MONITORING OF ICELANDIC GEOTHERMAL FIELDS DURING PRODUCTION

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ABSTRACT: The energy resources of geothermal systems are known to be limited and their developement can be compared to mining.The rate of energy extraction during utilization will normally greatly exceed their natural replenishment. This causes pressure draw-down with subsequent cooling in some cases or changes in production characteristics. Monitoring of production response parameters and chemical composition of the geothermal fluids is an important tool in the management of geothermal fields. The production response data are the neccessary basis for reservoir modelling and simulation of the response to different production rates. Chemical monitoring may give a warning before actual cooling or changes in production characteristics occur. During the last decade increasing efforts have been made to establish effective monitoring systems for the geothermal fields utilized in Iceland. A data network for monitoring production response data in low temperature geothermal fields is currently being expanded. Chemical monitoring has been effected in most high temperature geothermal fields from the beginning of utilization and is gradually coming into use in the low-temperature geothermal fields. The usefulness of monitoring has been amply demonstrated in both high-temperature and low-temperature geothermal developement by the discovery of production problems and prevention of trouble.

1. INTRODUCTION

Geothermal fields in Iceland are localized circulation systems with a limited energy resource and lifespan. During exploitation the energy extracted normally draws greatly on their natural power and the amount of fluid withdrawn is several times greater than the natural discharge. The response of the field to production may create problems during long-term utilization.

The primary influence of large-scale production of hot water or steam on a geothermal reservoir is a decrease in pressure. This is simply because more water is produced than recharges the system. Lower pressure causes the surface activity (hot springs) to change or disappear, free flow from wells to decrease and last but not least it will cause the water level in boreholes to drop. In many geothermal systems the pressure, or water level, continues to drop as hot water production continues with time and therefore the operators of a particular field may need to reduce the production before the pressure drop becomes too great. In other instances the pressure draw-down creates a potential danger for inflow of colder groundwater or seawater into a system followed by cooling and a change of production characteristics. It is therefore necessary to monitor changes in production, as well as changes in reservoir pressure and temperature (Grant et al., 1982). Lowering of the water level and the cooling of water from the production wells are the factors that limit the potential of a geothermal system.

A change in the chemical composition of geothermal waters will often precede cooling of the field, and data obtained by chemical monitoring of fluids may therefore give a warning in time for preventive action.

Regular monitoring is common practice in high-temperature geothermal fields in Iceland, but has often been neglected in the smaller low-temperature fields. Lately people have become increasingly aware of the importance of monitoring in the management of low-temperature fields. Experience has shown that reservoir studies, based on monitoring of both chemical and physical parameters is a necessary tool for operating a field in such a way as to keep profitability and production characteristics as near to an optimum for as long as possible. By careful monitoring, and subsequent reservoir modelling, amendments may be made and the production adapted to new conditions.

The monitoring programs applied in different geothermal fields may differ significantly. The programs have to be outlined carefully from the beginning of exploitation and later on adapted to new situations and the experience gained during the exploitation of the field.

2. MONITORING OF PRODUCTION DATA

Production response data are the neccessary basis of reservoir modelling and future predictions (Axelsson, 1991).

The need for monitoring and how it is effected is considerably different for high-temperature production compared to low-temperature geothermal production.

2.1 Low-temperature geothermal production.

Most of the low-temperature geothermal fields in Iceland (Fig.1) utilized for large district heating services (hitaveitas) are monitored regularly (Kristmannsdóttir et al., 1991). About 15 relatively large hitaveitas are now operated in Iceland and of those 12-13 have satisfacory monitoring programs. In those fields production response data are logged either manually or by automatic data loggers. For small hitaveitas the running of a monitoring program is rather a big undertaking so often monitoring is not initated until after problems have already occurred. About 10 % of

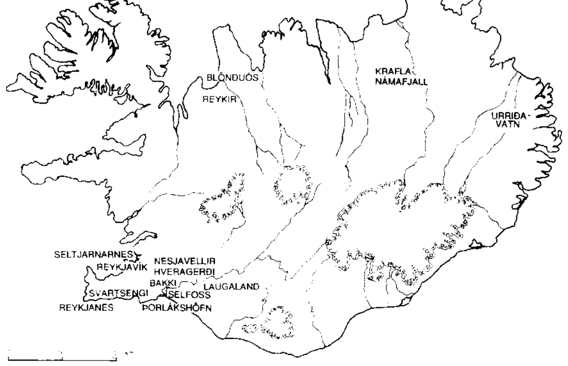

Figure 1. Map of Iceland showing the locations of the relevant geothermal fields.

the smaller hitaveitas in Iceland have monitored their production response data in a satisfactory manner (Kristmannsdóttir et al., 1991). Lately the importance of monitoring has become more generally acknowledged.

