MODELLING STUDY AND FUTURE PREDICTIONS FOR THE SEDIMENTARY GEOTHERMAL RESERVOIR IN GALANTA, SLOVAKIA

Report for GalantaTerm Ltd.

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Orkustofnun, GeoScience Division,

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SUMMARY

The Galanta sedimentary geothermal reservoir in SW Slovakia is located in the Central Depression of the Danube Basin (the northernmost part of the Pannonian Basin). Permeable aquifers in the reservoir occur in layers of sand and sandstone. Geothermal wells FGG-2 and FGG-3 were drilled in 1983 and 1984, each to a depth of 2 km, yielding free flowing 78°C water. Their utilisation through down-hole pumps started in the fall of 1996. The total production until the middle of May 2000 amounted to 2,310,000 m^3, corresponding to 20.7 L/s on the average. The pressure or water-level draw-down has been greater than anticipated on the basis of a short test in 1995. The reasons are believed to be a greater interference between wells and some boundaries, or reduced permeability, on the outskirts of the geothermal system.

The purpose of the present study was to accurately model the measured pressure response of the Galanta reservoir to enable reliable long-term future pressure draw-down predictions, which should aid GalantaTerm in the future management of the system. An analytical distributed parameter model of a horizontal reservoir with a great areal extent was developed. The model was assumed closed instead of extending to infinity. The model is, therefore, rather conservative and predictions calculated by the model should be considered pessimistic. The model has an effective reservoir thickness of 700 m and a permeability of $25 \cdot 10^{-15}$ m^2, corresponding to a permeability-thickness of 17 Darcy-m. The surface area of the model is about 240 km^2. The results of pressure response predictions for various future production scenarios clearly show that hot water production in Galanta may be increased considerably. Production from wells FGG-2 and 3 may be easily increased by 50% or more. Production from the reservoir may be increased even more through drilling of more production wells, which will cause a smaller water-level draw-down than a comparable increase in production from wells FGG-2 and 3 alone. Among factors that must be considered if production in Galanta is increased drastically, however, are the depth of production casings in wells, pressure interference, danger of colder water inflow and possibility of subsidence.

One of the most important results of the study is the great benefit achieved from reinjection. It is, therefore, recommended that reinjection be part of the future management of the geothermal reservoir. Thus the hot water production from the field may be increased through reducing pressure draw-down and interference. It must be kept in mind, however, that the fact that the model used is conservative may overestimate the long-term draw-down in the reservoir as well as the interference between wells. Yet it is clear that increased production coupled with reinjection will not cause a serious increase in water-level draw-down in the Galanta system. Reinjection is also in accordance with the increased global emphasis on sustainable energy production. The uncertainty involving possible cooling of production wells may be minimised by locating reinjection wells at a "safe" distance from production wells and by studying its effect through tracer tests. It is, furthermore, proposed that the so-called "Thisted-solution" be applied to avoid potential problems with sandstone injectivity.

Careful monitoring of the Galanta reservoir is essential for future management of this energy resource. This applies to physical (mass extraction, pressure and temperature) parameters as well as to chemical parameters. Changes in the latter may precede actual changes in reservoir conditions.

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1. INTRODUCTION

Geothermal wells FGG-2 and FGG-3 in the town of Galanta, Slovakia, were drilled in 1983 and 1984, each to a depth of about 2 km. They yielded free flowing water at a temperature of 78°C. Their utilisation through down-hole pumps started in the fall of 1996 and these wells have now been almost continuously in use for about 4 years. Flow-rates, well-head pressures or water levels, as well as water temperatures, have been monitored carefully for both wells, during most of this period. The total production until the middle of May 2000 amounted to 2,310,000 m^3, corresponding to 20.7 L/s on the average.

The pressure or water level draw-down in the wells has been considerably greater than anticipated on the basis of a test conducted in 1995 (Orkustofnun, 1995). That test was very short, however, and long-term predictions based on the test could not be expected to be very accurate. The initial water level response was studied briefly in the fall of 1998, to try to determine the possible causes of greater draw-down (Axelsson, 1998). Another brief evaluation of the pressure response of the Galanta reservoir was carried out a year later, on the basis of the data available by then (Axelsson, 1999).

The main results of these evaluations are the following: The reasons for the greater pressure draw-down than anticipated are believed to be a greater interference between wells and some boundaries, or reduced permeability on the outskirts of the geothermal system. The 1995 model predicts about 35% less pressure draw-down than has been realised. This is not unexpected considering that the 1995 test only lasted three weeks while the production history now approaches 200 weeks. The accuracy of predictions based on such a short test can not be expected to be very good.

The size and permeability of the Galanta reservoir appear to be considerably lower than estimated in 1995, according to a preliminary revision of the model carried out in 1999 (Axelsson, 1999). This applies in particular to the permeability thickness at the outskirts of the reservoir, which is only estimated to be about 0.3 Darcy-m. This may reflect a closed, or semi-closed, boundary, which in turn causes a greater pressure draw-down than predicted in 1995. Preliminary predictions calculated by the revised model indicate that the pressure should decline about 1 - 1.5 bar during the next two years, at a stable average rate of production.

The purpose of the present study is an accurate revision of the Galanta reservoir model to enable reliable long-term future pressure draw-down predictions. These long-term predictions will, consequently, enable GalantaTerm, the operator of the geothermal system, to assess the long-term production potential of the Galanta reservoir as well as aid in future management of the system.

The model revision is based on the measured production and response of wells FGG-2 and FGG-3 up to the middle of 2000. In addition, available data on the geological nature of the reservoir is considered. This will aid in the development of the model, in particular modelling of its boundaries. Emphasis is put on simulating the interference between wells, which is now believed to be greater than previously thought. Consequently predictions for different future production scenarios can be re-calculated.

A brief study of the possible benefit of reinjection into the Galanta reservoir was also incorporated in the model revision, since reinjection may be successfully used to counteract the continuously increasing pressure draw-own.

This report describes the outcome of the simulation study and is organised as follows: First a brief description of the Galanta geothermal system is given. Following this the available data on the production- and response history of the system is presented. The fourth chapter provides information on the technical details of the modelling study while the fifth chapter discusses the possible benefits of reinjection in Galanta. These chapters are followed by a presentation of the results of predictions calculated by the new model along with predictions on the effect of reinjection. This report is concluded by a summary of the main results and presentation of some recommendations.

It should be pointed out that the model previously developed, and revised, for the Galanta geothermal system was a so-called lumped parameter model (Orkustofnun, 1995; Axelsson 1999). Here a different kind of model is employed, an analytical distributed parameter model (Theis-model). It is believed to simulate better the interference between wells, and can be used to predict the effect of introducing new reinjection wells and/or production wells.

2. THE GALANTA GEOTHERMAL SYSTEM

Although geothermal systems mostly occur in volcanically and tectonically active regions, geothermal resources are found in many sedimentary regions. This applies, in particular, to regions where sufficient permeability exists at a depth where the temperature is high enough by virtue of the normal geothermal gradient, such that the hot water in-place may be produced economically. This applies in particular to deep sedimentary basins found in different parts of the world. Geothermal energy from such systems is utilised in The P.R. of China and in several European countries, in particular in Eastern Europe (Axelsson, 2000b).

Sedimentary geothermal systems are common on the European mainland. Such systems are utilised to a varying degree in Hungary, France, Germany, Serbia, Romania, Slovakia, Bulgaria, Bosnia/Herzegovina, Slovenia and Poland. Most of the sedimentary systems are found in the major sedimentary basins, the largest of which is the Pannonian basin in Hungary and neighbouring countries. These systems are either embedded in porous formations (sand- and siltstones) or in fractured carbonate formations (limestones and dolomites). They are usually extensive in area, but relatively thin. This is just the opposite of volcanic and convective type geothermal systems. The permeability and porosity of sedimentary systems is usually rather high. Heat flow is considerably above average in many of the basins. These systems are, in addition, all low-temperature or low-enthalpy systems, and their utilisation is in most cases limited to direct use.

The Galanta geothermal reservoir is part of such a sedimentary geothermal system. It is located in the so-called Central Depression of the Danube Basin, in SW Slovakia, which actually is the northernmost part of the Pannonian Basin (Fendek and Franko, 2000). The Depression covers an approximately circular area of the order of 4000 km^2. Permeable water aquifers occur in layers of sand and sandstone, which slope down to a depth of 3400 m in the centre of the Depression. These aquifers are confined by low permeability clays at the boundaries and bottom of the depression. About 34 geothermal boreholes have been drilled into the Central Depression.

Three geothermal wells have been drilled in the area near the town of Galanta, which is located about 45 km east of Bratislava. Information on the second and third well, FGG-2 and FGG-3, which are the focus of this study, is presented in Table 1 below. They are located next to the town and separated by a distance of about 1050 m (see Figure 1). After completion the wells yielded about 25 L/s each, by artesian flow. The water temperature was about 78°C and total dissolved solids amounted to approximately 5 g/L. The cumulative production thickness of the geothermal reservoir (sands/sandstone) was estimated to be about 100 m. Short tests at the end of drilling indicated that the permeability thickness of the reservoir was of the order of 55 Darcy-m (5.5×10^{-11} m^3) and that the wells would be rather productive with a relatively slow long-term pressure draw-down (Orkustofnun, 1994).

Table 1. *Information on geothermal wells FGG-2 and FGG-3 in Galanta, Slovakia.*

Well	Drilled	Depth (m)	Casing depth/diameter	Open section (m)
FGG-2	1983	2102	299m / 9 $^5/_8$"	1706 - 2032
FGG-3	1984	2101	300m / 9 $^5/_8$"	1731 - 1998

In 1995 the wells were tested for about three weeks, this time more carefully (Orkustofnun, 1995). On the basis of this test the permeability thickness of the Galanta limestone reservoir was estimated to be 24 Darcy-m, or about half of what had been estimated previously. Therefore, a slightly greater long-term pressure draw-down was predicted. Some interference between the wells was also observed. Lumped parameter modelling, on basis of the results of the 1995 test, indicated that the two wells could sustain a combined average artesian discharge of about 17 L/s for ten years, if the maximum flow per well would not exceed 15 – 20 L/s. The results also indicated that a considerably greater production could be sustained through the use of down-hole pumps. Furthermore, the analysis of water- and gas samples collected during the 1995 test indicated that it would be advisable to maintain a system pressure of 2 – 4 bar-g to avoid calcite scaling in pumps and surface equipment. It must be pointed out that even though the 1995 test was comprehensive, and carefully executed it lasted only three weeks, which is a very short time compared to an exploitation period lasting several decades.

