FIFTEEN YEARS OF TEMPERATURE AND PRESSURE MONITORING IN THE SVARTSENGI HIGH-TEMPERATURE GEOTHERMAL FIELD IN SW-ICELAND

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ABSTRACT

The Svartsengi high temperature field has been under exploitation since 1976. The reservoir is characterized by a 230-240 °C liquid dominated system below 600 m depth and a two-phase boiling zone extending to the surface. A detailed evaluation of all temperature and pressure logs in Svartsengi wells have resulted in a revision of a former conceptual reservoir model. A temperature reversal is observed in some wells at 1000-1300 m depth, indicating lateral flow, and a N-S striking upflow zone is proposed in the center of the wellfield. A substantial pressure drawdown due to production has resulted in expansion of the two-phase zone and may explain recent reduction in drawdown rates. The reservoir drawdown has also reduced flowing wellhead pressures by 0.3 bars/year and induced temporary events of colder fluid inflow. Observations of reservoir temperatures, during and after injection of cold fluids, indicate a rapid migration of the injected fluid between wells, reflecting the double porosity nature of the reservoir. The study shows that a minimum inflow temperature of 210 °C is necessary in order to maintain sufficient flowing well pressures. Land subsidence and pressure measurements in distant wells imply that the Svartsengi reservoir is hydrologically connected to the Eldvörp geothermal field, 7 km west of Svartsengi.

INTRODUCTION

The Sudurnes Regional Heating Company (Hitaveita Suðurnesja) has operated the Svartsengi geothermal co-generation power plant since 1976. The power plant utilizes geothermal brine and steam from the Svartsengi reservoir to heat cold groundwater for district heating purposes, and to generate electricity. The present capacity of the plant is 125 MW_t and 11,6 MW_e (Pálmason and Guðmundsson, 1990). The total mass produced from the reservoir amounts to more than 80 million metric tons and the average rate of production is presently around 230 kg/s.

The Geothermal Division of Orkustofnun has undertaken extensive well logging in Svartsengi since the drilling of the first well in 1971. At present, more than 500 different measurements and operations have been carried out in the wells. A detailed evaluation of this database has been carried out and the results are presented in this paper (Björnsson and Steingrímsson, 1991).

The analysis of the well-log database was divided into the following categories:

- Determination of reservoir temperatures and pressures, prior to production.
- Revision of an earlier conceptual reservoir model.
- Analysis of temperature changes due to influx of colder fluids and due to reinjection.
- Evaluation of the reservoir drawdown history.
- Correlation of pressure drawdown to the formation of calcite scaling plugs in wells.
- Effects of variable reservoir pressure and temperature on the output characteristics of wells.
- Pressure communication between Svartsengi and other high temperature fields on the Reykjanes peninsula, land subsidence and reservoir boundaries.

The objective of the study was initially to provide informations for a detailed reservoir simulation (Vatnaskil Consulting Engineers, 1989). However, several interesting phenomena showed up in the collected downhole data as the study progressed, which were found to be worth further investigation. They will be the subject of this paper.

GEOLOGICAL OUTLINE AND FIELD DEVELOPMENT

The Svartsengi high-temperature reservoir is among six geothermal fields associated with an active rift zone which is the landward extension of the Mid-Atlantic ridge on the Reykjanes peninsula, SW-Iceland (Figure 1). The reservoir was initially liquid dominated. Temperatures in the range 230-240 °C were observed in 12 wells drilled in the period 1971-1982. The well field is only 1 km^2 in area extent. The reservoir fluid is a brine with salinity corresponding to about 2/3 that of sea-water. An overview of the Svartsengi surface geology is given by Pullinger (1991). The subsurface geology, on the other hand, has been described by Franzson (1983,1990). It is characterized by fresh

