The United Nations
University

GEOTHERMAL TRAINING PROGRAMME
Orkustofnun, Grensásvegur 9,
IS-108 Reykjavík, Iceland

20th Anniversary Workshop
October 1998

THERMAL ENERGY EXTRACTION, BY REINJECTION, FROM A LOW-TEMPERATURE GEOTHERMAL SYSTEM IN N-ICELAND

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ABSTRACT

A long-term reinjection test is now underway 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 basalts 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. The purpose of the reinjection project is to extract some of this thermal energy and to demonstrate that energy production from fractured low-temperature geothermal systems may be increased by reinjection. The Laugaland reinjection test is a cooperative project involving a few companies and institutions in Iceland, Sweden and Denmark, partly supported by the European Commission. Between 8 and 14 kg/s have been injected since the test started on the 8th of September 1997. A comprehensive monitoring program has been implemented as part of the reinjection project. Also included are some tracer-tests, monitoring of associated micro-seismic activity, step-rate injection tests and temperature logging of the injection wells. The reinjection experiment will continue through the year 1999. Preliminary results indicate that reinjection is 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 utilized 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 (Flóvenz et al., 1995). Because of a low overall permeability and limited recharge this modest production has lead

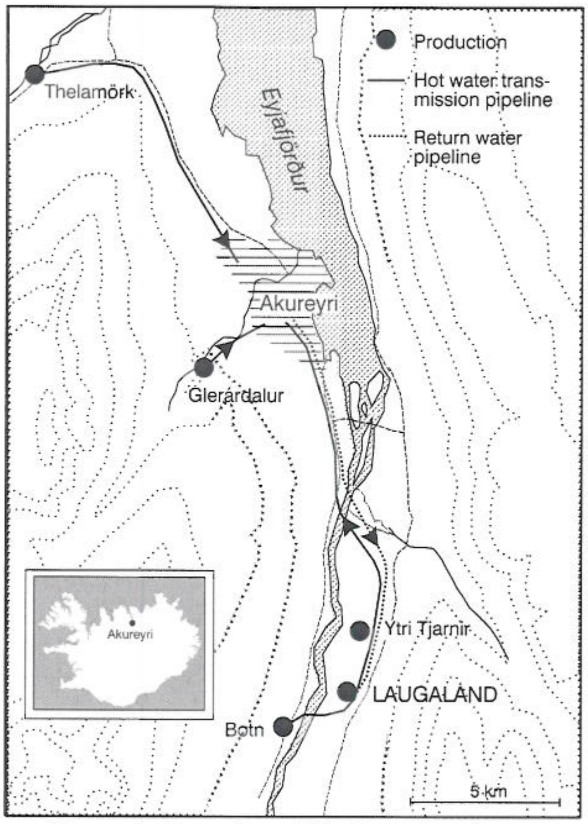

Figure 1: Location of the Laugaland area.

to a great pressure drawdown. It continues to increase with time if constant rate production is maintained. This forced the production from the field to be reduced by about 50% in the early eighties. 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 basalts, 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.

The production- and water-level history of the Laugaland system is presented in Figure 3, showing the rapidly increasing draw-down the first few years, which reached about 400 m at the beginning of 1982. A drastic reduction in production reversed this trend, however.

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

The productivity of the Laugaland geothermal system is limited by a low permeability and limited recharge. Most of the thermal energy in the geothermal system, however, is still stored in the 90-100 °C hot reservoir rock-matrix. More water is in fact needed to recover some of that energy. Therefore, HVA has been planning long-term reinjection during the last several years. In 1996 the Thermie sub-program of the European Commissions Fourth Framework Programme for Research and Technological Development decided to support such an experiment. This is a cooperative 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. It is the first long-term reinjection project to be started in an Icelandic low-temperature area (Stefánsson et al., 1995).

This paper describes the Laugaland reinjection project, which will continue through the fall of 1999. Data collected during the first year of the project will be presented along with the results of some preliminary analysis. The following chapter describe briefly the current conceptual model of the field, as well as the results of a short injection experiment conducted at Laugaland in June 1991.

2. PREVIOUS WORK

Exploration of the Laugaland field started in the early 1970s and extensive sets of geological, geophysical, chemical and reservoir engineering data are available for the field. In addition to these data, production response monitoring has provided a continuous 17 year record of weekly production, pressure draw-down and water temperature, in addition to some chemical monitoring data (Axelsson et al., 1998).

These data are the basis of the current conceptual model of the system, which involves a near vertical SW-NE trending fracture-zone, 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 this area are either located very close to or they intersect this fracture-zone. In the natural state, prior to production, 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.

