

## ACCURACY OF RESERVOIR PREDICTIONS FOR THE NESJAVELLIR GEOTHERMAL FIELD, ICELAND

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### ABSTRACT

The performance of the 1986 three-dimensional numerical model of the Nesjavellir geothermal field for predicting the deliverabilities and pressure decline of the wells during the period 1987 through 1991 is investigated. The model predicted adequately the flow rate and enthalpy transients of most wells, but overpredicted the pressure decline by 3 to 4 bars.

### INTRODUCTION AND FIELD DEVELOPMENT

The Nesjavellir geothermal field is situated north of the Hengill volcano in southwestern Iceland. It is a part of the Hengill geothermal area. Hitaveita Reykjaviku (HR; Reykjavik District Heating) purchased the Nesjavellir farm in 1964, and started to explore the field and develop it to provide hot water for space heating in Reykjavik and vicinity.

Nesjavellir is a high-temperature field, so that it was understood from the start that the geothermal fluid would not be used directly for space heating due to problems of silica scaling and high gas content. Utilization of the field would therefore be based on using the geothermal fluid to heat up fresh water in heat exchangers. In 1974-1990 a pilot heating plant was operated at Nesjavellir, where experiments were carried out with several types of heat exchangers and deaerators (Gunnarsson et al., 1992).

Drilling began at Nesjavellir in 1965 and five exploration wells had been drilled by 1972. Drilling was resumed ten years later and by the end of 1986 a total of eighteen wells had been completed; the deepest well being 2.2 km deep. The Nesjavellir wells are highly productive, and out of the eighteen wells, thirteen are commercial producers with an average thermal output of 60 MW<sub>t</sub> per well, or 9 MW<sub>e</sub> per well.

Concurrent with the drilling of the field and the utilization experiments in the pilot plant, a thorough geothermal exploration program was carried out (Arnason et al., 1986; Arnason, 1990; Gunnarsson et al., 1992). The exploration and well results have been summarized in a conceptual model of the field (Figure 1). It

features a two-phase upflow zone under the Hengill volcano, and lateral fluid flow along the SW-NE fissure system that intersects the volcano.

The conceptual model formed the basis for the development of a three dimensional simulation model of the field (Bodvarsson et al., 1990 and 1991). The main objective of the modeling studies was to predict the response of the field to fluid extraction and to estimate the generating capacity of the field, before any decisions were made on the future power plant size at Nesjavellir. By 1986 it became clear from the modeling studies that the field could supply a 300 MW<sub>t</sub> power plant for at least 30 years. Any plans for a larger plant would, according to the simulation model, require reinjection into the reservoir.

The City Council of Reykjavik decided on 20 November 1986 to begin the construction of a power plant at Nesjavellir. The plant was to be built in stages, the first phase being a thermal power plant of 100 MW<sub>t</sub>, which amounts to production of 560 l/s of 85°C hot water. The construction work started in early 1987. The first phase was completed and the plant went into operation in September 1990. Additional 100 MW<sub>t</sub> are being developed under phase two of which 50 MW<sub>t</sub> went on-line in November 1991 and the remainder is scheduled to be in operation by 1994. The planned capacity of the power plant when fully developed is for 400 MW<sub>t</sub> thermal power for district heating and 80-90 MW<sub>e</sub> for electric generation (expected completion date 2010). A plant of this size would call for a reinjection scheme, according to the numerical modeling results from 1986.

The three-dimensional model was calibrated against all available data up to the end of 1986, and matched well flow rate and enthalpy data from all wells, the initial (natural state) temperature and pressure distributions and pressure interference data between wells. Since 1986 considerable new information has been collected at Nesjavellir, as some of the wells have been continuously flowing and two new wells have been drilled

