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THERMAL ENERGY EXTRACTION BY REINJECTION FROM THE LAUGALAND GEOTHERMAL SYSTEM IN N-ICELAND

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ABSTRACT

A two-year reinjection experiment was completed in late 1999 in the Laugaland geothermal system in N-Iceland, the first such project undertaken in an Icelandic low-temperature area. The Laugaland system is embedded in low-permeability fractured basalt and its productivity is limited by insufficient recharge. More than sufficient thermal energy is, however, in-place in the 90 - 100 °C hot rocks of the system, some of which may be extracted by injection. The purpose of the reinjection project was to demonstrate that energy production from fractured low-temperature geothermal systems might be increased by reinjection. The Laugaland reinjection test was a co-operative project involving a few companies and institutions in Iceland, Sweden and Denmark, partly supported by the European Commission. Between 6 and 21 kg/s were injected into two reinjection wells and a comprehensive monitoring program was implemented as part of the reinjection project. Also included were three tracer-tests, monitoring of associated micro-seismic activity, step-rate injection tests and temperature logging of the injection wells. Results of the experiment indicate that reinjection will be a highly economical mode of increasing the production potential of the Laugaland system and reinjection is expected to be an important part of the management of the Laugaland reservoir for decades to come.

1. INTRODUCTION

Laugaland is the largest of five low-temperature geothermal fields utilised by Hita- og Vatnsveita Akureyrar (HVA) for space heating in the town of Akureyri in Central N-Iceland (Figure 1). Since late 1977 hot water production from the field has varied between 0.9 and 2.5 million tons annually (Flovenz *et al.*, 1995). Because of a low overall permeability and limited recharge this modest production has lead to a great pressure drawdown. It continues to increase with time if constant rate production is maintained. In the early eighties the draw-down reached about 400 m, which forced the production from the field to be reduced by about 50%. Therefore, reinjection has for long been considered a possible way to improve the productivity of the Laugaland system.

The Laugaland geothermal system is a typical fracture controlled system, embedded in 6-10 Myrs. old flood basalt, wherein the hot water flows along open fractures in otherwise low-permeability rocks. Twelve wells have been drilled in the area, only three of which are sufficiently productive to be used as production wells. Information on the wells currently in use in the field, as production-, observation- or injection wells, is presented in Table 1, and their locations are shown in Figure 2. More details on the Laugaland system may be found in Axelsson *et al.* (1998a & b).

Most of the thermal energy in the Laugaland geothermal system is still stored in the 90 - 100 °C hot reservoir rock-matrix. More recharge water is in fact needed to recover some of that energy. Therefore, HVA has been planning long-term reinjection during the last several years. A small-scale injection experiment was carried out at Laugaland in the spring of 1991, described by Axelsson *et al.* (1995 and 1998). It lasted about 5 ½ weeks and involved wells LJ-8 and LJ-5. The results of a tracer test were interpreted as indicating that the injected water diffused into a very large volume and that wells LJ-5 and LJ-8 were not directly connected. Water level data, on the other hand, indicated that reduced drawdown because of the injection should allow a considerable increase in production.

In 1996 the Thermie sub-program of the European Commissions Fourth Framework Programme for Research and Technological Development decided to support a two year reinjection experiment in the Laugaland area. This was a co-operative project involving a few companies and institutions in Iceland, Sweden and Denmark. Work on the project started in late 1996, while actual reinjection started on the 8th of September 1997. The experiment ended in late 1999, but reinjection is expected to continue. It is the first long-term reinjection project carried out in an Icelandic low-temperature area (Stefansson *et al.*, 1995).

This paper describes the Laugaland reinjection project. Data collected during the project will be reviewed along with results of data analysis and interpretation. The analysis and interpretation phase had not been completed at the time of writing of this paper, however. More details on the project can be found in Axelsson *et al.* (1998a & b).