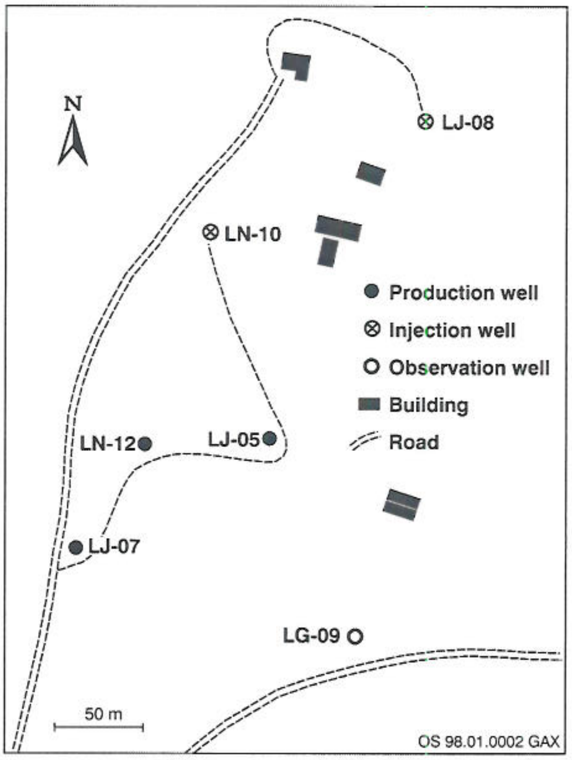

Figure 2: Wells in the Laugaland geothermal field

The reservoir engineering data have been analyzed to derive the reservoir characteristics of the Laugaland geothermal system. This includes lumped parameter modeling which has been used to simulate the pressure draw-down history of the geothermal system (Axelsson et al., 1988; Axelsson, 1989). The average permeability of the system is only of the order of a few mD and the reservoir volume is of the order of a few km^3. A distributed parameter model has, so far, not been developed for the Laugaland geothermal system.

A small scale injection experiment was carried out at Laugaland in the spring of 1991, described by Axelsson et al. (1993, 1995 and 1998). It lasted about 5½ weeks and involved wells LJ-8 and LJ-5. In addition to monitoring of the water-level in observation wells, and the production temperature of well

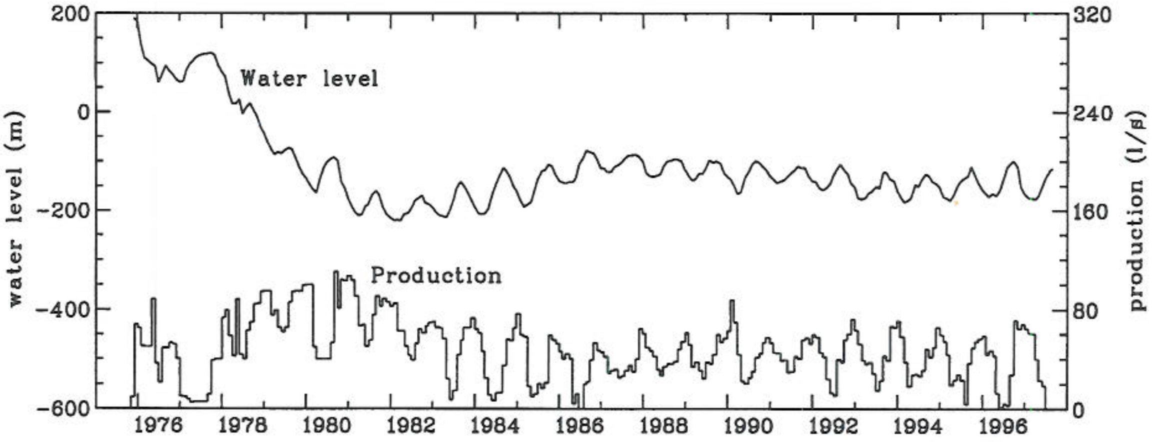

Figure 3: Production history of the Laugaland field

LJ-5, a tracer test was conducted to investigate the connection between the injection- and production wells. Two different tracers were employed, sodium-fluorescein and sodium-bromide. In the 1991 experiment the tracer-return was very slow, which was 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. The models commonly used to interpret tracer test data from Icelandic geothermal systems are discussed by Axelsson et al. (1995 and 1998). The water level data, on the other hand, indicated that the reduced draw-down because of the injection should allow a considerable increase in production.