In general monitoring of production response data comprises the following parameters:

1. Production for each well (flow or pumping) both the instantaneous flow (l/s) and total production (m^3) from the last reading.

2. Temperature of production water.

3. Water level (or pressure) in production wells.

4. Water level (or pressure) in observation wells.

5. Outside air temperature.

6. Temperature logs in observation wells and production wells when possible.

The frequency of readings depends on circumstances and cost. It is commonly once a week for the first five points by manual reading and often four times a day by an automatic system. The logging of observation wells is often once a year or every second year.

For automatic monitoring of production response data in low temperature geothermal fields Orkustofnun has recently developed a data logging system (Fig. 2). The purpose was to make a reliable and cost effective system designed for this purpose. It was tested for two years in two very different hitaveitas and subsequently installed in ten hitaveitas. Data are loaded into the logger six times a day and it can measure up to 16 different parameters. Twice a month the main frame computer at Orkustofnun downloads the data collected. Each user can connect to the logger through a modem and a PC computer displaying either instantaneous values from each sensor or long term graphs.

Numerous examples of the production response of low-temperature geothermal systems are available. Figures 3 and 4 show two such examples. Figure 3 shows the water level changes in the Laugaland geothermal system in S-Iceland (Fig. 1) from the beginning of exploitation. Laugaland is a small reservoir of low permeability which explains the great draw-down (Björnsson et al., 1993). Figure 4 shows the cooling of a production well in the Urriðavatn (Fig. 1) geothermal system (Benjamínsson and Gíslason, 1986). This cooling resulted from direct down-flow of cold groundwater to the shallow feed-zones of the well. Other examples of cooling are the cooling of the production fields of the hitaveita in Reykjavík (Tómasson, 1988) and the hitaveita in Selfoss (Tómasson and Halldórsson, 1981).

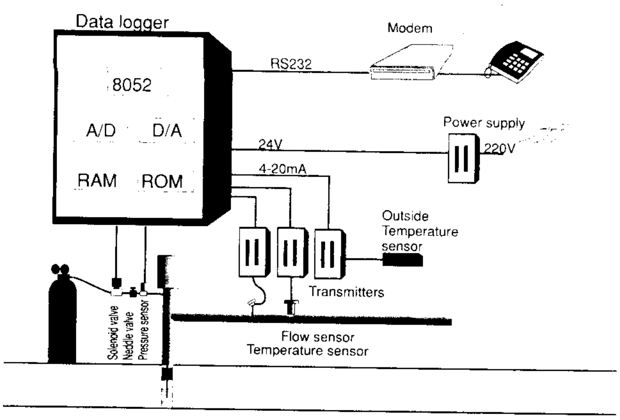

Figure 2. A scheme for the automatic data logger developed at Orkustofnun.

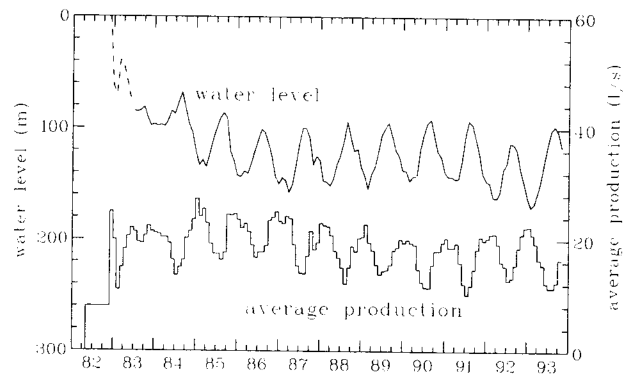

Figure 3. Changes in water level in a production well in the Laugaland geothermal field, S-Iceland.

