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REASSESSMENT OF THE THELAMÖRK LOW TEMPERATURE GEOTHERMAL SYSTEM IN N-ICELAND FOLLOWING SUCCESSFUL DEEPENING OF WELL LÞN-10

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ABSTRACT

The Thelamörk low-temperature geothermal system in N-Iceland has for the last nine years been a source of hot water for the Akureyri District Heating Service. The main production well in the Thelamörk field, LÞN-11, was drilled in 1992 intersecting a productive fracture at 450 m depth yielding 17 l/s of 91°C water. Geochemical data indicated deep reservoir temperatures around 100°C and drilling experience in the region shows that the best feed-zones are usually at depths between 1000 to 1500 m. Instead of drilling a new well to hit this target an old 900 m deep well, LÞN-10, was deepened and deviated towards the main fracture-zone of the system. The well intersected a good feed-zone at 1700 m depth with a temperature about 103°C. A five-month production test was performed with careful monitoring of production rates, water level changes and water temperature for well LÞN-10 as well as five other wells in the field. Observed water level changes were simulated with lumped parameter models. The simulation results indicate that the Thelamörk reservoir has a volume of about 1 km^3 and an average permeability of 1 Dm. Predicted water level changes during long-term production indicate that the geothermal system will sustain a production between 20 and 21 l/s of 103°C water for the next 8 years, with a draw-down less than 245 m. The deepening of well LÞN-10 has resulted in an increase in the energy production potential of the Thelamörk geothermal system from 4.4 MW_t to 6.4 MW_t.

INTRODUCTION

The Thelamörk geothermal field has been a source of hot water for space heating in the town of Akureyri in Central North Iceland, with a population of 16,000, since late 1994. The Thelamörk field is located in a glacier-sculptured valley approximately 13 km north-west of Akureyri, as seen on Figure 1.

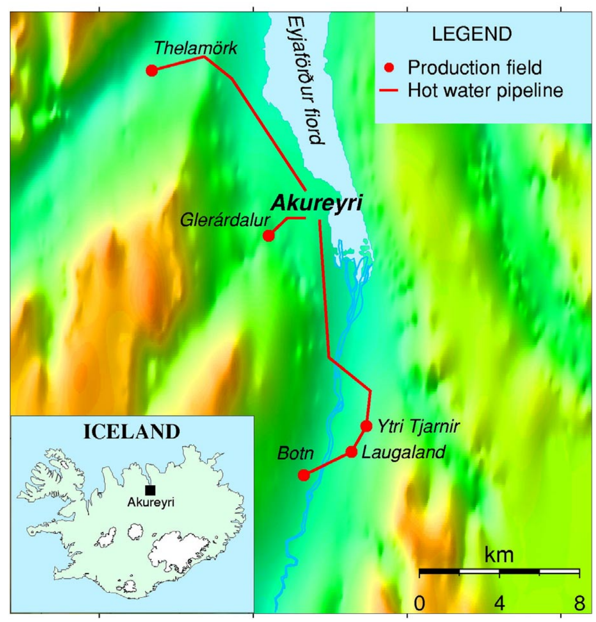

Figure 1: Topographic map showing locations of the geothermal fields in the vicinity of Akureyri, exploited for district heating of the town.

The Thelamörk geothermal field is one of the five low temperature fields utilized by Nordurorka, the local energy company, which provides district heating for Akureyri. Like the other four geothermal systems the Thelamörk system is embedded in 6-10 million years old Tertiary flood basalts. They are all liquid-dominated systems with reservoir temperature between 50 and 100°C. The geothermal systems are characterized by secondary permeability, associated with open fractures, in otherwise low permeability rocks. Only wells drilled through the fractures, or dikes connected to them are productive. The geothermal systems are rather small in volume and suffer from limited recharge because of their low permeability. Even modest production leads to considerable water level draw-down.

