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A SUMMARY OF MODELING STUDIES OF THE KRAFLA GEOTHERMAL FIELD, ICELAND

G.S. Bodvarsson, K. Pruess, V. Stefansson, and E.T. Eliasson

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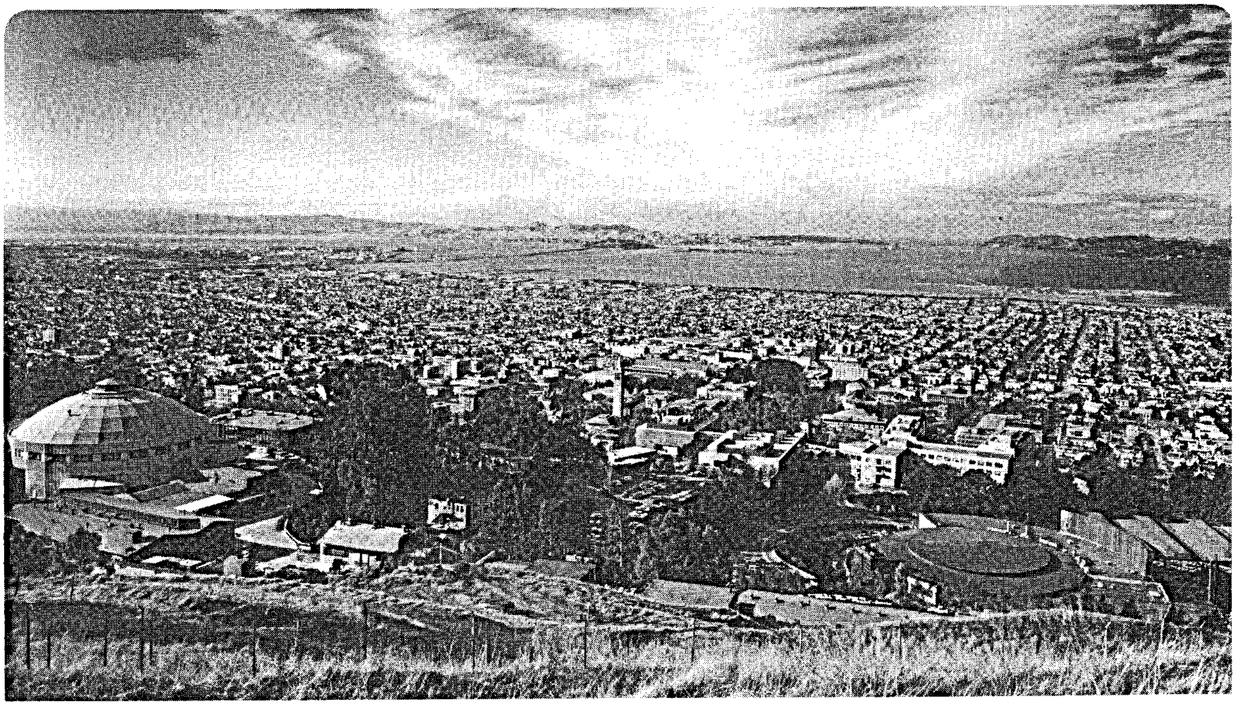

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ABSTRACT

A comprehensive modeling study of the Krafla geothermal field in Iceland has been carried out. The study consists of four tasks: the analysis of well test data, modeling of the natural state of the field, the determination of the generating capability of the field, and modeling of well performance. The results of all four tasks are consistent with field observations.

INTRODUCTION

Lawrence Berkeley Laboratory (LBL), in cooperation with the State Electric Power Works of Iceland (SEPW) and the Icelandic National Energy Authority (NEA), conducted a comprehensive modeling study of the Krafla geothermal field in Iceland. The study consisted of four tasks, the analysis of well test data, modeling of the reservoir system in its natural (unexploited) state, determination of the generating capacity of the different reservoir regions, and modeling of well performance based on different exploitation schemes.

For detailed modeling of a geothermal system, one must know or estimate many parameters that characterize the system. One of the most important parameters is the transmissivity (kH) of the reservoir, which represents the relative ease of fluid movement within the reservoir. The existing well test data from Krafla wells were analyzed to yield the transmissivity distribution in the reservoir.

