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Production Monitoring as a Tool for Field Development A Case History from the Nesjavellir Field, Iceland

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ABSTRACT

A tailor-designed monitoring programme has enabled step-wise escalation of production at the Nesjavellir geothermal field in SW-Iceland. A frequent update of a numerical model of the geothermal system has secured that the demand of the market for increased production of hot water for space heating and electricity has been met in a sustainable way. The scientific work has enabled an expansion of the Nesjavellir Power Plant fitting the resource; from a modest 100 MW_t thermal power plant in 1990 to an impressive co-generation power plant in 2005 with a production of 290 MW_{th} and 120 MW_e. The present understanding of the system through monitoring and modelling makes drilling of wells for expansion and replacement a low-risk operation.

The monitoring programme, which has been conducted since the early 1980s, includes measurements of the mass extraction and discharge enthalpy from the reservoir and regular discharge measurements of production wells and water level in non-discharging wells. Chemical sampling, and annual temperature and pressure loggings are used to monitor the response of the reservoir to utilization. The cumulative fluid extraction from the reservoir since 1975 is of the order of 141 million tons, no significant temperature changes have been observed during this period but a pressure drawdown of 6-8 bars has developed in the production zone.

1. INTRODUCTION

The Nesjavellir Geothermal Field is a high enthalpy geothermal system within the Hengill Central Volcano in southwestern Iceland. The Nesjavellir Geothermal Power Plant was commissioned in 1990, following an intensive drilling and testing phase in the 1980's (Gunnarsson *et al.*, 1992). By that time 14 production boreholes had been drilled, and all except one were successful. Initially the plant produced about 560 l/s of 82°C hot water for district heating (100 MW_t), using geothermal steam and water to heat cold groundwater. In 1991 the capacity was expanded to 150 MW_t, and in 1998 to 200 MW_t. At that time the production of electricity commenced with the installation of two 30 MW_e turbines. In 2001 the third turbine was installed, increasing the capacity to 90 MW_e. In 2003 the hot water production was increased to 290 MW_{th} and the fourth electricity turbine will be online production in 2005, bringing the capacity to 120 MW_e. The stepwise increases in production are summarized in table I. Initially only four geothermal wells were connected to the plant, but gradually more wells have been connected as the capacity of the power plant has been increased. Presently 14 boreholes are connected to the Nesjavellir plant, including 5 new wells drilled in 1999-2003. Figure 1 shows the layout of boreholes and the power station at Nesjavellir.

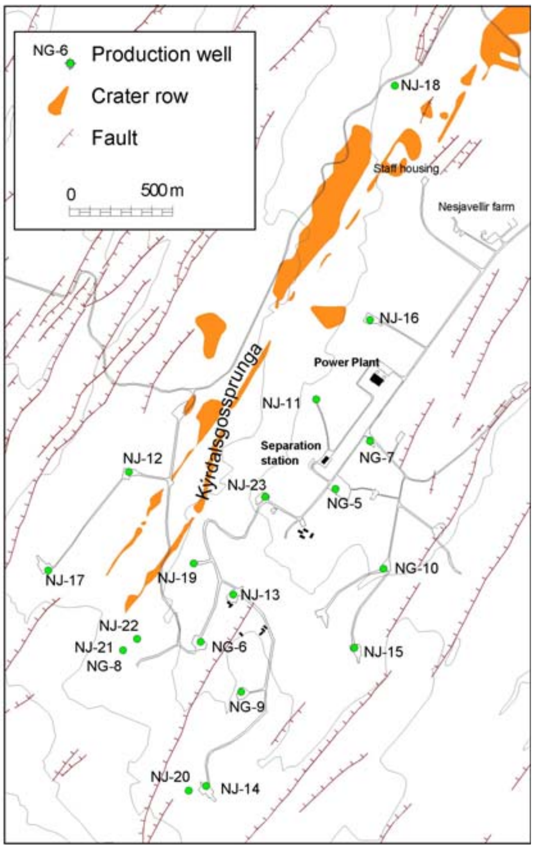

Figure 1: Nesjavellir, layout of boreholes and the power station

	Hot water		Electricity
	l/sec	MW_{th}	MW_e
1990	560	100	
1991	840	150	
1998	1120	200	60
2001			90
2003	1640	290	
2005			120

Table I: Co-generation of electricity and hot water at Nesjavellir

The modular development of the Nesjavellir Power Plant is a good example of the development of a geothermal resource. Initially the reservoir was tested with relatively small discharge/production, but with an intensive monitoring programme and revisions of a numerical model of the resource has allowed increased production in line with the known potential of the field. This paper describes how production monitoring and the use of numerical modelling has enabled the development of the geothermal resource in a sustainable manner.

2. THE MONITORING PROGRAMME

A programme to monitor the response of the Nesjavellir geothermal system as well as to record the influence of the utilization on the environment has evolved through the lifetime of the Nesjavellir project. A programme was set up to monitor the natural runoff from the field in the early 1980's, prior to the drilling and testing of production wells. Ever since drilling commenced in the 1980's downhole measurements and flow testing has been a part of the monitoring programme as well as chemical sampling. Currently the monitoring programme is put forward in a number of written operation procedures, and since 2003 the monitoring programme fulfills the requirements of ISO 9001.

2.1 Flow, pressure and water level monitoring

Regular monitoring of water level, well head pressure and flow measurement started late-1985, and since then all production wells have been recorded weekly. The data is stored in a specially designed geothermal database (Hauksson, 1994), and over the years this database has been an important tool in viewing the response of the reservoir to utilization. When boreholes are not in production their water level is monitored or the wellhead pressure is recorded, depending on the characteristics of the each borehole.

The measurement of flow rate from discharging wells has generally been limited to test periods when the well discharges into a silencer at well site, using lip pressure and water flow rate from silencer to calculate flow rate and water/steam ratio. With increasing production the boreholes are less and less available for flow measurements, as they are constantly connected to the power plant. Since the year 2000 flow rate is increasingly measured by Tracer Flow Testing or TFT (Hirtz et al., 2001). The advantage of this method is that flow rate can be measured without disturbing the production. From 2004 this method has largely replaced the older method.

