PROCEEDINGS, Twenty-Third Workshop on Geothermal Reservoir Engineering
Stanford University. Stanford. California, January 26-28. 1998
SGP-TR-158

LONG-TERM REINJECTION PROJECT IN THE LAUGALAND LOW-TEMPERATURE AREA 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 tow-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. About 8 kg/s are currently injected and the response of the geothermal system to the reinjection is monitored carefully. The first tracer-test has also been completed. Furthermore, the project involves monitoring of any associated micro-seismic activity. The Laugaland reinjection project will continue for the next 2 years. Preliminary results indicate that reinjection will henceforth be an important part of the management of the geothermal reservoir

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 the 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 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.

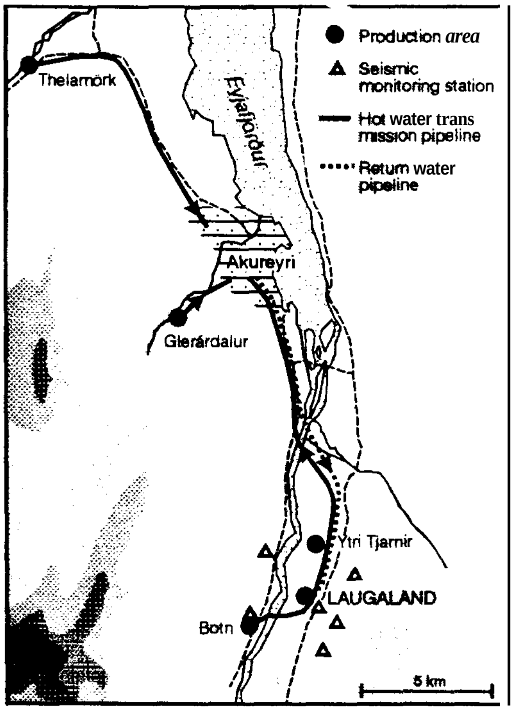

Figure **1.** *Location of the Laugaland area.*

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 location is shown in Figure 2.

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

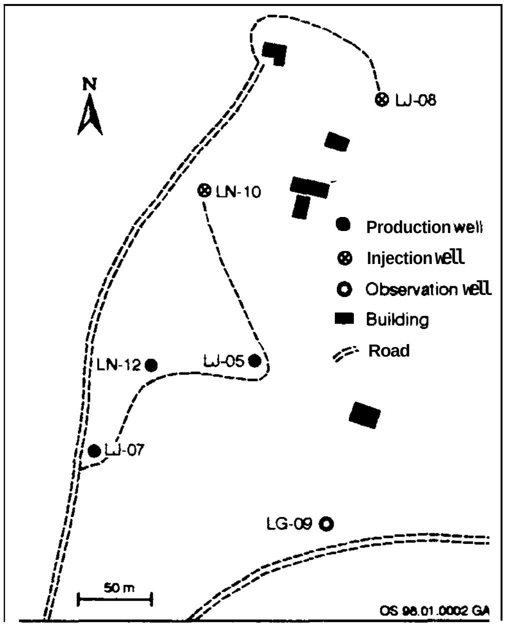

Figure 2. *Wells in the Luugaland geothermal field.*

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 38 bars at the beginning of 1982. A drastic reduction in production reversed this trend, however.

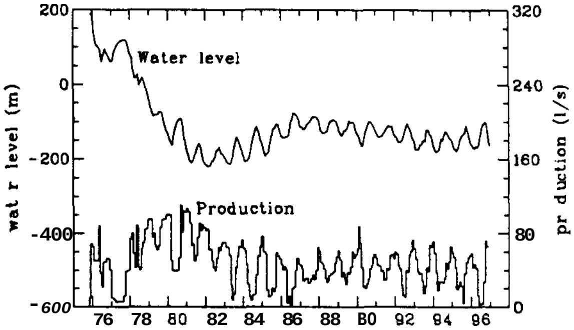

Figure 3. *Production history of the Laugaland field.*

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 is expected to continue for the next 2 years. Data collected during the first few months of the project will be presented along with some preliminary results. Analysis, or modeling of the data has not started, however. The next two chapters 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.

THE LAUGALAND CONCEPTUAL MODEL

A quite extensive set of reservoir engineering data, from the Laugaland field, is available. This includes some short-term well test data as well as other hydrological test data. But production response monitoring provides the most important data available. This is a 16 year record of weekly production, pressure draw-down and water temperature, in addition to some chemical monitoring data (Axelsson et al., 1997).