2. THE REINJECTION PROJECT

The results of the test in 1991 indicated that injection should be viable as the means to increase the production potential of the Laugaland geothermal system. At first injection of local surface- or ground water was considered. That idea was abandoned, however, since serious problems may be associated with the injection of such water. The most serious of these is the possibility of deposition of magnesium-silicates in the feed-zones of an injection well, which may cause the well to clog up in a relatively short time, rendering further injection impossible. Using return water from the Akureyri district heating system is ideal, because its chemical composition is almost identical with that of the reservoir fluid.

This, however, was more costly, since it required construction of a return water pipeline from Akureyri to Laugaland. Therefore, a few companies and institutions in Iceland, Sweden and Denmark applied for a grant from the European Commission, in the beginning of 1996, for undertaking this project. Later that year the Commission decided to support the proposed experiment.

The project included the following phases:

1. Manufacture and installation of a 13 km return water pipeline from Akureyri to Laugaland (see Figure 1).

2. Installation of high-pressure pumps at the two injection wells, LJ-8 and LN-10, and pumps in Akureyri for pumping the water to Laugaland as well as installation of a computerised control- and monitoring system.

3. Installation of an automatic network of six ultra sensitive seismic monitoring stations around Laugaland.

4. Continuous reinjection for a period of two years, along with careful monitoring of the reservoirs response to the injection and any associated seismic activity. Three tracer tests to study the connections between injection- and production wells.

5. Analysis and interpretation of data collected, including development of a numerical model for the geothermal system, predictions of the response of production wells to long-term reinjection and analysis of the economics of future reinjection.

The total project cost is estimated at 1.7 million USD. The Thermie sub-program of the Programme of Research and Development of the European Commission supported the project by a 0.7 million USD contribution. The first three phases had been completed at the end of October 1997. The fourth phase started in September 1997 and continued until early fall 1999. Work on the fifth phase was ongoing at the time of writing of this paper.

The principal participants in the project are: *HVA*, the Akureyri District Heating Service, *Orkustofnun*, the National Energy Authority of Iceland, *Uppsala University* in Sweden, *Hochest Danmark A/S* and *Rarik*, Icelandic State Electricity.

3. PRINCIPAL RESULTS

Reinjection started on the 8th of September 1997. Since then injection into well LJ-8 has been mostly continuous, varying between 6 and 21 kg/s. From the end of January until the middle of August 1998 about 6 kg/s were also injected into well LN-10. The combined injection rate during the whole project is shown in Figure 3. A total of 910,000 tons had been injected at the end of August 1999, or about 14.4 kg/s on the average. The temperature of the injected water has been in the range of 6 - 22 °C.

Figure 4 shows the daily average hot water production from the Laugaland field during the two-year project. The production has varied between 0 and 130 l/s and a total of 2,550,000 tons were produced from the field from the end of August 1997 until the end of August 1999. The reinjection, therefore, equals about 36% of the total production during the experiment. The production has been quite variable, mostly reflecting varying hot water demand in Akureyri. During the winter time two wells are commonly on line, either wells LN-12 and LJ-5 or wells LJ-5 and LJ-7. During a few shorter periods constant production was maintained to create semi-stable reservoir conditions. This was done to facilitate various tests and consequent data interpretation. The longest such period was from the end of August until the end of November 1997, when only well LN-12 was on line.

Figure 5 shows the wellhead pressure of injection well LJ-8, which varied between 4 and 11 bar-g during the first year of the project. During the second year of the project injection rates were higher, causing a wellhead pressure as high as 28 bar-g. Before injection started the water level in the well was at a depth of 126 m. Variations in production, and the consequent variations in reservoir pressure (water level), influence the wellhead pressure of well LJ-8, in addition to variations in injection rate. Some wellhead pressure transients may also be attributed to variations in viscosity and thermal effects. The injectivity of well LN-10 appears to be about 30% greater than the injectivity of well LJ-8.

The data presented in figures 3-5 were all collected by the automatic monitoring system. In addition to these data, water level measurements were taken on a regular basis in a number of wells inside, and outside, the Laugaland field. The comprehensive monitoring program also included: temperature logging of the injection wells, monitoring of production water temperatures and chemical content, as well as three tracer tests. All these data are presently in the process of being analysed, and interpreted. The analysis has focused on three main aspects: (1) water level changes, which yield information on reservoir properties and the pressure recovery resulting from the reinjection, (2) borehole logs, which yield information on the feed-zones of the injection wells, and (3) tracer tests, which provide information on the connections between injection and production wells, and hence the danger of premature, and rapid cooling, of the latter.

