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RESERVOIR ENGINEERING STUDIES OF SMALL LOW-TEMPERATURE HYDROTHERMAL SYSTEMS IN ICELAND

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ABSTRACT

Geothermal energy provides more than one third of the energy consumed in Iceland. Its primary use is for space heating and most of the 28 public *hitaveitur* (district heating services) in Iceland utilize small low-temperature geothermal fields that have a natural heat output of only a few 100 kW_t to a few MW_t. All of these small reservoirs respond to production by declining pressure and some by declining temperature. During the 1980's the emphasis in geothermal research in Iceland shifted from exploration to reservoir engineering. The reservoir engineering work carried out concurrent with the exploitation of these small fields includes: testing of individual wells, field wide tests, monitoring the response of reservoirs to long-term production and simple modeling.

INTRODUCTION

Geothermal energy plays a major role in the energy economy of Iceland. At present it provides more than one third of the energy consumed by the 250.000 inhabitants, or about 8500 GWh. The primary use of geothermal energy is for space heating and about 85% of all residential buildings in Iceland are heated by geothermal energy, in addition to most commercial and industrial buildings.

Most towns and communities in Iceland use geothermal water directly for space heating. The water is provided by various district heating sevices, which are named *hitaveitur* (plural) in Icelandic (hitaveita in the singular). At the present there are 28 public *hitaveitur* operating in Iceland (Figure 1) and excluding the few largest ones, such as the one serving the capital city of Reykjavík, they serve communities with only a few hundred to a few thousand inhabitants each.

The smaller *hitaveitur* use energy from some of the numerous low-temperature geothermal areas which are found in Iceland (Figure 1). The low-temperature areas, which have a reservoir temperature less than 150 °C, are all located outside the volcanic zone passing through the island. The largest low-temperature areas are located in SW-Iceland on the flanks of the volcanic zone, but smaller areas are found throughout the contry. The surface manifestations of the low-temperature activity are hot or boiling springs. Spring flow rates range from almost 0 l/s to a maximum of 180 l/s from a single spring.

The heat-source for the low-temperature activity is belived to be the abnormally hot crust in Iceland. Bodvarsson (1982, 1983) proposed a model for the heat-source mechanism of the activity, that appears to be consistent with the data now available (Björnsson et al., 1990). According to his model, which is presented in Figure 2, the recharge to a low-temperature system is shallow ground water flow from the highlands to the lowlands. Inside a geothermal area the water sinks through an open fracture, or along a dike, to a depth of a few km where it takes up heat from the hot adjacent rock and ascends subsequently because of reduced density. This convection transfers heat from the deeper parts of the system to the shallow parts. The fracture is closed at depth, but according to Bodvarsson's model the fracture opens up and continuously migrates downward during the heat mining process by cooling and contraction of the adjacent rock. Thus the low-temperature activity is a transient process. A steady state process can not explain the natural heat output of the largest low-temperature systems in Iceland, which may be of the order of 200 MW_t.

Recent data on the low-temperature systems indicate that dikes may not be the primary fluid conductors, but rather younger fractures or faults. In addition many of the low-temperature systems seem to be located at the intersections of such fractures or faults and older dikes (Björnsson et al., 1990).

Theoretical calculations based on Bodvarsson's model (Axelsson, 1985) indicate that the existence and heat output of the low-temperature systems is controlled by the temperature conditions in the crust and in particular the local stress field, which controls whether open fractures are available for the heat mining process and how fast these fractures can migrate downward. Given the abnormal thermal conditions in the crust of Iceland it appears therefore that the regional tectonics and the resulting local stress field control the low-temperature activity.