Another necessary step before the behavior of the reservoir under exploitation can be evaluated is to model the field in its natural state. Natural-state modeling can establish a plausible reservoir model and help quantify natural mass and heat flows in the reservoir.

The final two tasks deal with the generating capacity of the reservoir and well performance. We develop a simple lumped-parameter model for approximate estimation of the generating capacity of the field, which allows for natural recharge and reinjection. Then numerical methods are employed in a two-dimensional areal simulation of the Krafla system. Finally, a quasi-three-dimensional model is developed in which all wells are represented individually. The model achieves an approximate match of past production rates and enthalpies of the wells. It is then used to predict future well behavior (flow rates and fluid enthalpy) and overall reservoir depletion under various reservoir management schemes.

The present article gives a rather brief summary of the modeling work; a more complete description will be given in a forthcoming report (Bodvarsson et al., 1983a).

THE KRAFLA GEOTHERMAL FIELD

The Krafla geothermal field is located in the neovolcanic zone in northeastern Iceland. The zone is characterized by fissure swarms and central volcanoes. The Krafla field is located in a caldera (8 x 10 km) with a large central volcano, also named Krafla. The field has been under development for the last decade. At present, 21 wells have been drilled at the Krafla field (Fig. 1). In the "old" wellfield (west of the Hveragil gully) the wells have encountered two major reservoirs (Fig. 2); the upper reservoir (200-1000 m depth) contains single-phase liquid water with a mean temperature of 205°C. The deeper reservoir is two-phase, with temperatures and pressures following the boiling curve with depth. The two reservoirs are separated by a thin (200-500 m) low-permeability layer, but seem to be connected near the Hveragil gully. In the new wellfield (east of Hveragil; wells 14 and 16-20) the two-phase liquid-dominated reservoir extends close to the ground surface.

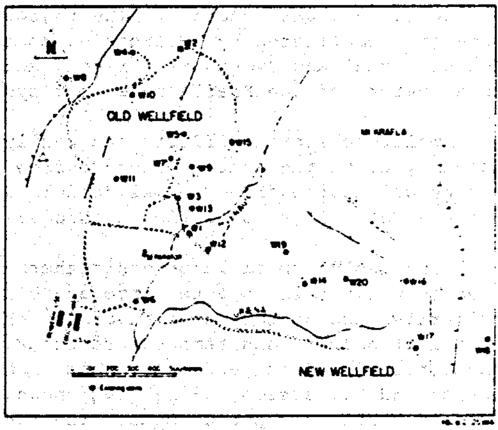

Figure 1. Well locations. Well 21 (not shown) is located approximately 2 km south of the power plant.

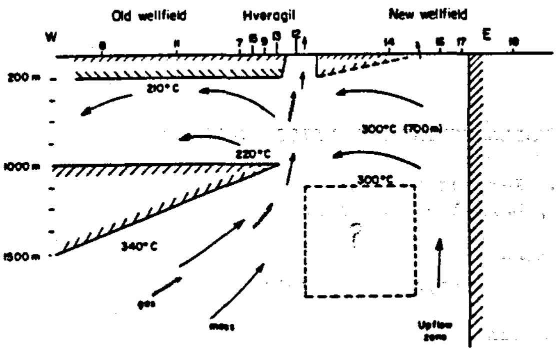

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Figure 2. Conceptual model of the Krafla field.

The production characteristics of the various reservoir zones at Krafla are vastly different. The low temperature of the fluids in the upper reservoir in the "old" wellfield make it unfavorable for the production of high-pressure steam. Consequently, in most of the wells in the old wellfield the upper zone is cased off. In the lower zone, the temperature of the reservoir fluids is high (300-340°C), but silica scaling and iron deposits hamper effective utilization of the fluids. In the new wellfield the chemical composition of the reservoir fluids is more favorable and scaling problems are minimal. A detailed description of the Krafla system is given by Stefansson (1981).

Electric power has been produced at Krafla since 1978 (Eliasson et al., 1981); presently (1982) approximately 20 MWe are produced at Krafla.