In addition to the studies mentioned above, the Galanta reservoir has been carefully studied by Slovakian scientists. A recent example is the study by Bonderenkova and Vranovska (1998) of the output data available at that time and the geothermal balance of the reservoir.

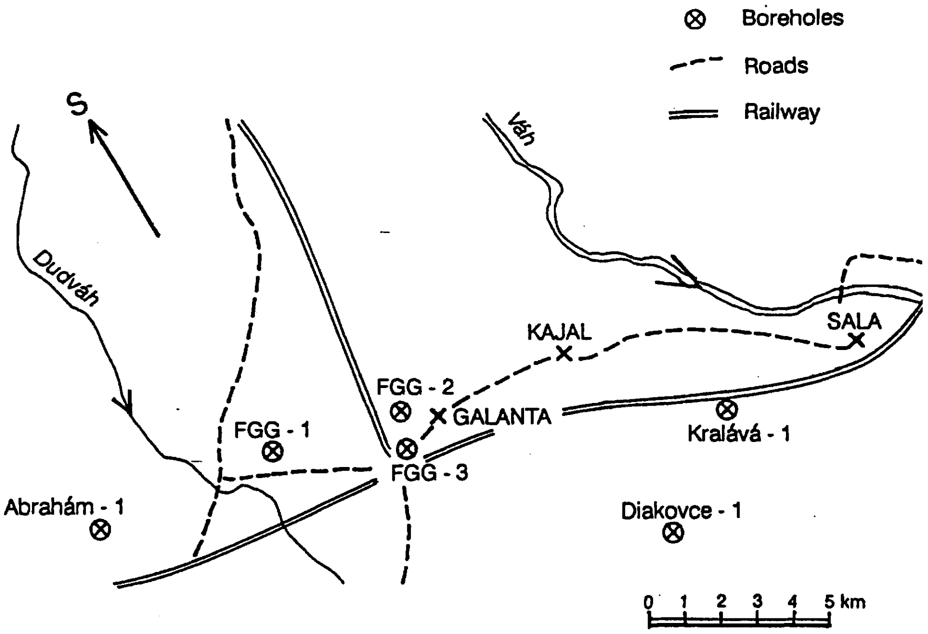

Figure 1. Location of wells drilled into the Galanta geothermal system.

3. PRODUCTION AND RESPONSE MONITORING DATA

Utilisation of wells FGG-2 and FGG-3 in Galanta started in the fall of 1996. The hot water is used for heating a large apartment complex and a district hospital, as well as providing domestic hot water (Franko, 1999). Flow-rates, well-head pressures or water levels, as well as water temperatures, have been monitored carefully for both wells, during most of this period, partially by an automatic/computerised monitoring system. Yearly reports with daily values of the monitored parameters have been sent to Orkustofnun for evaluation the last few years. Two reports on such evaluations have been issued so far (Axelsson, 1998 and 1999). Data until the middle of May 2000 was made available for the work described here.

Figure 2 through Figure 6 show the production and pressure variation data for the two wells. It should be pointed out that negative well-head pressures in Figure 3 and in Figure 5 indicate water level draw-down in the wells. Also that the figures are based on weekly averages for production and weekly water level readings. Figure 6 shows the cumulative production from both wells since the beginning of production in November 1996. The total production until the middle of May 2000 amounts to 2,310,000 m^3, which corresponds to 20.7 L/s on the average. The average yearly combined mass extraction rate from both wells is as follows:

1997	21.3 L/s
1998	21.0 L/s
1999	19.0 L/s

These numbers, as well as the figures below, show that the hot water production from the Galanta geothermal system has been reduced somewhat since 1997 because of a recommendation of Geological Survey of Slovakia. The maximum weekly combined production from the wells was about 42 L/s during the winter of 1997/98 but only about 33 L/s during the winter of 1998/99.

These data form the basis of the evaluation presented in this report (see next chapter). Some direct observations and results of previous evaluations are worth mentioning, however. Figure 3 and Figure 5 show that the pressure draw-down during the winter of 1998/99 was about 1 - 1.5 bar greater then during the winter of 1997/98. This is in spite of the fact that production does not seem to have increased from one year to the next. Such a great long-term draw-down was not predicted on the basis of the 1995 test (Orkustofnun, 1995). The reason for this is most likely some boundaries, or reduced permeability on the outskirts of the geothermal system, not seen in the three-week test in1995, in addition to greater interference between wells (Axelsson, 1998).

Axelsson (1998) calculated the pressure draw-down according to the 1995 on the basis of the data available then, a discrepancy of about 3 bar was obtained between reality and the model predictions. This is a difference of about 35%, which is not surprising considering the 1995 test only lasted three weeks. The accuracy of predictions based on such a short test can not be expected to be much greater.

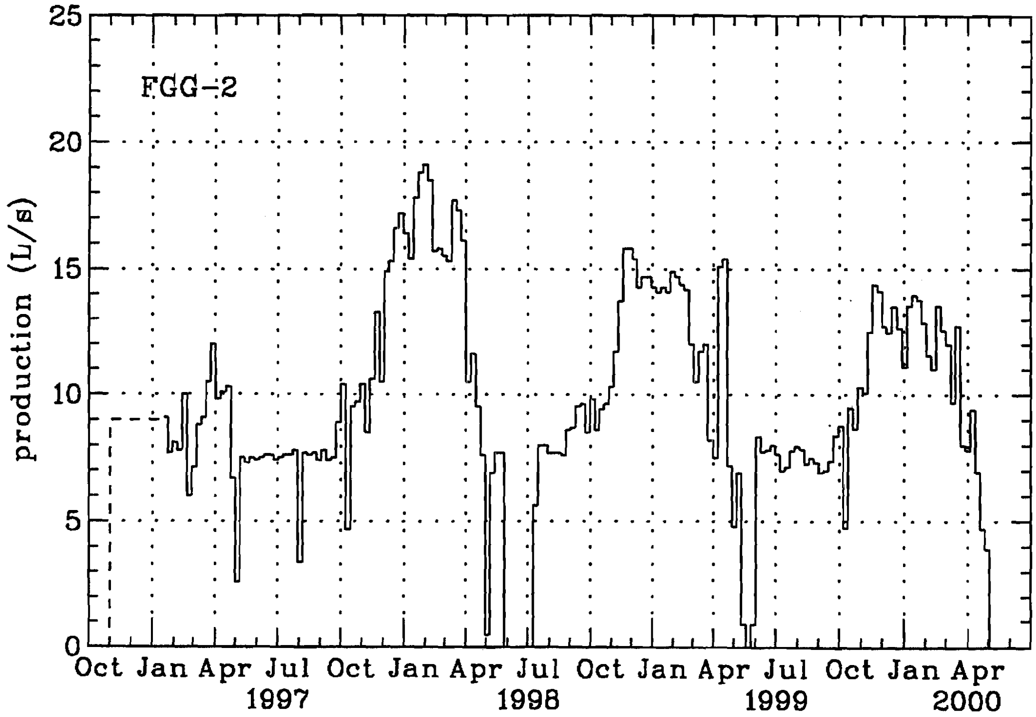

Figure 2. Weekly average hot water production rate for well FGG-2.

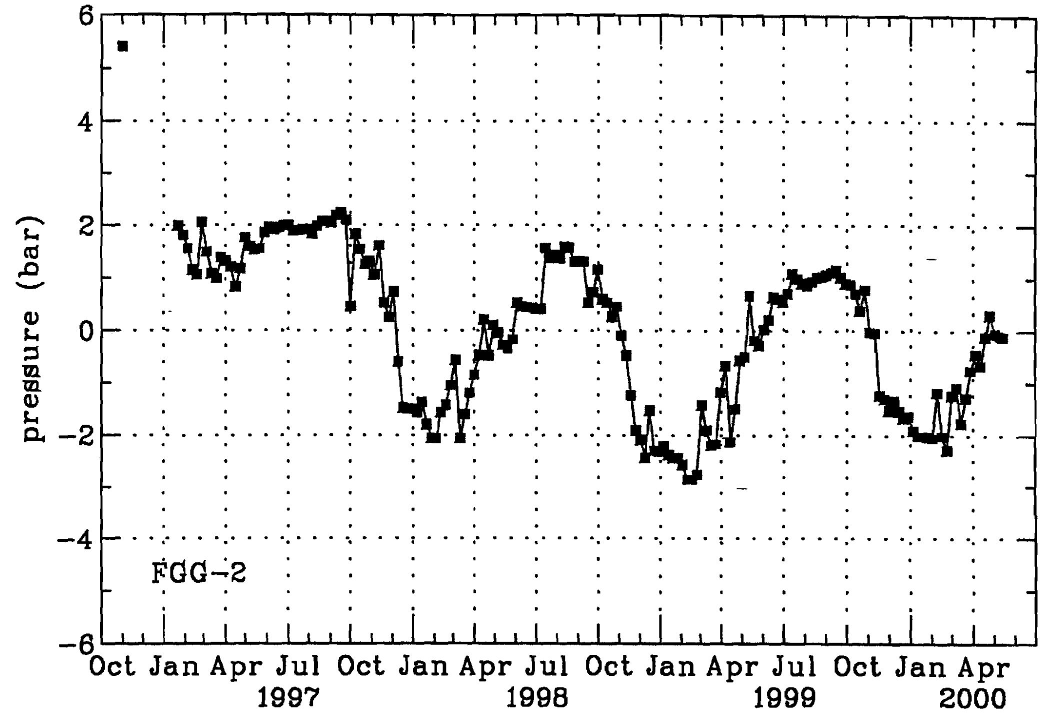

Figure 3. Weekly readings of well-head pressure or water-level for well FGG-2.

