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Tracer tests in geothermal resource management

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Abstract. Geothermal reinjection involves injecting energy-depleted fluid back into geothermal systems, providing an effective mode of waste-water disposal as well as supplementary fluid recharge. Cooling of production boreholes is one of the main disadvantages associated with reinjection, however. Tracer testing is an important tool for reinjection studies because tracer tests actually have a predictive power since tracer transport is orders of magnitude faster than cold-front advancement around reinjection boreholes. A simple and efficient method of tracer test interpretation, assuming specific flow channels connecting reinjection and production boreholes, is available. It simulates tracer return profiles and estimates properties of the flow channels, which are consequently used for predicting the production borehole cooling. Numerous examples are available worldwide on the successful application of tracer tests in geothermal management, many involving the application of this interpretation technique. Tracer tests are also used for general subsurface hydrological studies in geothermal systems and for flow rate measurements in two-phase geothermal pipelines. The tracers most commonly used in geothermal applications are fluorescent dyes, chemical substances and radioactive isotopes. New temperature-resistant tracers have also been introduced and high-tech tracers are being considered.

1. INTRODUCTION

The potential of the Earth's geothermal resources is enormous compared with the energy needs of mankind and they have the potential of contributing significantly to sustainable energy use worldwide, both for electricity generation and various direct uses of heat, as well as to help mitigate climate change. Yet their use worldwide is limited by present knowledge and technology. They are highly important in a number of countries like Iceland, the Philippines, Indonesia and El Salvador, to name examples, and of growing importance in many others.

Reinjection technology is an important, even essential, part of sustainable management of geothermal resources. It involves injecting energy-depleted fluid, originally extracted through deep boreholes drilled into a geothermal system, back into the system through specific injection boreholes. Reinjection started out as a method of waste-water disposal, but is also effective in counteracting pressure draw-down in geothermal systems, through providing a supplementary fluid recharge, and to extract more thermal energy from the rocks of the systems. The possible cooling of production boreholes as a result of reinjection is, however, a serious risk, which requires careful research, including tracer tests, and management. Reinjection is, furthermore, a central part of EGS, or enhanced geothermal system (see later), utilization and management.

Tracer testing has become a highly important tool in geothermal research, development and resource management. Its purpose is mainly threefold: (1) For general hydrological studies of subsurface flow, (2) for reinjection research and management and (3) for flow rate measurements in pipelines carrying two-phase water mixtures. Their role has, in fact, been most significant in reinjection studies. This is because tracer tests provide information on the nature and properties of connections, or flow-paths, between reinjection and production boreholes, connections that control the danger and rate of cooling of the production boreholes during long-term reinjection of colder fluid. Enabling such cooling predictions is actually what distinguishes tracer tests in geothermal applications (studies and management) from tracer tests in ground water hydrology and related disciplines.

This paper reviews the role of tracer testing in geothermal research and management. First a brief introduction to the potential and utilization of geothermal resources worldwide is presented followed by a discussion of the application of reinjection technology in geothermal resource management. Consequently geothermal tracer testing is reviewed. First its general role is discussed along with some examples. Then a simple and efficient method of tracer test interpretation, based on the assumption of specific flow channels connecting reinjection and production boreholes, is reviewed. It can simulate tracer return profiles quite accurately, and hence yield estimates of flow channel properties, which are consequently used for predicting the eventual production borehole cooling. Quite a number of examples of the successful application of this interpretation technique are available, as will be discussed. Finally some recent developments and advances in geothermal tracer testing are introduced.

2. GEOTHERMAL UTILIZATION

2.1. Geothermal resources worldwide

Geothermal resources are distributed throughout the Earth's crust with the greatest energy concentration associated with hydrothermal systems in volcanic regions at crustal plate boundaries. Yet exploitable geothermal resources may be found in most countries, either as warm ground-water in sedimentary formations or in deep circulation systems in crystalline rocks. Shallow thermal energy suitable for ground-source heat-pump utilization is available world-wide and attempts are underway at developing EGS-systems in places where limited permeability precludes natural hydrothermal activity.

Geothermal systems may also be classified based on their nature and geological setting [1]:

A. *Volcanic systems* are associated with volcanic activity and heat sources being hot intrusions or magma. Fluid circulation is controlled by fractures and fault-zones.
B. In *convective fracture controlled systems* the heat source is hot crust at depth in tectonically active areas, where geothermal fluid circulates to considerable depth (>1 km) extracting heat from the rocks.
C. *Sedimentary systems* are found in many sedimentary basins owing their existence to permeable sedimentary layers at great depths (>1 km) and above average geothermal gradients (>30° C/km).
D. *Geo-pressured systems* are deep sedimentary systems analogous to geo-pressured hydrocarbon reservoirs with pressures close to lithostatic. Not utilized anywhere as of yet.
E. *Enhanced geothermal systems (EGS)* consist of volumes of rock at useful temperatures but having low natural permeability. Experimental procedures involving hydro-fracturing have been applied in a number of locations to create artificial reservoirs or enhance already existent fracture networks. Previously termed hot dry rock (HDR) systems.
F. *Shallow resources* refer to the thermal energy stored near the surface of the Earth's crust, which is increasingly being used through the application of ground-source heat-pumps.