The principal results of the analysis are presented below, but the details await the final report for the project. First the current conceptual model of the Laugaland system is described briefly.

3.1 Conceptual model of the Laugaland system

The conceptual model of the Laugaland system has been revised on the basis of the data collected during the reinjection project (Axelsson *et al.*, 1998a; Hjartarson, 1999). The model involves a near vertical fracture-zone, trending close to N50ºE, with a moderate permeability, maintained by recent crustal movements. The permeability of the lava-pile outside the fracture-zone has been reduced drastically by low-grade alteration. Successful wells in the area are either located very close to or they intersect this fracture-zone. In the natural state convection in the fractures transferred heat from a depth of a few km to shallower levels. The heat was consequently transported into the low-permeability rocks outside the fracture-zone, mostly by heat conduction. This convective/conductive heat transfer is believed to have been ongoing for the last 10,000 years at least.

3.2 Water level changes

Figure 6 shows the water-level changes observed in three wells in the Laugaland field during the two-year injection project. These are observation well LG-09 and production wells LJ-5 and LN-12. Water level records, not presented here, are also available from a number of other wells, inside as well as outside the Laugaland field.

The details of the water level record will not be discussed here. It actually constitutes a series of pressure transient tests, however, several of which have been analysed as such (Hjartarson, 1999). The main results of this analysis are that the production wells intersect the NE-SW fracture zone, which has an estimated permeability thickness of about 15 Darcy-m. The injection wells are clearly outside this zone. The permeability thickness of the low-permeability rocks outside the fracture-zone is estimated to be about 2 Darcy-m.

A reduced water level drawdown is anticipated as the main benefit from reinjection. The water level data were, therefore, also analysed carefully in order to quantify the effect of reinjection on the water level in the production wells. This was done by simulating the 20 year water level history of the Laugaland field by a lumped parameter model (Axelsson, 1989). The deviation between observed and simulated data, after reinjection started, was consequently used to estimate the benefit. The results indicate that the hot water production rate may be increased by 60-70% of the reinjection rate, without causing additional drawdown. It should be mentioned that the short-term (days) benefit is minimal, and that the long-term (years) benefit is expected to be somewhat greater. Some water level recovery has been observed in a geothermal field about 2 km north of Laugaland, which also may most likely be attributed to the reinjection.

A few step-rate injection tests have been conducted in wells LJ-8 and LN-10. The purpose of these tests was to estimate the injection characteristics of the wells, in particular pressure losses due to turbulent flow inside the wells, and in the feed-zones next to the wells. The test was repeated in well LJ-8, after about 9 months of steady reinjection, to determine whether any changes had occurred in the well, either due to deposition in the feed-zone fractures or thermal effects. No significant difference was noted between the tests (Axelsson *et al.*, 1998b).

3.3 Analysis of temperature and televiewer logs

Several temperature logs are available for well LJ-8 during injection. A log measured before injection started, representing the undisturbed temperature conditions of the well, is also available. Figure 7 shows two of these logs as examples. At about 2000 m there is an obstruction in the well, which actually is more than 2800 m in depth. Temperature logs measured prior to, and during injection, are also available for well LN-10. There is unfortunately an obstruction in that well at a depth of about 470 m, while the well extends to a depth of more than 1600 m.