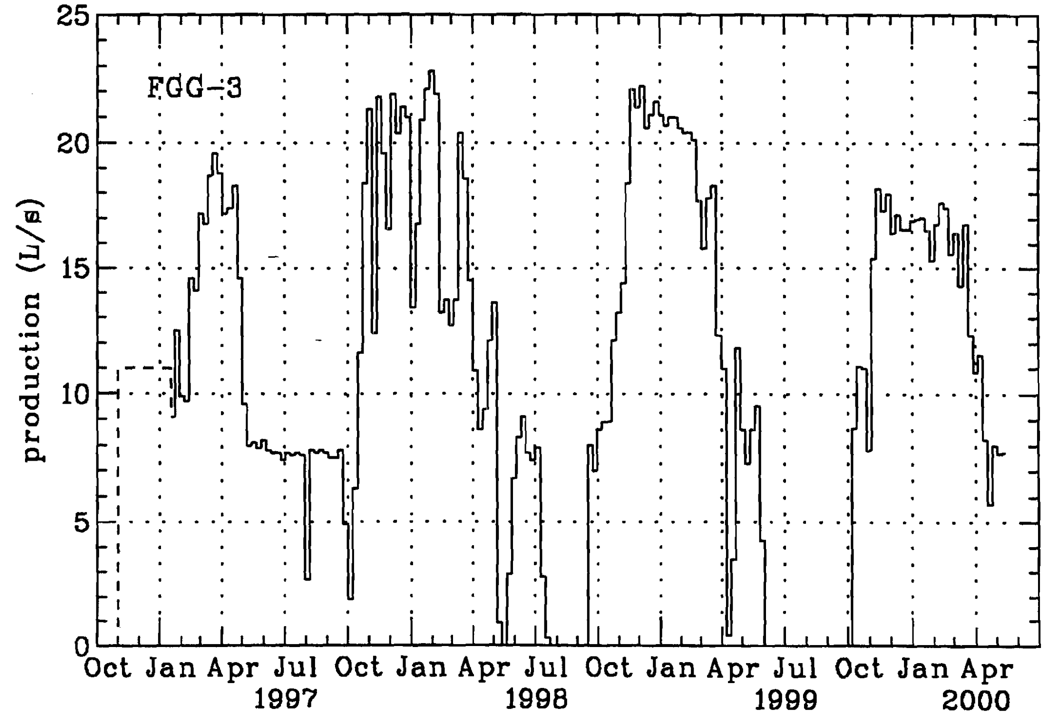

Figure 4. Weekly average hot water production rate for well FGG-3.

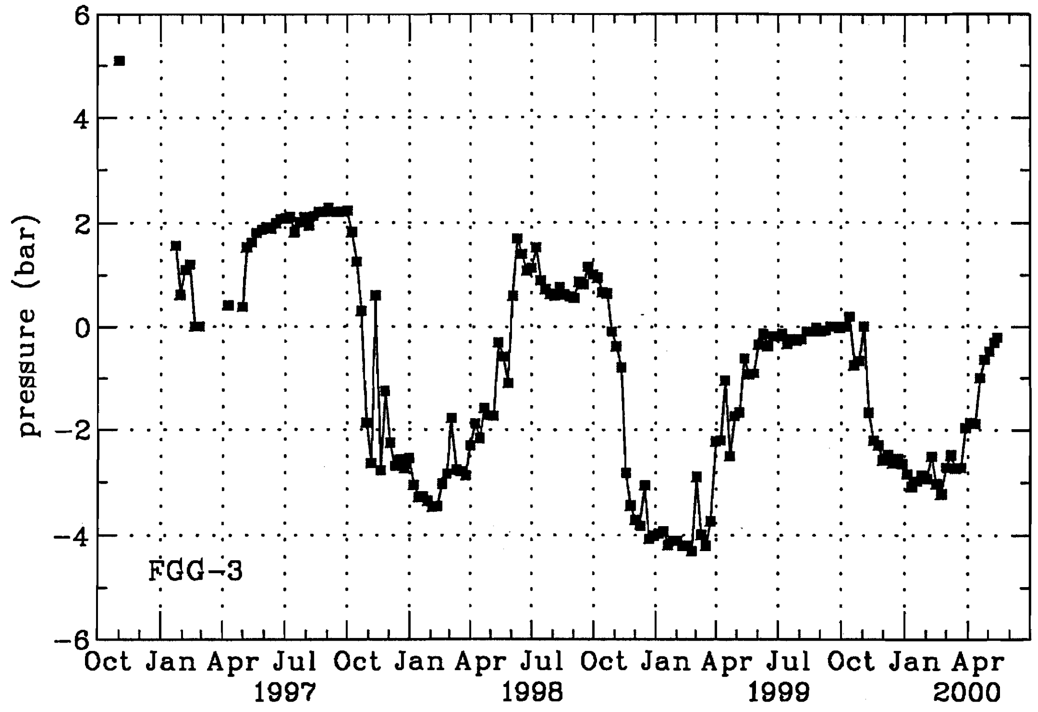

Figure 5. Weekly readings of well-head pressure or water-level for well FGG-3.

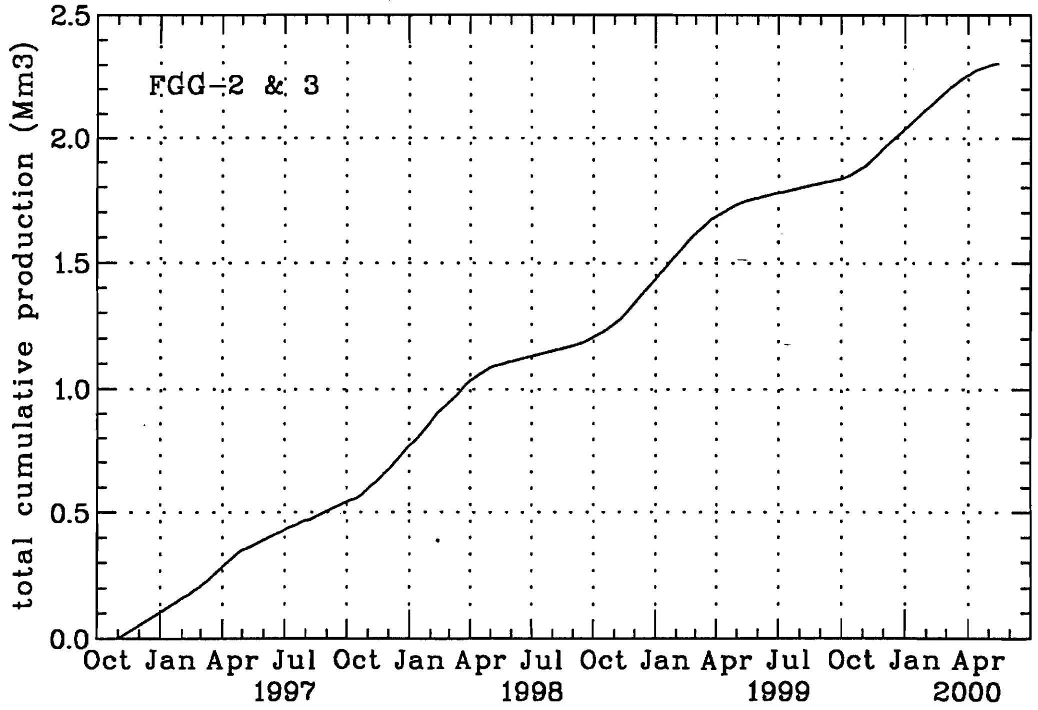

Figure 6. Total cumulative hot water production from wells FGG-2 and FGG-3.

4. MODELLING OF THE GALANTA GEOTHERMAL SYSTEM

4.1. Background

Modelling of geothermal systems, and the resulting response predictions and potential estimates, play an essential role in geothermal reservoir management (Bodvarsson and Witherspoon, 1989; Bodvarsson, 2000). In a few words modelling involves a model being developed that *simulates* some, or most, of the data available on the geothermal system involved. Various modelling approaches are currently in use by geothermal reservoir specialists. These can be (i) simple analytical models, (ii) lumped parameter models and (iii) detailed numerical models. The models provide information on the conditions in, and the properties of the actual geothermal system. But it is important to keep in mind that this information is not unique, but *model-dependent.* Subsequently the model is used to predict the future changes in the reservoir involved and estimate its production potential.

In simple analytical, and lumped parameter 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. In lumped models no a-priori assumptions on the nature or geometry of a system are, in fact, made. Simple models often only simulate one aspect of a geothermal systems response, such as pressure. 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.

A few different models have been developed for the Galanta geothermal system. Fendek (1992 and 2000) and Kang (2000), on one hand, describe some of this work, which has involved simple as well as detailed numerical modelling. Such work at Orkustofnun, on the other hand, has involved the use of lumped parameter models (Axelsson, 1998 and 1999). Lumped models, which can simulate pressure changes very accurately, are, however, more appropriate when only the total production from the field is to be considered, but neither the effects nor locations of individual wells. Therefore, an analytical distributed parameter model of a horizontal reservoir with a constant thickness and great areal extent was used in this study. In this model the location and production of each individual well is taken into account. Such a model was believed to be more appropriate, in particular in view of the need to simulate the interference between wells FGG-2 and FGG-3. This model is described in more detail below. It must be emphasised that these two simple models, i.e. the lumped and distributed models, are very different, even though they simulate the available pressure draw-down data equally well. On one hand there are no geometrical constraints inherent in the lumped model, in contrast to the fixed geometry of the distributed model. On the other hand the effects of individual wells may be simulated in the distributed model, while this is not the case for the lumped model.