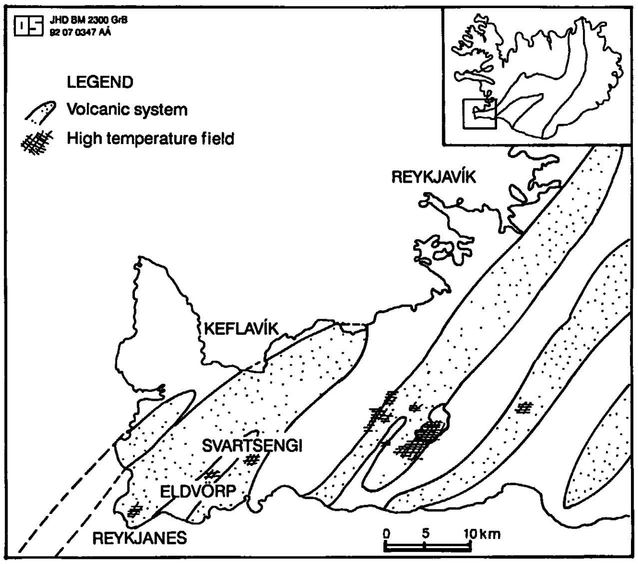

Figure 1: The Reykjanes, Eldvörp and Svartsengi geothermal fields and their geological surroundings.

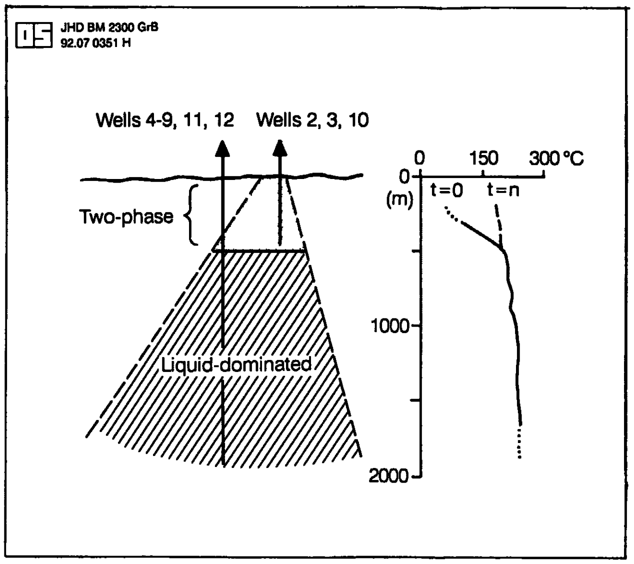

Figure 2: An earlier conceptual model of the Svartsengi Reservoir (Gudmundsson and Thorhallsson, 1986).

basaltic lavas at the surface, followed by sequences of lava flows and hyaloclastite, reflecting interglacial and glacial periods. At depths greater than 800 m, intrusives become a dominant formation. A substantial fraction of these intrusives are believed to have been horizontally intruded in the depth interval 1100-1300 m. They are highly permeable, observed by fast pressure communication between wells. The average reservoir permeability is in the range 100-150 mD (Kjaran et al., 1979).

Continuous monitoring of mass production and reservoir pressure has been carried out in Svartsengi almost from the first day of production. Wellhead flowrates and pressures are measured on a weekly basis, downhole temperatures and pressures are logged once or twice per year, waterlevel was measured continuously and land elevation and total gravity have been measured occasionally on a grid covering most of the Reykjanes peninsula. A regional resistivity survey has been carried out and interpreted in terms of subsurface temperature (Georgsson, 1984). The objective of all these measurements and observations has been, and still is, to provide information on the physical state of the reservoir and how it reacts to production. Several papers, discussing the field data, are available in the geothermal literature (Gudmundsson, 1983; Gudmundsson et al., 1984; Gudmundsson and Thorhallsson, 1986; Gudmundsson and Olsen, 1987).

An earlier conceptual model of the Svartsengi field is shown in Figure 2. The geothermal reservoir is divided into a two-phase zone near the surface and a liquid dominated reservoir, with a temperature of 235-240 °C, down to at least 2 km depth. The reservoir is furthermore assumed to be totally isolated from a warm ground-water system between 0-300 m depth.

ANALYSIS OF TEMPERATURE DATA AND REVISION OF THE CONCEPTUAL RESERVOIR MODEL

In the earlier conceptual model of the Svartsengi reservoir, an almost uniform 235-240 °C reservoir temperature is assumed below 600 to at least 2000 m depth. No indication of an upflow zone or reservoir boundaries had been detected in wellbore temperatures. Systematic interpretation of 250 available temperature logs resulted in a determination of formation temperature with an accuracy of 2-3 °C. Maps of the formation temperature, in cross and planar sections through the reservoir, are presented in figures 3-5.