Numerous volcanic geothermal systems (A) are for example found in New Zealand, The Philippines, Central America and Iceland while geothermal systems of the convective type (B) for example exist outside the volcanic zone in Iceland and in the SW United States. Sedimentary geothermal systems (C) are for example found in France, Hungary and China. The Soultz project in NE-France is a well-known EGS project (E) while shallow resources (F) can be found all over the globe.

The potential of the Earth's geothermal resources is enormous when compared to its use today and to the future energy needs of mankind. The technically feasible electrical generation potential of identified geothermal resources, which are likely to be only a small fraction of unidentified resources, has been estimated to be about 240 GW_e [2]. The most likely direct use potential of lower temperature resources (<150° C) is, furthermore, estimated to be 140 EJ/yr [2]. The Earth's ultimate geothermal potential is, however, impossible to estimate accurately at the present stage of knowledge and technology. Even though geothermal energy utilization has been growing rapidly in recent years, it is still miniscule compared with the Earth's potential. The worldwide installed geothermal electricity generation capacity in 2010 is estimated to have been about 10.7 GW_e in 2010 [3] and direct geothermal utilization in 2009 to have amounted to 438 PJ/yr [4]. Finally it has been estimated that by 2050 the electrical generation capacity may reach 70 GW_e and the direct use 5.1 EJ/yr [5].

The energy production capacity of natural geothermal systems (hydrothermal systems) is predominantly determined by the pressure decline caused by production. This is in turn mainly controlled by (1) the production rate, (2) the size of a system, (2) its permeability structure, (3) its boundary conditions (i.e. the significance of natural and production induced recharge) and (4) the reinjection management adopted. The production capacity is also determined by the available energy content of the systems.

Natural geothermal reservoirs can often be classified as either open or closed, depending on their boundary conditions, with drastically different long-term behaviour. Pressure declines continuously with time, at constant production, in systems that are closed and their production capacity is limited by lack of water rather than lack of thermal energy. Sedimentary geothermal systems are often examples of this. Pressure stabilizes, however, in open systems because recharge eventually equilibrates with the mass extraction. The recharge may be both hot deep recharge and colder shallow recharge. The latter will eventually cause reservoir temperature to decline. The production potential of open systems is, therefore, often limited by reservoir energy content.

The situation is somewhat different for EGS-systems and sedimentary systems utilized through production-reinjection doublets (borehole-pairs) with 100% reinjection. Then the production potential is predominantly controlled by the energy content of the systems involved. But permeability is still of controlling significance because it controls how much flow can be maintained through the doublets involved. In sedimentary systems the permeability is natural but in EGS-systems the permeability is to a large degree man-made, or at least enhanced.

2.2. Geothermal reinjection

Geothermal reinjection involves returning some, or even all, of the water produced from a geothermal reservoir back into the geothermal system, after energy has been extracted from the water. In some instances water of a different origin is even injected into geothermal reservoirs. Reinjection started out as a method of waste-water disposal in a few geothermal operations about 4 decades ago, i.e. in Ahuachapan in El Salvador, The Geysers in California, Larderello in Italy and the Paris Basin in France [6]. It has slowly become more and more widespread and is by now considered an important part of comprehensive geothermal resource management as well as an essential part of sustainable and environmentally friendly geothermal utilization [7].

Reinjection provides additional recharge and counteracts pressure draw-down due to production as well as extracting more thermal energy from reservoir rocks than conventional utilization. Reinjection, therefore, increases the production capacity of geothermal reservoirs. Without reinjection, the mass extraction, and hence energy production, would only be a part of what it is now in many geothermal fields. Reinjection is obviously also

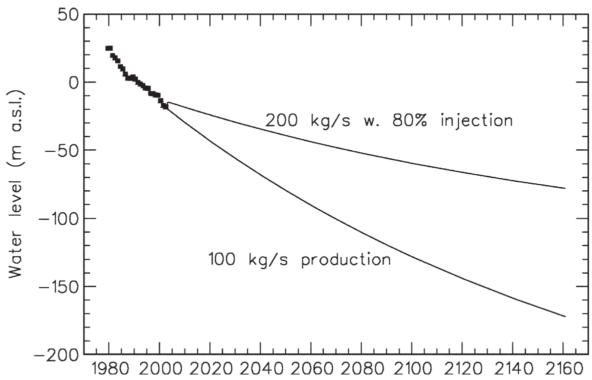

Figure 1. Predicted water level changes (pressure changes) in the Urban geothermal system under Beijing in China until 2160 for production scenarios with and without reinjection [9].

