Geothermal energy production – a subject for radiation protection

S.Feige, R. Roloff

*Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) mbH, Kurfürstendamm 200,
D-10719 Berlin*

Abstract:
Although geothermal energy is a comparable young industrial sector in Germany, it raised a lot of public interest. Risks associated with the use of deep thermal fluids require intensive evaluation and communication within the community and with the public. A deep insight into processes that appear during the entire life cycle of the facility and assessment of impacts upon different subjects of protection is necessary to analyse possible consequences of operation. For decades, GRS is contributing to the safety of industrial facilities and processes. The experiences from safety evaluations of nuclear industries with regard to radiation protection issues are a valuable input to a new field of work currently under development. Tools from probabilistic safety analysis has been applied to the geothermal sector to answer specific questions concerning radiation protection in this NORM industry. First results of a test case are described.

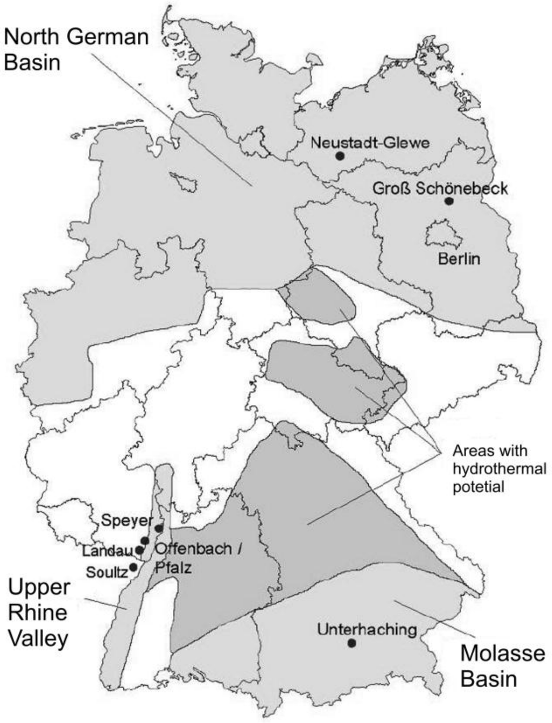
1 INTRODUCTION

Expanding the use of renewable energies is a goal of the German government with the aim to ensure a structural change in the energy supply towards climate–friendly technologies. An important instrument is seen in the Renewable Energy Sources Act (EEG) /1/ giving planning and financial security to investors supplying electricity and heat from renewable energies. Compared to other renewable energies like wind power, hydropower, biomass and solar energy, geothermal energy with its installed capacity of 7,5 MW in 2011 contributed with a total of 18,8 GWh (0,003 %) to the total electricity consumption /2/. So far, only the use of geothermal energy for district heating is already established in many places in Germany and contributes with about 0,5 % to the total heat supply /2/.

Three geothermal provinces had been identified in Germany to allow heat mining and electricity production using hot waters from a reasonable depth (Figure 1) with sufficient flow rates /3/. Within the North German Basin, thermal waters with temperatures up to 120 °C might get used from sandstone aquifers at a depth of about 2 500 m. Within the tectonic structure of the Upper Rhine Valley, hot thermal waters (up to 160 °C) from either fractured igneous rocks or Bundsandstein and Muschelkalk aquifers are mined at depth > 3 000 m. Fluids from the Northern Basin and the Upper Rhine Valley are highly mineralised NaCl-type waters with a salinity between 100 and > 200 g/l.

In the Molasse Basin in southern Bavaria, thermal waters with about 120 °C from a carstic Malm aquifer at a depth of around 3 500 are mined. Compared to thermal waters from the Northern Basin and the Upper Rhine Valley, waters of the Molasse belong to a Ca-(Mg)-HCO_3-type, generally much less mineralised (seldom > 1 g/l).

Figure 1: Geothermal provinces in Germany (after /3/)



In Germany just low-enthalpy geothermal resource are explored. Dubletts are common with a production hole and one or more reinjection holes to feed back the cooled water into the aquifer. In order to reach sufficient steam pressure to drive generators, binary cycles are operated. Typically geothermal power plants are operated at around 3 MWe, larger facilities are under construction.

