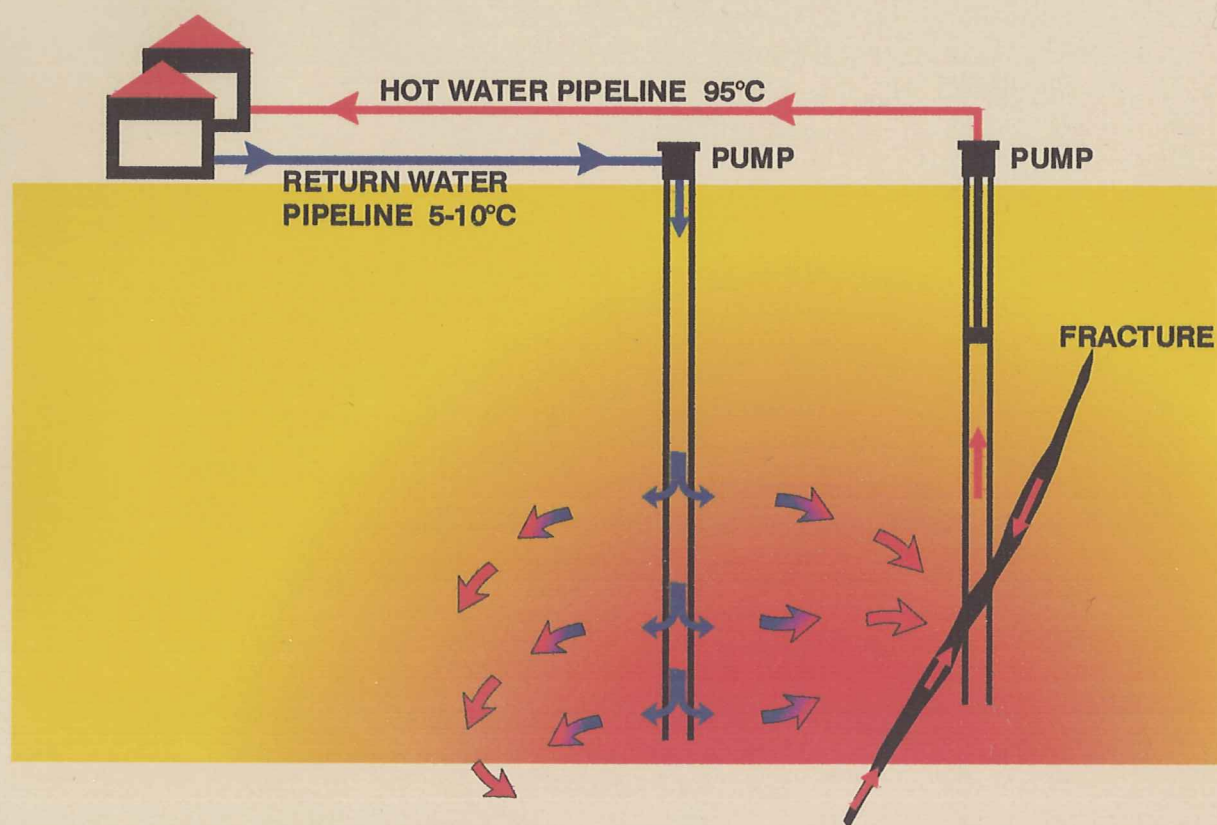


DEMONSTRATION OF IMPROVED ENERGY EXTRACTION FROM A FRACTURED GEOHERMAL RESERVOIR

Mid-Term Report for Thermie Project GE-0060/96



Hita- og Vatnsveita Akureyrar, HVA
Orkustofnun, National Energy Authority
Uppsala University
Hoechst Danmark A/S
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SUMMARY

The Thermie demonstration project in the Laugaland geothermal system in N-Iceland, which involves long-term reinjection with the purpose of improved energy extraction, is now at mid-term. It is 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.

The design phase of the demonstration project at Laugaland lasted from September 1996 through July 1997. It involved design of the return water pipeline, injection pumps, automatic monitoring- and control system and the seismic monitoring network, as well as logging of the injection wells. The manufacturing phase started in November 1996 by production and construction of the return water pipeline, followed by modification of existing seismic software and manufacture of monitoring equipment, injection pumps and seismic equipment. This phase lasted until the end of September 1997. The assembly and installation phase lasted from June through September 1997. It involved assembly and installation of the monitoring- and control system, the injection pumps and the seismic network. The commissioning phase of the project took place in August and September 1997, by start-up of the seismic network and reservoir monitoring. This was followed by the start-up of the re-injection on the 8th of September. The monitoring phase of the project started on the 1st of October 1997.

The progress of the project has been mostly in line with the time- and cost schedule of the corresponding contract and no major deviations have occurred yet. In early August 1998 about 320,000 m³ of geothermal return water had been reinjected, or about 11 l/s on the average. This may be compared to the production from the field, which during the same period has amounted to 1,250,000 m³, or about 43 l/s on the average. A comprehensive monitoring program has been implemented as part of the reinjection project. This involves monitoring of production- and injection rates, water temperatures, well-head pressures and water-levels by an automatic monitoring system. Also included are a number of tracer-tests, monitoring of associated micro-seismic activity, step-rate injection tests and temperature logging of the injection wells before and during injection. The reinjection experiment will continue through the year 1999, and later phases of the project will include detailed data analysis and numerical model development.

Preliminary results of the Laugaland reinjection project are positive. On the one hand, tracer test results show that an untimely thermal breakthrough is not to be expected in production wells in the field during long-term reinjection. On the other hand, results regarding the exact water level recovery that will be achieved, are rather inconclusive. But the available results indicate that hot water production from the field may be increased significantly by reinjection. The current reinjection system is, therefore, expected to be an important part of the management of the Laugaland reservoir for decades to come. Since the total project cost is estimated at only 1.8 million ECU and future operating and maintenance costs will be minimal, reinjection is expected to be a highly economical mode of increasing the production potential of the Laugaland system.

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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). Akureyri has a population of about 16.000 inhabitants. Since late 1977 the annual production from the field has varied between 0.9 and 2.5 million tons of 95°C hot water (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. Because of this, as well as the fact that most of the thermal energy in the geothermal system is still in-place in the 90 - 100°C hot reservoir rocks, reinjection has for long been considered a possible way to improve the productivity of the Laugaland system.

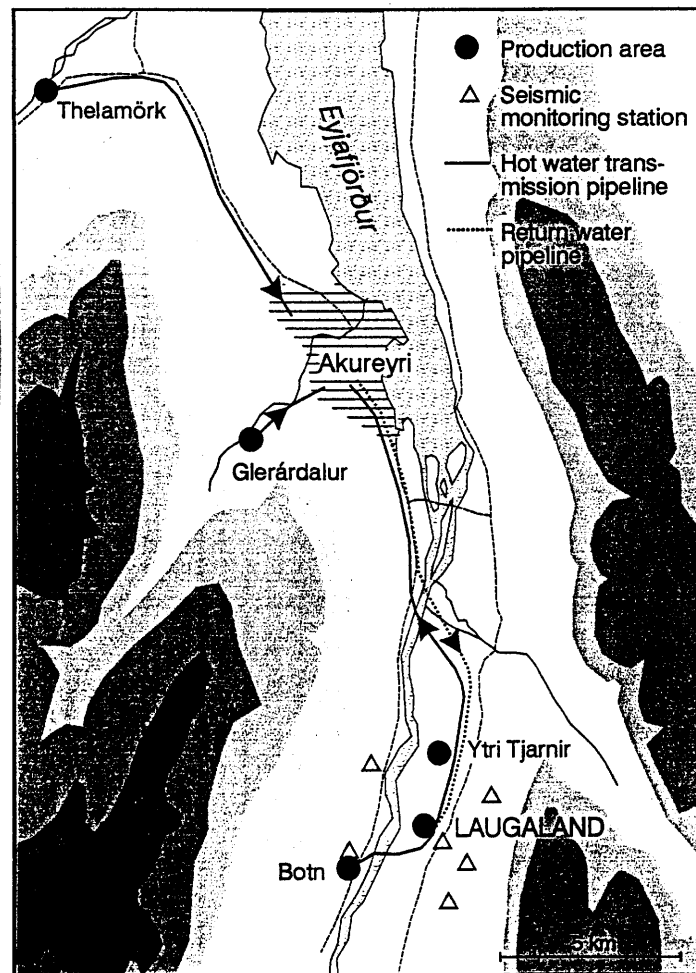


Figure 1. Location of the Laugaland area.

A demonstration project, involving long-term reinjection, is now underway in the Laugaland field supported by the Thermie sub-program of the European Commissions Fourth Framework Programme for Research and Technological Development, according

to contract GE-0060/96. This is a cooperative project involving companies and institutions in Iceland, Sweden and Denmark. The purpose of the reinjection project is to demonstrate that energy production from fractured low-temperature geothermal systems may be increased, in an economical way, by reinjection. Work on the project started in September 1996, following comprehensive design work carried out in the preproposal phase of the project. This report is a mid-term report issued after one year of monitoring, according to the project contract (Annex I). It describes the progress of the project until August 1998, presents data collected during the first half of the project as well as presenting some preliminary results. Detailed data analysis and modeling has only just started, however. The progress of the project has been mostly in line with the time- and cost schedule of the corresponding contract and no major deviations have occurred yet.

According to the contract the project is divided into phases of (1) design, (2) manufacture, (3) assembly/installation, (4) commissioning, (5) monitoring and (6) dissemination. These phases involve the following:

- A. Manufacture and installation of a 13 km return water pipeline from Akureyri to Laugaland (see Figure 1). A 150 mm, buried, uninsulated high-density polyethylene plastic pipe is used to minimize the installation cost.
- B. 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.
- C. 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).
- D. 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.
- E. 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.
- F. Dissemination of the results in a final report and at a workshop at the conclusion of the project.

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.

This report is organized as follows: A review of previous work and the present knowledge on the geothermal system at Laugaland (chapter 2) is followed by a description of the progress of the demonstration project. This is followed by a presentation of the data collected so far during the project as well as the results of some preliminary analysis (chapter 4). The report is concluded by a discussion of the planned continuation of the project as well as some concluding remarks.

