ORKUSTOFNUN

Testing of geothermal well F-3001, Beius (Romania). Assessment of the potential of the reservoir

Guðni Axelsson,
Magnús Ólafsson,
Halldór Ármannsson

Greinargerð GAx-MÓ-HÁ-2000-01

ORKUSTOFNUN
Greinasafn

TESTING OF GEOTHERMAL WELL F-3001, BEIUS (ROMANIA)

ASSESSMENT OF THE POTENTIAL OF THE RESERVOIR

Gudni Axelsson, Magnus Olafsson and Halldor Armannsson
Orkustofnun (National Energy Authority),
Grensasvegur 9, IS-108 Reykjavik, Iceland
e-mail: gax@os.is, phone: +354-569-6000

INTRODUCTION

Well F-3001 is located in the SE-part of the town of Beius in W-Romania. It was drilled in 1995 and 1996 to a depth of 2576 m. It intersected a productive geothermal reservoir between the depths of 1850 and 2460 m. The reservoir is embedded in fractured Triassic limestone and dolomite, with reservoir temperatures between 75 and 88°C. The existence of the geothermal reservoir is believed to result from a relatively good permeability of the fractured reservoir rocks, on one hand, and an above average heat-flow, on the other. Beius is located about 65 km south-east of the city of Oradea where 12 geothermal wells have been drilled into a geothermal reservoir of a comparable nature. The well is cased by a 13 $^{3}/_{8}$" casing to a depth of 914 m and by a 9 $^{5}/_{8}$" casing to 1873 m depth. Below that the well is open, drilled by an 8 $^{1}/_{2}$" drill-bit.

Well F-3001 was extensively tested, through the use of a down-hole pump, during the period from April 28th through September 23rd 1999. This report describes the results of an assessment carried out by Orkustofnun for the Beius geothermal reservoir, mainly on the basis of data collected during the pumping test of well F-3001. Some limited additional data were also considered. The principal purpose of the reservoir assessment was to estimate the long-term production potential of well F-3001 by predicting future water level changes for different production scenarios. In addition an attempt would be made to foresee undesirable chemical changes and reservoir cooling during long-term production, if applicable. The main phases of the reservoir assessment were:

1. Compilation of data collected during the six-month test period.
2. Analysis of production characteristics of the well, i.e. near-well and turbulence pressure losses.
3. Development of a very simple qualitative conceptual model of the geothermal system, based on available geological data and the results of the production test.
4. Simulation of the well-test data by simple but reliable models (lumped parameter models or other analytical models).
5. Simple models used to predict the water level changes in well F-3001 for different future production scenarios, including realistic scenarios with a seasonally varying rate of pumping.

6. Simple models used to investigate the effects of drilling of additional production wells. The effects of re-injection, i.e. water level recovery and declining production temperatures, will be investigated.
7. Analysis of chemical data, with emphasis on estimating the potential for scaling and corrosion, future chemical changes and possible reservoir cooling.

Preliminary results of this assessment has been presented by Axelsson (1999a & b).

Some limited older data are available on the response of the well to production from a short well-test in 1996 (Societatea Comerciala Foradex, 1996). These data are somewhat contradictory, however, but indicate that the water level draw-down in the well, during pumping of about 12 L/s for a period of 20 days, was between 10 and 30 m. Therefore, it appeared that the down-hole pump needed to be located at a depth of 150 m or so. The water level decline during the planned production of up to 50 L/s was highly uncertain before the test, however. Based on these older data the permeability-thickness of the production reservoir had been estimated at 28 Darcy-m or more. This indicated that the reservoir permeability was moderately high and that long-term water level draw-down should be slow, or of the order of 20 - 30 m during the proposed testing period.

THE PRODUCTION TEST

A down-hole pump was installed at a depth of 149 m in well F-3001, for the purpose of testing the well and the geothermal reservoir. It was proposed that the testing should be carried out for a period of up to six months. The initial plan for the production test involved the following:

1. An initial period where the pumping was increased in steps from 10 to 50 L/s. A total of 9 steps was suggested, i.e. 10, 15, 20, ..., 45, 50 L/s, each of a few hours duration.
2. Long-term pumping at a constant rate of 50 L/s for a period of up to 5 months.
3. A final stage of no pumping during which the water-level/pressure recovery of the geothermal reservoir will be monitored for up to one month.

Careful monitoring of the response of the well and reservoir during the well test was of paramount importance for the project. The following was proposed:

A. Accurate measurements of the rate of pumping, water level in the well and the water temperature.
B. Measurements of the bottom-hole pressure changes during the first and third part of the test. Temperature- and pressure logs during all three parts of the test (i.e. three runs).
C. Collection of water samples for chemical analyses. These may be sampled as frequently as every two weeks and analysed in a local laboratory. However, at least two additional samples should be collected, during the early and late stage of the well test, and sent to Orkustofnun in Iceland for full analysis.

The production test of F-3001 was carried out mostly according to this plan. Due to technical reasons measurements of bottom-hole pressure changes (B) were not possible. Therefore, water level measurements had to suffice. These do not provide as accurate information on the reservoir pressure, principally because of thermal expansion or contraction of the water column in the well when it is cooling down after pumping is stopped or heating up after pumping is started, respectively. Thus the final pressure recovery phase (3) was not as long as originally planned. This was also influenced by the behaviour of the geothermal reservoir, which of course was not known beforehand (see later).

For the same technical reasons temperature- and pressure logs (B) were only measured prior to the test. The number of chemical samples (C) was not as high as initially planned, because the samples collected were all analysed at Orkustofnun. These will be discussed later.

Two temperature logs from well F-3001 are presented in Figure 1. The first one was measured in August 1996 while the well was actually flowing during the pumping test mentioned earlier. The second one was measured in March 1999, prior to the test discussed here. In the latter case the well was static, and the temperature log should reflect the undisturbed temperature conditions in the sedimentary formations around the well.

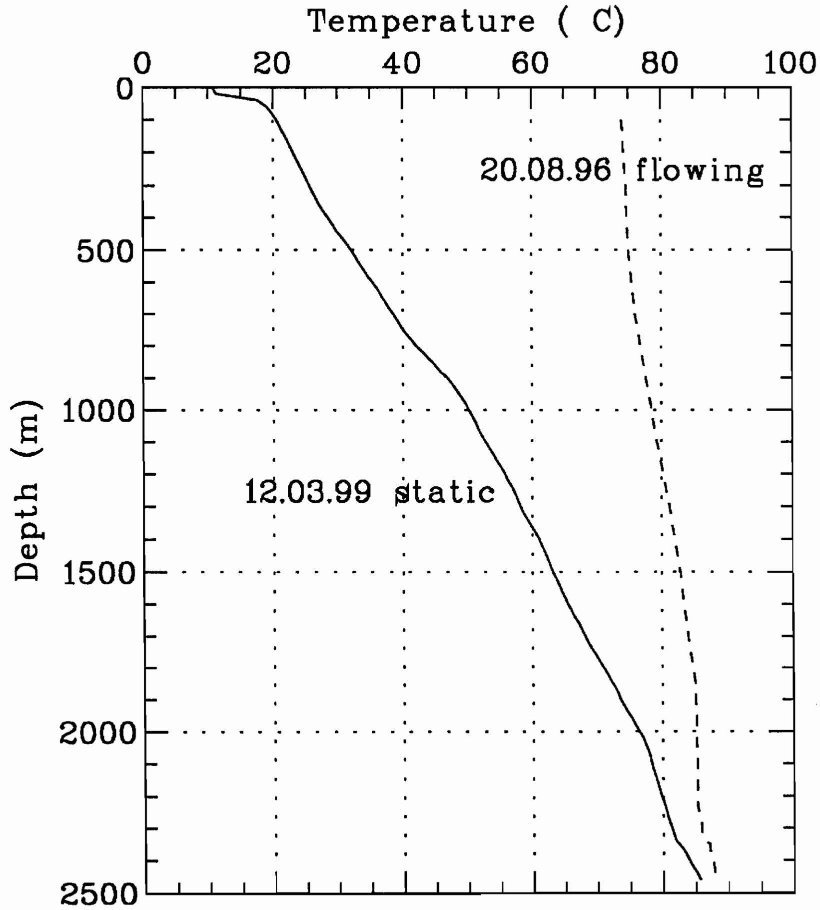


Figure 1. Two temperature logs from well F-3001.

These two logs can be used to estimate the difference in water level between a hot and a cold well, by taking into account the density variations down the well, but assuming no-flow conditions in both cases. This is accomplished through using the computer program PREDYP, which is part of the ICEBOX computer software package (United Nations University Geothermal Training Programme, 1994). The results of such calculations indicate that the difference in water level depth for these two states of the well can be as great as 30 - 40 m.

The production and water level data collected during the test are presented in figures 2 through 4. Figure 2 shows the cumulative production, which reached 508,000 m^3 during the test. This corresponds to an average flow rate of 39.6 L/s. Figure 3 shows the measured flow rate, which was measured daily except for periods of higher measurement frequency, when the pumping was changed or stopped. Figure 4 shows the measured water level, which was measured by measuring the pressure at the depth of the pump (149 m) utilising pressurised nitrogen. Therefore, the water level in the following figures and text is presented as pressure at 149 m depth. To convert that to depth to water level one can use:

$$\text{water level depth (m)} = 149 \text{ m} - p/0.095, \quad p \text{ in bars}$$

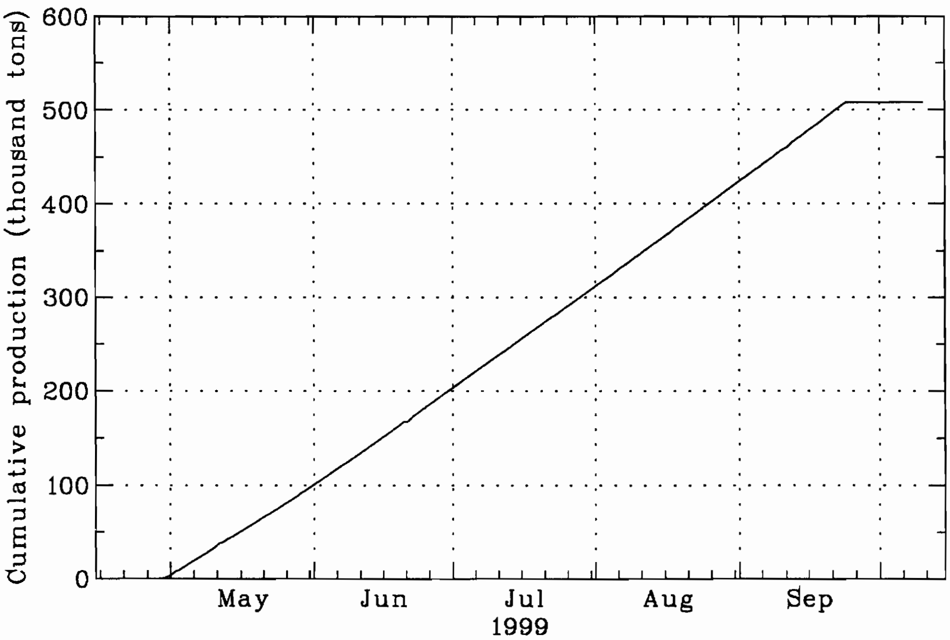


Figure 2. Cumulative production during the production test.