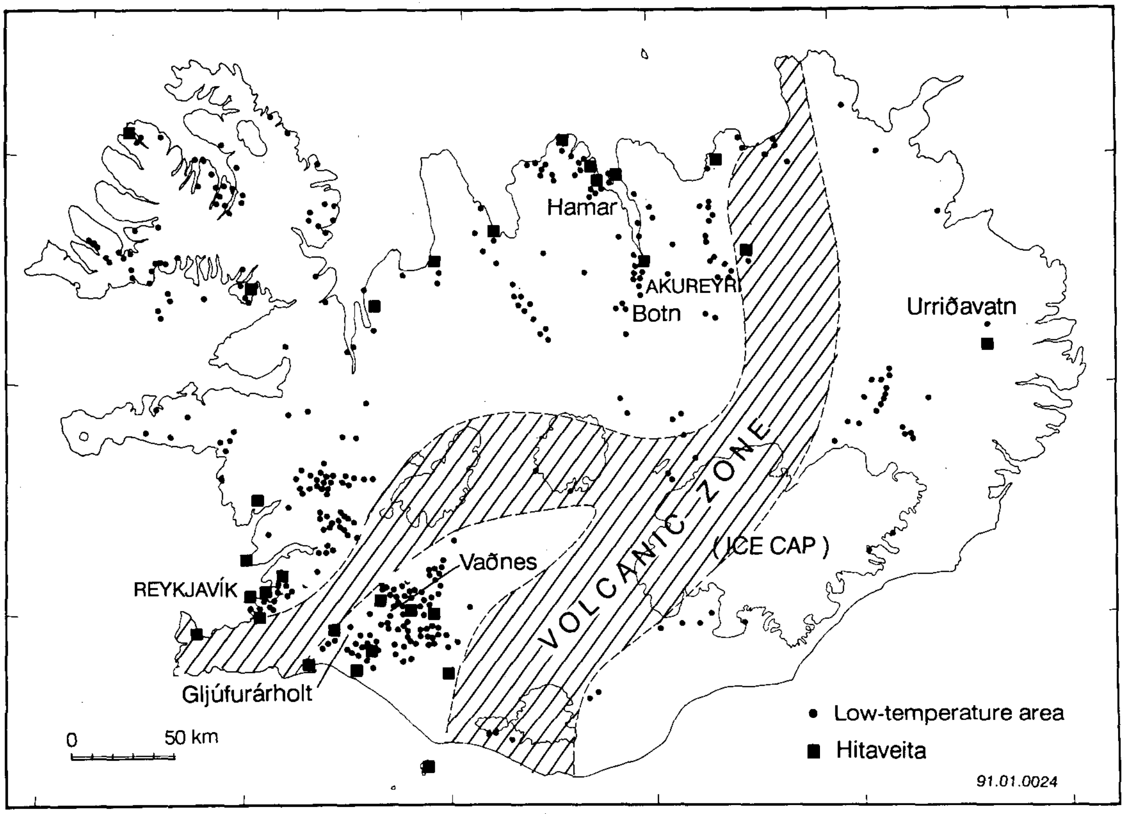

Figure 1. *Low-temperature hydrothermal areas and public* hitaveitur (*district heating services*) *in Iceland*

Most hitaveitur utilize the smaller low-temperature fields. The natural heat output of these fields is only of the order of a few 100 kW_t to a few MW_t, but the average power need of the smaller hitaveitur is between 5 and 20 MW_t. All of the reservoirs therefore respond to production by declining pressure and some also by declining temperature. Most of the low-temperature reservoirs currently under exploitation have been utilized for a decade or more. Considerable amounts of data on the response of these reservoirs are therefore available.

In this paper the reservoir engineering work carried out in connection with the exploitation of these small low-temperature fields will be discussed. The testing of individual wells, field wide tests, monitoring during long-term production and methods of modeling the reservoirs will be discussed and a few examples presented. The purpose of the reservoir engineering work has been to obtain information on the nature of the reservoirs, assess their production potential and predict their response to future utilization, in order to define long term operational strategies for the geothermal fields. The facts that data on the details of the subsurface conditions are in most cases scarce, and that funds for reservoir engineering work are often limited, constrain the methods that have been used to study and model the fields.

RESERVOIR ENGINEERING STUDIES

Regular reservoir engineering studies of geothermal fields in Iceland started in the mid 1960's (Thorsteinsson and Elíasson, 1970). For the next two decades the main emphasis in geothermal research in Iceland was, however, on geophysical and geological exploration of potential production fields for *hitaveitur*

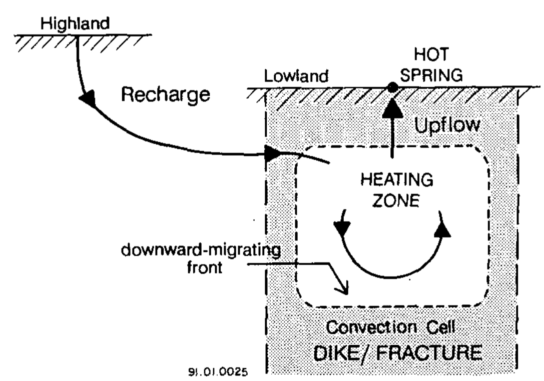

Figure 2. *Model of a low-temperature system in Iceland. Based on Bodvarsson (1983).*

that were in the planning stage, or already operating. Most of the wells currently in use by *hitaveitur* were drilled during this period.