The simple model used to interpret the tracer test data was consequently used to predict the outcome of long-term (20 yr.) injection. It should be kept in mind, however, that these predictions are inaccurate due to the short duration of the 1991 experiment and the simplicity of the model. The principal results, for a case of continuous 10 kg/s injection of 15 °C return- or ground-water into well LJ-8 and 48 kg/s average production from two of the production wells, were a 5°C decline in the temperature of water produced in 20 yrs, yet a integrated increase in energy production for this 20 year period of about 400 GWh. This can be compared to the annual energy production of HVA, which during the last few years has been on the order of 240 GWh.

3. 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, is more costly, since it requires the 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 to 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 includes the following phases:

1. Manufacture and installation of a 13 km return water pipeline from Akureyri to Laugaland (see Figure 1). A 150 mm, buried, uninsulated high-density polyetylene plastic pipe is used to minimize the installation cost.
2. Installation of high pressure pumps at the two proposed injection wells, LJ-8 and LN-10, as well as pumps in Akureyri for pumping the water to Laugaland. Installation of a computerized control- and monitoring system.
3. Installation of a network of six ultra sensitive, automatic, seismic monitoring stations around Laugaland (see Figure 1). This network should locate all micro-earthquakes of magnitude $M_L \geq -1$, which may be induced by the injection, in particular during periods when the reinjection will be carried out at well-head pressures between 20 and 30 bar. Thus some information on the locations of the fractures involved will hopefully be obtained (Slunga et al., 1995).
4. Continuous reinjection for a period of two years, along with careful monitoring of the reservoirs response to the injection. Also monitoring of any associated seismic activity. Injection of chemical tracers to study the connections between injection- and production wells.
5. Analysis of data collected, development of a numerical model for the geothermal system and predictions of the response of the three production wells to long-term reinjection. Determine the most efficient and economical mode of utilizing the Laugaland geothermal system. Estimation of the overall feasibility of reinjection in fractured low-temperature geothermal reservoirs.
6. Dissemination of the results in a final report and at a workshop at the conclusion of the project.

The total project cost is estimated at 1.8 million ECU. The Thermie sub-program of the Programme of Research and Development of the European Commission supports the project by a 0.64 million ECU contribution. At the end of October 1997 the first three phases had been completed according to schedule. The fourth phase started in September 1997 and is expected to continue until the end of July 1999. Work on the fifth phase has started with some preliminary data analysis and modeling.

The following are the principal participants in the project:

HVA, the Akureyri District Heating Service, is the project coordinator. HVA was responsible for installation of the return water pipeline and the pumps used, controls the reinjection as well as being responsible for monitoring the geothermal systems response to the injection.
Orkustofnun, the National Energy Authority of Iceland, is responsible for the scientific part of the experiment, as well as analysis of the data collected and consequent modeling. Orkustofnun has also planned the reinjection and monitoring in cooperation with HVA.
Uppsala University in Sweden was responsible for installing the seismic network, and is responsible for its operation (in cooperation with Orkustofnun, the Icelandic Meteorological Office and HVA) as well as for analyzing any micro-earthquake data collected.
Hochest Danmark A/S produced the return water pipeline in cooperation with an Icelandic sub-contractor, Set hf.
Icelandic State Electricity, or Rarik, provides the pumps used for the reinjection as well as the electrical power for operating the pumps.

In addition several companies and institutions have been involved in the project as subcontractors or suppliers.

4. PRELIMINARY RESULTS

Reinjection started on the 8th of September 1997. Until the 28th of January 1998 about 8 kg/s were injected continuously into well LJ-8. Since that time about 6 l/s have also been injected into well LN-10, raising the combined injection rate to 14 l/s as shown in Figure 4. Stable injection rates have been maintained, except for brief periods when the reinjection has been varied or discontinued. A total of 320,000 tons had been injected in early August 1998. The temperature of the injected water has been in the range of 6-21 °C, while the temperature drop in the 13 km return water pipeline has been of the order of 5 °C.