2. PREVIOUS WORK

2.1 Utilization of the Laugaland system

The Laugaland geothermal system is a typical fracture controlled system, embedded in 6-10 My. old flood basalts, wherein the hot water flows along open fractures in otherwise low-permeability rocks. Eight deep 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)	Casing (m)	Use
LJ-05	1975	1305	96	Production well
LJ-07	1976	1945	930	Production well
LJ-08	1976	2820	196	Obs./injection well
LG-09	1977	1963	37	Observation well
LN-10	1977	1606	9	Obs./injection well
LN-12	1978	1612	294	Production well

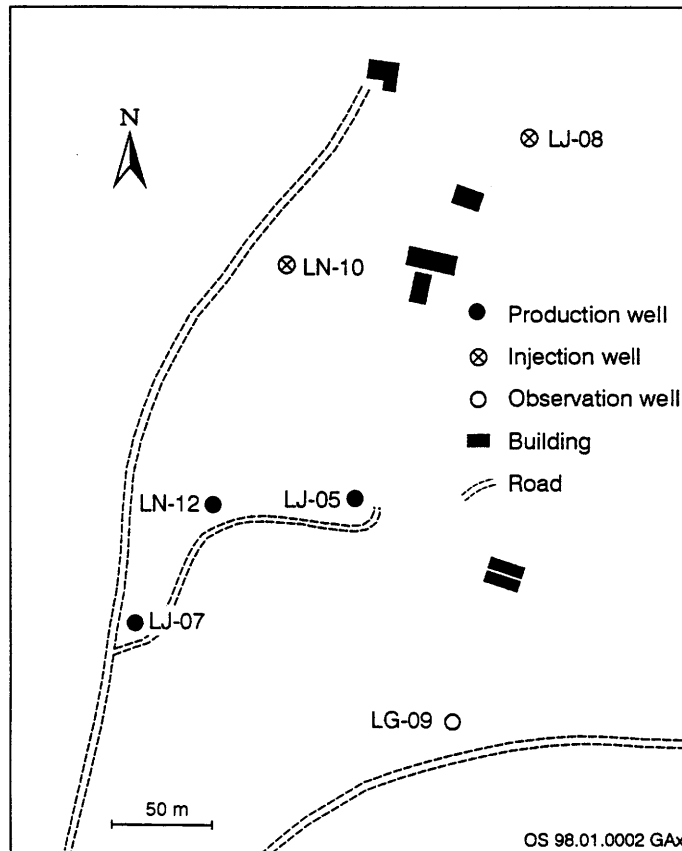


Figure 2. *Wells in the Laugaland geothermal field.*

The production- and water-level history of the Laugaland system is presented in Figure 3. The monthly average hot water production has varied between 0 and almost 120 l/s, and seasonal variations in energy demand can clearly be seen in the figure. Figure 3 also shows the rapidly increasing draw-down the first few years, which reached about 400 m at the beginning of 1982. The drastic reduction in production, in the early eighties, reversed this trend, however. During the period from 1984 through 1997 the average yearly production has been about 40 l/s, which the geothermal reservoir will apparently be able to sustain for the next one or two decades, at least (Flóvenz et al., 1995).

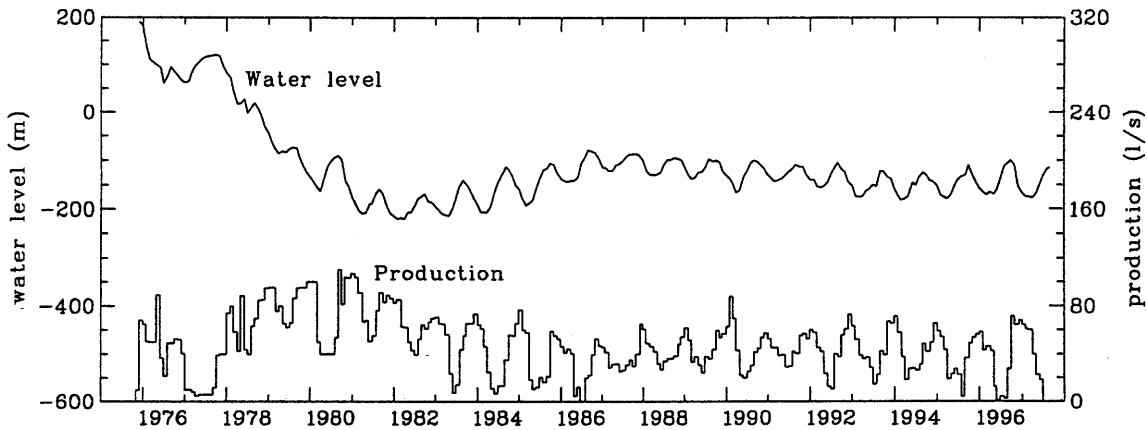


Figure 3. Production history of the Laugaland field.

While hot water production from the Laugaland geothermal system is limited by a low permeability, and limited recharge, most of the thermal energy in the system is still in-place in the 90 - 100 °C hot reservoir rocks. To recover more of that energy and increase production from the field, increased water recharge into the geothermal system is in fact needed. Therefore, HVA has been planning long-term reinjection during the last several years. The current project is the first long-term reinjection project to be started in an Icelandic low-temperature area (Stefánsson et al., 1995).

2.2 The Laugaland conceptual model

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 tectonic activity. 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 (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 km³. A distributed parameter model has, so far, not been developed for the Laugaland geothermal system.

2.3 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 5½ 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 appeared that the reduced draw-down would 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 LJ-8 at the beginning of the experiment. Secondly, sodium-bromide was released continuously into the injection water. During the experiment water samples were 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 was believed to indicate that the injected water diffused into a very large volume and that wells LJ-5 and LJ-8 were 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 m³) 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 to 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.

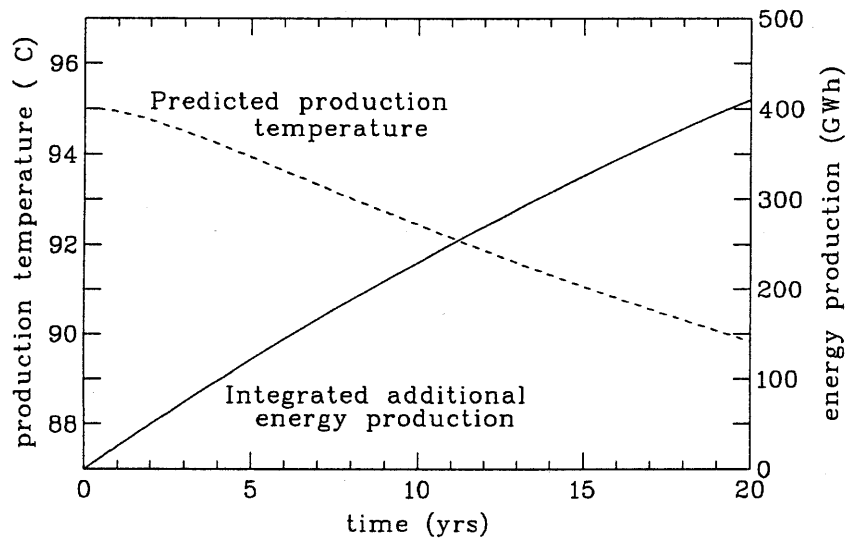


Figure 4. *Estimated temperature decline and additional energy production during 10 kg/s long-term injection at Laugaland, based on the 1991 model.*

The 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 the construction of a return water pipeline from Akureyri to Laugaland.

3. PROGRESS OF THE REINJECTION PROJECT

The structure of this chapter is based on the items described in the detailed breakdown of the project in table 21 of Annex I of the project contract, with some minor deviations. Work on the project started in September 1996 and the progress until early August 1998 is described. A progress diagram for the project is shown in Figure 5.

3.1 Design

3.1.1 Overall design of the project This part of the project was mostly finished during the preproposal phase. The overall design was reviewed in connection with the more detailed design of individual parts of the project, resulting in only minor changes from the original design. The overall design of the project is under constant re-evaluation during the progress of the project, however.

3.1.2 Logging The first logging phase was completed during the autumn of 1996 under the supervision of Orkustofnun. This included sonic-, resistivity- and borehole televiwer logging of the two re-injection wells as well as several other conventional logs.

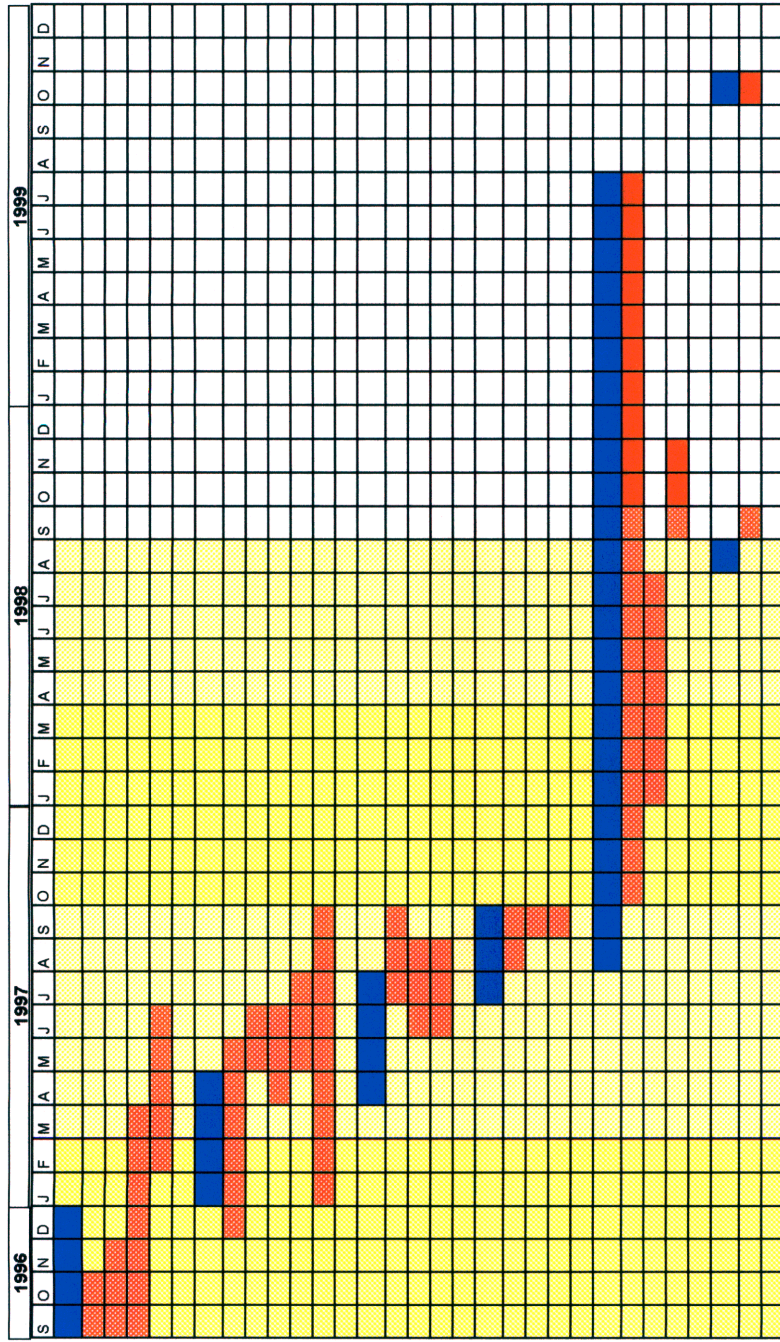
3.1.3 Pipeline design The general specifications for the return-water pipeline were available in October 1996 and its detailed design in November 1996. The design work was carried out by the technical department at HVA, with the assistance of consulting engineers.

3.1.4 Design of pumps The design of pumps for the re-injection system was completed at the end of February 1997. This was carried out by the technical department of HVA in co-operation with Orkustofnun, RARIK and consulting engineers.

3.1.5 Design of seismic monitoring system The design of the seismic monitoring system started in December 1996 and was finished by the end of June 1997. The design was the responsibility of the University of Uppsala in co-operation with Orkustofnun and HVA.

Field investigation of the Laugaland area, regarding selection of sites for the six seismic stations, was performed in January 1997. Good bedrock was found on hill-sides west and east of the river Eyjarfjardara, but the flat valley floor is covered by thick sediments, which cause unfavorable conditions for precise detection of high frequency seismic signals. The valley bottom was therefore avoided in site selections.

