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Two-dimensional Simulation of the Krafla-Hvíthólar Geothermal Field, Iceland.

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ABSTRACT

The Hvíthólar geothermal field is a part of the Krafla geothermal area in north-eastern Iceland. It has been exploited since 1984 for electrical production. Three wells have been drilled in the field to depths of 1200 – 1968 m. The two producers (KJ-21 and KJ-22) have a total flow capacity of 60 kg/s, sufficient for generation of 14 MW_e. The reservoir pressure in the field has declined by about 15 bar since 1982.

A two-dimensional model of the natural state of the reservoir has been developed. The model is a vertical cross section. The physical processes considered include mass transport, conductive and convective heat transfer, boiling, and condensation. The model adequately matches all relevant data from the field. The natural flow of hot fluids through the reservoir is estimated to be somewhat less than 10 kg/s. The natural state model was calibrated against the production history of the field, and three different future production schemes were evaluated. At current production rates, the field is expected to last no more than another decade.

INTRODUCTION

The Krafla geothermal area is located in the Neovolcanic zone in north-eastern Iceland (figure 1). Three geothermal fields, i.e. Hvíthólar, Leirbotnar, and Suðurhlíðar, within the Krafla area are under exploitation (Ármannsson et al., 1987). At Hvíthólar three wells, KJ-21, KJ-22, and KJ-23 were drilled in 1982 and 1983 (Guðmundsson et al., 1982, 1983; Steingrímsson et al., 1983, 1984; Ármannsson and Steingrímsson, 1984). Well KJ-21 was drilled to a depth of 1200 m; its main aquifers are at depths of around 975 m and at 630 m. This well yielded a total of about 40 kg/s, with 60% coming from the upper aquifer and 40% from the lower. Well KJ-22 was directionally drilled to 1877 m, corresponding to 1740 m in vertical depth. The bottom of the well is 540 m to the west of the wellhead (figure 1). The well intersects several aquifers, the principal ones at 600 m, 960 m, and 1270 m depth, and yields a total discharge of 20 kg/s, 40% of which comes from the upper aquifers and 60% from the lowest. Well KJ-23, which was drilled to a depth of 1968 m, intersected few aquifers, all of them small, the biggest at 600 m and 700 m depth. This well has never been put into production.

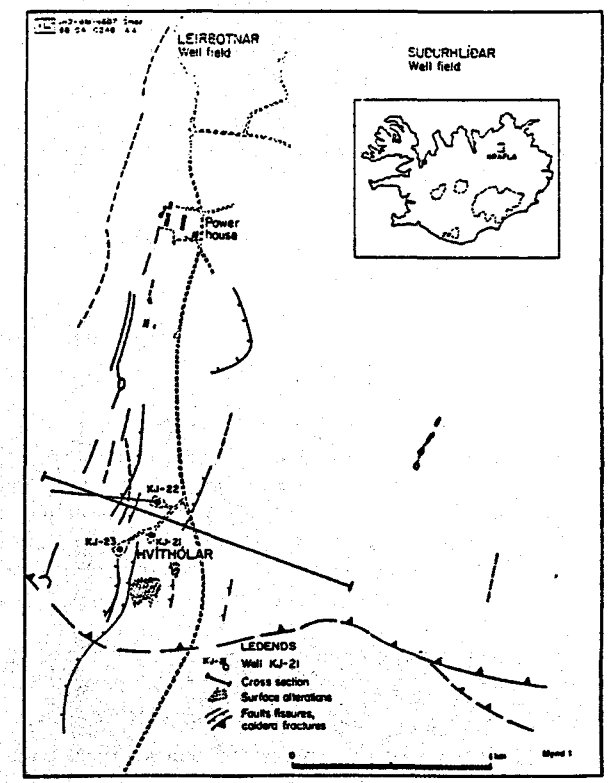

Figure 1. The Krafla-Hvíthólar well field.

Geological data indicate horizontal layering of basalts, hyaloclastites, and vertical or inclined intrusions (Ármannsson et al., 1987; Árnason, et al., 1984). There are no strong indications of reservoir connections between the Hvíthólar field and other parts of the Krafla area. Before production, the temperature in the field increased with depth down to 700 – 800 m, where it reached a maximum. Below 800 m there was a temperature reversal. The temperature at the bottom of well KJ-23 (1968 m) was 235°C. A fault separates KJ-23 from the upper part of KJ-22, and from all of KJ-21, and acts as a barrier between the wells. Since

KJ-22 is directionally drilled, it crosses this barrier at around 900 m depth (figure 2). A pressure drop of 6.5 bar across the fault was recorded.