The temperature logs measured in well LJ-8 during injection clearly show that the injected water exits the well through a few distinct exit-points (feed-zones), the deepest one being below 2000 m. An analysis of the log enables a determination of the water flow-rate as a function of depth in the well, and hence a determination of how much water exits the well at each exit-point. The basis for this is a balance between the flow of energy into the cooled well, by heat conduction, and the energy required to heat the injected water as it descends in the well (Axelsson *et al.*, 1998b). This analysis was carried out with the aid of a wellbore simulator (Bjornsson, 1987) and an example of a simulated profile is shown in Figure 7. The average results of the analyses of different profiles are as follows (Hjartarson, 1999):

depth	*fraction of inj. rate*
320m	*49%*
600m	*20%*
1335m	*20%*
1875m	*10%*
below 2000m	*1%*

The main exit points appear to be at depths of around 320, 600 and 1335 m. About 30% of the injected water appear to exit the well in the deeper part of the reservoir, below 1000 m. The main feed-zones of the production wells are below that depth. That part of the injection should directly influence the production wells, while the water exiting at 320 m depth is not expected to fully do so.

A televiewer log is available for two sections of well LJ-8, 500-1050m and 1220-1350m, measured by Potsdam Geoforschung Zentrum in 1996. This log was analysed to study the nature of the two exit points in these sections (Hjartarson, 1999). The results indicate that the exit-points at 600 and 1335 m depth are near vertical fractures, striking NE-SW and dipping to the NW. Of a number of fractures seen in the televiewer log, only these two strike NE-SW. This happens to be the same direction as that of the main fracture-zone, suggesting that this may be an optimal direction in the current stress field.

3.4 Tracer tests and cooling predictions

Three tracer tests were carried out between wells at Laugaland, during the reinjection project. The purpose of these tests was to study the connections between injection- and production wells in order to enable predictions of the possible decline in production temperature due to long-term reinjection. The first test started on September 25th 1997 when 10 kg of sodium-fluorescein were injected instantaneously into well LJ-8. Consequently its recovery was monitored accurately in well LN-12, the only production well on-line at the time. The results until the end of November 1997 are shown in Figure 8. At that time pumping from well LJ-5 started, and the previously stable conditions were disturbed. The fluorescein recovery was monitored until the end of the project, however, and the tracer has been recovered in all three production wells.

Other geothermal production wells in the Eyjafjordur-valley, outside Laugaland, were also monitored for tracer recovery (see Figure 1). A significant amount of fluorescein was actually recovered in production well TN-4 in the Ytri-Tjarnir field about 1800 m north of well LJ-8 (Axelsson *et al.*, 1998b). This confirms a direct connection between these two fields. No tracer has been recovered in production wells in the western half of the Eyjafjordur-valley.

The second tracer test started on February 19th 1998 when 45.3 kg of potassium iodide was injected into well LN-10. At that time both of wells LJ-5 and LN-12 were on line. Conditions were not as stable during this tracer test as during the previous one, because hot water production was more variable. Iodide was only recovered in well LJ-5, but neither in well neither LN-12 nor well LJ-7. The third, and final tracer test was conducted in the spring of 1999. This was actually a repetition of the first test, carried out to study the effect of increased injection rate (21 instead of 8 l/s). These data have not yet been fully analysed.

Even though the tracer breakthrough-times were relatively short, or only of the order of 1 – 2 days, the tracer recovery has been very slow. Until early October 1998 about 1.7 and 0.6 kg of fluorescein had been recovered through wells LJ-5 and LN-12, respectively. This amounts to 23%, of the tracer injected initially, in a little more than 12 months. At the same time about 12 kg of iodide had been recovered through well LJ-5, or about 35% in 7 ½ months. This indicates that the injection- and production wells are not directly connected through the major feed-zones of the latter. They appear to be connected through some minor fractures or inter-beds.

It is also clear that well LJ-5 is somewhat better connected to the injection wells than production wells LJ-7 and LN-12. This is most likely through the upper part of the Laugaland reservoir, above 1000 m depth, since well LJ-5 is only cased to a depth of 96 m. Wells LJ-7 and LN-12 are cased to depths of 930 and 294 m, respectively. Well LJ-8 is cased to a depth of 196 m, while well LN-10 is only cased to a depth of 9 m.