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. Other wells are virtually non-productive. In the natural state, prior to production, convection in these recent 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.

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 (Axeisson 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.

THE 1991 INJECTION TEST

A small scale injection experiment was carried out at Laugaland in the spring of 1991 (Axelsson et al., 1993; Axelsson et al., 1995). During the experiment, 80 "C water from a near-by geothermal field was injected into well LJ-8. At first 8 kg/s were injected with only a minor well-head pressure, later the injection rate was reduced to 4 kg/s. This experiment lasted for 5% weeks. During the experiment 38 kg/s of 95 "C water were produced from well LJ-5, which is 250 m away from well LJ-8. Concurrently the water-level in nearby wells was monitored carefully. The water-level rose almost instantaneously in response to the injection and it appears that the reduced draw-down will allow an increase in production, approximately equaling the injection. No change in production temperature of well LJ-5 was observed during the experiment.

The connection between the injection- and production wells was investigated by adding chemical tracers to the injected fluid. Two different tracers were employed. Firstly, 1 kg of sodium-fluorescein was injected instantaneously into well W-8 at the beginning of the experiment. Secondly, sodium-bromide was released continuously into the injection water. During the experiment water samples where taken frequently from the production well and the tracer concentrations measured. In this experiment the return of tracers was very slow, and in fact only about 1.7 g of 1 kg of sodium-fluorescein were recovered during the 40 day experiment. The tracer breakthrough occurred after about 10 days. This is believed to indicate that the injected water diffused into a very large volume and that wells LJ-5 and LJ-8 are not directly connected. This is in contrast to most other tracer tests conducted in Iceland, where the tracer return has been fast and tracer breakthrough times have been of the order of one to three days (Axelsson et al., 1995).

Icelandic tracer test data have been analyzed by an one-dimensional fracture-zone model, where the tracer return is controlled by the distance between injection and production wells, a small fracture-zone volume and dispersion. The Laugaland data, on the other hand, were analyzed by a very simple lumped model, where the tracer return is controlled by mixing in a relatively large reservoir volume (2,300,000 m^3) and geometry and dispersion neglected (Axelsson et al., 1993). This model consists of two interconnected tanks. The first tank simulates the geothermal system next to the injection well and the second tank simulates the part of the geothermal system around the production well. In addition hot recharge is assumed into the second tank. In this model instantaneous mixing is assumed and the delay due to the finite travel time from injection well to production well is neglected, in contrast to conventional models.

This simple model was later used to predict the effects 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 10 kg/s injection into well LJ-8 and 48 kg/s production from two of the production wells, are presented in Figure 4. Firstly, the injection of approximately 15 "C return-. or ground-water is expected to cause a decline in the temperature of water produced from 95 "C tc about 90°C in 20 yrs. Secondly, the figure shows the predicted integrated energy production for this **20** year period, resulting from the injection, which may be expected to reach 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.

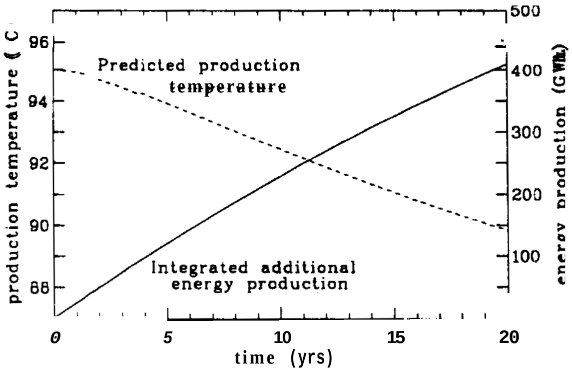

Figure 4. ***Estimated temperature decline and additional energy production during 10 kg/s long-term injection at Laugaland, based on the 1991 model.***

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 the 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 bars. 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. The most efficient and economical mode of utilizing the Laugaland geothermal system determined. 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 1.7 million USD. The so-called Thermie sub-program of the Programme of Research and Development of the European Commission supports the project by a 0.7 million USD contribution. At the end of 1997 the first three phases had been completed according to schedule and work on the fourth phase was under way. That phase is expected to continue until the end of July 1999.

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.

PRELIMINARY RESULTS

Actual reinjection started on the 8th of September 1997. Since that time about **8** kg/s have been injected into well LJ-8. The temperature of the injected water has been in the range of 15 - 20 "C, while the temperature drop in the 13 km return water pipeline has been of the order of ***5*** "C. About two weeks prior to that production had started from one of the production wells, LN-12, at a rate of about 38 kg/s, such that semi-stable pressure conditions had been achieved. 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. The following five figures show some of the data collected during this period. These data will be discussed briefly in the following, yet very limited analysis has been carried out so far.

