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ROLE AND MANAGEMENT OF GEOTHERMAL REINJECTION

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ABSTRACT

Geothermal reinjection, which involves injecting energy-depleted fluid back into geothermal systems, is an integral part of all modern, sustainable and environmentally friendly geothermal utilization projects. It is an efficient method of waste-water disposal as well as a means to provide additional recharge to geothermal systems. Thus it counteracts production induced pressure draw-down and extracts more thermal energy from reservoir rocks, and increases production capacity in most cases. Reinjection can also mitigate subsidence and be used to maintain important surface activity. Reinjection is also essential for sustainable utilization of geothermal systems, which are virtually closed and with limited recharge. Reinjection is either applied inside a production reservoir, on its periphery, above or below it or outside the main production field. Several good examples of successful long-term geothermal reinjection are available, both for low-temperature and high-temperature systems. Cooling of production wells is one of the problems/obstacles associated with reinjection, even though only a few examples of actual cold-front breakthrough have been recorded. This danger can be minimised through careful testing and research. Tracer testing, combined with comprehensive interpretation and cooling predictions (reinjection modelling), is probably the most important tool for this purpose. Tracer tests actually have a predictive power since tracer transport is orders of magnitude faster than cold-front advancement around reinjection wells. Numerous examples are available worldwide on the successful application of tracer tests in geothermal systems. The tracers most commonly used in geothermal systems are fluorescent dyes, chemical substances and radioactive isotopes while new temperature-resistant tracers have been introduced and high-tech tracers are being considered. Scaling and corrosion problems associated with reinjection can be controlled through different technical solutions, dependent on the particular situation. Finally, a solution is available for the rapid aquifer clogging, which often accompanies sandstone reinjection.

1. INTRODUCTION

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 but it has slowly become more and more widespread in later years. By now reinjection is considered an important part of comprehensive geothermal resource management as well as an essential part of sustainable and environmentally friendly geothermal utilisation. The issue of sustainable geothermal utilization is discussed in a different lecture of the present course (Axelsson, 2012). Reinjection provides an additional recharge to geothermal reservoirs and as such counteracts pressure draw-down due to production and extracts more of the thermal energy from reservoir rocks than conventional utilization. Reinjection will, therefore, in most cases increase the production capacity of geothermal reservoirs, which counteracts the inevitable increase in investment and operation costs associated with reinjection. It is likely to be an economical way of increasing the energy production potential of geothermal systems in most cases. 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 also a key part of all EGS (enhanced, or engineered, geothermal system) operations.

Some operational dangers and problems are associated with reinjection. These include the possible cooling of production wells, often because of short-circuiting and cold-front breakthrough, and scaling in surface equipment and injection wells because of the precipitation of chemicals in the water. Injection into sandstone reservoirs has, furthermore, turned out to be problematic. Because of this extensive testing and research are prerequisites to successful reinjection operations. This includes tracer testing, which is the most powerful tool available to study the connections between reinjection wells and production wells.

Stefánsson (1997) describes the status of geothermal reinjection more than a decade ago, which at that time was a rather immature technology. Since then considerable advances have been made in the associated technology and much has been learned through reinjection testing and research, as reviewed by Axelsson (2008a).

This paper reviews the role of geothermal reinjection in geothermal resource management, the management of long-term reinjection as well as associated reinjection research. It starts out by reviewing the short history of reinjection in geothermal operations. The paper continues with a discussion of the different purposes of reinjection and its management. The overall management of geothermal resource during utilization is reviewed Axelsson (2008b), however. After that a few examples demonstrating the main benefits of geothermal reinjection are presented. Subsequently the main obstacles to successful reinjection are reviewed along with possible solutions. Finally the most important aspects of reinjection research are discussed, with particular emphasis on tracer testing, which is the most important tool available for studying the connections between reinjection and production wells. The paper is concluded by general conclusions and recommendations.

2. HISTORICAL BACKGROUND

Reinjection is believed to have started as soon as in the late 1960's, both in high-temperature and low-temperature fields. Some smaller scale reinjection experiments may, however, have been conducted before that. The first known instance of reinjection into a high-temperature geothermal system is in the Ahuachapan field in El Salvador, starting in 1969 (Stefánsson, 1997). This was during the initial testing period of the field, some years before operation of the field for power production started (Figure 5). Reinjection in Ahuachapan was later discontinued, only to be re-started more than two decades later. Low-temperature reinjection also started in the Paris Basin in 1969 and has continued ever since (see later). During the 1970's the number of reinjection operations started picking up and reinjection experience really started growing.

Reinjection at The Geysers in California started in 1970, with the purpose of disposing of steam condensate. Operators in the field soon realized that this improved the reservoir performance (Stefánsson, 1997). Therefore the emphasis on reinjection at The Geysers has been increasing ever since. In addition to the condensate, surface water and recently sewage water, piped long distances, is injected (Barker et al., 1995; Stark et al., 2005). Declining electricity production at the Geysers is believed to result from a limited natural recharge. Injection substitutes the recharge to some degree, and hence improves the performance of the Geysers reservoir (Goyal and Conant, 2010). Observations indicate that reinjection at The Geysers has slowed the decline in electricity production down considerably (Figure 4).

At Larderello in Italy reinjection started in 1974, also as the means of disposing of steam condensate. Reinjection is now an integral part of the Larderello field operation aimed at enhancing heat recovery from the reservoir rocks (Stefansson, 1997; Capetti et al., 1995). Several studies and long-term tests performed in the Larderello field have revealed a significant increase in steam production as well as some reservoir pressure recovery, which may clearly be attributed to the reinjection (Figure 1). Reinjection has long been employed in the geothermal fields utilized for power production in the Philippines, mainly because of environmental reasons, but it has also been adopted to improve reservoir performance (Stefánsson, 1997).

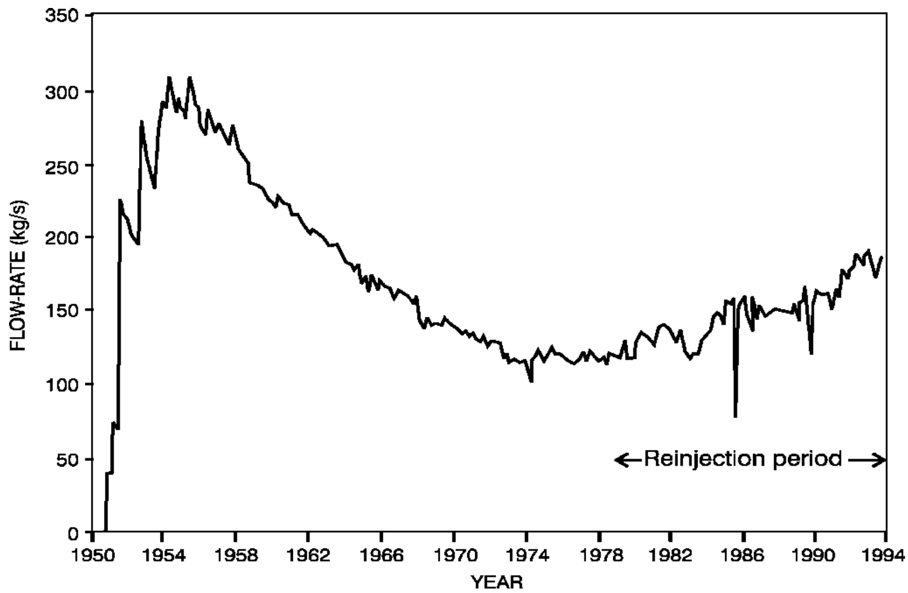

FIGURE 1: Flow-rate history of wells in the Larderello – Valle Secolo area, Italy, since the early 1950's demonstrating the benefit of reinjection (from Capetti et al., 1995)

Even though the focus in the geothermal literature has been on high-temperature operations, reinjection in low-temperature operations has become the rule rather than the exception in many countries. In many European countries regulations require e.g. that all return water be reinjected. Yet this is not the case in countries like Iceland and China where only a small part of the water produced is reinjected, even though these countries are amongst the world leaders in direct geothermal utilization. In Iceland low-temperature reinjection didn't start until 1997 when reinjection in the Laugaland field in north central Iceland commenced (Axelsson et al., 2000). The reasons for this are the fact that most low-temperature water in Iceland is relatively low in chemical content, and does therefore not pose an environmental threat, as well as the fact that due to their tectonic setting the recharge to the systems is in most cases substantial. Reinjection into low-temperature systems in Iceland is slowly picking up momentum, however (see later). Technical as well as management related obstacles have prevented reinjection from becoming the rule in China. Only in the Tianjin field has reinjection become a significant part of the operation of a geothermal field (Wang et al., 2006), while reinjection experiments have been conducted, or reinjection is slowly starting, in a few other locations (Duan et al., 2011).

