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 1980s, 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 services, 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 Reykjavik, 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 country. 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 believed 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 groundwater 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 Bovarsson'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 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.

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

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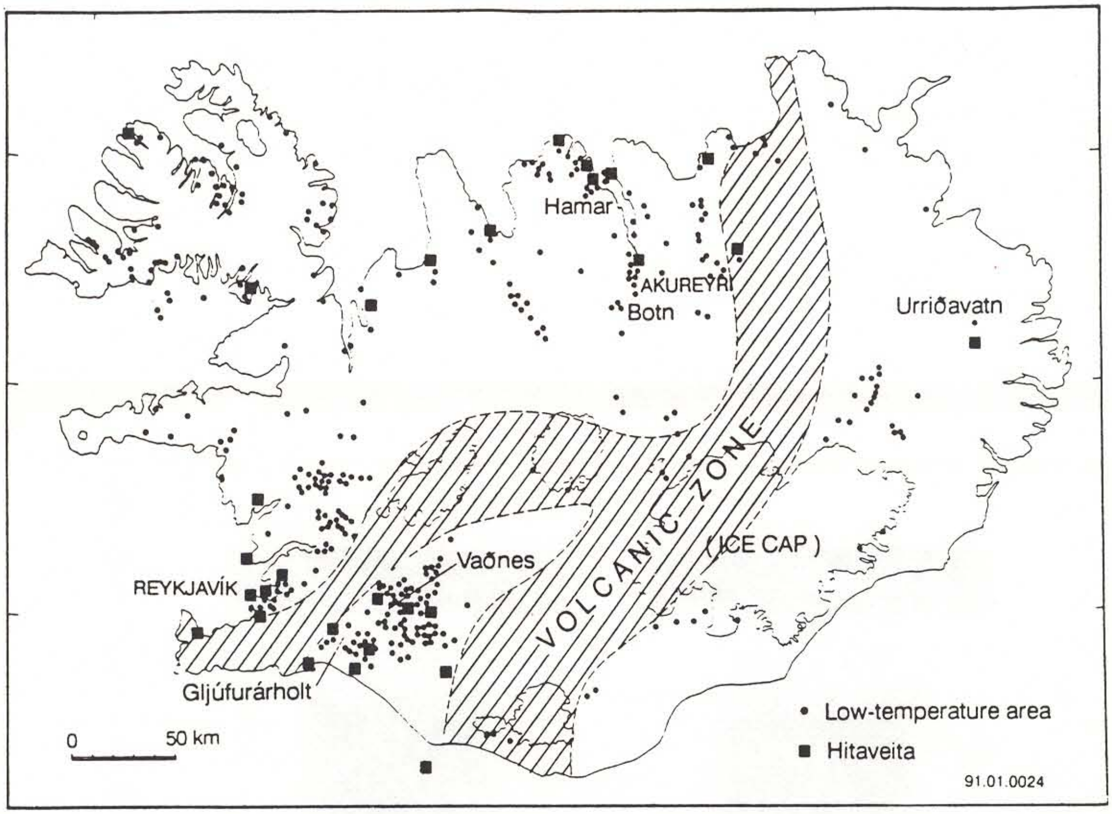

Figure 1. Low-temperature hydrothermal areas and public *hitaveitur* (district heating services) in Iceland.

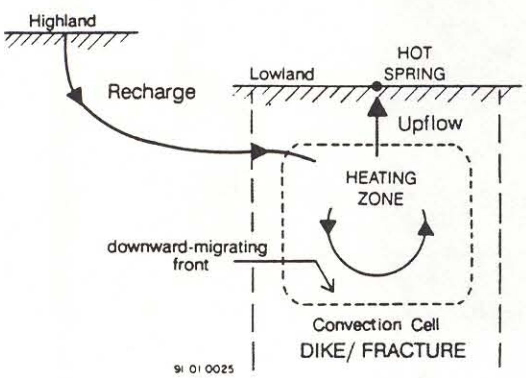

Figure 2. Model of a low-temperature system in Iceland. Based on Bodvarsson (1983).

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.

RESERVOIR ENGINEERING STUDIES

Regular reservoir engineering studies of geothermal fields in Iceland started in the mid-1960s (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* 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 1980s. By that time, more than 80% of the population enjoyed heating by geothermal energy, and the latest public *hitaveitur* 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 (Sigurdsson, et al., 1985). In many cases, the potential of a reservoir turned out to be less than previously believed 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 acquired 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 (>500 m) 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 well(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 reservoirs 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 are presented in the complete paper, but will not be detailed here. The examples are from the following areas: Vadnes and Gljúfurárholt in SW-Iceland which are utilized by the surrounding farms and vacation homes. Urridavatn in E-Iceland utilized by the Egilsstadir *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.

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 1980s. In the complete paper, the reservoir engineering work carried out concurrent with the utilization of small low-temperature geothermal areas in Iceland is discussed. A few examples are also presented: two involving short-term well tests, two involving longer-term interference and build-up 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 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 test* 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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