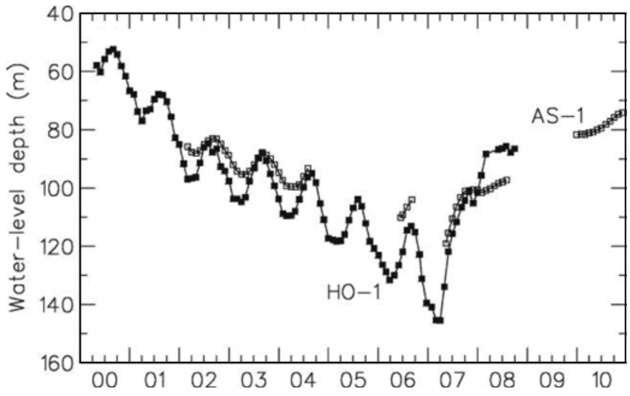

Figure 2. Pressure changes in the Hofstadir low-temperature geothermal system in W-Iceland [10] during the first 11 years of production, shown as water-level changes in the main production borehole (HO-1) and in a monitoring borehole (AS-1). A continuous pressure decline for 7 years is reversed in the spring of 2007 when reinjection commences.

an essential part of all EGS operations. In addition reinjection is in some cases applied to offset surface subsidence caused by production induced pressure decline and experiments have been conducted involving targeted reinjection to enhance, or revitalize, surface thermal features such as hot springs and fumaroles that have disappeared due to the pressure decline [8].

Reinjection clearly provides supplemental recharge and theoretical studies, as well as operational experience, have shown that injection may be used as an efficient tool to counteract pressure draw-down due to production, i.e. for pressure support. Since the production capacity of hydrothermal systems is controlled by their pressure response (see above) reinjection will increase their production capacity. This applies, in particular, to systems with closed boundary conditions and thus limited recharge. Figure 1 shows an example of the results of modelling calculations for the Urban sedimentary geothermal system under Beijing, China, based on actual monitoring data, which clearly demonstrate the beneficial effect of reinjection. Figure 2 shows an example of observed pressure recovery due to reinjection from the Hofstadir system in W-Iceland, which is an unusually closed (i.e. with limited recharge), fracture controlled low-temperature (<150 °C) system.

Through supplemental recharge reinjection extracts more of the thermal energy in place in geothermal reservoirs. Most of this energy is stored in the reservoir rocks, and only a minor part by the reservoir fluid (10–20%). Therefore only a fraction of the energy may be utilized by conventional exploitation. Reinjection can thus greatly improve the efficiency, and increase the longevity, of geothermal utilization.

Injection boreholes, or injection zones intended for the location of several injection boreholes, are sited in different locations depending on their intended function. In addition reinjection boreholes are designed and drilled so as to intersect feed-zones, or aquifers, at a certain depth-interval. The following options are possible:

(a) Inside the main production reservoir, i.e. in-between production boreholes. Often production /reinjection doublets.
(b) Peripheral to the main production reservoir, i.e. on its outskirts but still in direct hydrological connection.
(c) Above the main reservoir, i.e. at shallower levels.
(d) Below the main reservoir, i.e. at deeper levels.
(e) Outside the main production field, either in the production depth range or at shallower or deeper levels. In this case direct hydrological connection to the production reservoir may not exist.

Which option is used depends on the main purpose of the reinjection. If it is pressure support option (a) is the most appropriate even though options (b) – (d) can be used. If the main purpose is environmental protection option (e) is often used. In that case not much pressure support is to be expected. Therefore options (b) – (d) are often used as kinds of compromises.

Various additional examples are available on the successful application of reinjection in geothermal resource management. The best example of successful long-term reinjection into a low-temperature geothermal system is the reinjection applied in the Paris Basin in France [11]. The Paris Basin hosts a vast geothermal resource mainly associated with a limestone formation stretching over $15,000\,\mathrm{km}^2$. It is mainly used for space heating through a doublet scheme, consisting of a closed loop with one production borehole and one reinjection borehole. Utilization started in 1969 and its success can be attributed to its scale, solutions having been found for technical operation problems, no cold front breakthrough for several decades and a comprehensive monitoring program. Several other low-temperature examples are available as well a number of high-temperature (>200 °C) reinjection case-histories [7].

Some operational dangers and obstacles are associated with reinjection with the main problems being [7]:

A) Cooling of production boreholes, or cold-front breakthrough, often because of "short-circuiting" along direct flow-paths such as open fractures.

B) Scaling in surface pipelines and injection boreholes, including silica scaling (in high-temperature operations) and carbonate scaling. Appropriate solutions include dilution with steam-condensate and inhibitor application.
C) Rapid clogging of aquifers next to injection boreholes in sandstone reservoirs by fine sand and precipitation material. A solution involving highly efficient filtering and pressurizing with nitrogen (to keep production reinjection loops oxygen-free) has been developed and applied successfully in N-Germany [12].

The possible cooling of production boreholes has discouraged the use of reinjection in some geothermal operations although actual thermal breakthroughs, caused by cold water injection, have been observed in relatively few geothermal fields. In cases where the spacing between injection and production boreholes is small, and/or direct flow-paths between the two boreholes exist, the fear of thermal breakthrough has been justified, however.

The danger of cooling due to reinjection can be minimized by locating injection boreholes far away from production boreholes, while the main benefit from reinjection (pressure support) is maximized by locating injection boreholes close to production boreholes. A proper balance between these two contradicting requirements must therefore be found through careful testing and research. Tracer testing is probably the most important tool for this purpose.

3. GEOTHERMAL TRACER TESTING

3.1. General

Tracer tests are used extensively in surface and groundwater hydrology as well as pollution and nuclear-waste storage studies. Tracer tests involve injecting a chemical tracer into a hydrological system and monitoring its recovery, through time, at various observation points. The results are, consequently, used to study flow-paths and quantify fluid-flow. Tracer tests are, furthermore, applied in petroleum reservoir engineering. The methods employed in geothermal applications have mostly been adopted from these fields.