The increasing role of reinjection during the last decade or so is reflected in the number of geothermal fields where reinjection is an integral part of the field operation, as reported by different authors. Stefánsson (1997) reports 20 fields in 8 countries, Axelsson and Gunnlaugsson (2000) 29 fields in 15 countries, Axelsson (2003) at least 50 fields in 20 countries and Axelsson (2008a) suggest the number of fields to be higher than 60, i.e. a 200% increase from Stefánsson's number a decade earlier. Some of this apparent increase may be the result of better information, however, and a recent, reliable number has not been compiled.

3. PURPOSE OF REINJECTION

The purpose of employing reinjection in the management of geothermal resources may be one or more of the following:

(1) Disposal of waste-water (separated water and steam condensate) from power plants, and return-water from direct applications, for environmental reasons. Such waters often contain chemicals harmful to the environment as well as causing thermal pollution. Environmental issues are discussed in more detail by Axelsson (2008b).
(2) Additional recharge to supplement the natural recharge to geothermal systems, which often is limited.
(3) Pressure support to counteract, or reduce, pressure decline due to mass extraction.
(4) To enhance thermal extraction from reservoir rocks along flow-paths from injection wells.
(5) To offset surface subsidence caused by production induced pressure decline. Subsidence has been substantial and detrimental in a number of geothermal operations.
(6) Targeted reinjection to enhance, or revitalize, surface thermal features such as hot springs and fumaroles (Bromley et al., 2006).

Several of these items are, of course, interlinked. Supplemental recharge (item (2)) e.g. results in pressure support (item (3)) and enhanced thermal extraction (item (4)). It also counteracts surface subsidence (item (5)). The actual purpose of reinjection in the management of geothermal resources is in most situations a combination of several of the above items.

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 geothermal systems is controlled by their pressure response (Axelsson, 2008a) reinjection will increase their production capacity. This applies, in particular, to systems with closed, or semi-closed, boundary conditions and thus limited recharge. Figures 2 and 3 below show examples of the results of modelling calculations for two geothermal systems, based on actual monitoring data, which clearly demonstrate this beneficial effect. One is the Urban system under Beijing, China, and the other the Hofsstadir system in W-Iceland.

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 in the reservoir fluid (10 – 20%). Therefore only a fraction of the energy may be utilised by conventional exploitation. Reinjection is thus a method of geothermal energy production, which can greatly improve the efficiency, and increase the longevity, of geothermal utilisation.

Injection wells, or injection zones intended for the location of several injection wells, are sited in different locations depending on their intended function. In addition reinjection wells 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 wells. 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.

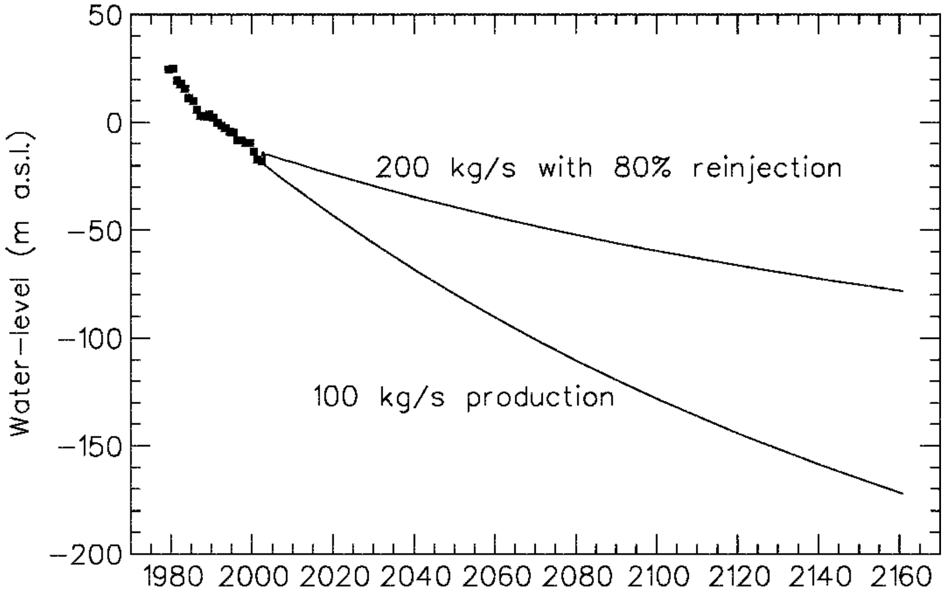

FIGURE 2: Predicted water level changes (pressure changes) in the Urban geothermal system under Beijing-city in China until 2160 for production scenarios with and without reinjection (Axelsson et al., 2005a; see also Axelsson, 2012)

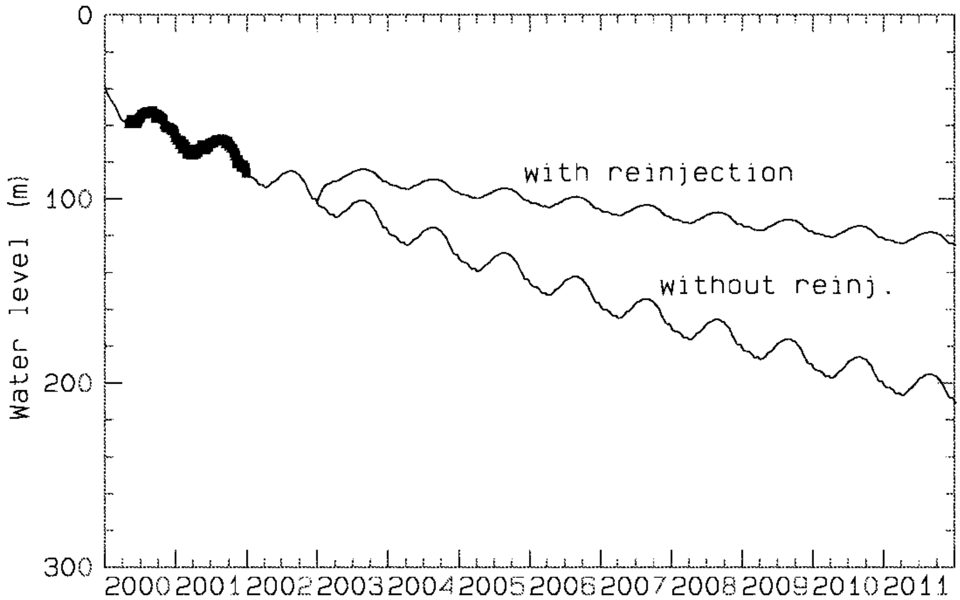

FIGURE 3: Water level predictions for the Hofsstadir low-temperature system in W-Iceland (Axelsson et al., 2005b). Both predictions assume the same production, while one assumes full reinjection and the other no reinjection. See Hofsstadir discussion later in the paper

Which option is used depends on 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 protecttion option (e) is often used. In that case not much pressure support is to be expected. Therefore options (b) – (d) are often used as kind of compromises.

Various theoretical modelling studies have been carried out to study reinjection into high-temperature systems. Both to study the effect of reinjection well location and the effect of reinjection into two-phase systems with different kinds of boundary conditions. The studies of Bodvarsson and Stefánsson (1989), Sigurdsson (1995), Kaya and O'Sullivan (2006) and Kaya et al. (2011) can be named as a few examples. Fewer low-temperature renjection modelling studies have been conducted, but the studies of Axelsson and Dong (1998), Ungemach et al. (2005) and Liu and Wang (2006) can be named as such examples.

4. REINJECTION EXAMPLES

Various examples are available on the successful application of reinjection in geothermal resource management. A few of these will be presented briefly below whereas numerous other examples are available, some discussed in the geothermal literature. The first example involves injection at the Geysers, which has already been discussed above. Figure 4 shows the production and injection at the Geysers, demonstrating the rapidly increasing importance of injection the last decade or two. Goyal and Conant (2010) conclude that the injection, along with other improvements in the steam field and power plants, has virtually stopped steam production from declining, a decline which was of the order of 6% in 1995.