2 THE SCOPE OF WORK

GRS is currently undertaking a system analysis of geothermal energy production within the project GeoSys. Key element of the interdisciplinary study is the assessment of the different risks affecting the subjects of protection. By law, biota & diversity, climate, cultural assets and - especially from radiation protection point of view – the human health are subjects to protect. The work includes the evaluation of impact facts that are to a large extent named and regulated by law. Such impact factors like emission of toxic substance are regulated e.g. by yearly or daily release limits.
In each of the stages of a geothermal power plant operation (exploration/construction – operation, incl. pot. incidents/accidents - post-closure phase - decommissioning/dismantling), specific impact factors will appear. Based on literature and reports from operators, a data acquisition with special emphasis on uncertainties has being started. A systematic evaluation of these factors using an evaluation grid and assessment criteria allowed the development of cause-effect-diagram that finally identified deficits in either regulation or available data.

An impact factor not yet regulated to a sufficient level is the exposure to ionising radiation, i.e. the risk of the subject of protection “Human health“ to be harmed by overexposure. For that reason, a more detailed investigation has begun. To achieve more than the results of a deterministic exposure assessment for a single case study, a method that is particularly suited to assess complex industrial facilities is applied in a test case: the Probabilistic Safety Analysis (PSA).

To structure the complex system of a geothermal power plant with respect to radiation protection issues, the broad spectrum of events that may lead to a deviation from the normal conditions of a system or facility was described in a first step using the Progression Analysis Code EVENTRE /4/. EVENTRE was selected as it allows a flexible branch architecture and

maintenance of uncertain parameters in a simple code environment. The event tree considered 10 typical scenarios with reported frequencies, duration, applicable exposure pathways and the relevant radiological data. Any of the collected data had been compiled with uncertainties. Doses had been calculated for the single exposure pathways in each scenario using adjacent FORTRAN codes that implemented a calculation method aiming at the radiation exposure due to mining burden radioactivity („Calculation Bases Mining" - Berechnungsgrundlage Bergbau) /5/.
To pay attention to the uncertainties, Monte Carlo simulation and uncertainty and sensitivity analyses had been carried out using the GRS tool SUSA /6/.
Any input data used had been compiled from reported literature values from the Upper Rhine geothermal province.

Central questions of the investigation are:

- What is the uncertainty of predicting that the radiation exposure does not exceed a certain limit?
- What are the crucial, uncertain parameters that contribute to the calculation of the dose quite much?
- Is it possible to identify weak points in radiation protection and vice versa to optimise occupational safety?

3 THE SPECIFIC RADIOLOGICAL SITUATION

3.1 Sources of radiation

Enhanced activity concentrations of natural radionuclides in highly mineralised waters had been discovered in thermal waters of the Northern Basin and the Upper Rhine Valley. Typically a disequilibrium within the decay chains of the U-238 and Th-232 series is observed with Uranium and Thorium isotopes below detection limit but dominating Radium isotopes at activity concentrations more than 50 Bq/l /7/. The ratio Ra-228/Ra-226 corresponds to the ratio of precursor Thorium and Uranium concentrations in the aquifer matrix.
The genesis of Radium-bearing brines can be explained by the interaction between formation water and the aquifer matrix. The process that is believed to be responsible for the transfer of Radium into the waters is a combination of alpha-particle recoil and chemical leaching by competitive cations. Within the Uranium and Thorium decay chain, Radium is the first isotope that remains soluble under the reducing conditions in the geothermal reservoir and is available for transport processes. High Radium activity concentrations in saline waters do not necessarily need the presence of Uranium enrichment in the aquifer as a sorption / desorption equilibrium is build up during the long residence time of the fluid.
Due to reducing conditions in the highly mineralised brines, lead isotopes remain soluble and as a consequence, Pb-210 contributes with enhanced activity concentrations to the total activity of the fluid.
Geothermal fluids from the Molasse basin are far less mineralised (salinity < 1g/l) and natural radionuclides are only slightly enhanced with specific activity concentrations < 1 Bq/l.