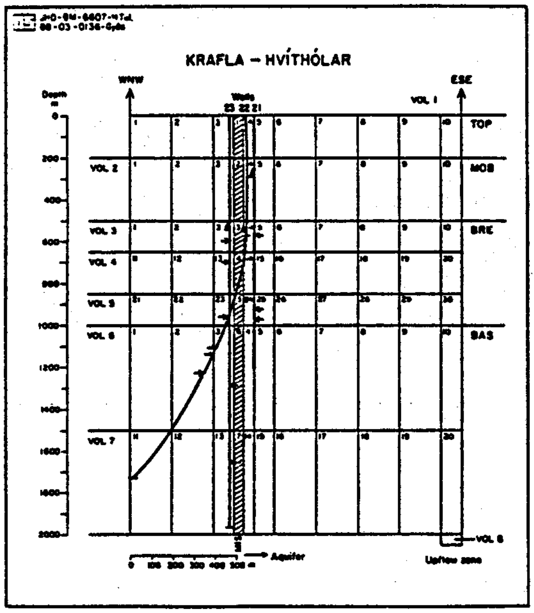

Figure 2. The two-dimensional distriubuted parameter model.

The computer program SHAFT79 (Pruess and Schroeder, 1980) was used for the simulation. In this program, flow through a porous medium is assumed. Several simulation studies have been performed on Icelandic high-enthalpy geothermal fields using this assumption, with good results (Böðvarsson, 1987; Böðvarsson et al., 1984 and 1986), even though the flow in Krafla and other high-enthalpy areas in Iceland is primarily through fractures and the storage is mostly in the rock matrix. The program furthermore assumes the reservoir fluid to be pure water, and the effects of gases and dissolved minerals are neglected. This should be a reasonable approximation because the gas and mineral content of the Hvíthólar reservoir fluid is low.

A two-dimensional model for the natural state of the Hvíthólar system is presented below. Field data from all three wells was used to develop the model.

CONCEPTUAL MODEL

All the available information on the field was used to construct the conceptual model. The undisturbed formation temperature is shown in figure 3. The temperature is similar at all the wells, though slightly higher at well KJ-21 in the depth range 600 – 1200 m. The highest temperature is about 250°C at wells KJ-22 and KJ-23, and 270°C at well KJ-21. The temperature at wells KJ-22 and KJ-23 falls to 190°C at 1400 m, where it increases again.

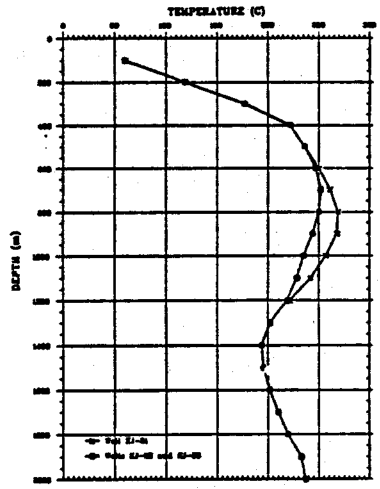

Figure 3. The estimated undisturbed formation temperature at wells KJ-21, KJ-22 and KJ-23.

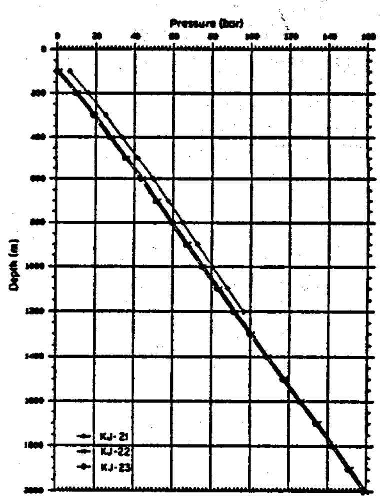

Figure 4. The estimated initial pressure at wells KJ-21, KJ-22, and KJ-23.

The estimated undisturbed inital pressure is shown in figure 4. The initial pressure is estimated to be 6.5 bar higher at well KJ-21 than at well KJ-23. This pressure difference is probably due to a barrier (fault/dyke) between these wells.