At the same time as boreholes have become less accessible for flow measurement, automatic recording of the combined flow of steam and water usage at the power plant has advanced, and from 1996 a continuous records of production data exist.

2.2 Downhole monitoring

Most of the wells at Nesjavellir produce very high enthalpy fluid (>1600 kJ/kg) and during discharge boiling occurs not only inside the well but extends to the feed zones and into the formations. Such wells recover slowly when shut in both in temperature and pressure. Monitoring for changes in these reservoir parameters at Nesjavellir is therefore limited to idle wells in the area or production wells shut in for a period of several months.

Annual downhole temperature and pressure logs have been carried out in all idle wells at Nesjavellir since 1985 and the data stored in Oracle database. In the beginning, several wells were available for the monitoring, but during the last 15 years most production wells have been connected to the power plant limiting, the monitoring programme today mainly to two wells; NJ-15 in the eastern part of the production area and well NJ-18 north of the production zone (see figure 1). Conventional Kuster tools have been used for the logging but a Kuster memory tool is expected to replace them in 2004 improving the data quality considerably.

2.3 Chemical sampling

Initially after a borehole starts discharging frequent sampling is carried out, but in the long run annual sampling from each production wells is preferred in order to evaluate any changes in the reservoir fluid chemistry and gas content. Sampling from a high enthalpy resource involves the sampling of geothermal water, condensed steam and non-condensable gases. In order to calculate the downhole composition it is necessary to know the enthalpy of the discharging fluids, i.e. to know the ratio between water and steam. As flow measurements have been limited with increasing production, the aim of annual sampling has not always been met. With the new TFT technology, measurements of flow rate and enthalpy can be carried out with boreholes in production, and this will enable annual sampling from all of the production wells.

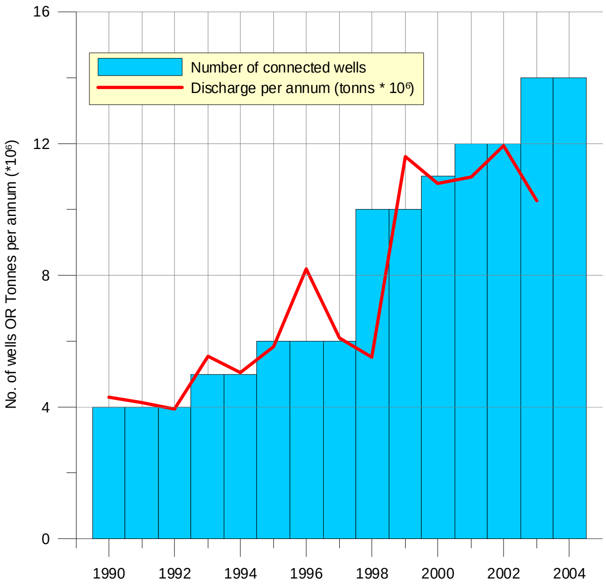

Figure 2: Annual discharge and the number of connected production wells

3. DISCHARGE

The volume of discharge from the Nesjavellir geothermal reservoir is monitored and the figures are updated annually (figure 2). The calculations are based on daily records on the operation of each well, using the setting of a control valve (if present), well head pressure and flow measurements. During the drilling and testing period in the 1980's flow measurements were frequent, but after production started these measurements are limited to short test periods, usually during the few maintenance stops of the power plant. The cumulative extraction of fluid is therefore evaluated from wellhead pressure using an established flow rate/wellhead pressure output curve for each well. The combined monthly discharge from all the wells is calculated and compared to the measured volume of geothermal steam and water in the separation station. Experience shows that there is a good agreement between these two independent methods, generally the difference is less than 1%.

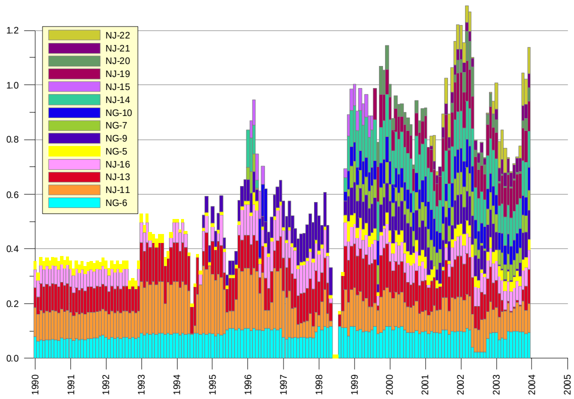

Figure 3: Monthly discharge (kg x 10^9)

The total monthly discharge from each well is shown in a stacked diagram in figure 3 for the whole period since the Nesjavellir Power Plant started operation. It shows the stepwise increase in fluid extracted from the boreholes, in step with the increasing output from the power plant. After the summer of 1998 there is a sharp increase in the discharge when the first 2 turbines had been installed. Very little decline in output from each well has been observed, as can be seen on figure 4, where the average discharge per connected wells is calculated (red line). Before 1998 there is very little decline in well output, the fluctuations are caused by the varying demand of hot water for space heating during summer and winter. At this time the varying demand was met by reducing the number of discharging wells (figure 4, green line) and/or by varying orifice sizes at well head. After 1998 there is an apparent decrease in the average well discharge, which can partly be explained by the use of control valves, which were installed gradually from 1995 to 2001 on all wells (figure 4, blue line). The use of control valves has reduced excess discharge from wells, ensuring a better use of the resource.