The data from the first test (Figure 8) have been analysed on the basis of a one-dimensional fracture-zone, or flow channel model, where the tracer return is controlled by the distance between injection- and production zones in the corresponding wells, the flow channel volumes and dispersion. This model is described by Axelsson *et al.* (1995) and has been used to simulate tracer test data from several Icelandic geothermal fields. Three separate flow channels are used in the simulation for wells LJ-8 and LN-12 and the simulated results presented in Figure 8. Axelsson *et al.* (1998b) and Hjartarson (1999) present the details of the analysis.

The main results are that, on one hand, the volumes of the channels appear to be quite small, or with a sum of the order of 20,000 m^3 (assuming an average porosity of 7%). On the other hand, only about 6% of the injected water appears to travel through these channels from injection- to production well. Most of the injected water, therefore, appears to diffuse throughout the much larger volume of the reservoir.

The model was finally used to calculate the temperature decline of well LN-12 during injection into well LJ-8, due to the flow through these channels. The results are presented in Figure 9. It should be pointed out that the injected water, which does not travel through these channels, may also cool the production wells to some degree. According to the results in the figure, 10 l/s injection will cause a temperature decline of less than 1°C in 20 years.

Finally it should be mentioned that changes in the temperature of water produced from wells LJ-5, LJ-7 or LN-12, which may be attributed to the reinjection, have not been observed. The small change predicted (Figure 9) might be masked by minor changes caused by variations in flow-rate and production pattern. Furthermore, no changes have been observed in chemical content.

3.5 Micro-earthquake activity

The seismic network was designed to locate all micro-earthquakes of magnitude $M_L > -1$, which might be induced by the injection. Thus some information on the locations of fractures involved was anticipated (Slunga *et al.*, 1995). No micro-earthquakes were recorded during the two-year reinjection project, however. Not even during stages of the project when wellhead pressures of up to 30 bar-g were realised. This is believed to result from the fact that about 70% of the injected water exits well LJ-8 above 1000 m depth, where stresses are relatively low.

4. CONCLUDING REMARKS

Even though analysis and interpretation of data collected during the Laugaland reinjection project had not been completed at the time of writing of this paper, available results are highly positive. On the one hand, an untimely thermal breakthrough or a rapid production temperature decline is not expected in production wells during long-term injection into well LJ-8. On the other hand, hot water production from the field may be increased by 60-70% of the reinjection, without causing an increased pressure draw-down. Thus, production from the Laugaland field may be increased by about 10 l/s, at an average injection rate of 15 l/s. This is equivalent to an increase in energy production of about 24 GWh/yr., which equals about 25% of the current yearly energy production at Laugaland.

Reinjection is practised in many geothermal fields in the world, in most cases to dispose of waste water due to environmental reasons (Stefansson, 1997). Reinjection with the purpose of extracting more of the thermal energy in the hot reservoir rocks, and thereby increase the productivity of a geothermal reservoir, has not been practised in many areas. This is more in line with the HDR-concept. Injection has, furthermore, not been part of the management of the numerous low-temperature systems utilised in Iceland. The positive results of the Laugaland reinjection experiment indicate that reinjection will be a highly economical mode of increasing the production potential of the Laugaland system. The current reinjection system should, therefore, be an important part of the management of the geothermal reservoir for decades to come. The results of the project will hopefully also encourage other operators of fractured low-temperature geothermal systems to consider injection as a management option.

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Table 1. Wells in use in the Laugaland field.

Well	Drilled	Depth (m)	Use
LJ-05	1975	1305	Production well
LJ-07	1976	1945	Production well
LJ-08	1976	2820	Obs./injection well
LG-09	1977	1963	Observation well
LN-10	1977	1606	Obs./injection well
LN-12	1978	1612	Production well

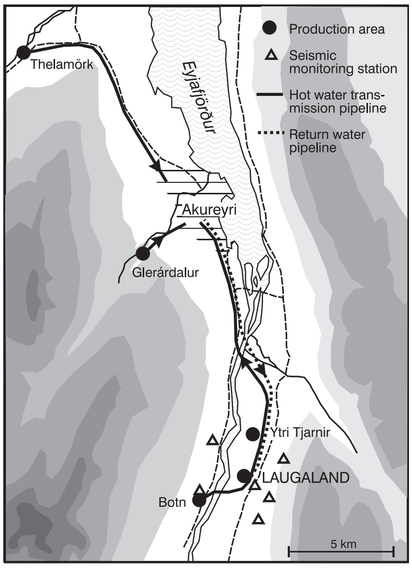

Figure 1. Location of the Laugaland geothermal area.

