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PREDICTING FUTURE PERFORMANCE OF A SHALLOW STEAM-ZONE IN THE SVARTSENGI GEOTHERMAL FIELD, ICELAND

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ABSTRACT

As a part of a feasibility study for adding new 30 MWe unit to the Svartsengi Power Plant, a simple reservoir model study has been carried out. The model concentrates on a shallow, production induced steam-zone which now resides at 200-700 m depth. Only 1-D vertical mass flow is assumed in the upper part of the model, and only horizontal radial flow in a base layer, extending 9 km out. The model simulates some key figures in the production history, such as deep and shallow reservoir pressures, enthalpy changes in steam wells and increasing steam flow to surface with time. The study indicates that during the first 15 years of production a substantial mass of fluid was pushed by steam expansion into the deeper, liquid dominated reservoir layer. However, as production declined recently, a rapid liquid backflow tock place into the already 500 m thick steam zone, hence reducing it's volume and production capacity. Modeling various future production scenarios suggests that the deep reservoir pressure should stay constant or even decrease continuously with time. This will maximize the steam production from the shallow, man made steam zone.

INTRODUCTION

The Sudurnes Regional Heating Company has been operating a geothermal power plant in the Svartsengi geothermal field for almost 30 years. In it's rather unique design, cold groundwater is heated by the geothermal brine for space heating purposes and 16.4 MWe are generated by backpressure and Ormat units. Since the oldest section of the power plant has now turned over 25 years old, and due to increasing market for electricity in Iceland, a decision was made to replace it with a 30 MWe turbine and 100 MWt heat exchanger plant. For this purpose 4 new wells were drilled in 1998. The new units are to be commissioned in the fall of 1999.

As a part of a pre-feasibility project, the Research Division of Orkustofnun undertook a modeling study, which should predict future reservoir response due to the planned production increase (Björnsson, 1998). The study should in particular concentrate on a shallow steam zone, which has evolved with time in Svartsengi. This zone contributes substantially to the energy flow in the present powerplant. Simultaneously, but independently, the Vatnaskil Consulting Firm (1997) did an update on their already existing simulator for the same purpose, but also taking into account several re-injection scenarios.

THE CONCEPTUAL RESERVOIR MODEL

The Svartsengi geothermal fields lies within the western volcanic zone of Iceland (Figure 1). It consists stratigraphically of a shallow groundwater zone in fresh, basaltic formations down to 300 m depth. They are followed by around 300 m thick hyaloclastite series. This is the caprock of the reservoir. Underneath the hyaloclastites come flood basalts. At 1000-1300 m depth intrusions become dominant (Franzson, 1983 and 1995). A fissure swarm is crossing the reservoir in the eastern part of the wellfield. Here fluid discharges to surface in the form of steaming fumaroles. This vertical "steam chimney" shows clearly up in Figure 2, which presents reservoir temperature distribution at 300 m u.sl (Björnsson and Steingrímsson, 1992).

The present conceptual reservoir model for Svartsengi is shown in Figure 3. The model is highly unusual as it's hot inflow zone has not yet been found. The model is therefore very simple, consisting of the 300 m thick shallow groundwater zone, a 300 m thick caprock of hyaloclastites and the underlain basalts which form the main reservoir volume. The reservoir fluid is 2/3 seawater and it's temperature is strikingly uniform at 235-240 °C.