Figure5 shows the well-head pressure of the injection well LJ-8, which slowly increased to about **8** bars-g at the end of November. Before the injection started the water-level in the well was at a depth of 126 m. The well head pressure 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. 15 - 20 "C instead of 80 "C, resulting in a viscosity-contrast of about **3.5.** The well-head pressure has also increased steadily, even though the reservoir pressure has been relatively stable (see later).

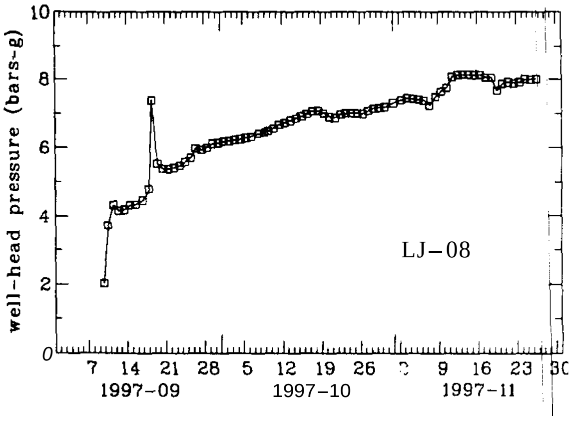

Figure 5. ***Well-head pressure during injection into well W-8.***

Figure 6 shows the results of a step-rate injection test conducted on September 18th. An almost linear relationship is evident, with some hysteresis superimposed on that. A linear relationship indicates that no turbulence pressure losses occur in, or next to, well LJ-8. This comes as a surprise since production testing of the well at the end of drilling indicated very significant turbulence losses.

Figure 7 shows the water-level changes observed in three wells in the Laugaland field until the end of November. These are well LN-IO, situated right in the center of the field, production well LJ-5 (not in use during this period) and observation well LC-9. The effects of the reinjection can clearly be seen in the figure. The water-level in LN-IO rises by about 15 m, but stabilizes in LJ-5 (and LG-9) 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.

On September 25th 10kg of sodium-fluorescein were injected instantaneously into well LJ-8 and consequently its recovery monitored accurately in well LN-12. The results are shown in Figure 8.

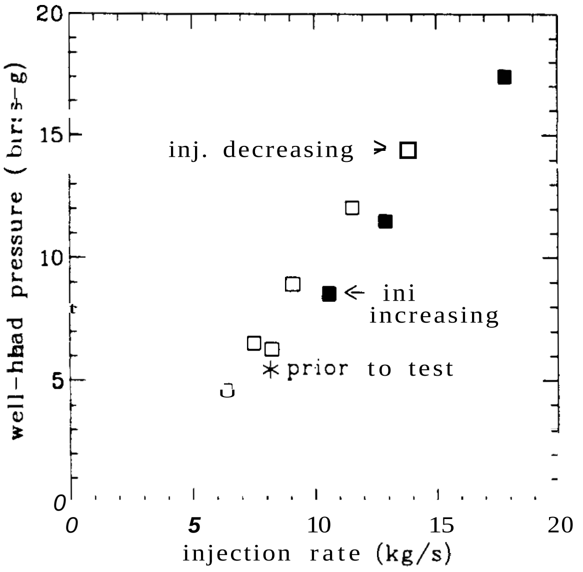

Figure 6. ***Results of step-rate injection into well W-8 on September 18th, 1997.***

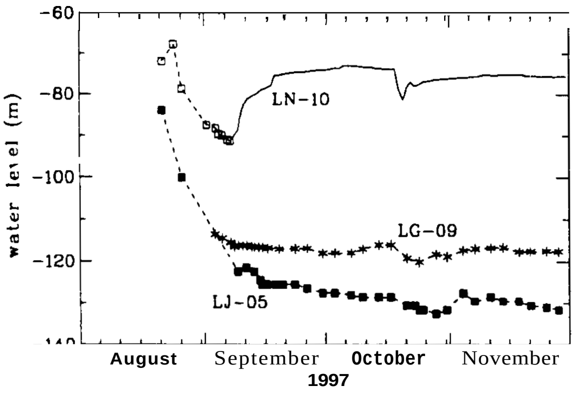

Figure 7. ***Water-level changes in three wells at Laugaland during the first three months of the project.***

In contrast to the 1991 test, when well LJ-5 was used, the tracer breakthrough-time was now only of the order of 24 - 30 hrs, instead of 10 days. Yet the mass of tracer recovered at the end of November amounted to less than ***5%*** of the mass injected. This indicates that the wells are directly connected through some minor fractures or inter-beds, but not through the major feed-zone of well LN-12. Therefore, most of the injected water appears to diffuse through a very large volume of the reservoir. This awaits further analysis, however. It should be mentioned also that some fluorescein has been recovered, at a concentration of about 0.05 ppb, in a production well in the Ytri-Tjarnir field (see Figure 1) about 1800 m north of well LJ-8. No tracer has been recovered, however, in production wells in the western half of the Eyjafjordur-valley.

