EXPERIENCE OF EXPLOITING ICELANDIC GEOTHERMAL RESERVOIRS

Omar Sigurdsson

Orkustofnun, Grensasvegur 9, 108 Reykjavik, Iceland

Snorri P. Kjaran

Vatnaskil Consulting Engineers, Armuli 11, 108 Reykjavik, Iceland

Thorsteinn Thorsteinsson, Valgardur Stefansson and Gudmundur Pálmason

Orkustofnun, Grensasvegur 9, 108 Reykjavik, Iceland

ABSTRACT

Geothermal reservoir engineering studies have been pursued for years in Iceland, concurrently with the utilization of the various geothermal fields. This has been essential in order to understand the responses of the reservoirs to exploitation, and to sustain and increase their production to meet a growing demand. The importance of geothermal energy has grown steadily in the past decades relative to other primary energy resources, providing at present about 40 percent of the total energy consumed in Iceland. In this article the mature experience gained from exploiting Icelandic geothermal reservoirs is reviewed. The geological setting of the hydrothermal systems is described as well as its relation to the axial rift zones, which constitute the land expression of the Mid-Atlantic Ridge rifting system. Several field examples are presented, demonstrating the effects that exploitation has on temperature and pressure in the reservoirs. Some effects of volcanic activity on the geothermal reservoirs are discussed. Such influences are unavoidable where the geothermal potential depends on magma as a heat source. Recent reinjection field experiments and their effects on the characteristics of production wells are described.

INTRODUCTION

Exploration of geothermal resources in Iceland can be said to have started in August 1755, when a 4.2 m deep well was drilled close to a thermal spring in what is now known as the Laugarnes field (Stefansson, 1980). Much earlier, or at the time of settlement in 876 A.D., the thermal springs in this same field had influenced the choice of the name Reykjavik for this area, which today is the capital of Iceland. After a long hiatus the first commercial wells in Iceland were drilled in the Laugarnes field in 1928. In 1930 a district heating service was initiated in Reykjavik, utilizing water issuing from the Laugarnes field for heating about 70 buildings, including a school house and a public swimming pool. In the 1940s the Reykjavik heating system was expanded considerably with the exploitation of the Reykir geothermal field about 17 km away from the city. Rapid development followed, especially after the impetus given by the increase in oil prices during the 1970s. At that time other uses began to emerge although the main emphasis was on space heating (Gudmundsson, 1982, 1983a).

Today, geothermal energy plays a large role in the energy economy of Iceland. The total annual geothermal energy consumption in Iceland is about $30 \cdot 10^{15}$ Joule. This constitutes about 40 percent of the total energy sold to users. In terms of oil equivalents the fraction is 27 percent (Orkustofnun Annual Report, 1982).

The geothermal potential of the high-temperature fields in Iceland, taking into account accessibility and recovery factors, is estimated to be 10^{20} Joule (Palmason, 1980). This assessment makes no predictions of the economical feasibility or the rate at which the energy can be withdrawn.

The exploration and research carried out in conjunction with the exploitation of the various geothermal fields has vastly deepened the understanding of the hydrothermal systems in Iceland. They have proved to be more diverse with respect to physical state, chemical composition, hydrological properties and geological control than previously thought. Some aspects of the developments of the Icelandic geothermal fields have been presented by Palmason and others (1983). In the present paper the experience from exploitation of geothermal fields in Iceland is reviewed. The main emphasis will be on the effects of exploitation on the reservoirs.

GEOLOGICAL FEATURES AND HYDROTHERMAL SYSTEMS

Iceland lies astride the Mid-Atlantic Ridge. The axial rift zones, which are divided into two parallel branches in southern Iceland (Figure 1), constitute the surface expression of the ridge. The western branch connects with the Reykjanes Ridge in the southwest. The axial rift zones are characterized by several fissure and fault swarms, most of which pass through a central volcano. Some of these have developed calderas (Saemundsson, 1978). The axial rift zones are flanked by Quaternary volcanics, characterized by sequences of subaerial lava flows intercalated by hyaloclastites and morainic horizons at intervals corresponding to glaciations. The Quaternary formations are flanked by Tertiary subaerial flood basalt sequences in the east, west and north of Iceland. The strata, which generally dip towards the active volcanic zones, reflect continuous volcanic activity and crustal spreading during the last 15 million years at least.

Like other constructive plate margins, the axial rift zones are characterized by a generally high, but variable heat flow. The mean heat flow falls gradually with increasing distance away from the rift zones. The thermal gradient in Iceland increases fairly regularly towards the volcanic zones from about 50°C/km in Tertiary rocks 100 km from the zones to about 165°C/km in early Quaternary rocks some 20 km from the axis (Palmason, 1973). Due to cold water circulation in the youngest strata within and close to the axial rift zones, a trend opposite to that of the regional surface gradient is observed locally.