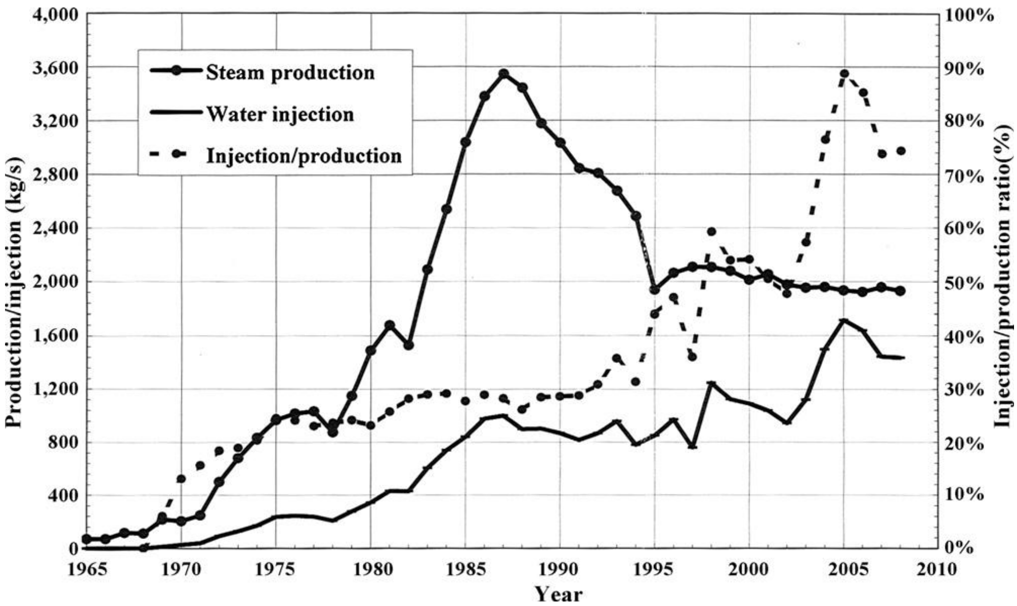

FIGURE 4: Steam production and water injection history of the Geysers geothermal field in California (Goyal and Conant, 2010)

The next example concerns the Ahuachapan geothermal system in El Salvador, which has also been discussed already in this paper. Reinjection in Ahuachapan started again at the end of the 20th century, after an almost 2 decade hiatus, during which waste-water was discharged to the ocean through an approximately 25 km long channel. Reinjection is now carried out in the adjacent Chipilapa field about 4 km from the main production field (Ábrego, 2010). Both fields are part of the same hydrological system so reinjection in Chipilapa provides pressure support for the Ahuachapan production reservoir. This can be clearly seen in Figure 5, which shows the production, reinjection and reservoir pressure history of the Ahuachapan system. The figure shows that in spite of a considerable increase in production in recent years reservoir pressure has not declined accordingly, thanks to the reinjection.

Another example of a successful reinjection operation is the Miravalles high-temperature geothermal field in Costa Rica (Mainieri, 2000). The largest part (the separated water corresponding to more than 80%) of the extracted mass has been reinjected back into the geothermal reservoir right from the beginning of utilization. Figure 6 shows the extraction and reinjection for the first 6 years and since then production and reinjection has increased substantially, with the installed capacity having increased to 164 MW_e from 125 MW_e in 1999 (Moya and Nietzen, 2010). So much mass extraction (currently ~2000 kg/s) wouldn't have been possible without the reinjection applied.

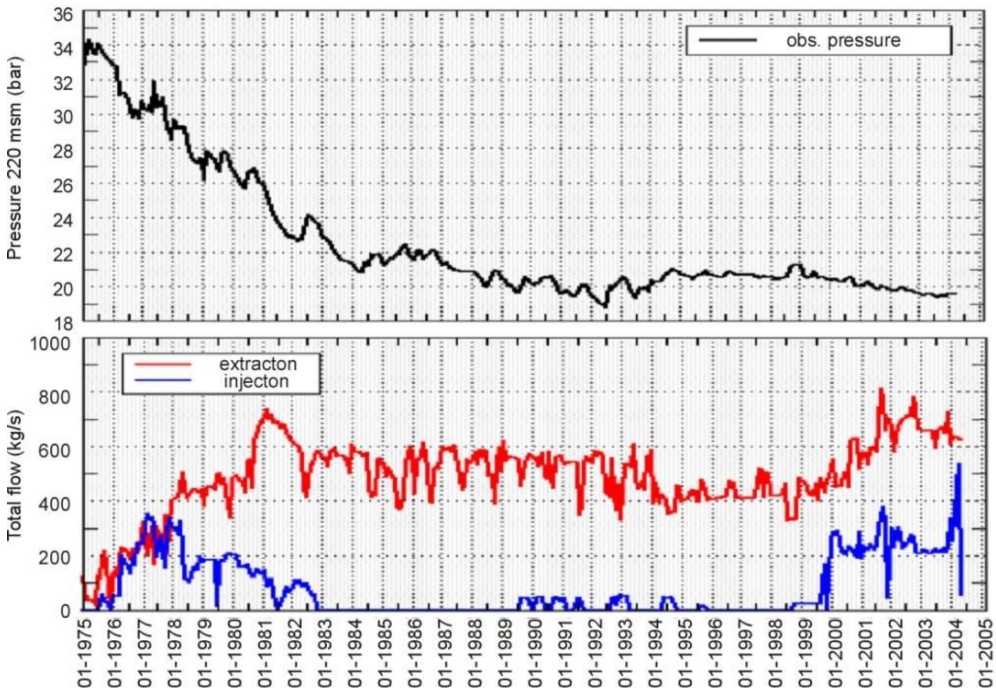

FIGURE 5: The production, reinjection and pressure response history of the Ahuachapan geothermal system in El Salvador (see also Monterrosa and Montalvo, 2010)

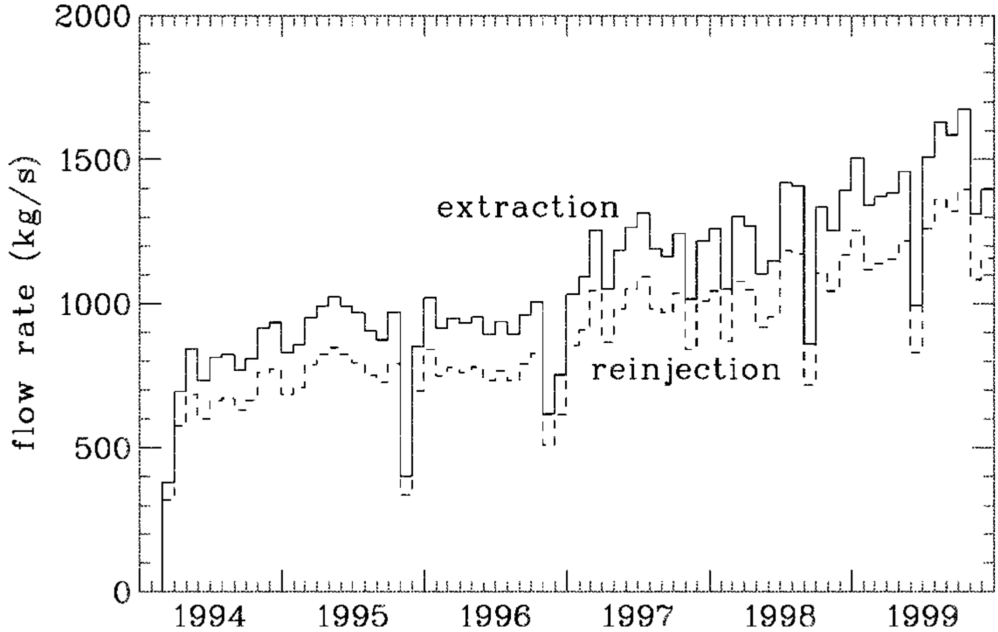

FIGURE 6: Extraction- and reinjection history of the Miravalles high-temperature field in Costa Rica 1994 – 1999. Since then production and reinjection has increase as installed capacity has increased from 125 MW_e in 1999 to 163 MW_e (see also Moya and Nietzen, 2010)

In addition to these examples it is worth mentioning that in the Philippines, which is the country with the second greatest install geothermal electrical generation capacity (1900 MW_e) in the world (Bertani, 2010) reinjection is the rule in all major geothermal operations (Dolor, 2005). In another top geothermal country, Iceland, reinjection into high-temperature geothermal systems is still in the development phase as the example presented by Gunnarsson (2011) shows.

