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SUSTAINABLE UTILIZATION OF LOW-TEMPERATURE GEOTHERMAL SYSTEMS WITH LIMITED NATURAL RECHARGE

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ABSTRACT

Experience from long-term utilization of many geothermal systems has shown that there usually exists a level of maximum energy production, E_0, below which it will be possible to maintain constant energy production from a geothermal system for a very long time (100-300 years). If the production rate is greater than E_0 it cannot be maintained for this length of time. Geothermal energy production less than or equal to E_0 is termed sustainable production. To maintain a production rate below E_0, i.e. sustainable production, reinjection is an extremely useful method, in particular for a low-temperature geothermal system with limited natural recharge. This paper presents a successful example, namely sustainable utilization with reinjection in the Hofstadir system, W-Iceland. Based on the utilization analysis and the reinjection mode assessment, the paper studies the possible change in the production temperature and the water level after reinjection started by using simple models, i.e. lumped parameter and tracer test models. As a geothermal system with insufficient recharge, the production capacity of the Hofstadir field is limited and the heat stored in the 86-87°C reservoir can only be used to a limited extent. Since 22-04-2007, the water level of production well HO-1 has recovered continuously due to reinjection at a ratio of 65-73% of the production. The reinjection has shown a good effect on supporting the reservoir pressure and improving heat mining. In order to evaluate production temperature change during the reinjection period, a tracer test was carried out from 29-08-2007 to 09-11-2010. The data from the tracer tests were simulated using a multiple flow-channel model. The results indicate that there are 3 direct paths between the injection and production wells. It is confirmed that there is quite good connectivity in the reservoir and the re-extracted water includes almost 90% of the injection water. A cooling forecast was done by using program TRCOOL, indicating that the temperature of well HO-1 may decline by 18-26°C for different reinjection-ratios. The monitored water level data provides strong evidence to prove the reinjection effect. By lumped parameter modelling, water level predictions were calculated for different scenarios of reinjection and production, based on the present situation, for the next 50 years. The predicted results show that reinjection will allow production to continue at the present rate for the coming decades. All the study results show that reinjection is one of the most important measures for the management and sustainable utilization of a geothermal system with limited natural recharge.

1. INTRODUCTION

As the natural heat flux in geothermal systems does not permit continuous exploitation forever, in particular geothermal systems with limited natural recharge will be faced with exhaustion of the geothermal resource fluid without careful management. For the sustainable use of such valuable resources, reinjection will become necessary and an important measure for geothermal reservoir management.

The purpose of geothermal reinjection is mainly: (1) the stabilization of the production capacity of the geothermal system through the maintenance of reservoir pressure, and (2) improvement of the heat mining, because 80-90% of the heat in the geothermal reservoirs is stored in the hot rock matrix. Successful reinjection should provide additional recharge and counteract pressure drawdown due to production as well as make it possible to extract more thermal energy from reservoir rocks than through conventional utilization.

In this report the sustainable utilization of geothermal resources with limited natural recharge is discussed and studied. First a series of successful instances of long-term utilization of a low-temperature geothermal system with reinjection is enumerated. Secondly, a specific example is studied, the Hofstadir system in W-Iceland. The temperature and water level changes in the production well of the field are discussed based on the reinjection practice from the beginning of reinjection. Reinjection efficiency of the geothermal well is also evaluated through calculations done to estimate the effect of geothermal reservoir cooling caused by reinjection of colder fluid. The study of the Hofstadir system involved the following:

1) A description of the long-term geothermal utilization in the Hofstadir system, namely utilization of well HO-01 which started in late 1999 and is mainly used for the town of Stykkishólmur. A description of the utilization of reinjection well HO-2;
2) An interpretation of data from a tracer test, which started on 29-08-2007 and stopped on 09-11-2010, by using ICEBOX software to model production temperature changes with reinjection between HO-1 and HO-2. The contribution of reinjection in counteracting drawdown in the production well is also analysed;
3) A revision of the current relatively simple lumped parameter model of the geothermal system, including an estimation of reservoir properties, such as the area and permeability of different parts of the reservoir. A much longer set of monitored data than previously available, from 19-03-1997 to 30-12-2010, was used for simulation;
4) A reinjection study, including a study of to what extent reinjection affects the water level in the production well using the best fit parameter models developed, and based on data collected when there was no reinjection. Another important aim was to estimate the properties of the flow channels between the injection well and the production well;
5) An optimization of the injection programme based on the best-fitting model parameters and predictions of the future water-level changes for various production scenarios; and
6) Finally, several modelling results and suggestions, which are important for the development of this field, are presented.

2. SUSTAINABLE UTILIZATION OF LOW-TEMPERATURE GEOTHERMAL SYSTEMS

2.1 General

2.1.1 Definition of sustainable utilization

Sustainable development has been defined as development that meets the needs of the present without compromising the ability of future generations to meet their needs. Geothermal resources have the potential to contribute to sustainable energy use and to help mitigate climate change. Experience from the use of geothermal systems worldwide, lasting several decades, demonstrates that by maintaining production below a certain limit, utilization may be maintained for a long time. Therefore, a definition for sustainable geothermal utilization has been proposed (Axelsson et al., 2001). It assumes there exists maximum energy production, E_0, below which it will be possible to maintain constant energy production from a geothermal system for a very long time (100-300 years). If the production rate is greater than E_0 it cannot be maintained for this length of time. Geothermal energy production less than or equal to E_0 is termed sustainable production while production greater than E_0 is termed excessive production. If energy production from a closed geothermal system is to be sustainable, the stored energy must be depleted at a relatively slow rate, and after a transient period, the reinjection to the reservoir must approximately equal the mass extraction rate (Axelsson, 2010).

2.1.2 Critical mode of sustainable utilization for systems with limited natural recharge

How to maintain production below E_0, i.e. sustainable production, especially for geothermal systems with limited natural recharge, has been discussed to some degree in the literature in recent years. Accordingly, it has been established that the critical mode of the sustainable management of such systems is reinjection. As an example, in most situations, injection of return water (including waste liquid from heat exchangers, brine from separators, and surplus condensed steam from power plant cooling circuits), or supplementary make-up water to replace liquid extracted for production, increases the production potential of geothermal systems (Axelsson, 2008a).

The main problems of long-term utilization of low-temperature geothermal systems with limited natural recharge are the decrease in pressure and liquid reserves with time in the corresponding reservoirs. Therefore, sustainable utilization of low-temperature geothermal systems usually focuses on how to maintain extraction and temperature of the reservoir to support geothermal use.

At present, reinjection is expected to be the best way to deal with this. Therefore, a low-temperature geothermal system with a limited natural recharge has to adopt reinjection as a key to guarantee the resource water supplies. There are a number of successful instances to prove the efficiency of reinjection used in low-temperature geothermal systems worldwide. Experience has also demonstrated that when reinjection is applied, cold front breakthrough can be avoided and thermal decline managed for decades (Axelsson, 2010). Good examples are the Laugaland low-temperature geothermal system in Iceland, Dogger geothermal reservoir in the Paris Basin, sedimentary sandstone reservoirs in the Pannonian Basin in SE-Hungary, the Tianjin geothermal reservoir in Tianjin Province, China, and Xiaotangshan geothermal reservoir in Beijing, China. Furthermore, in Iceland and China, which are among world leaders in direct utilization, the application of reinjection is constantly increasing.

2.2 Sustainable utilization examples with reinjection

2.2.1 Iceland

The Laugaland low-temperature system is located in the Eyjafjördur valley south of the Eyjafjördur fjord in central N-Iceland. It is the second largest of six low-temperature geothermal fields utilized by Nordurorka for space heating in the town of Akureyri at the bottom of the fjord (Flóvenz et al., 1995 and 2010). The Laugaland system has been utilized since late 1977 following a testing period in 1976. The name Laugaland means land, or farm, of warm-springs. The Laugaland geothermal system is a typical fracture controlled system, embedded in 6-10 million years old flood basalt, wherein the hot water flows along open fractures in otherwise low-permeability rocks with limited recharge. Twelve wells have been drilled in the Laugaland area, but only three of them are sufficiently productive to be used as production wells. The reservoir temperature at Laugaland is on the order of 100°C. The Laugaland system is drastically less permeable than other geothermal systems further north in the same region. The reason is believed to be the fact that the Eyjafjördur valley, where Laugaland is located, is much less tectonically active than the western side of the Eyjafjördur fjord, where the more productive fields are located. Because of the low overall permeability, and apparently limited recharge, reinjection had for long been considered a possible way to improve the productivity of the Laugaland system. Therefore, a comprehensive 2-year reinjection experiment was conducted in the field at the end of the 20th century (Axelsson et al., 2001). Since then reinjection, corresponding to about 25% of the mass extraction has been part of the management of the Laugaland geothermal system. It has helped to stabilize the pressure decline in the system (Axelsson et al., 2010).

Another example is the Gata (or Laugaland) system, discussed briefly by Axelsson et al. (1995) and Zhang (2003). It is located in the Holt district of the South Iceland lowlands, a few kilometres south of the highly active S-Iceland seismic zone. In spite of its proximity to the seismic zone, the permeability of the Gata system is unusually low and the system is poorly productive. It may be mentioned that numerous permeable, low-temperature systems are located inside and north of the seismic zone while hardly any systems are found south of the zone. The Gata geothermal system has been utilized since 1946, up to 1982, for local heating and a swimming pool, but after 1982 for geothermal central heating for the towns of Hella and Hvolsvöllur, east of Gata. The geothermal system has a reservoir temperature of 100-105°C. The average yearly production rate has varied between 10 and 22 l/s, the last few years it has been of the order of 15 l/s. One primary production well, 1000 m deep, has been in use since 1982. The continuously declining water level indicates very limited recharge to the Gata system. Therefore reinjection was started at Gata in early 2000. During the last few years production at Gata has been increased again causing the water level to decline once more (Axelsson et al., 2010).