In addition, the water temperature was monitored carefully during the test. Figure 5 shows the variations in the temperature during the first days of the production test. It rose rapidly during the first hours of the test and had reached about 80°C after about 24 hours. This is because of conductive cooling of the water flowing up the borehole, which slowly decreases with time, because the formation around the well is being slowly heated up by the hot water flowing up the well. Since the 29th of April, the second day of the test, the water temperature has been almost stable at 80°C. Some variations in water temperature reflect variations in pumping rate. This is also because of conductive cooling, which decreases with increasing flow-rate.

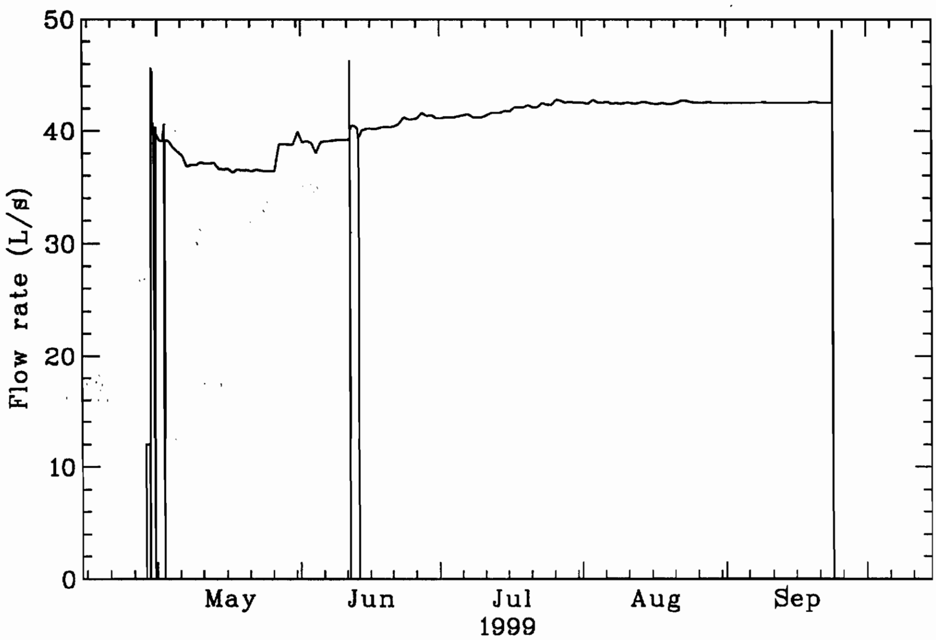


Figure 3. Measured flow-rate during the production test.

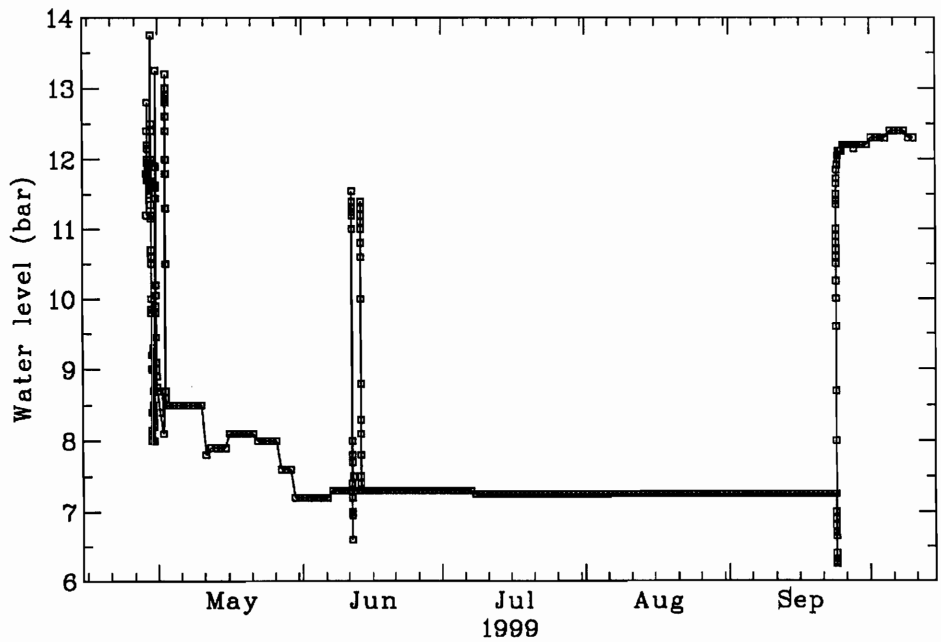


Figure 4. Measured water-level during the production test.

During most of the production test pumping rates between 36 and 42 L/s (Figure 3) were applied. The response of the well to greater production rates (up to 49 L/s) was tested for shorter periods of time at the beginning of the test, during the middle of

June and at the end of the test. Pumping was also stopped for brief periods. These variations in pumping rate are reflected in the water level changes, presented in Figure 4. At the end of the test, when pumping had been discontinued, the water level recovery in the well was monitored carefully for about three weeks. Such recovery data may usually be analysed to provide information on the hydrological properties of the reservoir in question. In this case the recovery data do not reflect pressure variations in the reservoir directly, due to the thermal contraction of the water column in the well which was discussed earlier. During testing of well F-3001 pumping was active for 3504 hrs of the 3557 hrs test period, i.e. for 98,5% of the time.

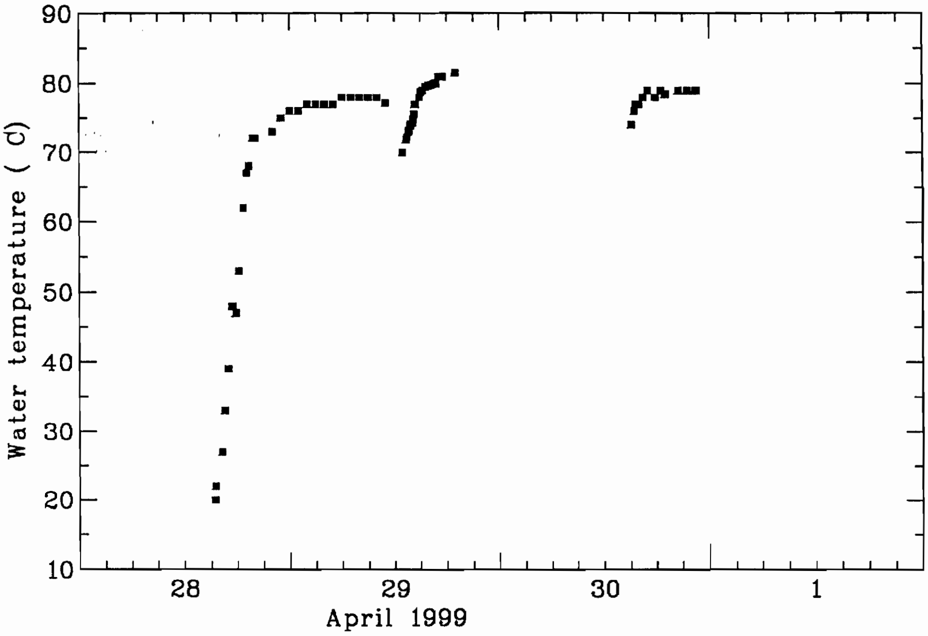


Figure 5. Measured water-temperature during the first days of the production test.

On April 29th, the second day of the test, the flow rate from the well was increased in several steps, constituting a step-rate test of the well (A). This was done in order to estimate the production characteristics of the well, in particular the turbulence pressure losses in the well. It should be pointed out that this was not done right after pumping from the well started, on April 28th, to avoid water level transients resulting from the heating up of the well. The results of this test are presented in Figure 6, which shows the water level as a function of flow rate. Fitted through the data points is a second order polynomial:

$$p = 13.80 - 0.0621 \times q - 0.00143 \times q^2$$

where p is the pressure at the pump depth in bars and q is the flow rate in L/s. The second order term results from the turbulence pressure losses in the well and the fractures feeding the well. These losses are, therefore, 0.00143 bar/(L/s)^2 or 0.0151 m/(L/s)^2.

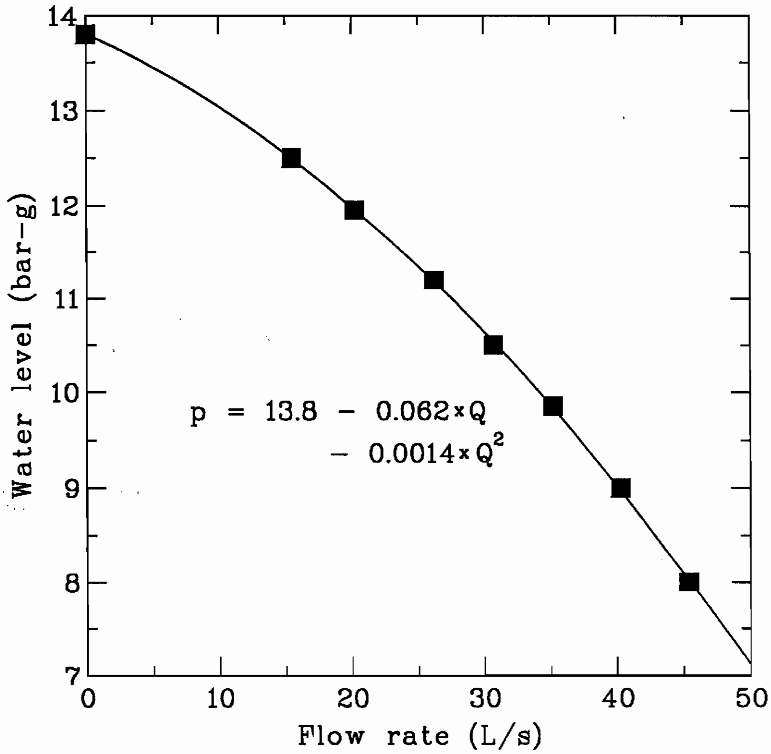


Figure 6. Results of a step-rate test of well F-3001 on April 29th 1999.

SIMPLE CONCEPTUAL MODEL

A conceptual model of a geothermal system is a qualitative, or descriptive, model. It should incorporate the essential features of a geothermal system that have been revealed by analysis of all available data. A conceptual model is not used for calculations, but provides the foundation for later quantitative, or numerical, models. Very limited direct data are available on the structure of the Beius geothermal reservoir, which can be used to construct a conceptual model of the system. This is because well F-3001 is the only well drilled so far in the area. The local participants in the project provided valuable information, however, that was used in developing such a model, in particular on the structural geology of the area (Stefan Olá, 1999). The data collected during the production test, of course, also add to the understanding of the system.

Only a highly simplified conceptual model of the Beius reservoir was developed for the purpose of the present reservoir evaluation. A sketch of this is presented in Figure 7. The Beius reservoir is composed of Triassic limestone and dolomite. It is extensive in area and semi-horizontal, according to the conceptual model. Its thickness is about 500 - 600 m. The reservoir rocks, which are found below 2000 m depth in well F-3001, reach the surface in the Codru – Moma mountains 8 – 10 km west of Beius. Precipitation in the mountains is believed to provide the main recharge to the Beius reservoir as shown in Figure 7. The conceptual model postulates additional recharge from depth through faults intersected by well F-3001. This is in fact supported by the results of the pumping test, as will be discussed later. The final aspect of the conceptual model is an impermeable boundary a few km east of well F-3001 (Figure 7). The nature of the Beius geothermal reservoir is also believed to be controlled, to a significant degree, by the tectonics of the region. On one hand, fracturing on a small spatial scale enhances the reservoir permeability. One the other hand, major faults may also play a significant role even though they are not included in the present conceptual model.