The examples presented above are for high-temperature operations but the best example of successful long-term reinjection in a low-temperature geothermal field is the reinjection applied in the Paris basin in France (Lopez et al., 2010). This is a vast geothermal resource associated with the Dogger limestone formation, which stretches over 15,000 km^2. Energy from the Dogger reservoir is mainly used for space heating and the exploitation is in most cases on the basis of a doublet scheme, including a heat-exchanger plant due to the high mineral content, where all the water is reinjected. Utilisation of the Dogger geo-thermal reservoir started in 1969 and following the two oil crises, fifty-three additional geothermal plants were constructed in the Paris basin. The production and reinjection wells of the Paris doublets are usually separated by a distance of about 1,000 m to minimise the danger of cooling due to the reinjection. Experience, lasting 3 – 4 decades, has indicated that no significant cooling has yet taken place in any of the Paris production wells (Ungemach et al., 2005; Lopez et al., 2010).

Other examples of low-temperature reinjection operations that may be mentioned are the Tianjin field in China where about 10% of the total extracted mass are presently reinjected (Wang et al., 2006), the Laugaland field in N-Iceland where about 20 – 25% are reinjected (Axelsson et al., 2000) and the Hofsstadir field in W-Iceland where reinjection started in 2006 with about 40 – 50% of the extracted mass currently being injected (Axelsson, 2011). The Hofsstadir system is an unusually closed (i.e. with limited recharge), fracture controlled low-temperature system where the benefit from reinjection is extremely clear (Figure 7), it's in fact considerably greater than that predicted (Figure 3). Reinjection is also successfully applied in low-temperature projects in Germany, such as in the Landau and Neustadt-Glewe projects.

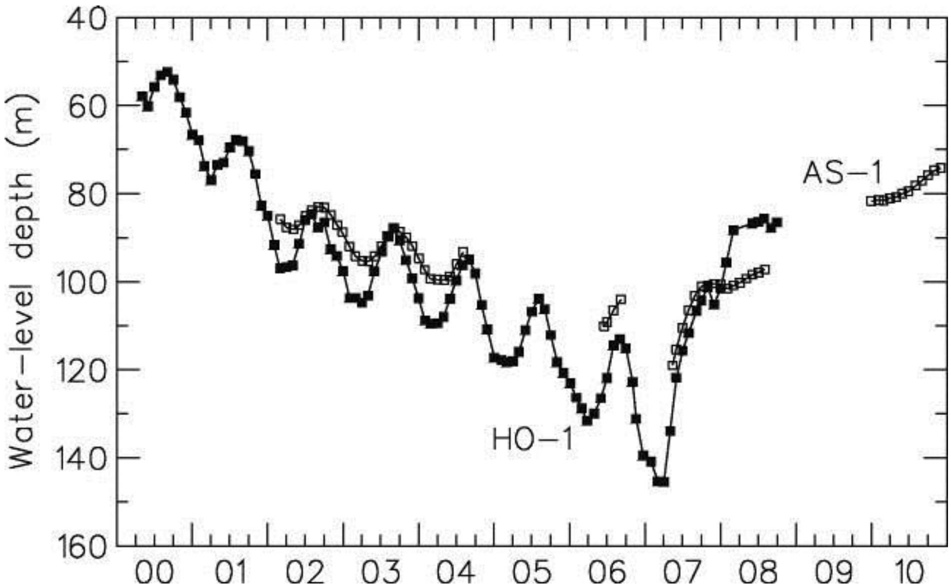

FIGURE 7: Pressure changes in the Hofsstadir low-temperature geothermal system in W-Iceland during the first 11 years of production, shown as water-level changes in the main production well (HO-1) and in a monitoring well (AS-1). A continuous pressure decline for 7 years is reversed in the spring of 2007 when reinjection commences. Figure from Axelsson (2011)

Finally it should be mentioned that reinjection is a vital part of all EGS (enhanced or engineered geothermal system) operations (Tester et al., 2007; Baria and Petty, 2008). Such projects generally involve the use of doublets or triplets (one reinjection well for each two production wells). No major EGS operations are in operation yet, but the Soultz-project in NE-France (Figure 11) is the most advanced of such projects. Other EGS projects are in the early development stages or in the preparation phase.

5. REINJECTION PROBLEMS AND OBSTACLES

The main problems and obstacles associated with reinjection are the following:

(A) Cooling of production wells, or cold-front breakthrough, often because of "short-circuiting" along direct flow-paths such as open fractures.
(B) Silica scaling in surface pipelines and injection wells in high-temperature geothermal fields. After flashing in a separator/power plant, the separated fluid becomes supersaturated in SiO_2 and silica will precipitate from the fluid.
(C) Other types of scaling and corrosion in both low-temperature and high-temperature operations. This includes e.g. carbonate scaling in low-temperature systems.
(D) Rapid clogging of aquifers next to injection wells in sandstone reservoirs by fine sand and precipitation material.

The possible cooling of production wells has discouraged the use of injection 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 wells is small, and direct flow-paths between the two wells exist, the fear of thermal breakthrough has been justified, however. Stefánsson (1997) reports that actual cooling, attributable to injection, has only been observed in a few high-temperature fields worldwide. The temperature decline of well PN-26 in Palinpinon in the Philippines, reviewed by Malate and O'Sullivan (1991), is a striking example. The thermal breakthrough occurred about 18 months after reinjection started. Subsequently, the temperature declined rapidly, dropping by about 50ºC in 4 years (Figure 8). Such examples are exceptions rather than the rule, however. Research aimed at grasping this problem will be discussed in more detail later in this paper.

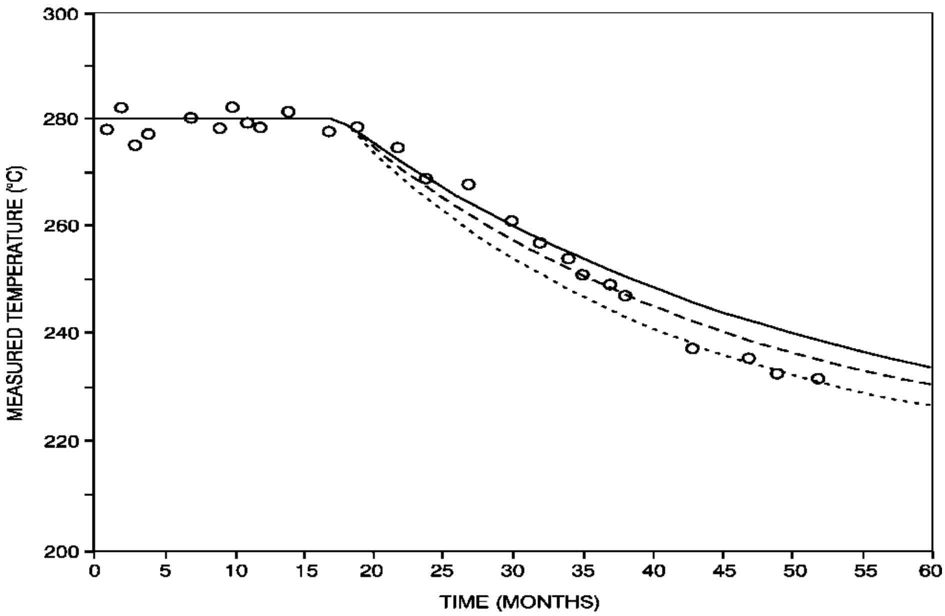

FIGURE 8: Measured and simulated temperature decline in well PN-26 in the Palinpinon field, Philippines (from Malate and O'Sullivan, 1991)

Silica scaling in high-temperature operations occurs because the geothermal fluid involved is in equilibrium with the rocks at reservoir conditions. After flashing in a separator or a power plant, the separated fluid (often called brine) becomes supersaturated in SiO_2 and silica will precipitate from the fluid. This is a complex process partly controlled by temperature, pH of the fluid, and the concentration of SiO_2. The problem of silica scaling may be avoided, in most cases, by proper system design. One design involves applying "hot" injection where the separated water is injected directly from a separator, at a temperature of 160–200°C, i.e. above the saturation temperature for silica scaling. Other designs use "cold" injection where the return water temperature is below the saturation temperature for silica scaling, because of cooling. This calls for preventive measures such as deposition of silica in ponds/lagoons or by special treatment such as with scale inhibitors, mainly aimed at pH lowering (Klein, 1995). Mixing the separated water by steam condensate, which dilutes the silica and lowers the pH, is often used as a remedy. Stefansson (1997) discusses this issue in more detail with particular reference to the experience in Japan, New Zealand and the Philippines. Sigfússon and Gunnarsson (2011) discuss this aspect of the operation of the Hellisheidi power plant in SW-Iceland along with experiments conducted to study the issue and design appropriate measures. Carbonate precipitation is usually curtailed by operating the production/ reinjection system at sufficiently high pressures or by utilizing scale inhibitors (usually injected into production wells at depth). Corrosion can also be controlled by inhibitors.