MODEL CONSTRAINTS

The modeling study was beforehand required to simulate the following observations made in Svartsengi:

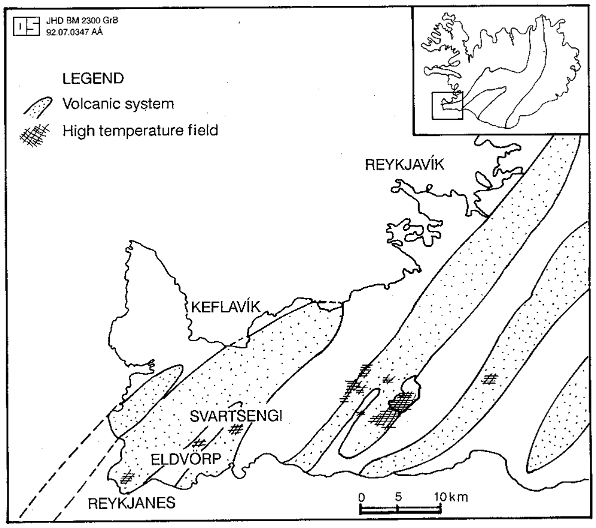

Figure 1: Location map of the Svartsengi field.

- Pressure history at 1000 m depth.
- Initial temperature and pressure in wells 2, 3 and 15, drilled into the steam-zone.
- Enthalpy change of well 10 in 1984, when in only few weeks it's enthalpy rose from 1020 kJ/kg to dry steam enthalpy.
- Wellhead pressure of well10, after it became dry.
- Increasing steam discharge to surface with time.
- Overpressure at 200 m depth in steam-zone, observed during drilling in 1993, but not during drilling of wells 2 and 3 in 1971 and 1972.

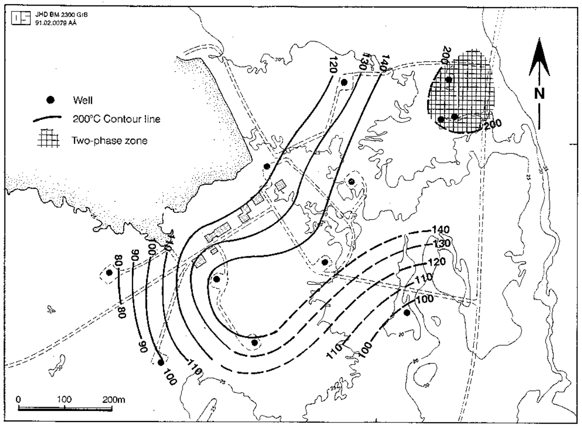

Figure 2: Temperature distribution at 300 m u.sl. The steam zone is shaded.

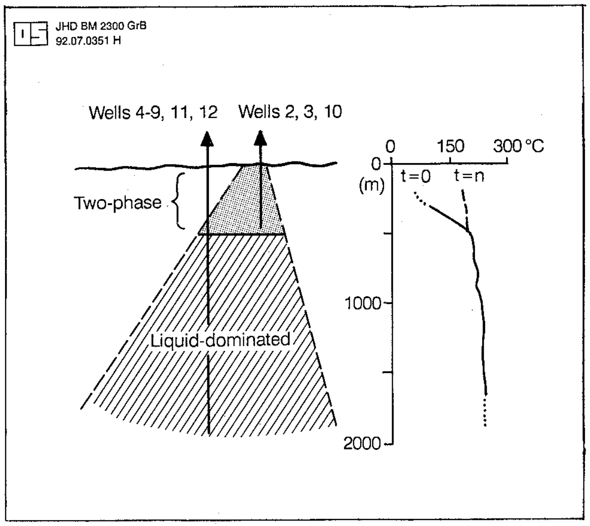

Figure 3: The conceptual reservoir model.

THE NUMERICAL MODEL

Figure 4 demonstrates the model grid, which was developed for the present study. It consists of a multilayer center part (5 m thick elements), which simulates the steam zone which has evolved in Svartsengi as the reservoir pressure declined. The area of this center part is presumed to cover 2 km^2, from geological and geochemical observations. Underlain is a radial layer, extending to 9 km laterally. This is the measured extent of land subsidence caused by the pressure drawdown. At this distance, a constant pressure boundary of 81 bars and 240°C is assumed.

Only two feedzones are present in the model. The upper one, at 400 m depth, resembles well 10 and new steam-zone wells in the future. The lower feedzone, at 1000 m depth, accounts for all remaining production in Svartsengi. The production rates of these feedzones are presented in Figure 5. At the top of the model a "safety valve" in the form of a productivity index is present. This is the only way for the model to discharge fluid to surface. It's value is 1.5x10^{-10} m^3.