Tracer testing has multiple applications in geothermal research and management:

1) The main purpose in conventional geothermal development is to study connections between injection and production boreholes as part of reinjection research and management. The results are consequently used to predict the possible cooling of production boreholes due to long-term reinjection of colder fluid.
2) In EGS-system development tracer testing has a comparable purpose even though it's rather aimed at evaluating the energy extraction efficiency and longevity of such operations through studying the nature of connections between reinjection and production boreholes.
3) For general hydrological studies of subsurface flow, such as flow under undisturbed conditions and regional flow.
4) For flow rate measurements in pipelines carrying two-phase water mixtures.

The power of tracer tests in reinjection studies lies in the fact that the thermal breakthrough time (onset of cooling) is usually several orders of magnitude (2–4) greater than the tracer breakthrough time, bestowing tracer tests with a predictive power. This is actually what distinguishes tracer tests in geothermal applications (see 1) and 2) above) from tracer tests in ground water hydrology and related disciplines. Numerous references on tracer tests in geothermal research and development can be found through the web-page of the International Geothermal Association, i.e. at World Geothermal Congresses held every 5 years [13,14]. The reader is also referred to a special issue of the international journal Geothermics devoted to tracer tests [15].

Geothermal tracer tests are mostly conducted through boreholes and can involve (i) a single borehole injection-backflow test, (ii) a test involving one borehole-pair (injection and production) as well as (iii) several injection and production boreholes. In the last setup several tracers must be used, however. The geothermal reservoir involved should preferably be in a "semi-stable" pressure state prior to a test. This is to prevent major transients in the flow-pattern of the reservoir, which would make the data analysis more difficult. In most cases a fixed mass of tracer is injected "instantaneously", i.e. in as short a time as possible, into the injection borehole(s) in question. Samples for tracer analysis are most often collected from producing boreholes, while down-hole samples may need to be collected from non-discharging boreholes. The duration of a tracer test is of course site specific and hard to pinpoint beforehand. The same applies to sampling plans, even though an inverse link between required sampling frequency and time passed can often be assumed [14].

The tracer selected needs to meet a few basic criteria: It should (a) not be present in the reservoir (or at a concentration much lower than the expected tracer concentration), (b) not react with or absorb to reservoir rocks (see however Sect. 3.4 below), (c) be thermally stable at reservoir conditions, (d) be relatively inexpensive, (e) be easy (fast/inexpensive) to analyse and (f) be environmentally benign. In addition the tracer selected must adhere to prevailing phase (steam or water) conditions. The following are the principal tracers used in geothermal applications (not a complete list):

Liquid-phase tracers:

- Halides such as iodide (I^-) or bromide (Br^-).
- Radioactive tracers such as iodide-125 ($^{125}I^-$) and iodide-131 ($^{131}I^-$).
- Fluorescent dyes such as fluorescein and rhodamine.
- Aromatic acids such as benzoic acid.
- Naphthalene sulfonates.

Steam-phase tracers:

- Fluorinated hydrocarbons such as R-134a and R-23.
- Sulphur hexafluoride (SF_6).

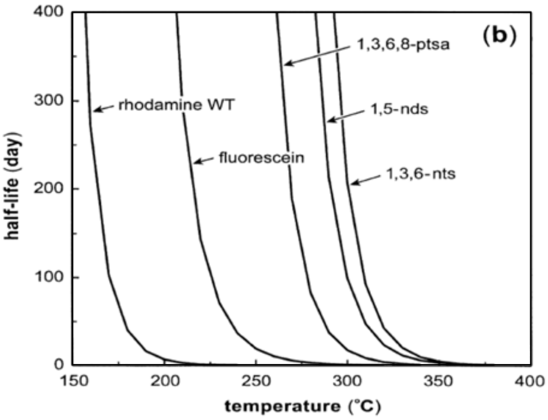

Figure 3. Graph showing the temperature dependence of the half-life of several naphthalene sulfonate tracers [16]. The temperature dependence of fluorescein and rhodamine are shown for comparison. Other naphthalene sulfonates are expected to have an even higher temperature tolerance, i.e. 2-ns, 2,6-nds and 2,7-nds.

Two-phase tracers:

- Tritiated water (HTO).
- Alcohols such as methanol, ethanol and n-propanol.

Sodium-fluorescein has been used successfully in numerous geothermal fields, both low- and high-temperature ones [14]. It meets most of the criteria listed above and, in particular, can be detected at very low levels of concentration (10–100 ppt). In contrast the detection limit of halides is several orders of magnitude higher.

The main disadvantage in using fluorescein is that it decays at high temperatures, a decay which becomes significant above 230 °C. Therefore new tracers with higher temperature-tolerance, but comparable detection limits, have been introduced, in particular several polyaromatic sulfonates [16]. These are increasingly being used in geothermal applications. Having several comparable tracers also enables the execution of multi-borehole tracer tests. Figure 3 presents the temperature-tolerance of a few of these compounds as well as that of fluorescein and rhodamine for comparison.