The temperature inversion and pressure distribution suggest that hot water is flowing towards the west on top of colder water. Well KJ-21 and the upper aquifers in well KJ-22 tap fluid from a reservoir east of well KJ-21. The lower aquifers in well KJ-22 (below 1000 m) and the aquifers in well KJ-23 are fed by a colder reservoir, which is probably connected to a north-south fissure swarm. This fissure swarm could be connected to the Krafla-Leirbotnar geothermal reservoir (Böðvarsson et al., 1984).

Drill cuttings from the three wells suggest a horizontal layering of basalts, hyaloclastites, and vertical or inclined intrusions. At the top there is about a 200 m thick layer, consisting primarily of fresh basaltic lavas, which are highly permeable and porous. Below it, extending to about 500 m depth, comes altered hyaloclastite with low porosity and permeability. This layer acts as a cap on the geothermal system. The next 500 m are primarily composed of more porous and permeable basalt breccias. Most of the aquifers are located in this layer. Below about 1000 m depth intrusions become more numerous and the permeability of the basalt decreases. Few aquifers are found below 1000 m depth.

THE COMPUTER MODEL

The wells are clustered together and therefore provide limited information on the lateral distribution of pressure and other parameters. The vertical structure in the geology and temperature is known but over a short lateral distance. Because of the limited lateral spread of the data, a two-dimensional model, i.e. a vertical cross section, was chosen. The cross section cuts the well field from WNW to ESE (figure 1). This way the model is close to being perpendicular to one of the main strike directions but parallel to the flow from the east. If the direction of the cross section had been at a right angle to the one chosen, very limited lateral and vertical changes would have been observed in the pressure and temperature data, and the model would therefore have been less appropriate for correlating the inflow to the system and other parameters.

In figure 2 the wells are projected onto the cross section. The cross section extends 600 m west of well KJ-21 and 1000 m to the east of it. Because of the geological structure of the geothermal system, the cross section was divided into five different geological units, each with different reservoir parameters. These units were further divided into smaller elements with different parameters (porosity, permeability). Table 1 lists the main parameters for the different units.

The geological unit MIS represents the fault between the wells and acts as a barrier. Its thickness is 50 m. The boundary nodes VOL 1 – VOL 8 control the inflow to, and the outflow from, the system and represent the surface. The node VOL 1 represents the atmosphere with an annual mean temperature around 5°C, and a pressure of one bar.

The boundary nodes are large enough to maintain constant temperature and pressure (table 2), even under the addition or withdrawal of large quantities of fluid. A constant temperature gradient and hydrostatic pressure are assumed in the nodes, which are not connected to each other. Because of their capacitive properties, these nodes can partly account for flow from the north along the north-south fissure swarm. Boundary node VOL 8 represents the upflow zone. To simulate the natural heat conduction from the earth a heat flux of 2 W/m^2 to the bottom unit was assumed. This value is the same as that used for Krafla-Leirbotnar (Böðvarsson, et al., 1984), but is an order of magnitude too high for Hvíthólar. This has little effect on the results of the simulation, except that it could accelerate the creation of two-phase condition.

Table 1. Element properties: Values of the parameters.

Name	Permeability* (10^{-15} m^2)	Porosity (%)	Density (kg/m^3)	Thermal conductivity (W/m°C)
TOP 1-10	10	15	2650	1.5
MOB 1-10	2x10^{-3}	5	2650	1.1
BRE 1-9	10	5	2650	1.7
BRE 11-19	10	5	2650	1.7
BRE 21-29	10	5	2650	1.7
BRE 10,20,30	10/20	5	2650	1.7
BAS 1-9	1.2	5	2650	1.7
BAS 11-19	1.2	5	2650	1.7
BAS 10,20	1.2/20	5	2650	1.7
MIS 1	0.45	5	2650	1.7
MIS 2	0.45	5	2650	1.7
MIS 3	0.45	5	2650	1.7
MIS 4	0.45	5	2650	1.7
MIS 5	0.45	5	2650	1.7
MIS 6	0.45/0.2	5	2650	1.7
MIS 7	0.45/0.2	5	2650	1.7

* Horizontal permeability/vertical permeability

Table 2. Boundary nodes.