The simulator TOUGH2-EOS1 was used for the modeling work (Pruess, 1991). The model assumes porous media. It turned out that only 4 rock properties were necessary for the model. They are listed in Table 1. Uniform porosity of 10%, rock density of 2650 kg/m3, heat conductivity of 2 W/m/°C and heat

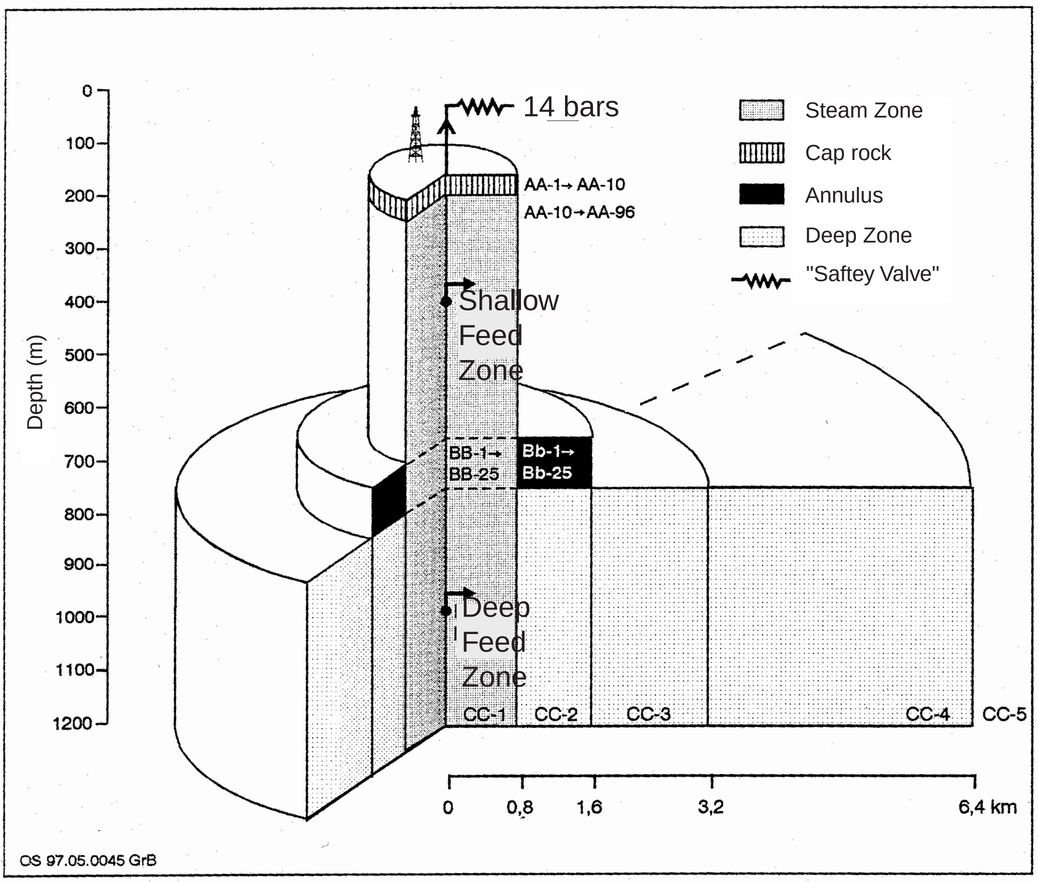

Figure 4: A sketch of the simple reservoir model.

capacity of 1000 kJ/kg/°C were assumed for all the rocks. Relative permeabilities were assumed to be of X-type, with the steam phase immobile at 5% steam saturation and the liquid phase at 60% steam saturation.

Table 1: Permeabilities in the Svartsengi model.