Nesjavellir Power Plant

**HENGILL**

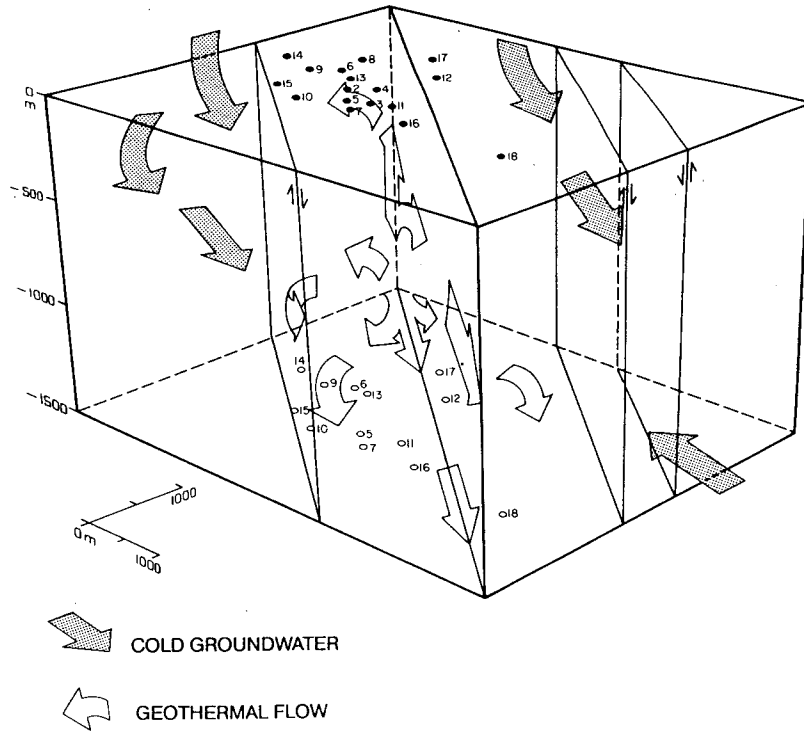
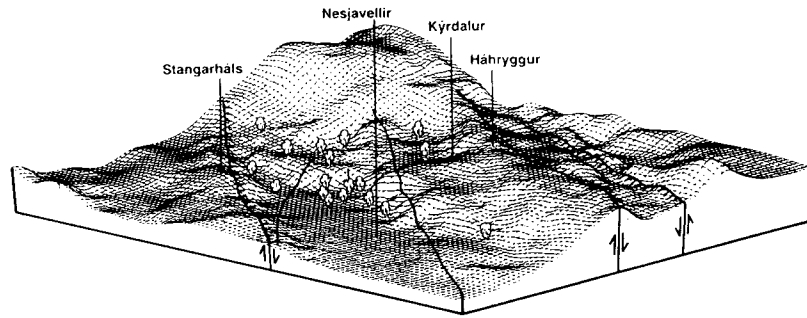


Fig. 1. A three-dimensional conceptual model of the Nesjavellir geothermal field.

(wells 17 and 18). All of these new data require that the three-dimensional model be updated, so that the model is consistent with all available data, and thus provides the best possible reservoir management tool.

In this paper the reservoir predictions for the Nesjavellir field are evaluated. The performance of the 1986 model is evaluated in terms of its predictions compared to the actual observed flow rates, enthalpies and pressure decline data for the last six years. The recalibration of the model and new performance predictions for the Nesjavellir field are given by Bodvarsson et al. (1993).

### THE THREE-DIMENSIONAL MODEL

Figure 2 shows an areal view of the basic grid used. The grid was designed to allow the modeling of each well individually, and to have reasonably small elements in the anticipated wellfield region. Note that the element numbers, for elements 2 through 16 correspond to the number of the well located within the element. It should be noted that Figure 2 only shows the central part of the grid used; the total grid extended 100 km in all directions in order to avoid boundary effects.

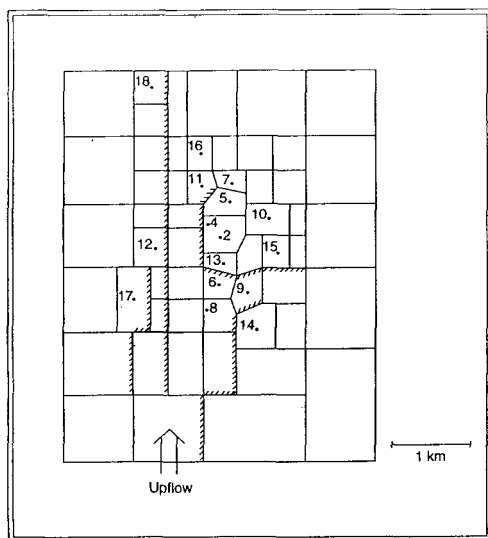


Fig. 2. Areal view of the central part of the numerical grid used in the simulations.

The three-dimensional model consisted of four layers, three of which were 400 m in thickness, while the bottom layer was 800 m thick. The choice of the number of layers and their respective thicknesses was made based on the observed thermodynamic conditions in the field and the locations of major feed zones in the wells.