Genetic Algorithms were used to invert for the best location of the stations. The criteria used in the inversion was maximizing the variance of the: a) distances up to 3500 m, b) angles from the source to the stations, and c) the angles within quadrant modules. The results showed a very strong dependency on the exact location of the closest station. To find a suitable site for the closest station, noise tests were carried out in April 1997 to record the ground motion from pumps in the hot water production wells, which can produce large signals especially close to the resonance frequency of the pumps.



- Design:**
 - Logging
 - Pipeline
 - Pumps
 - Seismic monitoring system
- Manufacture:**
 - Pipeline construction
 - Monitoring equipment
 - Pumps
 - Seismic equipment
 - Modification of seismic software
- Assembly / Installation:**
 - Monitoring equipment
 - Pumps
 - Seismic installations
- Commissioning:**
 - Seismic network startup
 - Startup monitoring
 - Startup injection
- Monitoring:**
 - Seismic/chemical/res. monitoring
 - Second injection hole
 - Increased injection pressure
- Reports:**
 - Reports

Legend:

- Time schedule according to the contract
- Actual/expected time schedule 31.8.1998
- Time periods for the progress report

Figure 5. Progress diagram for the Laugaland demonstration project GE-0060/96. The diagram shows the initial time schedule, the actual progress until 31.8.1998 and expected time schedule from that date

Contacts was established with the National Telephone Company P&S to get information about the availability of telephone lines in the area. The type of connection we were seeking ranged from: a) simple modem connection, b) X.25 connection, c) Internet subscription or d) ISDN connection. We selected the simple modem connection which was the alternative with the best price-performance ratio for our purpose.

Several alternatives were considered regarding the three component seismometers. Two main types of seismometers are available; active elements with feedback electronics and passive elements which do not include any electronic circuitry (pure mechanical). Considering the frequency range, the background ground motion and the size of the expected seismic signals we excluded the active seismometers due to the noise characteristics of these devices. The final decision made was to purchase separate passive 4.5 Hz elements for each component (vertical, North-South and East-West) and assemble them in a robust housing. The assemble work was carried out by Orkustofnun.

There are not many digitizers on the market meeting the requirements of up to 1000 samples per second, high dynamic range and very low electronic noise. The units with the best price-performance ratio were found in the HRD-24 24 bit digitizer from Nanometrics in Canada.

3.2 Manufacture

3.2.1 Pipeline construction Manufacture of plastic pipes for the 12 km long return-water pipeline from Akureyri to Laugaland was completed in early December 1996. Hocht Danmark was responsible for this part of the project with aid of a subcontractor, Set hf. The pipeline has an inner diameter of 150 mm.

An open tender for the construction of 8 km of the pipeline was launched in December 1996. The remaining 4 km were constructed by the staff of HVA as well as all welding and transport of the pipeline. A total of 5 contractors made bids. The lowest bid was accepted and a subcontract signed in December 1996. The lowest bid amounted to 38%, while the highest one was 83%, of the expected cost. These unusually low prices result from limited activities among contractors during the main winter season. The pipeline construction started in late December 1996 and 8 of the 12 km had been finished by the end of February 1997, in spite of difficult weather conditions. The remainder of the pipeline had been completed by the end of May 1997. The pipeline is buried at a depth of 1.2 m to avoid freezing in winter-time.

3.2.2 Monitoring equipment Automatic, computer-controlled equipment for monitoring various parameters describing the injection, and the response of the Laugaland reservoir to the injection, were manufactured in May and June 1997. These parameters include the flow-rate and temperature of the return-water leaving the pumping station in Akureyri, rate of injection, water temperature and well-head pressure for both injection wells, as well as flow-rate and water temperature for the three production wells at Laugaland. In addition the system monitors the frequency of the pump-motors involved.

3.2.3 Pumps Pumps for injecting the return-water into the two injection wells were manufactured during April through June 1997. These have capacities of 20 l/s at 30 bar-g pressure and 10 l/s at 10 bar-g pressure, respectively. A pump intended for pumping the return water from the pumping station in Akureyri towards Laugaland was manufactured during the same period.

3.2.4 Seismic equipment Digitizers of the type HRD-24 were ordered from a Canadian company, Nanometrics. Six vertical and twelve horizontal 4.5 Hz geophones were ordered from the company SENSOR in the Netherlands. An individual calibration test was ordered for each geophone element. Seven Pentium PC's with internal modems and one Sun SPARC Station was ordered from a local dealer. Optic cables for the data communication between digitizer in the seismic station vaults and the on-site computers were ordered from the National Telephone Company P & S. Power backup units are installed for all digitizers and all computers, both at the seismic stations and at HVA headquarters.

3.2.5 Modification of seismic software During December 1996 and January 1997 work focused on software development related to the interfacing of the Nanometrics HRD digitizer to the SIL Utility Software. Tests were performed for 500 samples per second on three channels using Pentium computer. The results showed a good performance. Configurable logging facilities was implemented for logging various "State Of Health" parameters available from the digitizer.

During the period from Mars through May 1997 work concentrated on adaptation of the phase-detection procedure to the 500 cps configuration and the higher frequency content of the data. Adaptation of the rest of the seismological software was carried out during May through July. This involved among other things the change from using single float representation of coordinate and time information into double precision. This was necessary due to the small size of the network area. To make the interactive view of the seismic activity more sensible, information regarding source location is displayed relative to the injection borehole, both in distance and angle.

Work during May and June 1997 involved software development and configuration of the standard Unix-to-Unix communication package (UUCP). Some modifications of the acquisition software related to the communication between the stations and the center was done. This mainly involved modifications or rewriting of Unix shell scripts.

3.3 Assembly/Installation

3.3.1 Monitoring equipment The automatic injection- and reservoir monitoring system was installed and tested during the period from July through September 1997. This work was carried out by the technical department of HVA, Raftákn Consulting Engineers and Raftó Electrical Contractors. Data collected by this system, as well as instantaneous information on the status of the injection and production wells, can be accessed through computers in the pumping station of HVA in Akureyri, as well as in its headquarters. Consequently these data are transmitted by e-mail to Orkustofnun for evaluation and analysis.

3.3.2 Pumps The pumps for pumping the return water from Akureyri to Laugaland, and hence into the injection wells, were assembled and installed during the period from June through August 1997. This was done by the staff of HVA and RARIK with the aid of Raftó Electrical Contractors.

3.3.3 Seismic installations The vaults housing the seismic stations, and the associated infrastructure, were constructed during the period from late May through the middle of July 1997. Figure 1 shows the locations of seismic stations. Some less sophisticated vaults were constructed for additional mobile seismic stations to be operated in case of observed seismic activity located in the reservoir.

The seismic network was installed during the period of July 15th through July 30th. Technically the network was in operation on July 30th and remotely available for parameter tuning and adjustments from Uppsala through the Internet. During August and September the main work concentrated on tuning the network parameters for the highest possible micro-earthquake detection ability, within the reservoir. The large amount of earthquakes north and north-east of the area (50 to 100 km distance) are avoided by using different detection parameters for different regions. The day by day control of the network operation is done in Uppsala through the Internet. All saved earthquake data is also transferred to Uppsala through the Internet at night.

3.4 Commissioning

3.4.1 Seismic network startup The start-up of the seismic network took place in late August 1997.

3.4.2 Startup monitoring The start-up of the monitoring took place during September 1997. This involved water-level measurements in a number of observation wells inside, as well as outside, the Laugaland area. It also involved the collection of water samples from hot water production wells, and a return water sample, for chemical analyses, which will be used as references during later phases of the project. Furthermore, the start-up of monitoring involved additional logging of the two injection wells, as well as start-up of the automatic monitoring system. Some fine-tuning of the automatic monitoring system was also performed in September. In addition, the start-up included a step-rate injection test of the main injection well.

3.4.3 Startup injection The start-up of the actual injection took place on the 8th of September 1997. A nearly constant injection rate of 8 l/s was maintained through the remainder of September. The temperature of the return-water, as it was injected, was around 21°C. The well-head pressure increased slowly to about 6 bar-g during this period. At the end of the start-up period a chemical tracer was injected into the injection well. The recovery of this tracer in the production wells in the Laugaland area has been monitored carefully.

3.5 Monitoring

The monitoring phase of the re-injection project at Laugaland started on October 1st 1997. Since that time 8 l/s have been injected almost continuously into well LJ-8. In addition 6 l/s have been injected into well LN-10 since January 29th 1998. A total of

about 320,000 tons of water have been reinjected into the Laugaland geothermal system since the startup of the injection in September 1997, until early August 1998.

In addition to production- and injection rates; water temperatures, well-head pressures and water-levels are observed by the automatic monitoring system mentioned above. These values are collected every ten minutes. Water levels are also monitored manually in a number of wells inside, as well as outside, the Laugaland area. Two tracer-tests have been successfully completed, each lasting a little over two months. The first one began at the end of the start-up period of the project, while the second one was started during the middle of March. A total of more than 500 tracer-samples, from a number of production wells, both inside and outside the Laugaland area, have been collected and analyzed during these tests.

During the first ten months of the monitoring phase step-rate injection tests have been conducted for each of the injection wells. The step-rate test for LJ-8 was repeated in late May 1998, while the test for LN-10 will be repeated later. The test for LJ-8 will be repeated one more time during the second year of the project. These step-rate tests are repeated in order to monitor changes in well injectivity, due to scaling etc. The temperature profiles of both wells have been measured during active reinjection. This is done to enable detection of the exit-points for the injected water, i.e. the feed-zones, and to allow estimates of the relative importance of different feed-zones in the injection wells. It is believed that such estimates, based on temperature profiles, may be as accurate as results of spinner-logging.

Very extensive and detailed data sets have been collected during the start-up phase, and the first ten months of the monitoring phase, of the Laugaland reinjection project. The most important of these will be presented in the following chapter along with the results of the preliminary analysis and interpretation, which has been carried out at the time of writing of this report.

4. PRELIMINARY RESULTS

4.1 Reinjection/production

Reinjection started on the 8th of September 1997. Until the 28th of January 1998 about 8 l/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 6. 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, as shown in Figure 7, while the temperature drop in the 13 km return water pipeline has been of the order of 5 °C.

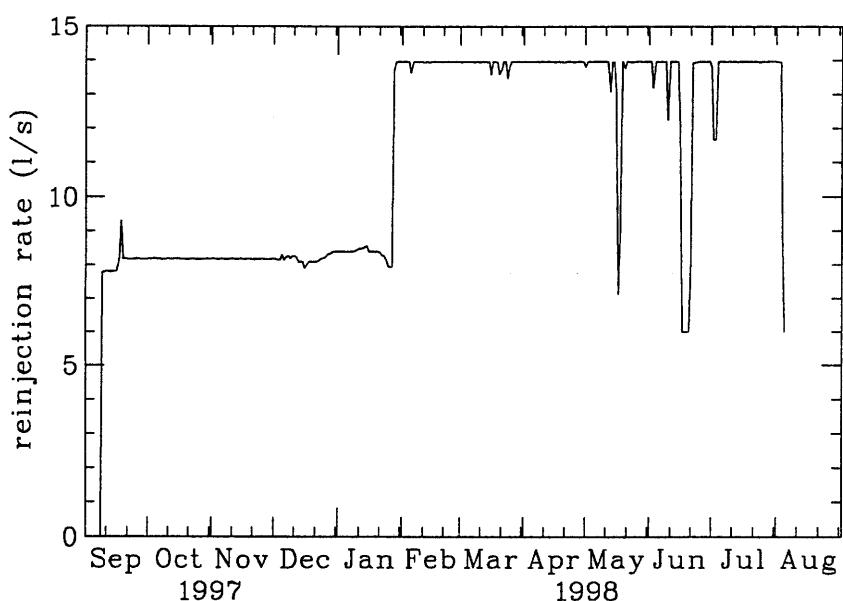


Figure 6. *Daily average reinjection into wells LJ-8 and LN-10 during the first year of the project.*

Figure 8 shows daily average hot water production from the Laugaland field during the first year of the 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 8). 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 (1998), 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.