According to Stefánsson (1997) reinjection into sandstone reservoirs had been attempted at several locations at the time of his study, but with limited success. During these experiments, or operations, the injectivity of the injection wells involved decreases very rapidly, even in hours or days, rendering further reinjection impossible. This is most likely because the aquifers next to the injection wells become blocked by fine sand and precipitation particles from the reinjection fluids. Attempts at solving this problem have involved flow-reversal through the use of down-hole pumps, but a more efficient solution to the injection problem has been developed in Denmark and Germany (Mahler, 2000; Seibt et al., 2005). This solution involves a sophisticated closed loop system wherein the reinjection water is kept completely oxygen free as well as being passed through very fine filters (down to 1 μm). Oxygen is believed to facilitate chemical reactions creating precipitation material. In addition, pressures are kept up by nitrogen during operation and when the operation is stopped. This solution to the sandstone injection problem, which has to be adapted to the specific reservoir conditions at each location, is believed to be the most dependable and lasting method available today (Seibt and Kellner, 2003; Seibt and Wolfgramm, 2008).

6. TRACER TESTS AND REINJECTION MODELLING

6.1 General

Tracer testing has become a highly important tool in geothermal research, development and resource management, with its role being 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 wells, connections that control the danger and rate of cooling of the production wells 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 chapter reviews geothermal tracer testing by discussing its general role, by introducing an efficient method of tracer test interpretation and for predicting production well cooling, by presenting a few examples as well as by introducing recent developments and advances in geothermal tracer testing.

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 extensively 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 (Axelsson, 2011):

1) The main purpose in conventional geothermal development is to study connections between injection and production wells as part of reinjection research and management. The results are consequently used to predict the possible cooling of production wells 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 wells.
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 (http://www.geothermal-energy.org), i.e. at World Geothermal Congresses held every 5 years. The reader is also referred to a special issue of the international journal Geothermics devoted to tracer tests (Adams, 2001) and a paper by Axelsson et al. (2005c).

Geothermal tracer tests are mostly conducted through wells and can involve (i) a single well injection-backflow test, (ii) a test involving one well-pair (injection and production) as well as (iii) several injection and production wells. 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 well(s) in question. Samples for tracer analysis are most often collected from producing wells, while down-hole samples may need to be collected from non-discharging wells. 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 (Axelsson et al., 2005c).

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 discussion on reactive tracers 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 the isotopes 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).

Two-phase tracers:

- Tritium (^3H);
- Alcohols such as methanol, ethanol and n-propanol.

Sodium-fluorescein has been used successfully in numerous geothermal fields, both low- and high-temperature ones (Axelsson et al., 2005c). 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 200°C. Therefore new tracers with higher temperature-tolerance, but comparable detection limits, have been introduced, in particular several polyaromatic sulfonates (Rose et al., 2001). These are increasingly being used in geothermal applications. Having several comparable tracers also enables the execution of multi-well tracer tests. Rose et al. (2001) present the temperature-tolerance of several of these compounds, which in some cases exceeds 300°C.

Radioactive materials are also excellent tracers since they are detectable at extremely low concentration (Axelsson et al., 2005c). 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 (Hirtz et al., 2001) 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 9 – 11 show three examples of the results of tracer tests conducted in geothermal systems of quite contrasting nature, also presented by Axelsson (2011). These are just presented as concise examples, without specific field details. Two more examples, with interpretation results, are presented below.

Figure 9 shows the tracer recovery during an unusually long tracer test conducted in the Hofsstadir low-temperature (reservoir temperature 85-90°C) geothermal system in W-Iceland already mentioned twice in this paper. The test involved tracer injection into an operating reinjection well about 1200 m from the production well. The relatively slow recovery indicates that reinjection induced cooling will be limited. This awaits confirmation through comprehensive interpretation and modelling.

Figure 10 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 well about 200 m from a production well. The relatively rapid recovery was interpreted as indicating a considerable danger of cooling of the production well. Therefore the reinjection well 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 (Sanjuan et al., 2006). The tests involved 4 wells ranging in depth from 3600 to 5300 m. A few different tracers very used, including fluorescein and some naphthalene sulfonates. Figure 11 shows the recovery during the test between wells GPK-3 and GPK-2 separated by 650 m, in which fluorescein was successfully used. It showed the most direct connection in the system.

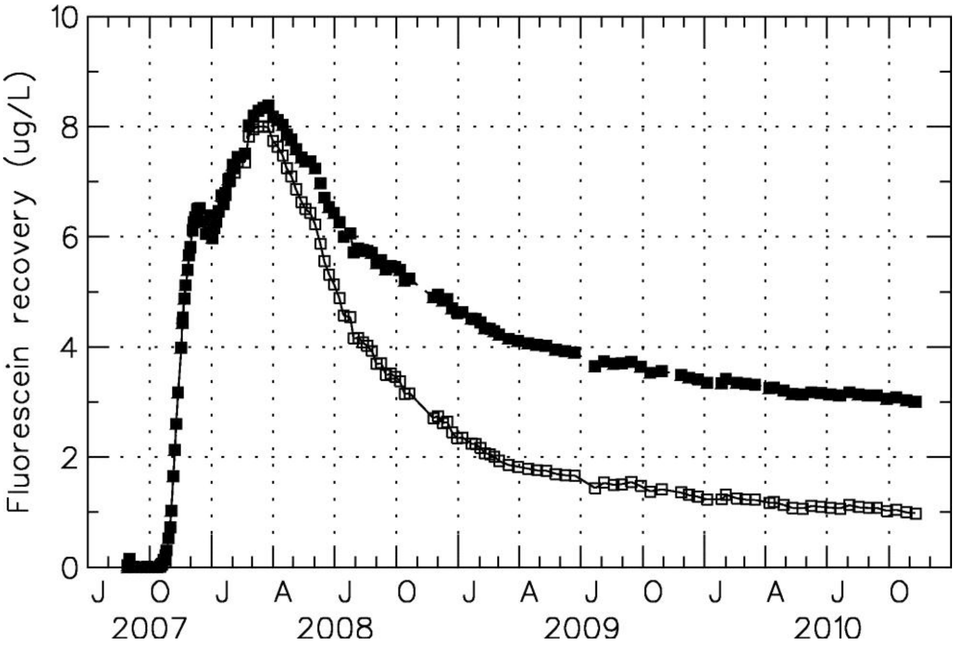

FIGURE 9: Fluorescein recovery in production well HO-1 in the Hofsstadir low-temperature system in W-Iceland (see Figures 3 and 7), following the injection of 10 kg of the tracer into reinjection well HO-2 (from Axelsson, 2011). The test lasted 3.5 years. The lower curve shows the recovery corrected for the tracer being reinjected (recirculated) after production from HO-1. About 70% of the tracer was recovered during the test

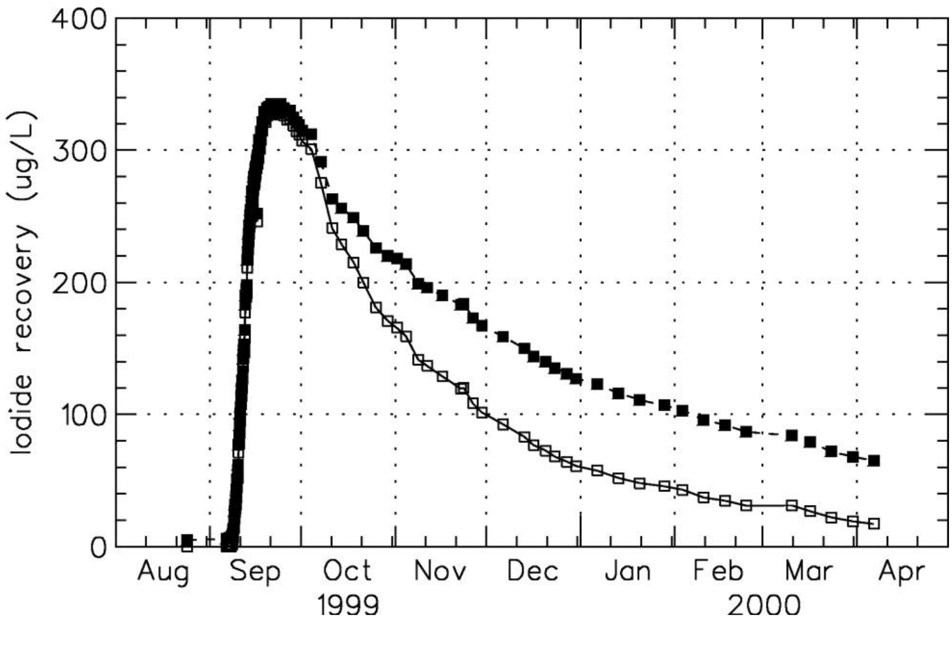

FIGURE 10: Iodide recovery in production well K-21 in the Krafla high-temperature system in N-Iceland, following the injection of 200 kg of KI into well K-22 (from Axelsson, 2011. The test lasted 7 months. The lower curve shows the recovery corrected for the tracer being reinjected (recirculated) after production. About 30% of the tracer was recovered during the test)