Radioactive materials are also excellent tracers since they are detectable at extremely low concentration. Their use is limited by stringent transport, handling and safety restrictions, however. When selecting a suitable radioactive tracer their different half-lives must be taken into account. Iodide-125 and iodide-131 have half-lives of 60 and 8.5 days, respectively, for example.

It should be mentioned that for flow-rate measurements in two-phase pipelines [17] fluorescein or benzoic acid are commonly used for the liquid phase. Naphthalene sulfonates are also promising as such. Steam-phase measurements are commonly done using SF_6 or a suitable alcohol.

Special techniques, of differing complexity, have been developed for sampling and analysing geothermal tracers. A discussion of these is beyond the scope of this paper, however.

Figures 4–6 show three examples of the results of tracer tests conducted in geothermal systems of quite contrasting nature. These are just presented as concise examples, without specific details. Two more examples, with interpretation results, are presented in Section 3.3 below.

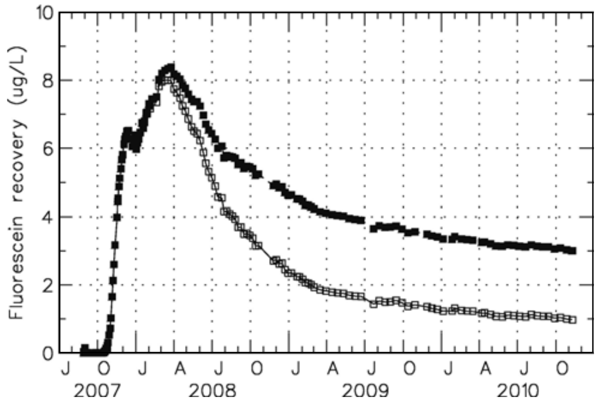

Figure 4. Fluorescein recovery in production borehole HO-1 in the Hofstadir low-temperature system in W-Iceland (see Fig. 2), following the injection of 10 kg of the tracer into reinjection borehole HO-2. The test lasted 3.5 years. The lower curve shows the recovery corrected for the tracer being reinjected after production from HO-1. About 70% of the tracer was recovered during the test.

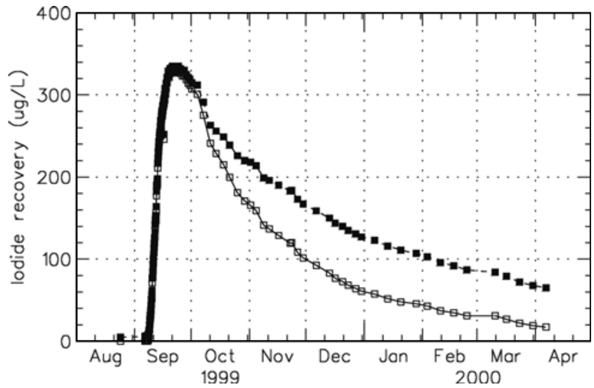

Figure 5. Iodide recovery in production borehole K-21 in the Krafla high-temperature system in N-Iceland, following the injection of 200 kg of KI into borehole K-22. The test lasted 7 months. The lower curve shows the recovery corrected for the tracer being reinjected after production. About 30% of the tracer was recovered during the test.

Figure 4 shows the tracer recovery during an unusually long tracer test conducted in the Hofstadir low-temperature (reservoir temperature 85–90 °C) geothermal system in W-Iceland already mentioned [10]. The test involved tracer injection into an operating reinjection borehole about 1200 m from the production borehole. The relatively slow recovery indicates that reinjection induced cooling will be limited. This awaits confirmation through comprehensive interpretation and modelling.

Figure 5 shows the tracer recovery during a tracer test conducted in the Krafla high-temperature (reservoir temperature 200–400 °C) geothermal system in N-Iceland. The test involved tracer injection into a temporary reinjection borehole about 200 m from the production borehole. The relatively rapid recovery was interpreted as indicating a considerable danger of cooling of the

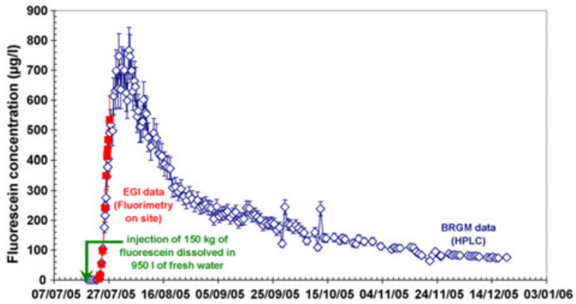

Figure 6. Flourescein recovery in borehole GPK-2 at the Soultz EGS-site in N-France, following the injection of 150 kg of fluorescein into borehole GPK-3 [18]. The test lasted 5 months. About 24% of the tracer was recovered during the test.

production borehole. Therefore the reinjection borehole was abandoned as such.

The third example involves tracer tests conducted at the Soultz EGS site in N-France during stimulation and testing between 2000 and 2005 [18]. The tests involved 4 boreholes ranging in depth from 3600 to 5300 m. A few different tracers were used, including fluorescein and some naphthalene sulfonates. Figure 6 shows the recovery in the test between boreholes GPK-3 and GPK-2 separated by 650 m, in which fluorescein was successfully used. It showed the most direct connection in the system.