WELL TEST DATA ANALYSIS

Most of the Krafla well test data have been obtained from injection tests performed following well completion. The purpose of the injection test is two-fold: (1) to attempt to stimulate the well, i.e., increase the water losses, and (2) to obtain data that can be analyzed to yield the transmissivity of the formation. In analyzing the data obtained from the injection tests one cannot blindly use the conventional type curve analyses developed in the oil and gas industry. The injection test data are complicated by wellbore storage effects, nonisothermal and two-phase effects, and the fractured nature of the Krafla reservoir system.

Wellbore storage effects can easily be eliminated by using the actual sandface flow rate, which can be calculated from the wellhead injection rate and the water level data (Bodvarsson et al, 1981).

One would expect large nonisothermal effects when 20°C water is injected into a 300°C reservoir, primarily because the water viscosity changes by a factor of 5 over this temperature range. However, theoretical studies (Bodvarsson and Tsang, 1980; Benson and Bodvarsson, 1982) have shown that injection tests in a porous medium reservoir with an existing cold spot (due to the injection during drilling and logging) yield data that only reflect the conditions of the hot reservoir. Bodvarsson and Benson (1983) have shown that this is also true for a reservoir with horizontal fractures.

Figure 3 shows the injection test data for well KJ-13. For several days prior to the test, water had been injected into the well at a rate of 20-30 kg/s. The injection test started with a falloff, followed by three increasing step-rates and a final falloff. The calculated sandface flow rates are shown as a broken line. Using the semi-analytical variable flow rate model ANALYZE (McEdwards and Benson, 1981) and the numerical simulator PT (Bodvarsson, 1981), the match of the observed and the calculated water level data shown in Figure 3 was obtained. On the basis of the theoretical work reported above, the kH of the well was calculated using the hot reservoir viscosity (μ). The match yielded a very high value for the storativity (ϕcH), reflecting the two-phase conditions of the reservoir (Bodvarsson et al., 1981).

In a similar manner, injection test data from other Krafla wells were analyzed. The results show that the Krafla reservoir has a low average transmissivity, 2.0 Darcy-meters (Dm), with values for most wells falling within the range 1.5-2.5 Dm. A detailed description of this work is given by Bodvarsson et al (1983b).

MODELING OF THE NATURAL STATE OF THE KRAFLA FIELD

Using the conceptual reservoir model of the Krafla reservoirs (Fig. 2) we developed a two-dimensional natural-state model for the Krafla field. The natural-state modeling quantifies natural mass and heat flows in the reservoir and establishes mass and heat recharge to the system (boundary conditions), providing valuable constraints for modeling field behavior under exploitation. A vertical cross-sectional model was considered adequate since the equipotential lines in the upper reservoir indicate that the main fluid flow is in the E-W direction. In the model (see Fig. 4) we use eight different zones to represent rocks with different material properties. The caprock and the confining layer (zones 1 and 2) have

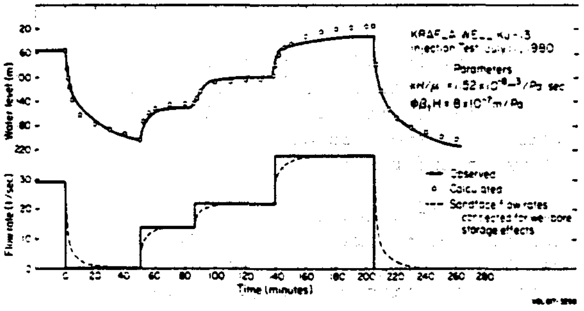

Figure 3. Comparison between observed and calculated water level data for injection test of well KJ-13.