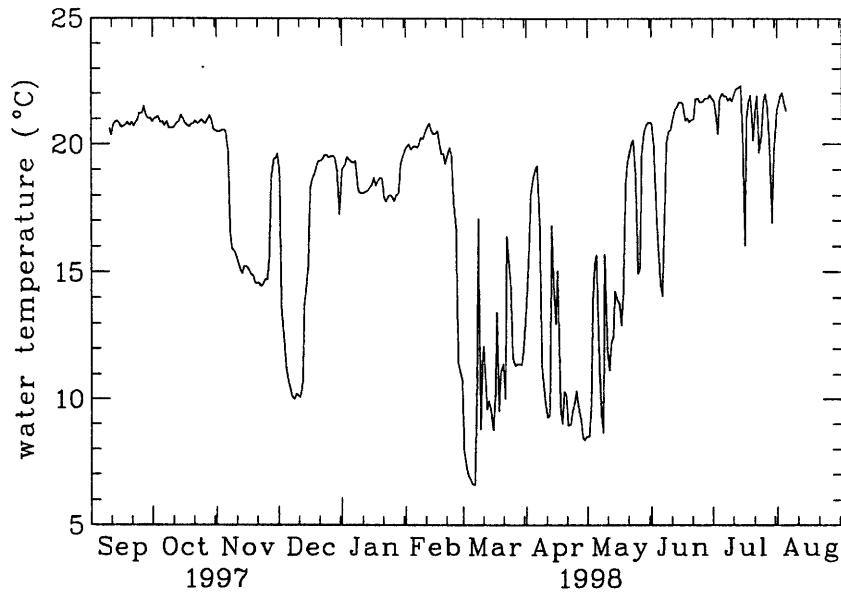


Figure 7. *Daily average temperature of return water reinjected during the first year of the project.*

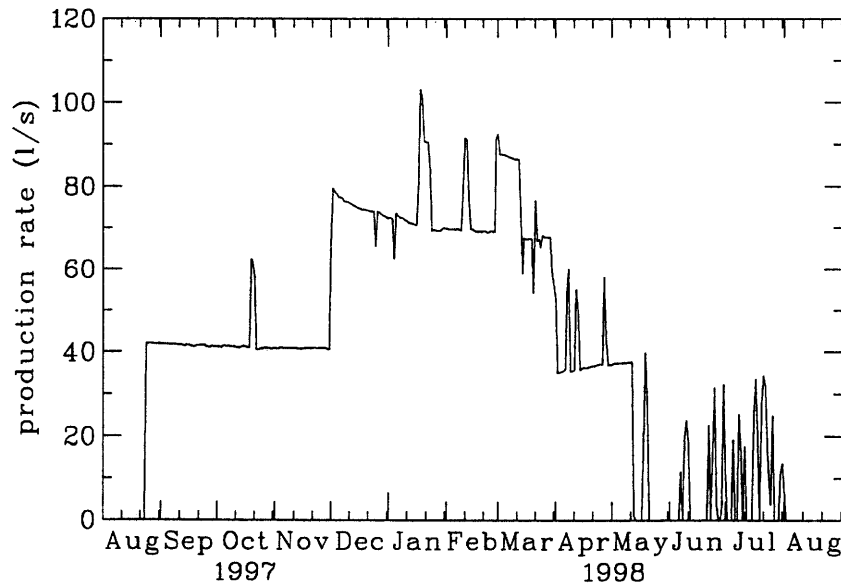


Figure 8. *Daily average production from wells LJ-5, LJ-7 and LN-12 at Laugaland during the first year of the project.*

Figure 9 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.

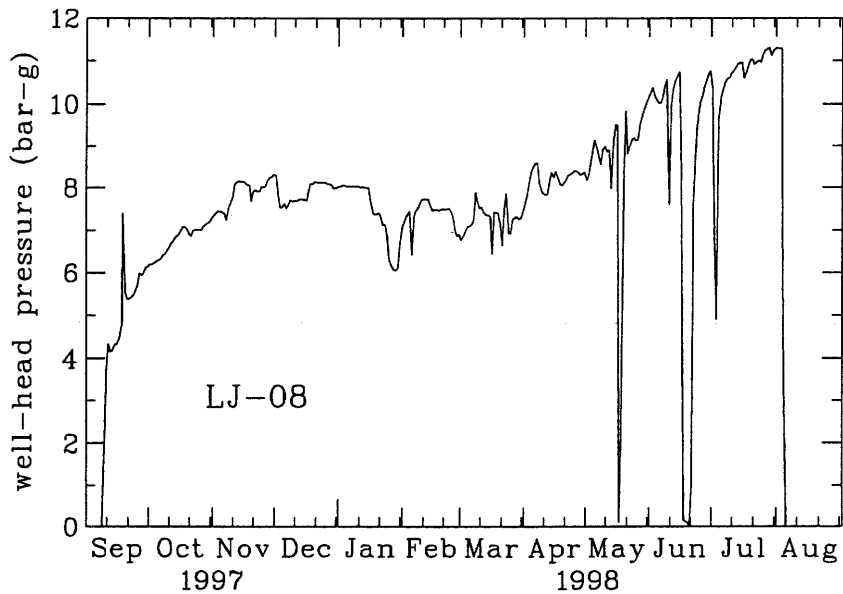


Figure 9. *Well-head pressure of well LJ-8 during the first year of the project.*

Well LN-10 responds quite differently to injection than well LJ-8, as shown in Figure 10. 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.

4.2 Water level changes

Figure 11 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. Some of these data are presented in figures 12 and 13.

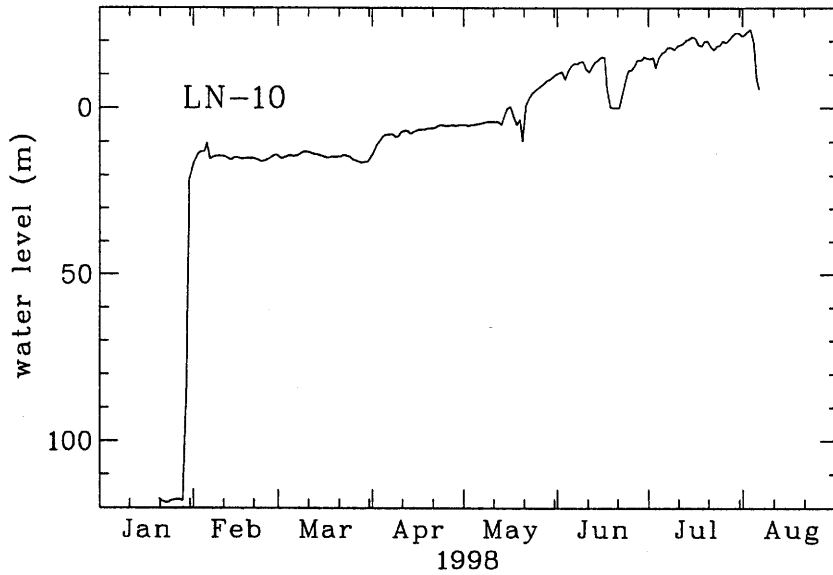


Figure 10. Water level in well LN-10 after injection into that well started at the end of January 1998.

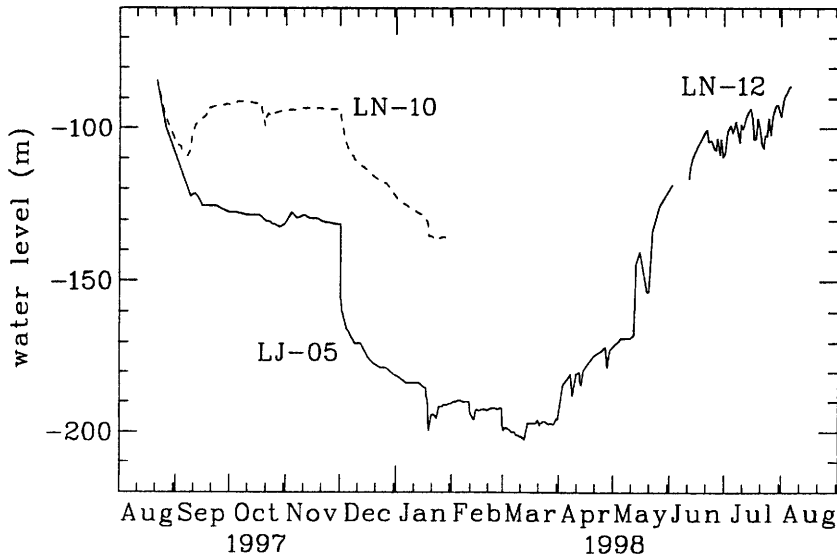


Figure 11. Water-level changes in three wells at Laugaland during the first year of the project.

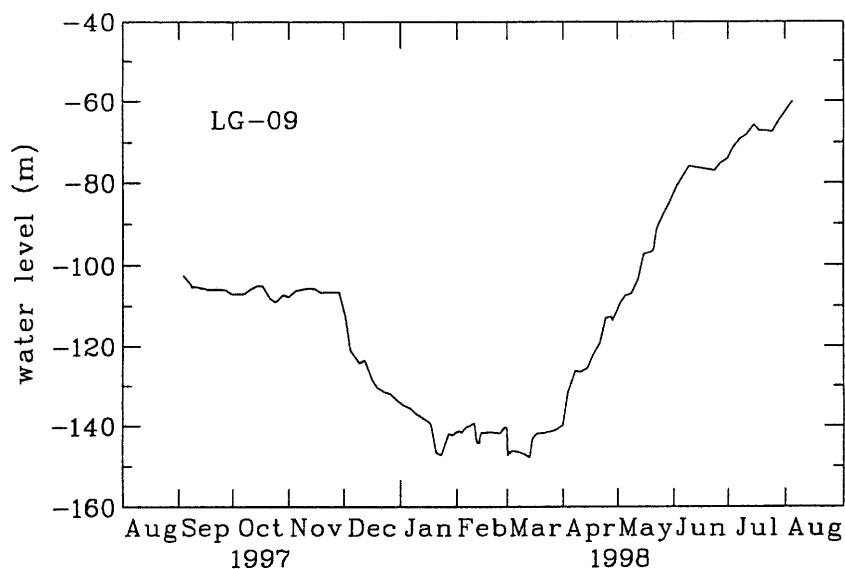


Figure 12. Water-level changes in observation well LG-9 at Laugaland.