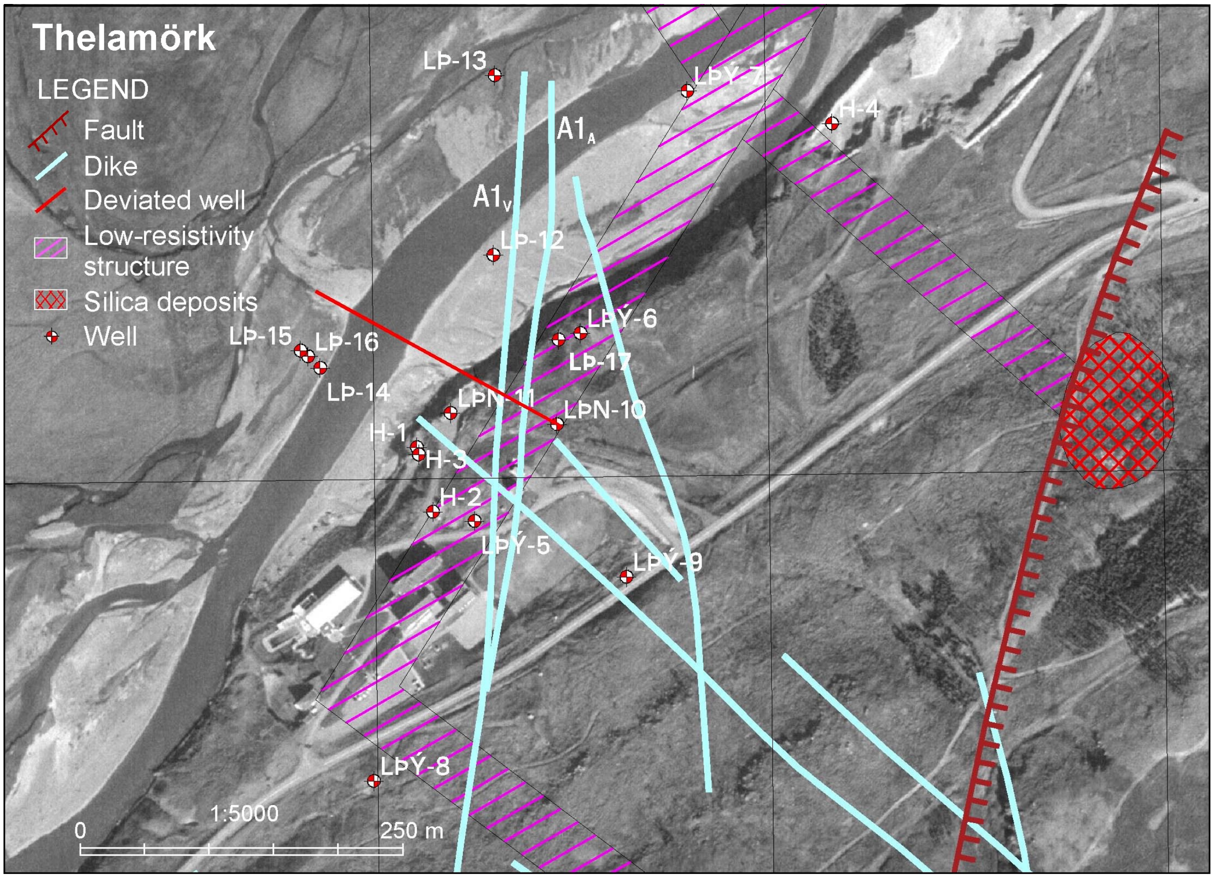

Figure 2: A geological map of the Thelamörk geothermal field, showing dykes, faults, resistivity structures and wells.