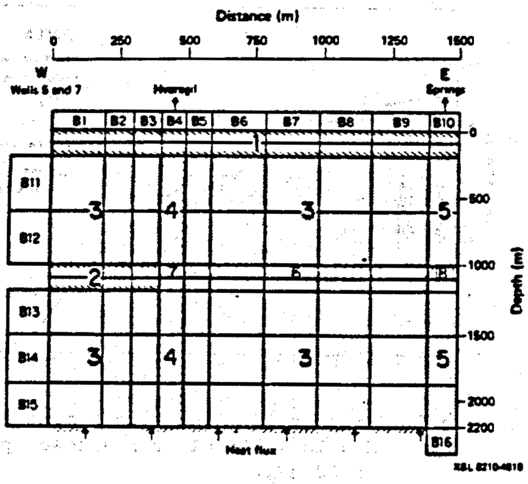

Figure 4. Grid blocks and different reservoir zones used in the natural-state modeling.

low permeability; zone 3 represents the main reservoir rock with an average horizontal transmissivity of 2.0 Dm as determined by the analyses of the injection tests. Reservoir zones 4-8 represent high-permeability regions due to upflow zones (faults) and major fractures. Geochemical data and pressure measurements indicate that upflow zones are present near the Hveragil gully and in the new wellfield (zones 4 and 5, Armannsson et al., 1982). The fracture zone, represented by zone 6, has been identified in all the wells drilled in the new well field. The boundary nodes (B-nodes) are necessary to model the correct boundary conditions as well as up-welling of fluids from depth. Fluid discharge to surface manifestations near the Hveragil gully and in the new wellfield are also considered in the model.

In the numerical simulations we use the multiphase, multicomponent numerical simulator MULKOM (Pruess, 1983). We selected a small set of the most reliable field data as input, and varied less well known parameters in a trial-and-error process until reasonable matches with all relevant field data were obtained. The simulations were carried out for tens or hundreds of thousands of years before steady state conditions were reached.

The best model obtained agrees very well with all field data from the Krafla field. The calculated temperature profiles in both wellfields generally agree with the field data to within a few degrees. Similarly, the pressure profiles in the old and new wellfields agree to within 1-2 bars at all depths. The model also predicts steam losses at surface manifestations in Hveragil and the new wellfield that agree very well with estimated values (Armannsson and Gislason, personal communication, 1982).

The primary conclusions from the natural state modeling are as follows. Fluids from an upflow zone recharge the reservoir in the new wellfield at a rate of .010 kg/s per meter of reservoir width. The fluids flow laterally along a high-permeability fracture zone at a depth of about 1 km and mix with fluids rising from the lower reservoir. The fluids mix in a ratio of about 1:1 with a higher mass flow coming from the lower reservoir in the old wellfield. The natural fluid flows are highest in the Hveragil fault zone, where about 0.008 kg/m.s of high-enthalpy steam is discharged to surface springs; the remainder (about 0.013 kg/m.s) recharges the upper reservoir in the old wellfield. In the Hveragil fault zone extensive boiling takes place, reducing the temperature of waters feeding the upper reservoir. The temperatures in other parts of the reservoirs are high, about 300°C at a depth of 1000 m and 345°C at a depth of 2000 m.

The heat losses through the caprock are estimated to be 1 W/m^2 (26 HFU) and the heat flux from the bottom as 2.0 W/m^2. A detailed description of the natural state modeling is given in Bodvarsson et al. (1983c).

THE GENERATING CAPACITY OF KRAFLA RESERVOIRS

In this section we first present a lumped-parameter model of the old wellfield and then distributed-parameter models of the different reservoir regions at Krafla.

Lumped-Parameter Model

We developed a general lumped-parameter model for geothermal reservoirs (Bodvarsson et al., 1983d). The model considers the mass and energy depletion of a wellfield with specified mass recharge (natural or artificial) from surrounding regions. The model can give rough-and-ready estimates of the generating capacity of a given field in MW$_e$-years.

Figure 5 shows the generating capacity of the old wellfield for different values of produced enthalpy and recharge factor (the latter being defined as the ratio of recharge mass to discharge).

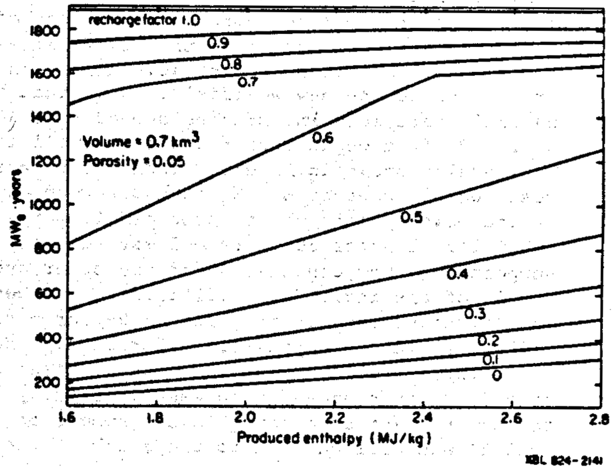

Figure 5. Lumped model-generating capacity of the old wellfield.