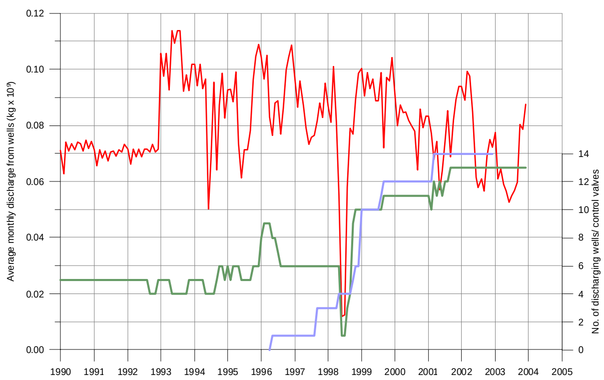

Figure 4: Average monthly discharge per well (red), number of discharging wells (green) and number of wells fitted with control valves (blue)

The volume of steam and brine from each well field is calculated and the total cumulative volume extracted form the well field is 141.5 million tons since the first well was drilled in 1975 till end of 2003 (figure 5). The productivity varies within the field and figure 6 shows the geographic distribution of the average yearly production from each well. The map shows clearly that the best producers are located close to and to the east of the young volcanic fissure (figures 1 and 6). The discharge enthalpy varies also within the field, where the highest enthalpy coincides with the best producers.

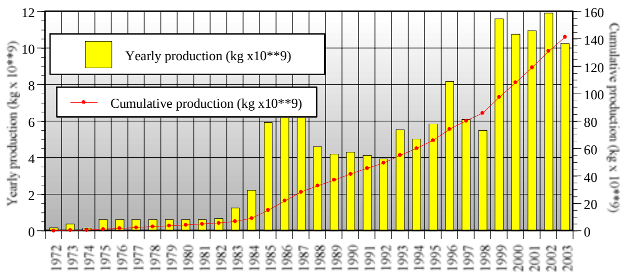

Figure 5: Yearly and cumulative production of steam and water from the Nesjavellir field

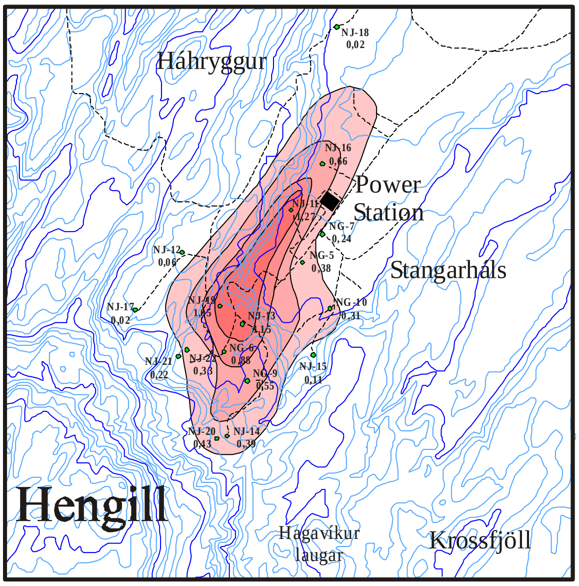

Figure 6: Average yearly production from production wells (kg x 10^9)

4. RESERVOIR RESPONSE TO UTILIZATION

4.1 Enthalpy

The discharge enthalpy varies greatly within the Nesjavellir well field, from around 1200 kJ/kg in the eastern part of the production field (wells NG-7, NG-10, NJ-15) to 2200-2600 in the western part (wells NJ-16, NJ-11, NJ-19, NJ-13), i.e. the enthalpy is higher the closer the well is to the young volcanic fissure which marks the western boundary of the current production field (figure 1). The enthalpy changes are influenced by the production in different parts of the production field.

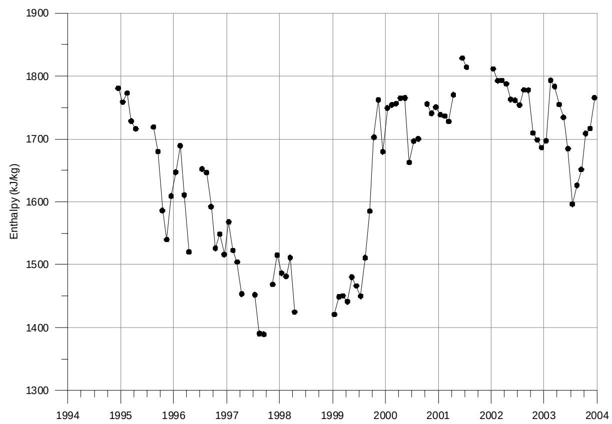

Figure 7: Average monthly enthalpy calculated from measured steam and water ratio in the separation station

The utilization has caused great fluctuation in the enthalpy of the discharge fluid. The utilization influences the enthalpy in most wells to some extent, although the high-enthalpy wells seems to be more sensitive than the wells with lower enthalpy. Since 1994 the flow of water and steam from connected wells has been monitored in the separation station, and in figure 7 the calculated average enthalpy there is shown. The changes in enthalpy in the separation station is to some extent caused by the different wells connected to the stations at different times, but also caused by actual changes in discharge enthalpy from the wells.

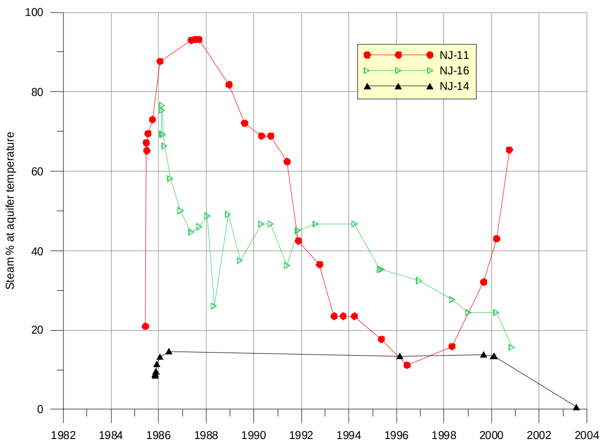

Figure 8: Calculated steam/water ratio at aquifer temperature (NJ-14: 270°C; NJ-11: 290°C; NJ-16: 290°C)

Figure 8 shows calculated steam/water ratio at aquifer temperature at selected wells, which is a reflection of the discharge enthalpy, as the inflow temperature is kept constant. It shows that small changes occur in the "low-enthalpy" wells (NJ-14), whereas dramatic changes take place in the very high enthalpy wells. Initially, when the power plant started operation in 1990 only the high-enthalpy wells were connected and discharging. This caused a localized low-pressure zone in the western part of the drill field and a subsequent inflow of fluid with lower enthalpy but similar temperature mainly from the east. No change in temperature was observed accompanying the enthalpy change. This is represented in figure 8 by the rapid decrease in steam/water ration in wells NJ-11 and NJ-16 between 1989 and 1998.

