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IMPORTANCE OF GEOTHERMAL REINJECTION

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ABSTRACT

Reinjection is fast becoming 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, in fact, essential for sustainable utilization of geothermal systems, which are virtually closed and with limited recharge. Reinjection is either applied inside a production reservoir, on the periphery of the reservoir, above or below the main reservoir or outside the main production field. One of the best examples of successful long-term low-temperature reinjection is the utilization of the Dogger formation in the Paris Basin, which started in 1969. Cooling of production wells is one of the problems /obstacles associated with reinjection, even though only a very 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. Scaling and corrosion problems can be controlled through different technical solutions, dependent on the particular situation. Finally, a solution has been found for the rapid aquifer clogging, which often accompanies sandstone reinjection. It involves highly efficient filtering and maintaining the whole production/reinjection system completely oxygen-free.

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. 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.

This paper discusses briefly the importance of geothermal reinjection. 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 by presenting a few examples demonstrating its main benefits. Consequently the main obstacles to successful reinjection are reviewed as well as the main tools of reinjection testing. In two preceding papers by the same author the factors controlling the production capacity of geothermal systems have been reviewed as well as the management of geothermal resources (Axelsson, 2008a and 2008b).

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. 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. Observations indicate that reinjection at The Geysers has slowed the decline in electricity production down considerably (Stark *et al.*, 2005).

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 (see 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).

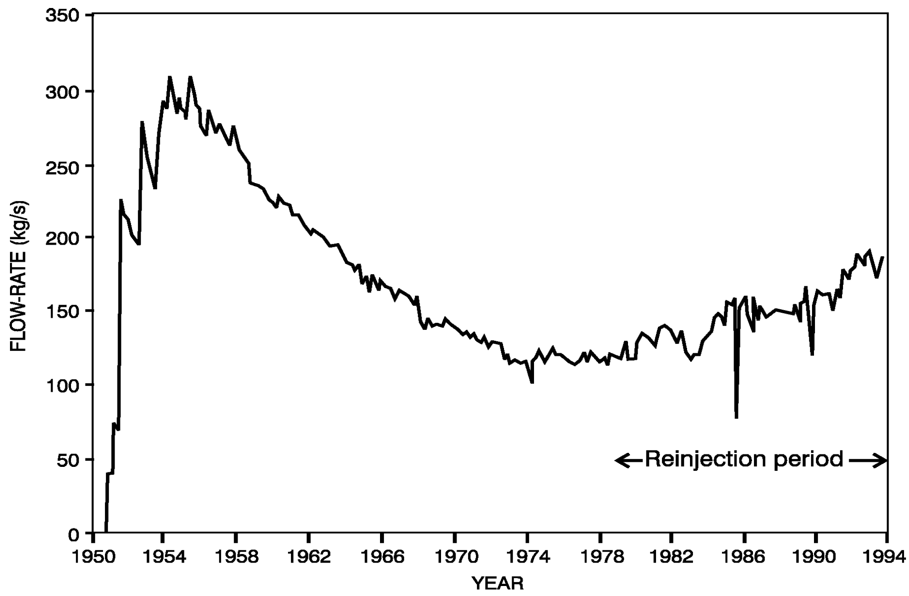

FIGURE 1: Flow-rate history of wells in the Larderello – Valle Secolo area, Italy (from Capetti *et al.*, 1995).

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. 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 in a few other locations.

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 and Axelsson (2003) at least 50 fields in 20 countries, i.e. a 150% increase. Some of this apparent increase may be the result of better information, however. A recent, reliable number has not been compiled, but the number of fields is likely to be more than 60 today.

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 (see 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 low-temperature 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 Hofstadir 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.