The figure shows that for the parameters assumed the maximum generating capacity is 1800 MW_e-years (60 MW_e for 30 years). However, due to the low overall permeability of the Krafla field, the recharge factor is unlikely to be higher than 50%, which yields 30 MW_e for 30 years (for a production enthalpy of 2200 kJ/kg). In general, the results we obtained with the lumped-parameter model show: (1) if (natural or artificial) recharge is limited, the reservoir will be depleted of fluids rather than heat, and the generating capacity will depend greatly on the porosity; (2) when the recharge factor exceeds 60% the field in general will be depleted of energy and the generating capacity will be independent of porosity and the enthalpy of the produced fluids.

Areal Distributed-Parameter Models

As shown in the previous section, fluid recharge is an important factor controlling the generating capacity of a field. In order to study the rate of natural recharge to the Krafla reservoir system, we developed several two-dimensional areal models. These models consider (i) the old wellfield only, (ii) the new wellfield only, and (iii) both wellfields together. In all three cases the entire wellfield is modeled as a single block, thereby assuming a uniform depletion of the wellfield region. However, the reservoir regions outside the wellfield are modeled in reasonable detail, to enable accurate determination of fluid recharge into the wellfield. We only modeled the two-phase reservoirs in the old and new wellfields, assuming a reservoir thickness of 1000 m. The transmissivity values used were those determined from analysis of injection test data. The mesh design and boundary conditions assigned were based on results from the natural-state modeling study.

Figure 6 shows the pressure decline in the whole wellfield versus time when fluids equivalent to 60 MW_e are produced. In this case, we assumed an average reservoir porosity of 5%, which is reasonable based on core data (H. Kristmannsdottir, personal communication, 1980). The two curves shown in Figure 6 represent two rather extreme cases; the broken line represents the case of no fluid recharge from depth to the new wellfield and the solid line corresponds to 16.7 kg/s recharge from depth to the new wellfield. Note that the natural-state modeling studies showed that 10 kg/s of fluids from depth recharge the new wellfield. The results shown in Figure 6 indicate that it is questionable whether 60 MW_e (the designed capacity of the power plant) can be produced from the existing wellfields for 30 years. These results are supported by the conclusions of the other areal models of the individual wellfields. The best assessment to date is that for a 30-year period the old wellfield can supply steam for 30 MW_e and the new wellfield 20 MW_e, suggesting that steam production from other areas is necessary to fully utilize the power plant capacity. In the summer of 1982, well 21 was drilled 2 km to the south of the old wellfield. The results are very promising.

A detailed description of the lumped-parameter model and the areal models for the Krafla reservoir is given by Bodvarsson et al. (1983d).

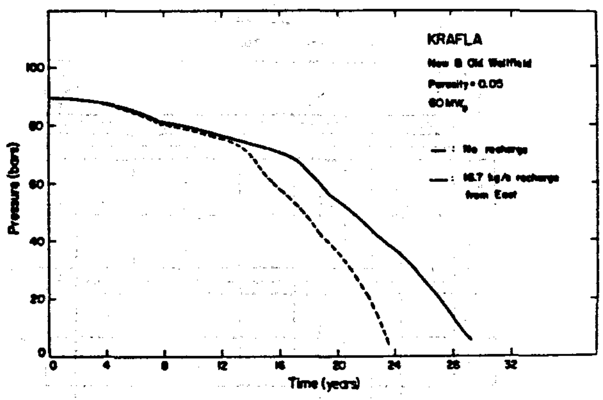

Figure 6. Pressure decline versus time in the Krafla wellfield for a power production of 60 MW_e.