Figure 5 shows daily average hot water production from the Laugaland field during the first year of the

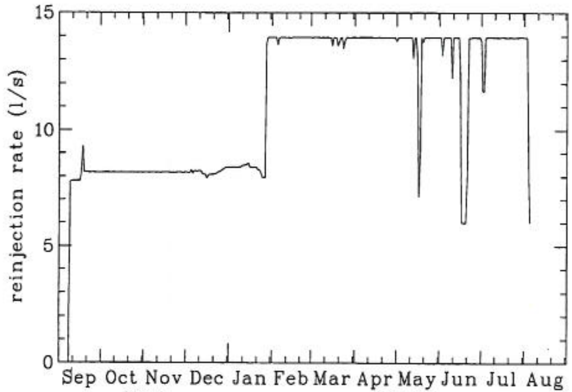

Figure 4: Daily average reinjection into wells LJ-8 and LN-10 during the first year of the project

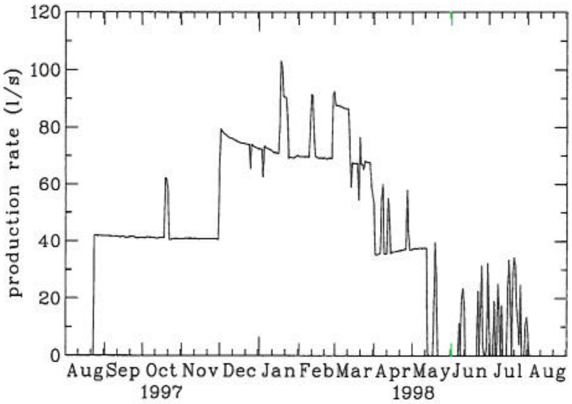

Figure 5: Daily average production from wells LJ-5, LJ-7 and LN-12 at Laugaland during the first year of the project

project. About two weeks prior to the start-up of the reinjection, production from one of the production wells, LN-12, was initiated after a summer break. This was done to create semi-stable pressure conditions in the reservoir when reinjection would start. During the period from the end of August until the end of November 1997, LN-12 was the only production well in use in the area. Therefore, this period provides a good opportunity for studying the effects of reinjection into well LJ-8. During last winter the production was more variable, because of greater hot water demand (Figure 5). From December through March two wells were continuously on line, either wells LN-12 and LJ-5 or wells LJ-5 and LJ-7. Intermittent production from well LJ-5 was also required during the following summer, because of unusually cold weather. Interpretation of data collected during the summer will, therefore, be more difficult. A total of 1,250,000 tons were produced from the field from late August 1997 until the beginning of August 1998. The reinjection during the same period equals about 26% of the total production.

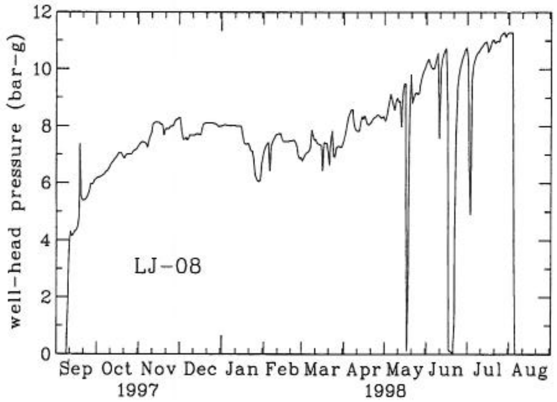

Figure 6: Well-head pressure of well LJ-8 during the first year of the project

Figure 6 shows the well-head pressure of injection well LJ-8, which slowly increased to about 8 bar-g at the end of November 1997. Before the injection started the water-level in the well was at a depth of 126 m. Until the end of March 1998 the well-head pressure did not increase, because of increased production from the field. The last several months the pressure has been rising again, in phase with rising reservoir pressure (water level), having reached slightly more than 11 bar-g at the beginning of August. The well head pressure of LJ-8 has been somewhat greater than anticipated on the basis of the 1991 test. This is the result of much colder water being injected presently than in 1991, i.e. 6-21 °C instead of 80 °C, resulting in a viscosity contrast of about 3.5. The first few months the well-head pressure also increased steadily, even though the reservoir pressure was relatively stable (see later). The cause for this has not been resolved, but it may also be the viscosity contrast between injection- and reservoir fluid, as well as thermal effects in the reservoir around well LJ-8. It should be noted that some of the variations in the well-head pressure of well LJ-8 are simply caused by variations in the temperature of the injected water.

Well LN-10 responds quite differently to injection than well LJ-8. In a couple of days, after injection into the well started, the water level in the well rose by about 100 m. Since then the water level in the well has changed very slowly, from a depth of about 10 m in the beginning of February to a well-head pressure of about 2 bar-g in the beginning of August. The injectivity of well LN-10, therefore, appears to be about 30% greater than the injectivity of well LJ-8. A steady increase in water level/pressure for the first months after injection is started, such as observed for well LJ-8, is not seen in well LN-10.