Rock name	Horizontal perm. (mD)	Vertical perm. (mD)
Steam zone	100	20
Cap rock	100	40
Annulus	100	0.3
Deep zone	16	0.001

NATURAL STATE SIMULATIONS

Figure 6 shows the model match to observed initial pressures and temperatures. The data are taken from the early days of production in Svartsengi, except for well 15 which was drilled after 24 years of production. The simulations involved defining the value of the productivity index at the top, and estimating radial heat losses in the topmost part of the model. They turned out to be essential in order to maintain a boiling curve with depth in the depth interval 200-300 m, otherwise a steam cap was formed.

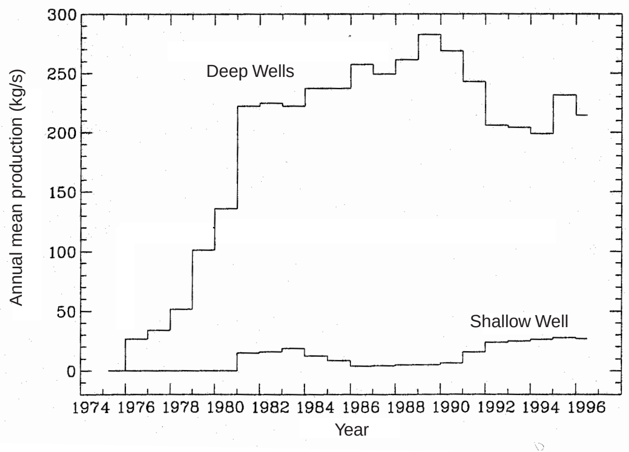

Figure 5: Deep and shallow production rates in Svartsengi.

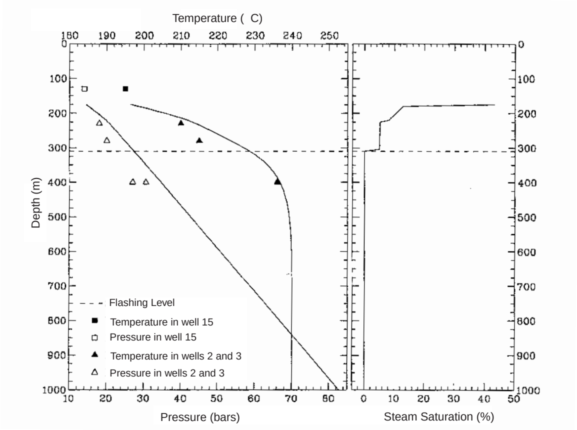

Figure 6: Measured and simulated initial pressures and enthalpies.

SIMULATING THE PRODUCTION HISTORY

Figure 7 shows the match between observed and calculated pressure at 1000 m depth in Svartsengi. A good fit is obtained. Note the pressure stabilization which occurs in 1990. Initially this was taken as a sign of increasing area of the steam zone, as the downward propagating flashing zone entered the main 240°C reservoir at 700 m. The annulus rock volume on Figure 4 was specifically added to the grid in order to allow for this.

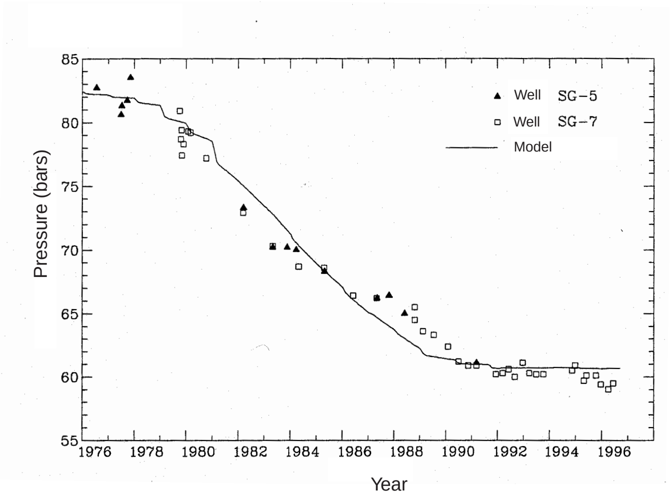

Figure 7: Observed and calculated pressures at 1000 m depth.