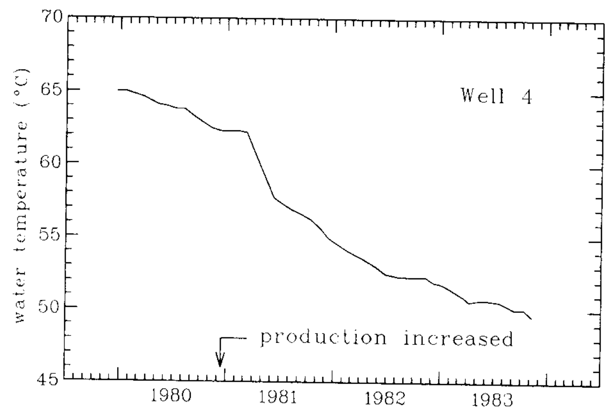

Figure 4. Cooling with time of a production well in the Urriðavatn geothermal field, E-Iceland.

2.2 High-temperature geothermal production

For high-temperature geothermal fields the need for monitoring of production response has been generally acknowledged. Mostly the same parameters are monitored as in low-temperature geothermal production, i.e. the wellhead pressure and flow together with wellhead pressure or draw-down in non- producing wells and down-hole logs of producing as well as non-producing wells. Also the enthalpy needs to be determined regularly. Table 1 summarizes the main features of the monitoring programs applied for the largest high-temperature geothermal production areas in Iceland.

Additional changes may occur and need to be monitored in high-temperature fields, which are not considered significant in low-temperature geothermal production. Among these are ground level and gravity changes as well as the formation of steam caps by degassing of the reservoir. In the Svartsengi (Fig. 1) high-temperature field ground level subsidence of 16 cm has been observed without any concurrent gravity changes (Eysteinsson, 1993). Seismic and volcanic activity is often monitored, even though this activity probably is not significantly influenced by production. It may on the other hand greatly influence the production of the fields in question. In the Krafla (Fig 1) high-temperature field this was clearly manifested in the seventies during repeated volcanic eruptions and extensive seismic activity in the area (Ármannsson et al., 1987).

Table 1. Monitoring of production response data (physical parameters) in high-temperature geothermal fields in Iceland: Krafla (Guðmundsson, 1988), Svartsengi (Thorhallsson and Kjaran, 1991, Björnsson and Steingrímsson, 1992), Reykjanes (Verkfræðstofan Vatnaskil hf, 1993) and Nesjavellir (Gunnlaugsson and Ívarsson, 1993).

Production	Wellhead Pressure bar	Flow rate Kg/s	Downhole logging Temp. and Press.	Number of obs. wells	Pressure draw-down in obs.wells
Krafla	1/week	2/year	1/year	5-7	-
Svartsengi	1/week	1/week*	1/year	1	3/week
Reykjanes	1/week	1/week*	2/year	1	-
Nesjavellir	1/week	1/year	1/year	7-9	1/week

* Estimated from pressure measurements

3. CHEMICAL MONITORING

As pointed out in the introduction, changes in the concentration of chemical constituents in the geothermal fluids will often precede actual physical changes. They can therefore give a warning in time for preventive action, if detected and interpreted correctly. How the changes are monitored and the usefulness of such information depends highly on the properties of the geothermal field in question, especially on the composition of geothermal fluid. Therefore there are significant differences between the methods of chemical monitoring of low temperature and high temperature production.

3.1 Low temperature geothermal production.

Low-temperature waters in Iceland are mostly dilute and the water utilized in Icelandic hitaveitas, contains typically less than 400 mg/l of total dissolved solids, with a maximum of 4000 mg/l (Kristmannsdóttir, 1990). It is always recommended to monitor the chemical composition of the fluids in a geothermal system, but the need varies for different types of systems. A monitoring scheme for chemical changes depends even more on the type of geothermal field (Kristmannsdóttir and Ármannsson, 1992) than the monitoring of production responce data. The inflow of cold freshwater into a geothermal system is often difficult to detect at an early stage, and thus more frequent sampling and analysis is required to enable the detection of changes with resonable certainty. The infiltration of seawater into a fresh-water geothermal system is on the other hand rather easily traced and needs much simpler means for chemical monitoring. A sample for analysis of all main constituents (pH, volatiles, silica, Na, K, Mg, Ca; Al, Fe, Mn, Cl, Br, B, SO4, F, NO3, TDS) is normally collected at least once a year from all fields and more frequently in fields where the water is slightly mineralized and there is fear of freshwater inflow. Occasionally samples for analysis of selected trace elements (Li, Sr, Cd, I, Zn, Hg, Pb, As) are collected. Additional samples for partial analysis may be collected several times a year. The constituents analysed in those samples may be selected cations, silica or fluoride depending on the type of water. Analysis of stable isotopes in the waters are often useful because geothermal waters and local groundwaters may have significantly different values. Where the water is more highly mineralized or seawater infiltration is expected additional samples for chloride and sulfate analysis and possibly also for selected cations and silica or even stable isotopes are collected. The samples are often collected six times a year, but the frequency varies from one field to another.