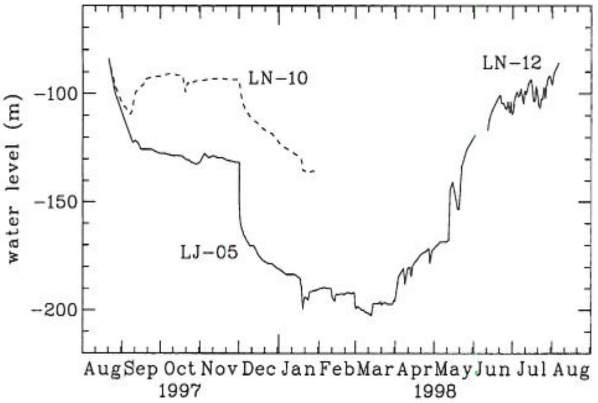

Figure 7: Water-level changes in three wells at Laugaland during the first year of the project

4.1 Water level changes

Figure 7 shows the water-level changes observed in three wells in the Laugaland field during the first year of the injection project. These are well LN-10, which is situated about halfway between the production wells and well

LJ-8 (Figure 2), and production wells LJ-5 and LN-12. The water level in LN-10 is presented for the period while the well was used as an observation well, prior to it becoming an injection well. The water-level measuring device in well LJ-5 broke down at the end of May 1998. At about the same time water level monitoring became possible in well LN-12, when the pump in the well was removed for maintenance. The water level is also monitored in one additional observation well in the Laugaland field, well LG-9, as well as in several observation- and production wells as far as 2 km away from Laugaland. These data are not presented here.

The effects of the start-up of the reinjection in early September 1997 can clearly be seen in the figure. The water-level in LN-10 rises by about 15 m, but stabilizes in LJ-5 after being declining rapidly due to production from well LN-12. It should be noted that wells LJ-5 and LN-12 are directly connected, through the same fracture zone, while well LN-10 does not intersect that zone. Other changes in water level are the results of changes in production, such as the rapid decline in early December 1997, which is the result of well LJ-5 being added on line, and the rapid rise in May 1998, which is the result of production from the Laugaland wells being discontinued for the summer.

These data will be modeled and analyzed carefully in order to extract information on the effect of reinjection into wells LJ-8 and LN-10, on the water level in the production wells. A reduced water level draw-down is anticipated as the main benefit from reinjection. Preliminary analysis, mainly based on the water level changes in September 1997, indicates that the injection of 8 l/s into well LJ-8 caused comparable water level changes in production well LJ-5 as a 5.4 l/s reduction in production. This indicates that about 2/3 of the injection into well LJ-8 will potentially enable an increase in production, on the time scale under consideration (about 1 month). The long-term effect is expected to be somewhat greater. This is only a preliminary result, however, which needs to be studied more carefully with specific tests aimed at extracting this information and modeling.

4.2 Step-rate injection tests

Figure 8 shows the results of three step-rate injection tests conducted in wells LJ-8 and LN-10. The purpose of these tests is 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 to determine whether any changes had occurred in the well, such as due to deposition in the feed-zone fractures. This has obviously not occurred in well LJ-8 (Figure 8).

According to the results of the step-rate tests the injectivity of well LN-10 is considerably greater than that of well LJ-8, agreeing with an earlier conclusion. The turbulence pressure losses appear to be comparable in these two wells, however, or of the order of 0.02 bar/(l/s)^2. This equals 0.5 bar at an injection rate of 5 l/s, 2.0 bar at a rate of 10 l/s and 4.5 bar at a rate of 15 l/s. Production testing of well LJ-8 at the end of drilling indicated turbulence losses on the order of 0.1 bar/(l/s)^2 (Thorsteinsson, personal information). The fact that turbulence losses appear to be half an order of magnitude less during cold water injection than during production may be the result of thermal contraction of the rock around the feed-zones of the well, which causes the feed-zone fractures to widen. It should be kept in mind, however, that the production test took place about 22 years ago.

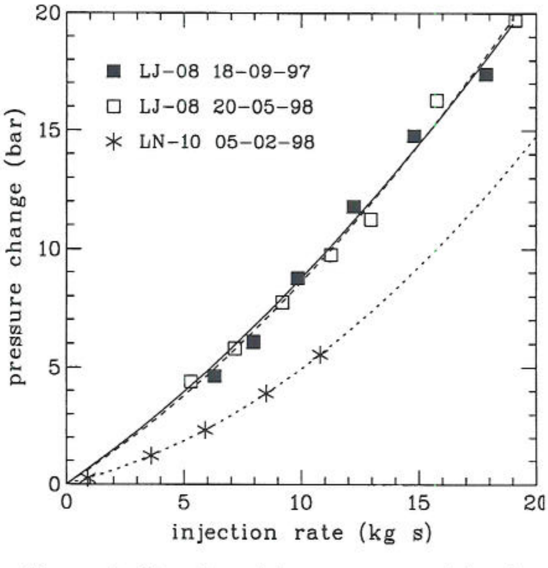

Figure 8: Results of three step-rate injection tests conducted in wells LJ-8 and LN-10

4.3 Analysis of temperature logs

Figure 9 shows two temperature logs measured in well LJ-8. One measured before injection started, representing the undisturbed temperature conditions of the well and the other measured after 70 days of reinjection. 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. These logs are not presented here, since 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.