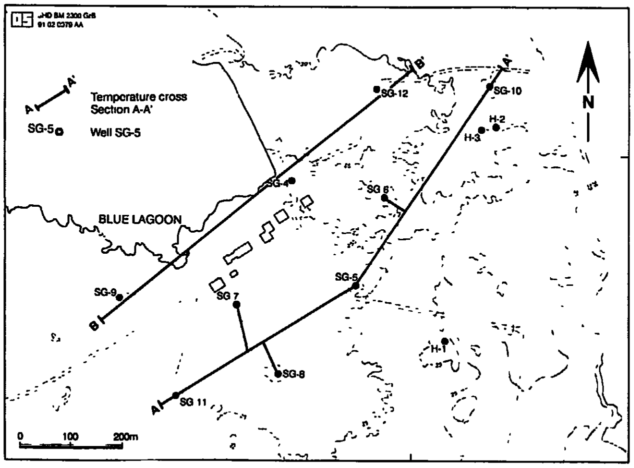

Figure 3: Location of temperature cross-sections.

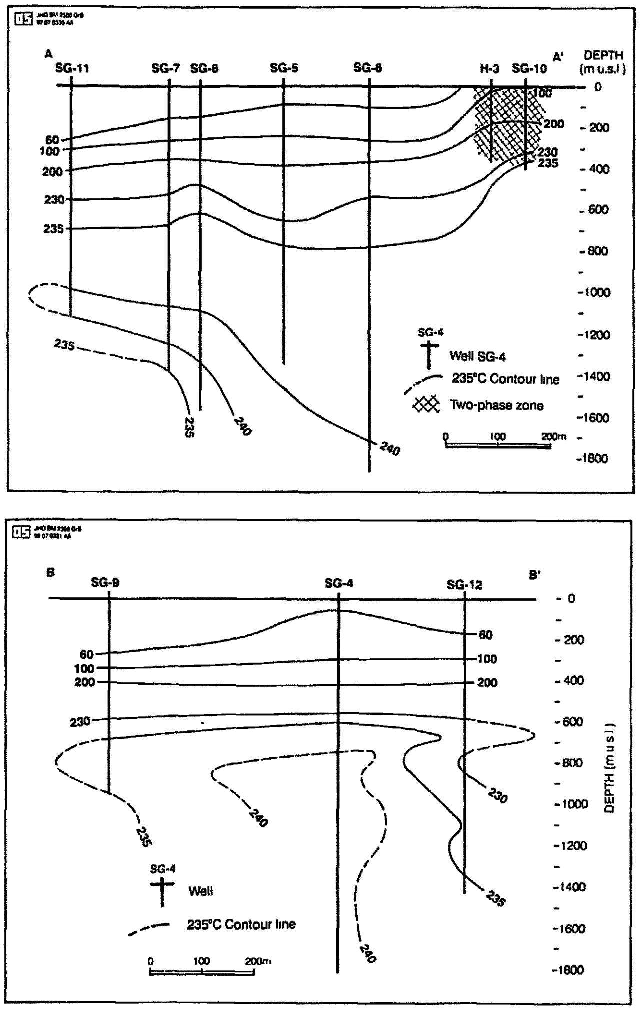

Figure 4: Temperature distribution in cross sections A-A' and B-B' (see Figure 3 for location).

The analysis confirmed previous ideas of three different aquifer systems within the Svartsengi reservoir, i.e. the warm groundwater system at 30-300 m depth, the main reservoir at depths greater than 600 m and a two-phase chimney in the NE-part of the wellfield. In addition a careful inspection of the temperature data reveals some finer flow structures in the reservoir. Relatively high temperatures in the warm groundwater lens close to the two-phase chimney indicate conductive heat flow between the systems. A vague temperature maximum (243 °C) is seen in the main reservoir close to well 4 (Figures 4 and 5). This anomaly is interpreted as an upflow zone. A temperature reversal is observed below 1000-1300 m depth in some wells away from the proposed upflow zone. The reversal is most likely caused by lateral fluid flow from the upflow zone along the horizontal intrusives at 1100-1300 m depth.