The above are examples of geothermal tracer test data without any quantitative interpretation. Below a specific interpretation method will be presented along with two interpretation examples.

3.2. Interpretation method

Comprehensive interpretation of geothermal tracer test data, and consequent modelling for management purposes (production well cooling predictions), has been rather limited, even though tracer tests have been used extensively. Their interpretation has mostly been qualitative rather than quantitative. This paper presents a review of simple and efficient methods that may be used for this purpose [14]. It is based on simple models, which are able to simulate the relevant data quite accurately. They are powerful during first stage analysis when the utilization of detailed and complex numerical models is not warranted. The more complex models become applicable when a greater variety of data become available that may be collectively interpreted.

The method of tracer test interpretation is conveniently based on the assumption of specific flow channels connecting injection and production boreholes. It has been used to analyse tracer test data from quite a number of geothermal systems in e.g. Iceland, El Salvador, the Philippines, Indonesia and China and consequently to calculate cooling predictions [14]. It has proven to be very effective. This method is based on simple models, which are nevertheless able to simulate the relevant data quite accurately.

The tracer transport model assumes the flow between injection and production boreholes may be approximated

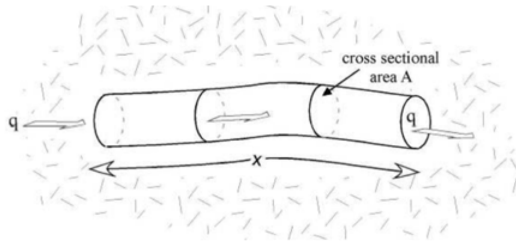

Figure 7. A schematic figure of a flow-channel with one-dimensional flow, connecting an injection borehole and a production borehole, used to simulate tracer transport [14].

by one-dimensional flow in flow-channels, as shown in Figure 7. These flow-channels may, in fact, be parts of near-vertical fracture-zones or parts of horizontal interbeds or layers. The channels may be envisioned as being delineated by the boundaries of these structures, on one hand, and flow-field stream-lines, on the other hand. In other cases these channels may be larger volumes involved in the flow between boreholes. In some cases more than one channel may be assumed to connect an injection and a production borehole, for example connecting different feed-zones in the boreholes involved.

In the case of one-dimensional tracer transport the relevant differential equation simplifies to [14]:

$$D\frac{\partial^2 C}{\partial x^2} = u\frac{\partial C}{\partial x} + \frac{\partial C}{\partial t}\cdot \tag{1}$$

Here D is the dispersion coefficient (m^2/s) of the material in the flow channel, C the tracer concentration in the channel (kg/m^3), x the distance along the channel (m) and u the average fluid velocity in the channel (m/s), given by $u = q/\rho A\phi$, with q the injection rate (kg/s), ρ the water density (kg/m^3), A the average cross-sectional area of the flow-cannel (m^2) and ϕ the flow-channel porosity. Molecular diffusion is neglected in this simple model (see later) such that $D = \alpha_L u$ with α_L the longitudinal dispersivity of the channel (m). Assuming instantaneous injection of a mass M (kg) of tracer at time $t = 0$ the solution is given by:

$$c(t) = \frac{uM\rho}{Q}\frac{1}{2\sqrt{\pi Dt}}e^{-(x-ut)^2/4Dt}. \tag{2}$$

Here $c(t)$ is actually the tracer concentration in the production borehole fluid, Q the production rate (kg/s) and x the distance between the boreholes involved. Conservation of the tracer according to $c \cdot Q = C \cdot q$, has been assumed. This equation is the basis for the method of tracer test interpretation presented here, which involves simulating tracer return data with equation (2). Such a simulation yields information on the flow channel cross-sectional area, actually $A\phi$, the dispersivity α_L as well as the mass of tracer recovered through the channel. This mass should of course be equal to, or less than, the mass of tracer injected. In the case of two flow-channels or more, the analysis yields estimates of these parameters for each channel. It should be pointed out that through the estimate for $A\phi$ the flow channel pore space volume, $Ax\phi$, has in fact been estimated. The tracer interpretation software

TRINV, included in the *ICEBOX* geothermal software package, can be used for this simulation [14].

It should be emphasised that this method does not yield unique solutions and that many other models have been developed to simulate the transport of contaminants in ground-water systems, and in relation to underground disposal, or storage, of nuclear waste. Many of these models are in fact applicable for the interpretation of geothermal tracer tests. It is often possible to simulate a given data-set by more than one model, therefore, a specific model may not be uniquely validated.

In addition to distance between boreholes and volume of flow-paths, mechanical dispersion is the only factor assumed to control the tracer return curves in the method presented above. Retardation of tracers by diffusion from the flow-paths into the rock matrix is neglected. It is likely to be negligible in fractured rock except when fracture apertures are small, flow velocities are low and rock porosity is high.

The main goal of geothermal tracer testing is to predict thermal breakthrough and temperature decline during long-term reinjection, or the efficiency of thermal energy extraction in EGS operations, as already stated. This is dependent on the properties of the flow-channel(s) involved, but not uniquely determined by the flow-path volume [14]. The heat transfer (cooling/heating) mainly depends on the surface area and porosity of the flow-channel(s). Therefore, some additional information on the flow-path properties/geometry is needed, i.e. geological or geophysical in nature.