The emphasis in geothermal research in Iceland changed during the 1980's. By that time more than 80% of the population enjoyed heating by geothermal energy, and the latest public *hitaveita* started operation in 1981. Therefore the need for geothermal exploration decreased considerably. However, the *hitaveitur* started encountering various problems associated with the production from the geothermal fields and the response of the reservoirs to long-term production (Sigurðsson et al.,1985). In many cases the potential of a reservoir turned out to be less than previously belived and interests in long term operational strategies for the geothermal fields increased. Thus the emphasis shifted to geothermal reservoir engineering.

The reservoir engineering work carried out concurrent with the utilization of the small low-temperature fields includes:

A. Short-term pump, injection and free-flow tests of individual production wells, of only a few hours duration.

B. Long-term tests such as build-up and interference tests, with a duration of days or weeks, that often involve several wells.

C. Tracer tests of several weeks duration.

D. Monitoring the response of a reservoir to long-term production.

E. Simple modeling based on data aquired under A to D above.

The short-term tests (A) provide information on the characteristics of production wells, such as pressure drop due to turbulence, but very limited information on the properties of a geothermal reservoir. Longer-term build-up and interference tests (B) provide more information on the properties of a reservoir, such as permeability and storage, and on the nature and boundaries of a reservoir. This information is, however, usually not sufficient to make accurate predictions on the long-term response of reservoirs to hot water production. Tracer tests (C) will not be discussed in this paper.

The most important information on the nature, properties and size of a geothermal reservoir are obtained by careful monitoring (D) of its production and response history. Monitoring is an important part of field management as well as the basis for reservoir engineering work, such as modeling. Increased emphasis has therefore been placed on monitoring in recent years in Iceland, and most *hitaveitur* follow a monitoring program as outlined below. It should be mentioned that in most of the small low-temperature fields now utilized production is by pumping from deep (>500m) wells. The following items are monitored:

1. Flow-rate history of each production well and a field as a whole.
2. Temperature of the water produced.
3. Water level in production well(s).
4. Water level in observation well(s) inside a geothermal reservoir.
5. Water level in observation wells(s) outside a geothermal reservoir.
6. Chemical content of the water produced.
7. Temperature logs in observation wells.

Not all items in the above list are monitored in the small low-temperature fields utilized by *hitaveitur* in Iceland. In a few fields the monitoring is still incomplete. But in most fields at least items 1, 2, 3 and 4 are monitored once a day to once a week and the chemical content (6) at least once a year. In a few cases the monitoring is computerized.

Simple modeling (E) has been used extensively for the small geothermal reservoirs, in particular to model their long-term response to production. Most of the reservoirs respond to production by decreasing pressure, which is monitored as water level changes in observation wells. Lumped models have been used successfully to simulate the pressure response data from several low-temperature reservoirs in Iceland. Axelsson (1989) has described the most commonly used method, which tackles the simulation as an inverse problem. It uses an automatic non-linear least-squares iterative technique which requires very little time compared to more detailed distributed parameter numerical modeling techniques. Detailed numerical modeling has only been attempted for a very limited number of the small low-temperature reservoirs. The reasons for this are that data on the subsurface conditions in these reservoir are often very limited and in addition that funds for detailed modeling have not been available to the smaller *hitaveitur*.

EXAMPLES

A few examples of reservoir engineering studies of small low-temperature fields in Iceland will now be presented. The examples are from the following areas: Vaðnes and Gljúfurárholt in SW-Iceland which are utilized by the surrounding farms and vacation homes. Urriðavatn in E-Iceland utilized by the Egilsstaðir *hitaveita* which serves a population of 1600. Botn in N-Iceland which is one of four small low-temperature fields utilized by the Akureyri *hitaveita* which serves a population of 13,000. Hamar in N-Iceland utilized by the Dalvík *hitaveita* which serves a population of 1400. The locations of the fields are shown in Figure 1.