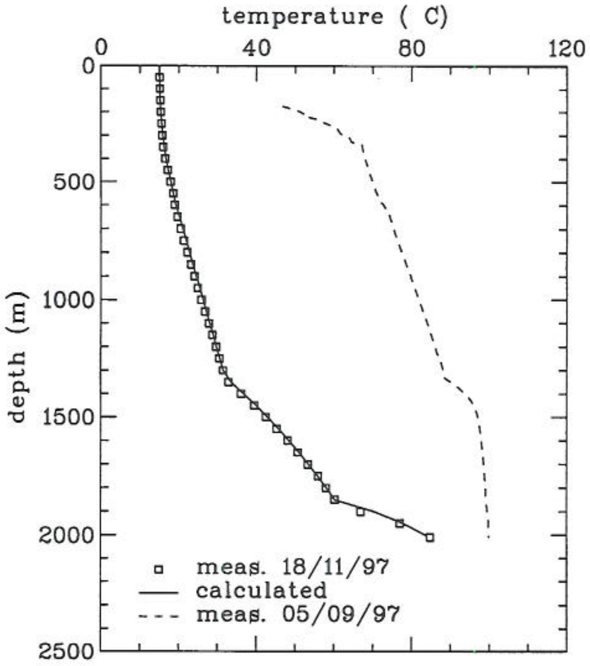

Figure 9: Two temperature logs from well LJ-8, measured prior to and during reinjection; also shown is a simulation of the second log by a wellbore simulator

The temperature log measured during injection into well LJ-8 clearly shows that the injected water exits the well at several 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 the following equation, which equates the flow of energy into the cooled well, by heat conduction, with the energy required to heat the injected water as observed.

$$q c_w \frac{dT}{dz} = 4k\pi (T - T_r)[\ln[\frac{4kt}{\rho_r c_r r_w^2}] - 1.154]^{-1} \qquad (1)$$

Here q = Flow-rate in the well at depth z;
T = Temperature in the well at that depth;
T_r = The undisturbed reservoir temperature given by the log measured prior to injection;
c_w, c_r = Heat capacities of water and rock, respectively;
k = Heat conductivity of the rock,;
ρ_r = The rock's density; and
r_w = Radius of the well.

The temperature log was interpreted (simulated) with the aid of a wellbore simulator (Björnsson, 1987). The results are presented in Table 2.

Table 2: Results of a simulation of a temperature profile measured during 8 l/s injection into well LJ-8

Exit point depth (m)	**Flow rate (l/s)**
380	3.5
600	1.2
1330	2.7
1850	0.7
below 2000	0.1

The main exit points appear to be at depths of around 380 and 1330 m. Slightly less than half of the injected water appears 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 380 m depth is not expected to fully do so.

It should be mentioned that the above estimates are believed to be as reliable as flow measurements done with spinner tools, which may be rather inaccurate at such low flow rates. A televiewer log is available for well LJ-8, which has not been fully analyzed. It indicates, however, that the exit-point at around 600 m is a narrow fracture, striking N-S and dipping to the east, while the exit-point at 1330 m looks more like an inter-bed.

4.4 Tracer tests

Two tracer tests have been carried out between wells at Laugaland, during the first year of the reinjection project. The purpose of these tests has been 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 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 10. At that time pumping from well LJ-5 started, and the previously stable conditions were disturbed. Yet, the fluorescein recovery is still being monitored. During the period from the beginning of December 1997 till the beginning of May 1998, when LJ-5 was on-line, fluorescein was recovered at an almost constant concentration of 3.3 ppb in that well. The concentration in well LN-12 dropped to about 0.5 ppb during the same period.