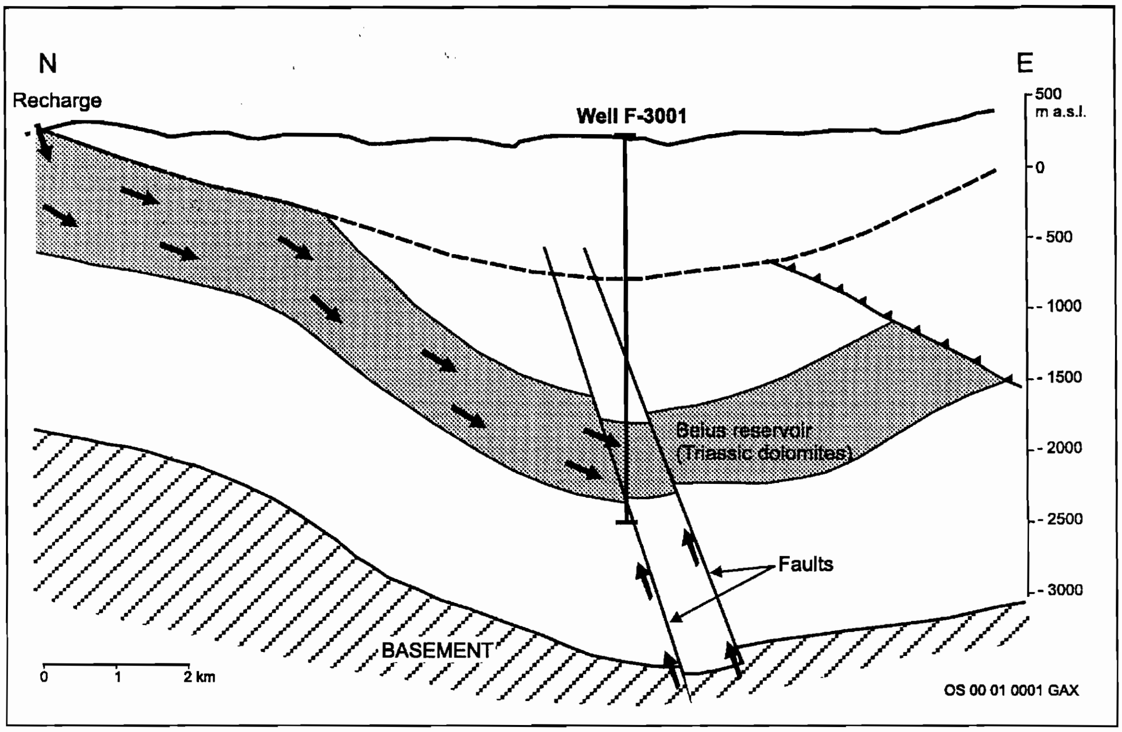


Figure 7. A simple conceptual model of the Beius geothermal reservoir depicted through an E-W cross-section (partly based on information provided by Stefan Olá, 1999).

LUMPED PARAMETER MODELLING OF TEST DATA

Background

Simple analytical models as well as complex numerical models are used to simulate geothermal systems (Bodvarsson *et al.*, 1986, Axelsson *et al.*, 1996). In simple models the real structure and spatially variable properties of a geothermal system are greatly simplified, such that analytical mathematical equations, describing the response of the model to hot water production may be derived. These models, in fact, often only simulate one aspect of a geothermal systems response. Detailed and complex numerical models, on the other hand, can accurately simulate most aspects of a geothermal systems structure, conditions and response to production. Simple modelling takes relatively little time and only requires limited data on a geothermal system and its response, whereas numerical modelling takes a long time and requires powerful computers as well as comprehensive and detailed data on the system in question. The complexity of a model is determined by the purpose of a study as well as the data available.

Simple modelling has been used extensively to study and manage the low-temperature geothermal systems utilised in Iceland, in particular to model their long-term response to production. Lumped models, in particular, have been used extensively to simulate data on water level and pressure changes in these geothermal systems. Lumped models can simulate such data very accurately, even very long data sets (several decades). Axelsson (1989) has described a method that tackles the simulation as an inverse problem. It automatically fits the analytical response functions of the lumped models to observed data by using a non-linear iterative least-squares technique for estimating the model parameters. Being automatic it requires very little time compared to other forward modelling approaches, in particular detailed numerical modelling. Today, lumped models have been developed by this method for 14 low-temperature and 2 high-temperature geothermal systems in Iceland, as well as geothermal systems in China, Turkey, Eastern Europe and El Salvador, as examples. Some examples of this are presented by Axelsson (1989 and 1991) and Bjornsson *et al.* (1994).

The theoretical basis of this automatic method of lumped parameter modelling is presented by Axelsson (1989), and in fact Bodvarsson (1966) discussed the usefulness of lumped methods of interpreting geophysical exploration data. The computer code LUMPFIT has been used since 1986 in the lumped modelling studies carried out in Iceland (Axelsson and Arason, 1992).

A general lumped model is shown in Figure 8. It consists of a few tanks and flow resistors. The water level or pressure in the tanks simulates the water level or pressure in different parts of the geothermal system. The resistors simulate the flow resistance in the reservoir, controlled by the permeability of its rocks. The first tank simulates the innermost (production) part of the geothermal reservoir, and the second and third tanks simulate the outer parts of the system. The third tank is connected by a resistor to a constant pressure source, which supplies recharge to the geothermal system. The model in Figure 8 is therefore open. Without the connection to the constant pressure source the model would be closed. An open model may be considered optimistic, since an equilibrium between production and recharge is eventually reached during long-term production, causing the water level draw-down to stabilise. In contrast, a closed model may be considered pessimistic, since no recharge is allowed for such a model and the water level declines steadily with time, during long-term production. In addition, the model presented in Figure 8 is composed of three tanks, in many instances models with only two tanks have been used.

Hot water is pumped out of the first tank, which causes the pressure and water level in the model to decline. This in turn simulates the decline of pressure and water level in the real geothermal system. When using this method of lumped parameter modelling, the data fitted (simulated) are the water level data for an observation well inside the well-field, while the input for the model is the production history of the geothermal field in question.

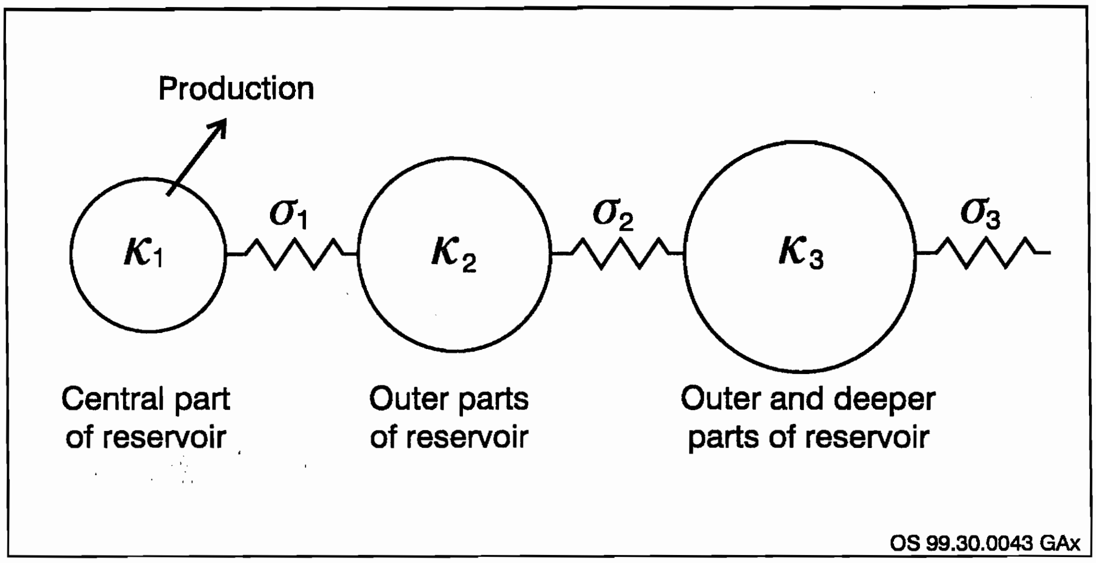


Figure 8. A general lumped parameter model used to simulate water level or pressure changes in geothermal systems.

Simulation of the Beius test data

The water level response of well F-3001 during the 5 month testing period was simulated by a lumped parameter model. The results of the simulation are presented in figures 9 and 10. The first figure presents the results of the simulation of the step-rate test that was conducted on April 29th. The second figure presents the whole test period. The model appears to simulate the data reasonably well. Some discrepancy is seen, however, both in the long-term pressure trend as well as during some short-term transients (not presented in detail). Part of this can most likely be attributed to lack of accuracy, and errors, in the water level measurements.

The water level data indicate that an equilibrium is reached during constant production. Therefore, an open model was required to simulate the data. In fact a two-tank model turned out to be sufficient. The properties of the model are presented in Table 1 below. These are the storage coefficients of the tanks, κ_i, which are defined such that if a mass m is removed from the tank the pressure in the tank drops by $\Delta p = m/\kappa_i$, and the conductances of the resistors, σ_i, which are defined such that the flow over a resistor $q = \sigma_i \Delta p$, where Δp is the pressure drop over the resistor. Tank number i simulates a volume of the reservoir V_i such that $\kappa_i = \rho_w c_t V_i$ where ρ_w is the density of the water in-place in the reservoir and c_t is the compressibility of the reservoir rocks given by $c_t = c_w\phi + c_r(1-\phi)$, where c_w is the water compressibility, ϕ the porosity and c_r the compressibility of the rock matrix. The volume $V_i = A_i h$ where A_i is the surface area of the corresponding part of the reservoir and h its thickness. Estimates of the volumes and areas are presented in Table 1.

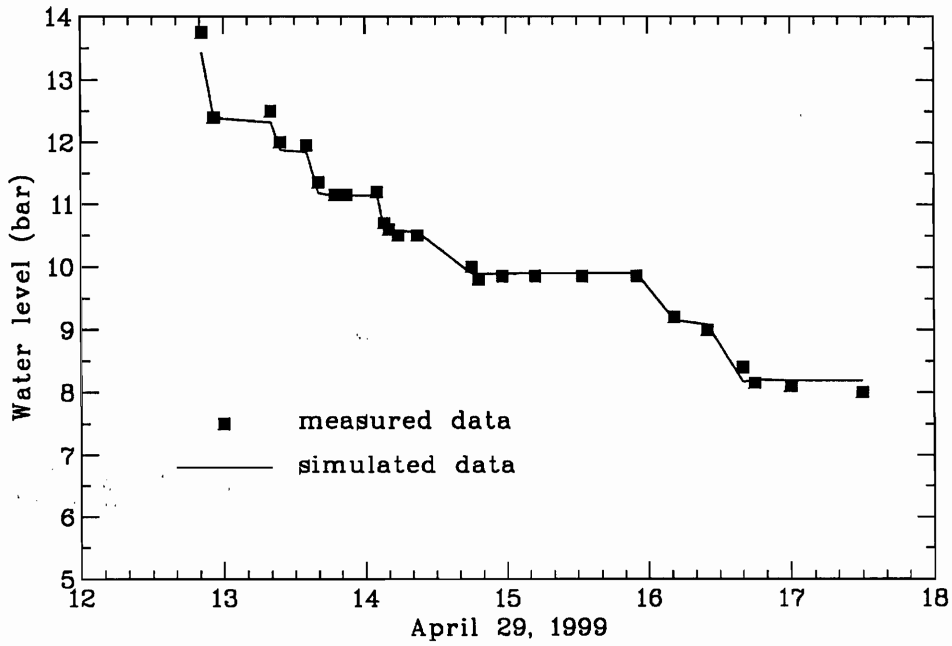


Figure 9. Water level changes in well F-3001, during the step-rate test on April 29th, simulated by the lumped parameter model.