To deal with this uncertainty heat-transfer predictions may be calculated for different assumptions on flow-channel dimensions, at least for two extremes. First for a small surface area, or pipe-like, flow channel, which can be considered as a pessimistic model with small heat transfer. Second a large surface area flow channel, such as a thin fracture-zone or thin horizontal layer, which can be considered as an optimistic model with large heat transfer. Additional data, in particular data on actual temperature changes, or data on chemical variations, if available may be used to constrain cooling predictions.

3.3. Examples

Figures 8–11 present examples of the results of geothermal tracer test analysis using the interpretation method presented. The results are only presented briefly here with some numerical findings presented in figure captions. More details can be found in the references cited.

Figure 8 shows the fluorescein recovery through a production borehole in the Laugaland low-temperature geothermal system (reservoir temperature 90–100 °C) in N-Iceland, conducted in 1997, simulated by the method presented above [19]. This was during initial reinjection testing in the field, since then reinjection has been part of the management of the system.

Figure 9 shows production temperature predictions calculated by a pessimistic model based on the tracer recovery simulation presented in Figure 8. They show that the long-term cooling of the borehole in question should be minimal, in particular in view of the considerable increase in productivity of the Laugaland system when reinjection is applied [19].

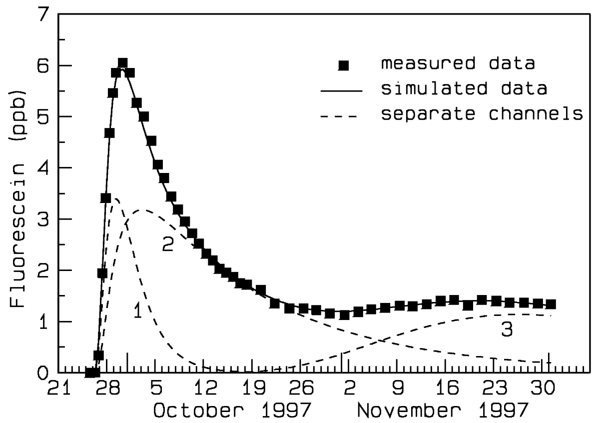

Figure 8. Observed and simulated (three flow channels) fluorescein recovery in borehole LN-12 at Laugaland in N-Iceland during a tracer test in 1997 [19]. Spent geothermal fluid was reinjection into borehole LJ-08 and production from borehole LN-12 about 300 m away. According to the simulation only about 6% of the tracer injected is recovered through this well and the combined flow-channel volume is estimated as 20, 000 m^3, assuming 7% porosity.

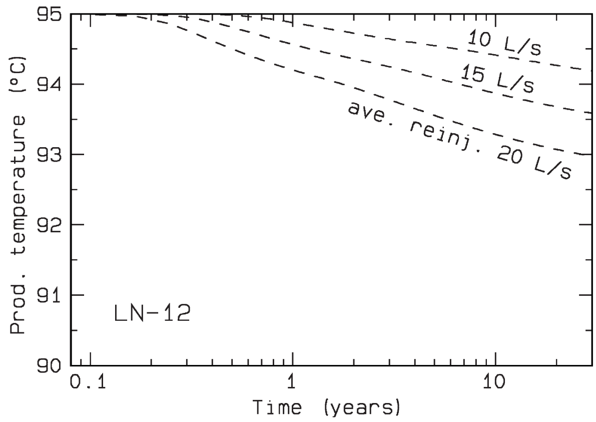

Figure 9. Estimated production temperature decline of borehole LN-12, due to flow through the three channels simulated, for three cases of average long-term reinjection into borehole LJ-8 and an average long-term production rate of 40 L/s [19].

The final interpretation example is from the Los Azufres high-temperature geothermal system (reservoir temperature ∼280 °C) in the state of Michoacán in Mexico. It involves interpretation of a tracer test conducted in late 2006 (see Fig. 10) in which SF_6 was used due to the fact that a steam zone has developed in the system and that production boreholes involved (NE-part of the field) produce mostly steam [20]. Cooling predictions based on the interpretation indicate that well AZ-5 may cool as much as 14 °C during 30 years of 8 kg/s reinjection into AZ-64 (compared with 21 kg/s production from AZ-5), cooling which is probably not acceptable.