Wells with inflow from two or more feed zones, each with its characteristic temperature and chemistry, are common.

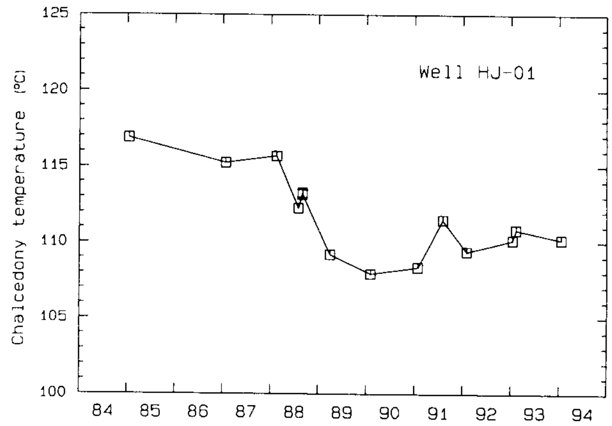

Figure 5. Changes in chalcedony temperature with time in production water at the Bakki field.

Changes in the mixing ratio of water from the different feed zones resulting from changes in relative pressure, may affect production characteristics drastically.

Chemical monitoring has effectively prevented operational problems in many of the Icelandic low-temperature geothermal fields (Kristmannsdóttir et al. 1991). As an example at the **Bakki** field (Fig. 1) utilized by the **Thorlákshöfn** hitaveita, cooling by cold groundwater inflow at the bottom of one of the production wells was detected by chemical monitoring (Kristmannsdóttir et al., 1990). Fig. 5 shows the change in chalcedony temperature of the

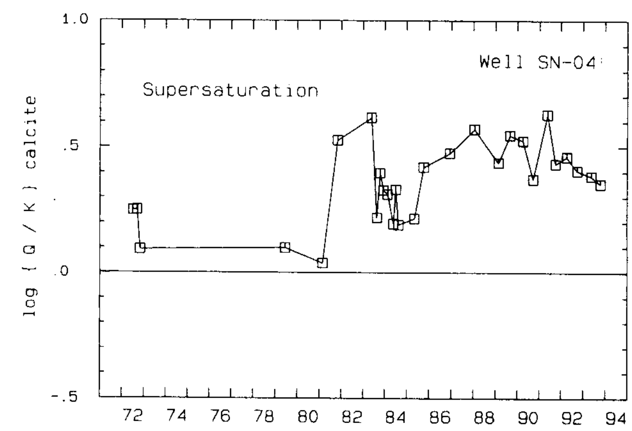

Figure 6. Changes in calcite saturation with time in the Seltjarnarnes geothermal field.

geothermal water in the well in question. Severe infiltration of seawater which has changed the production characteristics of the water by making it highly supersaturated with calcite (Fig. 6) was detected early on in the **Seltjarnarnes** geothermal field (Kristmannsdóttir, 1986). No cooling has occurred and so far no changes have been predicted by geothermometry. In the geothermal field at Reykir (Fig.1), utilized for the hitaveita at Blönduós, chemical monitoring revealed a broken casing (Orkustofnun data) so amendments could be made before too much harm was done.

Chemical monitoring schemes have been continuously adapted to the varying conditions in the fields. Therefore no absolute rules can be given. In many icelandic low temperature geothermal fields samples for total analysis are collected once or twice a year. In addition a varying number of samples are collected each year for partial analysis depending on the character of the field. Some chemical monitoring is performed on site in the bigger hitaveitas, such as measurements of dissolved oxygen and conductivity.

3.2 High temperature production

Icelandic high-temperature fluids are much more concentrated than the low-temperature geothermal fluids (Arnórsson et al., 1983). Changes are often more complex and sometimes quite dramatic. The discharge and production characteristics may change drastically due to changes in the reservoir or even in the well itself. A pressure draw-down in the field will create a growing steam zone in the upper levels and degassing of the lower reservoir into the steam. The fluid discharge of the shallowest wells may consequently dry up and its gas content greatly increase, which changes the production characteristics of these wells significantly. Early indications of this will be spotted by chemical changes in the discharge of the wells. High-temperature fields are closely connected to volcanic activity, and changes in the activity have to be watched carefully. Cooling effects will be reflected in chemical changes, but in high-temperature fields these are often indications of excessive production and not necessarily caused by inflow from a different source.