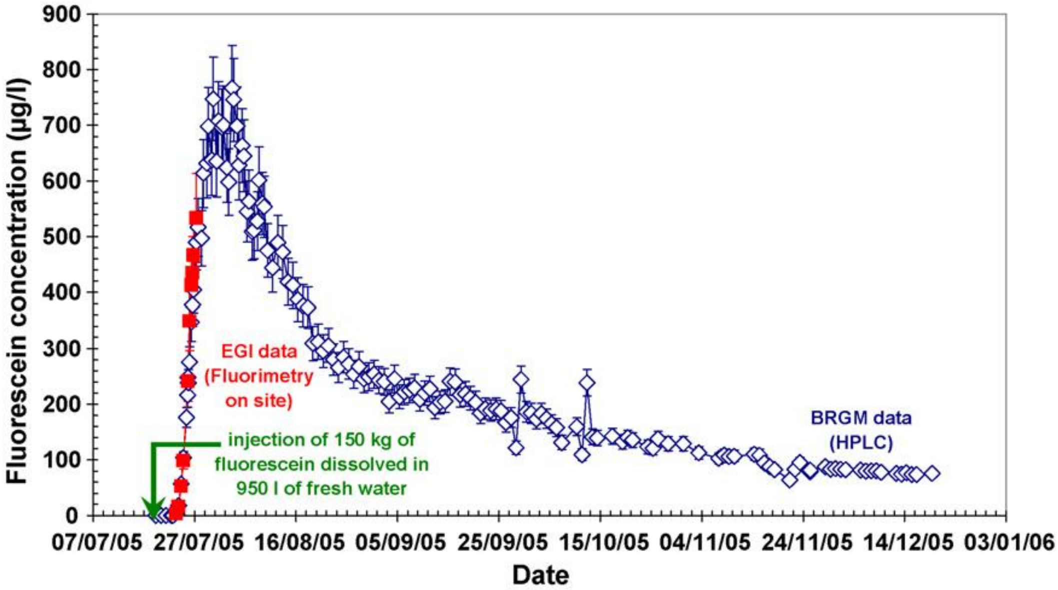

FIGURE 11: Flourescein recovery in well GPK-2 at the Soultz EGS-site in N-France, following the injection of 150 kg of fluorescein into well GPK-3 (figure from Sanjuan et al., 2006). The test lasted 5 months. About 24% of the tracer was recovered during the test

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.

6.2 Interpretation method and examples

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. Axelsson et al. (2005c) present a simple and efficient method that may be used for this purpose. 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 referred to is conveniently based on the assumption of specific flow channels connecting injection and production wells. 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 (Axelsson et al., 2005c). 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 involved assumes the flow between injection and production wells may be approximated by one-dimensional flow in flow-channels. 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 wells. In some cases more than one channel may be assumed to connect an injection and a production well, for example connecting different feed-zones in the wells involved.

The interpretation method involves simulating tracer return data, such as presented above, on basis of equations presented by Axelsson et al. (2005c). The simulation yields information on the flow channel cross-sectional area and dispersivity as well as the mass of tracer recovered through a given channel (equal to, or less than, the mass of tracer injected). In the case of two or more flow-channels the analysis yields estimates of these parameters for each channel. Through the estimates of flow channel cross-sectional area(s) the flow channel pore space volume(s) has (have) in fact been estimated. The tracer interpretation software *TRINV*, included in the *ICEBOX* geothermal software package, can be used for this simulation (Axelsson et al., 2005c).

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 wells 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 pore-space volume (Axelsson et al., 2005c). 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 (see also later discussion of recent advances).

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 a pessimistic model with minimal heat transfer. Second a large surface area flow channel, such as a thin fracture-zone or thin horizontal layer, which can be considered an optimistic model with effective 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.

Figures 12–14 present examples of the results of geothermal tracer test analysis using the interpretation method discussed above. 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 12 shows the fluorescein recovery through a production well in the Laugaland low-temperature geothermal system (reservoir temperature 90-100°C) in N-Iceland, conducted in 1997, simulated by the method presented above (Axelsson et al., 2001). This was during initial reinjection testing in the field, since then reinjection has been part of the management of the system. Figure 13 shows production temperature predictions calculated by a pessimistic model based on the tracer recovery simulation presented in Figure 12. They show that the long-term cooling of the well in question should be minimal, in particular in view of the considerable increase in productivity of the Laugaland system when reinjection is applied (Axelsson et al., 2001).

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 (Figure 14) in which SF_6 was used due to the fact that a steam zone has developed in the system and that production wells involved (NE-part of the field) produce mostly steam (Molina-Martínez and Axelsson, 2011). 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.

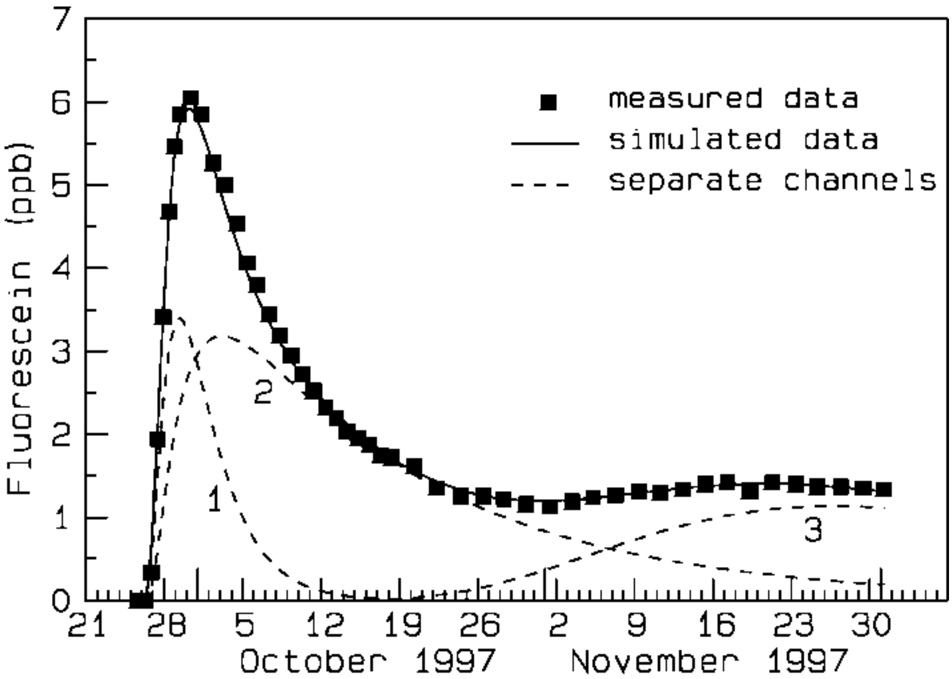

FIGURE 12: Observed and simulated (three flow channels) fluorescein recovery in well LN-12 at Laugaland in N-Iceland during a tracer test in 1997 (figure from Axelsson et al., 2001). Spent geothermal fluid was reinjection into well LJ-08 and production was from well LN-12 about 300 m away. According 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