3.2 Radioactive contamination of the geothermal facility

In the geothermal power plant, changes of pressure and temperature as well as chemical processes occur, lead to precipitation of scales at certain components of the above ground facility.
Beside the electro-deposition and chemical precipitation of lead compounds, carbonate and sulphate hard scales will be build up. Insoluble earth-alkaline sulphates ($BaSO_4$, $SrSO_4$) own the risk to reduce the inner diameter of tubing and cover the inner surfaces of heat exchanger, resulting in a lowered technical capacity (flow rate or heat exchange ratio) of the facility.

Due to its chemical analogy, Radium isotopes co-precipitate with Barium or Strontium by diadochic incorporation into the crystal lattice of Barite or Coelestine. Pb-210 substitutes stable Pb in elemental lead deposits or Galena (PbS).

Table 1 sum up reported maximum activity concentrations of scales from different geothermal power provinces:

Table 1: Maxium specific activity concentration in residues from geothermal energy production in Bq/g

Geothermal province	Ra-226	Pb-210	Ra-228	Ra-224	Th-228	Source of information
Northern German Basin	270	800	210		190	/8/
Upper Rhine Valley	1.347	1.100	442	384	459	/9/

The NORM activity is not equally distributed inside the facility. Heat sinks (like dominantly the heat exchanger units) and inlet / outlet filters are special points of interest. In addition, the nuclide vector mirrors the conditions of precipitation together with stable elements (Ba, Sr, stable Pb) allowing scales nearly free from Radium isotopes but dominated by Pb-210 and vice versa.

The scaling shows a fast grow up after cleaning the facility which correspond in a yet insuffiently described way with production rate and *modus operandi* of the facility /9/.

3.3 Radiation risks

3.3.1 Radiation exposure of workers

A typical scenario (routine daily work) considers the residence time close to contaminated parts of the facility i.e. focus on the exposure due to external gamma radiation. In addition to gamma radiation concerns, other activities require the opening of system and thus handling of unsealed radiation sources. Exchange and cleaning of filter elements typically requires the handling of powdery radioactive residues with the risk of internal contamination due the inhalation of radioactive dust. Periodically, the heat exchanger units require maintenance and cleaning with high pressure water streams.

Equivalent dose rates (EDR) of up to 12 µSv/h in 1 m distance had been found in the literature /8/. Dose rates reaches highest values close to the heat exchanger units and surface dose rate of up to 34 µSv/h had been measured. Hot spots of EDR are concentrated to the reinjection side of the plant where significant changes in temperature occur.

The dose rates might get reduced by cleaning contaminated parts of the facility but will reach similar levels after short time /9/.

While handling of NORM, common occupational safety is applied (glows, dust mask, overall) and intake of radionuclide unlikely even though can not be ruled out.

Removed scales and contaminated equipment can be stored outside of the main building of the facility in a special storage area until carried off from the premise. Rn-222 exhalation from the wastes is small because of dense crystal lattice of $Ba(Ra)SO_4$ and sealing wastes in drums.

3.3.2 Radiation exposure of the public

Release of long-lived natural radionuclides during operation of the plant does not take place as the mined brine is re-injected into the reservoir. During a revision e.g. of the generator, the thermal water still needs to be pumped up to keep the entire system at operating conditions. A substitutional heat sink (open cooling pond) combined with a gas separator is looped in. Similar conditions will appear during open-loop circulation tests. Even in case of the interim storage of thermal water during revision of the above-ground components, water will be re-injected after stored into the ponds.