2.2.2 Paris Basin in France

The utilization of the geothermal resources in the Paris Basin in France provides the most prominent and representative example of sustainable utilization of low-temperature geothermal resources with reinjection. In France, low-temperature geothermal resources are mainly found in the Paris Basin and the Aquitaine Basin, mostly used for space heating in winter. The Paris Basin hosts a vast geothermal resource associated with the Dogger limestone formation, which stretches over 15,000 km^2 (Lopez et al., 2010) at 1500-2100 m depth and 70°C average temperature. The Dogger resource is mainly used for space heating through a doublet scheme, consisting of a closed loop with one production well and one reinjection well. The first "Doublet-scheme" in the world was built at Melun l'Almont, which is near Paris, for the heating of 3000 houses in 1969. One of the wells was drilled to 2000 m depth in the reservoir and exploited geothermal fluid; the other well was able to accept injected geothermal fluid into the reservoir after heat extraction (Laplace et al., 2000). In 1995, a new geothermal well was drilled and a "Triplet-scheme" was set up, with two production wells and one reinjection well, providing space heating for 5200 houses. This historical geothermal operation is still running today. Because of the aftermath of the oil crises in the early 1980s, 74 "Doublet-schemes" were constructed in the Paris Basin, Aquitaine Basin and other regions from 1980 to 1986. From 1986 to 1990, geothermal utilization experienced a recession with the end of the oil crisis in France. Now, there are 61 geothermal heating systems that are still running, including 41 in the Paris Basin, 15 in the Aquitaine basin and 5 in other regions. These geothermal heating systems supply heating for approximately 200,000 apartments (Lopez et al., 2010).

Today some doublets which were previously abandoned due to economic reasons after the end of oil crises are being revitalized and new ones are being drilled. The production and reinjection wells of the Paris doublets are usually separated by a distance of about 1,000 m to minimize the danger of cooling due to the reinjection. Experience, lasting 3–4 decades, has shown that no significant cooling has yet taken place in any of the Paris production wells (Ungemach et al., 2005). This is in spite of various modelling studies, which indicated that the doublets should start to cool down after 2 decades or so (Lopez et al., 2010). The extensive experience gained in the Paris Basin provides a very valuable basis for future sustainable management of the resource as well as for other geothermal resources of a comparable geological nature, such as in other parts of Europe and in China (Liu, 2008).

2.2.3 China sedimentary resources

China is rich in geothermal resources, some of which have traditionally been used for washing, bathing, therapeutic purposes, and agriculture. During the last two decades, the utilization of geothermal energy has grown rapidly. Apart from power production on a small scale, and some direct applications, their main use is for space heating. Low-temperature geothermal systems are mostly present in many of the major sedimentary basins, in E- and NE-China in particular. According to various low-temperature geothermal sustainable utilization studies, reinjection is feasible for geothermal systems with limited natural recharge in China.

The first geothermal reinjection experiment conducted in China was a reinjection test in the southeast Urban geothermal field in Beijing in early 1982. At that time, from the geothermal field's 40 geothermal production wells, geothermal water extraction was more than 30 × 10^4 m^3/a, and geothermal reservoir pressure was declining. In order to fully use the geothermal resources and to study geothermal reinjection efficiency, 40°C geothermal heating waste water was injected into a well at 1275 m depth (Bai and Gong, 1984). At present, reinjection in China is considerable in Tianjin, and in Beijing geothermal reinjection has begun again, while in Xi'an geothermal reinjection is planned. Although geothermal reinjection development is still relatively slow in China, the role of reinjection has been widely recognized and attended.

After the reinjection experiments in the early 1980s, geothermal reinjection in Beijing didn't continue. In recent years, geothermal reinjection has, however, been classified as an important geothermal research and management task in Beijing. Xiaotangshan (about 30 km north of the city centre) is the best known geothermal field in the Beijing area. Its thermal waters have been used for bathing for more than 700 years. The geothermal resources are mainly found in Cambrian limestone, and in Mesoproterozoic Jixian dolomites. Water production from single wells is in the range of 35–125 m^3/h, with a wellhead temperature between 46 and 70°C (Liu, 2008). Over 90 geothermal wells had been drilled by the end of 2008 in the Xiaotangshan field, one with a depth of over 3500 m. The temperature of the return water is about 25–38°C. The overall thermal utilization ratio is about 53.2% (Duan et al., 2011). Because of ever increasing demands for the geothermal resources, groundwater reinjection in this area is rare, even though it is a closed geothermal system (Axelsson, 2002). This geothermal exploitation will inevitably lead to significantly reduced reservoir pressure. Reinjection has, therefore, become an essential tool of geothermal heat storage management in the Xiaotangshan field, and been in operation there since 2001. Return water from the geothermal heating systems, with temperatures of 24°C, is injected back into the reservoir. In 2007, there were seven injection wells in operation with a total injection of 1.23 × 10^6 m^3, accounting for 53% of the annual production. Since 2005, the water level in the geothermal reservoir has begun to gradually recover, showing that injection is effective in aiding the sustainable use of the Xiaotangshan geothermal resource (Figure 1) (Duan et al., 2011).

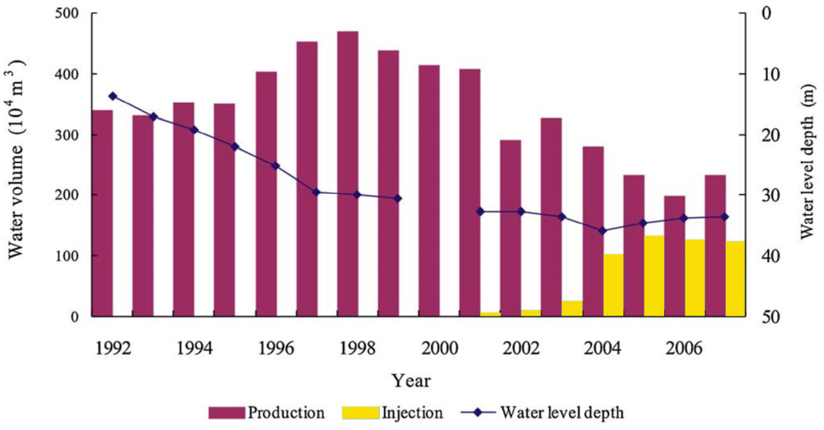

FIGURE 1: Exploitation history for the Xiaotangshan geothermal field in Beijing (Duan et al., 2011)

2.3 Reinjection mode

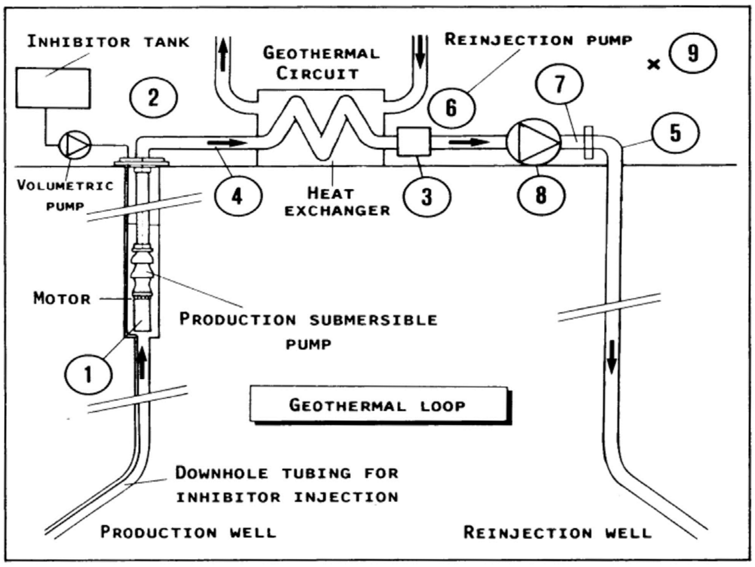

FIGURE 2: Principle of the Doublet-scheme reinjection mode (Axelsson, 2008b)

The doublet mode, as applied in the Paris Basin, is often referred to as the most appropriate utilization mode for low-temperature geothermal systems. The "doublet" technology consists of a closed loop with one production well and one injection well (Figure 2). There were two main reasons to inject the produced fluid in Paris. First, chemical processing of geothermal brines for surface disposal involved enormous additional costs, negatively affecting the project economics. In addition, single well exploitation would have progressively reduced the reservoir pressure, eventually affecting pumping conditions. This would have limited the possible number of wells able to tap the same reservoir, thus reducing the exploitable fraction of the potential resource (Menjoz and Sauty, 1982). Several advantages resulted from the full injection of the cooled geothermal brine:

- No environmental impacts;
- The production flow rate was maintained;
- The exploitation pressures were stabilized (beneficial pressure interference);
- The area impacted by pressure variation was limited and an exploitation domain could be legally defined by the authorities.

This last point is of crucial importance for public authorities that grant well defined exploitation zones, thus allowing an efficient strategy for the optimal management of the aquifer. Indeed, as natural heat flux does not permit continuous exploitation forever, the geothermal development of the densely populated Parisian suburbs will be faced with the inexorable exhaustion of the Dogger aquifer geothermal resource. In the long term, the cooled injected brines will eventually reach the production wells and cause temperatures to decline (Lopez et al., 2010). However, there has not been significant cooling during several decades of reinjection due to wells separated by about 1000 m to minimize the danger of cooling.

Another successful example of sustainable utilization with Doublet-scheme reinjection is the Hofstadir system utilization in W-Iceland. It will be presented below as a study on the role of reinjection for sustainable utilization of a low-temperature geothermal system with limited natural recharge.

3. GEOTHERMAL UTILIZATION OF THE HOFSTADIR FIELD, W-ICELAND

3.1 The Hofstadir geothermal system

3.1.1 Introduction

The Hofstadir geothermal field is located in W-Iceland. It is about 10 km south of the town of Stykkishólmur (Figure 3). The hot water from the Hofstadir geothermal field is mainly used for the Stykkishólmur district heating system. Although the Hofstadir geothermal field is lacking in surface features, based on the reconnaissance survey, a series of studies such as geological exploration, exploration drilling, production drilling, geochemical analysis, long-term monitoring and reservoir engineering modelling has been carried out since the late 1990s. The Hofstadir system is defined by a temperature gradient anomaly region around the Hofstadir field, and the Hofstadir system has been confirmed as a typical liquid-dominated convection low-temperature system with very low external permeability.