Hydrothermal activity is widespread in Iceland. The thermal areas are usually divided into two groups on the basis of the subsurface temperature in the geothermal system (Bodvarsson, 1961). By definition, the base temperature is higher than 200°C in the high-temperature areas, but lower than 150°C in the low-temperature areas.

The high-temperature areas are confined to the active volcanic zones, principally the axial rift zones, and are thought to draw heat mainly from local accumulations of igneous intrusions cooling at a shallow level in the crust. To date, 28 potential high-temperature areas have been identified in Iceland (Saemundsson and Fridleifsson, 1980). The common surface manifestations are fumaroles, steaming ground, boiling mudpools and thermally altered ground. Some of these areas are largely covered by glaciers. Isotope studies indicate that the fluid in the high-tempera-

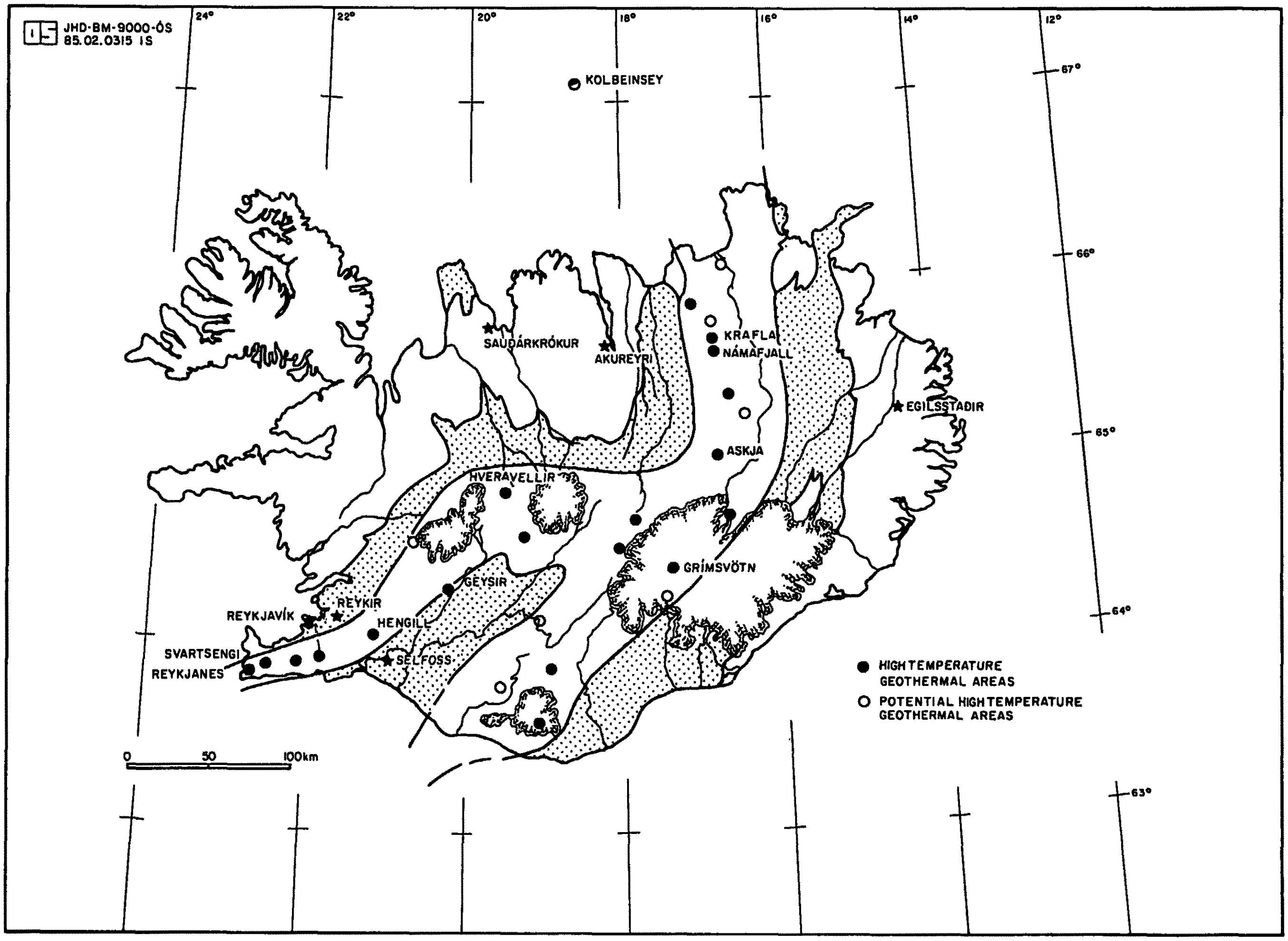

Figure 1. A map of Iceland showing the location of the high-temperature geothermal areas within the axial rift zones, the Quaternary formations (shaded), and some of the low-temperature areas (stars)

ture systems is mainly local water, related to precipitation that has fallen in the vicinity of the field (Arnason, 1976).