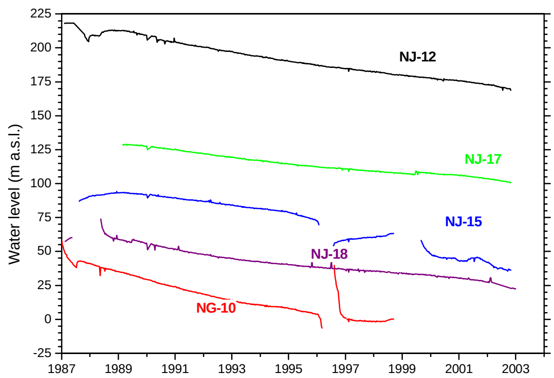

Figure 9: The pressure history at 1400 m b.s.l. in the monitoring wells

Despite this dramatic change in enthalpy, it did not influence the steam output of the wells, as decrease in enthalpy was caused by increased water discharge but more or less steady steam discharge. This is believed to be due to boiling in the formation and different mobility of the two phases. For instance the total discharge of well NJ-11 increased from about 40 kg/s in 1989 to 95 kg/s in 1994, and the respective enthalpy was 2600 and 1550 kJ/kg. In 1999 the average enthalpy had reached a minimum (1450 kJ/kg), and started to rise again, and has been fairly level at about 1700-1800 kJ/kg since the year 2000 (figure 7). The rise is caused by the recovery of some of the high enthalpy wells (for instance well NJ-11 in figure 8), although wells like NJ-16 remains at lower enthalpy.

4.2 Pressure and temperature

During the last fifteen years, six wells (drilled in 1985-6) have been used for monitoring downhole temperature and pressure changes at Nesjavellir. The annual pressure and temperature logs from each year are compared with previous logs and these parameters plotted as history plots at selected depths to display changes with time. The depth of the main feed zone in each well is of special interest being the main connection between the well and the geothermal reservoir. The location of the main feed zone is determined from circulation losses during drilling of the well, temperature logs during injection and pressure pivot point during warm up after drilling. In most of wells used for monitoring at Nesjavellir the main feed zone is found at 1200-1700 m depth. Temperature and pressure logs during warm up also give an estimate of present formation temperature and reservoir pressure. These estimate are used to evaluate future changes.

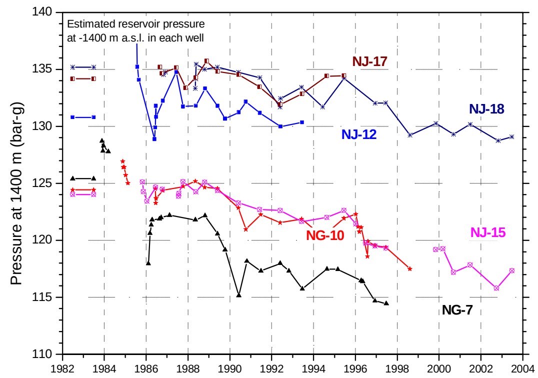

Figure 10. Weekly water level measurements in wells as at Nesjavellir during 1987 to 2003

Figure 9 shows the pressure history at 1400 m below sea level (1600-1700 m below surface) in the monitoring wells and the estimated reservoir pressures, when each well was drilled. These can be considered as undisturbed reservoir pressures prior to utilization as the wells were drilled in 1984-1986 when production had hardly began from the reservoir (see figure 5). Scattering of the data on figure 9 is mainly due to the inaccuracy of the Kuster pressure gauges (+/-1%) but recovery after drilling and flow tests are responsible for some of the scattering. All the wells show declining pressures with time. The pressure drawdown is lowest in wells furthest away from the production, and west of the eruptive fissure. These are wells NJ-12, NJ-17 (plugged since 1995) and NJ-18 with a pressure drawdown of some 6 bars. In the eastern part of the production zone well NJ-15 shows 7-8 bar pressure drawdown and well NG-10 showed similar pressure drawdown rates as NJ-15 up to 1998 when it was connected to the power plant. Well NG-7 is the well that shows the greatest pressure drawdown or some 10 bars up to 1998 when it was put into production for the power plant. The large drawdown in well NJ-7 is an anomaly and is believed to be to good permeability between the well and one of the nearby producers, probably well NJ-16 (Steingrímsson et al., 2000).

Weekly water level measurements in the monitoring wells are shown on figure 10. The measurements show similar trend as the pressure logs and the drop in the water level during the last 15 years is similar or little less than pressure logs indicate. The change from 1989 to 2003 is 34 meters in well NJ-18 but 56 m in NJ-15. The discrepancy between the pressure logs and the water level measurements can be explained by the inaccuracy of the Kuster gauges but it should be kept in mind that the depth to the water level fluctuates if the temperature conditions in the wells change. Examples of this on figure 10 are in 1996 when NG-10 and NJ-15 were shut in after flow test.

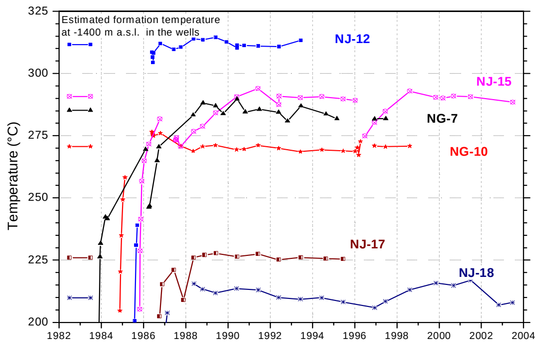

Figure 11: The temperature history at 1400 m b.s.l. in the monitoring wells

Figure 11 shows the temperature history at 1400 m b.s.l. in the monitoring wells along with the estimated formation temperatures in the mid 80'ies. The Kuster gauges are calibrated regularly and the accuracy of the logging data is considered +/- 3°C. The earliest data are from the heating-up period of the wells after the drilling, and later some disturbances are seen after wells have been flow tested in the late 80'ies and in 1996. Apart from these data points the temperature at 1400 m is fairly stable and does not deviate significantly from the estimated formation temperatures. Exception is well NJ-18. Estimated formation temperature at 1400 m b.s.l. is around 210°C in that well but the annual temperature logs show rising temperature to almost 220°C during 1995 to 2001. The well was used for few months injection testing in 2002 which explains relatively lower temperatures values in the most recent measurements.