The two bottom layers represent the main reservoir located below a depth of 800 m. It should be emphasized that it was assumed that no fluid recharge from depth (except for the upflow zone) would occur anywhere in the system. This is certainly a conservative assumption, but other assumptions regarding the deep end of the system are speculative and would lead to "unwanted" optimistic results. The upflow zone was assumed to be located south of the wellfield, which geographically represents a part of the Hengill volcano, east of Skeggi (Figures 1 and 2). For further details of the numerical grid and the three-dimensional model the reader is referred to Bodvarsson et al. (1990).

Various reservoir parameters were adjusted during the natural state and history match simulations, including permeabilities and porosities, the production indices for the wells and the mass recharge rate and the enthalpy of the upflow zone. The relative permeability curves used are the same as those used in the earlier simulations of Nesjavellir (Bodvarsson et al., 1990). The basic characteristics of the curves are that the sum of the relative permeabilities for the two-phases is unity for all values of saturation.

The reservoir fluid was assumed to be pure water. Thus, the effects of noncondensable gases and dissolved solids are neglected. These effects are not believed to be important at Nesjavellir because of low concentrations of these "impurities" in discharge fluids. The computer code MULKOM (Pruess, 1982) was used in this work.

### "NEW" NESJAVELLIR FIELD DATA

The most important data for a numerical reservoir model of a geothermal system are the production data from wells (flow rates and enthalpies), and the pressure decline data collected at idle (observation) wells. Wells 5, 6, 11, 13 and 16 have been continuously produced since 1986; the last four wells have provided hot fluids for the 100 MW<sub>e</sub> power plant since it commenced in September 1990. Production from well 9 was stopped in 1988, and production testing of recent wells 17 and 18 was carried out in 1987 and 1988. Periodic flow rate and enthalpy measurements are made for all of the flowing wells.

The pressure decline in the reservoir in response to production is monitored through periodic pressure surveys of the idle wells (wells 7, 10, 12, 14, 15, 17 and 18). The observed pressure decline varies greatly between the wells, being largest in well 7 (about 8 bars), considerable in well 10 (3 to 4 bars), observable in wells 14 and 15 (about 2 bars), and marginally detected in wells 12, 17 and 18 (see Table 1). These total pressure decline values were estimated from pressure surveys taken in October 1991.

The production records for the wells are annually compiled and show that the wells decline in flow rate very

Table 1: Observed and predicted total pressure decline in idle Nesjavellir wells from 1984 to late 1991.

Well	Observed Pressure Decline (bars)	Calculated Pressure Decline (bars)
7	8.5	7.5
10	3.0	6.5
12	1.0	1.0
14	1.5	6.0
15	2.0	6.5

gradually, but that the enthalpy of the wells is slowly declining. The data from recent wells 17 and 18 indicate that these wells are relatively colder than the other wells, with maximum temperatures of 240°C and 220°C, respectively. Most of the other Nesjavellir wells have maximum temperatures exceeding 300°C. These results are to be expected for well 18, which is located more than 1 km north of well 16. Well 17, however, is colder than expected given the observed temperature of well 12, and the fact that well 17 is located closer to the inferred upflow zone under the Hengill volcano than well 12. It is likely that the bottomhole location of well 17 lies west of one of the many N-S faults in the area, and that this fault zone partly or fully seals the flow of geothermal fluids to the west.

Natural state heat losses from the geothermal system control the mass and heat flow through the system in its undisturbed state. Modeling the natural thermodynamic conditions of a geothermal system requires reasonably accurate data regarding mass and heat flows from surface springs and fumaroles. For the 1986 model, estimates of surface discharge of springs and fumaroles were obtained from Arnason et al. (1986), and more recent studies have verified these estimates (Gudmundsdottir, 1988).

Franzson (1988) published a summary report on the interpretation of geological data from the Nesjavellir wells in terms of geological structures and fluid flow patterns. The results of his studies provide evidence for possible barriers to fluid flow that may be needed in the numerical model in order to match the available data, especially the observed thermal plume.

Hersir et al. (1990) give a comprehensive and detailed summary of the various geophysical measurements that have been done around the Hengill volcano, including results of resistivity, magnetic, gravity and microearthquake studies. Finally, Gudmundsson and Sigurdsson (1987) present the results of the drilling of two shallow "injection" wells, NN-1 and NN-2, located near wells 5 and 7, respectively. Although the wells are only 300 to 400 m deep, fluid samples taken from the wells show

significant component of hot geothermal fluids, estimated to be about 10%. The wells must therefore have some hydrological connectivity to the main geothermal reservoir.