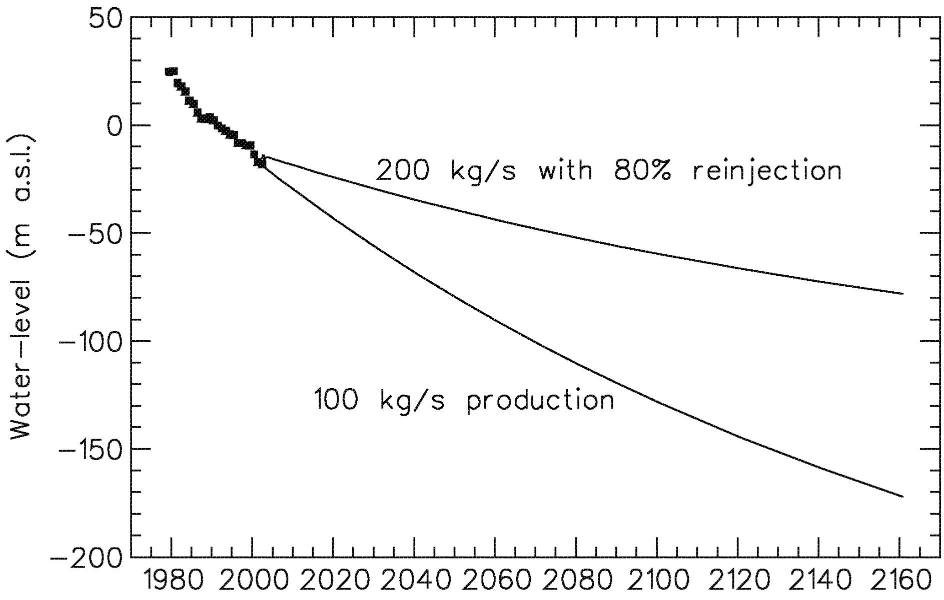

FIGURE 2: Predicted water level changes (pressure changes) in the Urban geothermal system under Beijing-city in China until 2160 for production scenarios with and without reinjection (Axelsson *et al.*, 2005a).

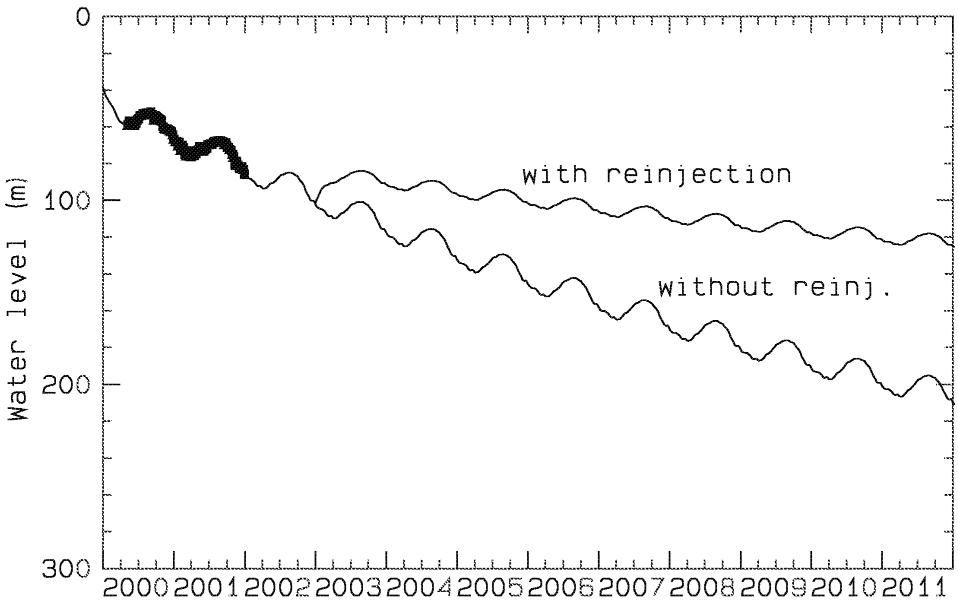

FIGURE 3: Water level predictions for the Hofstadir low-temperature system in W-Iceland (Axelsson *et al.*, 2005b). Both predictions assume the same production, while one assumes full reinjection and the other no reinjection.

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.

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 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 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) and Kaya and O'Sullivan (2006) 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. The best example of successful long-term reinjection in a low-temperature geothermal field is the reinjection applied in the Paris basin in France (Boisdet *et al*., 1990; Axelsson and Gunnlaugsson, 2000; Ungemach *et al.*, 2005). This is a vast geothermal resource associated with the Dogger limestone formation, which stretches over 15,000 km^2 (Figure 4). 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 (Figure 5). Utilisation of the Dogger geothermal reservoir started in 1969 and following the two oil crises, fifty-three additional geothermal plants were constructed in the Paris basin. During the late eighties a remote monitoring system was set up covering most of the doublets in which the data are collected through the telephone network to a central location. 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 (Figure 6). 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).

