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PRESSURE BUILDUP MONITORING OF THE KRAFLA GEOTHERMAL FIELD, ICELAND

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ABSTRACT

A break in electrical power generation from the Krafla geothermal plant was planned from beginning of May to early September 1984. Early in June most of the production wells were shutin and their pressure recovery monitored. A regular monitoring of the pressure buildup was carried out on a well to well basis until mid-August, when the wells were put back into production except for wells 12 and 16. They were used to monitor the pressure drawdown due to the start of production. This was abruptly brought to an end by a nearby volcanic eruption in early September.

The pressure buildup in the two-phase geothermal reservoir at Krafla is described and the first results presented. The results are compared with parameters determined on the completion of the wells and with predictions from numerical simulations of the reservoir. Finally the status of the Krafla geothermal system is discussed with regard to the comparison.

INTRODUCTION

The Krafla geothermal field is sited within the caldera (8x10 km) of the Krafla central volcano in northeastern Iceland. To date 23 wells have been drilled in low resistivity anomalies within the Krafla caldera. Their locations in relation to the power plant are shown in Figure 1. Most of the wells (1-13,15) are located in the Leirbotnar-field west of the Hveragil gully. Wells 14 and 16-20 are located in the Sudurhlidar-field on the southern flank of Mt. Krafla. The wells most recently drilled at Krafla (21-23) are located in the Hvitholar-field, about 1.5 km south of the power plant.

A detailed description of the reservoir system in the Leirbotnar-Sudurhlidar fields is available in the literature (Stefansson, 1981; Bodvarsson et. al., 1984). The following is a brief summary of this model. In the Leirbotnar-field pressure, temperature and chemistry data indicate the presence of two reservoirs. The upper reservoir contains single-phase liquid water at a mean temperature of 210 °C.

References and illustrations at end of paper.

This reservoir extends from a depth of 200 m to about 1100 m. Below there is a two-phase reservoir with temperatures and pressures corresponding to the boiling curve with depth. This reservoir directly underlies a confining layer at 1100-1300 m depth and extends to depths greater than 2200 m. This division into upper and deeper reservoirs does not extend across the Hveragil gully and in the Sudurhlidar-field only the two-phase liquid-dominated reservoir seems to be present. The reservoirs in the Leirbotnar-Sudurhlidar fields seem to be connected near the Hveragil gully.

In accordance with sales contracts, a break in electrical power generation from the Krafla geothermal power plant was planned from the beginning of May to early September 1984. This break was used to monitor the pressure recovery in the production fields in Leirbotnar and Sudurhlidar. Preparation for the work started in late May with the condition of the wells being checked.

A drillout operation was planned for wells 3 and 9 in July, but had to be put toward to early June. Due to this well 9 was shutin on June 1st, or before the regular monitoring project started. Therefore, pressure buildup started in the upper reservoir in the Leirbotnar-field before the other wells were shutin.

The monitoring project started on June 4th with the shutin of well 16 in the Sudurhlidar-field. Other wells there were shutin two days later. The same procedure was used for the Leirbotnar-field and started on June 7th with the shutin of well 12. Well 7 was kept in production to keep the pipelines hot. Wells 9 and 3 were drilled out during the period June 13-20th.

Soon after shutin a high wellhead pressure (>70 bar) had built up in well 14. To eliminate the risk of damaging the wellhead equipment, the well was opened up again only two days after shutin. Similarly, well 13 had to be put on restricted flow five days after shutin.

Pressure was monitored regularly in wells 12 and 15 in the Leirbotnar-field and in wells 16,17 and 20 in the Sudurhlidar-field. Water level was monitored in wells 3,5,8 and 10 in

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the Leirbotnar-field and in well 18 in the Sudurhlidar-field. This was carried out until August 14-17th, when the wells were put back into production except for wells 12 and 16. The plan was to monitor until mid-September their pressure drawdown due to the start of production. However, this was abruptly brought to an end by a nearby volcanic eruption on September 4th, 1984. The volcanic activity has previously caused in the liquid part of the system a large pressure increase, which is an order of magnitude larger than the effect caused by production in the field (Stefansson, 1981; Sigurdsson and Tiab, 1983).