A visible amount of water vapour is released from the gas separator. Together with water vapour, gases and aerosols will be emitted from the stack. Dispersion of radionuclides at the premise and abroad had been modelled by different authors. Deposition of radionuclides will not lead to a significant increase in annual doses even under worst case assumptions. Emission of Rn-222 will not contribute to an enhanced dose level round the plant /10-12/. Although in dependence on the operation modus emitted with an averaged emission rate in the order of 10^6 - 10^7 Bq h^{-1} /11,12/, Rn-222 is diluted in the unstable atmosphere rather quickly. Taking into account a limited duration of free release corresponding to an annual release in the order of 10^8 Bq a^{-1} this is negligible compared to the average annual earth surface flux density of about 4,7 10^5 Bq m^{-2} a^{-1} that amounts to a Radon emission of nearly 10^9 Bq a^{-1} from an unsealed premise area of 2 000 m^2.
Known continuous emitters like shafts of abandoned uranium mines in Eastern Germany releases Radon in the order of ~100 TBq a-1 (10^{12} Bq a^{-1}) /13/.
Public access to the facility is prohibited and distance between the facilities components and the outer fencing typically is larger than 10 m.

3.3.3 Disposal of NORM residues

Although the German Radiation Protection Ordinance does not mention residues from geothermal power production to require further surveillance, such NORM with activity concentrations > 100 Bq/g trigger radiation protection activities to protect members of the public. The § 102 StrSchV /14/ allows the competent authority to take the appropriate measures and to prescribe that and the manner in which the materials are be disposed of.
Options for disposal of such residues are limited due to a main reason: Transport of residues requires application of the transport regulation according European agreement concerning the international carriage of dangerous goods by road (ADR) and thus classification of the transported goods as class 7 (radioactive material) – even if the regulatory body classified them as „non-radioactive“. Operators of disposal facilities either feel reluctant to accept wastes delivered as class 7 because of public awareness or their operating licence just permit them to receive class 7 wastes. Recent investigations states that some tons of scales and mixed contaminated wastes will accumulate per year in future.

4 RESULTS

After setting up the event tree, a first test case without uncertain parameters was constructed to check compliance of the probabilistic tool with results of a deterministic dose assessment.
Following this first positive application of the PSA tool, uncertain parameters had been ranged within their limits using Monte Carlo simulation. The results pictured a similar view but indicated already that under certain circumstances, the doses might exceed the assessed exposure results of the deterministic approach. Statistical evaluation of the bulk data mass gave evidence that resulting radiation exposure at work will not exceed a value of 6 mSv/a with an uncertainty of 0,85 (85 %).
Valuable information where gained from uncertainty and sensitivity analyses performed to get a quantification of the combined influence of many of these uncertainty sources and a ranking of the individual sources according to their contribution to the uncertainty of the results.
A large variation had been discovered in the empirical distribution function for the scenario “cleaning of filter elements”. Sensitivity analysis of the relevant parameters revealed the presumption that the inhalable dust concentration in ambient air and, due to its highest inhalation dose coefficient, the Th-228 activity concentration in the residues dominates the calculation.
Calculated doses for scenarios that result in exclusively external exposure without risk of inhalation or ingestion are controlled by the frequency of the scenario and the ambient dose.

5 DISCUSSION

Enhanced Radium activity concentrations in mineralised brines had been observed in numerous NORM industries, mainly in the mining sector. Scaling of $Ba(Ra)SO_4$ had been reported from other industries like coal mining or the Oil & Gas sector, resulting in comparable radiation exposure of workers. Even if operated technologies equal within one industrial sector, geological conditions of the brines reservoir determine the availability and the activity concentration of natural radionuclides. Due to that, findings of one site should not be taken for granted but a site-specific evaluation is proposed.

Planned activities in a geothermal power plant as well as handling the NORM residues for reuse or disposal may lead to an increased exposure of staff and members of the public.
Since the EURATOM directive 96/29 had been implemented in the German Radiation Protection Ordinance in June 2001, essential pre-conditions were created for activities related to NORM and re-use or disposal of residues. In most cases, NORM can be released from radiological supervision according to the § 98 of the German Radiation Protection Ordinance (StrlSchV) /14/ in connection with the limits of specific activity given in Annex XII part B and C by means of an simplified procedure. Even if these limits are exceeded, the compliance of the corresponding effective dose limit of 1 mSv/a may be confirmend by means of a dose model according to Annex XII part D of StrlSchV or applying the “Berechnungsgrundlage Bergbau” /5/. The later one had been developed for the determination of Radiation Exposure due to Mining-caused Environmental Radioactivity but is missing specific assumptions for the handling of NORM residues.