Name	Temperature (°C)	Pressure (bar-a)
VOL 1	5.2	1.0
VOL 2	85.0	23.60
VOL 3	105.0	41.50
VOL 4	121.2	55.90
VOL 5	137.9	70.70
VOL 6	168.8	97.30
VOL 7	216.3	139.8
VOL 8	300	167.00

The values for the different parameters for each unit are essentially the same (table 1) as for the Leirbotnar and Suðurhlíðar fields (Böðvarsson et al., 1984). The values selected for porosity and thermal conductivity are the same as for the other fields. The porosity is 5% in all units except in the unit TOP, where it is 15%, and the heat capacity is 1000 J/kg°C in all units. The relative permeability of the water-steam mixture is assumed to be a linear function of steam saturation. Steam becomes immobile at 5% steam saturation as does water at 30% water saturation. This assumption has given good results for the Krafla fields (Böðvarsson et al., 1984).

NATURAL CONDITIONS

The objective of the study was to simulate the natural conditions in the Hvíthólar geothermal system prior to production, i.e. the prevailing temperature and pressure distributions at that time. Undisturbed temperature and hydrostatic pressure gradients (figures 3 and 4) were assumed in the system at the beginning of the simulation. An upflow zone, recharged by the boundary node VOL 8, is assumed east of well KJ-21.

The porosity and permeability in the different units were then changed along with the recharge rate in the upflow zone until a match with the initial temperature and pressure was reached. In the "best" model, near steady-state conditions were reached in about 900 years. At this point the changes in temperature and pressure everywhere in the system were less than 0.5°C and 0.5 bar, respectively, over 30 years.

Figures 5 and 6 show the natural state temperature and pressure distributions in the cross section, and figures 7 and 8 the calculated temperature and pressure profiles, for wells KJ-21 and KJ-23.

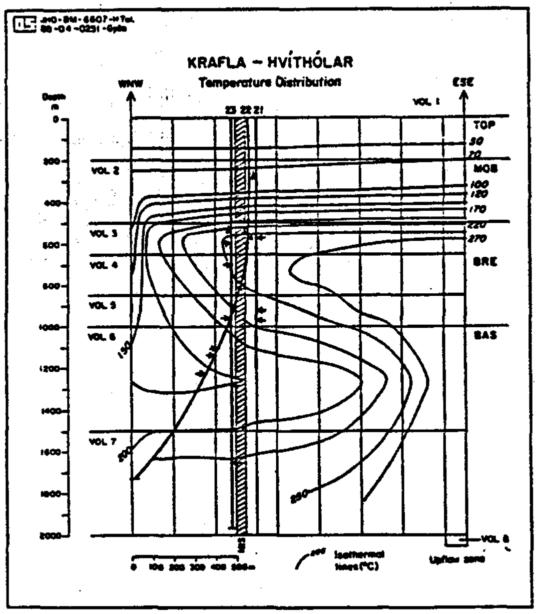

Figure 5. Calculated temperature distribution in the Krafla-Hvíthólar system.

By adjusting the permeability in the barrier (MIS), a pressure difference of 6.5 bar across the barrier could be obtained, in agreement with well measurements. In order to match the lower temperatures below 800 m, the upflow was directed along the east edge of the cross section by assigning a higher vertical than horizontal permeability to these elements. This is reasonable in view of the fracture/fault nature of the system.

In the "best" model the fluid turned out to be two-phase in the top layer of BRE from the barrier (MIS) to the east edge. In the upflow zone, two-phase conditions occurred in the BRE elements but not in the BAS elements. In the actual system it is not known whether the fluid was two-phase at 600 m depth in well KJ-21 prior to production, but is considered unlikely. The fluid at that depth was, however, expected to be at the boiling temperature. It should be noted that the presence of two-phase conditions in the model will influence the production predictions.

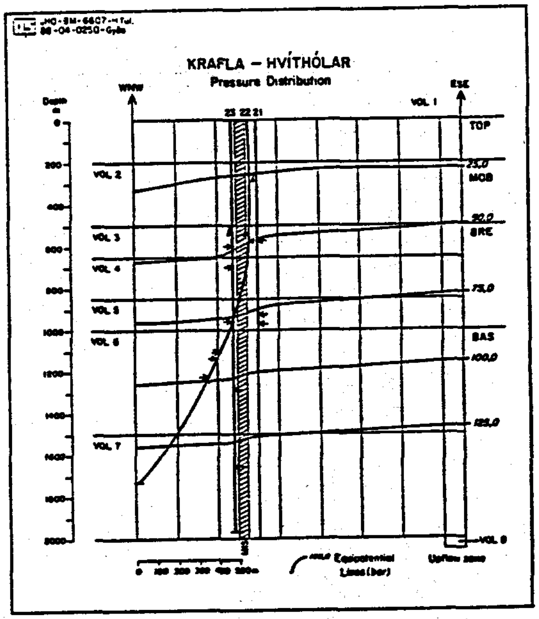

Figure 6. Calculated pressure distribution in the Krafla-Hvíthólar system.