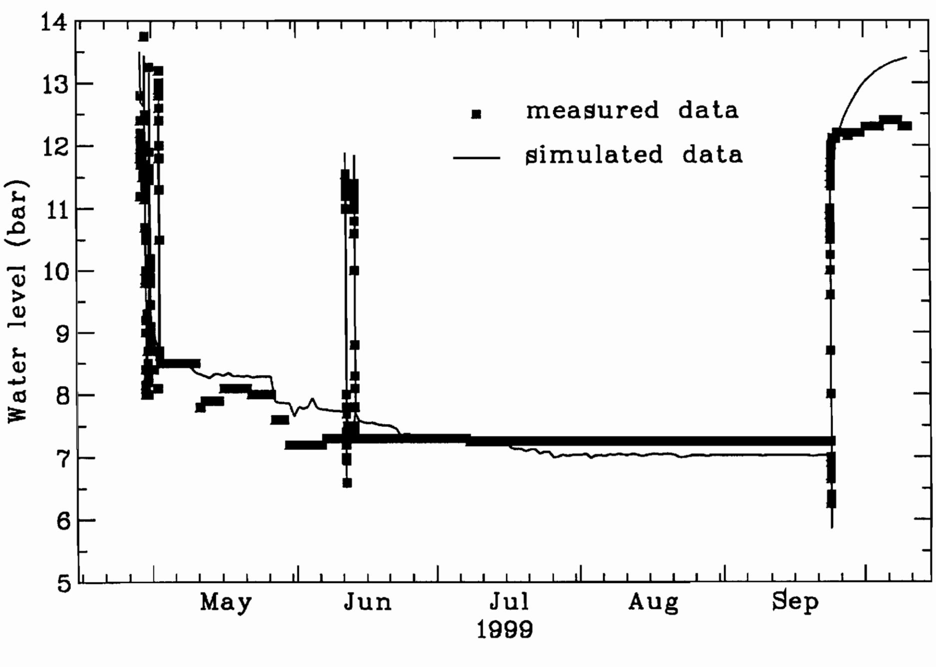


Figure 10. Water level changes in well F-3001, during the entire pump test, simulated by the lumped parameter model.

The reservoir permeability may be estimated on the basis of the σ-values. Assuming horizontal and radial flow between cylindrical tanks, $\sigma_i = 2\pi h(k/\nu)/\ln(r_{i+1}/r_i)$ with k the reservoir permeability, ν the kinematic viscosity of the water and r_i and r_{i+1}

estimates of the distances from one tank to the next. The permeability estimates are also presented in Table 1.

Table 1. *Properties of the lumped parameter model used to simulate the response of well F-3001 in Beius.*

Tank	κ_i (kg/Pa)	Volume[1)] (km^3)	**Surface area**[2)] (km^2)
1 2	0.022 115	0.000195 1.03	0.000390 2.05
Resistor	σ_i (kg/sPa)	r_{i+1}/r_i[3)] (m/m)	**Permeability**[4)] (Darcy)
1 2	0.000195 0.000232	410/5.5 1210/410	0.099 0.030

1) Assuming $\phi = 0.2$ (20%) and $\rho = 970$ kg/m^3
2) Assuming h =500 m for both tanks
3) Distances between tanks
4) Assuming h = 500 m and $\nu = 3.7 \times 10^{-7}$ m^2/s

The surface area of the first tank is very small, corresponding to a radius of only 11 m or so. Therefore, the first tank only corresponds to a small reservoir volume next to well F-3001. The surface area of the second tank is about 2 km^2, which is equivalent to a circular area with a radius of about 800 m. This is a much smaller area than the area of the Beius reservoir implied in the conceptual model. The implications of this will be discussed below.

The most important parameter of any hydrological reservoir is its permeability. The permeability estimates in the table are 0.1 and 0.03 Darcy, the higher value corresponding to the region next to the well and the lower value corresponding to the geothermal reservoir in general. The equivalent permeability thickness (kh) estimates are 50 and 15 Darcy-m, the lower value again corresponding to the reservoir in general. These values may be compared to the permeability thickness estimate from 1996 mentioned above, 28 Darcy-m. The present estimate is about half of the older value. Based on these estimates the permeability thickness of the Beius reservoir appears to be about average, compared to other productive geothermal reservoirs.

Figure 11 shows the calculated response of the lumped model, which clearly shows how it reaches equilibrium after about three weeks of constant production. The reason for this is a connection of the production reservoir to some hydrological system that maintains constant pressure. This could be a large, more permeable, geothermal system or the ground water system in the region around Beius. According to the conceptual model this could either be the extension of the reservoir formation up to the recharge area in the mountains to the west of Beius or the recharge from depth through the fractures intersected by well F-3001 (Figure 7). The small radius deducted from the size of the lumped parameter model (800 m) indicates that the recharge from depth is responsible for the equilibrium rather than the postulated recharge area in the mountains. A third, but unlikely, possibility is that a connection exists up to shallower ground water systems through the same fractures. If that was the case some chemical indications should appear. The changes in chemical content of the hot water produced during the pumping test are discussed in a later section.

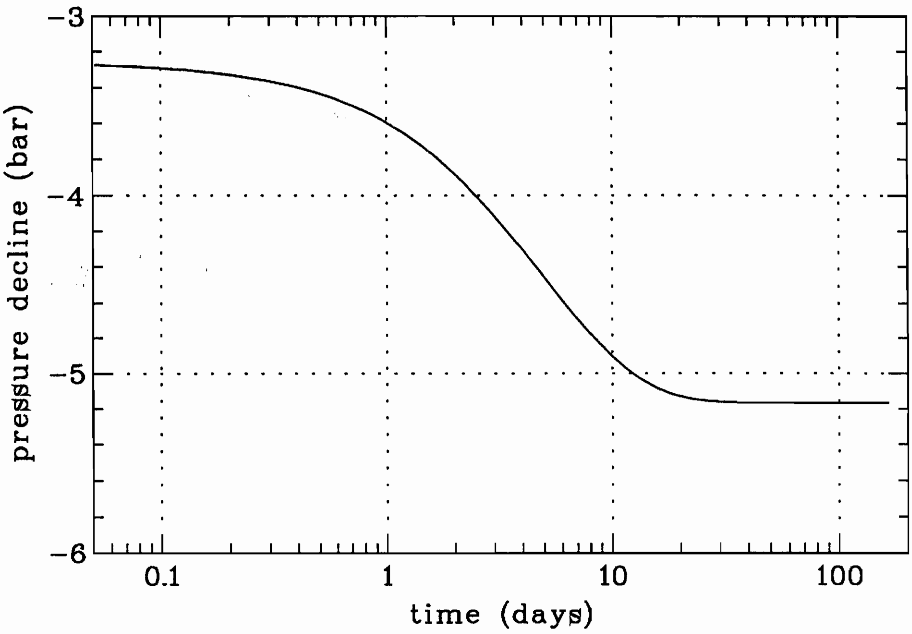


Figure 11. Calculated pressure decline of the lumped parameter model during steady 40 L/s production, logarithmic time-scale.

Potential of well F-3001

The fact that the water level in well F-3001 reaches an equilibrium during long-term production is highly important. Therefore, no long-term draw-down is expected in the Beius geothermal reservoir, during constant-rate production. This fact also makes it easier to predict the long-term draw-down in the well, since it is independent of time. The result of this prediction is presented in Figure 12, which shows the draw-down as a function of flow-rate. The difference between the predicted curve (Figure 12) and the data from April 29th (Figure 6) results from the additional draw-down occurring during long-term production (up to three weeks). The equations describing the draw-down are the following:

$$\Delta p = 0.0990 \times q - 0.00143 \times q^2, \quad \text{in bar}$$
$$\Delta h = 1.04 \times q - 0.0150 \times q^2, \quad \text{in m}$$

It may be pointed out that 3.6 bar of a total draw-down of 8.5 bar, during 50 L/s production, result from turbulence pressure losses.

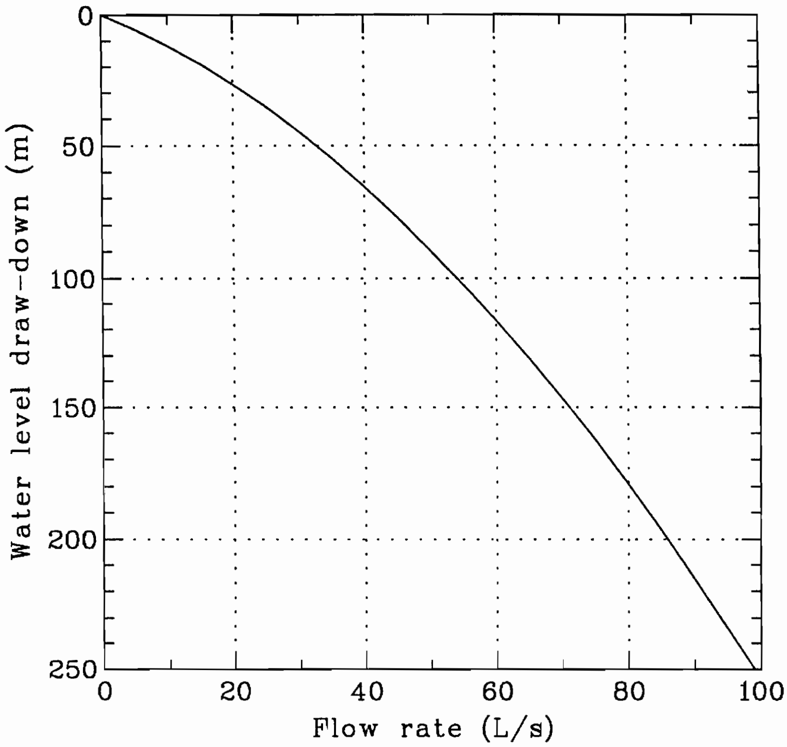


Figure 12. Production potential of well F-3001 presented as predicted water level draw-down as a function of production.

The figure shows that with a pump at a depth of 150 m, the potential of well F-3001 appears to be about 60 L/s. In addition the results indicate that with a pump at a depth of 250 m the production potential of the well should be about 90 L/s. These figures allow for a 20 - 25 m water column above the pump in each case. It should be pointed out that Figure 12 indicates the short-term (weeks) as well as the long-term (years) potential of the well because it reaches equilibrium relatively fast.

The production potential of a geothermal not only depends on water-level or pressure draw-down. In some instances the potential of geothermal wells decreases because of reservoir cooling caused by colder water inflow. Such cases are relatively rare, however. Cooling may often be detected beforehand through long-term chemical changes, as will be discussed later. Therefore, careful monitoring of the chemical content of the water produced from well F-3001 is highly important in the future. Significant cooling of the water must be considered unlikely, however, because of the depth of the reservoir.