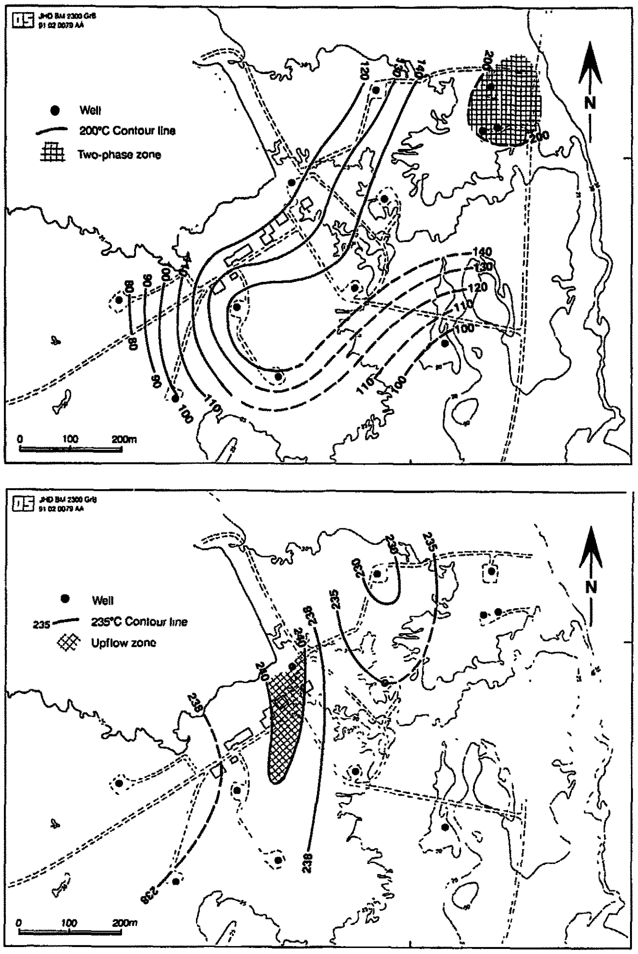

Figure 5: Temperature contours at 300 and 800 m u.s.l.

ANALYSIS OF PRESSURE DATA

One of the characteristics of the Svartsengi reservoir is an almost uniform pressure distribution in the wellfield due to the extremely high permeability. Pressure histories are, therefore, almost identical for all wells. Figure 6 shows the pressure data points measured at 900 m b.s.l. in 8 wells during the period 1976-1992, along with the annual mean production rates. An estimated reservoir pressure history is shown as a solid line. According to Figure 6 the total reservoir drawdown between 1976 and 1992 is on the order of 22 bars. The average rate of drawdown is around 1.2 bars/year but considerably lower drawdown rates are observed during the last two years.

The reduction in drawdown rate after 1990 is of particular interest. A straight forward explanation is the 10-15 % reduction in production rates which took place between the years 1991 and 1992 (Figure 6). However, as the reservoir drawdown rate changed already in 1990, we suggest that increased boiling in the reservoir may also explain this change in the pressure history. The decreasing reservoir

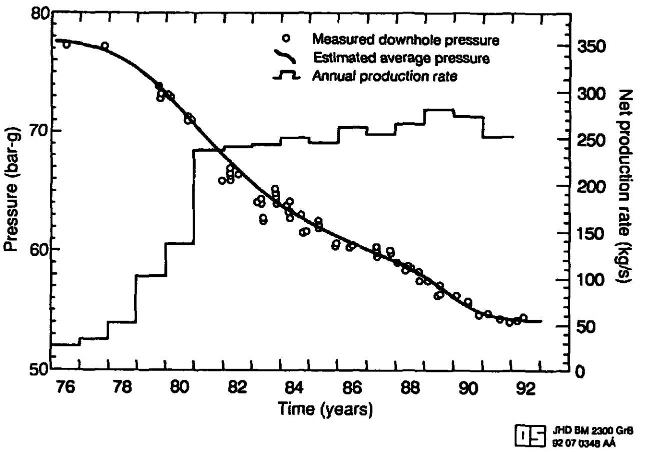

Figure 6: Pressure and production history of the Svartsengi reservoir.

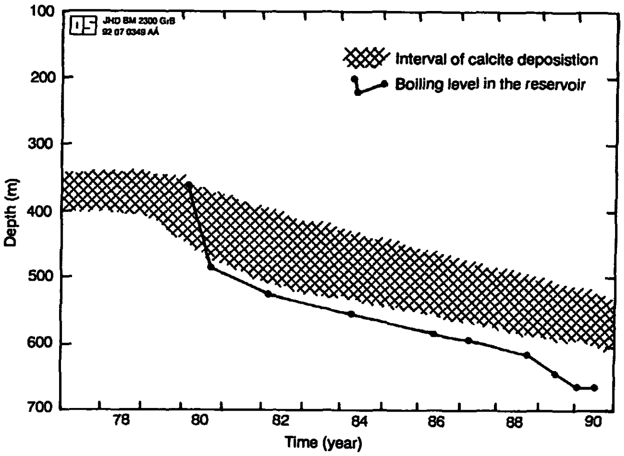

Figure 7: Calcite scaling and boiling level in Svartsengi wells.