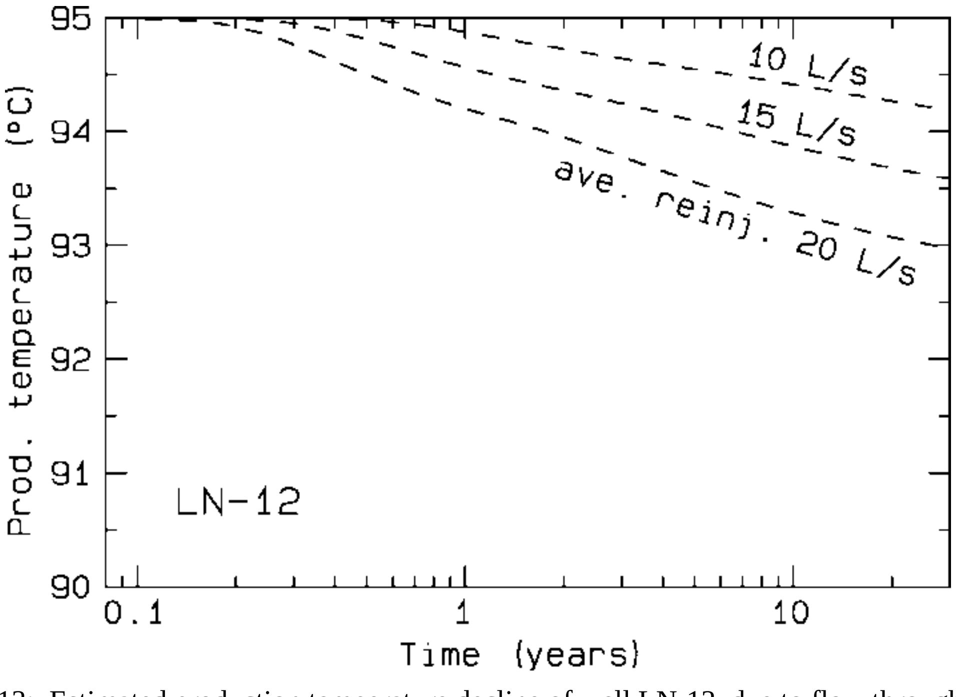

FIGURE 13: Estimated production temperature decline of well LN-12, due to flow through the three channels simulated (Figure 12), for three cases of average long-term reinjection into well LJ-8 and an average long-term production rate of 40 L/s (figure from Axelsson et al., 2001)

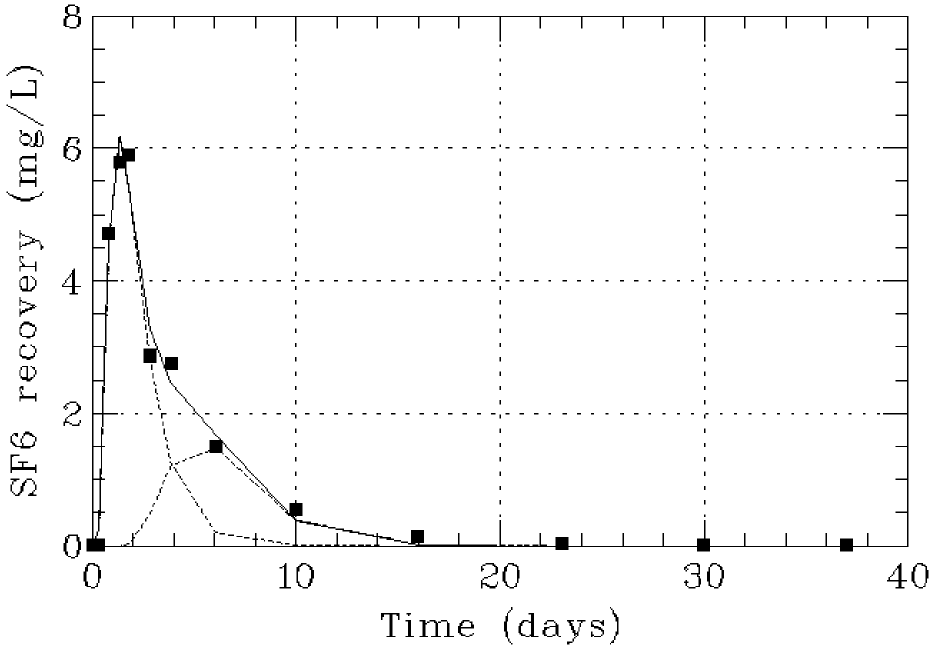

FIGURE 14: Observed and simulated (two flow channels) SF_6 recovery in well AZ-5 in the Los Azufres high-temperature field in Mexico, following injection into well AZ-64 200 m away (Molina-Martínez and Axelsson, 2011). The very rapid recovery is attributed to steam-phase transport. Almost 50% of the tracer was recovered through a combined flow channel volume of 200,000 m^3 (~10% porosity)

6.3 Recent advances

The main uncertainty in reinjection operations and EGS development involves the heat-transfer efficiency of flow-channels between reinjection and production wells. 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 (see e.g. Rose et al. (2011). By applying two tracers, one conservative and the other reactive, it should be possible to estimate both the flow-channel pore-space volume and its surface area (the transport of the reactive tracer depends on the available surface area as well as the volume).

7. CONCLUSIONS AND RECOMMENDATIONS

The application of reinjection in geothermal resource management has been rapidly increasing during the last one or two decades, and reinjection is now considered an integral part of all efficient, sustainable and environmentally friendly geothermal operations. Its main significance is in providing supplemental recharge and thus providing pressure support and enhancing energy extraction. Its other main purpose is to dispose of waste water for environmental reasons. In addition reinjection can be used to counteract production induced subsidence and to help maintain geothermal surface features.

One of the principal obstacles to geothermal reinjection is the danger of production well cooling. This danger can be minimized through careful planning and research, with the most important tools being tracer tests with quantitative interpretation and cooling modelling. Other obstacles include scaling, corrosion and sandstone aquifer clogging. Practical technical solutions have been developed for these problems, which have to be adapted to local conditions, however. Geothermal system modelling plays a key role in planning reinjection, including selecting appropriate and beneficial reinjection zones.

Careful and comprehensive monitoring of reinjection wells, and the possible effects of reinjection, is essential for successful reinjection management.

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

Ábrego, J.C., 2010: Ahuachapan reinjection system ensurement. *Proceedings World Geothermal Congress 2010, Bali, Indonesia*, 10 pp.

Adams, M.C. (guest editor), 2001: Special issue on tracer applications in geothermal fields. *Geothermics, 30*, 571-781.

Axelsson, G., 2012: Sustainable geothermal utilization. *Proceedings of " Short Course on Geothermal Development and Geothermal Wells", organized by UNU-GTP and LaGeo, Santa Tecla, El Salvador*, 18 pp.

Axelsson, G., 2011: Tracer tests in geothermal resource management. *Proceedings of Tracer 6 – International Conference on Tracers and Tracing Methods, Oslo, Norway*, 8 pp.

Axelsson, G., 2010: Sustainable geothermal utilization – Case histories, definitions, research issues and modelling. *Geothermics, 39*, 283–291.

Axelsson, G., 2008a: Importance of geothermal reinjection. *Proceedings of "Workshop for Decision Makers on the Direct Heating Use of Geothermal Resources in Asia", organized by UNU-GTP, TBLRREM and TBGMED, Tianjin, China*, 15 pp.

Axelsson, G., 2008b: Management of geothermal resources. *Proceedings of "Workshop for Decision Makers on the Direct Heating Use of Geothermal Resources in Asia", organized by UNU-GTP, TBLRREM and TBGMED, Tianjin, China*, 15 pp.

Axelsson, G., 2008c: Production capacity of geothermal systems. *Proceedings of "Workshop for Decision Makers on the Direct Heating Use of Geothermal Resources in Asia", organized by UNU-GTP, TBLRREM and TBGMED, Tianjin, China*, 14 pp.

Axelsson, G., 2003: Essence of geothermal resource management. In: *Lectures on the sustainable use and operating policy for geothermal reservoirs*. IGC2003 short course, United Nations University Geothermal Training Programme, 2003–1, Reykjavík, Iceland, 129–152.

Axelsson, G., and Dong, Z., 1998: The Tanggu geothermal reservoir (Tianjin, China). *Geothermics, 27*, 271–294.

Axelsson, G. and Gunnlaugsson, E. (convenors), 2000: Long-term monitoring of high- and low-enthalpy fields under exploitation. International Geothermal Association, *World Geothermal Congress 2000 Short Course, Kokonoe, Kyushu District, Japan*, 226 pp.

Axelsson, G., Stefánsson, V., and G. Björnsson, 2005a: Sustainable utilization of geothermal resources for 100–300 years. *Proceedings World Geothermal Congress 2005, Antalya, Turkey,* 8 pp.

Axelsson G., Björnsson, G., Egilson, Th., Flóvenz, Ó.G., Gautason, B., Hauksdóttir, S., Ólafsson, M., Smárason, Ó.B., and Saemundsson, K., 2005b: Nature and properties of recently discovered hidden low-temperature geothermal reservoirs in Iceland. *Proceedings World Geothermal Congress 2005, Antalya, Turkey,* 10 pp.

Axelsson G., Björnsson, G., and Montalvo, F., 2005c: Quantitative interpretation of tracer test data. *Proceedings World Geothermal Congress 2005, Antalya, Turkey*, 12 pp.

Axelsson, G., Flóvenz, Ó.G., Hauksdóttir, S., Hjartarson, Á., Liu, J., 2001: Analysis of tracer test data, and injection-induced cooling, in the Laugaland geothermal field, N-Iceland. *Geothermics, 30*, 697–725.