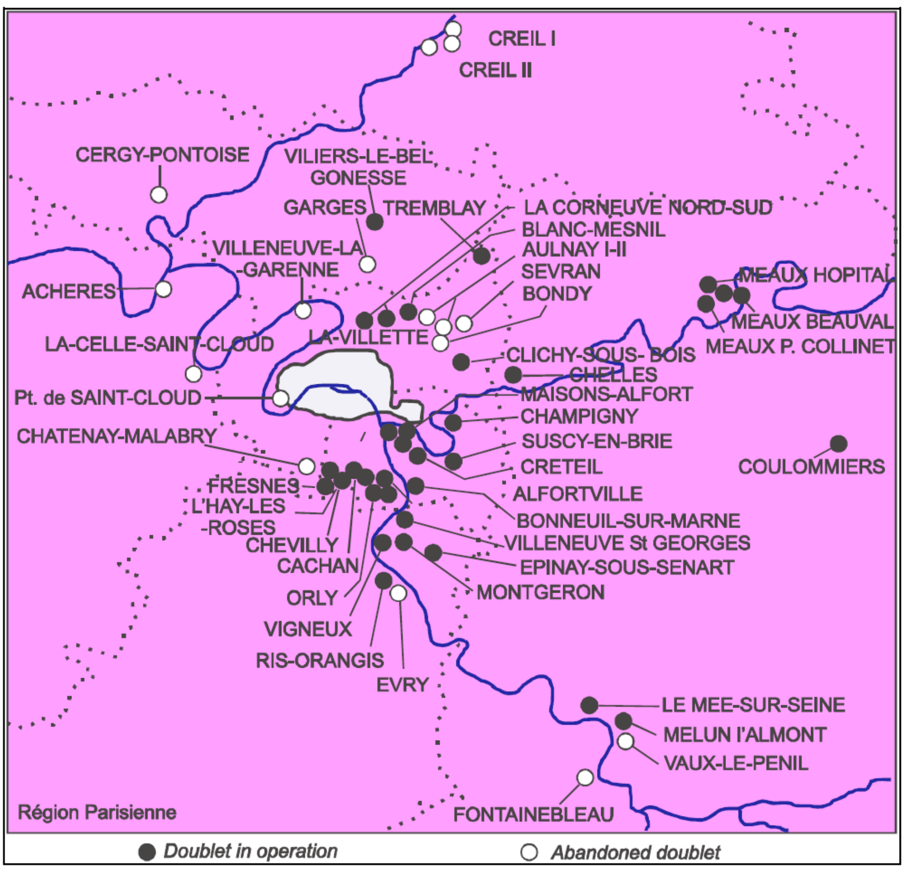

FIGURE 4: Location of geothermal district heating sites (doublets) in the Paris Basin (from Ungemach *et al.*, 2005).