In the summer of 1992 a successful well, LÞN-11, was drilled in the Thelamörk field after 10 years of geothermal research (Flovenz *et al.*, 1995A). It intersected a permeable fracture-zone at 450 m depth yielding 17 l/s of 91°C water. After a nine-month production test, including partial reinjection and tracer tests, the energy production potential of the field was estimated on the basis of lumped parameter modeling (Björnsson *et al.*, 1994). On basis of that study Nordurorka (then Hita- og vatnsveita Akureyrar) decided to exploit the Thelamörk field. After the installation of a 11 km long pipeline to Akureyri in the fall of 1994 production from the field started). The 1994 reservoir assessment will be discussed in a later section.

The hot water demand for space heating in Akureyri has been increasing by about 2% per year for the last decade. The total energy production capacity of the five geothermal systems is, however, limited and the geothermal systems can only meet the increasing energy demand for a few years to come (Hauksdottir *et al.*, 2001). The latest attempt to find additional energy sources for Nordurorka involved the deepening of well LÞN-10 in the Thelamörk field. This was undertaken on the basis of geochemical data from the field, which indicated deep reservoir temperatures around 100°C, as well as drilling experience in the region, which shows that the best feed zones are at depths of 1000 to 1500 m. Instead of drilling a new well, an old 900 m deep well, LÞN-10, was deepened and deviated towards the main fracture-zone of the reservoir in August 2000. The deepening was successful and the well intersected a good feed zone at 1700 m depth, with a reservoir temperature between 103 and 104°C. Air-lift testing at the end of drilling indicated that well LÞN-10 was now more productive than well LÞN-11. A rotary shaft pump was consequently installed in the well down to 245 m along with an air tube for water level measurements.

In order to reassess the energy production potential of the field a five-moth production test was performed. This paper describes how lumped parameter models were used to simulate the observed pressure response and predict future water level changes for a few given production scenarios from well LÞN-10. Comparable lumped parameter methods were used in 1994 for the earlier assessment of the Thelamörk field.

PRODUCTION TESTING OF WELL LÞN-10

Production testing of well LÞN-10 started on the 28th of November 2000 after a one-month recovery following the shut-in of well LÞN-11. It ended on the 5th of May 2001 after five months average production of 20.2 l/s. Such a long test was considered necessary for a reliable potential assessment. The total production from the field during the production test was about 276,000 tons of about 103 °C water.

Table 1: Wells in use in the Thelamörk field.

Well	Drilled	Depth (m)	Casing (m)	Type
H-2	1965	1088	446	Observation
LÞY-5	1989	239	23	Observation
LÞY-8	1989	251	12	Observation
LÞN-10	1992/2001	1700	420	Prod./Observ.
LÞN-11	1992	452	250	Prod./Observ.
LÞN-17	2000	252	12	Observation

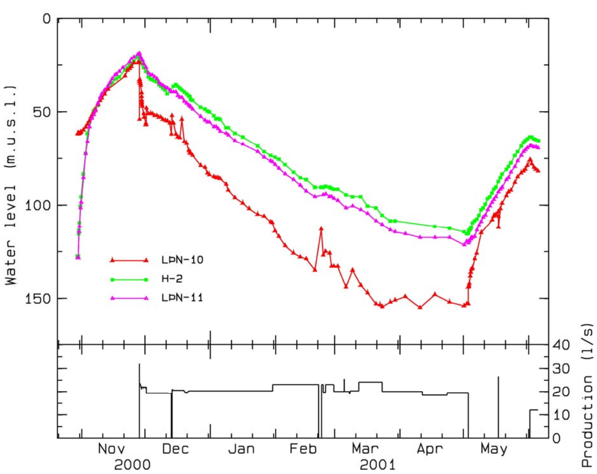

Figure 3:Production from well LÞN-10 and observed water level in wells LÞN-10, H-2 and LÞN-11 in the Thelamörk field from late October 2000 until early June 2001.

The test involved careful monitoring of production rates, water level changes and water temperature for well LÞN-10 and water level observations in five other wells in the field. Information on the wells currently in use in the Thelamörk field is presented in Table 1. Their locations are shown in Figure 2, along with the most important geological features. From late October 2000 until early June 2001 about 1,000 water level observations were made in the six wells in the field. Only the data from wells LÞN-10, H-2 and LÞN-11 are shown in Figure 3, but the data from the other three wells falls between the data from wells H-2 and LÞN-11.