Well tests

Figure 3 shows the results of short-term step-rate pumping tests of two wells of approximately the same depth (300 - 400 m) and diameter (0.2 m), but with

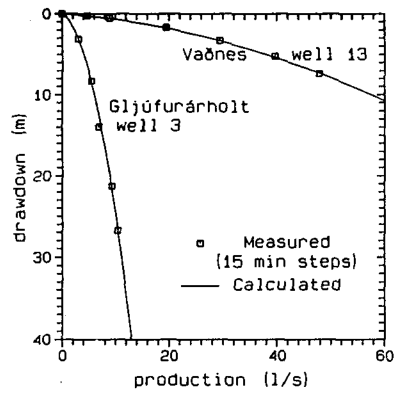

Figure 3. *Results of short-term step-rate pumping tests in the Vaðnes and Gljúfurárholt fields.*

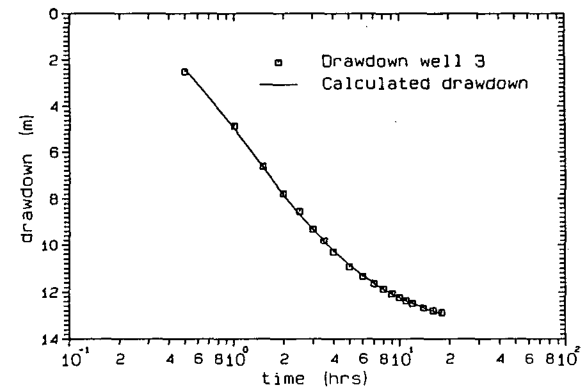

Figure 4. *Results of an interference test in the Urriðavatn field in 1987.*

otherwise very different characteristics. One is in the Vaðnes field and the other in the Gljúfurárholt field. They are both small low-temperature fields, Vaðnes with a reservoir temperature of about 80 °C and Gljúfurárholt about 100 °C. The turbulence pressure loss in the wells can be approximated by:

$$(1) \qquad \Delta h = C\, q^2$$

where Δh is the loss in terms of water level, C is a constant and q the pumping rate. Well 13 in the Vaðnes field is highly productive with very little drawdown due to turbulence, or $C = 0.0022\ m/(l/s)^2$. Well 3 in the Gljúfurárholt field is a poor producer with great drawdown due to tubulence, or $C = 0.207\ m/(l/s)^2$. In addition the permeability is much lower in the Gljúfurárholt reservoir than in the Vaðnes reservoir.

Long-term tests

Figure 4 shows the results of a 24 hour interference test performed in the Urriðavatn low-temperature field. The Urriðavatn field is located at the bottom of a small lake and production from the field started in late 1979 (Axelsson et al.,1988). A total of 8 wells have been drilled into the reservoir but only wells 4, 5 and 8 turned out to be productive. Wells 4 and 5 only intersected shallow (200 - 300 m) aquifers and the temperature of the water produced from these wells decreased drastically the 3 - 4 years they were in use. Well 8 intersected a good aquifer at around 800 m depth. Production from that well started in late 1983 and the response of the reservoir after that time will be discussed later in this paper.

During the interference test 15 l/s were pumped from well 5 and the resulting drawdown observed in well 3 130 m away. The data were simulated by a simple analytical model of a homogeneous and isotropic *vertical slab* of width b with two-dimensional flow and constant pressure at the surface. A vertical slab is consistent with the conceptual model of the field and the constant pressure is maintained by the lake above the reservoir. Based on this model the apparent permeability width of the upper part of the Urriðavatn reservoir is $bk = 1.0 \times 10^{-11}\ m^2$ and the apparent compressibility width $bc_t = 6.5 \times 10^{-9}$ m/Pa, where c_t is the compressibility of the liquid saturated formation. Assuming that the width is about 100 m this corresponds to a permeability of $10^{-13}\ m^2$ and a porosity of 9.0%.

Figures 6 and 7 show the data obtained during an 11 week long build-up and interference test performed in the Botn field (Flóvenz et al., 1989) during the summer of 1990. Pumping from well H-10, the main production well in the field, was stopped for about a month and then restarted in early July (Figure 6). The resulting water level changes were monitored in several wells inside as well as outside the field (Figure 5). The water level changes in wells B-2, B-4 and H-12 are presented in Figure 7. The data obtained are currently being analyzed but the first results indicate a small reservoir with a limited permeability that, however, appears to be connected to a much larger geothermal system.