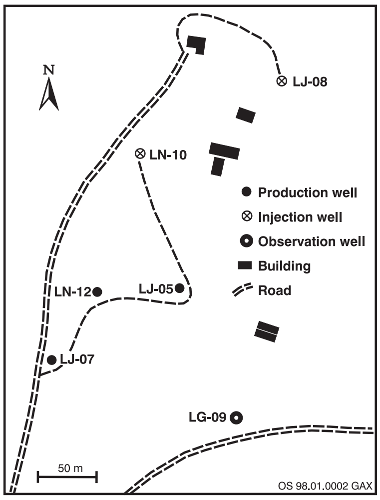

Figure 2. Wells in the Laugaland geothermal field.

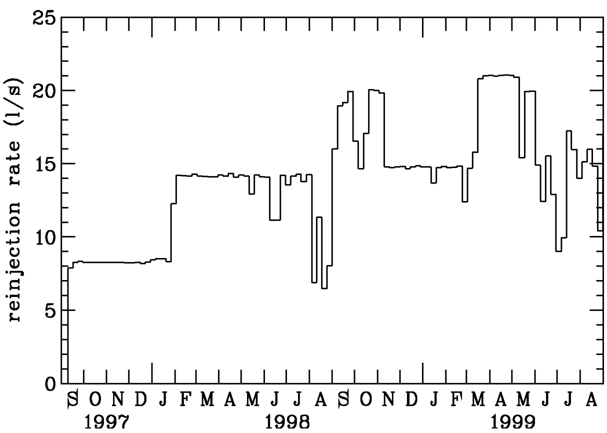

Figure 3. Weekly average reinjection into wells LJ-8 and LN-10 during the reinjection project.

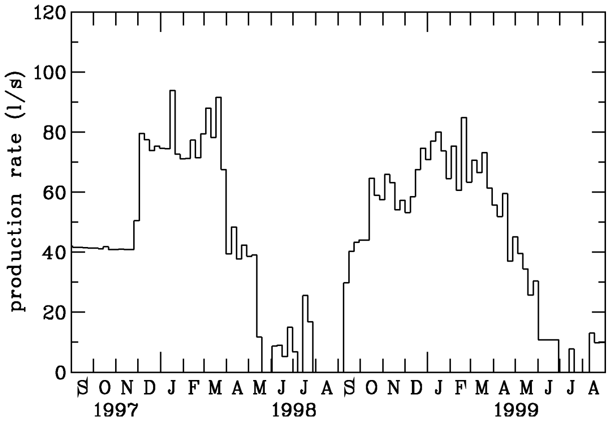

Figure 4. Weekly average production from wells LJ-5, LJ-7 and LN-12 at Laugaland during the reinjection project.

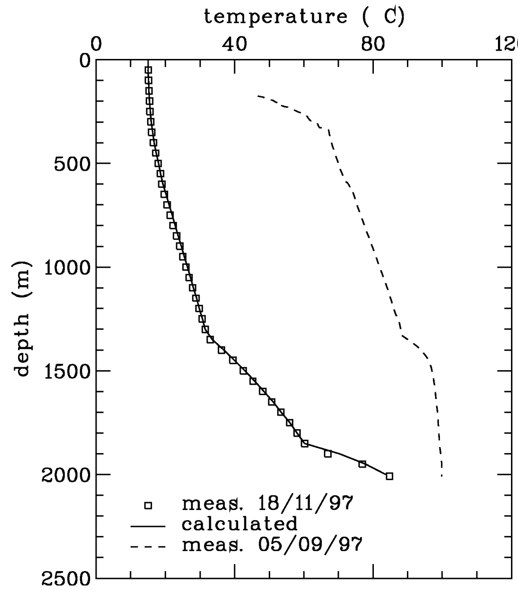

Figure 7. Two temperature logs from well LJ-8, measured prior to and during reinjection, Also shown is a simulation of the second log by a wellbore simulator.