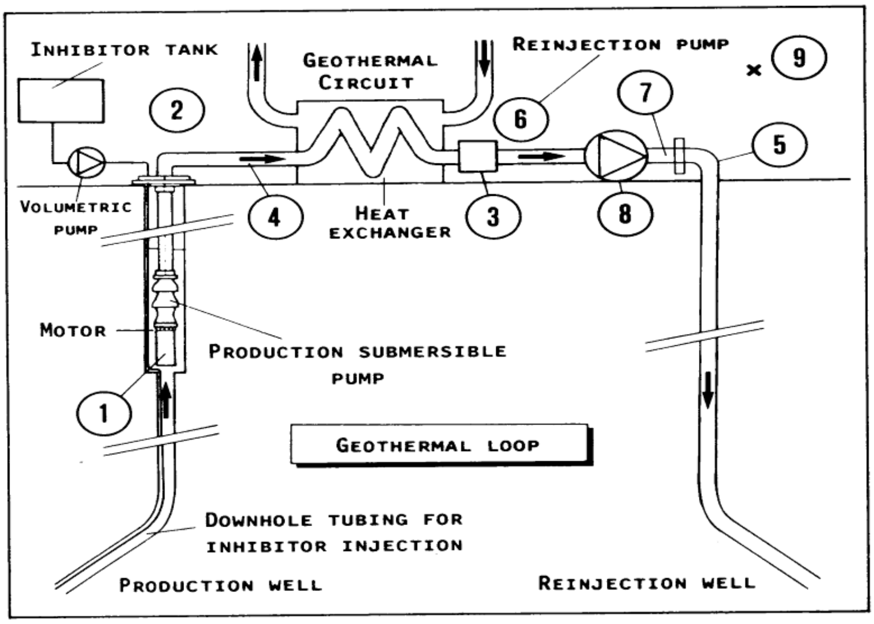

FIGURE 5: Diagram showing the principle of the geothermal doublets utilized in the Paris-basin, and the measuring points for the remote data acquisition (from Boisdet *et al.*, 1990).

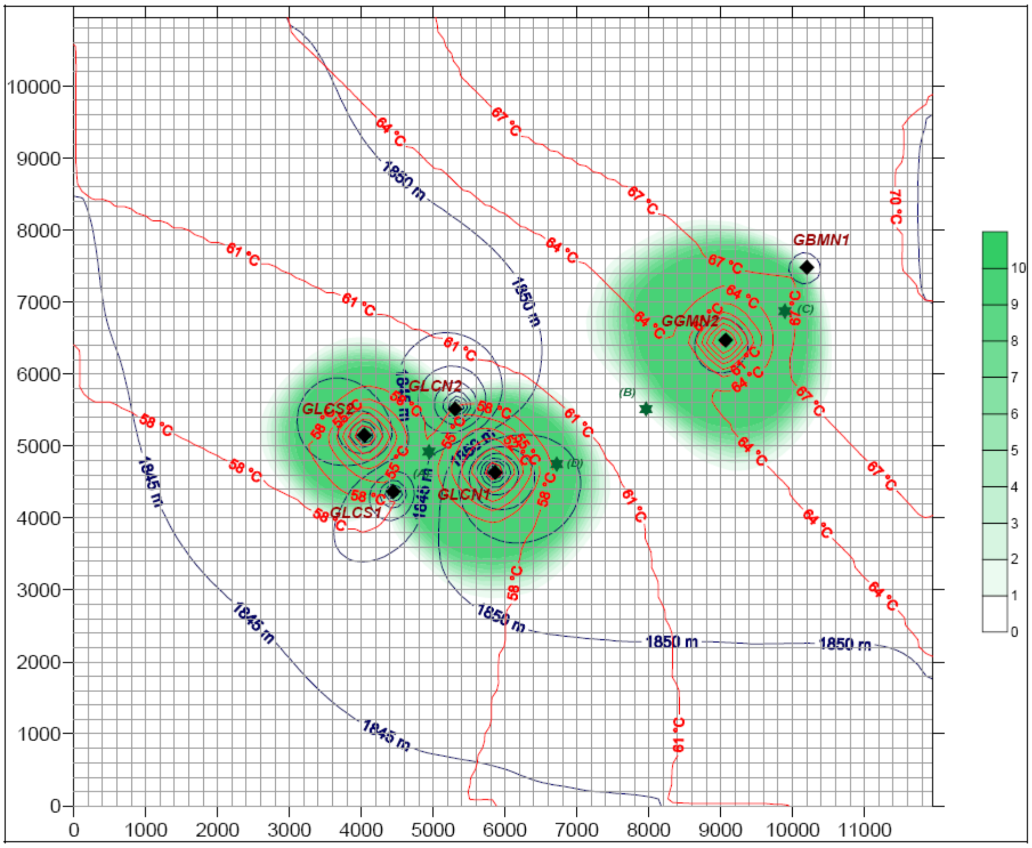

FIGURE 6: Results of model calculations of the effect of reinjection in the Dogger formation in a selected area of the Paris Basin (from Ungemach *et al.*, 2005). Red lines are temperature contours.