The climbing water levels in May 2001, resulting from the shut-in of well LÞN-10, were interpreted as a pressure build-up test in the production well and interference tests between the production well and the other five observation wells. The tests were studied through conventional pressure transient analysis to obtain estimates on permeability thickness (kh) and storativity ($c_t h$) of the geothermal system, as well as other reservoir characteristics. Two simple models were used in the analysis: An infinite reservoir model, sometimes called the Theis model, and a single fracture model.

The main results of the pressure transient analysis show that the two production wells LÞN-10 and LÞN-11 are connected through the fracture-zone in the system, while the other three wells H-2, LÞY-5 and LÞY-8, are not connected directly to the production well LÞN-10 through the fracture-zone. The average permeability thickness is estimated 1.0 Dm (1.0×10^{-12} m^3) and the average storativity 6.0×10^{-9} m/Pa. The fracture models were used to estimate the total length of the fracture zone. By assuming storativity values between 8×10^{-8} and 6×10^{-9} m/Pa, the total fracture zone length is estimated between 0.5 and 2 km (Hjartarson *et al.*, 2001).

Like many other fracture dominated geothermal systems in Iceland, the systems in the Eyjafjördur region are believed to have formed about 10,000 years ago during the last deglaciation (Bödvarsson, 1982). Increased tectonic activity following the deglaciation is believed to have formed, or reopened, macroscopic fractures. The geothermal system then developed into existence by self-sustaining water convection in the hydraulically conductive fractures. The fracture-zone length estimate presented above is therefore considered reasonable.

LUMPED PARAMETER MODELING

The method of lumped parameter modeling has been used successfully over a decade to simulate data from several low-temperature geothermal reservoirs in Iceland and elsewhere (Axelsson and Gunnlaugsson, 2000). The lumped simulators have been used to assess the production capacity of reservoirs by predicting the future water level changes for various production scenarios. This method tackles the simulation problem as an inverse problem. It automatically fits the analytical response functions of lumped models to the observed data by using a nonlinear iterative least-squares technique for estimating the model parameters (Axelsson, 1989).

Figure 4 shows the two-tank open model and the three-tank closed model used to simulate the observed water level changes resulting from the production from well LÞN-10. The innermost tank in both models, which has a mass storage coefficient κ_1, simulates the volume of the production part in the geothermal system. This tank is connected by a conductor σ_1 to the second tank (κ_2), which simulates the outer and the deeper parts of the reservoir. The conductor simulates the rock conductivity (permeability) between those two parts. In the open model the second tank is connected to a constant pressure recharge source. In the closed model the second tank is connected to the third tank, which probably, simulates both the deeper parts of the reservoir and the overlaying groundwater system (Axelsson, 1989).

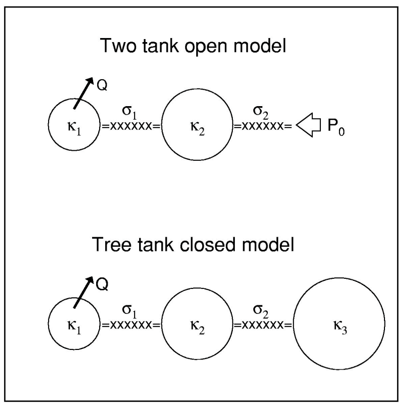

Figure 4: A two tank open model and three tank closed model used to simulate the observed water level changes during the production testing of well LÞN-10 in the Thelamörk field.

A constant long-term production from a geothermal system simulated by the open tank model will result in a stable water level after some time while the closed model will give a draw-down constantly increasing with time. The open model will, therefore, give optimistic forecasts while the closed model will give pessimistic forecasts.