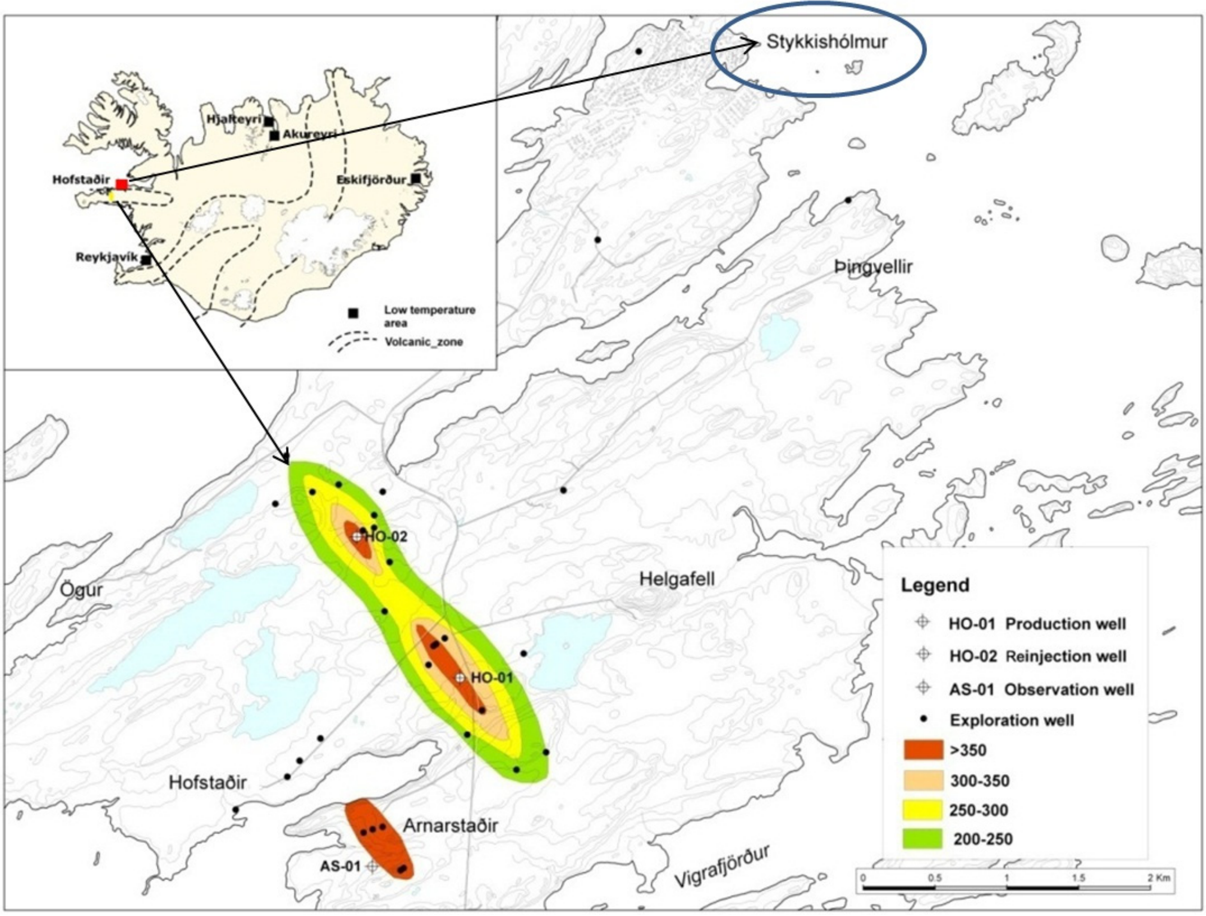

FIGURE 3: The Hofstadir geothermal field and Stykkishólmur town (adopted from Guo, 2008)

3.1.2 Formation lithology and structures

The bedrock in the Hofstadir area is mainly composed of Miocene basalts. The reservoir rock of this field consists primarily of coarse-grained basaltic units with thin layers of sediments, two of which could be acidic, and a number of mostly basaltic intrusions. From 780 to 855 m depth, i.e. to the bottom of well HO-01, the rock consists of gabbroid intrusions. Pyrite, mixed-layer clays of smectite and chlorite, with chalcedony, quartz, and calcite are found from the surface to 150 m depth (Björnsson and Fridleifsson, 1996). At depths below 150 m, the high-temperature alteration minerals, chlorite and epidote, are found. The reservoir rock is altered to a high degree with epidote below 150 m depth, indicating an alteration temperature of approximately 250°C. Below 300 m, the rock is altered with amphibole, which suggests an alteration temperature of ~300°C (Björnsson and Fridleifsson, 1996).

The dominant structure in the area is NE-SW trending and consists of faults and the strike of the basalts (Björnsson et al., 1997). Narrow inlets from the sea cut into it from NE-SW. The geothermal field involves two sub-parallel fissures spaced 1200 m apart trending SSE-NNW. The two fissures are only locally recognizable by surface criteria but they show up clearly in the thermal gradient of some 30 shallow (most 50 m deep) boreholes. A more recent tectonic pattern of E-W faults and rare NW-

SE trending dykes is less conspicuous. This is interpreted as a conjugate set in response to the maximum WNW-ESE horizontal compression. The geothermal system at Hofstadir is related to dykes trending NW-SE.

Although of Miocene age, the old structures form a plane of weakness which breaks up under the present stress field (Björnsson et al., 1997). Due to secondary mineralization, the Miocene basalts and dykes within this peninsula have low permeability. Permeable anomalies are fissure controlled, the feature near Hofstadir being the largest traced so far in the surroundings. These provide the necessary pathways for sufficiently deep circulation of groundwater down to at least 2000 m to sustain the geothermal system.

3.1.3 Reservoir features

According to the results of drill cutting analysis, well logs which include resistivity well logs, televiewer logs and pumping tests, there are two main production aquifers in this field (i.e. in well HO-1). The main one is located at a depth of 819 m (90% of the flow-rate), and the other about 4 m in thickness located at 171-175 m depth (7% of the flow-rate). Besides these two main feed-zones, several minor aquifers were also found at depths of 262, 451, 778, 785, and 830 m. The aquifer at 171-175 m is in a fracture within a basaltic layer, whereas the main aquifer is related to a fracture in a gabbroic intrusion. Since the completion of drilling, a total of 15 temperature logs have been conducted in production well HO-1; the first was carried out at the end of drilling, while the last was measured in April 2000 (Figure 4). The temperature logs show a reservoir temperature of about 86-87°C.

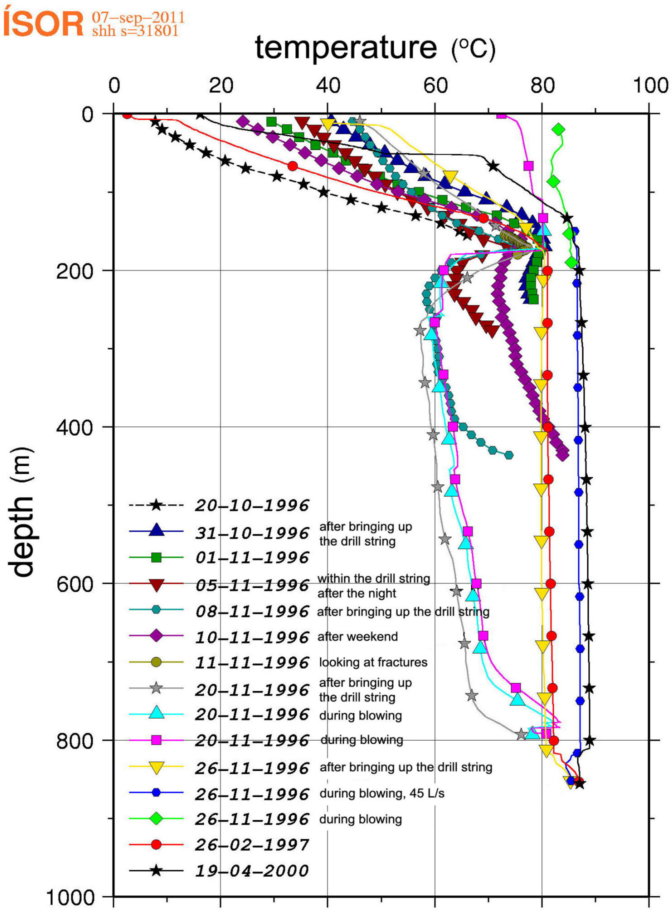

FIGURE 4: The HO-1 temperature logs

According to chemical analysis results, the geothermal water took a long time to come to equilibrium with the rock matrix; the geothermal water is brackish, calcium is the dominant cation, and the water is of a Cl-Ca-Na type. The isotopic composition of the thermal water indicates that it is not strictly a mixture of the seawater and fresh water of the present day. The results from geothermometry calculations indicate that chalcedony controls the silica concentration in the reservoir (Kania and Ólafsson, 2005).

3.1.4 Utilization history

Production well HO-1 was drilled in the centre of the main temperature gradient anomaly during the autumn of 1996. The depth of the well is 855 m. Air-lift testing at the end of drilling indicated that the well was quite productive (~40 l/s) (Björnsson et al., 1997).

In order to appraise the feasibility of a utilization system based on the well, including the hot-water transmission pipeline from the Hofstadir field to Stykkishólmur town, and the distribution system within the town, well HO-1 was production tested from late 1997 for 4 months (from 19-03-1997 to 30-06-1997), with a pumping flow rate of 15-20 l/s. The Hofstadir geothermal heating system began operation at the end of 1999, with well HO-1 in production phase, with the running efficiency being satisfactory until the present day. The total production of geothermal water has been 7350 × 10^3 m^3 (Table 1) and the average flow rate has been 21.4 l/s from 2000 to 2010 (see Figure 5).