ANALYSIS OF DATA

The wells where water level was measured regularly had not been producing for years before the shutin of the fields, except for well 3. In the Leirbotnar-field these wells (3,5,8,9,10) are mainly connected to the upper reservoir. Figure 2 shows the water level as measured in well 10, but other wells (5,8) show identical behavior. The early buildup is due to the premature shutin of well 9, but then there is a change in the slope after about 320 hr, which is due to the shutin of well 3. Using the time of interception and other available data for the upper reservoir (Pruess et. al., 1984), the distance between wells 10 and 3 is calculated as 535 m, but the measured distance between their wellheads on the surface is about 540 m.

Later a drop in the water level is observed, caused by the onset of production in mid-August. Then there is a sudden rise of the water level of about 50 m, which is caused by the volcanic activity north of the Leirbotnar-field in early September. This effect was observed in all wells where water level was measured, but the magnitude of the response differed from well to well.

The response of well 12 in Leirbotnar to the shutin is shown in Figure 3. The data points are fitted by the solid curve with a double porosity analytical model. Results from the match are presented in table 1, and indicate a negative skin for the well, high wellbore storage and fractures with restricted flow capacities.

Well 13 in Leirbotnar is directionally drilled to east and cuts a NNE-SSW directed near vertical fracture along the Hveragil gully. Figure 4 shows the four measurements available from well 13 during the five days shutin period. The well had not yet stabilized, so the data is fitted with an infinite acting system. It indicates a high wellbore storage and a positive skin. This agrees with the fact that scaling is occurring in the well. Due to the high wellbore storage and few data points a match with a vertical fracture model was not obtained.

In Figure 5 the data points and match for well 15 in Leirbotnar is shown. Some difficulties were in matching the data because of its behavior for the first 30 hours, which may be caused by the high gas content of this well's fluid. The figure shows a match with a double porosity model. However, the model does not indicate any major connection to a fracture.

The data from well 16 in Sudurhlidar are presented in Figure 6 and show a better match with a double porosity model than the alternative vertical fracture model. The match indicates that the well intercepts a fracture in a rock mass of rather low permeability. There is a small restriction in the fracture. This well was monitored for three weeks after other wells in Sudurhlidar had been put into production again. During that period no pressure decline was observed in the well. However, a pressure pulse of 3.7 bar caused by the volcanic activity was observed. This indicates that at least in the eastern part of the Sudurhlidar-reservoir the fluid is still mostly single-phase liquid.

Results for well 17 in Sudurhlidar are shown in Figure 7. The data is matched with an infinite acting system. The match results in a large negative skin, which is caused by a thin and highly permeable near horizontal layer or fracture, intersected by the well.

Well 20 in Sudurhlidar is directionally drilled to the north and intersects two nearly vertical fractures or faults. Figure 8 shows the measurements from well 20 along with the match from a double porosity model. A match with a vertical fracture model was not as good, because the analytical model was not able to handle a strong early wellbore storage behavior, possibly enhanced by thermal effects in the well. This may cause the double porosity model to give too low estimates for the transmissivity (Miller, 1980). On the other hand the double porosity model indicates, that the well intersects a relatively large volume fracture.

DISCUSSION OF RESULTS

In table 2 a comparison is made between the transmissivity values obtained in an injection test at the end of drilling and those presently estimated. The general trend leads to a slightly lower estimate now, than at the end of drilling. This comparison also indicates that the short non-isothermal injection tests, performed at the completion of the wells, give fairly reliable estimates of reservoir transmissivity.

The present estimate for well 13 is 3 times greater now than after drilling. This may reflect the transmissivity of the fracture itself through the Hveragil gully, but not the combined fracture rock transmissivity, because the data from well 13 have a short time span.

The estimated transmissivity for well 20 is most probably about 50% too low due to the analytical model used to match the data. As mentioned earlier this could be related to a thermally enhanced wellbore storage effect.

The initial pressure of the main feed points extrapolated to the depth of measurement are presented for each well in table 3 followed by the average reservoir pressure as presently estimated. A comparison of these values reveals no pressure drawdown in the eastern part of the Sudurhlidar-field, but possibly a small pressure decline in the northen part. However, this difference is not significant.

In the eastern part of the deeper Leirbotnar-reservoir a pressure decline of 5 to 6 bar is estimated (12,13). These wells have been about 3-4 years longer in production, than the wells in the Sudurhlidar-field. Resent measurements of the direction and inclination of wells in the Leirbotnar-field indicate that the wells are generally directed toward south-east and therefore draw fluid from a much smaller and denser part of the reservoir, than was anticipated by their wellhead location (Gudmundsson and Gudmundsson, 1984). Actually, the depleted volume in the deeper Leirbotnar-reservoir is estimated to be only half of what would be expected from the wellhead location (0.3 km^3).