Simulation results

Figure 5 shows the match between observed and simulated water level changes in well LÞN-10. The eight-year production history of well LÞN-11, since 1992 (Figure 6), was used as an input for the simulations, since it obviously affects the production test in well LÞN-10. Also, the models could not converge to a solution without it. The open and the closed models simulated the observed water level equally well. This indicates that the reservoir is either connected to a constant pressure source or to a system with a very large mass storage coefficient. This could either represent the overlaying groundwater system or the deeper parts of the geothermal system, or both. This has the positive implications that the draw-down in the field will either stabilize, or that the water level decline rate will be small, during constant long-term production.

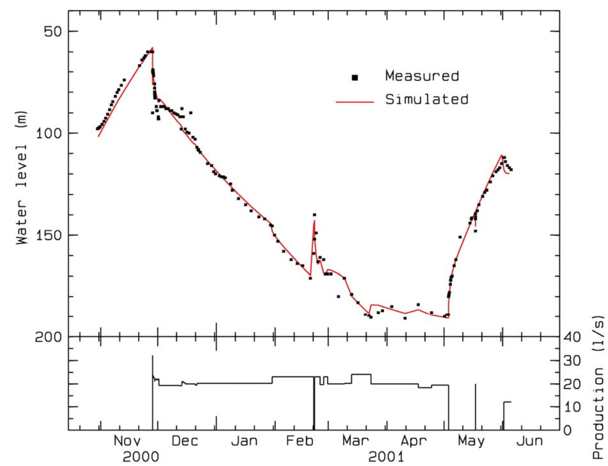

Figure 5: Production rate as well as measured and simulated water level changes in well LÞN-10 in the Thelamörk field.

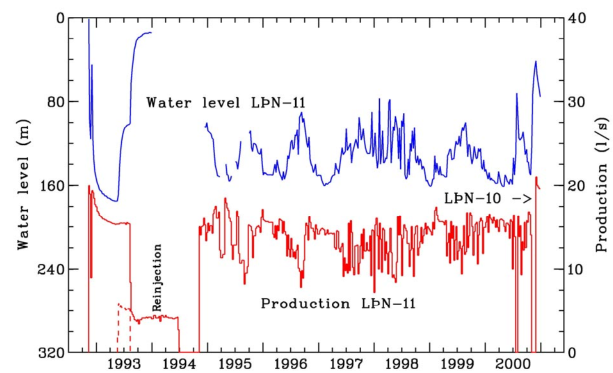

Figure 6: Production and water level history of well LÞN-11 in the Thelamörk field.

The mass storage coefficient of the innermost tank in both models (κ_1), which simulates the production part of the reservoir, corresponds to a volume of 0.2 km^3, based on an average porosity of 7 %. The second tank in both models (κ_2), which simulates the overall reservoir, corresponds to a volume of about 1 km^3, by using the same porosity. The recharge part of the system appears to be unconfined, which is reflected in a large mass storage coefficient and, therefore, depends on its area instead of its volume (Axelsson, 1989). The storage coefficient of the third tank in the closed model corresponds to an area of 3.0 km^2, assuming 7 % porosity, as before. The volume of the Thelamörk reservoir is small compared to the volume of some of the other reservoirs utilized by Nordurorka. The Laugaland system, for example, which is the largest of the five, has an estimated volume of 33 km^3 (Axelsson *et al.*, 1988).

The properties of the flow conductors (σ_1 and σ_2) can be used to estimate the reservoir permeability by assuming a given reservoir geometry. By assuming radial flow in a conventional Theis reservoir with thickness 1500 m the permeability between the first and second tank is 36 mD, and 1 mD between the second tank and the recharge part. The latter value is in good agreement with the value obtained by the pressure transient analysis, as presented above, and also with earlier findings (Björnsson *et al.*, 1994).

Predicted water level changes

In order to reassess the production capacity of the Thelamörk field, after the deepening of well LÞN-10, the lumped parameter model were used to predict the future water level changes due to long-term production. Figure 7 shows two cases of constant 19 and 21 l/s production for both the open two-tank model and the closed three-tank model.