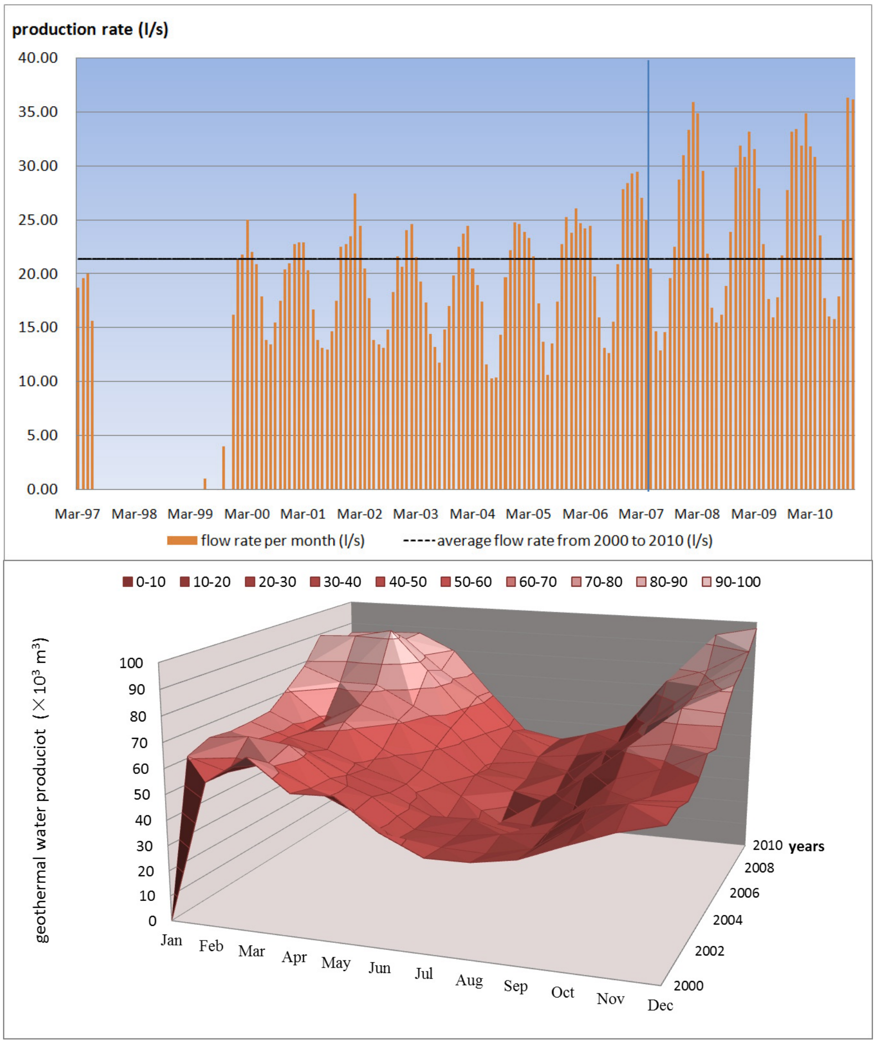

FIGURE 5: The production of well HO-1; the upper figure shows the average production (l/s) from 2000 (1997) to 2010 on a monthly basis; the lower one shows the total production on a monthly basis

Discharge temperature, water level and production rate in well HO-1 (including the well test data) have been monitored carefully from the beginning of utilization. This has resulted in continuous water level draw-down (Figure 6), which indicates that this geothermal system has almost closed boundaries with limited natural recharge.

TABLE 1: Yearly water production of well HO-1 (Aradóttir, 2010 and 2011)

Year	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**
Water production (×10^3 m^3)	546	586	602	573	569	615
Year	**2006**	**2007**	**2008**	**2009**	**2010**	**Total**
Water production (×10^3 m^3)	663	725	812	825	838	7354

In order to stop the rapid water-level decline and maintain the water-table at a level so that thermal water discharge from the production well could be maintained, the reinjection well HO-2 was drilled to a depth of 414 m in 2006. The distance between HO-1 and HO-2 is 1200 m. Reinjection started on 22-04-2007, with an injection efficiency of 65% - 73% of the production achieved. The water level of HO-1 has risen continuously since then, with the rise of the groundwater table of the reservoir also demonstrated by water level changes in monitoring well AS-1 (Figure 6). Although the injection flowrate was not monitored accurately at the beginning, more accurate monitoring of the reinjection flow rate was started later at a modified sampling frequency. According to the injection monitoring

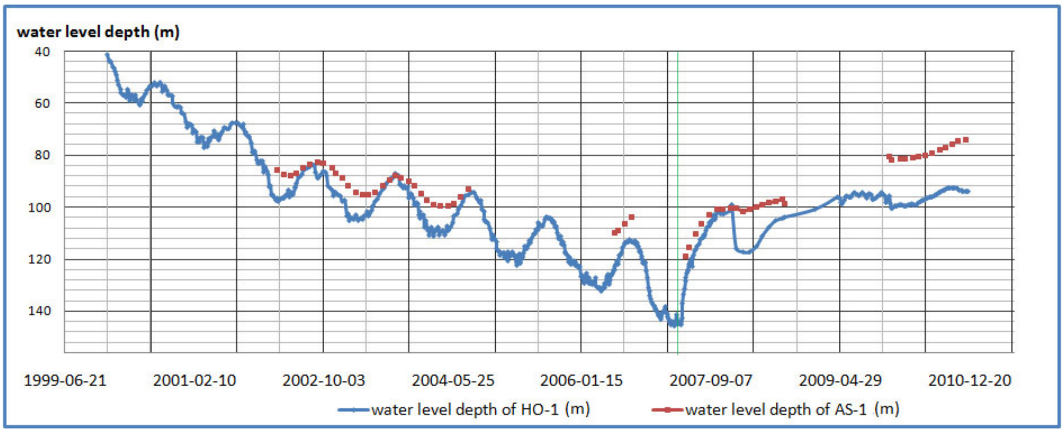

FIGURE 6: Changes in water level in wells HO-1 and AS-1 (see Figure 3) from 2000 to 2010; the upper curve is for the monitoring well AS-1 and the lower one for production well HO-1

flow-rate data for well HO-2, the amount of water injected into HO-2 was 600 × 10^3 m^3 and 558 × 10^3 m^3 in 2009 and 2010, respectively, corresponding to reinjection ratios of 72.7% and 66.6% (Figure 7) (Aradóttir, 2010 and 2011).

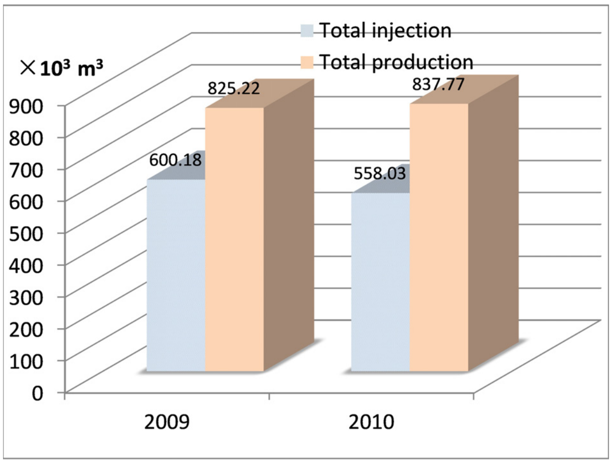

FIGURE 7: Total reinjection and production at Hofstadir in 2009 and 2010

3.2 Production temperature assessment for Hofstadir

3.2.1 General

According to the monitoring reports for the Hofstadir field, the discharge temperature from HO-1 has not shown obvious cooling from 2000 to 2010, and temperature fluctuations usually depend on pumping as the temperature rises during the summer months and decreases in winter (Figure 8). Figure 8 shows a clear correlation between the temperature change and the production rate. A clear decline in the temperature of HO-1 is seen from 2007 to 2010 with increasing production, which also coincides with the time of injection. A drop in measured temperature at the end of 2008 is so sudden that it’s unlikely to be real, but could rather be caused by some change in the temperature sensor(s) used. The average water temperature from HO-1 was 86.3 and 86.1°C in 2009 and 2010, respectively, indicating that the annual average temperature dropped 0.2°C (Aradóttir, 2010; 2011).

3.2.2 Tracer test design

Tracer testing is a very useful tool for studying connections between reinjection and production wells and analysing the possibility of cooling in the reservoir. Its main purpose is twofold in low-temperature geothermal systems:

1) For general hydrological studies of subsurface flow; and
2) For reinjection research and management.

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 (Axelsson, 2010).

For situations like those in the Hofstadir geothermal system, tracer tests are mostly conducted through one borehole-pair, in this case production well HO-1 and injection well HO-2. The selected tracer should 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 be absorbable by reservoir rocks;
c) Be thermally stable at reservoir conditions;
d) Be relatively inexpensive;
e) Be easy (fast/inexpensive) to analyse;
f) Not be harmful to environment.

In addition, the tracer selected must adhere to prevailing phase (steam or water) conditions.