Detailed numerical modelling was not carried out during this study, principally because the limited data available was not considered enough to warrant such modelling. The simple analytical model used simulates the available data, in fact, quite accurately. Detailed modelling would also have taken up too much time and, therefore, been too costly for this project. In addition this simple analytical model, as well as the previous lumped model, can be utilised, and revised, as part of the reservoir management of the Galanta geothermal system in the future. It may be mentioned that a similar modelling study has been carried out for the Tanggu sedimentary geothermal system in the P.R. of China (Axelsson and Dong, 1998).

4.2. Modelling results

The simple model used to simulate the production response of the Galanta geothermal system was an analytical distributed parameter model of a horizontal reservoir with a great areal extent. The reservoir has a constant thickness in this model, as well as constant properties (permeability and porosity). In addition a fault may be introduced in the model, serving as either a no-flow boundary or a constant pressure (recharge) boundary, as well as permeability anisotropy. In this model the location and production of each individual well, are taken into account. The geometrical constraints, however, are in a general agreement with the geology of the Galanta system. The input for this model are, firstly, the co-ordinates of each well, secondly, the production history of each well (Figure 2 and Figure 4) and thirdly, parameters involving the properties of the reservoir. The parameters involving the reservoir properties are the transmissivities in the x- and y-directions, T_x and T_y respectively, defined by $T_j = k_j h/\mu$, for j = x and y, and the storage-coefficient, $c_t h$. Here k is the reservoir permeability, h its thickness, c_t its total compressibility (rock and water) and μ is the dynamic viscosity of water. These properties are varied (trial and error) until the calculated response simulated the observed pressure/water level changes (Figure 3 and Figure 5) sufficiently well. The computer program VARFLOW was used to calculate the response of the model (EG&G and LBL, 1982).

At first, an attempt was made to simulate the pressure response data by incorporating a closed boundary some distance from the wells as well as considerable permeability anisotropy. After numerous attempts it became obvious that this would not result in quite a satisfactory match with the observed data. This concerned mostly the long-term draw-down, which is apparent in the data, but could not be matched. To solve this problem the model was modified by assuming it to be closed instead of extending to infinity. This was simply simulated by adding a slowly increasing long-term pressure draw-down to the calculated response given by the equation:

$$\Delta p(t) = \sum Q(t) / (\pi r^2 c_t h)$$

Here $\Delta p(t)$ denotes the additional pressure change at time t and $\sum Q(t)$ the cumulative volumetric production from the system up to that time. It is, furthermore, assumed that the reservoir volume is circular with radius r. It should be stated here that this makes the results of the modelling rather conservative, i.e. future predictions will be rather conservative or pessimistic. This is in agreement with the general philosophy of reservoir engineering of trying to be more on the conservative side, when making predictions.

After this modification to the model a satisfactory match between observed and simulated data was obtained. This match is shown in Figure 7 and in Figure 8. The fit is, in fact, quite good, in particular the simulation of the long-term trend. It should be noted that observed data from periods when the wells are closed don't represent the reservoir pressure correctly, and are not included. It should also be noted that turbulence pressure losses in the wells are also incorporated in the simulation by assuming a turbulence loss coefficient C = 0.0022 bar/(L/s^2) for both wells (Orkustofnun, 1995). To take differences in near-well permeabilities into account both wells were assigned "skin-factors" in the calculations. For well FGG-2 this factor was almost zero, while being s = -1 for well FGG-3. This simple model now developed is believed to simulate the production response of the Galanta geothermal reservoir quite accurately.

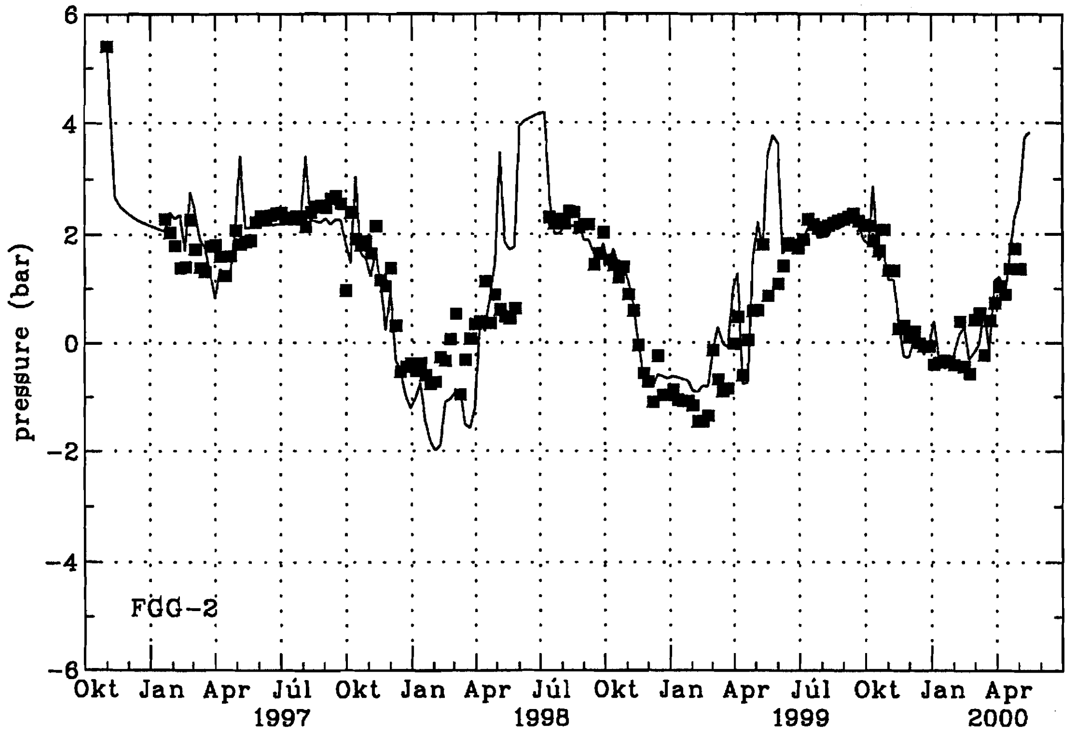

Figure 7. Observed and simulated well-head pressure and water-level data for well FGG-2.

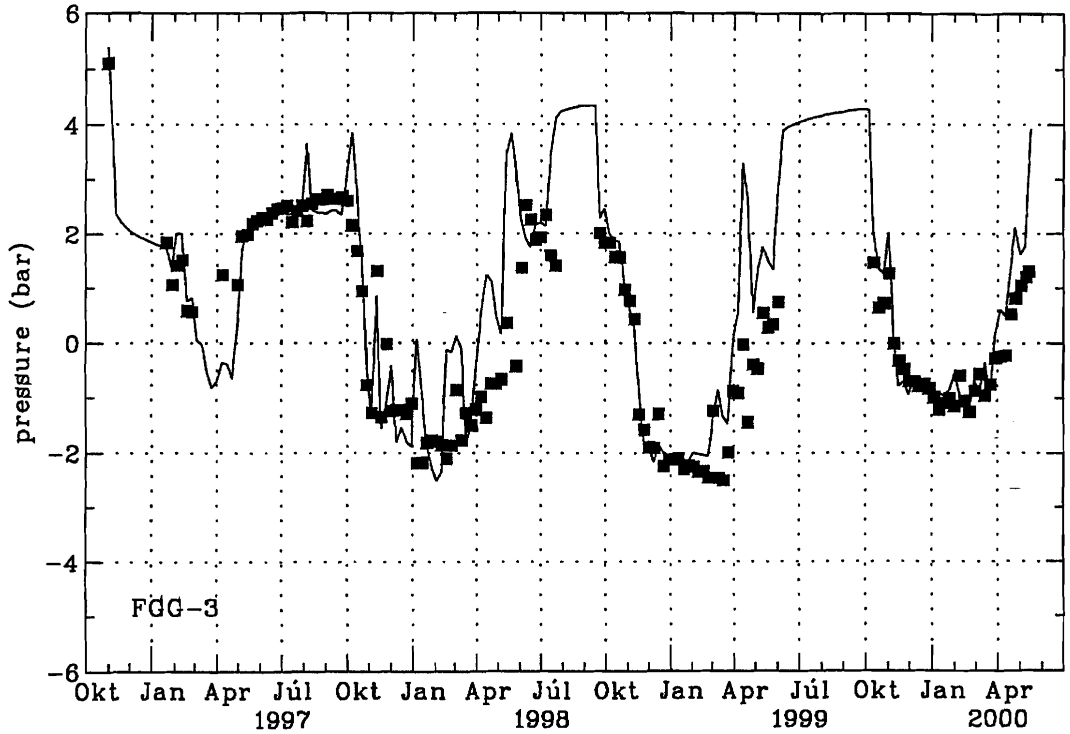

Figure 8. Observed and simulated well-head pressure and water-level data for well FGG-3.

In the final version of the model the permeability is assumed to be isotropic. Otherwise the properties of the best fitting model are the following:

$$kh/\mu = 4.8 \cdot 10^{-8}\ m^2/Pa{\cdot}s$$

$$c_t h = 7.0 \cdot 10^{-8}\ m/Pa$$

$$\pi r^2 c_t h = 16.7\ m^3/Pa$$

Assuming a porosity of $\phi = 0.15$ and total compressibility $c_t = 1.0 \cdot 10^{-10}\ Pa^{-1}$, the storage coefficient yields an effective reservoir thickness of 700 m. This is very thick in comparison with the approximately 300 m open sections of both wells. One must keep in mind that the total reservoir thickness in this region may be of the order of 2 km, however. Other factors may cause an apparent thickness of this magnitude, such as anisotropy, leakage from above or free-surface storativity.