4.3 Chemistry

Samples of geothermal steam and water are collected at arbitrary pressure, depending on the location of sample points and well characteristics. To compare series of samples, they have to be recalculated to common criteria, based on the chemistry and the steam/water ratio at the time of sampling (i.e. discharge enthalpy). In the following discussion each sample has been recalculated to the reservoir temperature in each well, varying from 270 to 290°C between wells. Due to the very high enthalpy most wells have two phases at this temperature, despite varying enthalpy during the period.

Chloride (Cl^-) along with fluoride (F^-) is the main component in geothermal fluid, which is least controlled by temperature. Its concentration in groundwater is basically determined by the Cl concentration in the rock and the contact between rock and water. It is therefore well suited to differentiate between water types and to trace water movements.

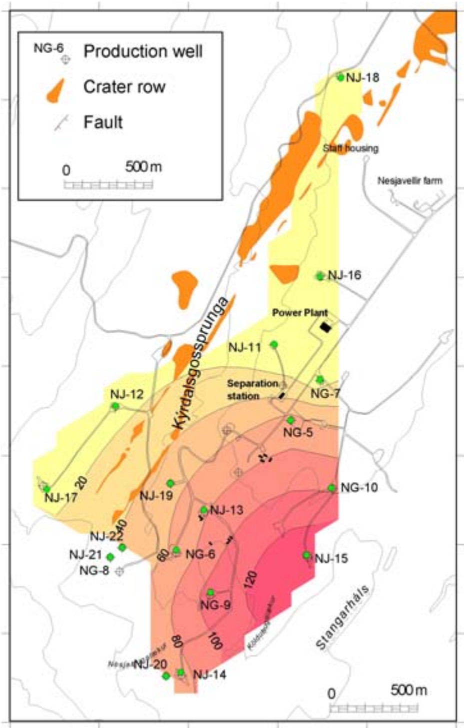

Figure 12: Initial chloride concentration (mg/kg) at aquifer temperature

The Nesjavellir reservoir shows great variation in initial Cl concentrations and important changes due to utilization. Initially the Cl concentration in the wells closest to the young eruptive fissure was unusually low, often below 10 ppm, but higher concentration was found in the lower enthalpy wells in the eastern part of the field (figure 12).

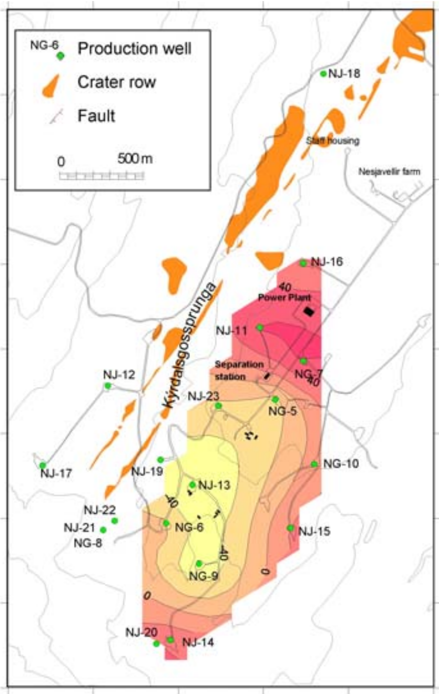

Figure 13: Changes in chloride concentration (mg/kg) during the period 1986 – 1996

During the first eight years of utilization all the production was from the high-enthalpy, low-chloride wells in the western part of the field. This caused inflow of geothermal fluid of lower enthalpy and with higher Cl content from east to west in the northern and southern part of the field, and currently the low-chloride waters have disappeared except for wells NJ-13 and NG-9 where the Cl remains fairly low. Figure 13 shows the changes in Cl concentration over a period of ten years.

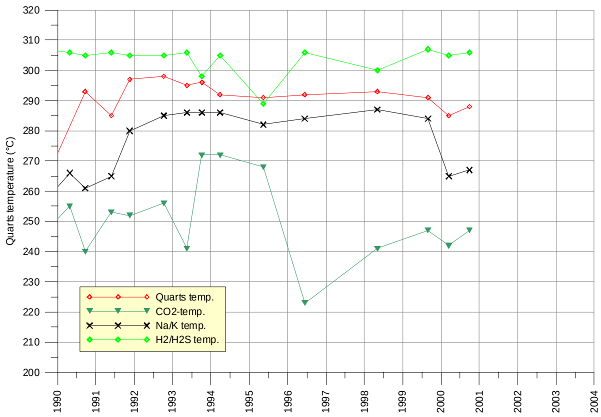

Figure 14: Calculated geothermometers for well NJ-11

Quartz temperature is in good agreement with measured aquifer temperature (290°C), where as other geothermometers show systematic deviation from the measured temperature (figure 14). The figure shows also that despite drastic changes in enthalpy as well as inflow of different waters, there are little fluctuations in geothermometers, but a modest decline in calculated temperatures. Figure 15 shows the calculated quartz temperature for all the wells since production started, and it shows that all the wells except wells NG-7 and NG-9 seems to be converging at around 275-280°C. Temperature measurement does not show the same trend, and apparently the utilization is causing the geothermal fluid from the different parts of the reservoir to be mixing and reducing the chemical variations within the system. No indication of cold inflow has been detected.