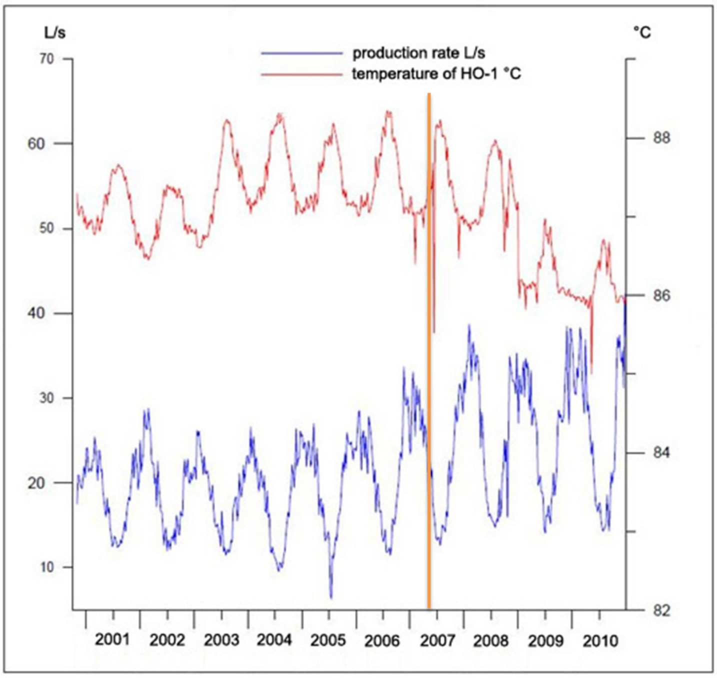

FIGURE 8: Production rate (below) and temperature curve (above) in HO-1 from 2001 to 2010

A 10 kg mass of Na-fluorescein was injected “instantaneously”, namely in as short a time as possible, into well HO-2 on 29-08-2007. Samples for tracer analysis were collected from production well HO-1, but sampling frequency should in general be quite high initially, for instance sampling twice per day or at least once; later it might be reduced to twice or three times per month as the test progresses. The monitoring duration was from 29-08-2007 to 09-11-2010 or 1167 days. The duration of a tracer test is of course case specific and hard to determine beforehand. The same applies to sampling plans, even though an inverse link between required sampling frequency and time passed can often be assumed.

3.2.3 Tracer modelling principle

It is an important aspect of geothermal tracer testing that the thermal breakthrough time (onset of cooling) is several orders of magnitude (2–4) greater than the tracer breakthrough time. This is actually what distinguishes tracer tests in geothermal applications from tracer tests in ground water hydrology and related disciplines. The principle of tracer test modelling is to confirm the existence of flow paths between production well(s) and reinjection well(s) and to simulate volumes and dispersivity of the flow channels based on assuming flow paths like in Figure 9. Consequently the purpose is to assess cooling breakthrough-time and to estimate cooling danger based on parameters obtained by the tracer modelling by using theoretical calculations.

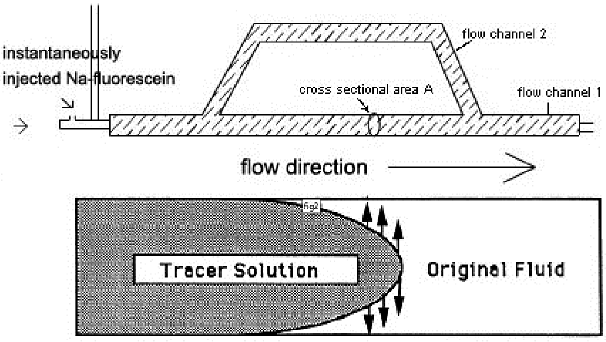

FIGURE 9: The flow channel model (above) and the mechanical dispersion of a tracer solution in a flow channel (below)

The TRINV software (Axelsson et al., 2005a) can be used to model the flow properties of the flow paths, it assumes the flow between the reinjection and the production well(s) may be approximated by one-dimensional flow in specific flow-channels. The transport and mechanical dispersion of tracer solution may be described by the below equations and Figure 9:

$$F_x = F_{x,advection} + F_{x,dispersion} \tag{1}$$

$$F_{x,advection} = u_x \phi C \tag{2}$$

$$F_{x,dispersion} = -\phi D_x \, \partial C / \partial x \tag{3}$$

$$D_x = \alpha_x u_x + D^* \tag{4}$$

where F_x = Mass flow rate of solution in x-direction (kg/m^{2}s);
u_x = Fluid particle velocity in x-direction (m/s);
α_x = Dispersivity in x-direction (m);
ϕ = Porosity of flow channel (%);
C = Solute concentration (kg/m^3);
D^* = Coefficient of molecular diffusion.

Because tracer transport is assumed to be through a one-dimensional flow-channel controlled by fluid velocity u, with $u = q/\rho A\emptyset$, the tracer transport solution equation simplifies to:

$$c(t) = \frac{uM\rho}{Q} \frac{1}{2\sqrt{\pi D t}} e^{-(x-ut)^2/4Dt} \tag{5}$$

$$c \times Q = C \times q \tag{6}$$

where $c(t)$ = Tracer concentration in the production well fluid (g/l);
Q = Production rate (kg/s);
x = Distance between the wells in question (m).

Here the coefficient of molecular diffusion D^* is neglected, so $D = \alpha_L u$, Some parameters can be obtained directly, such as maximum fluid velocity reflected by the tracer breakthrough-time, average fluid velocity reflected by the time of maximum concentration, and flow-path dispersion reflected by the width of tracer pulses. Further characteristics can be obtained more accurately by modelling. The TRINV simulation software yields information on the flow channel cross-sectional area through estimating the parameter $A\emptyset$, the dispersivity α_L as well as the mass of tracer recovered through the channel M_i (equal to or less than the mass of tracer injected), M_i/M gives the fraction of total injection travelling through the channel. By defining a model with one or more flow channels, TRINV uses non-linear least-squares fitting to obtain model properties, i.e. flow channel volume ($xA\emptyset$), dispersivity (α_L), and tracer mass recovered (M_i) for all the channels (Axelsson et al., 2005a).

3.2.4 Hydrodynamic connection assessment

In the unusually long tracer test at Hofstadir, the mass recovery was 72% during approximately 3.2 years; the tracer recovery was relatively slow, however. By simulating the tracer test monitoring data from production well HO-1, with one tracer pulse to three pulses, the best fit coefficient of determination was found to be 99.9%. The simulation was done with three tracer pulses (Figure 10), while there are two peak values of tracer concentration in the concentration curve. The first peak showed up after 102 days, and the second one appeared after 193 days. This also indicates that there are at least two flow channels connecting wells HO-1 and HO-2.

The parameters of the modelling results are listed in Table 2. Comparing the calculated mass recovery from the three channels at infinite time, two main channels can be confirmed, i.e. channel 1 and channel 3; the mass of tracer solution transported through them to HO-1 were 33% and 52%, respectively. The mass recovery through the second channel was low, i.e. only 4.6%; this means the second channel did not contribute much to the transportation of the tracer although it had a

TABLE 2: Parameters of the best fit modelling of the Hofstadir tracer recovery data

Channel ID	**Length, x (m)**	**U (m/s)**	**AØ (m^2)**	**α_L (m)**	**M_i/M (%)**
1	1200	6.79×10^{-5}	101	110	33
2	1250	1.53×10^{-4}	6.20	26.2	4.6
3	1300	2.57×10^{-5}	416	553	52
Total					89

U = Mean flow velocity; AØ = Cross-sectional area; ϕ = Porosity (porosity is assumed 10%);
α_L = Longitudinal dispersivity of the flow-channel; M = Total mass of tracer injected.
M_i= Calculated mass recovery of tracer through corresponding channel, until infinite time

comparatively high flow velocity. In accordance with the results of the calculated flow channel volumes, the mean flow velocities were 6.8×10^{-5}, 1.5×10^{-4}, and 2.6×10^{-5} m/s for the three channels, respectively, which are rather small values.

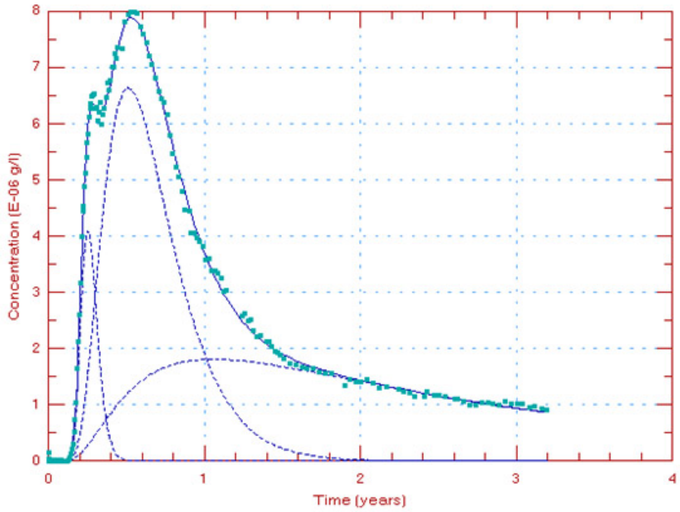

FIGURE 10: Observed and simulated Na-fluorescein recovery in well HO-1, the test lasted 3.2 years. The blue data points show the recovery corrected for the tracer being reinjected after production from HO-1. The lines show the modelled recovery. About 70% of the tracer was recovered during the test

According to the results above, the presence of three flow channels was verified by lithological analysis, namely there are two main feed-zones located at 171-175 m and 819 m in production well HO-1, and one main aquifer at a depth of 360 m in injection well HO-2. For the first channel, the thickness indicated by well logging is 4 m at 171-175 m depth, but it has a large cross-sectional area which is 101 m^2 (Table 2). Therefore, the flow-channel can't look like a pipe; on the other hand, it should be more like a thin fracture-zone, or an opening along an interbed. The connection appears to be not so direct because of relatively large dispersivity and a slow average flow velocity. The surface area of the channel is large, deduced from a large flow channel volume and the 1200 m distance between HO-1 and HO-2. The large surface area of the third flow-channel can be confirmed based on the large cross-sectional area and long distance between the wells. Comparing dispersivity, mass recovery and the cross-section area between channels 1 and 3, all the parameter values are comparable, even though the distance is slightly longer for channel 3 than for channel 1. However, conditions are considerably different for the second channel which has a relatively small surface area due to the smallest *AØ* value. For the second channel, the height and diameter are estimated to be about 41.5 m and 1.5 m for rectangular and pipe mode, respectively. Furthermore, the dispersivity of the second channel is about 26 m, which is about 4 times and 20 times less than that of the first and third channels, respectively, which could result in increasing the cooling risk in the production well.

A conclusion can, therefore, be drawn from the point of view of hydrodynamics and tracer recovery, that the prospect of reinjection in this field is quite good.