Axelsson, G., Flóvenz, Ó.G., Hjartarson, Á, Hauksdóttir, S., Sverrisdóttir, G., Árnason, F., Árnason, Á. and Bödvarsson, R., 2000: Thermal energy extraction by reinjection from the Laugaland geothermal system in N-Iceland. *Proceedings World Geothermal Congress 2000, Kyushu-Tohoku, Japan*, 3027–3032.

Baria, R., and Petty, S., 2008: Economic and technical case for commercial exploitation of EGS. *Proceedings 33rd Workshop on Geothermal Reservoir Engineering, Stanford University, California, USA,* 5 pp.

Barker, B.J., Koenig, B.A., and Stark, M.A., 1995: Water injection management for resource maximization: observations from 25 years at The Geysers, California. *Proceedings World Geothermal Congress 1995, Florence, Italy*, 1959–1964.

Bertani, R., 2010: Geothermal power generation in the world – 2005–2010 update report. *Proceedings World Geothermal Congress 2010, Bali, Indonesia*, 41 pp.

Bodvarsson, G.S., and Stefánsson, V., 1989: Some theoretical and field aspects of reinjection in geothermal reservoirs. *Water Resources Research, 25*, 1235–1248.

Bromley, C.J., Mongillo, M., and Rybach, L., 2006: Sustainable utilization strategies and promotion of beneficial environmental effects – Having your cake and eating it too. *Proceedings of the New Zealand Geothermal Workshop 2006, Auckland, New Zealand*, 5 pp.

Capetti, G., Parisi, L., Ridolfi, A., and Stefani, G., 1995: Fifteen years of reinjection in the Larderello-Valle Secolo area: Analysis of the production data. *Proceedings World Geothermal Congress 1995, Florence, Italy*, 1997–2000.

Dolor, F.M., 2005: Phases of geothermal development in the Philippines. *Proceedings of "Workshop for Decision Makers on Geothermal Projects and Management", organized by UNU-GTP and KenGen, Naivasha, Kenya,* November, 10 pp.

Duan, Z., Pang, Z., and Wang, X., 2011: Sustainability evaluation of limestone geothermal reservoirs with extended production histories in Beijing and Tianjin, China. *Geothermics, 40*, 125–135.

Goyal, K.P., and Conant, T.T., 2010: Performance history of The Geysers steam field, California, USA. *Geothermics, 39*, 321–328.

Gunnarsson, G., 2011: Mastering reinjection in the Hellisheidi field, SW-Iceland: A story of successes and failures. *Proceedings 36th Workshop on Geothermal Reservoir Engineering, Stanford University, California, USA*, 8 pp.

Hirtz, P.N., Kunzman, R.J., Broaddus, M.L., and Barbitta, J.A., 2001: Developments in tracer flow testing for geothermal production engineering. *Geothermics, 30*, 727-745.

Kaya, E., and O'Sullivan, M.J., 2006: Modelling of injection into geothermal systems. *Proceedings of the New Zealand Geothermal Workshop 2006, Auckland, New Zealand*, 8 pp.

Kaya, E., O'Sullivan, M.J., and Brockbank, K., 2011: Reinjection into liquid-dominated two-phase geothermal systems. *Proceedings 36th Workshop on Geothermal Reservoir Engineering, Stanford University, California, USA*, 8 pp.

Klein, C.W., 1995: Management of fluid injection in geothermal wells to avoid silica scaling at low levels of silica oversaturation. *Proceedings World Geothermal Congress 2000, Kyushu-Tohoku, Japan*, 2451–2456.

Liu, J., and K. Wang, 2006: Geothermal reinjection in China. *Proceedings of the 7th Asian Geothermal Symposium*, Qingdao, China, July, 59–65.

Lopez, S., Hamm, V., Le Brun, M., Schaper, L., Boissier, F., Cotiche, C., and Giuglaris, E., 2010: 40 years of Dogger aquifer management in Ile-de-France, Paris Basin, France. *Geothermics, 39*, 339–356.

Mahler, A., 2000: Geothermal plant with efficient absorption heat pumps driven by incineration CHP plant. Successful injection in sandstone aquifer. Country update Denmark. *Proceedings World Geothermal Congress 2000, Kyushu-Tohoku, Japan*, 307–312.

Mainieri, A., 2000: Costa Rica country update. *Proceedings World Geothermal Congress 2000, Kyushu-Tohoku, Japan*, 313–318.

Malate, R.C.M., and O'Sullivan, M.J., 1991: Modelling of chemical and thermal changes in well PN-26 Palinpinon geothermal field, Philippines. *Geothermics, 20*, 291–318.

Molina-Martínez, A., and Axelsson, G., 2011: Assessment of thermal interference in the northern part of Los Azufres Geothermal Field, Mexico, by tracer test analysis. *Geothermal Resources Council Transactions, 35*, 1505–1511.

Monterrosa, M., and Montalvo, F., 2010: Sustainability analysis of the Ahuachapan geothermal field – Management and modelling. *Geothermics, 39*, 370–381.

Moya, P., and Nietzen, F., 2010: Production-injection at the Miravalles geothermal field, Costa Rica. *Proceedings World Geothermal Congress 2010, Bali, Indonesia*, 11 pp.

Rose, P., Riasetto, D., Siy, J., Bartl, M., Reimus, P., Mella, M., Leecaster, K., and Petty, S., 2011: Quantum dots as tracers in geothermal and EGS reservoirs. *Proceedings of the 36th Workshop on Geothermal Reservoir Engineering, Stanford University, USA*, 7 pp.

Rose, P.E., Benoit, W.R., and Kilbourn, P.M., 2001: The application of the polyaromatic sulfonates as tracers in geothermal reservoirs. *Geothermics, 30*, 617-640.

Sanjuan, B., Pinault, J.L., Rose, P.E., Gérard, A., Brach, M., Braibant, G., Crouzet, C., Foucher, J.C., Gautier, A., and Touzelet, S., 2006: Tracer testing of the geothermal heat exchanger at Soultz-sous-Forêts (France) between 2000 and 2005. *Geothermics, 35*, 622-653.

Seibt, P., and Wolfgramm, M., 2008: Practical experience in the reinjection of thermal waters into sandstone. *Proceedings of the "Workshop for Decision Makers on the Direct Heating Use of Geothermal Resources in Asia", organized by UNU-GTP, TBLRREM and TBGMED, Tianjin, China*, 18 pp.

Seibt, P., and Kellner, T., 2003: Practical experience in the reinjection of cooled thermal waters back into sandstone reservoirs. *Geothermics, 32*, 733–741.

Seibt, P., Kabus, F., and Hoth, P., 2005: The Neustadt-Gleve geothermal power plant – Practical experience in the reinjection of cooled thermal waters into sandstone aquifers. *Proceedings World Geothermal Congress 2005, Antalya, Turkey*, 9 pp.

Sigfusson, B., and Gunnarsson, I., 2011: Scaling prevention experiments in the Hellisheidi power plant, Iceland. *Proceedings 36th Workshop on Geothermal Reservoir Engineering, Stanford University, California, USA*, 5 pp.

Sigurdsson, Ó., Arason, Th., and Stefánsson, V., 1995: Reinjection strategy for geothermal systems. *Proceedings of the World Geothermal Congress 1995, Florence, Italy*, 1967–1971 .

Stark, M.A., Box Jr., W.T., Beall, J.J., Goyal, K.P., and Pingol, A.S., 2005: The Santa Rosa – Geysers Recharge Project, Geysers Geothermal Field, California, USA. *Proceedings World Geothermal Congress 2005, Antalya, Turkey*, 9 pp.

Stefánsson, V., 1997: Geothermal reinjection experience. *Geothermics, 26*, 99–130.

Tester, J., Blackwell, D., Petty, S., Richards, M., Moore, M., Anderson, B., Livesay, B., Augustine, C., DiPippo, R., Nichols, K., Veatch, R., Drake, E., Toksoz, N., Baria, R., Batchelor, A.S., and Garnish, J., 2007: The future of geothermal energy: An assessment of the energy supply potential of Engineered Geothermal Systems (EGS) for the United States. *Proceedings 32nd Workshop on Geothermal Reservoir Engineering, Stanford University, California, USA*, 1 pp.

Ungemach, P., Antics, M., and Papachristou, M., 2005: Sustainable geothermal reservoir management. *Proceedings World Geothermal Congress 2005, Antalya, Turkey*, 12 pp.

Wang, K., Han, J., and Wang, Y., 2006: The geothermal development and utilization in Tianjin, China. *Proceedings of the 7th Asian Geothermal Symposium, Qingdao, China*, 151–154.