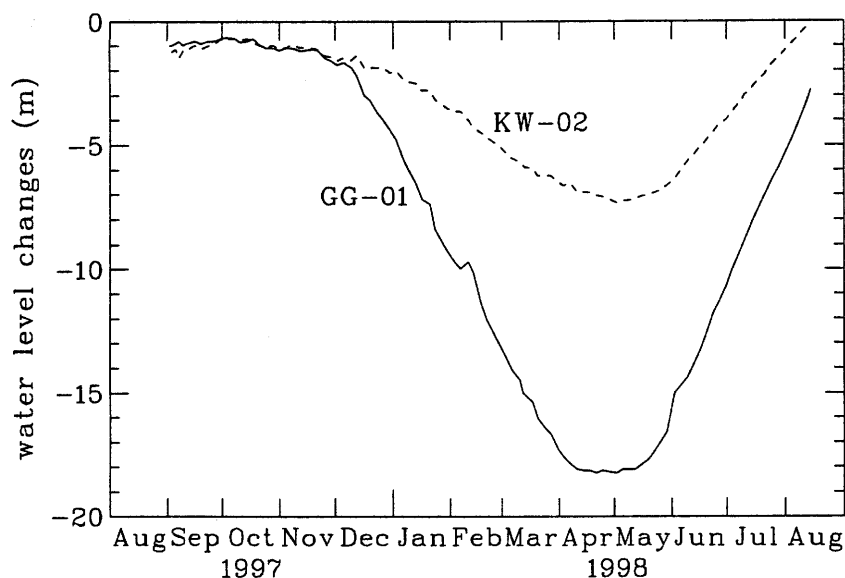


Figure 13. Water-level changes in two observation wells outside Laugaland. Well KW-2 is situated 1 km S of Laugaland and well GG-1 1.6 km WNW of Laugaland.

The effects of the start-up of the reinjection in early September 1997 can clearly be seen in Figure 11. 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.

4.3 Step-rate injection tests

Figure 14 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 14).

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 $0.02 \text{ bar}/(\text{l/s})^2$. 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 $0.1 \text{ bar}/(\text{l/s})^2$ (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.

4.4 Analysis of temperature logs

Figure 15 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.

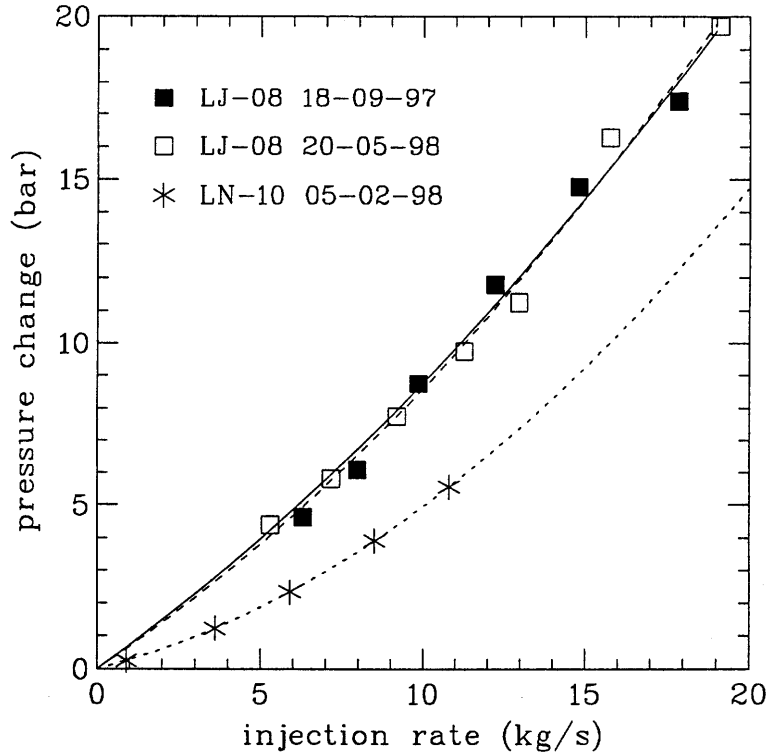


Figure 14. Results of three step-rate injection tests conducted in wells LJ-8 and LN-10.

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 cause the observed heating of the injected water as it travels down the well.

$$(1) \quad qc_w \frac{dT}{dz} = 4k\pi (T - T_r) \left[\ln \left(\frac{4kt}{\rho_r c_r r_w^2} \right) - 1.154 \right]^{-1}$$

Here q denotes the flow-rate in the well at depth z , T the temperature in the well at that depth, T_r the undisturbed reservoir temperature given by the log measured prior to injection, while c_w and c_r are the heat capacities of water and rock, respectively, k the heat conductivity of the rock, ρ_r its density and r_w is the 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.

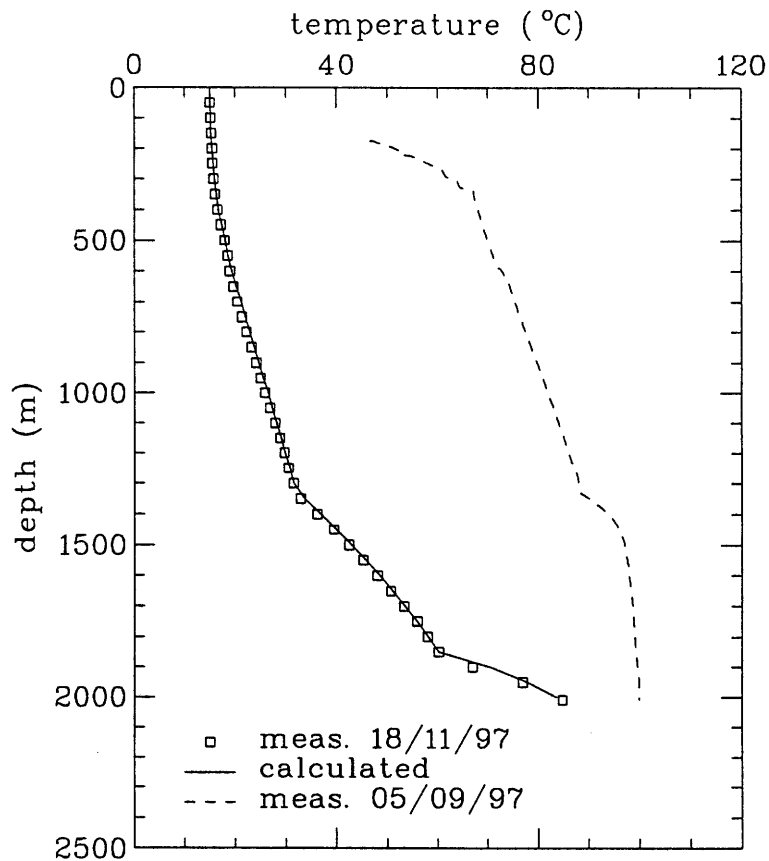


Figure 15. Two temperature logs from well LJ-8, measured prior to and during reinjection. Also shown is a simulation of the second log by a wellbore simulator.

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 televiwer 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.

4.5 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 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 16. 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 ppm in that well. The concentration in well LN-12 dropped to about 0.5 ppm during the same period.

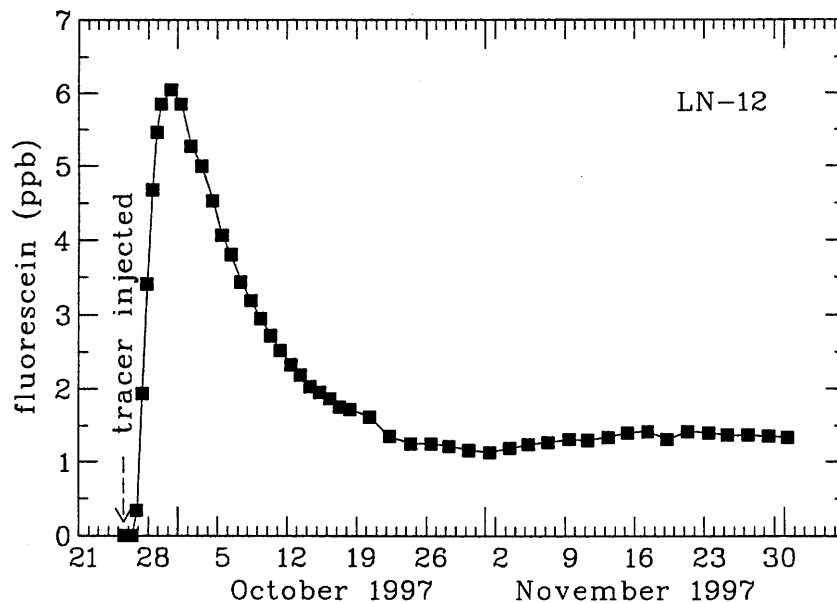


Figure 16. Observed fluorescein recovery in well LN-12 during injection into well LJ-8.

Other geothermal production wells in the Eyjafjörður-valley, outside Laugaland, have also been monitored for tracer recovery (see Figure 1). As shown in Figure 17 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 11). No tracer has been recovered in production wells in the western half of the Eyjafjörður-valley.

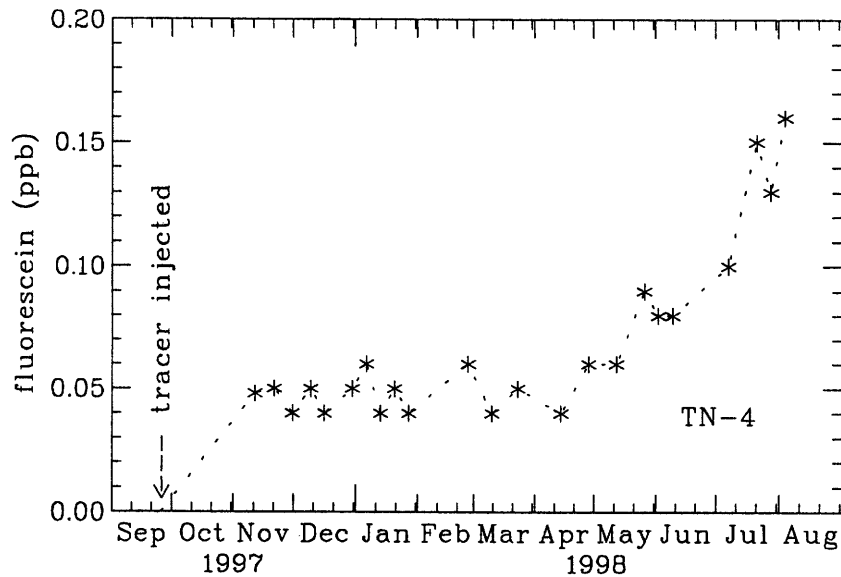


Figure 17. *Observed fluorescein recovery in well TN-4
1800m north of Laugaland.*

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 18 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 8) 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.

A preliminary analysis of the data presented in Figure 16 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 fracture-zone, which supplies 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.