3.2.5 Prediction of possible reinjection cooling

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 with respect to pressure is maximised by locating injection wells close to production wells. Cooling of production wells is not only determined by flow-path volume, but also depends on the surface area and the porosity of the flow channel. A large surface area usually leads to slow cooling, while a small surface area leads to faster cooling. Additional information, or assumptions, based on geological and geophysical information is necessary for cooling predictions. The model for cooling predictions depends on assumptions about geometry, i.e. for a fracture zone with h > b (Figure 11).

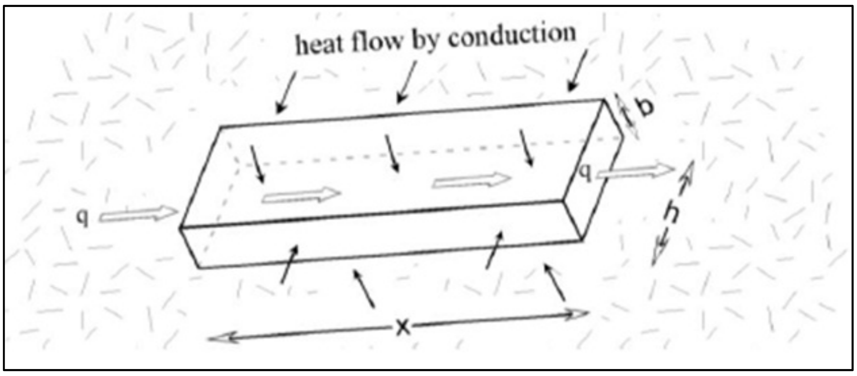

FIGURE 11: Model assumptions for cooling predictions; according to geological and well logging information, models may be set up for three different assumptions depending on different porosity, surface area and flow channel volume. The figure shows a model of a flow-channel, along a fracture zone or a horizontal interbed or layer, used to calculate the heating of injected water flowing along the channel, and the eventual cooling of a production well connected to the channel (Axelsson et al., 2005a)

The analytical solution for the temperature of the production well fluid is:

$$T(t) = T_0 - \frac{q}{Q}(T_0 - T_i)\left[1 - \mathrm{erf}\left\{kxh/c_w q\sqrt{\kappa(t - x/\beta)}\right\}\right] \tag{7}$$

$$\text{with}\quad \beta = \frac{qc_w}{\langle\rho c\rangle_f hb} \tag{8}$$

$$\text{and}\quad \langle\rho c\rangle_f = \rho_w c_w \phi + \rho_r c_r(1 - \phi) \tag{9}$$

where $T(t)$ = Production temperature (°C);
T_0 = Initial reservoir temperature (°C);
T_i = Reinjection temperature (°C);
q = Injection rate (kg/s);
Q = Production rate (kg/s);
k = Thermal conductivity of reservoir rock (W/m/°C);
κ = Thermal diffusivity of rock (W/m/°C);
ρ = Density of water (kg/m^3);
c = Heat capacity of rock (J/kg/°C).

It is important to notice that the parameter q_i does not denote the injection rate, but rather the flow rate in each flow channel, so for fracture i, $q_i = (M_i/M)q$. Here, M_i is the mass recovery of tracer from fracture i, and M is total mass injected, because the percentage of mass recovery is assumed to be the same as the percentage of flow in each fracture. A calculation is made according to the above equation to find how much of the water injected into well HO-2 will return to production well HO-1 and can eventually be re-extracted without causing additional pressure decline. The re-extracted water is supposed to be almost 90% of the injection water (Table 2). A comparable return value also indicates that flow channels between HO-1 and HO-2 have a relatively good porosity.

A computer program TRCOOL (included in the ICEBOX package) has been developed using this method (Axelsson et al., 1994), and has been used for several geothermal fields in Iceland as well as fields in other parts of the world. The cooling needs to be estimated or predicted for each flow channel, which will affect the final temperature. To predict cooling in each flow channel, however, it is calculated by considering the mass of tracer recovery in each channel which indicates the ratio of colder injection water travelling through each flow channel, i.e. the channel transferring a large proportion of tracer recovery will play a greater role in the total cooling. In this case, the mass recoveries were 33%, 4.6% and 52% in channels 1, 2 and 3, respectively. Channels 1 and 3 are the main flow channels for cooling prediction.

Several model-versions can be used to calculate the cooling danger, such as (Axelsson et al., 2005a):

1) High porosity, small surface area pipe-like flow channel. This is a most pessimistic case (rapid cooling);
2) Low porosity, large volume flow channel. To simulate dispersion throughout a large volume or fracture network;
3) High porosity, large surface area flow channel, such as a thin fracture-zone or thin horizontal layer. This is a most optimistic case (slow cooling).

According to information obtained from logging of well HO-1 and the analysis above, the three channels are modelled in two modes. Channel 1 and channel 3 are more likely to fit conditions of the slow cooling mode, the most optimistic case for cooling predictions, i.e. a high porosity and large surface area flow channel, while channel 2 is more likely to fit the characteristics of the rapid cooling mode, which is the most pessimistic one. The parameters of the three channels, used in the cooling predictions, are listed in Table 3.

TABLE 3: Model parameters used in cooling predictions for production well HO-1 and reinjection well HO-2

Parameters	**x (m)**	**b (m)**	**h (m)**	**Φ (%)**
Channel 1	1200	4	253	10
Channel 2	1250	1.5	41.5	10
Channel 3	1300	15	275	20

Because the average injection rate at Hofstadir has ranged between 15 and 20 l/s, the cooling trend is predicted for two different reinjection rates (Figure 12). As shown in the figure, the temperature of HO-1 will decline 18-26°C in 50 years for different reinjection rates, according to the predictions.

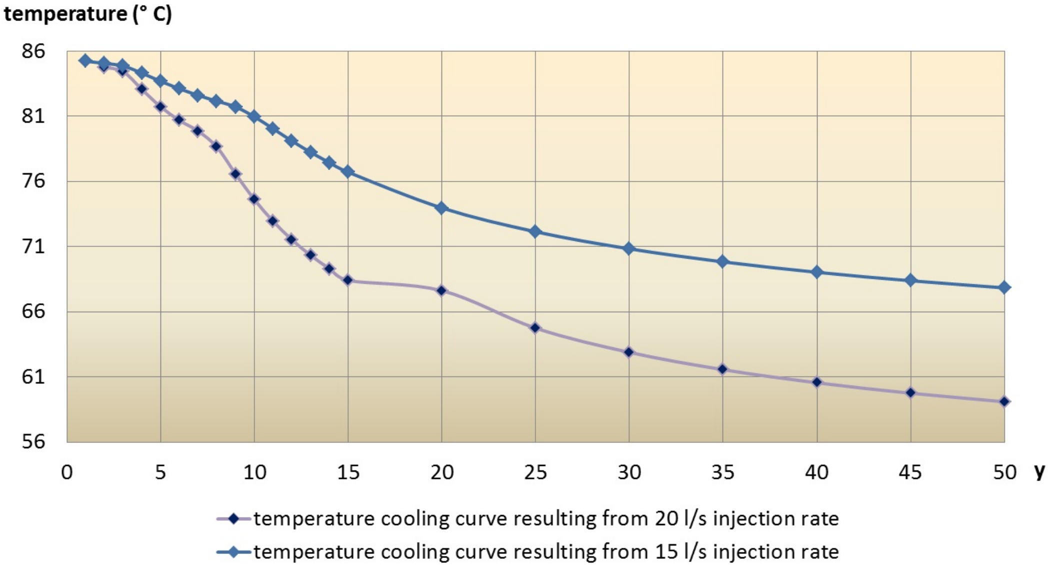

FIGURE 12: Cooling predictions calculated for well HO-1 during reinjection into well HO-2 for 50 years, for different injection rates

3.3 Water level evaluation for Hofstadir after reinjection started

3.3.1 General

The monitoring data for production well HO-1 provides evidence of a substantial water level rise after reinjection started, as shown in Figure 6, thereby proving that reinjection is an important measure in utilization management and that it can definitely support the production from the Hofstadir geothermal system. According to the analysis of production and water level data for HO-1, the water level has been rising year after year since the middle of 2007, although water production has increased from 2005 to 2010 (Table 1). For long-term utilization the most ideal situation would be to achieve a long-term equilibrium between discharge and reinjection in the geothermal reservoir, providing the best way for geothermal system management. If no account is taken of the temperature and this problem is just considered from the point of view of hydrodynamics, then the hydraulic relationship between the reinjection well and the production well can be estimated by using the injection and production flow rate data, and the water-level changes in the production well (Guo, 2008).

3.3.2 Modelling principle

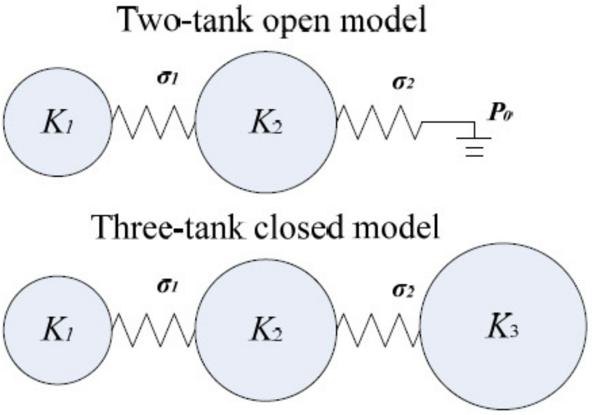

FIGURE 13: Two-tank open model and three-tank closed model in LUMPFIT; general lumped parameter models are used to simulate water level or pressure changes in a geothermal system (Axelsson, 1989)

Lumped parameter models are equivalent to distributed parameter models with a very coarse spatial discretization. As Axelsson (1989) described, a general lumped model consists of a few tanks and flow resistors (Figure 13). The tanks simulate the storage capacity of different parts of the geothermal system. A tank has a storage coefficient (capacitance: κ_1, κ_2, and κ_3) describing how they respond to a load of liquid mass with a pressure increase. The capacitors are connected by resistors (conductors: σ_1 and σ_2), which simulate the flow resistance in the reservoir, controlled by the permeability of the rocks. The mass conductance (inverse of resistance) of a resistor describes how easily it transfers units of liquid mass, per unit time (e.g. kg/s), at the impressed pressure differential Δp. The pressure or water level in the tanks represents the pressure in different parts of the reservoir and the production is simulated by water withdrawal from one of the tanks (Vitai, 2010). In an open lumped model, the outermost tank is connected to a constant pressure recharge source (represents open boundary conditions). In a closed model the final tank is not connected to a constant pressure source, but is assumed to simulate both the deeper parts of the reservoir and the overlying groundwater system.