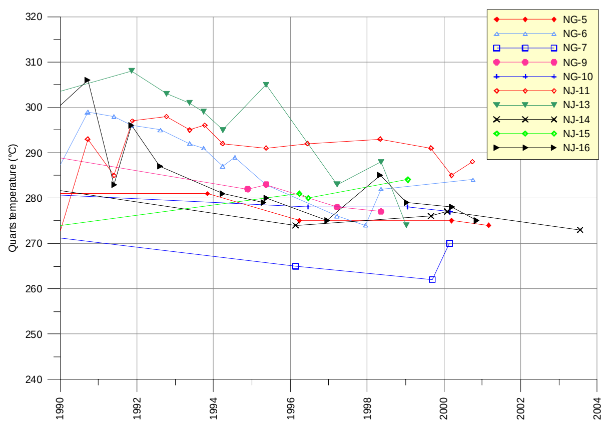

Figure 15: Calculated quartz temperature for the production wells at Nesjavellir

The content of dissolved gases is relatively small in the steam from the Nesjavellir reservoir, in the range 0.3-0.5 wt%. The gas content is generally higher in the high-enthalpy wells and the content of gases have fluctuated in these wells in unison with the enthalpy changes.

5. NUMERICAL MODELING

5.1 The first model, 1984-1986

Numerical models have been an integral part of field developments and reservoir management of the Nesjavellir field since 1984. The first model was developed during 1984 to 1986, using the MULKOM computer code (Pruess, 1982). It was a 3 dimensional model extending 12 km in all directions and consisted of 4 layers, three of which were 400 m thick (layers U, M and L) while the bottom layer (layer R) was 800 m, bringing the model thickness to 2 km similar to the depth range of the production wells (figure 16) The model was calibrated against the estimated initial pressure and temperature distribution of the field and the limited production history of the wells. Predictions were then made on future behavior of the production wells and on pressure drawdown in reservoir. This preliminary model study resulted in a generating capacity estimate of 300 MW_{th} for 30 years without re-injection, (Bodvarsson et al., 1990).

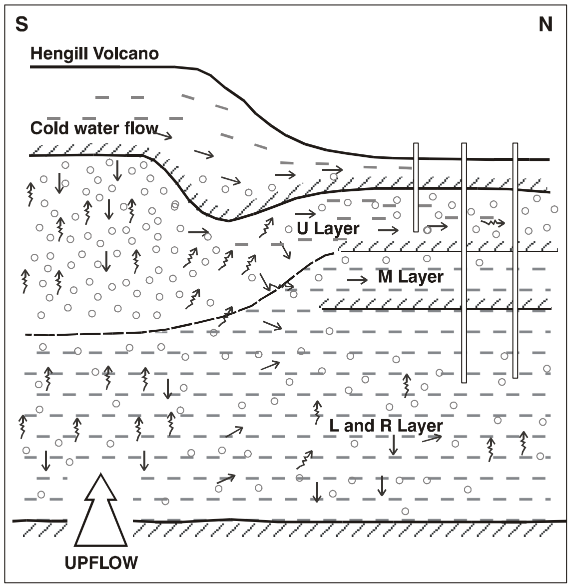

Figure 16: A model of the upflow zone and flow patterns for various layers. Straight arrows indicated liquid flow and wriggled arrows vapor flow

5.2 The 1992 recalibration

The predictions of the 1986 model were compared with the new monitoring data during the next years. By 1992 it was evident that the model overestimated pressure drawdown rates by a factor of 2-4 in all wells except the anomalous well NG-7. Otherwise the model had predicted the field status remarkably well. A recalibration was carried out. Few adjustments were needed to make the model match the production and monitoring data collected between 1986 and 1992. Of these adjustments, possibly the most important one was to extend the model base layer from 12x12 km to 100x100 km, increasing the model outer permeabilities. The anomalous pressure drawdown in NG-7 was believed to be due to good hydrological connection between that well and one of the nearby production well, most likely well NJ-16. The boundary pressure support, provided by the increased outer model permeabilities, raised the estimated generating capacity of the Nesjavellir field from 300 to 400 MW_{th} (Steingrímsson et al., 2000).

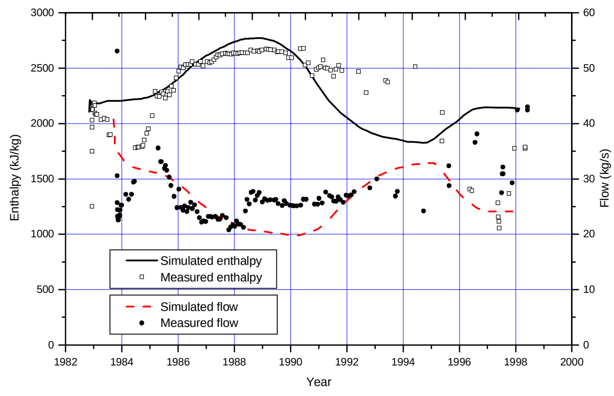

Figure 17. Comparison between predicted and observed flow rates and enthalpies for well 6 up to 1998 (the 1992 model)

5.3 Recalibration 1998 and 2000

The Nesjavellir model of 1992 matched very well new monitoring data (figure 17). The model was, however, recalibrated in 1998 and again in 2000 to study the effect of increased fluid production from the field as the power plant was expanded and make future prediction. Only some minor modifications were needed on the model, mostly in conjunction with the well field permeability and porosity distribution. Based on modeling effort it was concluded that the Nesjavellir reservoir could easily sustain for 30 years the proposed power plant expansion in 1998 to 200 MW_{th} thermal and 60 MW_e electric, which was further, expanded to 90 MWe in 2001. The expansion called for drilling of some 4-5 make-up wells. However, predicted enthalpy declines would make some of the peripheral wells less productive with time. This will eventually reduce electrical generation in Nesjavellir in the future while the thermal part of the power plant still will receive enough steam and brine for many decades (Bodvarsson, 1998; Björnsson et al., 2003).

5.4 The new model of 2002

All the above-mentioned updates of the Nesjavellir models were developed using the TOUGH2 numerical simulators Pruess et al., 1999). A break-through occurred in the year 2000 when the inversion code iTOUGH2 were applied for the first time (Finsterle, 1999).