3.4. Recent advances

The main uncertainty in reinjection operations and EGS development involves the heat-transfer efficiency of

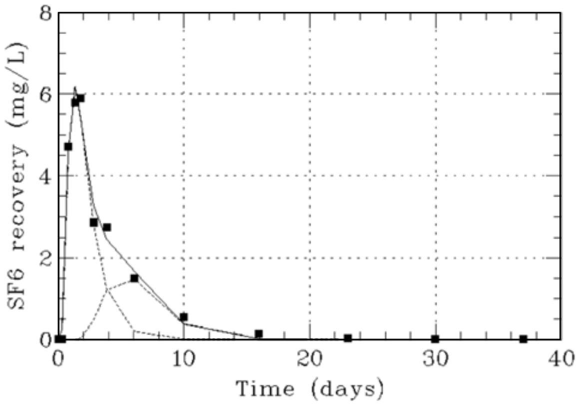

Figure 10. Observed and simulated (two flow channels) SF_6 recovery in borehole AZ-5 in the Los Azufres high-temperature field in Mexico, following injection into borehole AZ-64 200 m away [20]. The very rapid recovery is attributed to steam-phase transport. Almost 50% of the tracer was recovered through a combined flow channel volume of 200, 000 m^3 (∼10% porosity).

flow-channels between reinjection and production boreholes. This depends on the surface area of the flow-channels, information which conventional tracer testing using conservative tracers does not yield. Therefore, emphasis has been placed on the introduction of reactive tracers, in particular in EGS-research, as they can provide this information. This includes high-tech tracers such as nano-particles and quantum-dots [21].

4. CONCLUDING REMARKS

Tracer testing plays an important role in geothermal research and management, in particular concerning heat-transfer efficiency in reinjection operations and EGS development. Advances have been made in the introduction of new tracers, which both add to the multiplicity of high-sensitivity tracers available as well as being increasingly temperature tolerant. But the geothermal industry needs to follow advances in other disciplines and adopt those which are beneficial. This applies, in particular, to advances in modelling of tracer return data, which has been limited so far, especially modelling of reactive tracer data, which can yield information on flow-channel surface areas in addition to their volumes.

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References

[1] K. Saemundsson, G. Axelsson, B. Steingrímsson, *Proceedings of a short Course on Surface Exploration for Geothermal Resources*, San Salvador, El Salvador, 16 pp. (2009)

[2] V. Stefánsson, *Proceedings of the World Geothermal Congress 2005*, Antalya, Turkey, 5 pp. (2005)

[3] R. Bertani, *Proceedings of the World Geothermal Congress 2010*, Bali, Indonesia, 41 pp. (2010)

[4] J.W. Lund, D.H. Freeston, T.L. Boyd, *Proceedings of the World Geothermal Congress 2010*, Bali, Indonesia, 23 pp. (2010)

[5] I.B. Fridleifsson, R. Bertani, E. Huenges, J.W. Lund, Á. Ragnarsson, L. Rybach, In: Hohmeyer O. and T. Trittin (eds.), *Proceedings of the IPCC Scoping Meeting on Renewable Energy Sources*, Luebeck, Germany, 59–80 (2008)

[6] V. Stefánsson, Geothermics **26**, 99–139 (1997)

[7] G. Axelsson, *Proceedings of the Workshop for Decision Makers on the Direct Heating Use of Geothermal Resources in Asia*, Tianjin, China, 15 pp. (2008)

[8] C.J. Bromley, M. Mongillo, L. Rybach, *Proceedings of the New Zealand Geothermal Workshop 2006*, Auckland, New Zealand, 5 pp. (2006)

[9] G. Axelsson, V. Stefánsson, G. Björnsson, J. Liu, *Proceedings of the World Geothermal Congress 2005*, Antalya, Turkey, 8 pp. (2005)

[10] G. Axelsson, G. Björnsson, Th. Egilson, Ó.G. Flóvenz, B. Gautason, S. Hauksdóttir, M. Ólafsson, Ó. B. Smárason, K. Saemundsson, *Proceedings of the World Geothermal Congress 2005*, Antalya, Turkey, 10 pp. (2005)

[11] S. Lopez, V. Hamm, M. Le Brun, L. Schaper, F. Boissier, C. Cotiche, Geothermics **39**, 339–356 (2010)

[12] P. Seibt, *Proceedings of the Workshop for Decision Makers on the Direct Heating Use of Geothermal Resources in Asia,* Tianjin, China, 18 pp. (2008)

[13] http://www.geothermal-energy.org/304,iga_geothermal_conference_database.html (2011)

[14] G. Axelsson, G. Björnsson, F. Montalvo, *Proceedings of the World Geothermal Congress 2005*, Antalya, Turkey, 12 pp. (2005)

[15] M.C. Adams (guest editor), Geothermics **30**, 571–781 (2001)

[16] P.E. Rose, W.R. Benoit, P.M. Kilbourn, Geothermics **30**, 617–640 (2001)

[17] P.N. Hirtz, R.J. Kunzman, M.L. Broaddus, J.A. Barbitta, Geothermics **30**, 727–745 (2001)

[18] B. Sanjuan, J.L. Pinault, P.E. Rose, A. Gérard, M. Brach, G. Braibant, C. Crouzet, J.C. Foucher, A. Gautier, S. Touzelet, Geothermics **35**, 622–653 (2006)

[19] G. Axelsson, Ó.G. Flóvenz, S. Hauksdóttir, Á. Hjartarson, J. Liu, Geothermics **30**, 697–725 (2001)

[20] A. Molina-Martínez, G. Axelsson, accepted for GRC Annual Meeting Proceedings (2011)

[21] P. Rose, D. Riasetto, J. Siy, M. Bartl, P. Reimus, M. Mella, K. Leecaster, S. Petty, *Proceedings of the 36th Workshop on Geothermal Reservoir Engineering*, Stanford University, U.S.A., 7 pp. (2011)