Another example of a successful reinjection operation is the Miravalles high-temperature geothermal field in Costa Rica. Almost all (the separated water corresponding to 85%) of the extracted mass has been reinjected back into the geothermal reservoir right from the beginning of utilization (Mainieri, 2000) as shown in Figure 7. Other examples of low-temperature reinjection operations 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 (see later) where about 20 – 25% are reinjected (Axelsson *et al.*, 2000) and the Hofstadir field in W-Iceland where reinjection started in 2006 with about 40 – 50% of the extracted mass currently being injected (Rezvani-Khalilabad and Axelsson, 2008). Reinjection is also successfully applied in low-temperature projects in Germany, such as the Landau project and the Neustadt-Glewe project (Seibt *et al.*, 2005). Small scale reinjection and reinjection experiments, have been conducted in the geothermal fields of Beijing in China (Liu and Wang, 2006; Pan, 2006).

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 is the most advanced of such projects. Other EGS projects are in the early development stages or in the preparation phase.

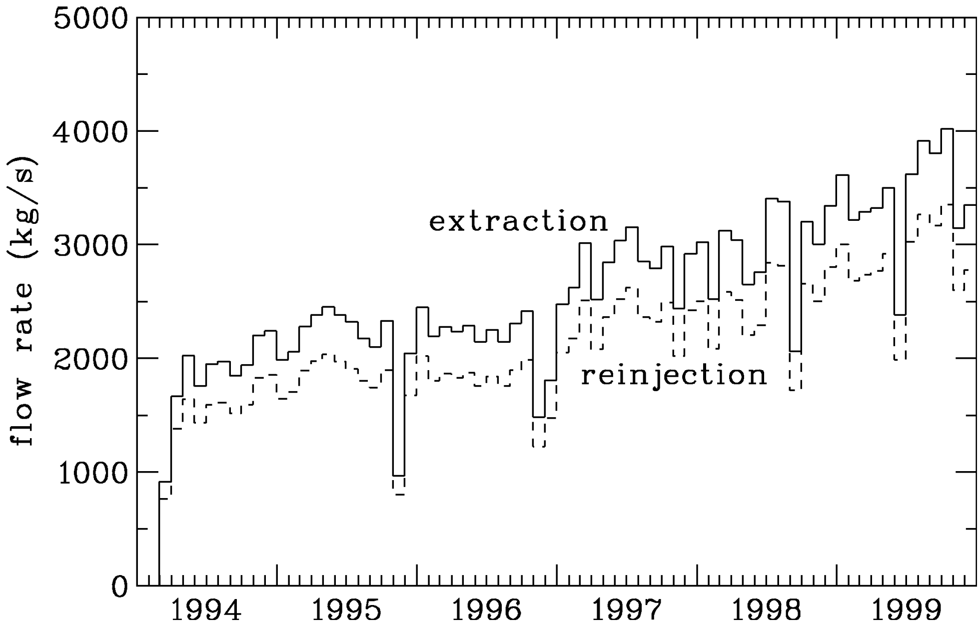

FIGURE 7: Extraction- and reinjection history of the Miravalles high-temperature field in Costa Rica 1994 – 1999 (Mainieri, 2000).

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 good 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.

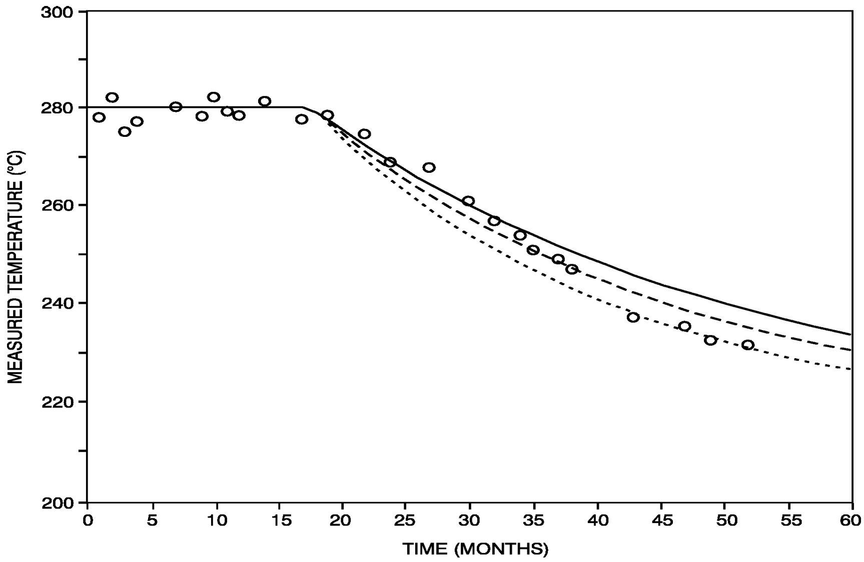

FIGURE 8: Measured and simulated temperature decline in well PN-26 in the Palinpinon field, Philippines (from Malate and O'Sullivan, 1991).

