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Impact of natural radionuclides on geothermal exploitation in the Upper Rhine Graben

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ABSTRACT

The deep geothermal fluids in the Upper Rhine Graben exhibit rather similar chemical compositions. They have a high NaCl content of about 100 g/l. Circulation of geothermal fluid through the rock formations of the Upper Rhine Graben leads to chemical interactions at the liquid–solid interfaces. Some of these processes result in the transfer of natural radionuclides from solid to fluid. Due to the variation of the fluid's temperature and pressure as it passes through the surface plant during operation, solid deposits containing trapped radionuclides can accumulate in heat exchangers and filters causing health hazard, disposal cost and adverse effects on the surface installation. Radiological investigations at Bruchsal and Soultz-sous-Forêts were performed for the quantitative and qualitative determination of natural radionuclides that may occur in geothermal fluids and in the host rock with the aim to find a link between the specific activity of the source rock and the measured activity concentration in the fluid. The results of the fluid study show a distinct dominance of radium isotopes; however radium appears to be not supported by its parent nuclides. Thus, the geothermal fluid is in a state of radioactive imbalance. This phenomenon is observed for both geothermal sites at Bruchsal and Soultz-sous-Forêts. It seems that there are interaction processes for radium release in the reservoir fluids that are working for both geothermal sites despite of different reservoir rocks (sandstone at Bruchsal vs. granite at Soultz). Furthermore, radium could be transported into the geothermal power plant and incorporate in barium/strontium sulphate precipitations. By regular monitoring of the local dose rate all over the surface installation, the plant operator meets its obligation concerning employee safety. In addition, the operator receives site-specific information about the formation of scalings and their growth characteristics, which can be used to determine strategies to avoid precipitations.

1. Introduction

Natural radionuclides exist throughout the geosphere. Primordial nuclides are notable for their long half-lives and are still present in measurable quantities today. The origin of these radionuclides was at the time of nucleosynthesis. Here, ^{40}K, ^{238}U, ^{235}U and ^{232}Th are essential primordial nuclides, whereas the last three form the starting points of natural decay chains.

In a closed system all daughter nuclides of ^{238}U, ^{235}U and ^{232}Th will achieve secular equilibrium with their parent isotopes after $\sim 2.5 \times 10^6$ years. Thus, the state of radioactive balance is usually found in systems such as crystalline rocks or sediments with significantly low porosity and low permeability. In contrast, in systems where an exchange of radionuclides can take place between different phases, a fractionation of daughters and parents within the same decay chain can be observed due to their differing chemical and physical properties (Hussain and Krishnaswami, 1980). Such fractionation results in a state of disequilibrium within the phases and is typical in multi-phase-systems such as permeable aquifers, where liquid, solid and gaseous phases often coexist.

In geothermal energy systems, a huge quantity of geothermal fluid is circulated in the underground reservoir during the exploitation phase and could generate interaction between surface geothermal fluid and host rock potentially capable of modifying natural radionuclides exchanges. During the operation of a geothermal power plant, hot water or steam from the underground is pumped or carried to the surface via a production well. After delivering its usable thermal energy to the power plant, the cooled fluid will be re-injected into the underground reservoir zone via a second well (Fig. 1).

Radionuclides have been investigated in several geothermal fields in Italy, US and Australia. In the Cesano geothermal field,

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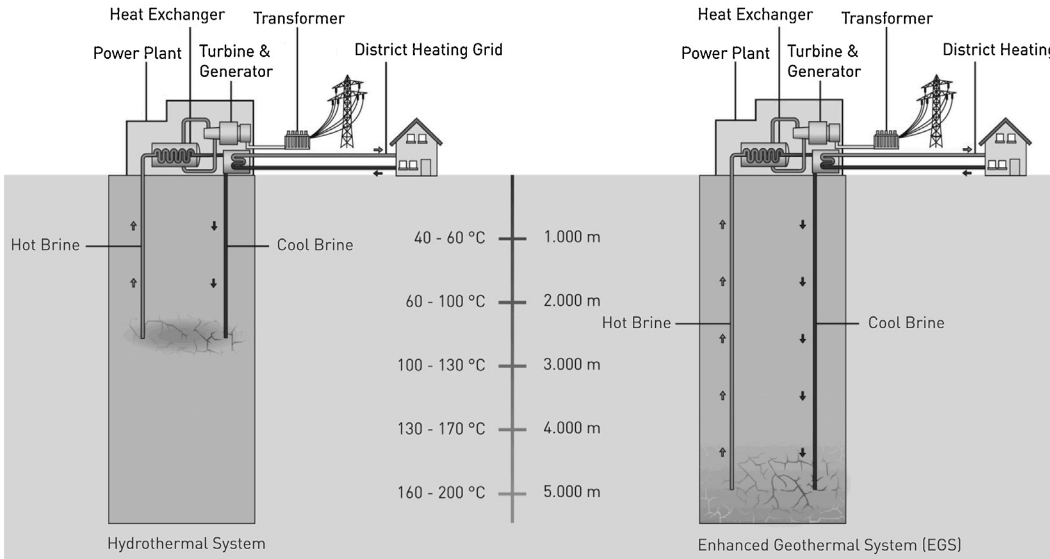

Fig. 1. Processes for the generation of energy from geothermal source: hydrothermal system (Bruchsal type) and enhanced geothermal system (Soultz type).