Based on this thickness the model permeability is found to equal $k = 25 \cdot 10^{-15}\ m^2$, or *0.025 Darcy* (with $\mu = 3.6 \cdot 10^{-4}\ Pa{\cdot}s$). The corresponding permeability-thickness equals $kh = 17 \cdot 10^{-12}\ m^3$, or ***17 Darcy-m***. This is only slightly less than the 24 Darcy-m permeability-thickness estimated after the test in 1995 (Orkustofnun, 1995). The difference now is that the present model is entirely closed. According to the revision of the lumped parameter model in 1999 (Axelsson, 1999) the permeability-thickness of the centre of the reservoir equals 11 Darcy-m, again fairly close to the present estimate. The revised lumped model indicated drastically reduced permeability further out, however, which here is accounted for by assuming the model to be closed.

Finally the size of the model may be estimated from the value of $\pi r^2 c_t h$. This yields an estimate of the reservoir surface area of about 240 km^2. This is much smaller than the area of the whole Central Depression of the Danube Basin (4000 km^2), which definitely indicates that the whole depression is not fully interconnected hydrologically. We must keep in mind, however, the conservative nature of the present model, which causes this estimate of the reservoir area to be a lower bound for the area. Decreasing thickness away from the centre of the depression as well as faults and sedimentary formations that act as hydrological barriers.

Pressure response predictions, for various future production scenarios will be presented in chapter 6. These may, consequently, be used to estimate the production potential of the Galanta geothermal reservoir, with the present wells, as well as for cases assuming the drilling of additional production wells. Some of the future scenarios also consider reinjection being part of the management of the energy resource below Galanta. Therefore, the following chapter is devoted to a brief discussion of geothermal reinjection.

5. BENEFITS OF REINJECTION

5.1. General

Fluid reinjection is currently carried out in several geothermal fields in the world. Geothermal reinjection started out as a method of disposing of wastewater from geothermal power plants in order to protect the surrounding environment. Today injection is still mostly practised to dispose of wastewater due to environmental reasons, but it is also used for pressure maintenance, and for extracting more of the thermal energy in the rock in geothermal reservoirs (Axelsson, 2000a).

Theoretical studies, as well as field experiments, have shown that injection may be used to counteract pressure draw-down due to production, i.e. for pressure support, and for extracting more of the thermal energy in place in geothermal reservoirs. Most of this energy is stored in the reservoir rocks, and only a minor part in the reservoir fluid. Therefore, only a fraction of the energy may be utilised by conventional exploitation. Reinjection is a method of geothermal energy production, which can greatly improve the efficiency, and increase the longevity, of geothermal utilisation. It also contributes to the sustainability of geothermal energy production. Therefore, injection is increasingly becoming an important part of geothermal resource management. Injection also helps reduce land subsidence caused by large-scale geothermal production.

Waste water from geothermal power plants, return water from direct applications such as space heating, ground-water, surface-water and even sewage water is injected into geothermal reservoirs. Even though injection will cause an initial increase in operation costs, it will in most cases prove to be an economical way of increasing energy production from a geothermal system. Injection cannot yet be considered a very widespread method of reservoir management. Its role is slowly increasing in significance, however, as more successful injection experiments are completed, and more emphasis is globally put on sustainable energy production.

It is, therefore, proposed that reinjection be considered as part of the future management of the Galanta geothermal reservoir. This will reduce the pressure draw-down and interference, which appear to be the main factors limiting the potential of the geothermal system. Reinjection is assumed in some of the future scenarios presented in next chapter.

As injection is one of the most complex aspects of geothermal exploitation, careful planning, testing and research are prerequisites for a successful injection operation. Four key issues determine whether reinjection into a geothermal system will be beneficial in terms of increasing energy extraction from the system:

A. The reinjection must result in a water-level or pressure recovery.

B. The reinjection must not cause a too great cooling of production wells.

C. The reinjcetion must not cause significant scaling, corrosion, or deposition/clogging in reinjection wells or in surface equipment.

D. The reinjection must be economically viable.

5.2. Danger of cooling due to reinjection

The possible cooling of production wells, or thermal breakthrough, has discouraged the use of injection in some geothermal operations. In cases where the spacing between injection and production wells is small, and direct flow-paths between the two wells exist, the fear of thermal breakthrough has been justified. However, actual thermal breakthroughs, caused by cold water injection, have been observed in a relatively few geothermal fields (Stefansson, 1997).

The cooling effect can in fact be minimised by a proper selection, or location, of injection wells. In particular, by choosing injection locations at a considerable distance (a few km) from production wells. Yet, to achieve the maximum benefit from injection, i.e. pressure recovery, injection wells should be as close to production wells as possible. For successful injection a proper balance between these two contradicting requirements must be selected. Therefore, careful testing and research are prerequisites for planning successful injection.

To estimate roughly the appropriate distance between reinjection and production wells a simple volumetric method was used to calculate the thermal breakthrough time as a function of distance between wells. The following equation was used:

$$t_{breakthrough} = (d\, b\, h <\rho\beta>) / (<q>\, \beta_w)$$

where d is the distance between wells, b is the width of the flow-channel connecting the wells (here assumed to equal d/10), h is the height of the channel, $<\rho\beta>$ is the average volumetric heat capacity of the reservoir (water + rock), $<q>$ is the long-term average water flow rate (kg/s) between the reinjection well and each production well and β_w is the heat capacity of water. Figure 9 shows the results of such calculations for one reinjection well and one, two and three production wells. In the case of more than one production well the injected water is distributed between two or more wells, which causes the thermal breakthrough time to be longer. The average reinjection rate is assumed to be 80% of the present production, or 16 kg/s. The height of the flow-volume is assumed to be 300 m, or less than half of the reservoir thickness estimate presented above.

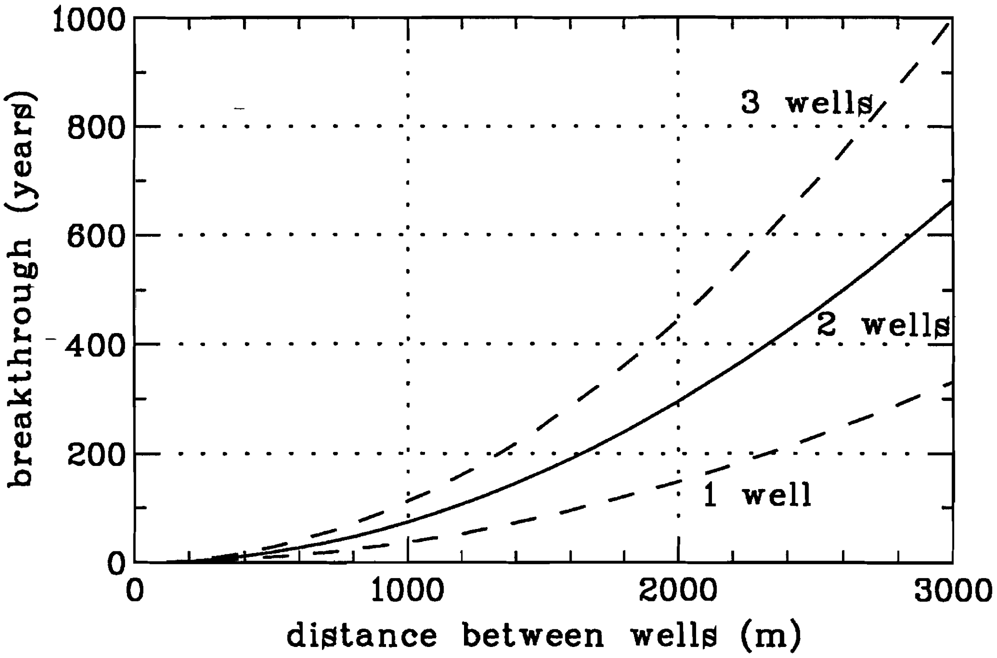

Figure 9. An approximate estimate of thermal breakthrough time as a function of distance between reinjection and production wells for an average reinjection rate of 16 kg/s and one, two and three production wells.

Even though the results in Figure 9 are only approximate they give an indication of what would be a "safe" minimum distance between reinjection and production wells. This appears to be of the order of 1 km for two or more production wells, since in that case the cold-front breakthrough time is estimated of the order of 100 years. This result is highly uncertain, however, since it depends on a lot of assumptions. One of these is the effective height of the flow-volume, which here is assumed to be 300 m. If this height is greater than 300 m the breakthrough time will be longer. If it is smaller, i.e. in the case when a single fracture or a fracture-zone is the main fluid conductor between the wells involved. This is unlikely, however, considering the nature of the reservoir rocks. ***The uncertainty involved simply emphasises the need for careful reservoir testing and research, such as tracer tests, before long-term reinjection is started in Galanta.***

Tracer tests are the most powerful tool for studying connections between injection and production wells, and hence the danger of thermal breakthrough. Numerous such tests have been carried out in geothermal fields during the last two decades (Stefansson, 1997). The method has been adopted from similar methods used in groundwater and nuclear-waste storage studies. In principle the tracer breakthrough time should reflect the thermal breakthrough time, and a short tracer breakthrough time reflects a short thermal breakthrough time. As a rule of thumb the thermal breakthrough time is normally one or two or more orders of magnitude slower than the tracer breakthrough time.

Numerous models have been developed, or adopted, for interpreting tracer test data and consequently for predicting thermal breakthrough and temperature decline during long-term reinjection (Pruess and Bodvarsson, 1984; Horne, 1985; Stefansson, 1997). These models will not be discussed here. It must be pointed out, however, that while tracer tests provide information on the volume of flow paths between injection and production wells, thermal breakthrough and decline is determined by the surface area involved in heat transfer from reservoir rock to the flow paths, which most often are located in fractures. Axelsson *et al.* (1995) describe a few tracer tests carried out in geothermal fields in Iceland during the early nineties. Four such experiments are discussed along with the theoretical models used for analysing the data collected.