pressure after 1976 have led to a gradual sinking of the two-phase/single-phase boundary between the boiling chimney and the main liquid reservoir. The constant rate of drawdown in the period 1976-1990 indicates that the area extent of this interface has remained the same, and that 15 m of reservoir rock were added to the steam chimney every year. However, in 1990 the boiling interface entered the main reservoir at 600-620 m depth. Subsequently, the lateral extent of the two-phase zone has increased rapidly, leading to reduced drawdown rates for the last two years.

The proposed mean pressure curve on Figure 6 was used as a reference in order to estimate lateral pressure gradients in the reservoir. The result of this study indicate that wells 5, 6, 7 and 8 do not deviate markedly from the mean pressure value. Wells 9, 11 and 12, on the other hand, show in most cases lower downhole pressures than the reservoir average. This is in agreement with the proposed upflow zone being close to well 4 (Figures 4 and 5).

The continuous pressure drawdown in the reservoir is seen at the surface as a steady reduction of wellhead pressures (0.3 bars/year) of wells produced at constant mass flow rate. The depth of calcite deposition in production wells also follows the pressure drawdown. The calcite scaling occurs right above the wellbore boiling level. As the reservoir pressure decreases, the boiling and, hence, the calcite deposition occurs at subsequently greater depths in production wells. The wells have to be worked over regularly with a drill rig in order to clean the depositions. Figure 7, which compares the location of the calcite scaling with the depth of flashing in well 7, is based on informations from the work-over operations since 1977.

RESERVOIR COOLING DUE TO NATURAL INFLOW AND REINJECTION OF COLDER FLUIDS

Temporary cooling of the Svartsengi reservoir has been observed on a few occasions early in the production history of the field. These cooling events lasted from a few days to a few weeks and the maximum cooling detected was 15 °C. One of these events occurred in May 1983. Figure 8 contours the cooling within the wellfield during this event. It is based on downhole temperature surveys conducted during this event. The cooling is most pronounced in the NE- and the SW-corner of the wellfield, indicating an influx of colder water controlled by a horizontal fracture. The cooling within the wellfield is 2-15 °C. At the same time, wellhead pressures declined by 1-6 bars. Within four weeks the downhole temperatures and wellhead pressures had recovered back to normal values. The exact nature of these cooling events is not known, but colder inflow due to opening of fractures at the reservoir peripheries has been suggested. No sudden cooling has been observed since 1988. This may be the result of the pressure drawdown in the reservoir. Decreasing fluid pressure increases effective stresses which makes the rock more resistant to fracturing.

Between 20 and 40 kg/s of 75 °C water have been injected in Svartsengi from 1984 in order to slow down the pressure drawdown (Gudmundsson et al., 1984). The fluid was injected into well 12 up to 1988 and after that into well 5. Figure 9 demonstrates how the injected fluid has affected downhole temperatures in well 6, which is located 600 m to the south of well 12. The figure shows temperature at 800, 1400 and 1900 m depth. The main feedzone in well 6 is at 1600 m depth. The injection into well 12 started in 1984 and already in 1985 a cooling of the 1600 m feedzone in well 6 is visible. This cooling reached a maximum of 8 °C in 1989.

Injection into well 12 was terminated in May 1988. During the warm-up period of the well a heat recovery survey was conducted. The temperature data is shown in Figure 10. The downhole logs show clearly the main feedzones of the well at 1000 m, 1025 m and at 1200 m. Thermal recovery of the uppermost feedzone was rapid and mass and heat balance calculations indicate a 239 °C temperature for that

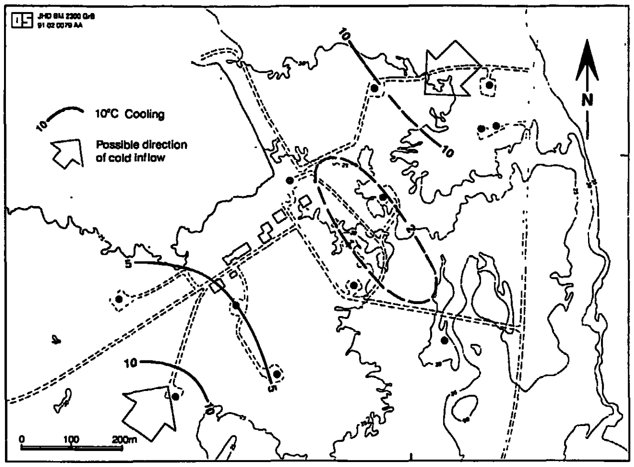

Figure 8: Temporary cooling of the Svartsengi reservoir in May 1983.