The reservoir pressure for well 15 (table 3) is abnormally high, which is explained by the fact that the main feed point is at 1600 m depth. However, the measurements had to be made at 950 m depth, because of scaling in the well. The well is hot (>300 °C) and very gas rich. Therefore, the fluid column between 1600 m and 950 m depths is two-phase, but the initial pressure value is extrapolated up to 950 m for single-phase liquid and therefore it is too low.

A fairly detailed distributed parameter model has been made of the Leirbotnar-Sudurhlidar fields to produce history match for the fields up to the year 1982 (Pruess et. al., 1984). A prediction is available from the numerical simulations for the period 1982 to 1992. It predicts a pressure decline of 4 to 5 bars during this period in each field, but before 1982 a negligible pressure decline was estimated in the deeper reservoir at Leirbotnar and none in the Sudurhlidar-reservoir. This is still the case in 1984 for the Sudurhlidar-reservoir, where none or negligible pressure decline is estimated. However, the pressure decline in the deeper Leirbotnar-reservoir is 2 to 3 bars in excess of the numerical simulation prediction. The numerical model assumes a reservoir volume of 0.7 km^3 for the deeper Leirbotnar-reservoir from the wellhead distribution, but as pointed out before, the wells are mostly depleting a reservoir volume which is only half of that. This could explain the excess pressure decline compared to the model prediction.

CONCLUSIONS

1. An interference is observed between wells in the upper single-phase Leirbotnar-reservoir.

2. A general trend towards slightly lower estimates of transmissivities for individual wells compared to transmissivities determined from injection tests at the completion of wells is observed.

3. None or negligible pressure decline has occurred in the Sudurhlidar-reservoir during its 3 to 4 years production history. This agrees well with prediction from numerical simulation of the field.

4. A pressure decline of 5 to 6 bars is observed in the eastern part of the deeper Leirbotnar-reservoir. This is 2 to 3 bars in excess of what is predicted by numerical simulation of the reservoir. However, recent measurements of wells directions and inclinations in that field indicate, that they are depleting only half of the reservoir volume assumed with regard to their wellhead locations on which the numerical simulation is based.

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REFERENCES

Bodvarsson, G.S., Benson, S.M., Sigurdsson, O., Stefansson, V. and Eliasson, E.T., 1984: "The Krafla Geothermal Field, Iceland 1. Analysis of Well Test Data," Water Resources Research, (in press).

Gudmundsson, G. and Gudmundsson, A., 1984: "Halla- og Stefnumælingar i Borholum," Proceedings Hrafnathing November 1-2, (in Icelandic), State Electric Power Works, Krafla Division, Akureyri, Iceland.

Miller, C.W., 1980: "Wellbore Storage Effects in Geothermal Wells," Soc. Pet. Eng. J. (Dec.), p 555-566.

Pruess, K., Bodvarsson, G.S., Stefansson, V. and Eliasson, E.T., 1984: "The Krafla Geothermal Field, Iceland 4. History Match and Prediction of Individual Well Performance," Water Resources Research, (in press).

Sigurdsson, O. and Tiab, D., 1983: "Analysis of Pressure Pulses Resulting from Magmatic Activity in the Vicinity of Geothermal Wells," Proceedings SPE 53rd Annual California Regional Meeting, March 23-25, p 775-782.

Stefansson, V., 1981: "The Krafla Geothermal Field, Northeast Iceland," in Geothermal Systems: Principles and Case Histories, L. Rybach and L.J.P. Muffer, eds., John Wiley and Son Ltd., p 273-294.