5.3. Sandstone reinjection

Geothermal reservoir rocks are predominantly fractured. But geothermal resources are also widespread in sedimentary rocks, such as is the case in Galanta. Reinjection into limestone aquifers has been successful where attempted, but reinjection into sandstone reservoirs has met limited success at several locations where it has been attempted (Stefansson, 1997). During many sandstone reinjection tests the injectivity of injection wells decreases very rapidly, even in a matter of hours or days, rendering further reinjection impossible. The reasons for this are not fully understood, but most likely the aquifers next to the injection wells clog up (fine sand and precipitation particles). Research aimed at solving this problem is currently being carried out in Europe (Stefansson, 1997).

In at least three locations solutions to this problem have apparently been found, however. The first is the Tanggu geothermal area in the P.R. of China, where a novel approach, whereby the flow is reversed, was used during a reinjection experiment (Axelsson and Dong, 1998). The solution involved installing a down-hole pump in the injection well that is used to produce from the well for a period of a few hours once its injectivity has dropped after a period of reinjection. During a reinjection test in 1996 the injection well needed to be cleaned after reinjection periods of 7-11 days. After cleaning, its injectivity was fully restored. A similar approach was adopted in Neustadt-Glewe in Germany, apparently with success.

The third location where a solution to the sandstone injection was found is Thisted in Denmark, where 45°C water from a sandstone reservoir is utilised in a district heating plant and hence reinjected (Mahler, 1998). The solution in Thisted involves a very sophisticated closed loop system wherein the reinjection water is kept completely oxygen free as well as passed through very fine filters (one micron). The solution also involves not allowing injection after plant construction work, and other breaks in operation, until the water is checked clean and oxygen free. In addition, sufficient pressures are kept up by nitrogen when the plant is stopped. This system has been in operation since 1984. This sort of system is now being adopted in more locations in Europe.

It is proposed that the Thisted-solution be considered to solve potential problems with sandstone reinjection in Galanta in the future.

6. PRESSURE RESPONSE PREDICTIONS

A simple analytical distributed parameter model has now been developed for the Galanta geothermal system, and calibrated by 3 ½ years of pressure response data for wells FGG-2 and FGG-3. It is considered quite reliable because of the good agreement between observed and simulated data as well as its agreement with the general geological conditions of the Galanta geothermal system. The model was, therefore, used to calculate pressure/water-level predictions for the two wells for several future production scenarios. It should be kept in mind that the model is rather conservative, as discussed previously, and hence the predictions should be rather pessimistic. This applies, on one hand to the long-term draw-down, and on the other to the interference between wells.

Information on the five future scenarios considered is presented in Table 2. Relative locations of the wells used are, furthermore, presented in Figure 10. The response predictions are finally presented in figures 11 through 18.

Table 2. *Information on future production scenarios considered in pressure response predictions for the Galanta geothermal system.*

Scenario	Wells	Production/reinjection
I	FGG-2 and 3	Same as 1999
II	FGG-2 and 3	Scenario I + 50% increase
III	FGG-2, 3 and PROD-4	Scenario I + new well (50% increase)
IV	FGG-2, 3 and INJ-1	Scenario I + 80% reinjection (1 well)
V	FGG-2, 3, PROD-4, INJ-2 and 3	Scenario III + 80% reinjection (2 wells)

In addition to wells FGG-2 and FGG-3 one new production well (PROD-4) is assumed in scenarios III and V at about 1 km distance from the currently existing wells (Figure 10). One and two reinjection wells are assumed in scenarios IV and V, respectively. These are also located at about 1 km distance from the production wells, so as to avoid premature cold-front breakthrough, in accordance with the results of section 5.2 (Figure 10). It should be noted that well PROD-4, which is a production well in scenarios III and V is turned into a reinjection well (INJ-1) in scenario IV. Reinjection wells INJ-2 and INJ-3 are utilized in scenario V.

Scenario I may be considered a "status quo scenario" since it is quite similar to the production pattern of 1999, albeit somewhat simplified. It assumes a constant production of 15 and 20 L/s from wells FGG-2 and FGG-3, respectively, during a six month winter period and a constant production of 6 and 0 L/s from the same wells during a six month summer period. Some internal variations in this scenario, such as switching the summer production between wells, without changing the total production, will not influence the pressure response predictions considerably. The same two production wells are utilised in ***scenario II***, but at a 50% increase for both wells. Thus the annual average production is increased to almost 31 L/s and the winter time total average production to almost 53 L/s, for this case. In ***scenario III*** the total production is again increased by 50%, but in this scenario through the new production well, PROD-4. In scenario III the production from wells FGG-2 and FGG-3 is assumed the same as in scenario I.

The last two scenarios are considered to simulate the effect of reinjection on the pressure response of the Galanta reservoir. In ***scenario IV*** the effect of reinjection of 80% of the return water in scenario I into one reinjection well (INJ-1) is studied, while in scenario V the effect of reinjection of 80% of the return water for scenario III, into two reinjection wells (INJ-2 and INJ-3), is considered.

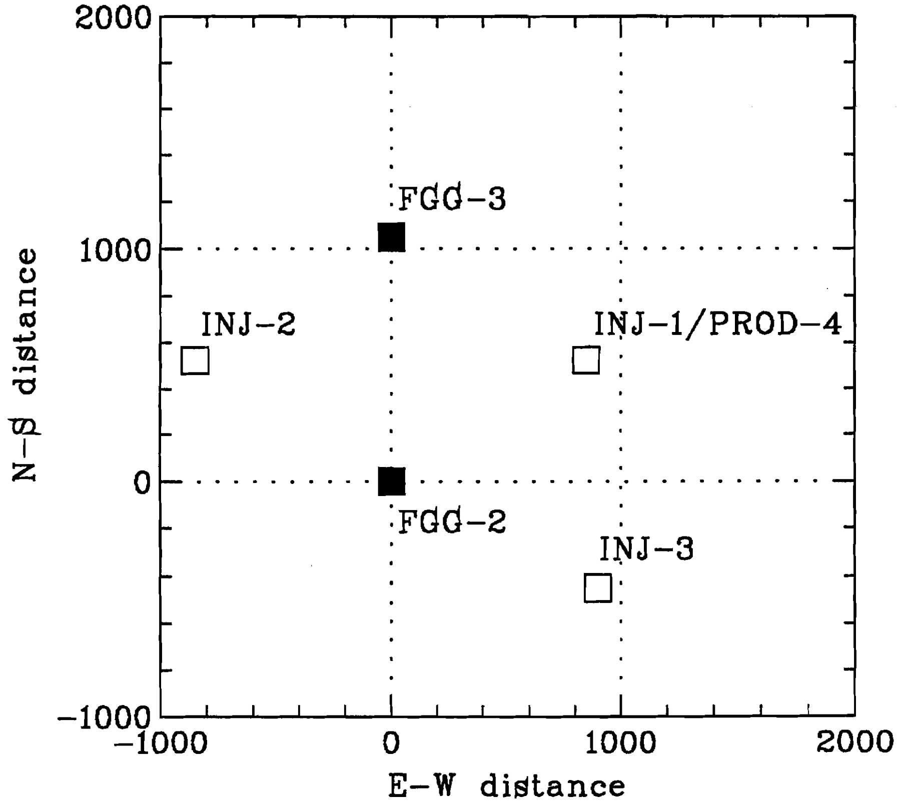

Figure 10. Relative locations of wells considered in the modelling of the Galanta geothermal reservoir.

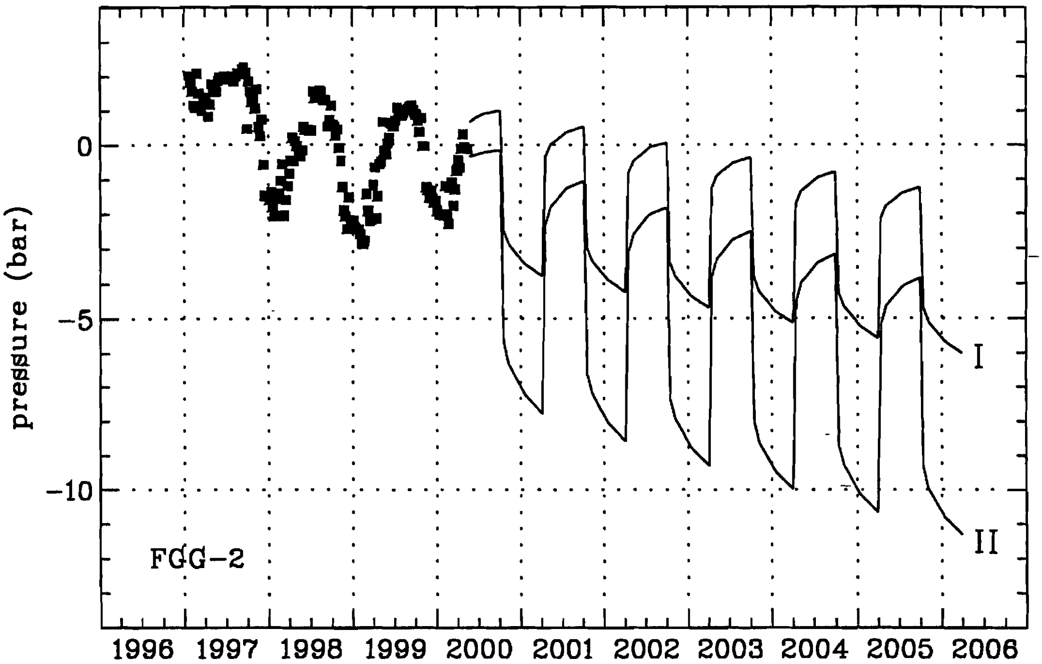

Figure 11. Predicted pressure/water-level variations for well FGG-2 and future utilisation scenarios I and II.