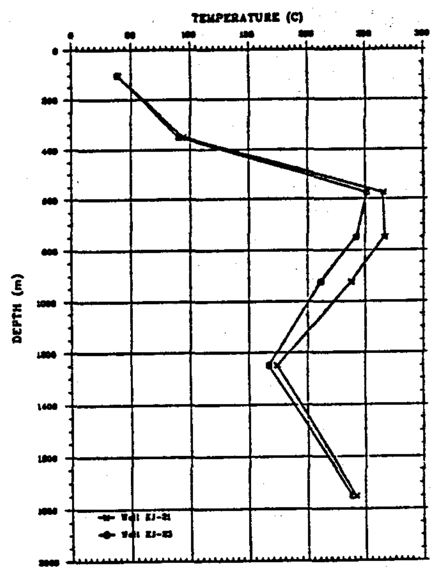

Figure 7. Calculated formation temperature at wells KJ-21 and KJ-22, prior to production.

PRODUCTION

The production histories for wells KJ-21 and KJ-22, from October 19, 1982, when KJ-21 was put into production, and until the end of 1987, are shown in figures 9 and 10, respectively. Well KJ-22 was not put into production until August 19, 1983, but the same time scale is used for both wells. The "best" model was calibrated against the production data. The end product of the natural state model was used as the initial condition for this calibration.

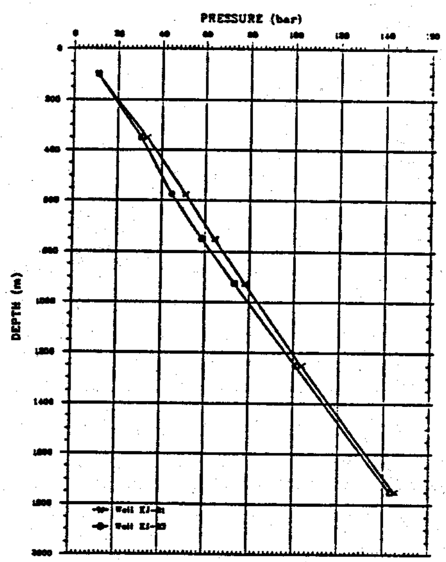

Figure 8. Calculated initial pressure at wells KJ-21 and KJ-22, prior to production.

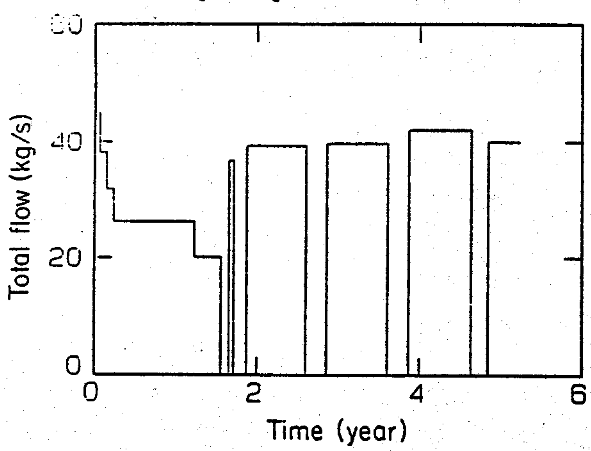

Figure 9. Well KJ-21, production history.

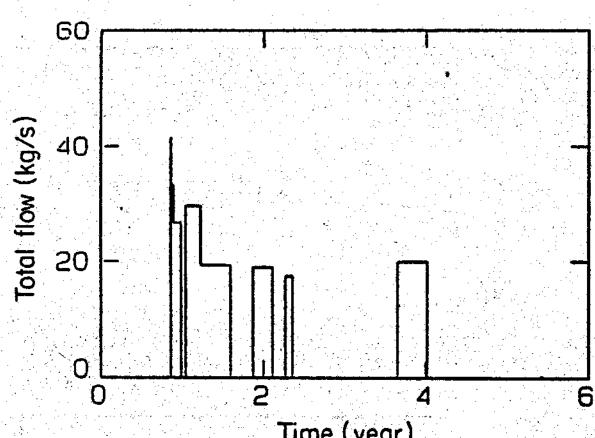

Figure 10. Well KJ-22, production history.