Voltaggio et al. (1987) developed a method for dating newly formed minerals based on natural radionuclides. In the Salton Sea geothermal field, Zukin et al., 1987 investigated naturally occurring radionuclides for a better understanding of the transport processes between matrix and fractures within the reservoir. In Australia, Dickson and Herczeg (1992a,b) also investigated naturally occurring radionuclides. Their work concerned springs and groundwater around a lake. These authors focused on the enrichment or depletion of radionuclides related to the shallow groundwater system.

As potential reservoir zones in the Upper Rhine Graben are in crystalline (e.g. granite) or eroded and relocated crystalline rocks (clastic sediments), their mineralogical compositions include radionuclides. Fluid/solid interactions during hydraulic circulation can thus become significant. Variations of fluid temperature and pressure along the circulation path of geothermal fluid through the underground access wells and in parts of the surface plant tend to result in the formation of scale deposits, that trap radionuclides on, for example, pipe walls, filters and heat exchangers.

The study of the behaviour of natural radionuclides is rather new in the field of geothermal energy despite some work having been done within the oil and gas industry. Moreover, the recent experiences gained during development and operation of geothermal projects in deep basement rocks is giving new insight into exploiting energy from granitic source zones. For example, investigations have been made in Australia into the formation of NORM deposits (naturally occurring radioactive material) that may arise from hot-rock geothermal power plants. The study was done on a granitic reservoir in South Australia (Battye and Ashman, 2008). In Germany, VKTA (Verein für Kernverfahrenstechnik und Analytik) performed an extensive radiological analysis program for the geothermal site in Neustadt-Glewe where hot water is extracted from an aquifer in sandstones (Degering et al., 2009).

This paper presents a study of radionuclides present within the scale depositions for two existing power plants operating in the Upper Rhine Graben, at Bruchsal in Germany and at Soultz-sous-Forêts in France, original geochemical data on natural radionuclides in the geothermal fluids are described and the scaling in the two operating geothermal power plants exploiting deep-seated rocks is discussed.

2. Geothermal context

2.1. Upper Rhine valley

The Upper Rhine valley is part of the European Cenozoic Rift System that extends from the Mediterranean to the North Sea coast (Ziegler, 1992). Thus, it is characterized by a NNE-SSW striking extension structure with a length of around 300 km and a width of up to about 40 km. The deep Hercynian basement consisting of Paleozoic granites is overlaid by clastic sediments (sandstones) from Permian to Lower Trias and by Middle Mesozoic to Cenozoic sediments. The base of the sediments in the middle of the valley is about 3000 m deeper than at the valley's shoulders (Ziegler, 1992).

The Upper Rhine valley offers favourable conditions for the exploitation of geothermal energy. This is supported by spatially varying local heat flow anomalies and temperature anomalies at great depth. Most of the thermal anomalies are related to large-scale fluid circulation (Pribnow and Schellschmidt, 2000).

2.2. Bruchsal site (Germany)

The Bruchsal site is located at the eastern main boundary fault of the Rhine valley. The geothermal plant extracts energy from a hydrothermal reservoir in the Lower and Middle Buntsandstein, but also in Upper Permian formations. The Upper Rotliegend and Zechstein were revealed to have a total thickness of around 180 m during the drilling of the production well GB-2. The drilling section comprises Mesozoic formations with a total thickness of 900 m, whereby the Buntsandstein was found between 2166 and 2360 m. Buntsandstein sediments (clastic sandstones) are affected by large-scale normal faults as it is shown in the 3-D block diagram in Fig. 2 (Meixner, 2010). Caused by the complex tectonic structure, the Buntsandstein reservoir at injection well GB I differs in depth and thickness from GB II. For that reason, on the injection site (GB I), the reservoir is already to be found 2000 m below surface.

The measured temperature of the reservoir is 130 °C, a geothermal gradient of 60 K/km can be observed. At present, the hot water is produced with a flow rate of 24 l/s. First geochemical analysis of the NaCl fluid demonstrated a high mineralization (TDS ≈ 130 g/l) including heavy metals and gases with a pH of 5 (Eggeling et al., 2011a).