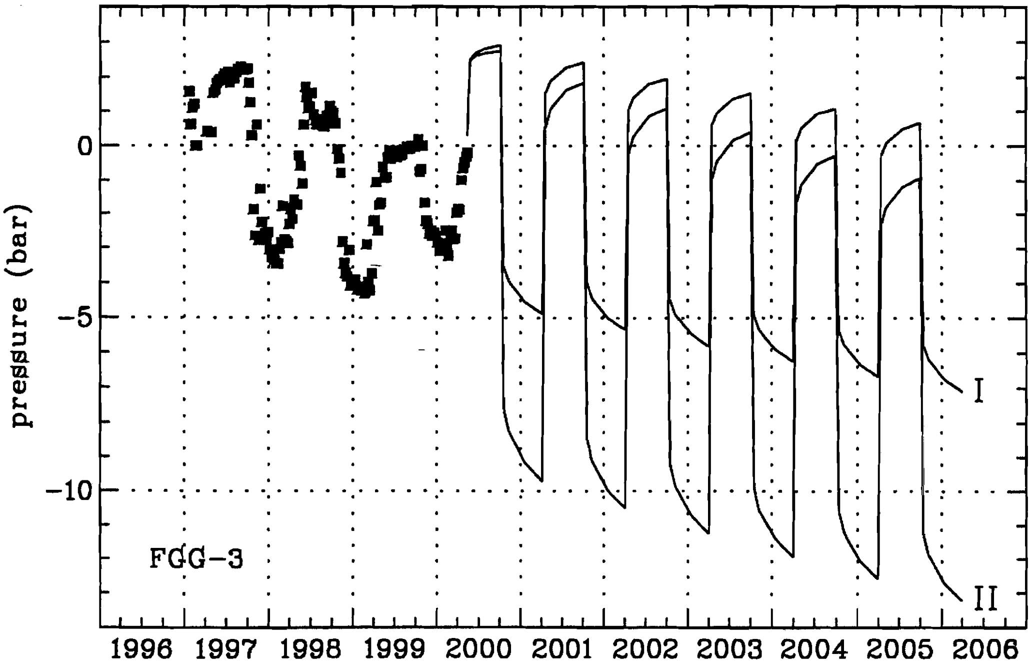

Figure 12. Predicted pressure/water-level variations for well FGG-3 and future utilisation scenarios I and II.

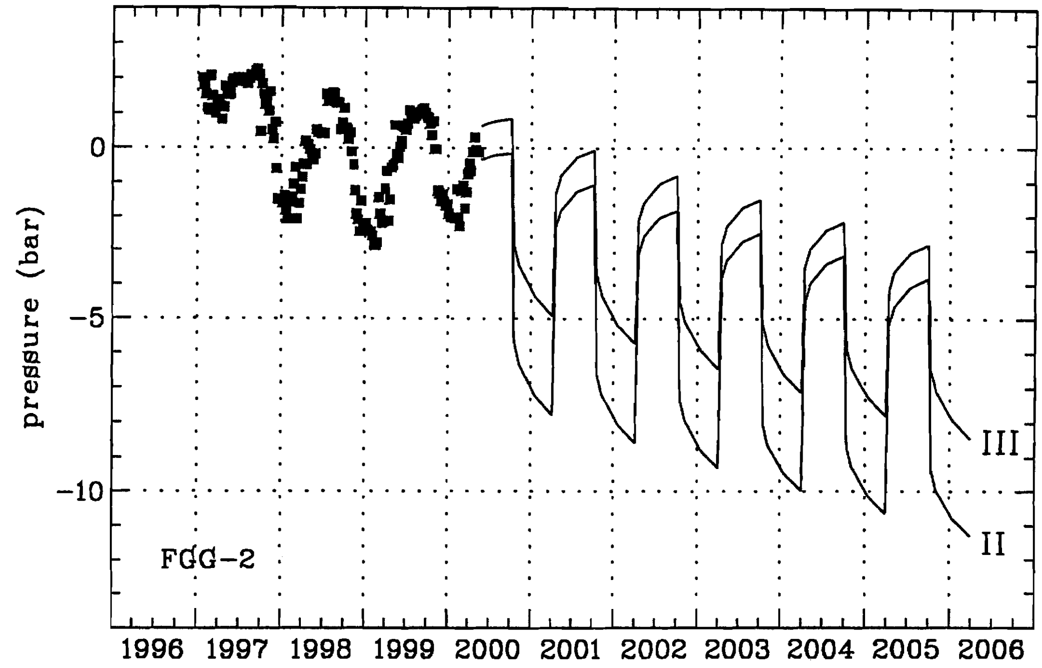

Figure 13. Predicted pressure/water-level variations for well FGG-2 and future utilisation scenarios II and III..

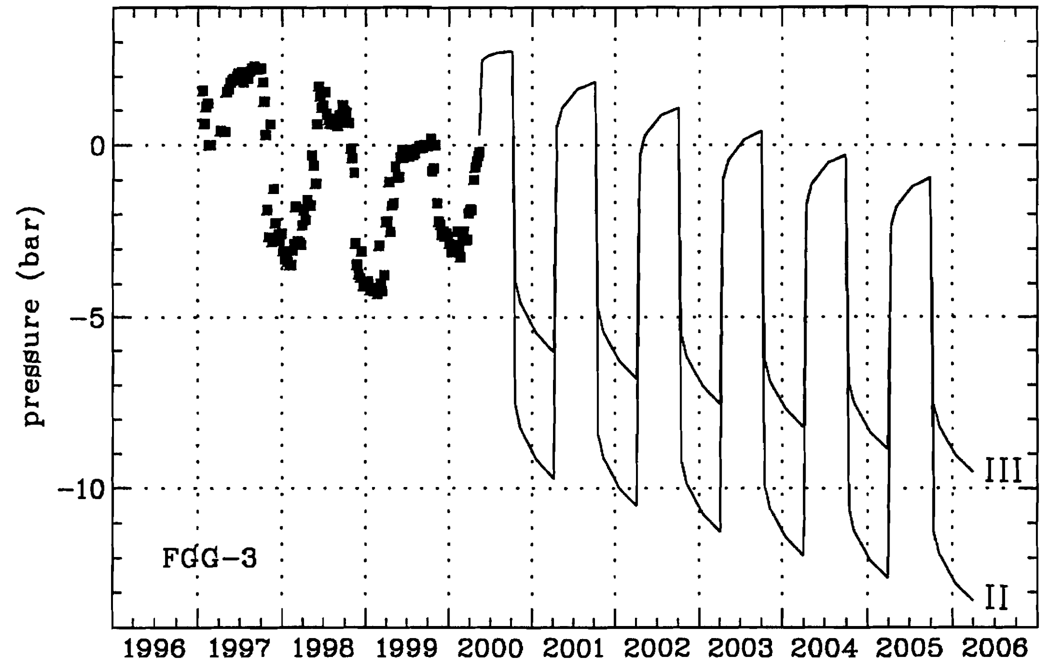

Figure 14. Predicted pressure/water-level variations for well FGG-3 and future utilisation scenarios II and III.

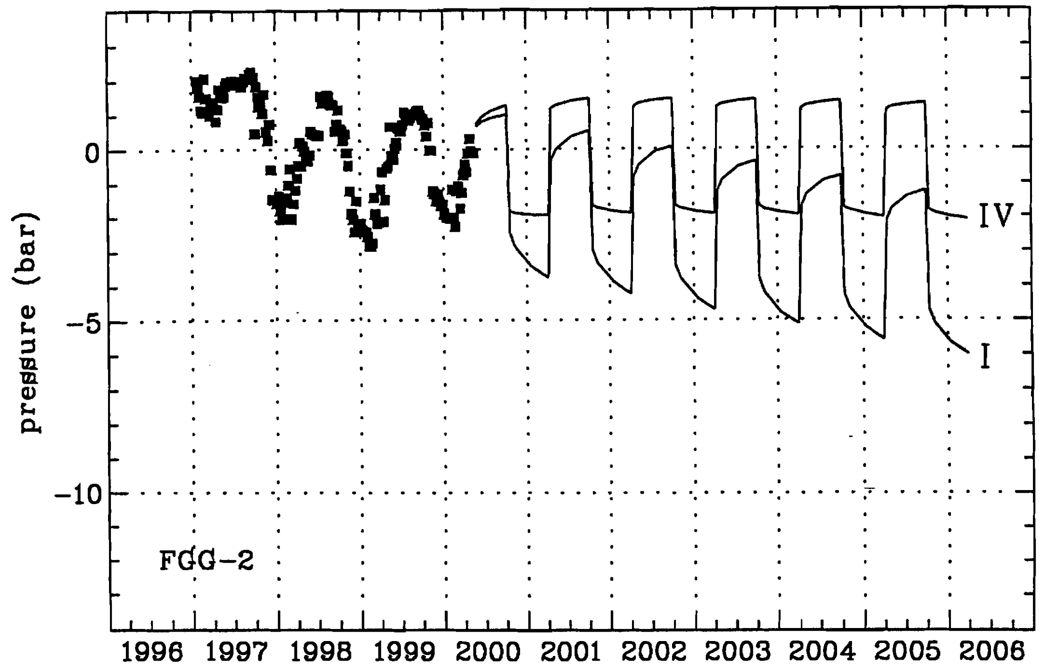

Figure 15. Predicted pressure/water-level variations for well FGG-2 and future utilisation scenarios I and IV.