Figure 8 shows feedzone pressure and enthalpy at 400 m depth in the steam-zone. An enthalpy change takes place in 1983, one year too early actually. A nice fit is obtained between the feedzone pressure and the wellhead pressure after the year 1983, when the well turned dry. Note especially the measured and calculated pressure decline after the year 1990 for a later reference.

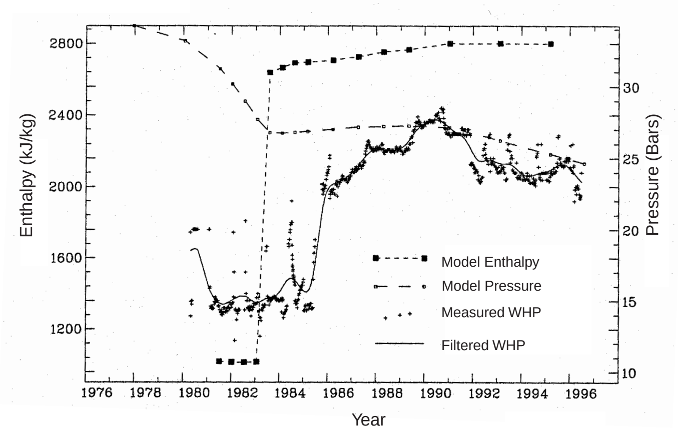

Figure 8: Measured and calculated enthalpy and wellhead pressure in the steam-zone well no. 10.

Increased steam discharge to surface with time was one of the model requirements. Figure 9 shows this. In the natural state simulation, 10 kg/s of 195°C water came through the model caprock and 1 kg/s of steam. As time passes by, the liquid flow diminishes and the steam flow increases to 7 kg/s. The massive outflow during 1976 to 1980 may be a consequence of rapid steam expansion in the initially 100 m thick boiling curve with depth. This may be an overestimate as the model has uniform area but the reservoir is more of a conic shape as inferred by the temperature distribution map in Figure 2.

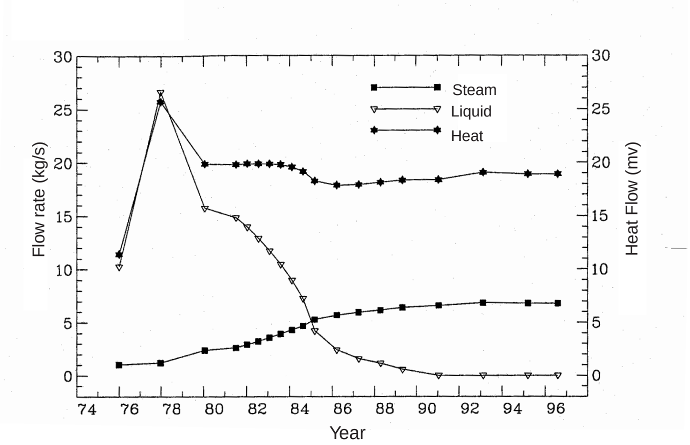

Figure 9: Calculated mass and heat flow to surface.

Also of interest is the mass flow between the steam zone and the base layer of the reservoir model. Figure 10 shows this. At early times the volume expansion of steam, due to the downward migrating flashing level, causes substantial liquid flow into the base layer. This down flow decreases after 1980 when the steam well #10 comes on line. In 1990, when production is decreased, the flow direction turns around due to a pressure recovery in the base layer. Instead of observing increasing reservoir pressure, a liquid inflow and condensation takes place in the two-phase steam-zone.