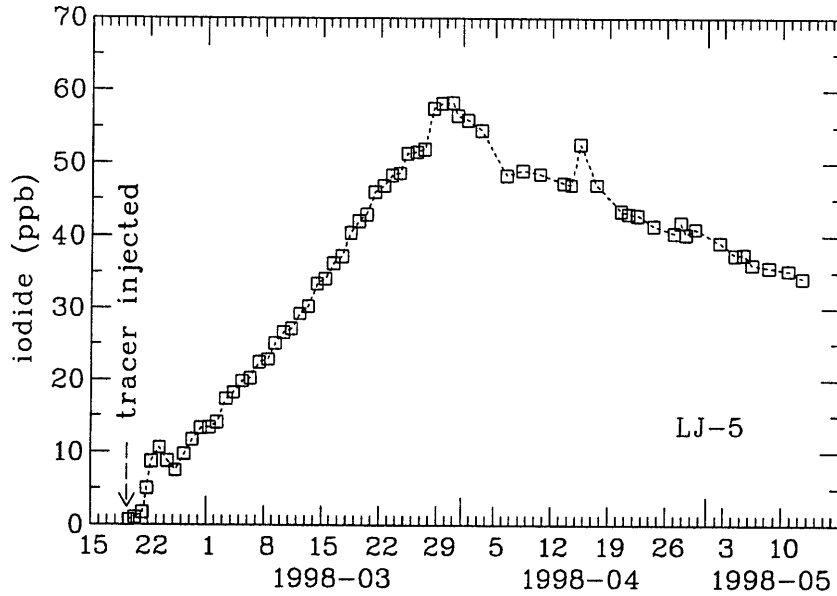


Figure 18. *Observed iodine recovery in well LJ-5 during injection into well LN-10.*

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 in Figure 16 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, the flow channel volume 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 results presented in Figure 19. 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

In the table u denotes the mean flow velocity, A the cross-sectional area, ϕ the porosity and α_L the longitudinal dispersivity of the flow-channel. The variable M_i denotes the calculated mass recovery of tracer through the corresponding channel, until infinite time, while M denotes the 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 m³.

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 20. 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.

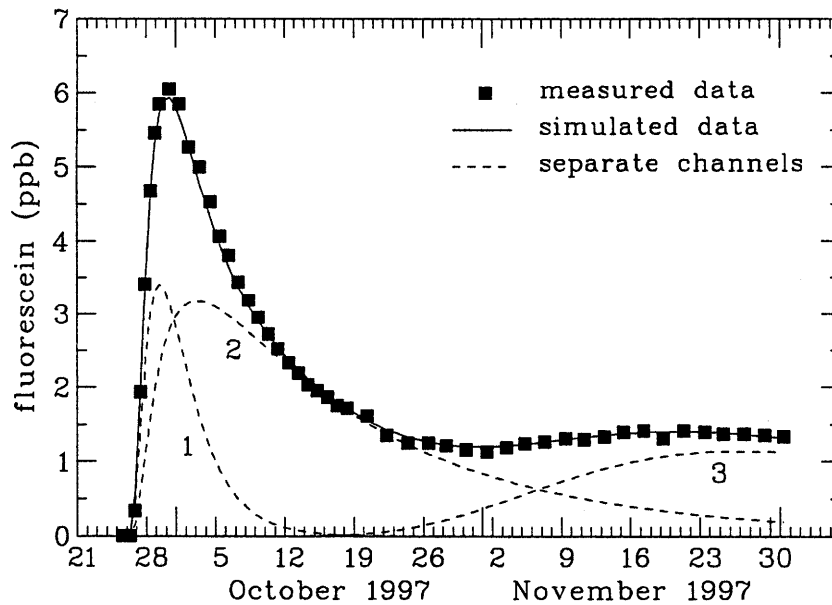


Figure 19. *Observed and simulated fluorescein recovery in well LN-12 during injection into well LJ-8.*

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.

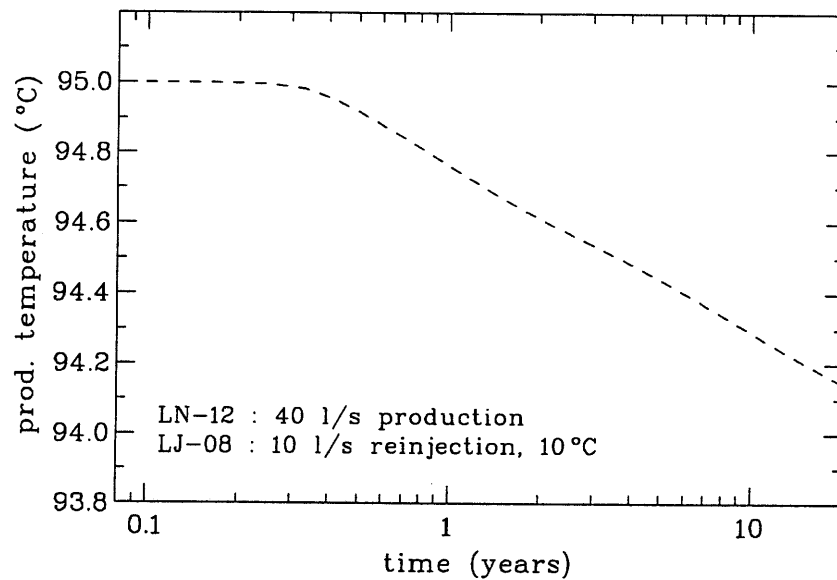


Figure 20. *Estimated decline in the temperature of well LN-12 during injection into well LJ-8, due to flow through the three channels simulated in Figure 15.*

4.6 Water temperature changes

No changes in the temperature of the water produced from wells LJ-5, LJ-7 or LN-12 have been observed, which can be attributed to the reinjection. Some minor changes have been observed, however, but these appear to be caused by changes in the flow-rate from the wells, as well as being affected by whether any of the other production wells are on-line at the same time. Because of this, changes of the order of 0.1 - 0.2°C will be difficult to detect. Yet it may be possible to detect, at the end of the project, whether changes of the order of 0.5°C have occurred due to the reinjection.

4.7 Micro-earthquake monitoring

The seismic network has been operated continuously during the first year of the reinjection project. No micro-earthquakes were recorded during this period, however. 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.

Figures 21 through 25 show examples of some of the data collected during the seismic monitoring. Figure 21 shows typical noise recordings at the six stations. The vertical component is shown for each station, the horizontal components being similar. At one station, AKO, which is the top trace, frequent transients due to water flow close to the station reduce the value of that station for event detection. The event detection is therefore based on transient detection at the remaining five stations.

Figure 22 shows a small earthquake ($M_L = 2.4$) north of Iceland at a distance of 95 km from Laugaland. The four top traces show the recordings at some of the stations in

northern Iceland operated by the Icelandic Meteorological Office, the so-called "SIL" stations. The lower six traces show the recordings at the six stations of this project. One can see that these stations produce recordings of similar quality as the "SIL" stations. From the distance to this event, from the frequency content, and from the signal to noise ratio one can conclude that microearthquakes within the hydrothermal site down to $M_L = -1$ are expected to be detected.

Figure 23 shows a blow-up of the first part of the signals in Figure 22. The top- and bottom traces are from "SIL" stations, while the six remaining traces are from the six stations around the Laugaland site. At these six stations the first cycle is very similar while the later part of the signals differs due to multipathing. Note the high signal to noise ratio.

Two small explosive devices were detonated April 21st, 1998, to test the seismic network. The upper part of Figure 24 shows the first explosion, which involved about 8 g of high explosives, as recorded at the closest station ALA. This figure is produced by the phase detector and the three bottom traces are the three original recordings east-, north-, and vertical component. The explosion took place at about 300 m depth. The lower part of Figure 24 shows the larger, 75 g explosion as recorded by ALA. Theoretically the amplitude should be about twice as large as for the smaller charge. It is, however, only 1.5 times larger. The frequency of the waves is in the range of 15 - 70 Hz. The signal to noise ratio is about 10. The distance from the shot point to the station is about 350 m, and the next closest station is at 5 times this distance. No signals can be detected from these two explosions at that or the remaining stations. This is reasonable as the damping can be expected to be rather high at such shallow depths.

Finally, Figure 25 shows the amplitude spectrum of the vertical component of the signal of the larger explosion recorded at station ALA (see Figure 24). We see that the peak is between 15 and 70 Hz. The higher frequencies are quickly damped.

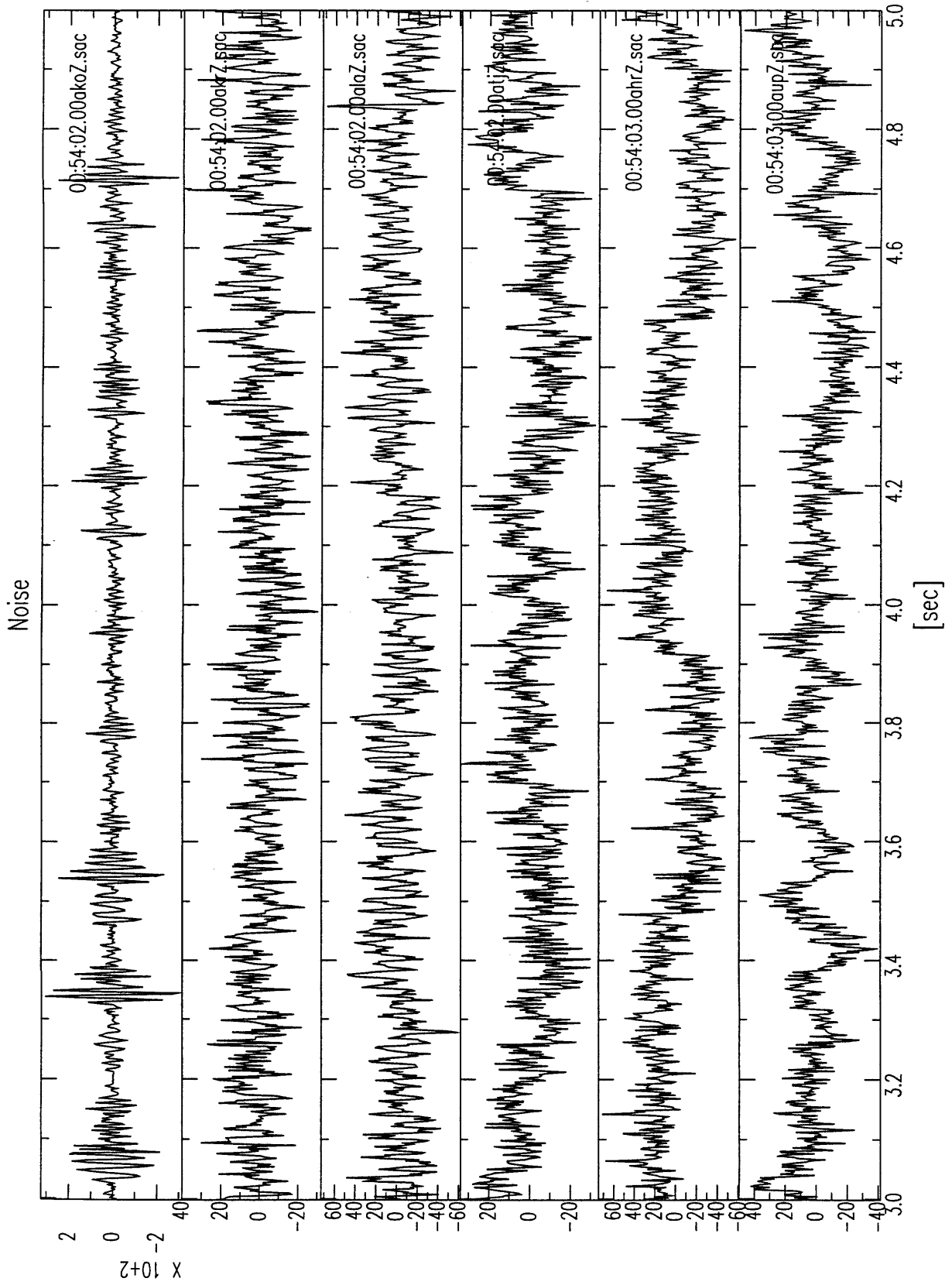


Figure 21. Typical noise recordings at the six seismic monitoring stations.