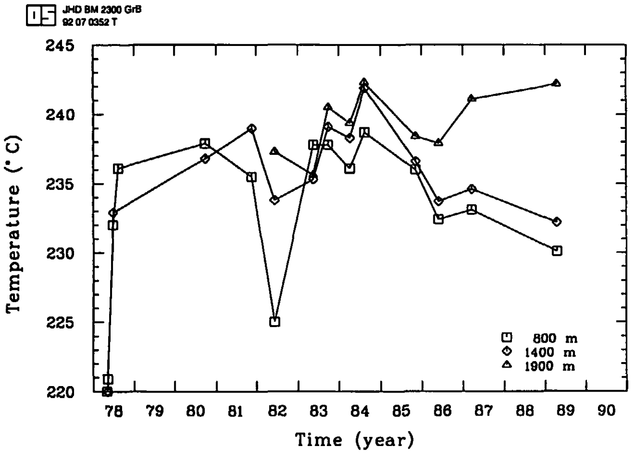

Figure 9: Temperature changes in well 6 due to injection in well 12.

feedzone in October 1988. Furthermore, the calculations imply that approximately 40 % of the produced mass comes from the feedzone at 1000 m.

The heat recovery data for well 12 is typical for fractured reservoirs (double porosity reservoirs). The main feedzones of the injection well absorb most of the injected fluid and shortcut it through the reservoir fracture network to nearby production wells, in this case well 6. A minor part of the injected fluid is absorbed by low permeability feedzones which, on other hand, distribute the fluid into the rock matrix. This behavior is evident in Figure 11, which shows the warm-up history of well 12 during discharge at several depths above and below the major feedzones. If the temperatures at depths at and above 1200 m are extrapolated in time, a 238-240 °C inflow temperature was obtained in late year 1990. The low permeability feedzones in the bottom part of the well recover, on the other hand, much slower due to little fluid convection at these depths.

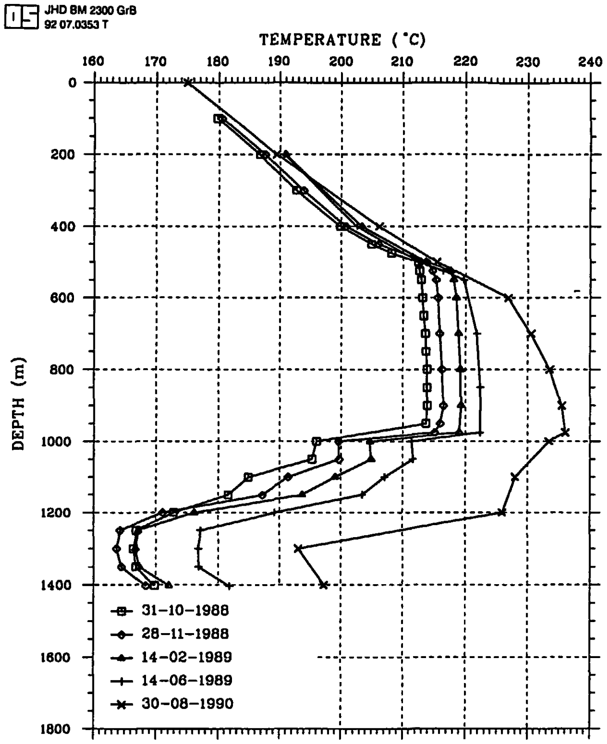

Figure 10: Temperature logs measured during thermal recovery of well 12.