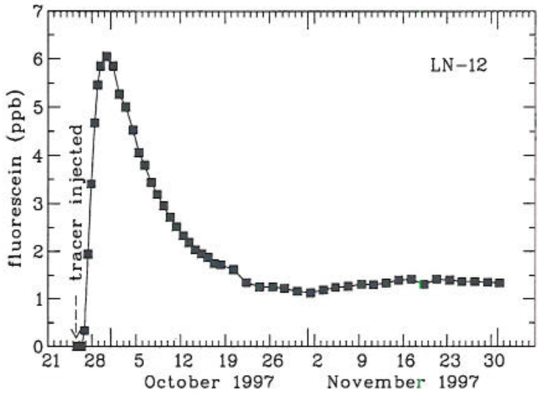

Figure 10: Observed fluorescein recovery in well LN-12 during injection into well LJ-8

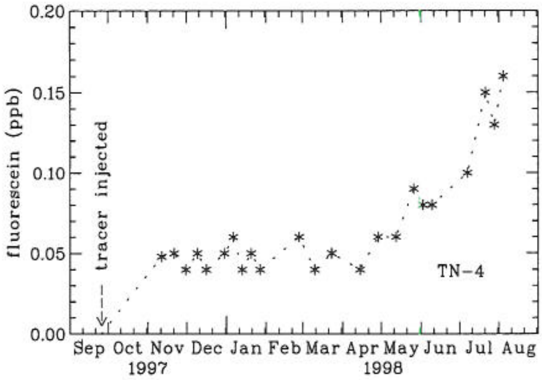

Figure 11: Observed fluorescein recovery in well TN-4 1800m north of Laugaland

Other geothermal production wells in the Eyjafjördur-valley, outside Laugaland, have also been monitored for tracer recovery (see Figure 1). As shown in Figure 11 some fluorescein has been recovered in production well TN-4 in the Ytri-Tjarnir field about 1800 m north of well LJ-8. This indicates a rather direct connection between these two fields. An increase in the concentration during last summer is most likely a result of increased reservoir pressure at Laugaland (Figure 7). No tracer has been recovered in production wells in the western half of the Eyjafjördur-valley.

The second tracer test started on February 19th 1998 when 45.3 kg of potassium-iodide were injected into well LN-10. At that time both of wells LJ-5 and LN-12 were on line. Figure 12 shows the iodide recovery in well LJ-5 for the next 80 days, or until production was discontinued in the spring. Conditions in the reservoir were not as stable during this tracer test as during the previous one. Hot water production was more variable (Figure 5) and until late March either one of wells LN-12 or LJ-7 was also on line. Analysis of the results of this test will therefore be more difficult. Iodide was recovered in neither well LN-12 nor well LJ-7.

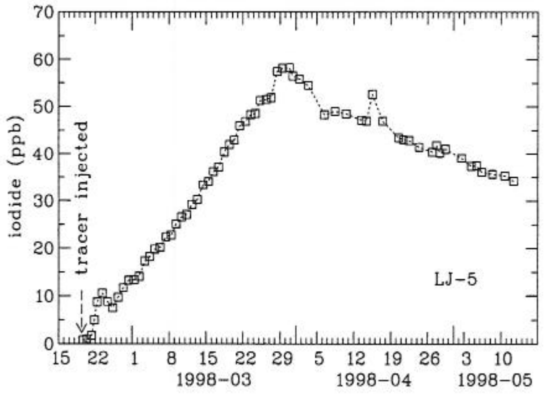

Figure 12: Observed iodine recovery in well LJ-5 during injection into well LN-10

A preliminary analysis of the data presented in Figure 10 has been carried out and will be discussed briefly in the following. The data from both tracer tests awaits further analysis, however. Yet some conceptual results are available at this time. Even though the tracer breakthrough-times were relatively short, or only of the order of 24 - 48 hrs for the two tests, the tracer recovery has been very slow. Until early May about 1.5 and 0.6 kg of fluorescein had been recovered through wells LJ-5 and LN-12, respectively. This amounts to 21%, of the tracer injected initially, in about 7½ months. At the same time about 9.7 kg of iodide had been recovered through well LJ-5, or about 28% in 2½ 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. Therefore, most of the injected water appears to diffuse through a very large volume of the reservoir.

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.

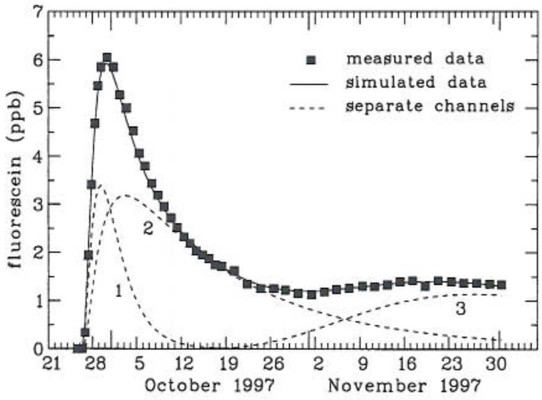

Figure 13: Observed and simulated fluorescein recovery in well LN-12 during injection into well LJ-8

The data in Figure 10 have been analyzed 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. 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 results presented in Figure 13. The properties of the channels are presented in Table 3. It should be kept in mind, however, that these are only preliminary results.