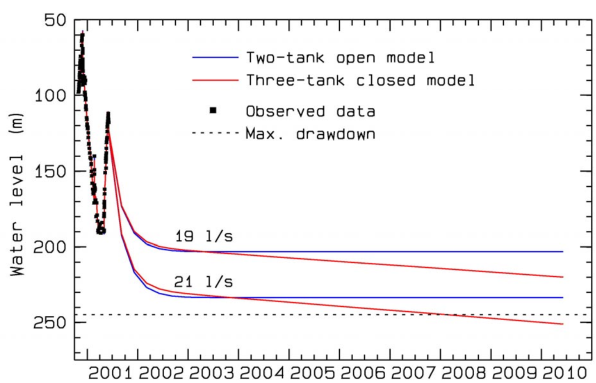

Figure 7: Predicted water level changes in well LÞN-10 due to constant 19 and 21 l/s production, according to the open two-tank model and the closed three-tank model.

As seen on the figure, the open model gives more optimistic forecasts than the closed model. According to both models the field is capable of sustaining constant 20-21 l/s production of 103°C water through the year 2009, with a draw-down less than 245 m, which is the limit set by the down-hole pump presently installed. If, however, a new pump, which can withstand 300 m draw-down is installed, the field should be able to sustain a constant 24-25 l/s production up to the same time.

THE 1993 RESERVOIR ASSESSMENT

After the drilling of well LÞN-11 in 1992 a nine-month production test was performed along with partial reinjection and tracer tests, as already mentioned. The data collected were analyzed through simple reservoir models comparable to the ones used in this study. Detailed information on the 1994 assessment is provided by Björnsson e*t al.* (1994).

A closed three-tank lumped parameter model simulated the water level changes resulting from the 1992-1993 production test and was used to calculate water level predictions. In 1999 the reliability of the 1993 model was scrutinized by comparing the response of the model to the production history up to that time with water level changes measured in well LÞN-11 (Axelsson *et al.*, 1999). The results are presented in Figure 8. They show a fairly good agreement with the model prediction being somewhat pessimistic, as planned. Thus it appears that this kind of lumped parameter modeling is fully reliable, if based on adequately long data sets.

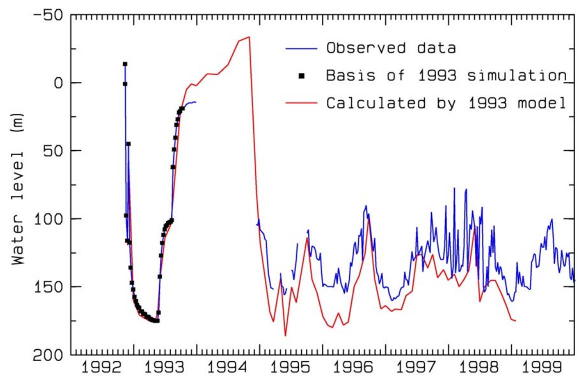

Figure 8: A comparison of observed water level changes in well LÞN-11 and changes calculated by the 1993 lumped parameter model. Black dots indicate the water level data from the production test that were used in the simulations (Axelsson et al., 1999).

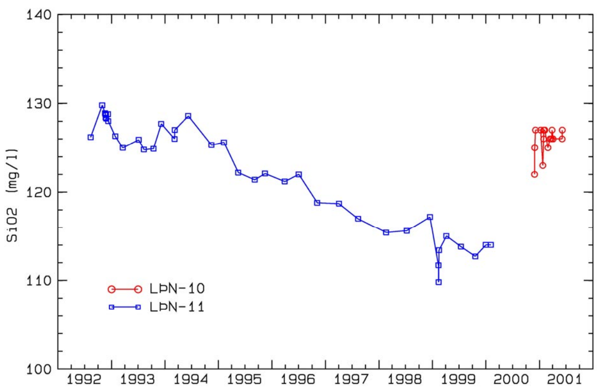

Figure 9: Silica concentration in water produced from wells LÞN-10 and LÞN-11.