ADDITIONAL PRODUCTION WELLS

Production from the Beius geothermal reservoir may certainly be increased by drilling additional production wells in the area in the future. An attempt has been made to estimate how much this will increase the production potential of the reservoir. Estimating the potential of additional production wells and the combined production potential of two or more wells, is more difficult and uncertain than estimating the potential of well F-3001 alone. This is principally because of the difficulty of estimating the interference between wells. No wells are, in fact, available in the area, for actually measuring this interference. All estimates in this regard are, therefore, highly uncertain at this stage. Yet the potential of wells drilled close to well F-3001 (within a distance of a few km) may be expected to be quite similar to that of well F-3001. The combined potential is, however, less than the sum of the potentials of each of the wells.

A few simple models have been set up, or developed, for the purpose of estimating this interference and the combined potential of a few production wells (Axelsson 1999a and 1999b). These are: (1) a model of an infinite horizontal reservoir with a permeability-thickness of 15 Darcy-m, (2) a model of an infinite, but leaky, reservoir that reaches a draw-down equilibrium and (3) a model of a horizontal reservoir with a constant pressure as well as a no-flow boundary. Results based on calculations by the third model will be presented here. A schematic figure of this model is presented in Figure 13. It attempts to incorporate the possible recharge to the reservoir in the hills and mountains west of Beius, by a constant pressure boundary. A closed boundary is also included to the east of Beius in accordance with the conceptual model (Figure 6). This model reaches equilibrium during long-term production, but neither as fast as is the case with well F-3001 nor as fast as the second model mentioned above. Of the three models the first one predicts the greatest interference while the second one predicts the smallest interference. The model used here (model 3) predicts interference in-between the predictions by the other two models. Therefore, that model was chosen here. It may predict somewhat greater interference than will be the case in reality, i.e. yield slightly pessimistic predictions. This, however, is highly uncertain at the moment.

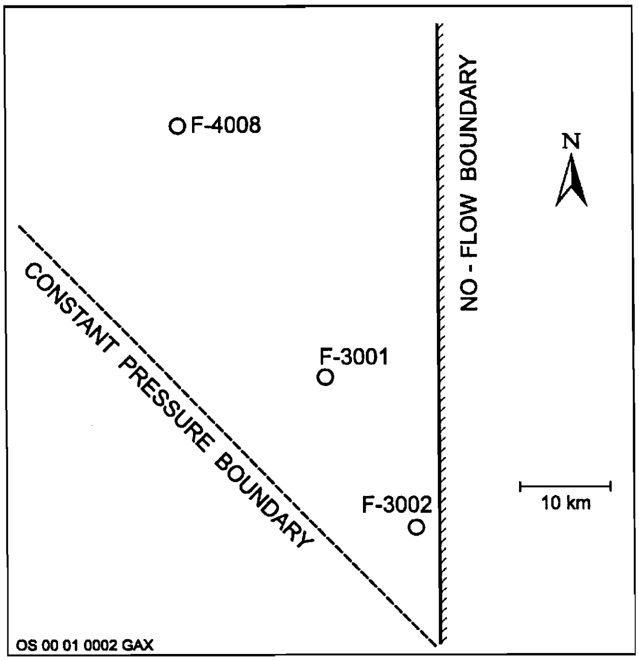


Figure 13. The reservoir model used to estimate the long-term interference between wells drilled into the Beius geothermal reservoir.

The long-term pressure draw-down in the model presented in Figure 13 is calculated by:

$$\Delta p = (Qv/2\pi kh)\ \{\ \ln (R_1 \cdot R_2 \cdot R_3 \cdot R_4) - \ln (r \cdot r_1 \cdot r_2 \cdot r_3)\ \}$$

where Q is the flow-rate from the production well and r is the distance from the production well to the observation well where the draw-down, or interference, is to be calculated. The distance is calculated by:

$$r^2 = (x - x_0)^2 + (y - y_0)^2$$

with x and y the coordinates of the observation well and x_0 and y_0 the coordinates of the production well. The other r_i's and R_i's are distances to image wells required for the calculations, which are defined by:

$$\begin{aligned}
r_1^2 &= (x + x_0)^2 + (y - y_0)^2 \\
r_2^2 &= (x - x_0)^2 + (y + y_0)^2 \\
r_3^2 &= (x + x_0)^2 + (y + y_0)^2 \\
R_1^2 &= (x - y_0)^2 + (y - x_0)^2 \\
R_2^2 &= (x - y_0)^2 + (y + x_0)^2 \\
R_3^2 &= (x + y_0)^2 + (y - x_0)^2 \\
R_4^2 &= (x + y_0)^2 + (y + x_0)^2
\end{aligned}$$

Figure 14 presents the long-term interference calculated by this model, due to a well constantly producing 50 L/s, as a function of distance from the well. It can also be used to estimate the interference in cases of greater or lower production rates through multiplying the draw-down in the figure by the corresponding flow-rate ratios. These results may now be used to estimate the interference between well F-3001 and other wells that may be drilled in the Beius area in the future, as well as to estimate the combined production potential of several wells.

Plans are available, which assume that two more production wells, and one injection well, will be drilled in Beius. These wells will here be called F-2, F-3 and F-I, respectively. The two production wells are located on the south and north-west sides of Beius, at distances of approximately 1100 and 2500 m from F-3001, respectively. The distance between wells F-2 and F-3 is about 1600 m. The injection well is located on the north-east side of Beius at a distance of 1600 m from F-3001, a distance of 1300 m from F-2 and a distance of 1100 m from F-3. Now the model (Figure 13) may be used to estimate pressure changes, and the production potential, for several production scenarios. The results of three such cases are presented here:

1) A constant production of 40 L/s from each of the three wells with a cumulative production of 120 L/s.
2) A production of 50 L/s from each well with a cumulative production of 150 L/s.
3) A production of 70 L/s from each well with a cumulative production of 210 L/s.

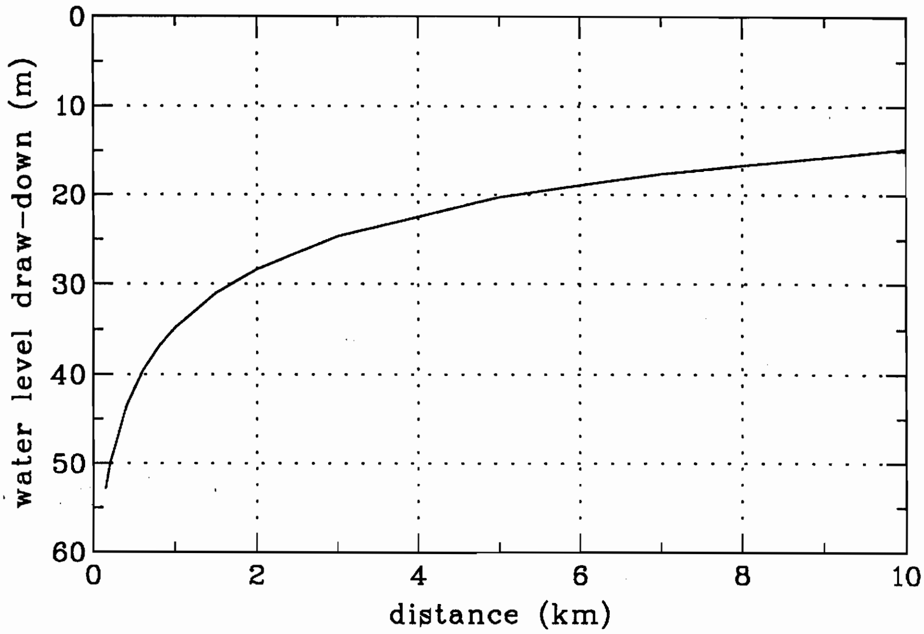


Figure 14. Estimated long-term interference from a production well producing 50 L/s as a function of distance between wells.

Table 2 below presents the results of the calculations for each of these cases. Only the results for well F-2 are presented:

Table 2. *Results of calculations of the combined water level (in m) draw-down in well F-2 due to production from three production wells in Beius. Wells F-2 and F-3 are not drilled yet.*

Scenario	Due to production from well itself	Interference from well F-3001	Interference from well F-3	Combined water-level draw-down
1) 3 x 40 L/s	66	27	24	117
2) 3 x 50 L/s	90	34	30	154
3) 3 x 70 L/s	146	48	43	237

These results indicate that for a combined production of 120 L/s from these three wells (40 L/s each) the additional draw-down due to interference may be close to 50 m, and that pumps in the wells would need to be located at a depth of about 140 m or more. For a combined production of 150 L/s the estimated additional draw-down equals about 65 m, and pumps in the three wells would need to be placed at about 180 m depth. Finally, the results in Table 2 indicate that for a combined production of 210 L/s from these three wells (70 L/s each) the additional draw-down due to interference may be about 90 m, and that pumps in the wells would need to be located at a depth of at least 260 m.

In addition, the results in Table 2 indicate that the combined production potential of the three geothermal wells suggested for Beius would be of the order of 120 L/s with pumps at a depth of 150 m. This is twice the potential of a single well. The results also indicate that the combined production potential of these three wells would be of the order of 200 L/s with pumps at a depth of 250 m. This is again about twice the potential of a single well. It must be emphasised, however, that these results are highly uncertain and that they should only be considered as very rough estimates. A greater interference than predicted by the model will result in a smaller combined yield, while lesser interference will enable greater combined pumping.

More wells will, of course, add more to the combined production potential of geothermal wells in Beius. If a maximum pump depth of 250 m is assumed, a fourth production well must be drilled to raise the combined potential above 200 L/s. If the fourth well is not located too close to the other three wells the combined production potential may be expected to increase to about 250 L/s.

It should be mentioned that significant information, which may help provide more accurate answers to this question, could come from Oradea, where several geothermal wells have been drilled into a comparable reservoir. It is unknown to the authors, however, whether any interference data are available from these wells. This should be looked into before more wells are drilled in the Beius area.

REINJECTION

Water injection is presently an integral part of field operations in more than 25 geothermal areas world-wide (Axelsson and Stefansson, 1999). In most cases the purpose is to dispose of waste-water due to environmental reasons. Yet, reinjection is increasingly becoming an important part of geothermal resource management. In these cases injection is used to counteract pressure draw-down and for extracting more of the thermal energy in place in geothermal reservoirs. In spite of causing an initial increase in operation costs, reinjection will in most cases prove to be an economical way of increasing energy production from a geothermal reservoir. It is a mode of utilisation which may be expected to increase the potential of the Beius geothermal reservoir significantly. Therefore, reinjection should be considered in Beius in the future.

The principal benefit from reinjection is, of course, pressure recovery, which may be used to increase the pumping from production wells without an increase in pressure draw-down. This also depends on the interference between the reinjection and production wells. According to Figure 14, 50 L/s reinjection into the proposed reinjection well will cause a long-term water level recovery of about 30, 32 and 34 m in production wells F-3001, F-2 and F-3, respectively.

Figure 15 shows the calculated increase in production possible due to 50 L/s reinjection into a well located between 1000 and 1500 m from the production well. The figure shows this as a function of the production rate without reinjection. This increase decreases with increasing production, because of turbulence pressure losses. It is assumed that a single reinjection well will not accept a higher injection rate than about 50 L/s.