The program LUMPFIT (included in the ICEBOX package) tackles the simulation problem as an inverse problem and automatically fits the analytical response functions of lumped models to the observed data by using a non-linear iterative least-squares technique for estimating the model parameters (Axelsson, 1989). For details, the reader is referred to Axelsson (1989).

Lumped parameter modelling has many benefits, including time and cost effectiveness, high precision, and an easily grasped basis. Therefore, lumped parameter models have been used extensively to simulate data on pressure (water-level) changes in geothermal systems in Iceland as well as in the P.R. China, Central America, Eastern Europe, The Philippines, Turkey and many other countries during the past few decades. They can simulate such data very accurately, if the data quality is sufficient (Axelsson et al., 2005b).

The procedure for finding the best fitting parameters for a specific model, which can best fit the observed data, is as follows: First, one begins with fitting a one-tank closed model, then turning to a one-tank open model. After that, a two-tank closed model and then a two-tank open model follows. Each previous model will give suggestions on the initial guesses of the model coefficients for the next more complex model (Figure 13). In this way, it should be continued step by step until a three-tank open model has been reached, if possible, the most complicated model allowed by the program. A three-tank model, or even a two-tank model, is sufficient for most systems. The pressure response P(t) of a general open lumped model with N tanks, to a constant production (Q), since time t = 0, is given by the equation:

$$p(t) = p_0 - \sum_{j=1}^{n} Q\frac{A_j}{L_j}\left[1 - e^{-L_j t}\right] \tag{10}$$

The pressure response of an equivalent N-tank closed model is given by the equation:

$$p(t) = p_0 - \sum_{j=1}^{n} Q\frac{A_j}{L_j}\left[1 - e^{-L_j t}\right] - QBt \tag{11}$$

where A_j, L_j and are functions of capacitance (κ_j) and conductance coefficients (σ_j). Further detailed information can be obtained in the paper by Axelsson (1989).

The following is required for the simulation:

1) Production and pressure (or water level) time series in known units. Data collected during long term production from a centrally located observation well are preferable, but data from production wells are also acceptable after being corrected for turbulence pressure losses and skin effect;
2) Appropriate choice of the kind of lumped model (number of tanks, open or closed system);
3) A good first guess for the model parameters before the iteration (otherwise non-convergence may occur).

The program changes the model parameters by the automatic iterative process until the best fit (in the least-square sense) is achieved. After this, the new model parameters can be used for estimating some properties of the reservoir and predicting future changes in pressure or water level depending on the production rate (Vitai, 2010).

3.3.3 Water level simulation analysis for well HO-1

In order to evaluate the potential of the Hofstadir geothermal field, a more reliable lumped parameter model was developed, in which longer data sets than before were used. Firstly, a part of the data were rearranged due to observed water level data of production well HO-1, changes since 22-04-2007. The water level monitoring equipment was replaced during the time period, so it was necessary to combine the data in accordance with the standard format of program LUMPFIT as a new input file. The file has a continuous series of 13 years production and water level history. Then, the data was simulated from the simplest 1-tank model and onward, step by step.

To keep the data consistent the period when the injection was operated was skipped. Hence, the data formed a continuous series from the start of production, i.e. monitored water level from 19-03-1997 to the beginning of reinjection on 22-04-2007, and was then simulated again. The best fit coefficients of determination were obtained for a 2-tank open model and a 3-tank closed model. The modelling results for the two models are shown in Figure 14 and they coincide almost completely. The simulation parameters are listed in Table 4.

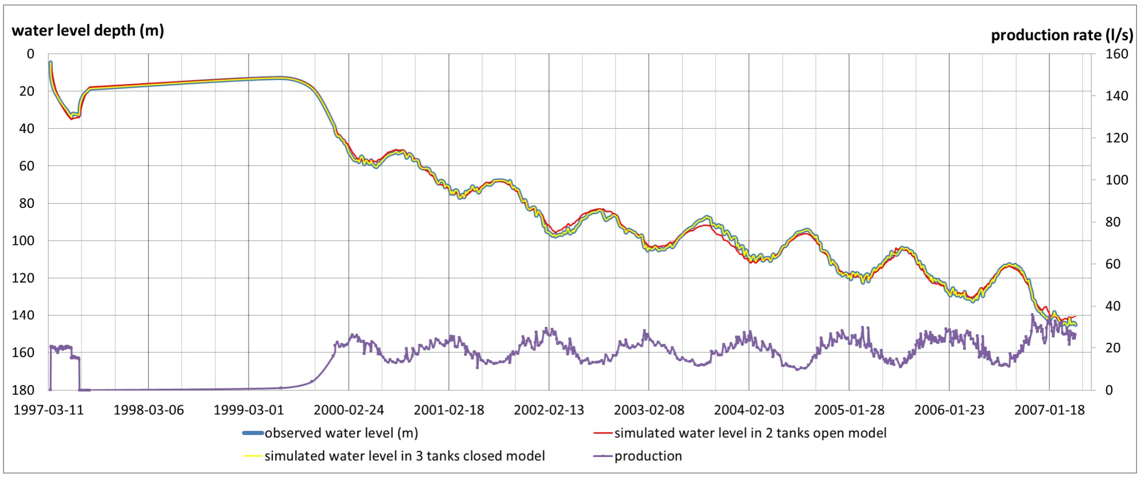

FIGURE 14: Simulation results of different models based on water level data for well HO-1 until reinjection began in 2007. A lumped parameter model is used; production curve is at the bottom; measured and simulated water level is above

The coefficients of determination for the 2-tank open model and the 3-tank closed model are 99.7 % and 99.8%, respectively, so the 2-tank open model and the 3-tank closed model were chosen for further simulation and predictions.

TABLE 4: Parameters of lumped models for production well HO-1 based on all water-level monitoring data before reinjection started

Simulation parameters	2-tank open model	3-tank closed model
A (1) (m^2)	5.30×10^{-7}	5.52×10^{-7}
A (2) (m^2)	4.81×10^{-8}	5.02×10^{-8}
A (3) (m^2)		
L (1) (m)	4.05×10^{-7}	4.66×10^{-7}
L (2) (m)	8.31×10^{-9}	1.54×10^{-8}
L (3) (m)		
B (m/s)		8.14×10^{-9}
κ_1 (ms^2)	176.68	167.28
κ_2 (ms^2)	2036.06	1685.35
κ_3 (ms^2)		10679.4
σ_1 (10^{-5} ms)	6.57×10^{-5}	7.02×10^{-5}
σ_2 (10^{-5} ms)	1.84×10^{-5}	2.44×10^{-5}
σ_3 (10^{-5} ms)		
Root mean square misfit	2.05	1.92
Estimate of standard deviation	2.06	1.92
Coefficient of determination (%)	99.727	99.762

There was a shift in the observed water level after the equipment was replaced. The change in the observed water level of the production well was more than 110 m, which is clearly due to incorrect values of data during the equipment replacement. If there are future predictions of the water level carried out, the incorrect part of the data should be corrected.

To be able to use the data from the start of injection i.e. 22-04-2007 until 30-12-2010, a discharge file was made by subtracting the injection rate from the production rate, then the file was used to simulate the water level in production well HO-1 during the reinjection period. The simulation results are quite close to the values based on the experiences of the engineer working at the pumping station of well HO-1, i.e. the shift should most likely be about 10 m; see Figure 6.

3.3.4 Water-level change predictions

Whether an injection project can be carried out successfully within a given geothermal field depends on two factors: (1) there must be flow paths between an injection well and a production well; and (2) the flow channels should have proper characteristics for the reinjection project.

The prediction study process can be described as follows: as a first step the best fitting parameter model was selected, a model which is proper and can best represent the actual situation of the reservoir in question. Here a 2-tank open model and a 3-tank closed model were used for this purpose. In the second step, the production data were re-arranged by subtracting a given percentage of the injection flow rate from the production flow rate. This, in turn, was assumed to enable an equivalent production increase without further pressure decline. In the third step, the best fitting parameter model was used to simulate the water level for the injection period with the corrected data as input. In the fourth step, the simulation results were judged by simply comparing the coefficient of determination for various scenarios. Finally, in the fifth step, the assumed percentage of reinjection rate was adjusted and the water-level simulated repeatedly until the best results were found.

For the purpose of this study, a series of assumed future production/ reinjection cases were used to predict future water level changes in the Hofstadir system. According to the actual implementation of reinjection, the reinjection ratio was 65-73% of the production, and the water level markedly increased during reinjection. A scenario of reinjection and production based on the present situation of production was chosen, namely with an average production rate of 27 l/s, set up as follows:

1) The injection rate was proportional to the production flow rate selecting the reinjection ratio as 68, 74, 78 and 92% of production;
2) The prediction period was chosen to be 50 years.

The prediction results are shown in Figure 15. The 2-tank open model gave more optimistic forecasts than the 3-tank closed model. Even though the 3-tank model gave pessimistic results, its predictions still show that 70-80% reinjection should allow production from well HO-01 to continue for a long time. For the 2-tank open model, the water level would be stable, namely a new equilibrium would be gained between reinjection and production in the reservoir.