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 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 to 15-100°C. This calls for preventive measures such as deposition of silica in ponds/lagoons or by special treatment such as with scaling inhibitors. Dilution of the silica by steam condensate is also used. Stefansson (1997) discusses this issue in more detail with particular reference to the experience in Japan, New Zealand and The Philippines. 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. Some attempts at solving this problem have involved flow-reversal, i.e. by installing down-hole pumps in reinjection wells, which are used to produce from the wells for periods of a few hours, once their injectivity has dropped after a period of reinjection (Axelsson and Dong, 1998; Axelsson and Gunnlaugsson, 2000).

Another solution to the sandstone injection problem was developed in Thisted, Denmark, and has e.g. been adopted in the Neustadt-Glewe sandstone geothermal reservoir in N-Germany (Mahler, 2000; Seibt *et al.*, 2005). The Thisted system has been in operation since 1984. This solution involves a sophisticated closed loop system wherein the reinjection water is kept completely oxygen free as well as passed through very fine filters (down to 1 μm). Oxygen is believed to facilitate chemical reaction creating precipitation material. The solution also involves not allowing injection after plant construction work, and other breaks in operation, until the water is checked clean and oxygen free. 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, this volume). It should be mentioned that this method has recently been successfully tested in sandstone reinjection in Tianjin, China.

6. TRACER TESTS AND REINJECTION MODELLING

The danger of cooling due to reinjection can be minimised by locating injection wells far away from production wells, while the main benefit from reinjection (pressure support) is maximised by locating injection wells close to production wells. A proper balance between these two contradicting requirements must be found. Therefore, careful testing and research are essential parts of planning injection. Tracer testing is probably the most important tool for this purpose (Axelsson *et al.*, 2005c). 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.

The main purpose in employing tracer tests in geothermal studies, and resource management, is to predict possible cooling of production wells due to long-term reinjection of colder fluid through studying connections between injection and production wells. Their power lies in the fact that the thermal breakthrough time is usually some orders of magnitude (2-3) greater than the tracer breakthrough time, bestowing tracer tests with predictive powers.

Comprehensive interpretation of geothermal tracer test data, and consequent modelling for management purposes (production well cooling predictions), have been rather limited, even though tracer tests have been used extensively. Their interpretation has mostly been qualitative rather than quantitative. It must be pointed out, however, that while tracer tests provide information on the volume of flow paths connecting injection and production wells, thermal decline is determined by the surface area involved in heat transfer from reservoir rock to the flow paths, which most often are fractures. With some additional information, and/or assumptions, this information can be used to predict the cooling of production wells during long-term (years to decades) reinjection.

The theoretical basis of tracer interpretation models is the theory of solute transport in porous and permeable media, which incorporates transport by advection, mechanical dispersion and molecular diffusion. Axelsson *et al.* (1995) and Axelsson *et al.* (2005c) present a method of tracer test interpretation, which is conveniently based on the assumption of specific flow channels connecting injection and production wells. This method has been used to analyse tracer test data from several geothermal systems in e.g. Iceland, El Salvador, The Philippines and China and to calculate cooling predictions. It has proven to be very effective. This method is based on simple models, which are able to simulate the relevant data quite accurately. The utilisation of detailed and complex numerical models is seldom warranted, at least as first stage analysis.

Figures 9 – 11 show examples of tracer test analysis by the method discussed above and consequent cooling predictions (Axelsson *et al.*, 2001). The latter two figures demonstrate how such results may be used for management purposes. The example is from the Laugaland low-temperature system in central N-Iceland where a reinjection experiment conducted during 1997 – 1999 has been followed by continuous reinjection. Based on the results of the reinjection research, the increase in energy production, enabled through long-term reinjection, was estimated by combining the possible increase in mass extraction estimated and the predicted temperature changes. Figure 12 shows the final result, or the estimated cumulative additional energy production for one of the production wells during a 30-year period. These results also provide the basis for analysis of the economics of future reinjection at Laugaland.