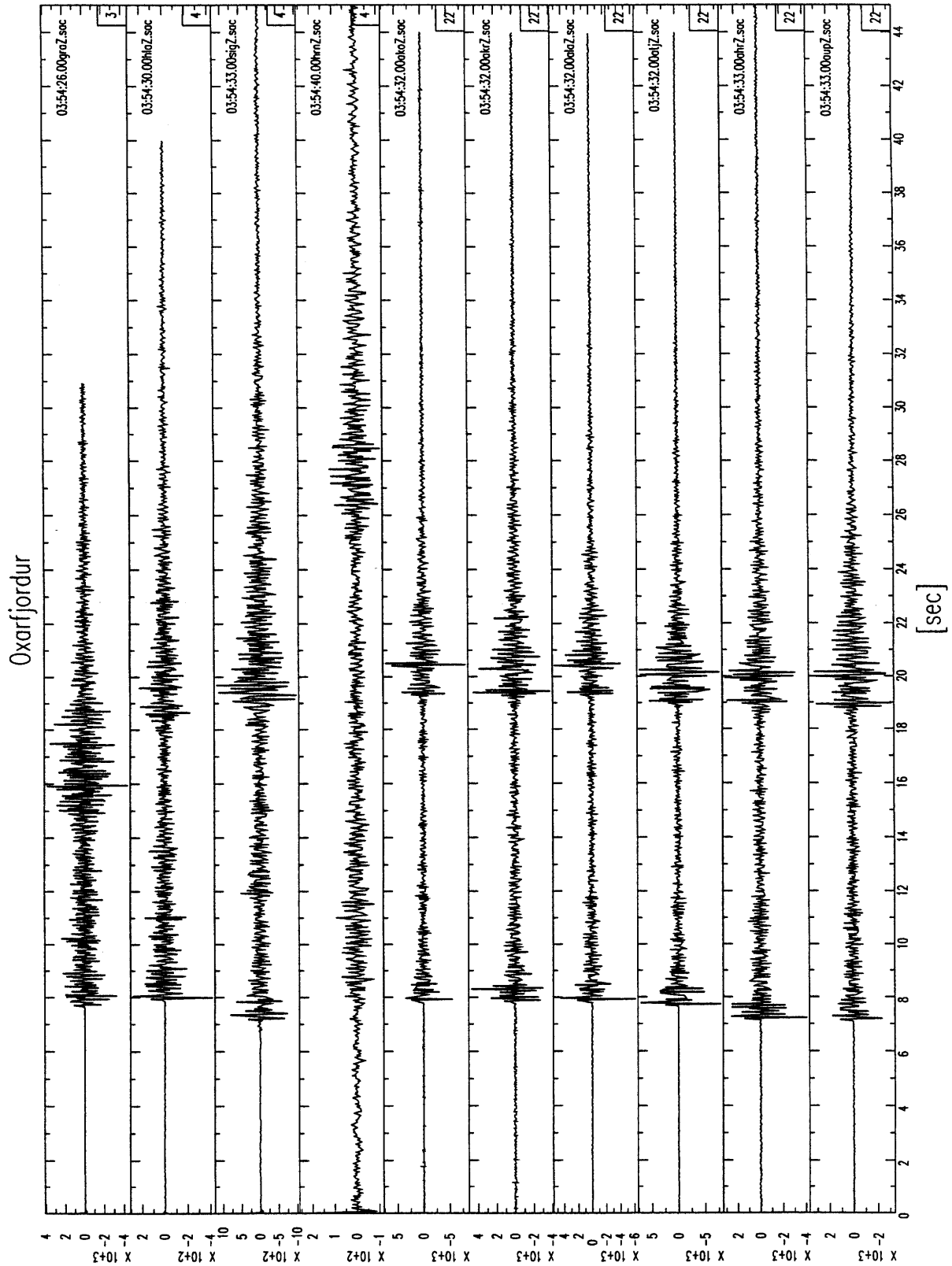


Figure 22. A small earthquake ($M_L = 2.4$) north of Iceland recorded by the seismic network. The top four traces are recordings of the "SIL"-network, shown for reference.

9 dec 1997 03:54:25.1 ML = 2.38

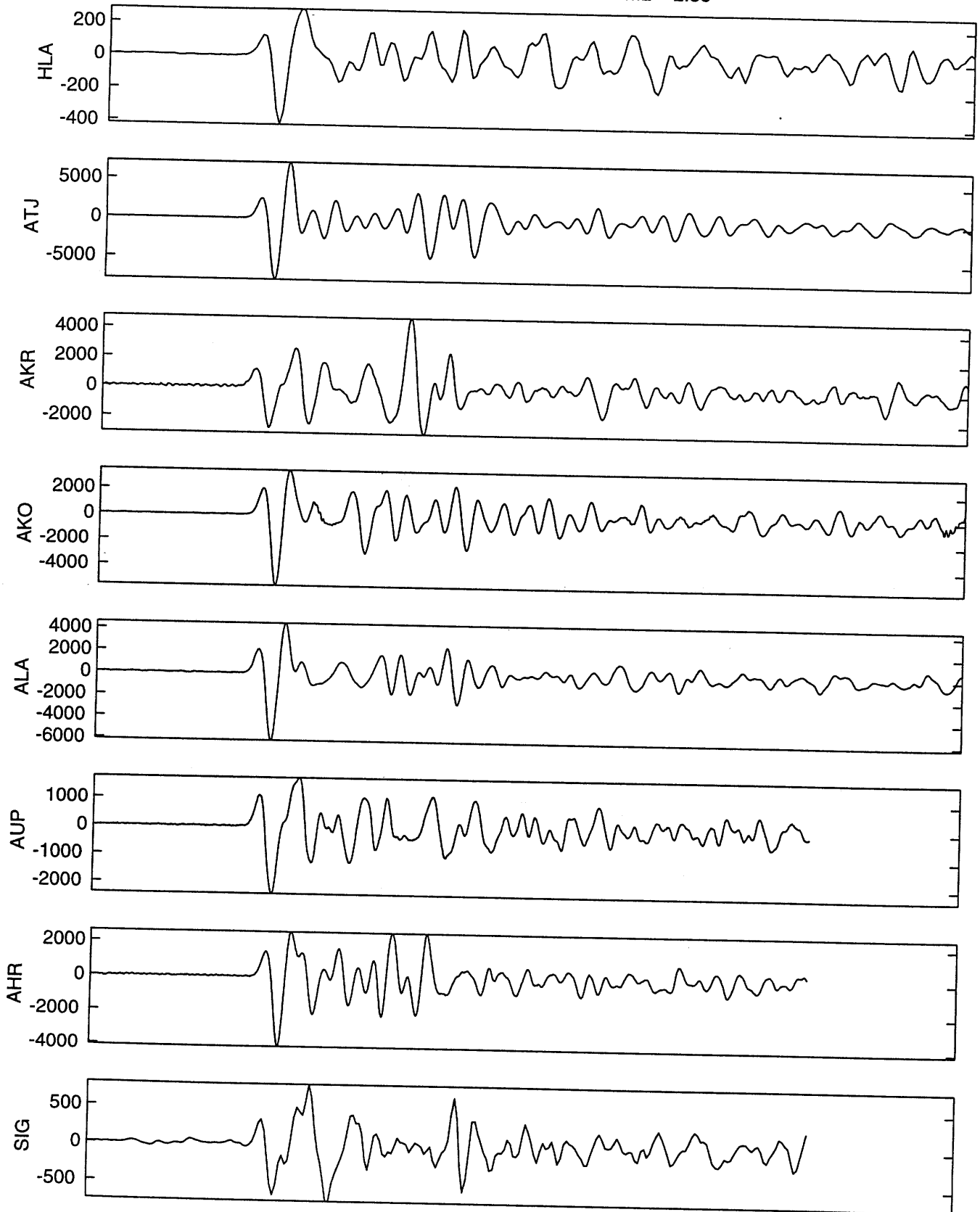
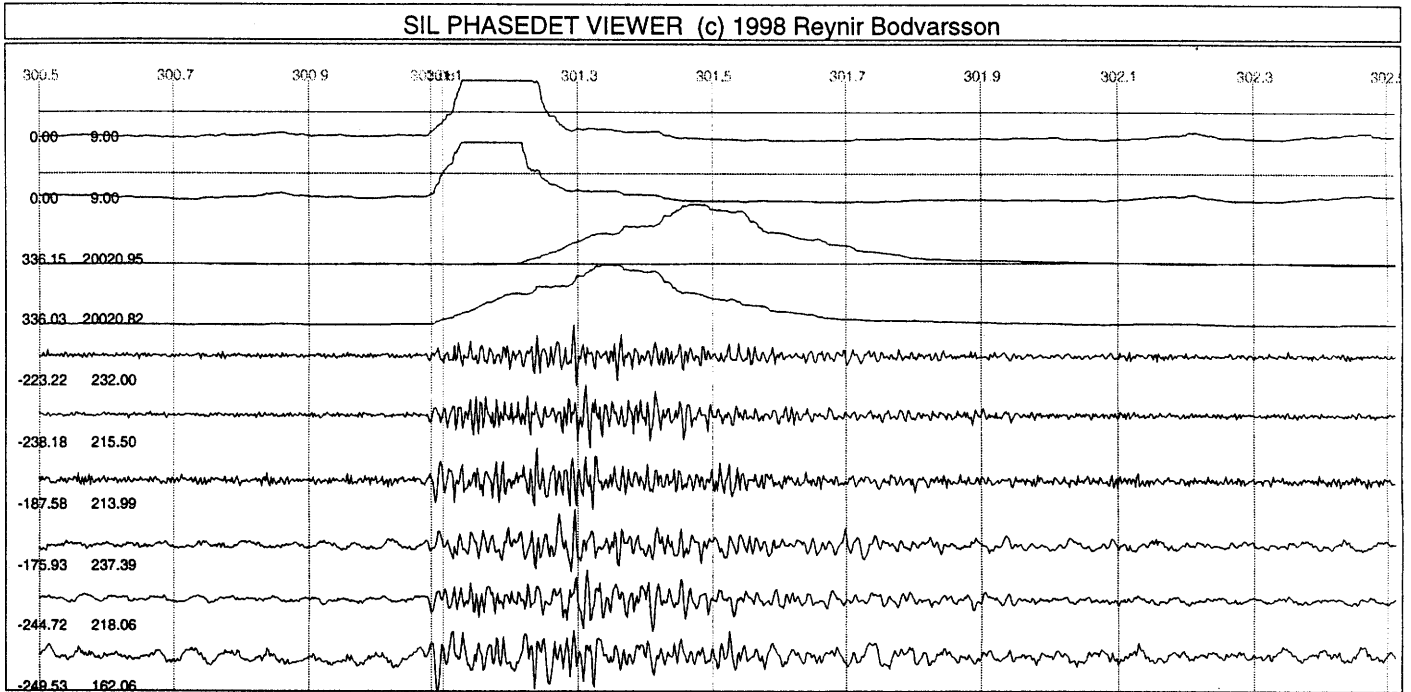


Figure 23. A blow-up of the first part of the signals in Figure 22. The top- and bottom traces are from "SIG" stations, while the rest are from the Laugaland network.