Table 1. Well Test Analysis

Well	Flow rate kg/s	Transmissivity m^3/Pa s	Formation storage m/Pa	Skin factor	Wellbore Storage C_D
12	3.2	1.6×10^{-8}	3.3×10^{-8}	-2.2	1.2×10^{4}
13	6.9	6.1×10^{-8}	2.0×10^{-7}	2.1	1.1×10^{4}
15	3.4	1.0×10^{-8}	9.4×10^{-7}	1.1	1.7×10^{2}
16	4.4	0.4×10^{-8}	6.7×10^{-9}	-5.2	2.6×10^{1}
17	9.6	1.4×10^{-8}	5.2×10^{-9}	-6.3	2.1×10^{3}
20	10.6	0.8×10^{-8}	3.9×10^{-8}	-5.9	1.0×10^{1}

Table 2. Transmissivities in Krafla wells (m^3/Pa s)

Well	Year drilled	At completion	Estimated in 1984
12	Nov. 1978	$1.2\text{-}2.4 \times 10^{-8}$	1.6×10^{-8}
13	Aug. 1983	1.9×10^{-8}	6.0×10^{-8}
15	Oct. 1980	1.5×10^{-8}	1.0×10^{-8}
16	June 1981	$0,9 \times 10^{-8}$	0.4×10^{-8}
17	July 1981	2.5×10^{-8}	1.4×10^{-8}
20	Aug. 1982	1.6×10^{-8}	0.8×10^{-8}

Table 3. Reservoir pressure at Krafla (bar)

Well	Depth of measurement	Initial pressure	Estimated in 1984
12	1000 m	79.8	73.6
13	1000 m	95.9	89.0
15	950 m	74.6	98.0
16	1300 m	102.7	104.4
17	1300 m	105.4	106.8
20	1300 m	99.5	97.8

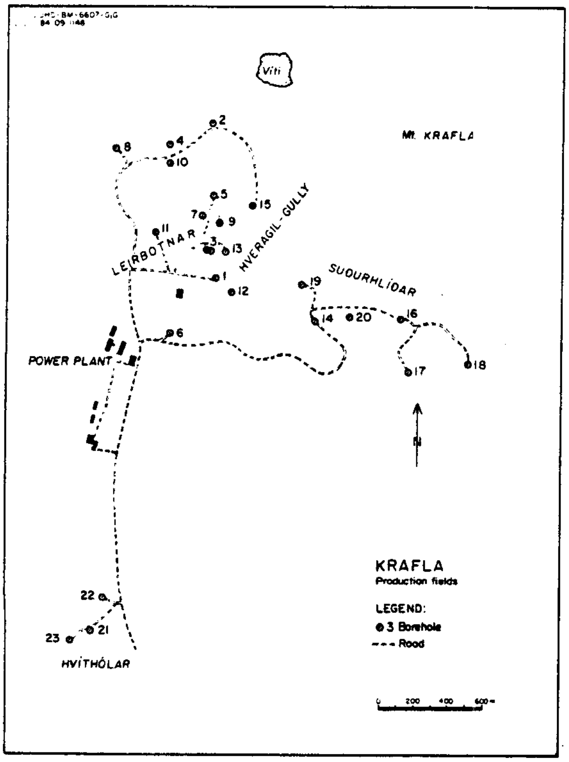

Figure 1. The production fields for the Krafla geothermal power plant.

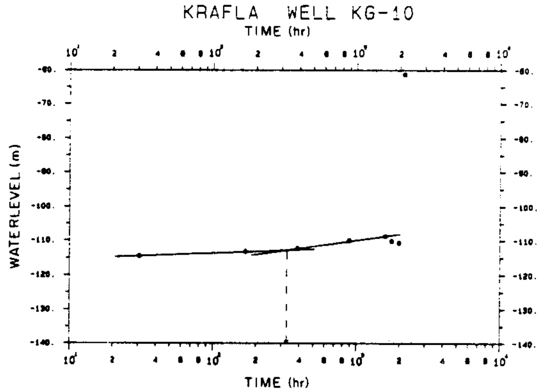

Figure 2. Waterlevel data from well 10 in Leirbotnar.

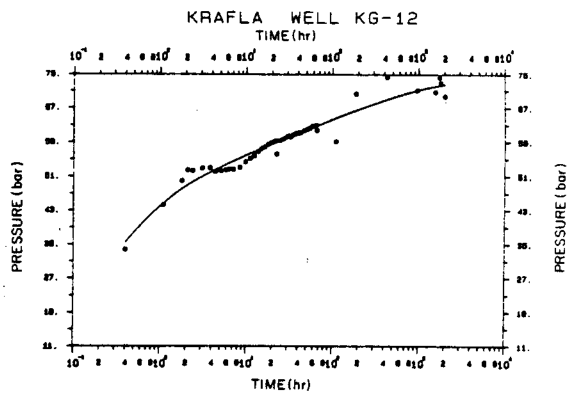

Figure 3. Pressure response of well 12 in Leirbotnar.