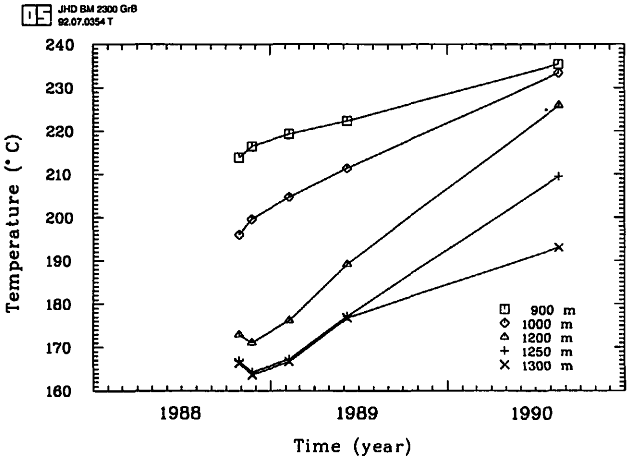

Figure 11: Temperature recovery of well 12 at different depths.

CORRELATION OF INFLOW TEMPERATURES AND WELLHEAD PRESSURES

Analysis of wellbore pressures in Svartsengi, during and after discharge, show that the drawdown, next to the wells is only of the order of 1-2.5 bars at flowrates 50-70 kg/s. This means that output characteristics of Svartsengi wells are mainly dependent on the wellbore geometry, flowrate and fluid enthalpy.

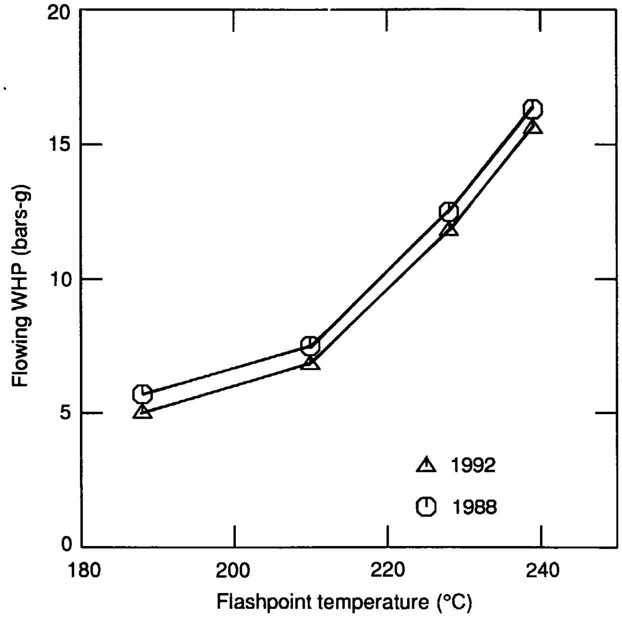

Figure 12: Correlation of flashpoint temperature and flowing wellhead pressure for 9 5/8" diameter wells in Svartsengi.

Figure 12 is plotted to demonstrate the strong influence of inflow temperature on the wellhead pressure in liquid fed wells. The figure shows flowing wellhead pressure as a function of flashpoint temperature in a hypothetical Svartsengi well with minor local drawdown. The data in the figure is derived from flowing pressure logs in several Icelandic high-temperature wells. These wells produce from liquid dominated reservoirs at different temperatures. All of them flash during production inside their 9 5/8" diameter production casings. Figure 12 shows that flashpoint temperatures in the range 180-210 °C correspond to flowing wellhead pressures of 5-7 bar-g. The minimum operating pressure for the power plant in Svartsengi is, however, 6 bar-g. This means that cooling of the reservoir to inflow temperatures below 210 °C will drastically reduce the output of the power plant.

The analysis in Figure 12 demonstrates that the greatest potential danger to fluid production from Svartsengi wells is inflow of colder fluids into the fracture network. Such a cooling can invade during natural events, as was observed in the early years of production, or they can be induced by injection of colder fluids into wells within or close to the present wellfield. The double porosity nature of the reservoir implies that any type of cold fluid injection should be performed under ultimate control and as far away from the wellfield as possible.

RESERVOIR BOUNDARIES

The fluid production in Svartsengi, which started in 1976, has caused a large scale pressure drawdown followed by a land subsidence. Figure 13 shows the rate of land subsidence observed between 1982 and 1987 in Svartsengi and vicinity (Eysteinsson et al., 1991). The pressure drawdown has induced up to 15 cm subsidence in the wellfield but the anomaly extends a considerable distance from the production area, especially to the WSW. The anomaly encloses the Eldvörp geothermal field (Franzson, 1987) which is located 7 km to the west of Svartsengi, indicating a good hydrological connection between the two geothermal fields. This has also been confirmed by pressure logs in an exploration well, drilled in Eldvörp in 1983. The pressure logs show more than a 10 bar pressure drawdown during the last 9 years, which is almost the same drawdown as measured in Svartsengi.