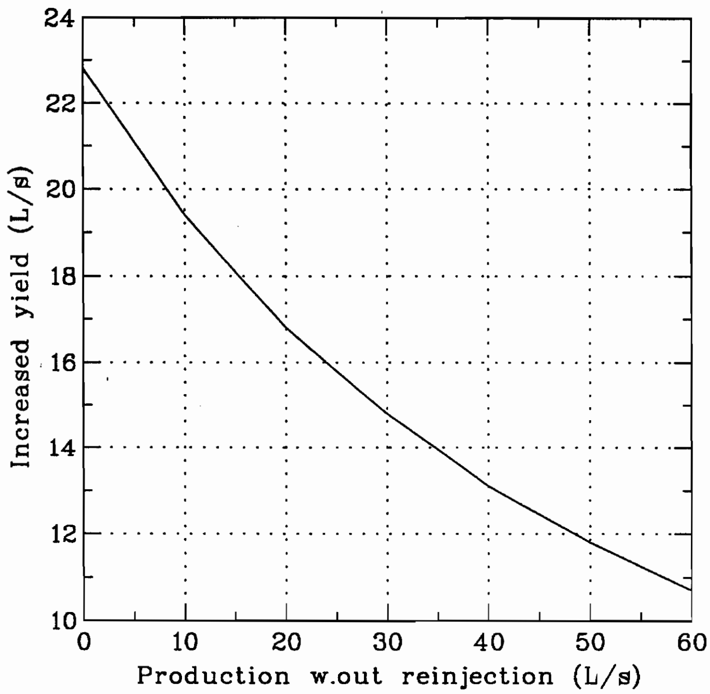


Figure 15. Estimated increase in the yield (assuming no change in water level draw-down) of a production well located about 1000 – 1500 m from a reinjection well with a constant injection rate of 50 L/s.

Figure 15 indicates that for one production well producing at 60 L/s, reinjection (50 L/s) will increase its yield by about 11 L/s, or by 18%. In the case of three production wells producing a total of 120 L/s, reinjection (50 L/s) will increase their combined yield by about 40 L/s, i.e. by 33%. For the production scenario of three production wells producing 200 L/s cumulatively, reinjection (50 L/s) will increase their cumulative yield by about 30 L/s, or by 15%. In the last case the combined production potential of three production wells with pumps located at 250 m depth, and a reinjection well accepting 50 L/s is therefore expected to be about 230 L/s. The uncertainty in these estimates must again be stressed. This may, in fact, not be accurately determined until more wells have been drilled. If the interference turns out to be greater than estimated here, reinjection will have a larger positive effect. On the other hand if the interference is smaller, reinjection will have a smaller positive effect.

Reinjection into the proposed reinjection well F-I will most likely need to be carried out through the use of high-pressure pumps, rather than by gravity flow. Figures 12 and 14 may again be used for the purpose of estimating the pressure needed. In the case where well F-3001 is the only production well, producing between 60 and 90 L/s, an injection pressure between 5 and 3.5 bar, respectively, would be needed according to the results. The uncertainty involved must, however, be kept in mind. Comparable estimates indicate that in the case where three production wells are producing a combined total of 120 L/s, a well-head pressure of about 1 bar may be needed to reinject 50 L/s. In the case where the three wells are producing a total of 200 L/s gravity flow will most likely suffice. The injection capacity needs to be tested carefully once a reinjection well has been drilled.

Injection is one of the most complex aspects of geothermal exploitation (Axelsson and Stefansson, 1999). Therefore, careful planning and research are prerequisites for successful injection. The most serious problems associated with injection are cooling of production wells (thermal breakthrough) and silica scaling in surface equipment and injection wells. In addition, long-term injection into sandstone reservoirs has met limited success. The main danger associated with reinjection in Beius is probably cooling of production wells. This depends on the distance between wells as well as other factors, such as whether the injected water will travel through some narrow paths (fractures) connecting the reinjection well to production wells or whether it will disperse throughout a large part of the 500 m thick reservoir. Therefore, injection wells closer than about 1000 m to production wells should not be considered. This must be studied by actual tests, such as tracer tests, once a reinjection well has been drilled (Axelsson et al., 1995). Until that has been done, theoretical studies must suffice.

ANALYSIS OF CHEMICAL DATA

Three water samples from well F-3001, collected during the production test from May to September 1999 and analysed by the Orkustofnun chemical laboratory were considered, the first one relatively incomplete (Table 3). A sample analysed by a Romanian laboratory, collaborating on the project, is also listed in Table 3 for comparision.

As the water originates in limestone/dolomite sediments it is very rich in calcium and magnesium and there certainly seems no sign of equilibrium with respect to alkali metals. The samples plot in the extreme Mg corner on a Na-K-Mg triangular diagram (see Figure 16).

Equilibrium considerations suggest that even though the temperature is low as 81°C the silica concentration may be essentially quartz-controlled. This means that silica concentration is relatively low and there should be no danger of supersaturation with respect to amorphous silica. There is, therefore, no danger of silica deposition from the water as depicted in Figures 17 and 18 for samples from 1999-06-11 and 1999-09-23, respectively (see explanation below concerning Figures 19 and 20).

Subsurface temperature, based on the assumption that the silica concentration of the water is controlled by the silica mineral quartz, has been calculated to be 85 to 90°C, only a few degrees higher than the temperature of the water at wellhead.

The water is slightly supersaturated with respect to calcite at wellhead temperature as well as at temperatures exceeding 50°C. If the water is degassed it becomes significantly supersaturated with respect to calcite. The saturation index, log(Q/K), at various cooling and degassing conditions, has been calculated for the samples from 1999-06-11 and 1999-09-23 and is displayed in Figures 19 and 20. The starting point for all the calculations is the water sample at wellhead temperature, 83.5°C for sample

1999-06-11 and 81.0°C for sample 1999-09-23. Curve a in Figures 19 and 20 demonstrates conductive cooling of the water in a closed system, without any degassing. Curves b, c and d, show different degrees of degassing and cooling by 0.5°C from wellhead temperature and subsequent conductive cooling. Curve d describes equilibrium degassing, whereas curves c and b show less, and probably more realistic, degassing. Curves e, f and g show calcite saturation during variable but continuous degassing and cooling from wellhead temperature.

It is believed that curves b and c describe the calcite saturation state of the water most realistically for a situation where water is pumped from a well to a storage tank with little degassing and cooling and subsequently piped through the distribution system where it cools conductively. In Iceland, water with saturation index as high as 0.5 log units has been used for a number of years without encountering any calcite scaling problems. This is especially true for waters with low chloride and TDS concentrations. The water from well F-3001 is extremely low in chloride and low in TDS as well, so one can deduce by referring to Figures 19 and 20, that there is little danger of calcite scaling from direct use of the water.

The gas associated with the hot water is mainly nitrogen (N_2) and carbon dioxide (CO_2), the latter being due to the origin of the water in calcite-rich sediments. This CO_2 and the presence of hydrogen (H_2) might reflect on a hotter source either at a greater depth or in earlier times. The large difference in the gas-composition of the two samples from well F-3001 (Table 3) is for the most part unexplained. It should however be mentioned that sampling and analytical methods were different, although it can hardly explain this difference.

Minor amounts of dissolved oxygen (O_2) were detected at wellhead during sampling. It is possible that atmospheric oxygen may have entered the sampling equipment prior to the oxygen analysis. However, the concentration is low and it is believed it will not cause corrosion problems within the system. In the sample from 6th June 1999 a minor amount of hydrogen sulphide (H_2S) was detected. The concentration is just above the detection limit for the analytical method used. Dissolved oxygen and hydrogen sulphide should not be able to coexist in the water due to the following simplified reaction.

$$H_2S + 2O_2 \leftrightarrow SO_4^{-2} + 2H^+$$

If the pressure equilibrium reached during the production test results from a connection to the surrounding ground-water system, which cannot be ruled out, the inflow will be of a lower temperature and different chemical content. This may cause some long-term chemical changes and eventually some cooling of the water produced. Comparison of the concentration of several chosen constituents in the water from the well, over the test period, suggests that there was actually no change in the chemical composition of the fluid induced by the test (Figures 21a-h).

Table 3. *Chemical composition (mg/l unless otherwise stated, n.d.: not determined) and geothermometer temperatures for well F-3001, Beius, Romania.*

Laboratory	Orkustofnun Chemical laboratory			ICPT Campina S.C. TRANSGEX
Date of sample	1999-05-02	1999-06-11	1999-09-23	1999-06-15
Water composition				
Temperature (°C)		83.5	81.0	
pH/°C	n.d.	7.12/22.1	7.28/21.6	7.1
Carbon dioxide (CO_2(t))	n.d.	184	177	163
Hydrogen sulphide (H_2S)	n.d.	0.04	<0.03	
Boron (B)	n.d.	0.06	0.03	
Conductivity (µS/cm /°C)	n.d.	446/25	436/25	500
Silica (SiO_2)	37.2	37.0	36.6	48
Total dissolved solids (TDS)	n.d.	269	274	
Oxygen (O_2)	n.d.	0.008	0.012	
Sodium (Na)	14.1	14.3	13.9	19.0
Potassium (K)	6.25	6.20	6.18	4.4
Magnesium (Mg)	19.7	19.7	19.0	20.7
Calcium (Ca)	49.1	49.0	50.8	54.1
Fluoride (F)	0.56	0.53	0.57	
Chloride (Cl)	2.67	1.94	1.95	6.89
Nitrate (NO_3)			<0.5	<1
Nitrite (NO_2)			<0.1	<0.1
Phosphate (PO_4)			<0.1	<0.1
Sulphate (SO_4)	57.1	58.5	60.7	70.4
Alumina (Al)	n.d.	n.d.	0.022	0.10
Manganese (Mn)			0.0035	
Iron (Fe)	n.d.	n.d.	0.215	1.4
δD (‰ SMOW)	n.d.	n.d.	-74.1	
δO^{18} (‰ SMOW)	n.d.	n.d.	-10.33	
Geothermometer temperatures (°C)				
Quartz	88	88	88	
Chalcedony	57	57	56	
Gas composition (vol-%)				
Hydrogen (H_2)	n.d.	0.57	0.03	
Carbon dioxide (CO_2)	n.d.	85.73	5.29	
Oxygen (O_2)	n.d.	0	0.77	
Nitrogen (N_2)	n.d.	13.47	93.89	
Argon (Ar)	n.d.	0.20	n.d.	

