \frac{P_{Generator}}{\Delta \dot{Q}}$$

Exergetic efficiency of the cycle e:

$$\varepsilon = \frac{P_{mech,Turbine}}{\Delta \dot{E}}$$

First calculations and optimization procedures were carried out for an organic Rankine cycle (ORC, Figure 5) with the software Cycle-Tempo (DUT, 2000). Cycle-Tempo is a program for thermo-dynamic modeling and optimization of systems that produce electricity, heat and refrigeration. The primary aim of the program is to calculate the magnitude of the relevant mass and energy flows in the system.

In addition to the layout of the basic cycle and the apparatus design as well as the selection of the working fluid, the following optimization variables control the system: evaporation pressure and temperature, steam quality, degree of superheating and condensation pressure.
Fig.6 illustrates the results of the parameter variations. The following benchmark figures went into the cal-culation: Reservoir temperature 150°C, mass flow of the brine 20 kg/s (72 t/h), cooling water temperature 15°C, tempe-rature rise of the cooling water 5°C, steam quality 100% (not superheated), no recuperation. Calculations were performed for two working fluids: iso-pentane and iso-butane.

Design and operation of a geothermal plant vary widely with the desired products (electricity and/or heat). In most cases optimization aims at improving the net capacity,
which is a combination of the ability of the system to cool the brine and the efficiency of the conversion cycle.

Increasing evaporation temperature of the working fluid results in less cooling of the brine, therefore transmitted energy is diminished, while efficiencies increase. Consequently a maximum of the net capa-city is identified. At 597 kW_{el} and 538 kW_{el}, the maxima are close to each other, so that the choice of the working fluid hinges upon more technical para-meters, e.g. sealing issues or pressures in the plant. Evaporation pressures in i-butane cycles (9 bar to 28 bar) are larger than the pressures in i-pentane cycles (3 bar to 16 bar).

The influence of the evaporation tem-perature on the return temperature of the brine is much less dramatic for i-butane than for i-pentane. So, if a geothermal well should produce heat and electricity simultaneously, high return temperatures are favored. In this case a power plant using i-pentane with 13 bar evaporation pressure (130 °C evaporation temperature) is the better choice. It still generates 297 kW_{el}, permitting more than 110 °C return temperature, which is suitable for direct use in a heating plant.

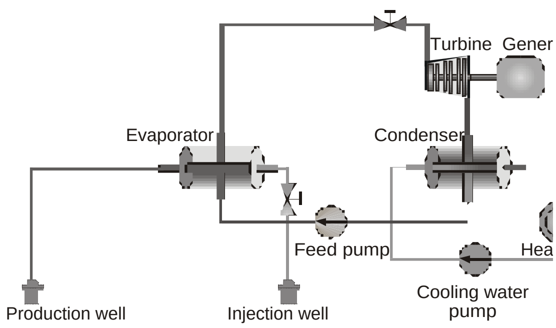

Figure 5: Block diagram Organic Rankine Cycle (ORC)

Summary

Research on developing methods to improve the performance of low permeability geothermal aquifers involves expe riments in boreholes as well as investigations of rock and fluid samples in the laboratory. The core installation of the current interdisciplinary project at GFZ is a former gas exploration well, drilled in 1990 and reopened 2000, which will serve as an down-hole laboratory. A first production test showed approximately 150 °C at 4294 m depth, but insufficient flow rates. Injection experiments and subsequent massive stimulation are currently being designed and will be carried out this year. Process engineering topics as well as design and layout of binary power plants have to be considered to reached the long term goal: the installation of power plant with approximately 0.6 MW_{el} net capacity, which would be the first geothermal power plant in Germany.

Acknowledgements

This multidisciplinary project is a joint venture of research institutes (GeoForschungsZentrum Potsdam, Bundesanstalt für Geowissenschaften und Rohstoffe in Hannover and Institut für Geowissenschaftliche Gemeinschaftsaufgaben in Hannover), universities (Ruhr Universität Bochum, Technische Universität Berlin, and Universität Stuttgart) and industrial partners (Geothermie Neubrandenburg GmbH and MeSy-MeßSysteme Bochum).

It is funded by BMWi (Federal Ministry of Economics and Technology), BMBF (Federal Ministry of Research and Education), MWFK Brandenburg (Ministry of Science, Research and Culture of Brandenburg).

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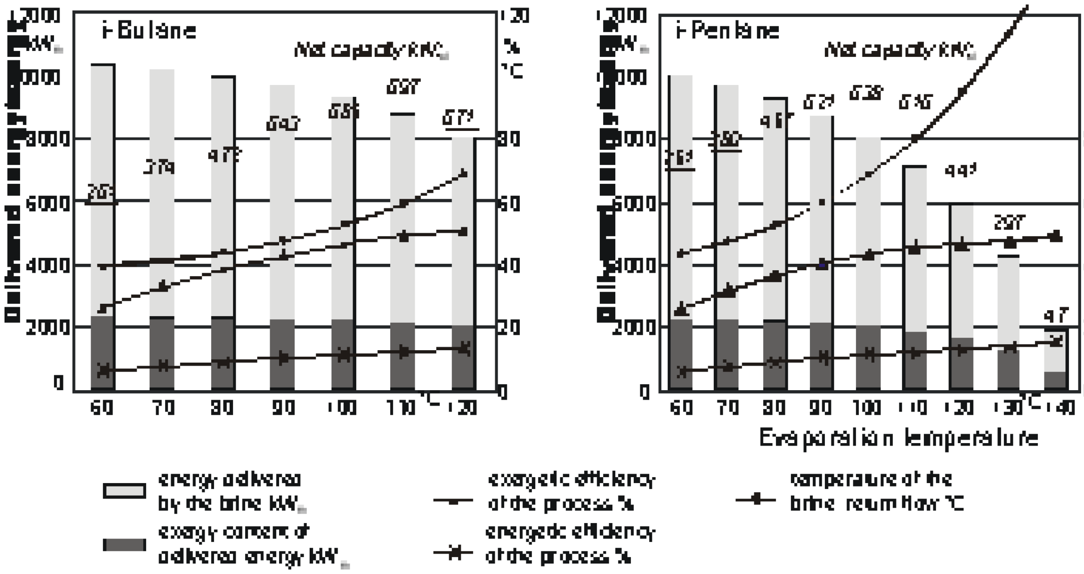

Figure 6 : Results of cycle simulations for working fluids i-butane and i-pentane