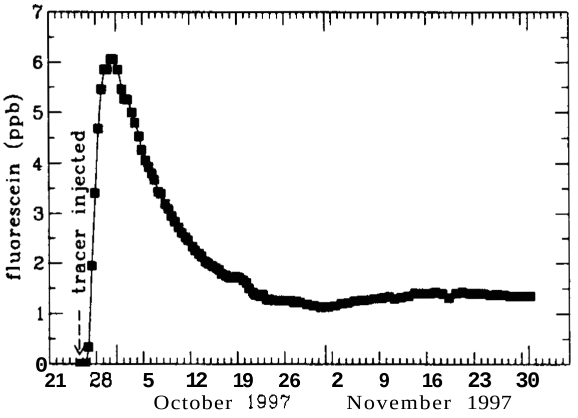

Figure 8. ***Observed fluorescein recovery in well LN-12 during injection into well W-8.***

Figure 9 shows two temperature logs measured in well LJ-8, before and during the injection. By comparing these two logs one can determine the exit-points of the injected water. The main exit points appear to be at depths near 320, 590 and 1330 m. A small part of the injected water appears to reach a depth of 1860 m. For comparison the main feed-zones of production wells LJ-5, LJ-7 and LN-12 are at depths of 1200, 1470 and 1600 m, respectively. A televiewer log available for well LJ-8 indicates that the exit-point at 590 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.

Finally it should be mentioned that no micro-earthquakes have been recorded so far during the project. The highest well-head pressure achieved has been around 8 bars-g, but during a later stage of the project well-head pressures of up to 30 bars-g are expected. Micro-earthquakes are more likely to occur at such pressures.

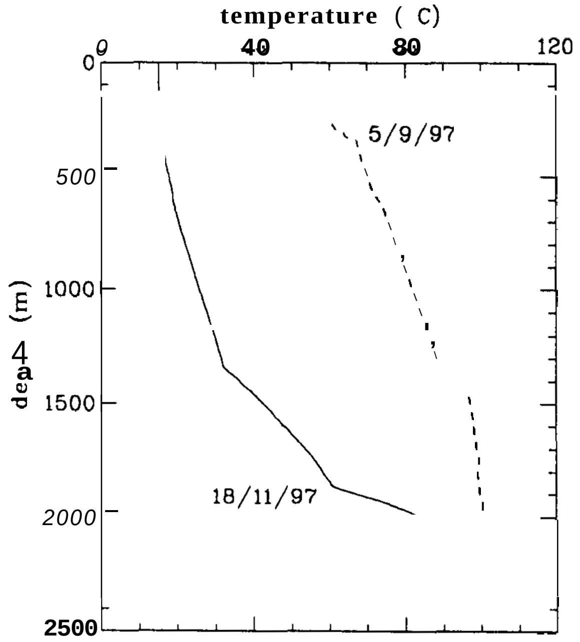

Figure 9. *Two temperature logs from well W-8, before and during reinjection.*

CONCLUDING REMARKS

So far the progress of the Laugaland reinjection project has been mostly according to schedule. Work on the main phase, the actual reinjection, which started in early September 1997, will continue until the end of July 1999. The following will be the main highlights:

- Reinjection into well LN-10, which is considerably closer to the production wells than well LJ-8 (see Figure 1), will start at the end of January 1998 at a rate of approximately 8 kg/s. A tracer test will be conducted concurrent with that. Two production wells, LJ-5 and LN-12, will most likely be in use during this stage, which will probably last until April 1998.
- The step-rate injection test of well LJ-8 will be repeated to determine whether any changes have occurred in the well, such as due to deposition in the exit-point fractures. Well LN-10 will also be step-rate tested.
- 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 bars-g will be achieved. This stage will also involve a tracer test.

encourage other operators of fractured low-temperature geothermal systems to consider injection as a management option.

ACKNOWLEDGEMENTS

participants
paper, for thei
Commission for it
also thank Mr. Grímu
for critically reviewing th

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