WELL-BY-WELL MODELING

We developed a quasi-three-dimensional model of the Krafla reservoir, in which all producing wells are represented individually. The main objectives of this work are to match well histories (flow rates and enthalpies) of all producing wells, predict their future performance, and study the overall reservoir depletion under various reservoir management schemes. This provides the field operator with data which can be used to determine the number of make-up wells required and help select the proper exploitation plan for the Krafla reservoir system.

The reservoir model used is shown in Figure 7. The upper and lower reservoir zones are each represented by single horizontal layers. Vertical flow within and between the layers is neglected.

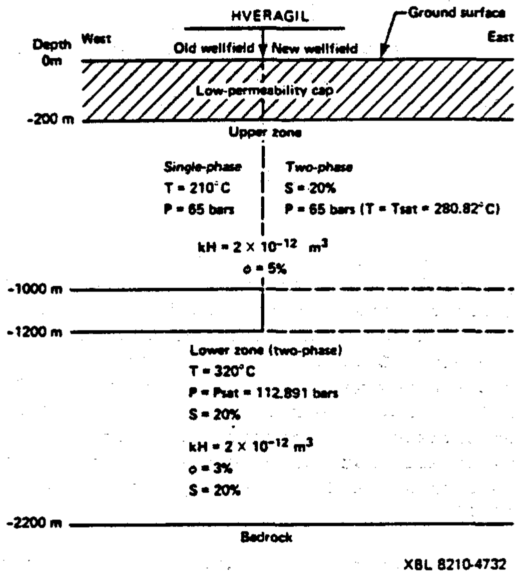

Figure 7. Cross section of model used in simulations of individual well behavior.

The chief parameters adjusted in developing a detailed history match for well performance are reservoir porosities and permeabilities, and productivity indices for wells. The permeabilities in the vicinity of wells are known from analysis of the short-term injection tests. Permeabilities further away, especially in the two-phase zone, as well as the effects of major fractures and faults are uncertain. Natural recharge through the system as established by the natural-state modeling is included in the modeling.

After many iterations, a reasonable history match with observed flow rates and enthalpies of all producing wells in the new and old wellfields was achieved. The mesh used and the distribution of porosities and transmissivities in the lower reservoir required to obtain the match are shown in Figure 8. In all, 23 different values of the rock properties were necessary for the match obtained. In the upper reservoir, 6 different porosity-transmissivity combinations were sufficient. Several fluid flow barriers (faults) were necessary to obtain a reasonable match with both flow rates and enthalpies of wells (Fig. 8). Figure 9 shows the comparison between observed flow rates and enthalpies of well 7 and those calculated by our model. The agreement is satisfactory except in 1982 when cleaning of well 13 interfered with the performance of well 7. Similar matches were obtained for all the other wells. In general the history match showed that pressure and vapor saturation changes are quite slow in the Krafla reservoir system due to the large compressibility of the two-phase fluids. The time constant for well-to-well interference is about a year but the long-term effects can be quite substantial. Some of the flow barriers inferred from the history match can be related to known faults whereas others may be nonexistent.

Using different reservoir management criteria, the future performance of the Krafla wells was predicted. Figure 10 shows the predicted flow rates and enthalpies of well 7 under different production and injection schemes. In general, we predict a very small decline in the flow rates of the Krafla wells in the future, or 1-4% annually for the no-injection cases. When injection was considered, the flow rates of the nearby wells increase drastically (see Figure 10) but the enthalpy of the produced fluids declines similarly. These two effects tend to offset each other, yielding small net effects on the steam rate at the separators. This is in agreement with injection data from the field (Stefansson et al, 1982) as well as recent theoretical work by Bodvarsson et al. (1983e).

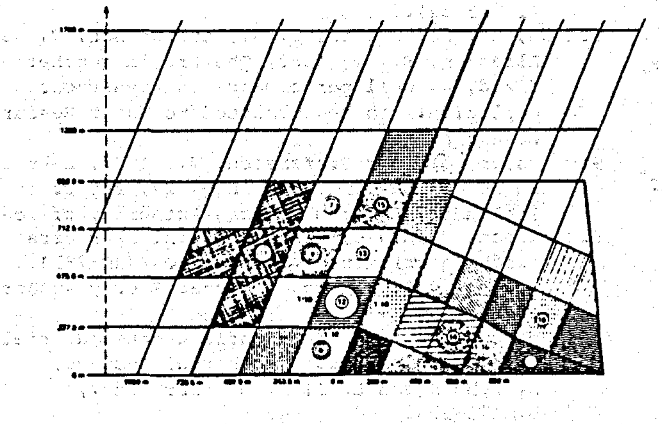

Figure 8. Properties of different zones and flow restrictions in the lower reservoir used in the well performance modeling.