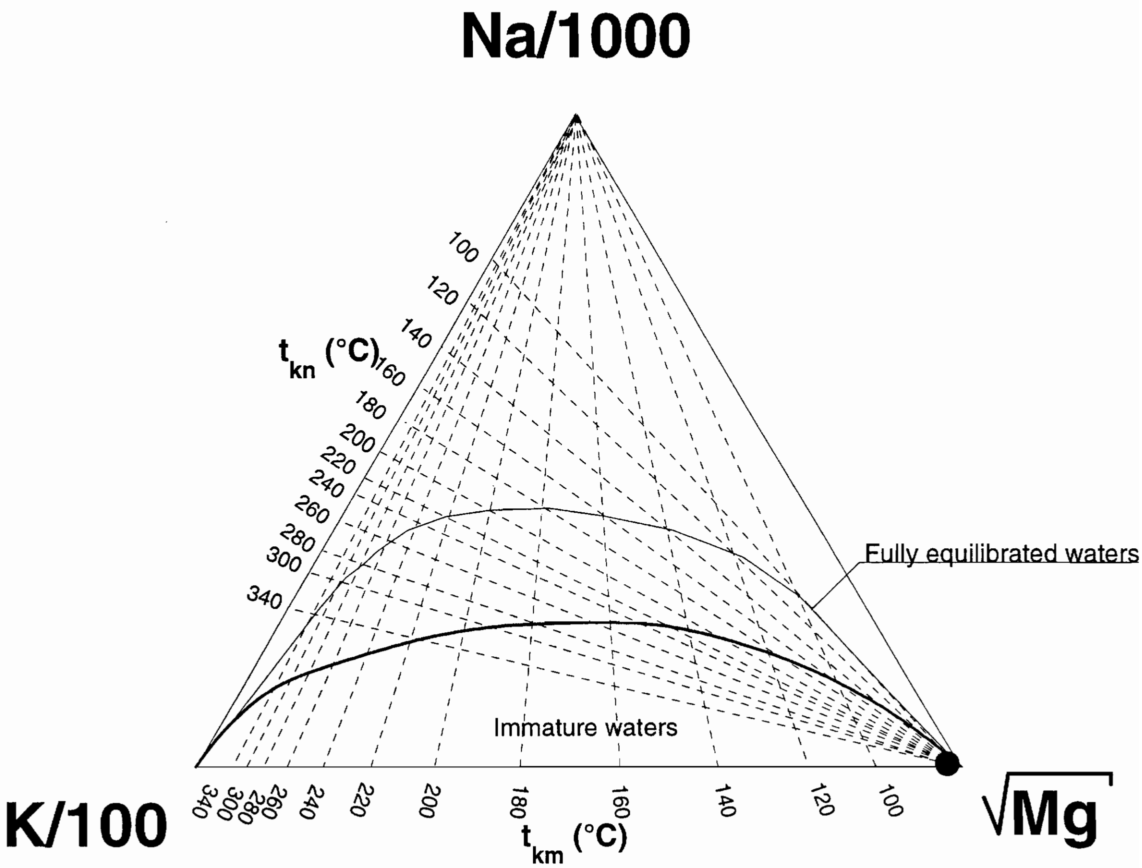


Figure 16. Na-K-Mg diagram for well F-3001 in Beius.

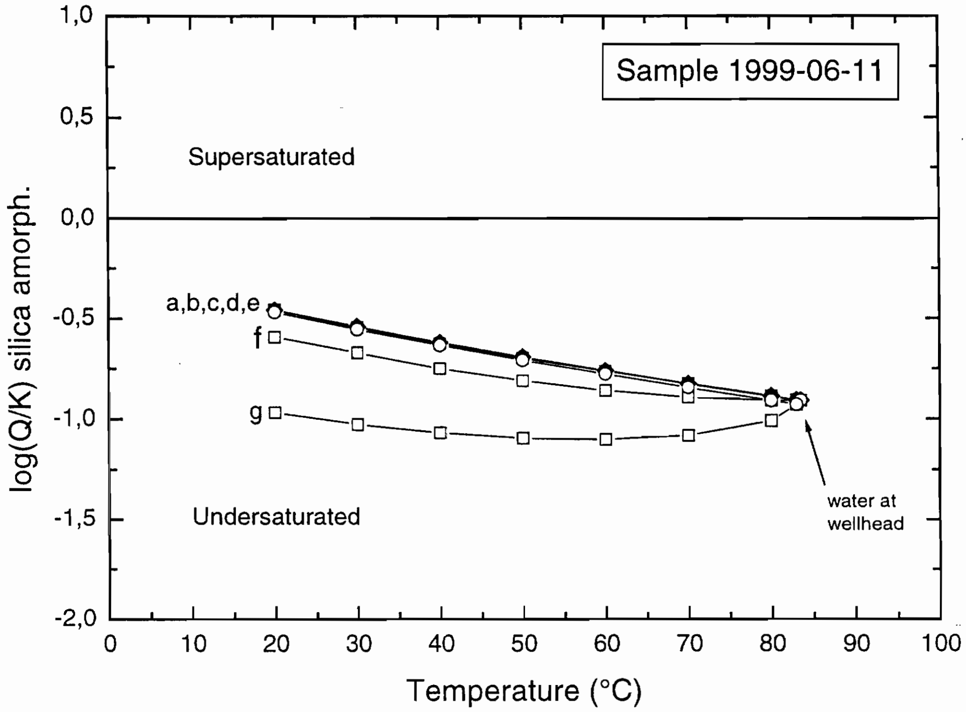


Figure 17. Silica saturation of sample 1999-06-11 at various cooling and degassing conditions.

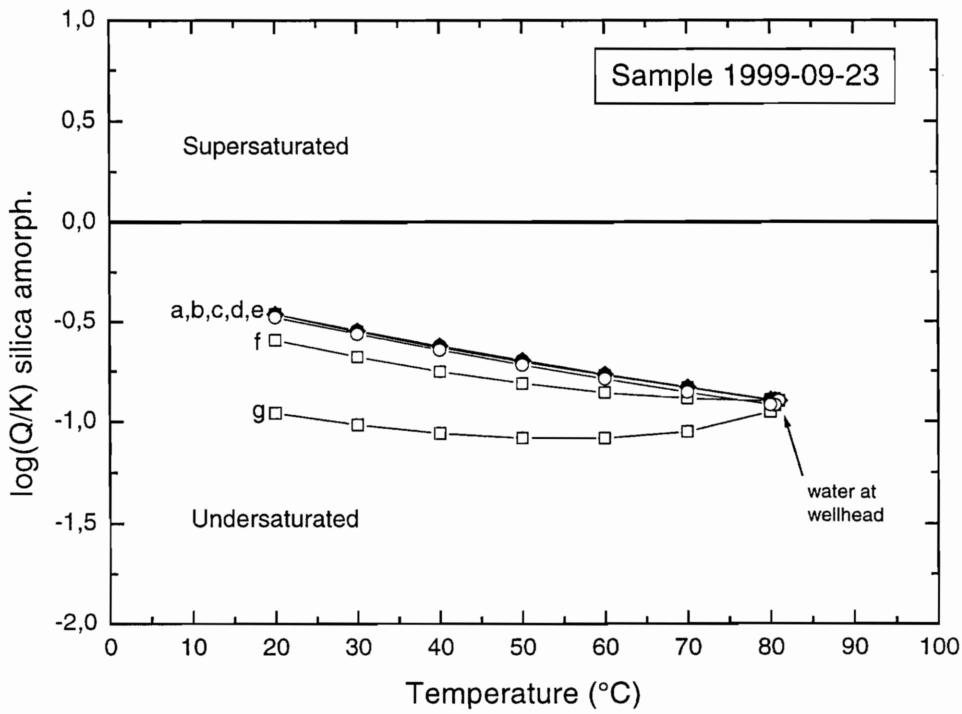


Figure 18. Silica saturation of sample 1999-09-23 at various cooling and degassing conditions.

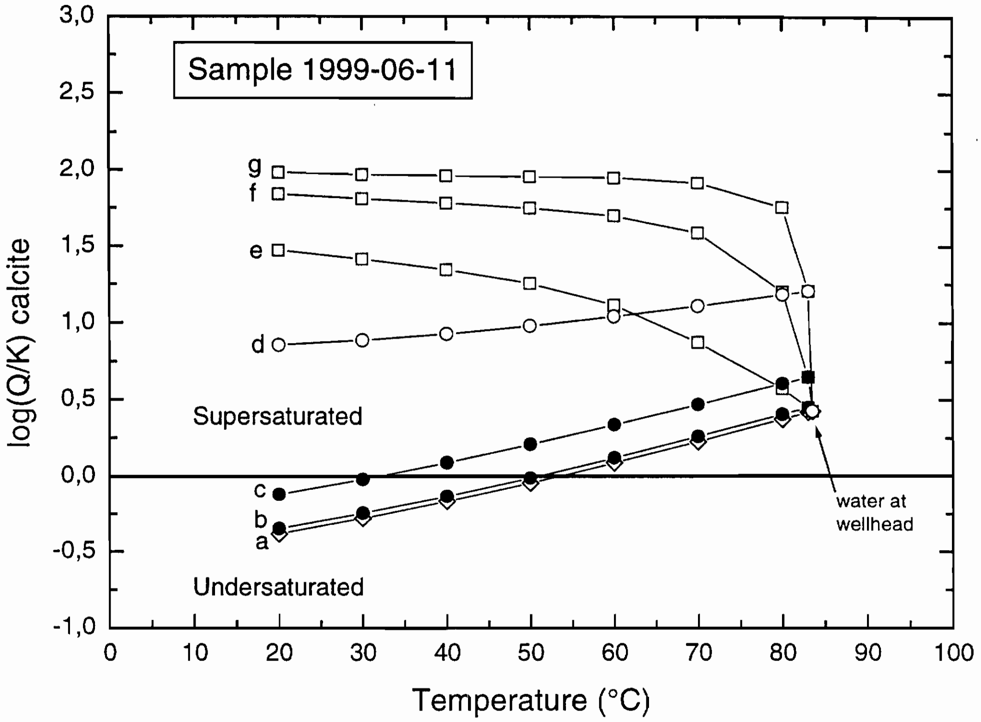


Figure 19. Calcite saturation of sample 1999-06-11 at various cooling and degassing conditions.

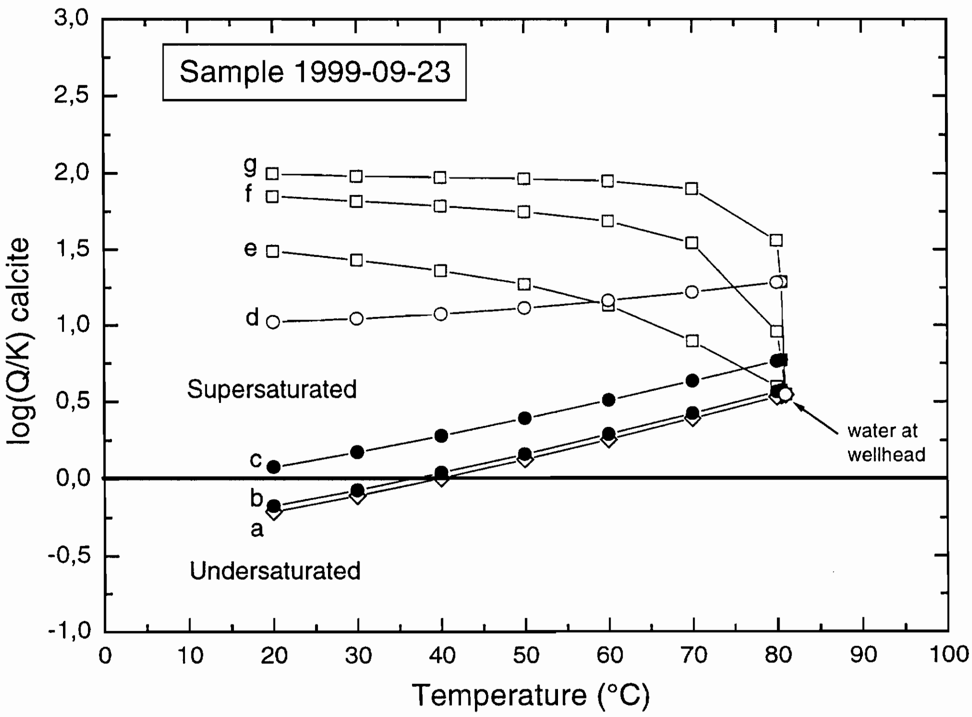
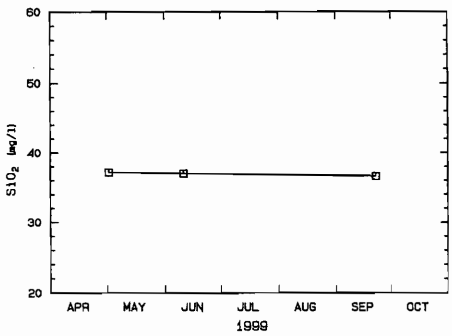
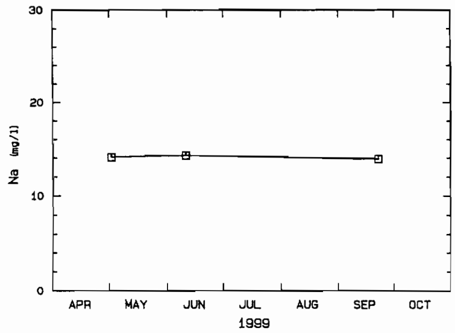