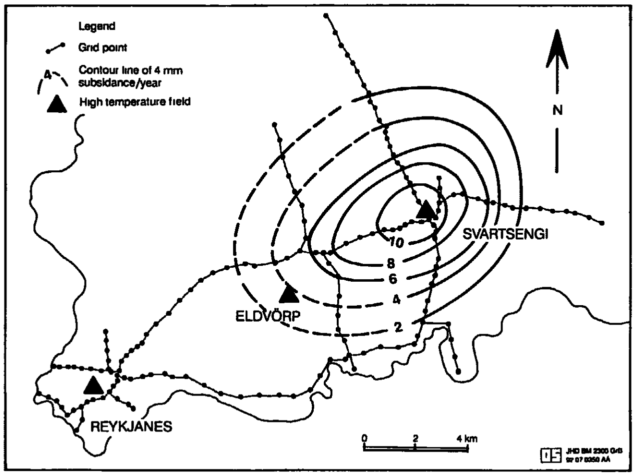

Figure 13: The average rate of land subsidence in the Reykjanes peninsula.

The Reykjanes geothermal reservoir is located 10 km further to the WSW of Eldvörp (Gudmundsson et al., 1984). No drawdown has been observed in the Reykjanes reservoir, which implies a low-permeability barrier between Reykjanes and the Svartsengi-Eldvörp system.

Combined interpretation of land elevation changes and pressure monitoring of these three geothermal fields on the Reykjanes peninsula shows that the Svartsengi-Eldvörp system is of elongated shape. The length of the system is approximately 12 km. The eastern margin seems to be close to the Svartsengi wellfield and a western boundary close to the Eldvörp geothermal field.

CONCLUSIONS

The main conclusions of the work described in this paper may be summarized as follows:

- Evaluation of temperature logs confirms the main features of an earlier conceptual model of the Svartsengi reservoir. A warm ground water system is found over most of the wellfield between 30 and 300 m depth, the main geothermal reservoir, which is a liquid dominated system, lies beneath 600 m depth, but a two-phase system extends to the surface in the NE-part of the wellfield.

- In addition the evaluation shows a temperature reversal in some wells below 1000-1300 m depth, which indicates lateral flow in this depth interval. A slight temperature maximum is also observed close to well 4, which is interpreted as the upflow zone of the reservoir.
- Pressure data show a total drawdown of more than 22 bars since 1976. The rate of drawdown was rapid during the first years of production, but declined later to an almost constant rate of 1.2 bars/year. Expansion of the two-phase boiling zone in the reservoir is a likely explanation for the recent reduction in the rate of drawdown.
- A careful analysis of lateral pressure gradients in the reservoir supports the idea of an upflow zone close to well 4.
- Production wells in Svartsengi are operated at a constant flowrate. The declining reservoir pressure has therefore resulted in an annual decline in wellhead pressures of 0.3 bars. This pressure drop is due to increasing distance between wellhead and boiling level in wells during production.
- Several events of temporary reservoir cooling were observed during the first years of production in Svartsengi. These events are most likely due to episodic fracturing at the reservoir boundaries, which resulted in inflow of colder fluids.
- Reinjection of 75 °C fluid into the wellfield reduced the inflow temperature of one production well by as much as 8 °C. A heat recovery survey, conducted in an injection well well after injection was terminated, reflects the fractured nature of the reservoir. The main feedzones of the well, which absorbed most of the injected fluid during several years of injection, recovered back to the normal reservoir temperature in the order of months. Rapid fluid migration between production and injection wells, via the fracture system, explains the fast thermal recovery rate of the feedzones.
- Cooling of the reservoir fracture system is a potential danger for the operation of the wellfield in Svartsengi. The inflow temperature of wells must remain above 210 °C, otherwise the wellhead pressure will drop below the operational pressure of the steam gathering system.
- Land subsidence and pressure measurements in distant wells show that Svartsengi is hydrologically connected to the Eldvörp geothermal field, 7 km west of Svartsengi. The Svartengi wellfield is close to the eastern margin and the Eldvörp geothermal field is near the western boundary of this combined geothermal system.

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