The water level changes in well H-12 are very strange. On one hand the water level does not start to rise in that well until 5 days after the pressure build-up starts in the reservoir. On the other hand the water level starts to drop at the same moment the water level

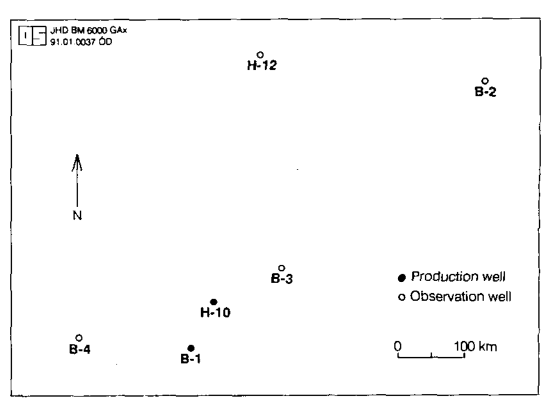

Figure 5. *Production and observation wells in the Botn field.*

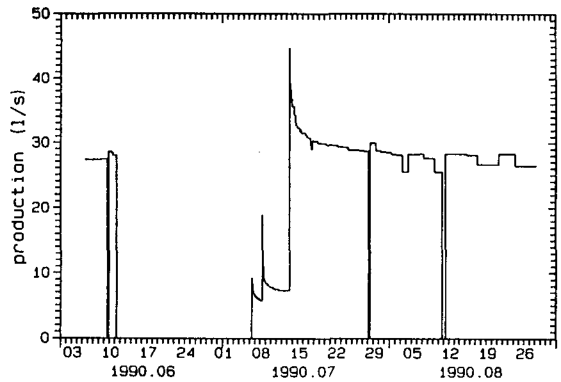

Figure 6. *Production from well H-10 in the Botn field during the summer of 1990.*

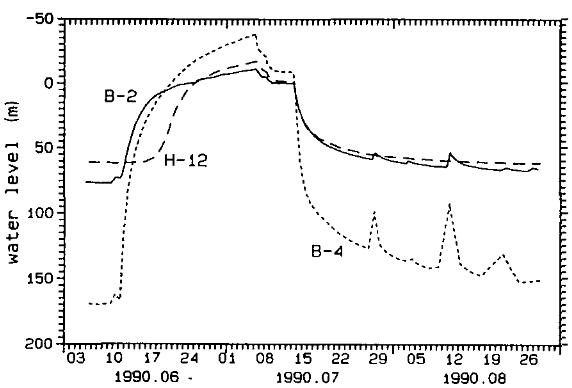

Figure 7. *Water level changes in wells B-2, B-4 and H-12 in the Botn field during the summer of 1990.*

starts to drop in the other wells. A possible explanation is that fractures along dikes that connect the production well (H-10) and well H-12 were closed before the build-up period because of the great pressure drawdown in the reservoir. As the pressure increased in the reservoir the fractures may have opened slowly until after about 5 days they had opened all the way to well H-12. When the drawdown started again the fractures were open, resulting in a simulataneous drawdown in H-12 and the other wells. This kind of behavior has not been observed previously in Iceland.

Monitoring and simple modeling

The first of two examples of simple modeling, based on long-term monitoring, presented here is from the Hamar field. Production from this small field started in 1969. Two production wells, with feed zones between depths of 500 and 800 m, are currently in use and the reservoir temperature is 64 °C. Figure 8 shows a 7 year record of the production from the field and the resulting water level changes. The figure also shows the water level changes simulated by the lumped model approach discussed earlier (Axelsson, 1988). The lumped model used is shown in Figure 9. According to the model the innermost part of the reservoir has a

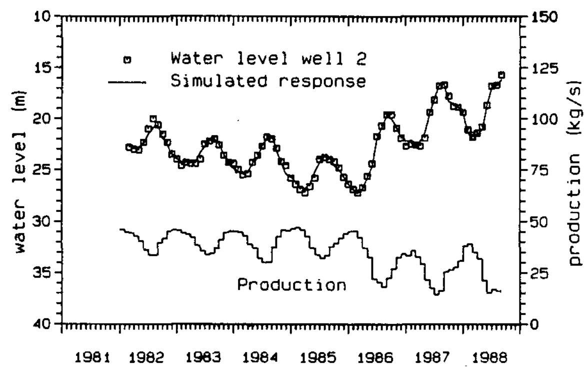

Figure 8. *Production from the Hamar field along with observed and simulated water level changes.*

storage coefficient Vc_t = 0.071 m^3/Pa, where V is the volume of that part of the reservoir and c_t its compressibility. Assuming that the porosity of the innermost part is between 5 and 10 % then its volume is between 1.1 and 1.6 km^3. The recharge part of the reservoir appears to be unconfined (free-surface) and cover an area of 8 to 12 km^2 (assuming porosities between 10 and 15 %). Thus the recharge part of the lumped model may represent the groundwater system in the area.