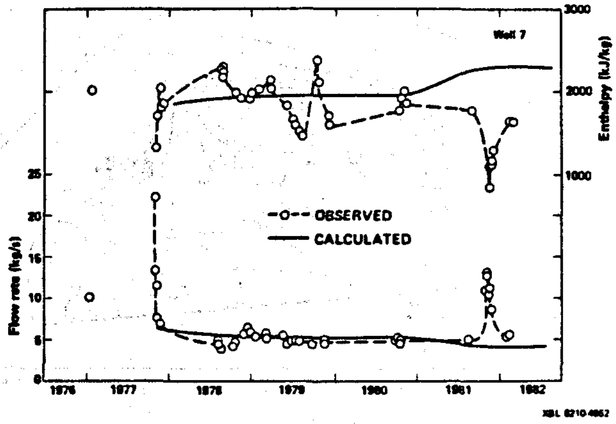

Figure 9. Comparison between observed and calculated production data for well KJ-7.

Figure 11 shows the computed vapor saturation contours in the lower zone at the end of 1982. Our simulation studies show that during the next decade a steam zone of substantial volume will develop in the Krafla field. The steam zone will grow rapidly if injection is not employed.

The interference effects between wells show that some additional wells may be drilled in the existing wellfields. These additional wells will decrease somewhat the energy output of the existing wells, but the total output will be increased.

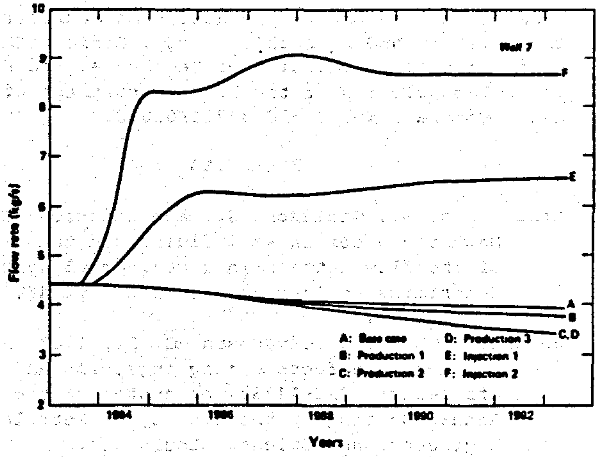

Figure 10. Predicted flow rates of well 7 for different production/injection schemes.

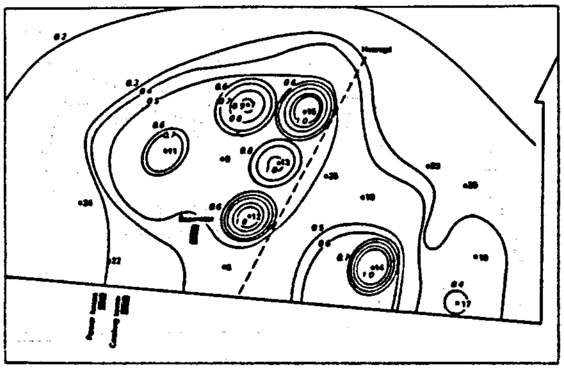

Figure 11. Vapor saturation contours in the lower zone at the end of 1982.

CONCLUSIONS

In this paper we summarized modeling studies of the Krafla geothermal field in Iceland. The well test analysis yielded the transmissivity distributions in the Krafla reservoir. A natural state model was developed that matches all relevant data from the Krafla field. Using a lumped-parameter model and two-dimensional areal models, we estimated the generating capacities of different reservoir zones. Finally, we developed a quasi-three-dimensional model that approximately matches performance data from all wells. The model was used to predict future behavior of wells and reservoir depletion under different reservoir management schemes.

ACKNOWLEDGEMENTS

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