To simulate the production, several sinks were added to the model, approximately where the aquifers are located in the wells. In this way the pressure drawdown in the reservoir was simulated. Figure 11 shows the calculated pressure at 750 m depth in well KJ-21, and the corresponding measured pressures at 700 m and 800 m. In the simulation the production from each sink was varied until the "best" match was found. The results indicate that just over 60% of the total output comes from the upper aquifer at 600 m depth in well KJ-21, and the rest from the lower one at 975 m depth. The elements BRE 5 and BRE 25 indicate these two aquifers. In well KJ-22 about 40% of the total output comes from the upper, hotter aquifers (BRE 4) and 60% from the lowest (BAS 2).

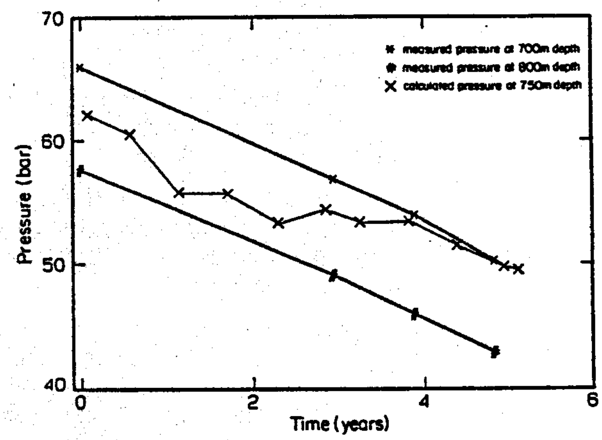

Figure 11. Calculated and measured pressure in well KJ-21.

The calibration against the production data indicated that the required lateral thickness for this two-dimensional model to sustain the production was of the order of 500 m. Furthermore, the natural recharge to the hot reservoir was estimated to be about 10 kg/s of fluid at 300°C.

As can be seen from figure 11, the calculated pressure response matches the observed one rather well. The applicability of the two-dimensional natural state model to exploitation studies of this system is, however, limited for the following reasons. The model is just two-dimensional, and the grid blocks are large. The third dimension, north-south, is kept constant, which means that mass production affects the whole thickness (N-S). One of the major strike directions in the area is N-S, which means the permeability could be greater in that direction close to the main fissures. Pressure drawdown in the production area could therefore cause an inflow from the north or the south. This is only partially accounted for by the present model, in the boundary nodes.

PREDICTION

After obtaining the "best" model and calibrating it against the production history, it was employed to predict pressure and temperature changes in the future. It should be kept in mind that this model is rather rudimentary, and therefore gives only a general idea about the system's response to further production. Three cases were examined.

1. Same production scheme as is currently employed at Hvíthólar. Well KJ-21 produces 40 kg/s (60% from 600 m and 40% from 975 m) nine months a year. The well is shut in during the months of June, July and August. Well KJ-22 produces 20 kg/s (40% from 600 m and 60% from 1100 m), and is shut in two weeks for every one it is in production. Well KJ-22 is also shut in during the months of June, July and August.
2. Same as case 1 except the wells are not shut in during the summer months, i.e. constant production during the whole year.
3. The lower aquifer in well KJ-22 is closed off, and it is assumed that the upper aquifer produces 8 kg/s for the whole year. Production from well KJ-21 is the same as in case 1.

Figures 12 – 14 show these three cases. For cases 2 and 3 the pressure drops so rapidly in the upper aquifer in well KJ-21 that production from the well stops after about a year, 275 days in case 2, and 473 days in case 3. Production from the system can be maintained much longer, however, under the present scheme (rest for three months a year). It appears that some kind of equilibrium is reached after about seven years, in late 1994. The pressure at the upper aquifer is then rather low or about 20 bar. In these calculations, the total flow is kept constant, and the increasing steam fraction of the fluid mixture is ignored. This could mean that less total flow is required for the same energy output from the well. Under real-life conditions the energy production can be constant, while the total fluid production declines. This would mean that the pressure drop at the wells is less than that calculated here, over the same period of time.

Temperature changes are small in all cases, at the most around 16°C at the upper aquifer in well KJ-21 for case 1. Temperature equilibrium is reached when the wells have dried up and only steam is produced.