The average permeability of the Hamar reservoir was estimated as follows: First the *unit step response* of the reservoir was calculated by the lumped model. The *unit step response* is the response to a constant production of a unit volume (or mass) per unit time. Then the *unit step response* was simulated by a simple analytical model of an unconfined (free-surface) homogeneous and isotropic half-space (Axelsson and Bodvarsson, 1987). The results are presented in Figure 10. An unconfined model was chosen in view of the results of the lumped modeling. Based on this model the apparent permeability of the Hamar reservoir is 9.6×10^{-15} m^2.

The main objective of reservoir engineering work is to assess the production potential of a geothermal reservoir and predict its response to future utilization. In the case of the Hamar field the lumped model was used to predict the water level drawdown in the reservoir for different future production rates. The results are presented in Figure 11. It should be

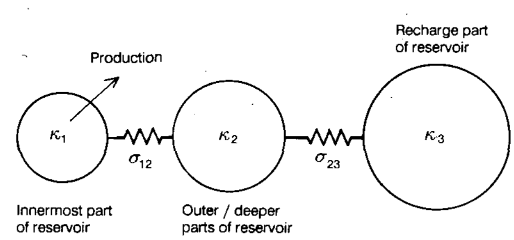

Figure 9. *Three capacitor lumped parameter model of the Hamar reservoir.*

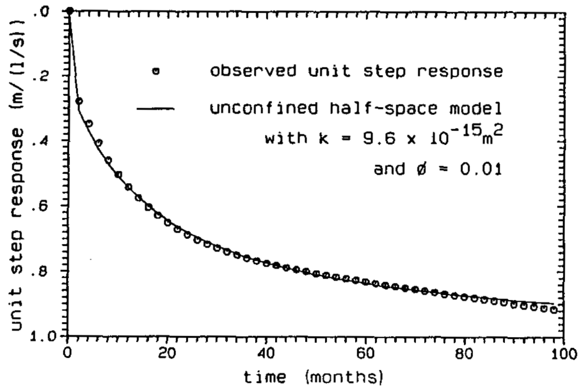

Figure 10. *Observed and calculated unit step response of the Hamar reservoir.*

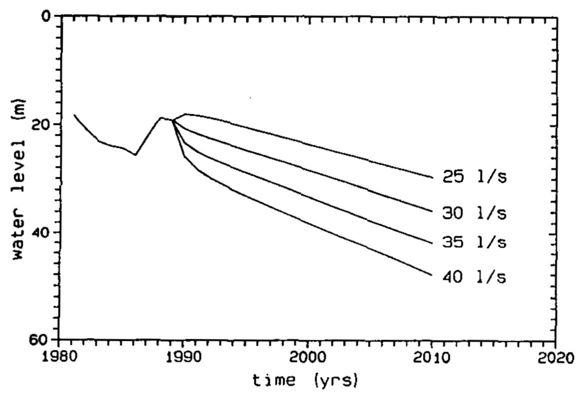

Figure 11. *Predicted water level changes in the Hamar reservoir.*

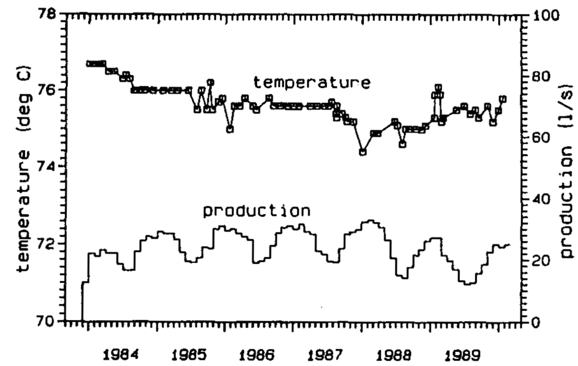

Figure 12. *Production from well 8 in the Urriðavatn field and resulting changes in temperature.*