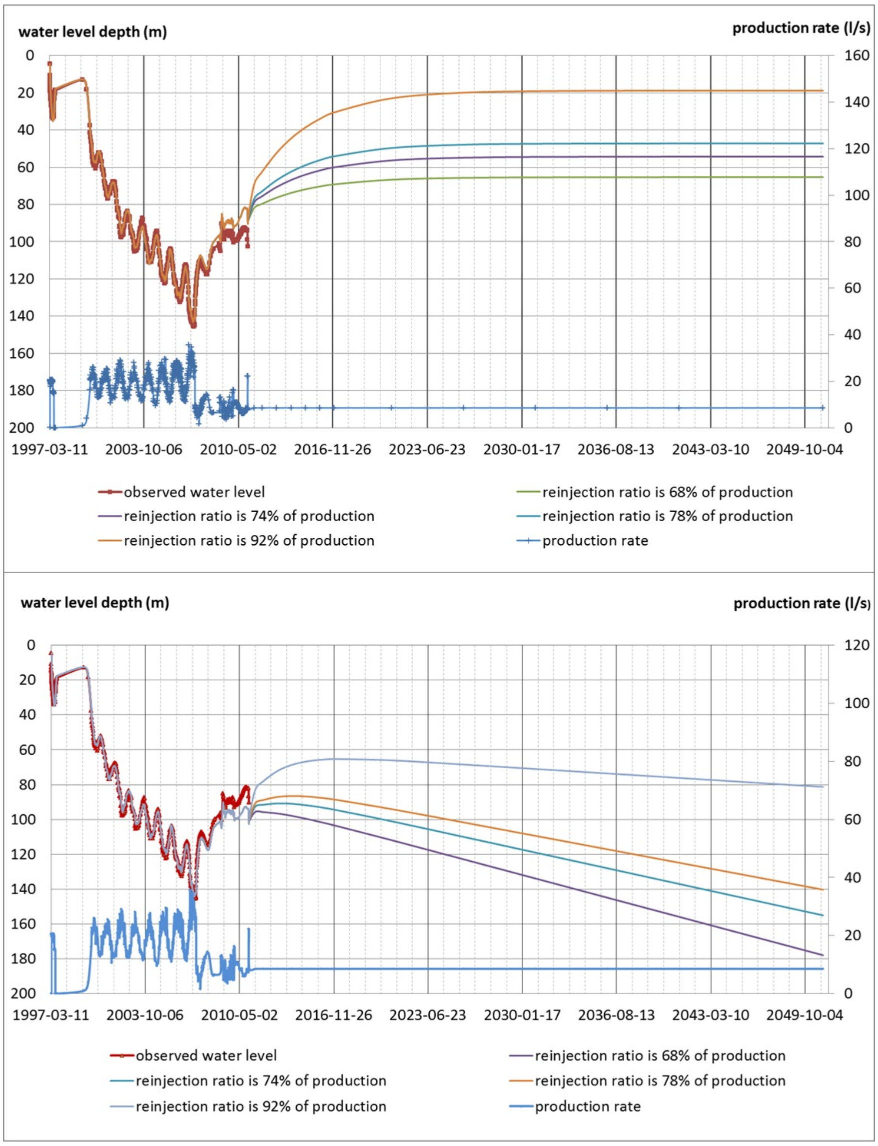

FIGURE 15: Water level forecasts for well HO-1 for different reinjection scenarios calculated by LUMPFIT; above for the 2-tank open model; and below for the 3-tank closed model

4. PROBLEMS, CHALLENGES AND SOLUTIONS

4.1 General

Colder water injection into geothermal reservoirs is a very complex technology. The location of reinjection wells is key in minimizing cooling of reservoir or production wells, while the reinjection technique is critical for injection capacity of reinjection wells. In order to study the reinjection effect on the sustainable utilization of a reservoir, long-term and comprehensive monitoring must be carried out.

4.2 Cooling and tracer tests

The reinjected colder water is able to change the status of the reservoir, and sometimes the colder water can travel a great distance in the reservoir. The cold-front breakthrough depends usually on the outward expansion modes of the injected colder water, i.e. the pressure change, the fluid mechanical dispersion and heat conduction. The reservoir pressure changes are much more rapid than both chemical and temperature changes. Cold-front migration by mechanical dispersion is much slower than either pressure or chemical front propagation, because of the actual fluid particle velocities. Cold-front migration by heat conduction is the slowest, because the colder water has to be gradually heated along the path from the reinjection well to the production well.

In the reinjection project design, it is important to control the distance between the reinjection well and the production well. Too short a distance will result in faster movement of colder water from the reinjection well into the production well, which could rapidly reduce the temperature in the production well, while too long a distance between the reinjection well and the production well or the reservoir does not allow reinjection to increase pressure in the reservoir nor does it support geothermal field production capacity. The geothermal reinjection is also strongly dependent on the site conditions, i.e. reinjection designs should be based on the different geological conditions between the reinjection wells and the production wells. Therefore, reinjection tests, including tracer tests, must be carried out before actual reinjection begins.

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; 2005a) presented a method of tracer test interpretation which is conveniently based on the assumption of specific flow channels connecting injection and production wells. Comprehensive interpretation of geothermal tracer test data, and consequent modelling for management purposes such as 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 (Axelsson, 2008b).

As a precaution, and to avoid reinjection and production wells being too close, the reinjection wells can be located near the edge of the geothermal field; then the possibility of cooling due to reinjection will be greatly reduced. After that, however, the reasonable amount of reinjection needed to avoid premature thermal breakthrough should be studied.

4.3 Sandstone clogging and reinjection design

Physical and chemical clogging often occur in reinjection operations in sandstone geothermal systems, and result in a reduction of the reinjection capacity of wells. The physical clogging is mainly caused by solid particles in the water, which are attached to the wall or in the fractures in the reservoir, due to the injection pressure. It is also caused by the air/gas-bubbles which are produced in the reinjection procedure. In order to avoid, or reduce, physical clogging, the solid particles have to be removed by using filters prior to injection. If the water level of the reinjection well is below the surface, a reinjection pipe should be installed to ensure the transport of the injected water directly below the groundwater table in the reinjection well in order to bypass the possibility of injected water mixing with air bubbles which could result in a decrease in the reinjection capacity (Seibt et al., 2005).

Chemical clogging is usually a result of mineral deposition due to a reaction between geothermal water and rocks, i.e. scaling (mainly silica or calcium carbonate, etc.) or corrosion. Scaling and corrosion problems can be controlled through different technical solutions, dependent on the particular situation (Axelsson, 2008b). In general, scaling and/or corrosion are usually more severe in high-temperature geothermal systems and, therefore, they will not be discussed in detail in this report.

4.4 Reinjection effect and long-term monitoring

In order to assess the reinjection effect and to detect problems in the reinjection procedure in time, long-term monitoring of the geothermal system has to be carried out.

For the reinjection wells, the injected water quantities, the injected water temperature, wellhead pressure (water level) and water quality are required as observables. For the production wells, the production rate, the production water temperature, pressure (water level), the production water quality, and tracer concentration are required to be monitored. In addition, the other geothermal wells, which surround the system in question, should be monitored. When production or reinjection stops, or during pauses, the temperature profile should be measured based on a certain time interval in the production wells and the reinjection wells for observing warming of the reinjection wells and cooling of the production wells (Liu, 2003).

The short-term reinjection effects can be analysed through the monitoring data. Nevertheless the assessment of the long-term reinjection effects has to be gained by the establishment of appropriate models. A model with a relatively simple application is based on the parameters of tracer tests, while numerical models need to be set up for complex situations.

5. CONCLUSIONS

In accordance with the information reviewed and the example analysed in this report, reinjection is an essential tool to support production from a low-temperature geothermal system with limited natural recharge. This is demonstrated by the sustainable utilization example of the Hofstadir geothermal system in W-Iceland.

The temperature of well HO-01 in the Hofstadir system has not demonstrated a perceptible reduction from the start of actual production until now; with a reservoir temperature of about 86-87°C. The production temperature was still 86.1°C in 2010. There is, however, a visible relationship between temperature change and the production rate. The decrease in temperature in HO-1 accelerated from 2007 to 2010 with increasing production and injection, while the water level of HO-1 has recovered continuously since reinjection started, despite increased production.

In order to study the relationship between the production temperature and production rate, and the possible cooling due to reinjection, simulation and forecasting were conducted on the basis of comprehensive tracer test data. The connection between the wells was modelled by 3 channels (program TRINV) between production well HO-1 and reinjection well HO-2. Channels 1 and 3 are the main paths for transporting water from HO-2 to HO-1. The modelling confirms that there is quite good connectivity in the reservoir between the production well and the reinjection well. The re-extracted water is estimated to be almost 90% of the injection water. Based on temperature analysis, a cooling forecast was done using the program TRCOOL; the temperature of well HO-1 was predicted to decline by 18°C and 26°C in 50 years with an average reinjection rate of 15 and 20 l/s, respectively. If this pessimistic prediction materializes, some modification of the reinjection set-up may have to be done in a few decades, perhaps by drilling a new reinjection well.

The water-level monitoring data for production well HO-1 provided clear evidence of considerable water level recovery since reinjection started. In order to evaluate the water level change during the reinjection period in the Hofstadir geothermal system, program LUMPFIT was used to simulate corrected water level data and two best fitting models were obtained, a 2-tank open model and a 3-tank closed model. According to the actual reinjection implementation, the reinjection ratio was 65-73% of the production. Therefore, a scenario of reinjection and production based on the present situation was considered, namely with an average production rate of 27 l/s and a variable reinjection ratio for the next 50 years. The results show that the water level in the geothermal system can be maintained within acceptable limits through reinjection in the future.

The study results confirm that reinjection is one of the most important measures for geothermal reservoir management and sustainable utilization of geothermal resources and is especially important for sustainable utilization of geothermal systems which are virtually closed and have limited recharge. The utilization with reinjection at the Hofstadir system provides a good model for sustainable utilization of other geothermal fields in the world, especially low-temperature fields. The experience gained could be used in geothermal fields in China, such as in Beijing, Tianjin, etc., where reinjection is being considered as a future mode of reservoir management.

Reinjection is a complicated technique, so before starting any large-scale reinjection projects, feasibility studies and experiments should be carefully carried out.

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