Careful monitoring of chemical changes during the 1992-1993-production test pointed to some inflow of colder water into the Thelamörk reservoir during production (Björnsson *et al.*, 1994). This was used as the basis for cooling predictions for well LÞN-11, included in the 1994 reservoir assessment. A few degree cooling was predicted causing a slight decline in the potential estimate for the well. No such cooling has been noted yet, but chemical changes indicate that the colder inflow is continuing (see Figure 9), which would certainly have caused well LÞN-11 to cool down eventually. Chemical data from well LÞN-10 indicates undisturbed reservoir conditions for that well. Colder inflow is not expected to influence the much deeper feed-zone in well LÞN-10 significantly in the near future.

INCREASED PRODUCTION POTENTIAL

Prior to the deepening of well LÞN-10 the Thelamörk field could sustain constant 17 l/s production of 91°C water, through well LÞN-11, with a water level draw-down less than 245 m. This corresponds to an energy production potential of 4.4 MW_t (based on an average return water temperature from houses in Akureyri of 27°C (Flovenz et al., 1995B)) After the deepening of well LÞN-10 the energy production potential is estimated to be 6.4 MW_t.

Therefore the main result of this study is that the energy production potential of the Thelamörk field has increased from 4.4 MW_t to 6.4 MW_t, or by 45%, by the deepening of well LÞN-10. This is on one hand due to greater productivity of the 1700 m feed-zone in well LÞN-10 than the 450 m feed-zone in well LÞN-11 and on the other hand due to higher water temperature.

The possibility of utilizing reinjection to sustain reservoir pressure and enhance heat mining was studied as part of the Thelamörk assessment in 1993 (Björnsson *et al.*, 1994). The main result was that this could be achieved to a small degree through small-scale injection into two shallow wells in the area. Large-scale reinjection did not seem possible because of the short distances, and direct connections between feed-zones, involved. Now the situation has changed drastically because the main feed-zone of well LÞN-10 is located at 1-1.5 km greater depth than the feed-zones of the shallow wells in the area. Therefore long-term reinjection of the order of 5-15 l/s should be possible, without posing a too great cooling risk for well LÞN-10. This could perhaps enhance the production potential of the field by ~50%.

SUMMARY AND CONCLUDING REMARKS

In August 2000 an old well, LÞN-10, in the Thelamörk geothermal field in N-Iceland was deepened towards the principal fracture-zone of the system. The well intersected a good feed-zone with reservoir temperature of 103 °C. The main results of an analysis of a five-month production test performed in order to reassess the energy production potential of the field can be summarized as follows:

- Water level data collected during the production test were simulated with two lumped reservoir models, an optimistic open two-tank model and a pessimistic closed three-tank model. Both models simulate the data equally well.
- The model mass storage coefficients indicate a reservoir volume of the order of 1 km^3. The fluid flow coefficients of the models reflect an overall average permeability of about 1 mD.
- The geothermal reservoir appears to be connected to a constant pressure source or a hydrological system with great storage capacity.
- The models indicate that the field should be able to sustain a constant 20-21 l/s production through the year 2009.
- A comparison of water level changes calculated by a lumped parameter model from 1993 show a fairly good agreement with the observed water level history through 1999. Thus it appears that this kind of modeling is fully reliable, if based on adequately long data-sets
- The estimated energy production potential of the Thelamörk field has increased from 4.4 MW_t to 6.4 MW_t, or by 45%, through the deepening of well LÞN-10.
- Colder inflow is not expected to influence the well LÞN-10 significantly in the near future in contrast with well LÞN-11.
- Significant long-term reinjection should now be possible in the Thelamörk field, without posing a too great cooling risk for well LÞN-10. This could perhaps enhance the production potential of the field by ~50%.

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