Although the old Nesjavellir numerical model can be regarded as highly successful during its 14 years of existence, it became evident in year 2000 that the model mesh was unable to account properly for the new Nesjavellir wells. It was therefore decided that in the next update of the model to reconstruct the numerical mesh completely. Already in 2001 Reykjavik Energy considered adding the fourth 30 MWe at Nesjavellir bringing the power generation to 120 MWe in 2005. At the same time Reykjavik Energy was then carrying out an intense exploration programme at Hellisheidi in the southern part of the Hengill geothermal area (Gunnlaugsson et al., 2005). It was decided to develop a new model of the greater Hengill area. This model was supposed to simulate nearly all available subsurface data, to investigate possible pressure interference between well fields and, finally, should run under the iTOUGH2 structure and use parallel processing to estimate several model parameters simultaneously.

The work on the new model started in August 2001. In the beginning the main emphasis was on the calibration of the Nesjavellir part of the model in order to evaluate the feasibility of installing the fourth turbine at Nesjavellir. A reasonably good match was available already in June 2002 even though the model was not fully calibrated. The continuing work to calibrate the model for Nesjavellir and Hellisheidi was completed in October 2003 (Björnson et al., 2003; Björnson and Hjartarson, 2003).

The new three-dimensional mesh is made of 8 horizontal layers, with a vertical layering similar to that of the old Nesjavellir model and the area extent is 100 x 100 km as in the old model. The layering is shown in Table 2. Figure 18 shows the inner mesh covering the fields of Nesjavellir and Hellisheidi.

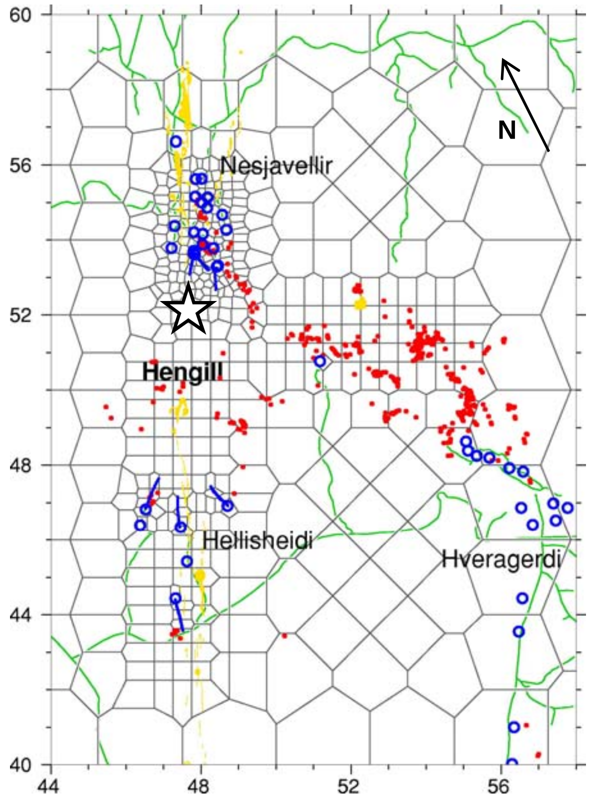

Figure 18: Inner parts of the Hengill mesh. Fumaroles and hot springs are shown in red, wells by blue circles and main roads by green lines. A star shows the model upflow zone. The finest mesh coincides with the volcanic rift zone and a possible transverse structure towards the ESE. Young volcanic fractures are shown in yellow and roads in green

Layer name	Thickness (m)	Center (m.a.s.l)	Property
Y	200	300	Inactive, atmosphere
U	400	0	Partially active
M	400	-400	Fully active
G	100	-650	Fully active
L	300	-850	Fully active
R	500	-1250	Fully active
S	500	-1750	Fully active
B	400	-2200	Inactive, impermeable

Table 2: Layering of the Hengill model

The inverse modeling technique of iTOUGH2 and the capability of the Linux cluster resulted in a relatively fast model calibration process. The most important parameters that were inverted are permeabilities, porosities and productivity indices for wells on deliverability. Strength and enthalpy of the upflow zone is also estimated, as well as conductive heat flow into the base of the model. Parameters and history data matched by the inversion process included initial temperature and pressure distribution of the well fields and the histories of well enthalpies, flow rates and pressure drawdown. Example of the matching of pressure drawdown data and the simulation for wells NJ-15 and NJ-18 at Nesjavellir is shown on figure 19.

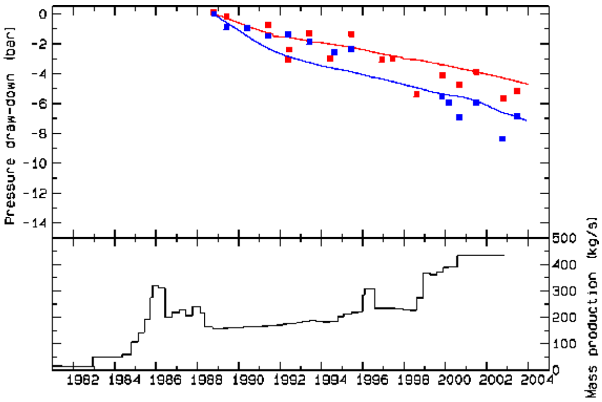

Figure 19: Pressure response of wells NJ-15 (blue) and NJ-18 (red) at Nesjavellir. Points are based on the annual pressure log data (see figure 9) but the curves are the calculated response based on the production history of the field

The June 2002 version of the Hengill reservoir model was applied to study the feasibility of adding the fourth 30 MW electrical units to the Nesjavellir power plant. (Björnsson and Hjartarson, 2003) Two sets of model parameters were considered for the predictions, one that had been defined as the *dry model* and overestimates the mean enthalpy history of the field while the *wet model* underestimates the mean enthalpy. These parameter sets may define two extremes in the future field response to production and, thereby, assist in the power plant decision-making. Four production scenarios were studied for the wet and the dry parameter sets (table 3).