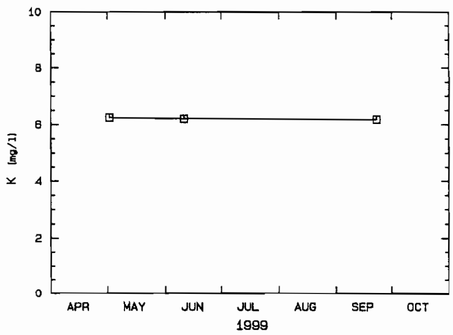
Figure 20. Calcite saturation of sample 1999-09-23 at various cooling and degassing conditions.



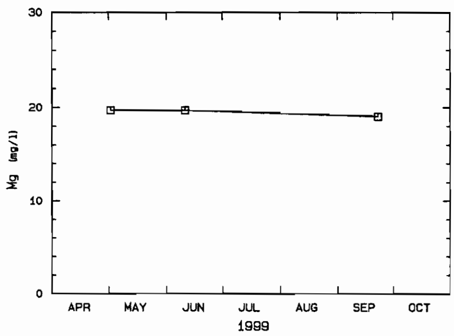
a) Silica during flow test



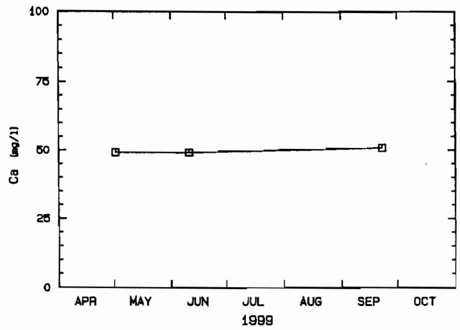
b) Sodium during flow test



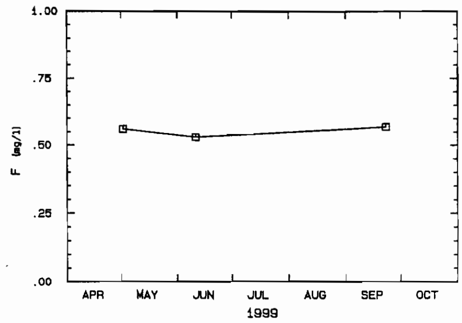
c) Potassium during flow test



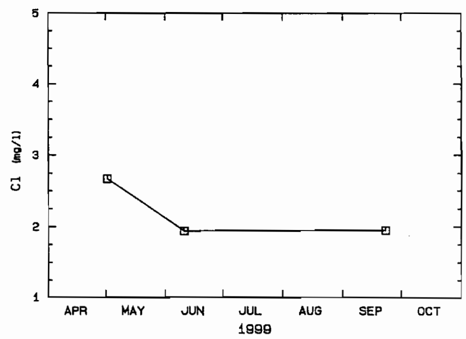
d) Magnesium during flow test



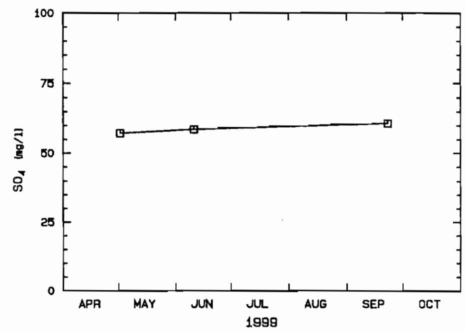
e) Calcium during flow test



f) Fluoride during flow test



g) Chloride during flow test



h) Sulphate during flow test

Figure 21. Temporal variation in constituent concentrations for well F-3001, May – September 1999.

SUMMARY AND CONCLUSIONS

During the assessment of the Beius geothermal reservoir discussed here the principal emphasis was placed on estimating the long-term potential of well F-3001 itself, on one hand, and developing a model of the geothermal reservoir, on the other hand. The model was, consequently, used to estimate the pressure interference between wells, the total potential of the geothermal reservoir in the Beius-area and the benefit of reinjection. The main results of the assessment may be summarised as follows:

1. One of the most important results of the pumping test is that the water level draw-down in well F-3001 reaches an equilibrium after about three weeks of constant production. The reason for this is a connection of the production reservoir to some hydrological system, which maintains constant pressure. According to the conceptual model this could either be a recharge area in the mountains to the west of Beius or the recharge from greater depth through the fractures intersected by well F-3001 (Figure 7). The short time required for equilibrium to commence indicates that the recharge from depth is responsible for the equilibrium rather than the postulated recharge area in the mountains.
2. The long-term production potential of well F-3001 is estimated to be 60 and 90 L/s, for pump depths of 150 and 250 m, respectively.
3. The permeability-thickness of the Beius reservoir is estimated to be about 15 Darcy-m. A simple model of a horizontal reservoir with a constant pressure boundary intended to simulate recharge, as well as a no-flow boundary, was used to estimate the combined production potential of a few production wells. The results indicate that three production wells in Beius, seperated by 1 – 2.5 km, should have a combined production potential of the order of 120 L/s and 200 L/s, for pump depths of 150 and 250 m, respectively.
4. Reinjection is a mode of utilisation that should increase the potential of the Beius geothermal reservoir, through pressure recovery, which may be used to increase pumping from production wells without increased pressure draw-down. The simple model used predicts that the yield of a production well producing 40 - 60 L/s will increase by 33 - 18%, respectively, through 50 L/s reinjection into a well located about 1100 – 1600 m away. In the case of three production wells producing a total of 120 L/s, reinjection (50 L/s) will increase their combined yield by about 40 L/s. The combined production potential of three production wells with pumps located at 250 m depth, and a reinjection well accepting 50 L/s is expected to increase about 30 L/s to 230 L/s. Reinjection will most likely need to be carried out through the use of high-pressure (0 – 10 bar) pumps, rather than by gravity flow.
5. The results on additional production wells, and the effect of reinjection, are highly uncertain and speculative at this stage. Further studies conducted once a new production well has been drilled, as well as data from the Oradea area, will greatly increase the reliability of the results.
6. Analysis of the chemical content of three water samples collected during the production test indicates that there should be no danger of silica deposition from the water. Subsurface temperature within the reservoir is expected to be 85-90°C, based on equilibrium with the silica mineral quarz. The water becomes highly supersaturated with respect to calcite if totally degassed with subsequent danger of

calcite scaling. However, minor degassing followed by conductive cooling, as within a reservoir tank and a distribution system, is believed to cause little danger of calcite scaling and the water can therefore be used directly. No changes in the chemical composition did occur during the five months test. Neither a direct connection to the ground-water in Beius is, therefore, likely nor a significant cooling of the water during long-term production.

7. It must be emphasised that careful monitoring is essential once utilisation of the Beius geothermal reservoir starts (Kristmannsdottir *et al.*, 1995; Stefansson *et al.*, 1995). This includes physical monitoring (flow-rates, water-level and water temperature), which will provide the basis for a re-evaluation of the reservoir assessment presented here, and chemical monitoring which will enable the operators of the field to see undesirable changes such as reservoir cooling, scaling and corrosion, in advance. Once a reinjection well has been drilled a tracer test must be conducted to enable reliable estimates of the danger of production well cooling, due to reinjection. Careful monitoring of the injectivity of the reinjection well is also important.

REFERENCES

Axelsson, G., 1999a: Testing of well F-3001 in Beius, Romania. Preliminary results. Orkustofnun memorandum, August 25th, 1999, 7pp.

Axelsson, G., 1999b: Testing of well F-3001 in Beius, Romania. Memorandum on status of geothermal modelling and available results. Orkustofnun memorandum, November 19th, 1999, 5pp.

Axelsson, G., 1991: Reservoir engineering studies of small low-temperature hydrothermal systems in Iceland. *Proceedings 16th Workshop on Geothermal Reservoir Engineering*, Stanford University, USA, 143-149.

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. and Th. Arason, 1992: LUMPFIT. Automated simulation of pressure changes in hydrological reservoirs. User's Guide, version 3.1, September 1992, 32pp.

Axelsson, G. and V. Stefansson, 1999: Reinjection and geothermal reservoir management – associated benefits. *Proceedings of a Workshop on Geothermal Energy*, Ljubljana, Slovenia, November 1999, 85-104

Axelsson, G., G. Bjornsson, B. Steingrimsson and V. Stefansson, 1996: Modeling of geothermal systems in Iceland (Extended Abstract). *Proceedings of the Second Nordic Symposium on Petrophysics and Reservoir Modelling*, Goteborg, Sweden, January 1996, 28-30.

Axelsson, G., G. Bjornsson, O.G. Flovenz, H. Kristmannsdottir and G. Sverrisdottir, 1995: Injection experiments in low-temperature geothermal areas in Iceland.

Proceedings of the World Geothermal Congress 1995, Florence, Italy, May 1995, 1991-1996.

Bodvarsson, G., 1966: Direct interpretation methods in applied geophysics. *Geoexploration*, **4**, 113-138.

Bodvarsson, G.S., K. Pruess and M.J. Lippmann, 1986: Modeling of geothermal systems. *J. Pet. Tech.*, **38**, 1007-1021.

Bjornsson, G., G. Axelsson and O.G. Flovenz, 1994: Feasibility study for the Thelamork low-temperature system in N-Iceland. *Proceedings 19th Workshop on Geothermal Reservoir Engineering*, Stanford University, USA, 5-13.

Kristmannsdottir, H., H. Armannsson, G. Axelsson, M. Olafsson, S. Hakonarson and S. Thorhallsson, 1995: Monitoring of Icelandic geothermal fields during production. *Proceedings of the World Geothermal Congress 1995*, Florence, Italy, May 1995, 1813-1818.

Olá, S., 1999: Personal communication.

Stefansson, V., G. Axelsson, O. Sigurdsson and S.P. Kjaran, 1995: Geothermal reservoir management in Iceland. *Proceedings of the World Geothermal Congress 1995*, Florence, Italy, May 1995, 1763-1768.

Societatea Comerciala Foradex, 1996: Test de presiune tranzitorie sonda nr. 3001 Beius. Report, Societatea Comerciala Foradex S.A., Bukarest, 8 pp.

United Nations University Geothermal Training Programme, 1994: *ICEBOX*. 2nd edition, complied by Th. Arason and G. Bjornsson, Orkustofnun, Reykjavik, 66pp.