CONCLUSIONS

A simple two-dimensional model of the Krafla-Hvíthólar geothermal system was developed, one which can simulate the pressure and temperature distribution in its natural state. This model was calibrated against the production history of the system, and employed to make rough predictions for future production.

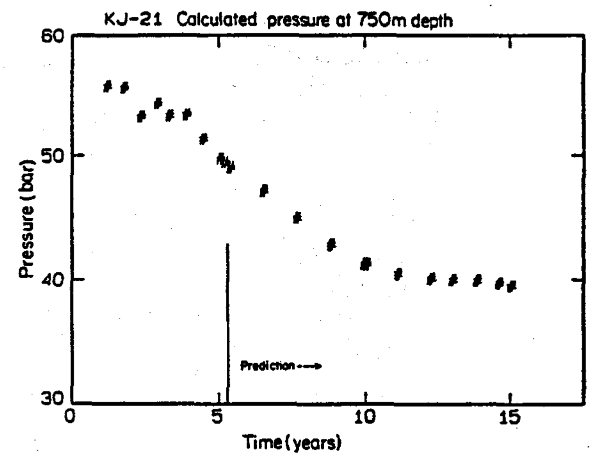

Figure 12. Prediction case 1, pressure at 750 m depth.

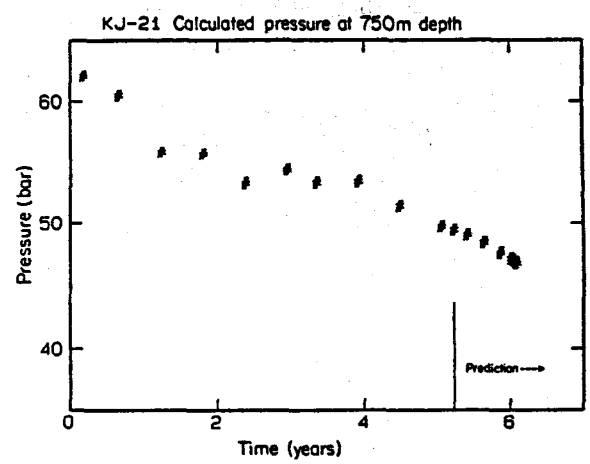

Figure 13. Prediction case 2, pressure at 750 m depth.

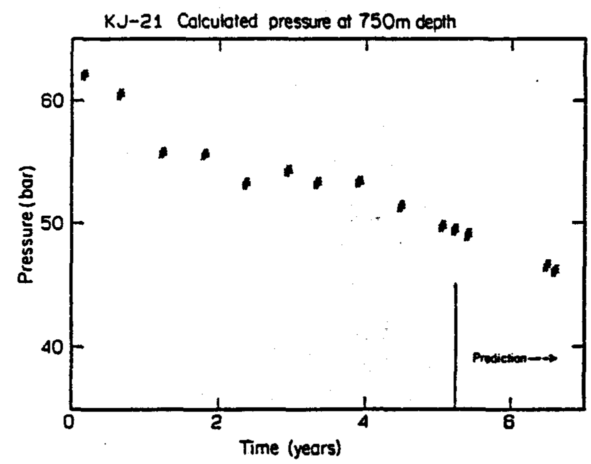

Figure 14. Prediction case 3, pressure at 750 m depth.

In the model, 60% of the fluid produced from well KJ-21 is from the upper aquifer (600 m) and about 40% from the lower (975 m). About 40% are produced from the upper aquifers in well KJ-22 and 60% from the lowest.

Natural recharge into the hot reservoir is estimated to be about 10 kg/s of 300°C fluids.

The system is rather small, probably somewhere between 0.3 and 0.5 km^3, which could correspond to 500 m in a north-south direction, a thickness of 500 – 1000 m (at a depth of 500 – 1500 m), and 1000 m in an east-west direction.

Under the current production scheme the system is predicted to last ten additional years, at the most.

FUTURE WORK

It has been recommended to the power plant operators (Landsvirkjun) that the model should be modified and the third dimension included. The recommendations are:

1. Modify the current two-dimensional model to obtain a better fit to the field data.
2. Add the third dimension, and thereby allow for directionally dependent inflow to the producing wells, as well as changes in their enthalpy and flow.
3. Include well-by-well simulation or refine the grid to match better the characteristics of individual wells.
4. Make new predictions for the Krafla-Hvíthólar system.

ACKNOWLEDGEMENT

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