Explosion at 14:50



Explosion at 16:00

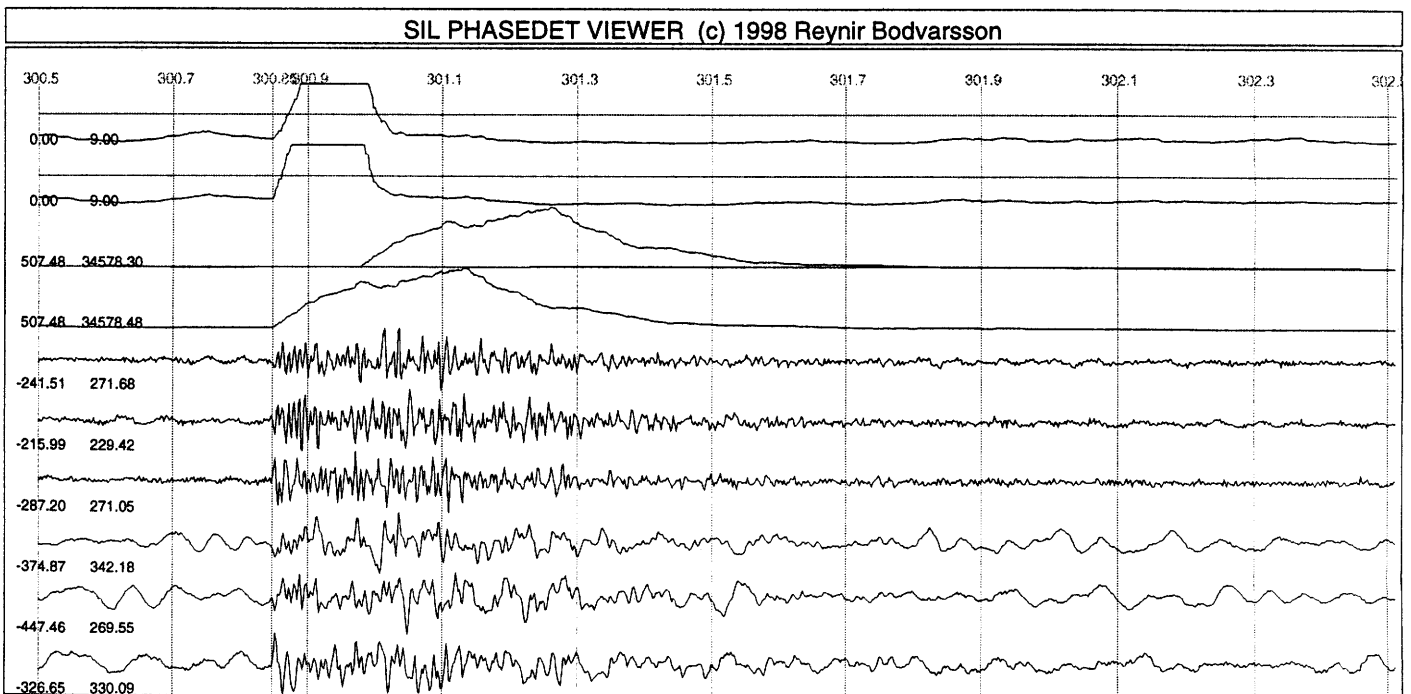


Figure 24. Recordings (station ALA) of two test explosions detonated April 21st, 1998.

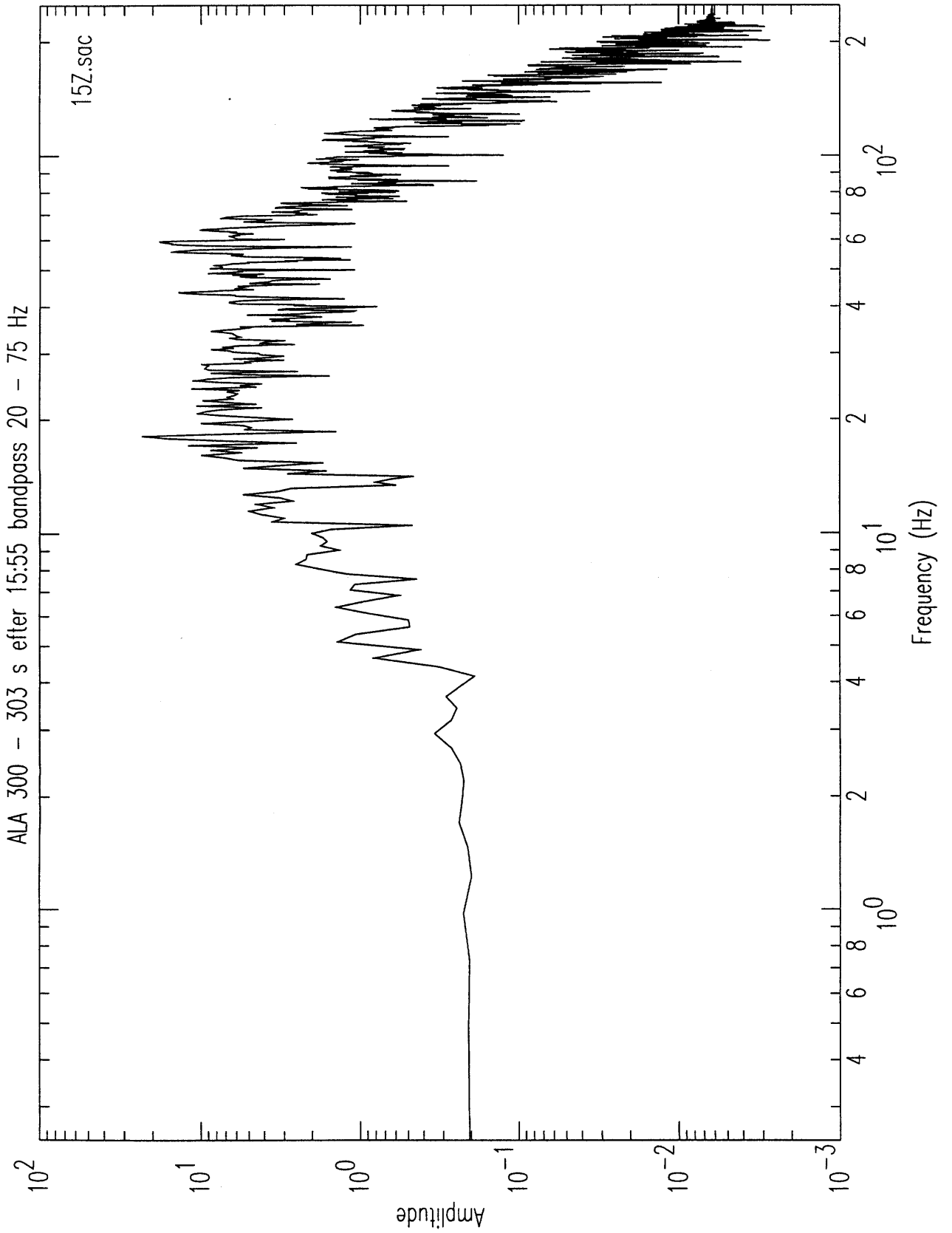


Figure 25. *The amplitude spectrum of the vertical component of the signal of the larger explosion in Figure 24.*

5. FURTHER WORK AND CONCLUDING REMARKS

During the first year of the project the progress of the Laugaland reinjection experiment has been mostly according to schedule. The project will continue till the end of November 1999, while the main phase of the project, i.e. the monitoring phase, which involves the actual reinjection, will continue until the end of July 1999. The last 16 months of the project will involve the following phases:

1. Injection into well LJ-8 at a maximum rate (of the order of 20 l/s) such that a well-head pressure of up to 30 bar-g will be achieved. This phase will last a few months, and will include:
 - Careful monitoring of well-head and reservoir parameters, such as carried out during earlier stages of the monitoring part of the project.
 - A tracer test aimed at determining whether new flow channels open up at the much higher pressures.
 - Temperature logging of well LJ-8 aimed at determining the relative importance of the different exit points during injection at the maximum rate.
 - Continued monitoring of micro-seismic activity, which is considered most likely to occur during this phase.
2. The last half year of the reinjection experiment will be used for further testing. This has not been planned in detail at the time of writing of this report, but will be done later this fall (1998) on the basis of the outcome of the maximum pressure phase and the results of data analysis and modeling available at that time. It should be pointed out, that the overall design of the project is under constant re-evaluation during the progress of the project. The step-rate injection tests need to be repeated for both injection wells, in order to detect possible changes in the wells. Emphasis needs also to be placed on determining the exact water level recovery that will be achieved by the reinjection, since results on this aspect have been rather inclusive.
3. During the remainder of the project emphasis will be placed on data analysis and numerical model development, which currently has started to a limited extent. The available data will be used to determine the water level recovery achieved during the first year of the project.
4. Analysis of the economics of long-term reinjection will also be carried out.
5. A final report on the Laugaland demonstration project will be published in October 1999, according to the project contract.
6. A workshop will be held in Akureyri at the conclusion of the project.

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 an 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.

REFERENCES

- Axelsson, G., 1989: Simulation of pressure response data from geothermal reservoirs by lumped parameter models. *Proceedings 14th Workshop on Geothermal Reservoir Engineering*, Stanford University, USA, 257-263.
- Axelsson, G., G. Sverrisdóttir, Ó.G. Flóvenz, F. Árnason, Á. Árnason and R. Bodvarsson, 1998: Long-term reinjection project in the Laugaland Low-temperature area in N-Iceland. *Proceedings 23rd Workshop on Geothermal Reservoir Engineering*, Stanford University, USA, 412-419.
- Axelsson, G., G. Sverrisdóttir and Ó.G. Flóvenz, 1998: The Akureyri District Heating Service. Geothermal monitoring in 1997 (in Icelandic). Report OS-98032, National Energy Authority, Reykjavík, 56 pp.
- Axelsson, G., G. Björnsson, Ó.G. Flóvenz, H. Kristmannsdóttir and G. Sverrisdóttir, 1995: Injection experiments in low-temperature geothermal areas in Iceland. *Proceedings of the World Geothermal Congress 1995, Florence, Italy, May 1995*, 1991-1996.
- Axelsson, G., Ó.G. Flóvenz, H. Kristmannsdóttir and G. Sverrisdóttir, 1993: Injection experiment at Laugaland in Eyjafjörður, Central North Iceland (in Icelandic). Report OS-93052, National Energy Authority, Reykjavík, 69 pp.
- Axelsson, G., H. Tulinius, Ó.G. Flóvenz and P. Thorsteinsson, 1988: Geothermal resources of the Akureyri District Heating Service (in Icelandic). Report OS-88052, National Energy Authority, Reykjavík, 35 pp.
- Björnsson G., 1987: Multi-Feedzone, Geothermal Wellbore Simulator. Lawrence Berkeley Laboratory Report LBL-23546, 102 pp.
- Flóvenz, Ó.G., F. Árnason, M. Finnson and G. Axelsson, 1995: Direct utilization of geothermal water for space-heating in Akureyri, N-Iceland. *Proceedings of the World Geothermal Congress 1995, Florence, Italy, May 1995*, 2233-2238.
- Slunga, R., S.Th. Rögnvaldsson and R. Bödvarsson, 1995: Absolute and relative location of similar events with application to microearthquakes in South Iceland. *Geoph. J. Int.*, **123**, 409-419.
- Stefánsson, V., 1997: Geothermal reinjection experience. *Geothermics*, **26**, 99-130.
- Stefánsson, V., G. Axelsson, Ó. Sigurðsson and S.P. Kjaran, 1995: Geothermal reservoir management in Iceland. *Proceedings of the World Geothermal Congress 1995, Florence, Italy, May 1995*, 1763-1768.