Other examples of quantitative tracer test analysis and cooling predictions based on reinjection modelling have e.g. been presented by Axelsson *et al.* (1995), Axelsson *et al.* (2005) and Wang (2005).

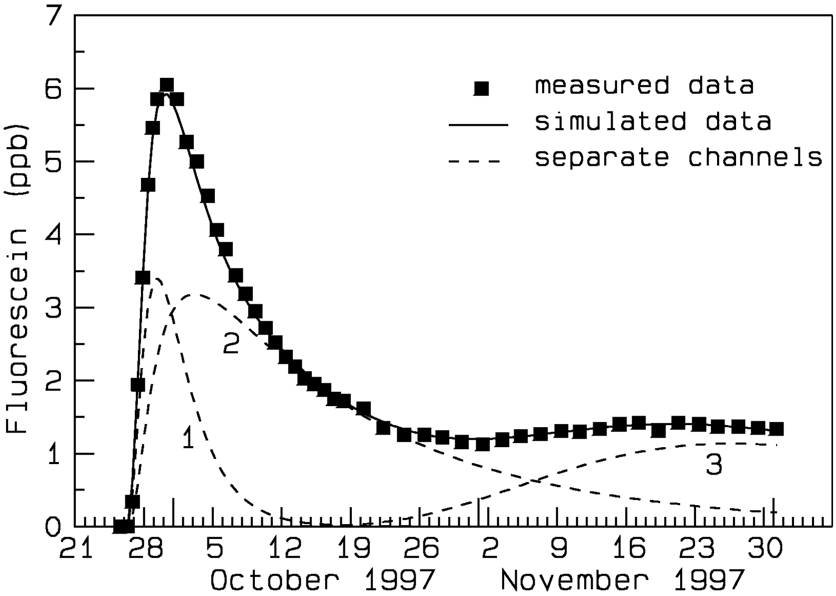

FIGURE 9: Observed and simulated fluorescein recovery in well LN-12 in the Laugland low-temperature geothermal field in central N-Iceland during the first of three tracer test conducted during 1997 – 1999 (Axelsson *et al.*, 2001). Reinjection into well LJ-08 and production from well LN-12.

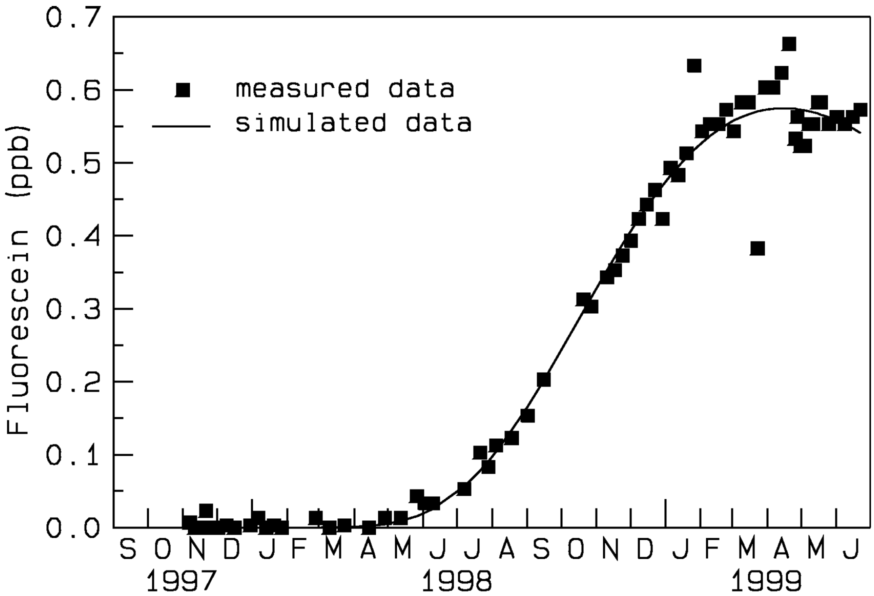

FIGURE 10: Observed and simulated fluorescein recovery in well TN-04 at Ytri-Tjarnir, 1.8 km north of Laugaland during the 1997 – 1999 reinjection experiment (Axelsson *et al.*, 2001).