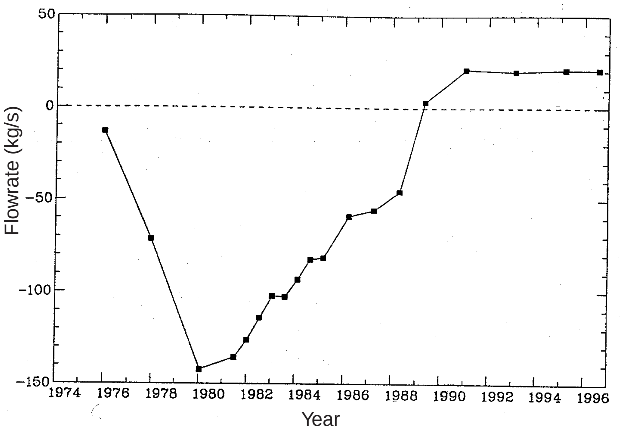

Figure 10: Mass flow between the shallow part and the base layer of the reservoir model. Negative flowrate means that fluid is flowing from the shallow system to the deep one.

It is also of interest to plot the model steam saturation with depth at different times. The saturation is strongly dependent on the relative permeability curves used, as clearly seen on Figure 11. The large area of the boiling surface and annual pressure drawdown of 1.2 bars added constantly new volume to the two-phase zone, thus providing near constant steam flow to well 10. In 1990, however, the flashing level began to rise. As the production from well 10 continued, the only way for the reservoir to respond was by internal boiling from the rock matrix. This lead to a calculated increase in the steam-zone saturation from 60 to 70% during 1990 to 1996.

Figure 12 shows finally calculated model pressure profiles at different times. Two features in the figure are of significance. Firstly that the pressure at 200 m depth increases from under hydrostatic to 25 bars during production. This is coherent with the overpressure observed during drilling in 1993 but not in 1978. Secondly a local pressure drawdown of 3 bars occurs after 1990 when the deep reservoir pressure stabilized. This is in accordance with the measured WHP of well 10 (Figure 8).

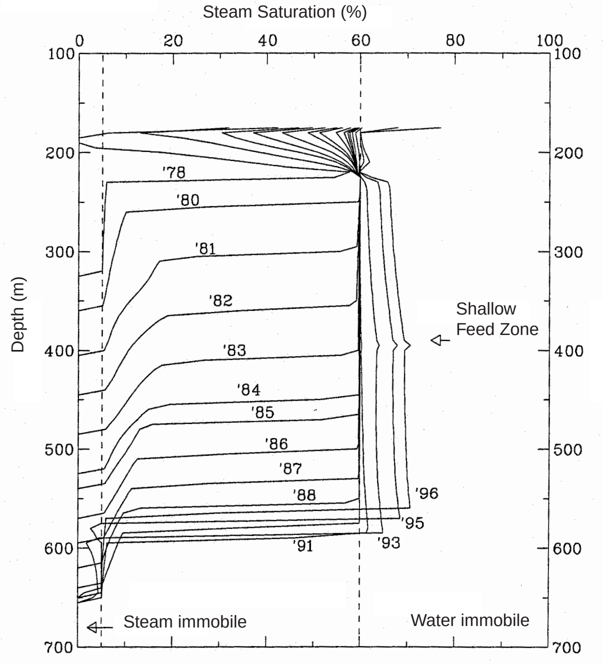

Figure 11: Calculated steam saturation profiles with time. Numbers refer to the year.