The monitoring programs applied and the frequency of sampling vary from one area to another. Mostly the same parameters are analysed in the waters as in the low-temperature fields, but in addition the constituents of the steam phase are analysed (CO_2, H_2S, H_2, CH_4, N_2, O_2, Ar). Most samples are collected for total analysis, but in some cases samples for partial analysis are collected in connection with production problems. Regular monitoring of production related parameters (e.g. gas, carry-over, pH) is carried out in most of the fields. The main sites of high-temperature geothermal utilization in Iceland are the Krafla, Svartsengi, and Nesjavellir fields. There is also some exploitation of the Námafjall, Reykjanes, and Hveragerði fields (Fig. 1).

The **Krafla** and **Námafjall** areas have been affected by volcanic activity (Björnsson, 1985) since commencement of utilization, and therefore they have needed a special monitoring program. A number of the changes in chemistry and production characteristics are related to this volcanic activity (Ármannsson et al. 1987, 1989, Darling and Ármannsson, 1989, Truesdell et al. 1989).

When the volcanic activity was at its height, ten or more samples per year were collected from each well. A monitoring program involving the collection of two samples per year from each well was established in 1982 after the volcanic activity had waned and it was reduced to one per year in 1988, the reasons being high cost due to difficult conditions in the winter and the fact that the field has been operated for only eight months each year (Guðmundsson, 1988).

In the **Nesjavellir** field (Gunnlaugsson and Ívarsson, 1993) each well is sampled at least once a year and normally twice a year. This field has been utilized for the last five years and under developement for more than twenty five years. The area has not been volcanically active during that time. Significant changes due to production have not yet been detected.

The chemistry of fluids in the **Svartsengi** field has been monitored regularly during the twenty years since drilling commenced (Bjarnason, 1988). For most of this period samples for total chemical analysis have been collected at least twice a year from each well, and more frequently when changes have been detected or suspected. Production from the field has resulted in a substantial pressure draw-down, which, in turn, has caused the fluid to flash in the formation. The concomitant degassing and other changes (Bjarnason, 1988) have been monitored closely, and in some cases this program has given early warning. A case in point is one of the production wells whose discharge turned to dry steam in 1984 after the water level in the field dropped below the main feed zone. In 1994 the sampling frequency was reduced to one sample per year for economic reasons.

In a few other high temperature geothermal fields like the **Hveragerði** (Steingrímsson, 1991) and **Reykjanes** (Verkfrædistofan Vatnaskil, 1993) there has been a more limited monitoring programme due to limited or irregular production.

The sampling frequency in high-temperature geothermal fields elsewhere in the world (Ellis and Mahon, 1979, Grant et al., 1981, Celati et al., 1973) is usually a function of the stability of the chemical composition and is known to be at a minimum of 1 - 2 samples per year from each well up to twenty times a year in the fields which show the most variation (Kristmannsdóttir and Ármannsson, 1992). As compared to this samples are collected relatively infrequently in icelandic high temperature geothermal fields in spite of production problems in some of them. More frequent sampling has been recommended, but due to economic reasons it has not yet been done.

4. CONCLUSIONS

Monitoring of production response data and changes in the chemical composition of geothermal fluids have proved to be an indispensable part of the management of geothermal fields. In many instances chemical montoring has forecast imminent cooling of geothermal fields or changes in their production characteristics.

The production response data, which are monitored depend on the type of geothermal field. Monitoring programs have to be specially designed for each field as well as adjusted with time, as experience is gained. In low temperature geothermal production, monitoring centers around measurements of production and changes of pressure and temperature with somewhat variable frequency. High temperature production may require monitoring of some additional parameters such as ground subsidence and microseismicity.

The chemical monitoring schemes vary even more than those for the production responce data. Generally, it appears that samples for total analysis need to be collected at least once a year in a low-temperature geothermal field with additional samples taken for partial analysis several times a year depending on the nature of the field. In the icelandic high temperature geothermal fields sampling frequency is often as low as once a year, which can hardly be considered satisfactory. The minimum sampling frequency recommended in high-temperature fields is twice a year from a production well, but more frequent sampling is often required.

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