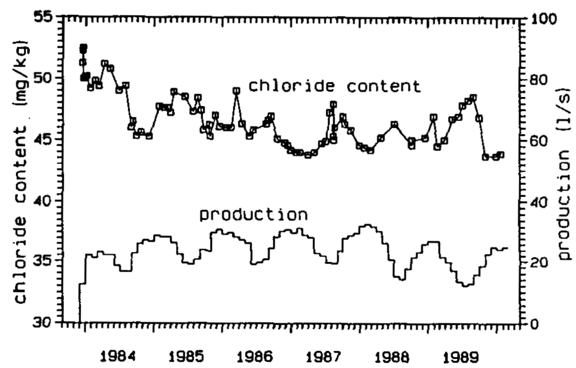

Figure 13. *Production from well 8 in the Urriðavatn field and resulting changes in chloride content.*

emphasized here that since the recharge into the Hamar system may be cold groundwater the temperature of the water produced may eventually decrease in addition to the predicted water level changes. No cooling has, however, been observed to date in the Hamar field.

The last example presented here is the long-term response of the Urriðavatn low-temperature reservoir. Figures 12 and 13 show the production from the field since late 1983 along with the resulting changes in temperature and chloride content (Axelsson et al., 1989). It is believed that down-flow of cold water from the lake above the field into the geothermal reservoir is causing these changes. The chloride content of the freshwater in the lake is about 10 mg/kg. The chloride content of the water produced therefore indicates mixing by freshwater of up to 20 %. It is evident that the cooling of the water produced will continue in the future. The future rate of decline is of a great importance for the management of the Egilsstaðir *hitaveita*. An attempt has been made to predict the changes in temperature for different cases of future production by using a simple curve-fitting approach. The results are presented in Figure 14.

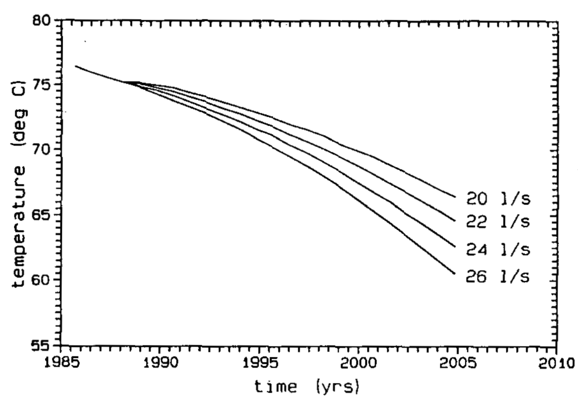

Figure 14. *Predicted changes in temperature of water produced from well 8 in the Urriðavatn field.*

CONCLUDING REMARKS

Geothermal energy is of a great economical importance in Iceland and many small low-temperature geothermal fields are utilized for space heating. The emphasis on geothermal reservoir engineering has increased steadily since the early 1980's. In this paper the reservoir engineering work carried out concurrent with the utilization of small low-temperature geothermal areas in Iceland has been discussed. A few examples were also presented; two involving short-term well tests, two involving longer-term interference and buildup tests and finally two examples involving monitoring and simple modeling.

Most of the small low-temperature reservoirs utilized in Iceland respond to production by water level changes and simple lumped models have been used successfully to simulate their response. A method described by Axelsson (1989) has to date been used to simulate response data from 10 small low-temperature fields in Iceland. However, a few low-temperature fields have also responded by declining temperature. Changes in temperature can be expected in the future in most, if not all, of the small fields utilized in addition to the long-term water level changes.

The emphasis on geothermal reservoir engineering is likely to continue in the future. For the small low-temperature reservoirs the emphasis may be expected to be in the following areas:

- Continued research into *the nature of the low-temperature activity.* Great amounts of data are available on the low-temperature activity in Iceland but several questions on the nature of the activity remain unanswered.
- Continued *monitoring* of production and response histories. In a few of the small fields in Iceland monitoring is still incomplete.
- *Detailed numerical modeling* where simple modeling is insufficient. This involves natural-state modeling, well-by-well modeling and combined modeling of pressure, temperature and chemical changes.
- *Re-injection tests* including comprehensive monitoring programs. Injection may help maintain pressures and extract more energy from some of the small geothermal reservoirs in the future. But before long-term injection can be started in any of the fields careful re-injection tests need to be performed.

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