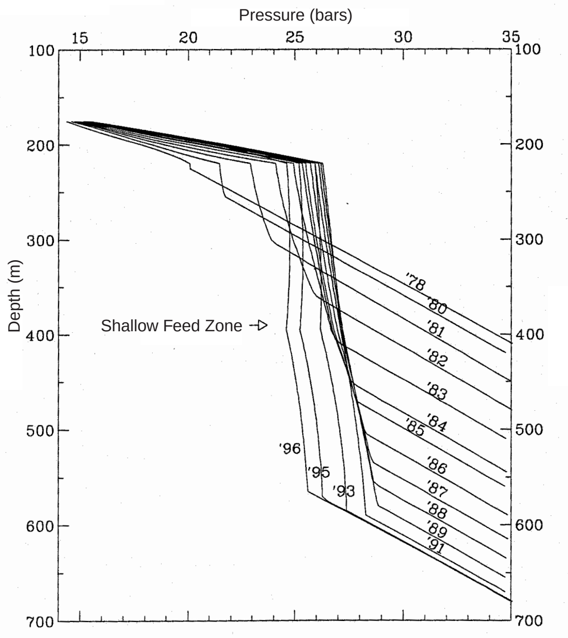

Figure 12: Calculated pressure profiles with time. Numbers refer to the year.

FUTURE RESERVOIR PERFORMANCE

After the simple reservoir model for the Svartsengi field was considered fully calibrated, several cases of future production scenarios were studied. In total 12 combinations of 30, 50 and 70 kg/s of shallow production and 100, 200, 270 and 340 kg/s of deep productions were simulated. For reference, the today's production rates are in the order of 30 kg/s of shallow and 270 kg/s of deep production.

Figures 13 shows predicted enthalpies and pressures at 400 m depth for constant 50 steam production from the steam-zone. One can see that if more than 200 kg/s are flowing totally from the deep wells, a constant 50 kg/s steam generation is maintained until somewhere between 2006 and 2016. After that a decline in flowrates should be expected. Given that the deep production is reduced drastically to 100 kg/s (massive re-injection) a sharp return to liquid enthalpy is predicted around 2008. This is the consequence of a rapid pressure recovery in the deep system and diminishing volume of the two-phase zone as the flashing level rises with time. Similar results were obtained for the present 30 kg/s steam flowrate case, except that the pressure decline rate is much slower and appears to be on the safe side during the 20 years of prediction time.

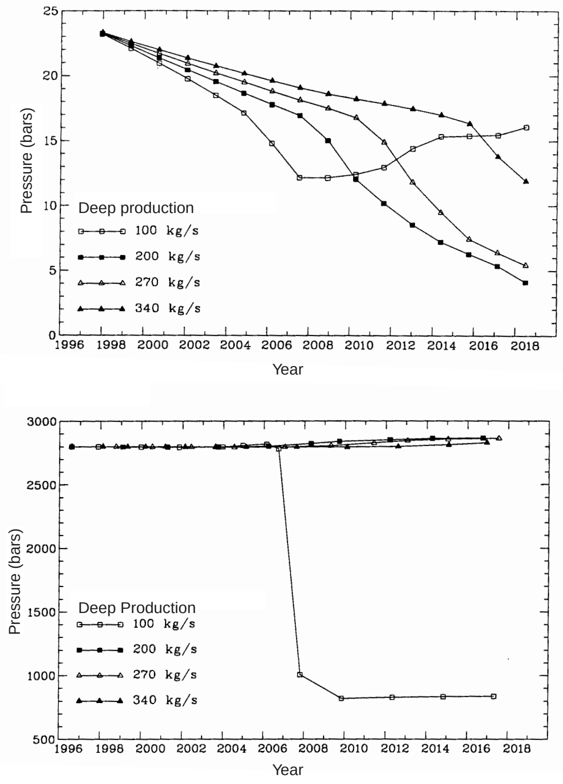

Figure 13: Flowing pressures and enthalpies at the 400 m feedzone for a constant 50 kg/s production.

Increasing the shallow steam production to 70 kg/s appears to be fatal for the steam-zone (Figure 14). Rapid pressure decline is predicted and even superheated steam flow for one of the cases.