Apart from a junction of several EU directives from the same regulatory field (radiation protection, nuclear safety), the new EU-Basic Safety Standards, approved in Mai 2012 /15/, aims at the consideration of the ICRP recommendation 103, published in 2007 /16/. Contemporaneous amendment of the IAEA International Basic Safety Standards /17/ harmonise with the European recommendation.
These new basic safety standards introduce some significant changes and will, by transposition into national law, impact the German NORM industry including the geothermal sector: The geothermal energy production had been added to a list of industrial practices involving NORM and leading to exposure of workers or members of the public which cannot be disregarded from a radiation protection point of view (Article 24, ANNEX V in /15/).
Based on activity concentrations or radiation exposure, criteria will be adopted that will affect both, the degree of regulatory control as well as release of residues for reuse or disposal. Especially the clearance criterion “specific activity concentration” will not be met in several cases and regulatory activities are predictable. Moreover, final disposal of such NORM residues is an unsolved question in Germany, hindering the operator to get rid of residues.

Simplified procedures for a dose assessment will be appreciated by operators and regulatory bodies in future, not to hinder the further growth of geothermal energy production but to ensure the occupational safety at work. Obviously the PSA instrument is a suitable and flexible tool

6 OUTLOOK

The applied probabilistic safety analysis method allows considering uncertainties of physical parameters, of the frequency and even of the used model of the dose assessment by either directly naming these values or calculating them in appropriate codes and models. Experiences from the operation like frequency of occurrence of certain events, results of serial surveys as well as the distribution pattern of a data volume can be used at the same time without changes in the model parameters.
A deterministic dose assessment usually considers a conservative scenario collection to take into account the uncertainties in the parameter table. In case of significant changes in the operating modus (technical modifications, modified procedures), a re-evaluation of the dose will be required. Distinction of cases, consideration of incidents or accidents might result in a

confusing collection of numerous scenarios. The event tree is a flexible instrument with direct access to user-defined branch- or case-specific parameters.

It was possible to show that the event tree is able to draw a reliable picture of the system of geothermal energy production within the meaning of radiation dose assessment. The event tree analysis is a suitable tool for drawing conclusions beyond deterministic considerations.
Similar to deterministic dose assessment models, results of a PSA are only as good as the quality of the input data.

Further work will concentrate on implementing yet insufficiently described relations of uncertain parameter among each other into the model. To develop the PSA into an effective tool to predict future evolution of the radiation dose field at certain positions inside the facility during operation, a focus will be laid on the in-grow function of scales with time. Characteristics of the chemical precipitation of minerals require association with certain operational conditions and, further on, description in a geochemical model of the scaling processes.
Parameters whose uncertainties might be a result of a permitted pooling of data (especially as a result of differing hydrological and geochemical conditions in the reservoir or variable operational modes) need to be identified to decide whether either site-specific or greater area event trees will be cultivated.
A lack of information exists regarding the air-borne activity like mobilized dust with enhanced NORM activity. To cope with this, uncertainties for these parameters were enlarged in this early approach. To clean-up the model from conservative assumptions, further data from operated plants have to be gained.

An enhanced geochemical monitoring of the geothermal plant with special emphasis on the relevant parameter of the dose assessment (continues monitoring of scalings and resulting radiation exposure) would support further work a lot. In addition, consideration of the specific activity concentration of natural radionuclides in the thermal fluid in the frame of a continuous monitoring will free yet idle but valuable geochemical information that allow hydrogeological modelling of the reservoir behaviour and thus to enhance the technical capacity of the geothermal plant.

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