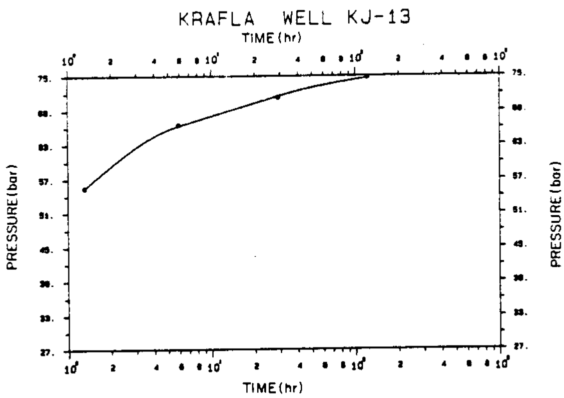

Figure 4. Pressure data from well 13 in Leirbotnar.

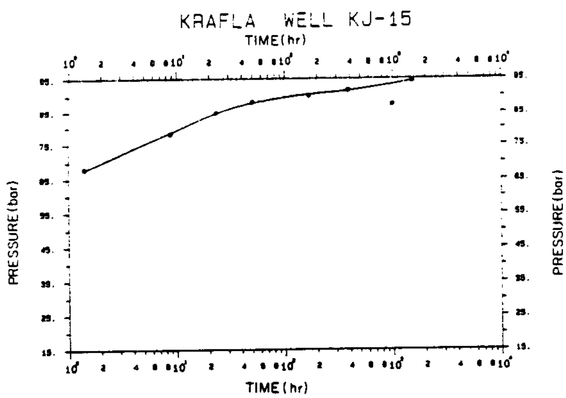

Figure 5. Pressure response of well 15 in Leirbotnar.

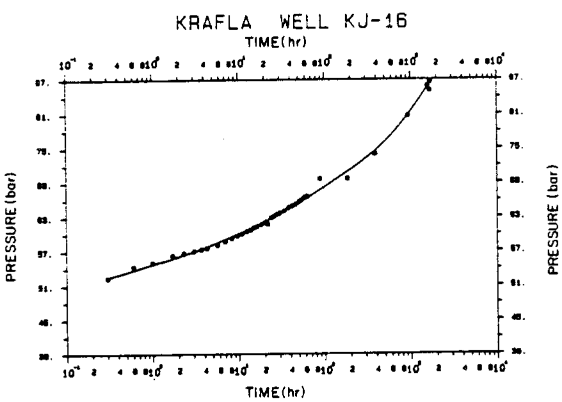

Figure 6. Pressure response of well 16 in Sudurhlidar.

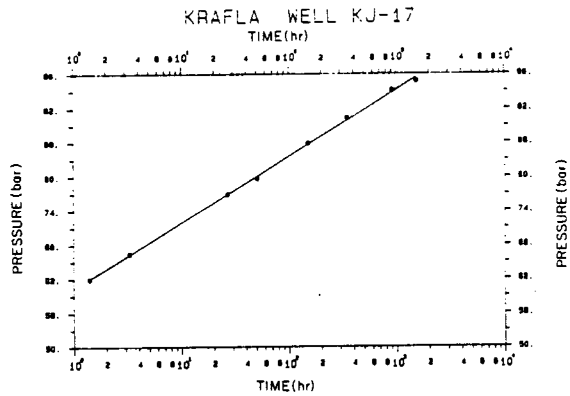

Figure 7. Pressure response of well 17 in Sudurhlidar.

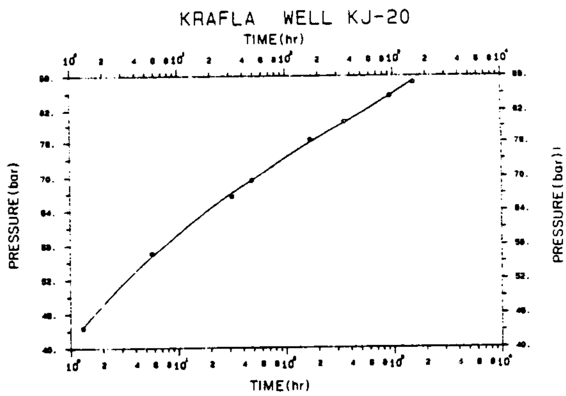

Figure 8. Pressure response of well 20 in Sudurhlidar.