Case number	Generation (MWe)	Parameter set	Make-up wells in layers
1	90	Dry	G,L,R,S
2	90	Wet	G,L,R,S
3	120	Dry	R,S
4	120	Wet	R,S
5	120	Dry	L,R
6	120	Wet	L,R
7	120	Dry	G,L
8	120	Wet	G,L

Table 3: Production scenarios for the Hengill model

The first scenario assumes that the current operation (90 MW_e and 200 MW_{th}) of the field will continue for another 30 years. The other three scenarios assume all that the fourth 30 MW unit will be added to the power plant. The difference of the scenarios is that make-up wells will produce either from deep, intermediate or shallow layers. This results in 8 future production scenarios. The new make-up wells are assumed to come on line every 5 years. Their productivity indices were adjusted such that each drilling project yielded the right amount of high-pressure steam to sustain the 90 or 120 MW generation rates. Steam is separated at 10 bars and it is assumed that 2 kg/s of high-pressure steam flow generate 1 MW_e.

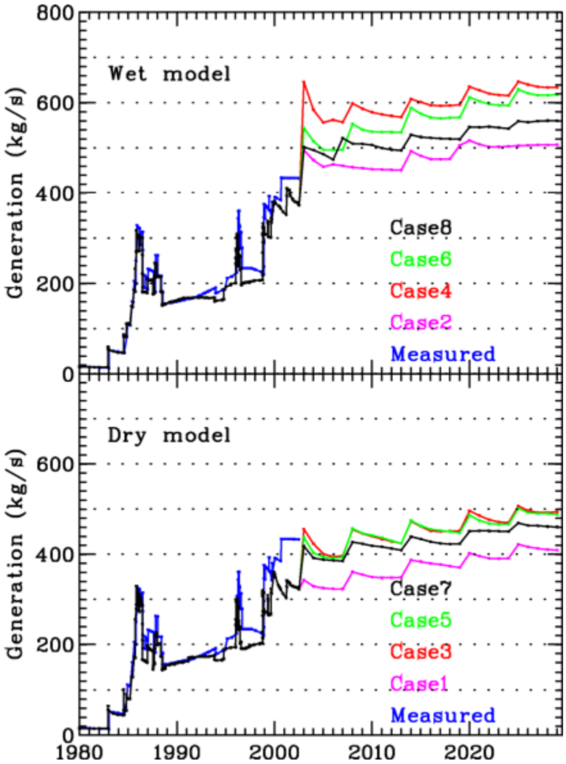

Figure 20. Predicted total generation rates for the Nesjavellir field. Jumps in the flowrate curves coincide with times when make-up wells start discharge

Figure 20 shows predicted total generation rates in the different production scenarios. In general the wet model is producing ~20 % more total mass than the dry one. Also a gentle increase in the total mass generation is seen for all the model cases. This behavior is the consequence of a predicted decline in the mean field enthalpy.

In order to operate the Nesjavellir power plant at full load (120 MW_e) for the next 30 years somewhere between 5 and 15 make-up wells may be required. It was also observed according to the model if the new make-up wells encountered very deep feed zones, a much lower productivity index will provide similar mass flow rates compared to wells that tap the shallow layers. The mean enthalpy of the Nesjavellir wells is at present around 1700 kJ/kg but is predicted to decline down to around 1500 kJ/kg during the 30 years prediction period. The enthalpy decline is a combined effect of cooler boundary recharge and less intensive boiling inside the current well field.

5.5 Modeling reinjection

The discharge of geothermal brine from the Nesjavellir power plant has increased with expanding production, and will be in the range of 200 kg/s at full capacity. Until January 2004 all geothermal brine was discharged in the cold shallow groundwater close to the station (Gíslason, 2000). The groundwater flow is towards the nearby Lake Þingvallavatn where the monitoring of a number of warm springs showed that improvement of disposal of brine was needed with increasing discharge from the power plant.

Various options for reinjection into the geothermal reservoir were tested in the numerical model. The response of the field to production shows an intensified recharge from the outer boundaries of the field into the producing reservoir. Accordingly the numerical model does not show any increased production capacity if the used geothermal brine is reinjected into the geothermal reservoir.

Therefore an alternative solution was adopted to dispose of the geothermal fluid from the power plant. In January 2004 a large scale test of reinjection into a warm groundwater at 400 m depth was initiated. Extensive tracer tests and ground water model studies have proven that the brine will not enter the geothermal reservoir, but will be absorbed into the general groundwater flow from the islands interior towards the sea.

6. CONCLUSIONS

The tailor designed monitoring programme for the Nesjavellir project is a necessary tool to manage the Nesjavellir reservoir and to map its response to utilization. During the operation of the field some 141 million tons have been extracted from the reservoir. This has led to 6-8 bar pressure draw down but reservoir temperatures have been fairly stable. Variations in production enthalpy are explained by boiling in the formation; enthalpy decreases during steady operation of the field, but rises when production is stepped up. The moderate pressure draw down at Nesjavellir is explained by a massive recharge to the system from the permeable outer boundaries.

The utilization of the Nesjavellir reservoir has to some extent caused changes in the chemistry of the reservoir fluid. Pre-production differences in chemistry within the field, such as chloride concentrations, are decreasing as the pressure changes have intensified fluid movements within the reservoir. The chemistry does not show any signs of temperature changes due to the production.

The intensive monitoring programme and frequent revisions of a numerical modeling at Nesjavellir has constantly enhanced the understanding of the geothermal system, and how it reacts to exploitation. This has enabled planners and designers the stepwise expansion of the power production in harmony with the abilities of the geothermal resource and made it possible to meet the demands of the marked.

No drastic changes were predicted in the field performance between the present 90 and future 120 MW electrical power plants studied. As a best case the field operation may require only 5 make-up wells during 30 years of operation and as a worst case around 15 wells.

Reinjection is not expected to improve the performance of the Nesjavellir reservoir due to high recharge rates from the outer boundaries of the system.

Overall, the estimated generating capacity of Nesjavellir field has increased gradually as more field data became available for the model calibration. Continuous maintenance and recalibration of geothermal reservoir models appears, therefore, feasible as a reservoir management tool.

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