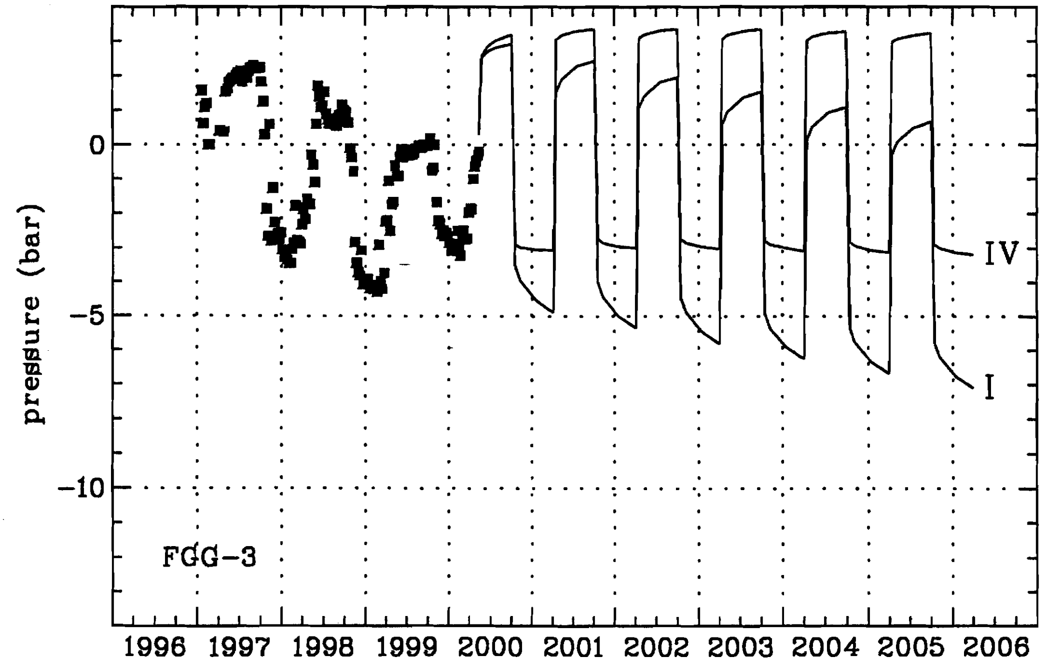

Figure 16. Predicted pressure/water-level variations for well FGG-3 and future utilisation scenarios I and IV.

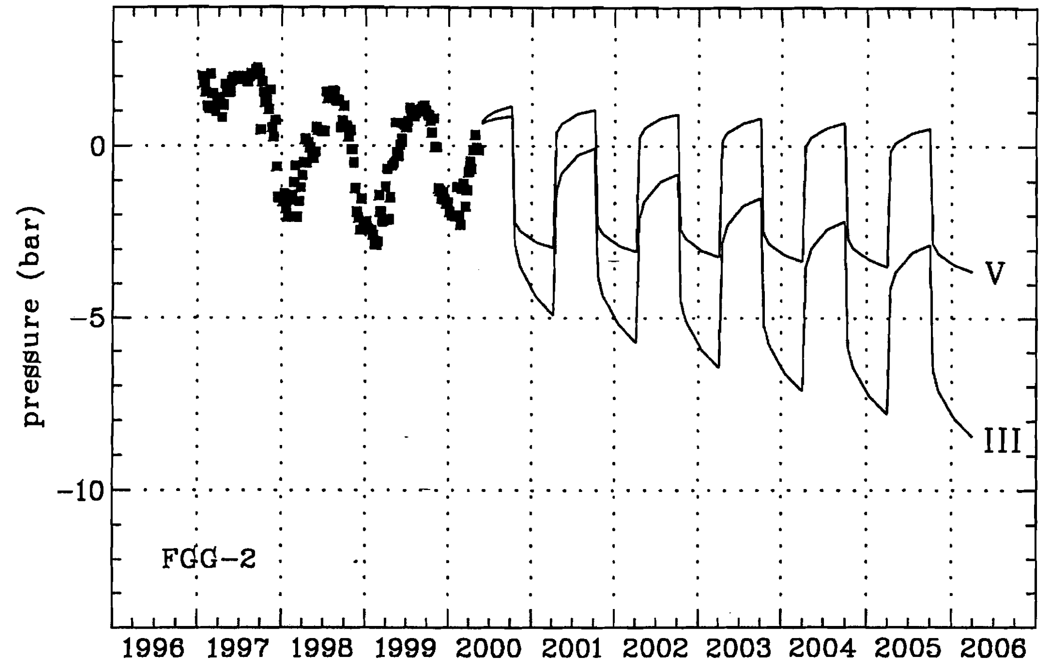

Figure 17. Predicted pressure/water-level variations for well FGG-2 and future utilisation scenarios III and V.

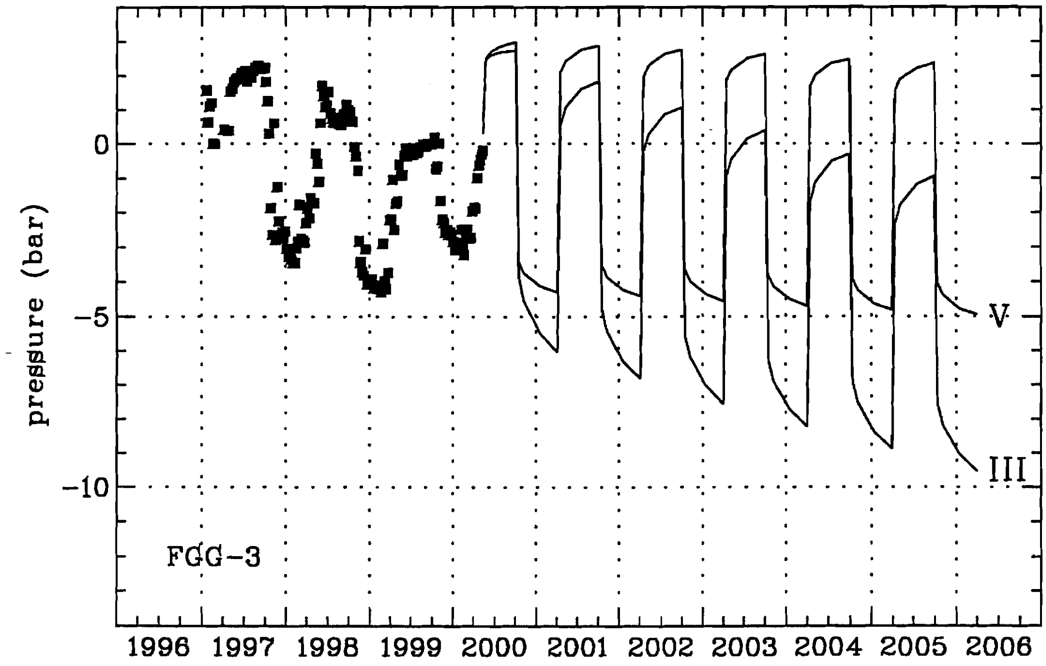

Figure 18. Predicted pressure/water-level variations for well FGG-2 and future utilisation scenarios III and V.

The results presented in Figure 11 through Figure 18 clearly show that hot water production in Galanta may be increased considerably. Prediction based on scenario II show that a 50% increase in production will cause an additional 50-60 m increase in water level draw-down during the winter. This can be easily met by lowering the down-hole pumps in wells FGG-2 and FGG-3 down to 150 – 200 m depth. It's beyond the scope of this study to estimate the ultimate production potential of wells FGG-2 and FGG-3. For this to be possible a maximum allowable draw-down must be set. This would be determined by several factors, one of which is the depth of production casings in the wells (300 m). Other factors that must be considered are interference in other areas, danger of colder water inflow, possibility of subsidence, etc. But the ultimate production potential of wells FGG-2 and FGG-3 is clearly greater than 150% of the present (1999) production, most likely about 200%, or more.

It is also clear from scenario III that increased production through drilling of additional production wells will, naturally, cause a smaller water-level draw-down than a comparable increase in production from wells FGG-2 and FGG-3 alone. Therefore, production from the Galanta geothermal system may be increased even more than already discussed (scenario II) if further production wells are drilled. Such wells need to be located at an adequate distance from the present production wells (see Figure 10), however.

One of the most important results of the predictions is the great benefit on the water-level draw-down in the Galanta reservoir from reinjection. Scenario IV shows that the foreseeable long-term water-level draw-down may be eliminated through 80% reinjection. Furthermore, the predictions show that reinjection will enable a drastic increase in production. In scenario V reinjection does more than eliminate the draw-down due to a 50% increase in production.

It must be kept in mind, however, that the fact that the model used is conservative may result in an overestimate of the long-term draw-down in the reservoir as well as the interference between wells. Thus the long-term draw-down will perhaps be smaller than predicted as well the benefit from reinjection. Yet it is clear that_increased production coupled with reinjection will not cause a serious increase in water-level draw-down in the Galanta geothermal system.

7. CONCLUDING REMARKS

This report has described the background and results of a revision of a model of the Galanta geothermal reservoir in Slovakia aimed at calculating reliable long-term pressure draw-down predictions. The results prompt the following concluding remarks and recommendations:

1. The hot water production from wells FGG-2 and FGG-3 may easily be increased by 50% or more. Production may be increased even more through drilling of more production wells. Other future production scenarios may be easily studied with the model now available.

2. It is highly recommended that reinjection should be part of the future management of the Galanta geothermal reservoir. Thus the hot water production from the field

may be increased through reducing pressure draw-down and interference. Reinjection is also in accordance with the increased global emphasis on sustainable energy production. The uncertainty involving possible cooling of production wells may be minimised by locating reinjection wells at a "safe" distance (>1000 m) from production wells as well as studied through carefully executed tracer tests. It is, furthermore, proposed that the so-called "Thiested-solution" be applied to avoid potential problems with reduced sandstone injectivity.

3. Careful monitoring of the Galanta reservoir is essential for future management of this energy resource. This applies, on one hand, to physical parameters such as mass extraction and pressure/water-level draw-down as well as to water temperature, which has not been discussed here. Careful and accurate monitoring of water temperature may yield information on reservoir changes due to colder water inflow. No water temperature changes have been detected yet for wells FGG-2 and FGG-3. The need for careful monitoring applies, on the other hand, to chemical parameters, changes in which may precede actual changes in reservoir conditions (Gunnlaugsson, 2000).

4. The model, which has now been developed, may be revised in the future, and consequently the pressure response predictions, as more pressure response data become available. The model is conservative at the moment, being entirely closed. This restriction may be lifted, as the response history becomes longer. A lumped parameter model may be considered again, during later model revisions, as the response of the Galanta geothermal system deviates further from the behaviour of a Theis-type model. The development of a detailed numerical model should be considered in the future, as more data become available (also through the drilling of new wells).

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