Table 3: Model parameters used to simulate fluorescein recovery for the well pair LJ-8/LN-12 at Laugaland

Channel length (m)	**u (m/s)**	**$A\phi$ (m^2)**	**α_L (m)**	**M_i/M**
300	7.8×10^{-4}	0.083	54	0.0077
400	3.8×10^{-4}	0.67	199	0.0303
1000	1.7×10^{-4}	1.17	66	0.0241
Total				**0.0621**

u = Mean flow velocity in flow channel; A = The cross-sectional area of flow channel;
ϕ = Porosity of the flow channel; α_L = Longitudinal dispersivity of flow-channel;
M_i = Calculated mass recovery of tracer through the flow channel, until infinite time;
M = Total mass of tracer injected.

The results in Table 3 indicate that only about 6% of the injected water travels through these channels from injection- to production well. Most of the injected water, therefore, appears to diffuse throughout the reservoir volume. The volumes of the channels also appears to be quite small. If one assumes an average porosity of 7% the sum of the volumes of the three channels equals only 20,000 m^3.

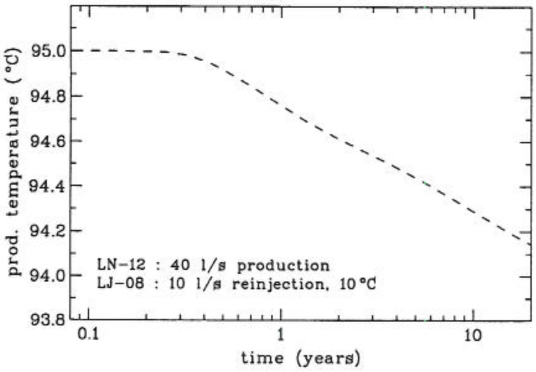

Figure 14: Estimated decline in the temperature of well LN-12 during injection into well LJ-8, due to flow through the three channels simulated in Figure 13

The results in Table 3 were 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 14. It should be emphasized again that these are only preliminary results. The injected water, which does not travel through these channels, may also cool the production well 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.

The constant tracer recovery in well LJ-5 during the first tracer test may be used to estimate a volume of mixing and consequently a thermal breakthrough time for injection into well LJ-8 and production from LJ-5. This approach assumes that a porous volume is involved, rather than different flow channels such as before. The results indicate a breakthrough time of about 80 years. Therefore, the tracer test results indicate that an untimely thermal breakthrough or a rapid production temperature decline are not to be expected in production wells in the Laugaland field during reinjection, in particular during injection into well LJ-8.

4.5 Micro-earthquake activity

Finally it should be mentioned that no micro-earthquakes have been recorded during the first year of the reinjection project. The highest well-head pressure achieved has been around 11 bar-g, but during a later stage of the project well-head pressures of up to 30 bar-g are expected. Micro-earthquakes are more likely to occur at such pressures.

5. CONCLUDING REMARKS

During the first year the progress of the Laugaland reinjection project has been mostly according to schedule. Work on the main phase, actual reinjection, which started in early September 1997, will continue until the end of July 1999. During the fall of 1998 injection into well LJ-8 will continue at a maximum rate such that a well-head pressure of up to 30 bar-g will be achieved. This stage will also involve a tracer test aimed at determining whether new flow channels open up at higher pressures. Consequently, the last half year of the reinjection experiment will be used for further testing. During the remainder of the project, until the fall of 1999, emphasis will be placed on data analysis and numerical model development, which currently has started to a limited extent, as well as on analysis of the economics of long-term reinjection.

Reinjection is practiced in many geothermal fields in the world, in most cases to dispose of waste water due to environmental reasons (Stefánsson, 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 practiced 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 utilized in Iceland. Preliminary results of the Laugaland reinjection experiment are positive, and indicate that reinjection will be a highly economical mode of increasing the production potential of the Laugaland system. The current reinjection system will, therefore, hopefully 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.

ACKNOWLEDGEMENTS

The authors thank the numerous project participants, which are not mentioned in the paper, for their cooperation and the European Commission for its support. The authors also thank Mr. Ómar Sigurdsson at Orkustofnun for critically reviewing the paper.

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