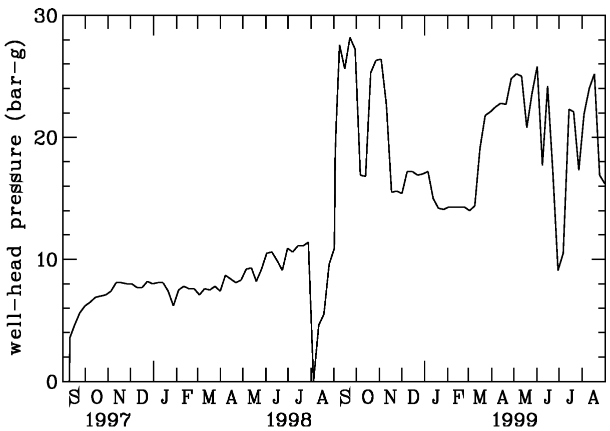

Figure 5. Well head pressure of well LJ-8 during the reinjection project.

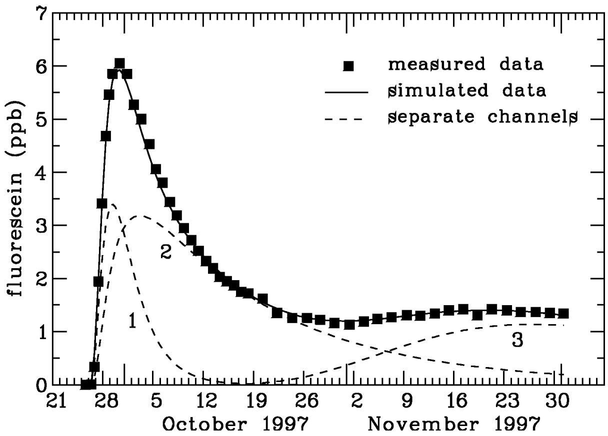

Figure 8. Observed and simulated fluorescein recovery in well LN-12 during injection into well LJ-8.

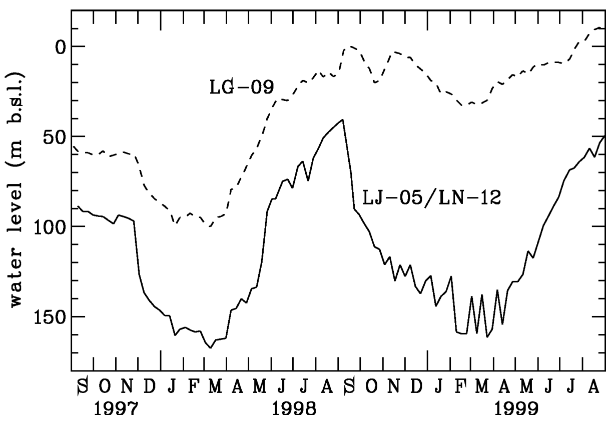

Figure 6. Water level changes in three wells at Laugaland during the reinjection project.

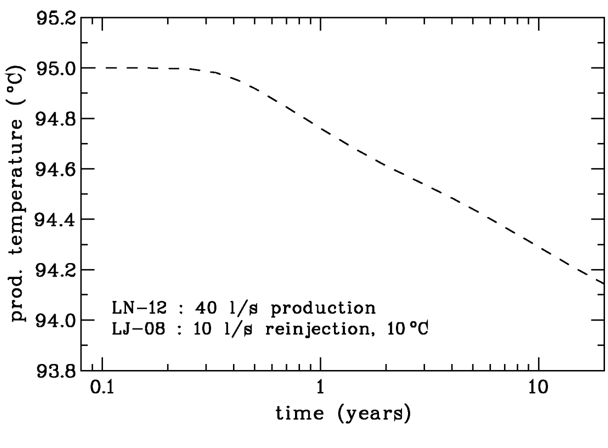

Figure 9. Estimated temperature decline for well LN-12 during injection into well LJ-8.