#### PERFORMANCE OF THE 1986 MODEL

It is of interest to investigate how well (or poorly) the predictions made using the 1986 model have agreed with the observed behavior of the Nesjavellir wells during the last 6 years (1987 to 1992). An evaluation of the predictive capabilities of the 1986 model is obtained by prescribing the actual flow periods for all of the wells and then compare the calculated flow rates and enthalpies of the flowing wells with those observed during the last six years. In addition, one can compare the computed pressure decline at all of the observation wells with observed values. As an example Figures 3 and 4 show the comparison between observed and calculated flow rates and enthalpies for wells 5 and 6. In general, the model results are in acceptable agreement with the observed data, especially since the prediction period (about 6 years) is considerably longer than the calibration period for most of the wells (one to two years). The "rule of thumb" is that a model cannot be expected to predict accurately for a period longer than the calibration period. The model over estimates the flow rate decline of well 6 considerably, and this was found to be the case for many of the other wells. The model also overestimated the enthalpy of the produced fluids for some of the wells.

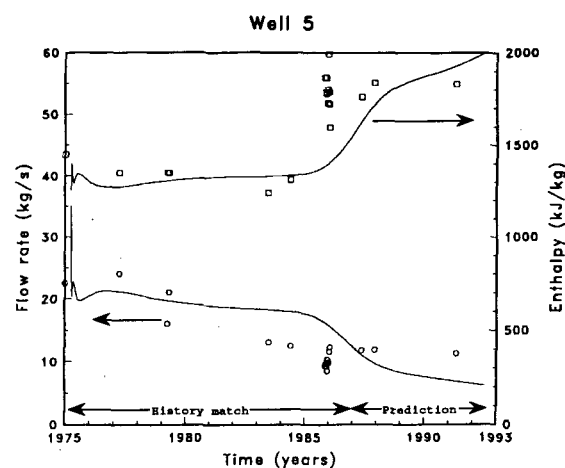


Fig. 3. Comparison between predicted and observed flow rate and enthalpy transients for well 5.

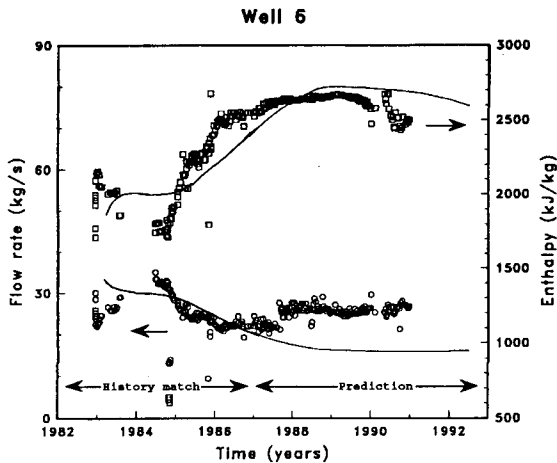


Fig. 4. Comparison between predicted and observed flow rate and enthalpy transients for well 6.

Table 1 shows the estimated observed pressure decline of wells 7, 10, 12, 14 and 15 as of October 1991 as well as the results of the 1986 model. The data given in Table 1 show that the 1986 model overpredicted significantly the pressure decline for most of the wells. The model predicted the pressure decline for well 7 reasonably well, but overestimated the pressure decline for wells 10, 14, and 15 by a factor of 2 to 4. The model predicted the pressure decline for well 12 acceptably well, or practically no pressure decline, as this well is separated from the producing wells by faults acting as permeability barriers. These results strongly suggest that the 1986 model is based on permeabilities that are too low, and consequently the performance predictions based on the 1986 model are conservative for the Nesjavellir reservoir system.

## CONCLUSIONS

- (1) The 1986 model model predicted remarkably well the flow rate and enthalpy behavior of most of the Nesjavellir wells for the period 1987 to 1992, although the data available for calibration for most of the wells was very limited.
- (2) The 1986 model overestimated the pressure decline in the Nesjavellir reservoir during the period 1987 to 1992. This was to be expected since the available pressure decline data in 1986 were very limited, and actually the trend was misled by the data from well 7 which showed relatively large pressure decline. The observed pressure decline of well 7 is now believed to be controlled by one of the actively producing wells, assumed to be well 16 in the 1992 numerical model.

## ACKNOWLEDGEMENTS

The authors thank E. Antunez and C. H. Lai for their critical review of this work. This work was supported by Reykjavik District Heating and in part by the Assistant Secretary of Conservation and Renewable Energy, Office of Renewable Energy Technologies, Geothermal Technology Division of the U. S. Department of Energy under Contract No. DE-ACO3-76SF00098.

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