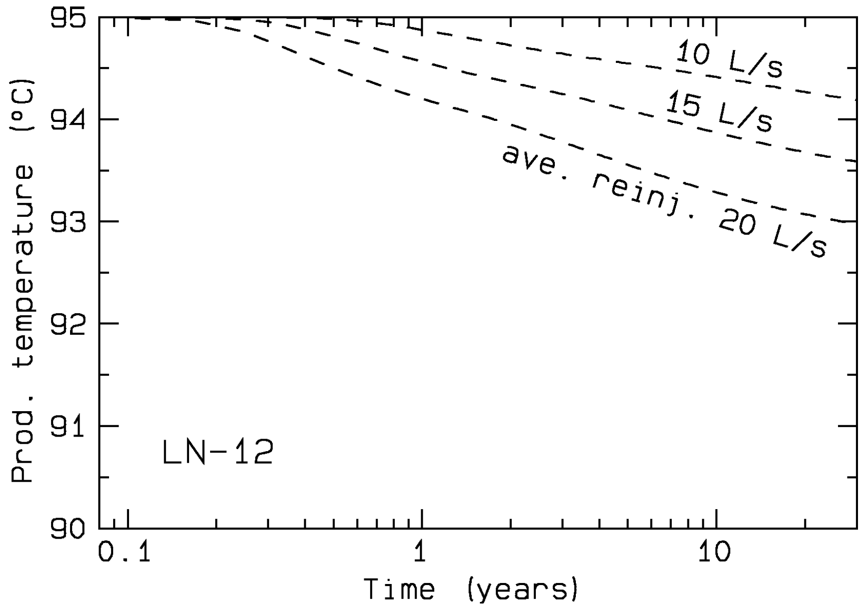

FIGURE 11: Estimated decline in the temperature of well LN-12 at Laugaland for three cases of average long-term reinjection into well LJ-08, due to flow through the three channels simulated in Figure 9 (Axelsson *et al.*, 2001).

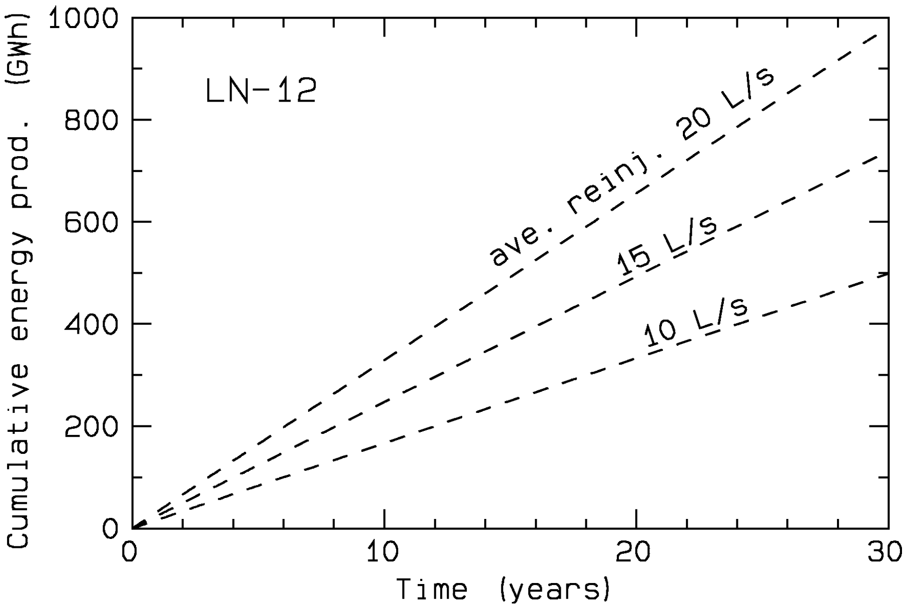

FIGURE 12: Estimated cumulative increase in energy production for 30 years of reinjection into well LJ-08 at Laugaland (Axelsson *et al.*, 2001). Calculated for three cases of average injection and assuming production from well LN-12, having taken into account the cooling predictions of Figure 11 (Axelsson *et al.*, 2001).

7. CONCLUSIONS

In conclusion the following should be emphasised:

- 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.
- Geothermal system modelling plays a key role in planning reinjection, including selecting appropriate and beneficial reinjection zones.

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