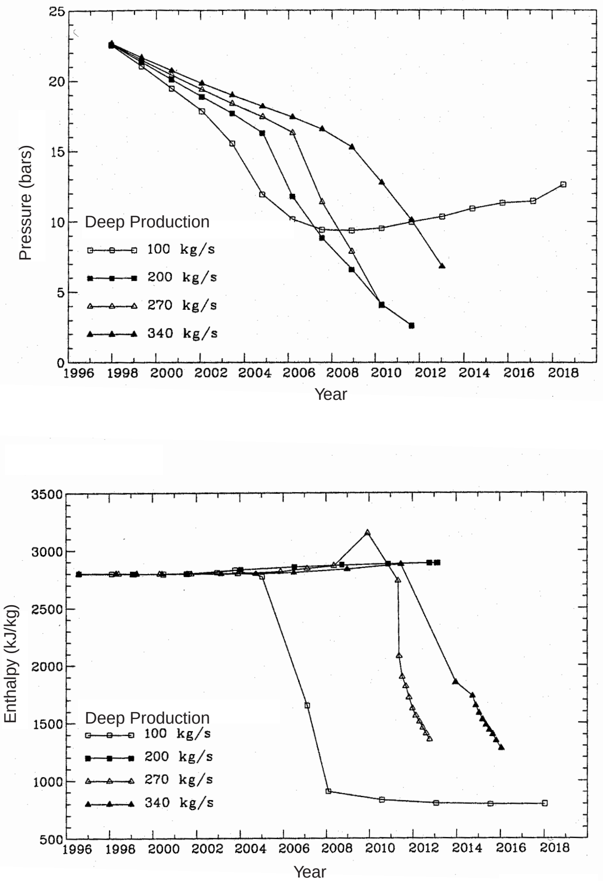

Figure 14: Flowing pressures and enthalpies at the 400 m feedzone for a constant 70 kg/s production.

A model study carried out independently by the Vatnaskil Consulting Firm (1997) came up with almost identical results. It therefore appears that the present shallow steam zone in Svartsengi can sustain flowrates in the order of 30-50 kg/s for the next 15-20 years, given than the deep reservoir pressure stays constant or continues to decline.

CONCLUSIONS AND DISCUSSION

The following conclusions are drawn from a recent modeling study on the Svartsengi geothermal field:

- A simple model, consisting basically of a vertical steam-zone column and a radial, horizontal base layer, is able to simulate several key figures in the natural and production state of the reservoir.

- Only four rock types are used. Permeabilities range between 20 and 100 mD.
- A dominant process in the model is a rapid, vertical movement of a flashing zone, separating single- and two-phase sections of the model grid. It's location follows hand in hand with the pressure of the deeper, liquid dominated part of the reservoir.
- Annual pressure drawdown of 1.2 bars/year during the initial 15 years of production caused intense steam expansion at shallow depths and pushed substantial liquid volumes into the deeper reservoir layer.
- This process reversed in 1990, following a reduction in total production rates. A backflow of liquid water took place into the two-phase zone where adequate "new" pore volume became available by steam condensation. This led to reduced wellhead pressure of the main steam producer, but stabilized the deep reservoir pressure.
- Reservoir performance predictions indicate that the shallow steam zone is capable of providing steam flow in the range 30-50 kg/s for the next 15-20 years. This depends, however, on the depth to the flashing level in the reservoir and, hence, the deep reservoir pressure.

The Sudurnes Regional Heating Company intends to use the above conclusions together with their existing reservoir simulator as a production management tool. In principle the reservoir operation will focus on a stable or even gently declining, deep reservoir pressure with time. The steam-zone is, however, not the only source of high-enthalpy fluid for the power plant. The drilling of 1998 together with precise discharge measurements has namely showed that an extensive two-phase zone is now propagating at approximately 700 m depth throughout the present wellfield. This has caused an enthalpy increase from the standard 1030 kJ/kg to 1150 kJ/kg in at least two wells. It seems therefore appropriate for the Svartsengi reservoir management to maintain the present pressure drawdown.

\Finally it should be mentioned that a model study of this kind probably only determines the pore volume of the two-phase reservoir but not it's actual extent. It may be that a porosity in the order of 30-40% is near reality for the hyaloclastites which host most of the present steam zone. Hopefully this topic will be addressed in a later study.

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