The low-temperature areas are found predominantly in valleys or other topographical lows with the major areas located on the flanks of the volcanic zones in Quaternary formations, but smaller areas are found almost all over the country. The surface manifestations are thermal springs. Over 600 thermal springs have been recognized in about 250 localities. The springs are characterized by hot water with temperature varying from a few degrees above the mean annual temperature up to 100°C. The flow rate varies from a trickle up to a maximum of 180 l/s from a single vent. The water in the low-temperature areas originates as rain falling in the highlands. It percolates deep into the bedrock and flows laterally along permeable dikes, faults, fractures and horizons in the upper part of the crust, driven by a density difference and the hydrostatic gradient. The water may flow for long distances (>100 km) before it ascends to the surface, often along faults and dikes, in valleys in the lowlands (Einarsson, 1942). On its way, the water draws heat from the surrounding rock. This heat is furnished by the high regional heat flow. The temperature of the water depends on the depth of the main flow paths and the flowing time.

During the last decades, Schlumberger and dipole-dipole equatorial resistivity soundings have been the most powerful geophysical tools for geothermal exploration and reservoir delineation in Iceland. The resistivity soundings in combination with detailed geological mapping are used for siting exploration and development wells in both high- and low-temperature geothermal fields. Other frequently employed exploration methods in high-temperature fields include aeromagnetic surveys, seismic surveys, and particularly, geochemical analyses of springs and fumaroles to identify potential upflow vents (Bjornsson and Hersir, 1981; Armannsson, Gislason and Hauksson, 1982). In low-temperature fields the emphasis has been more on ground magnetic surveys and, in recent years, on head-on resistivity profiling to detect near vertical water bearing structures, such as dikes and fractures (Flovenz and Georgsson, 1982; Cheng, 1980).

PRESSURE EFFECTS DUE TO EXPLOITATION

Reservoir Evolution

Geothermal energy in Iceland is primarily used for space heating. Most of the (mainly low-temperature) geothermal fields exploited by the district heating services had natural discharge to the surface at the time of their discovery. The natural discharge from the thermal springs in some of the fields was large enough to be collected in a cistern and piped to the users, thereby establishing a district heating service. Where demand for geothermal energy was in excess of what the natural discharge supplied, shallow wells (< 600 m) were drilled. In fields with natural discharge the wells increased the rate and the temperature of the discharge. In many cases, the free flow from the wells met the requirements of the heating services, and in some fields it still does. Where demand had exceeded the natural recharge, free flow from the fields diminished, and down hole pumps had to be installed. This, in turn, required deeper, larger diameter wells to exploit deeper aquifers so that a growing demand could be met in spite of increasing drawdown of the piezometric surface.

A classical example of the evolution of a typical low-temperature field in Iceland is the Reykir field. The Reykir field is about 17 km from the city of Reykjavik and has been the principal source of thermal water for the Reykjavik Municipal District Heating Service since 1944 (Figure 2). Prior to 1933, when exploratory drilling began at Reykir, a natural discharge of 120 l/s was estimated from the thermal springs in the field (Barth, 1950). By 1955 the extraction rate from the field had been increased to 360 l/s as a free flow from 69 shallow, narrow-gauge wells (Thorsteinsson, 1975). In 1970, when a redevelopment program for the field was initiated, the flow rate had diminished to an estimated 300 l/s. During the period 1970 to 1977, 37 large-gauge wells of 800 to 2040 m depth were drilled. The well completions were of the open hole type with production casing diameters up to 13 ⅜" (200 m) and hole size up to 12 ¼" to 1400 to 1600 m. Improved productivity characteristics are attributed to the larger diameter wells. The production history for the field after 1970 is shown in Figure 3. The increased production with pumping had eliminated the free flow from the older wells by 1975, but in 1983 the average annual discharge had reached 982 l/s. This is an increase of about 700 l/s compared to 1970, resulting in about 70 m drawdown from the relatively steady-state level in 1970.

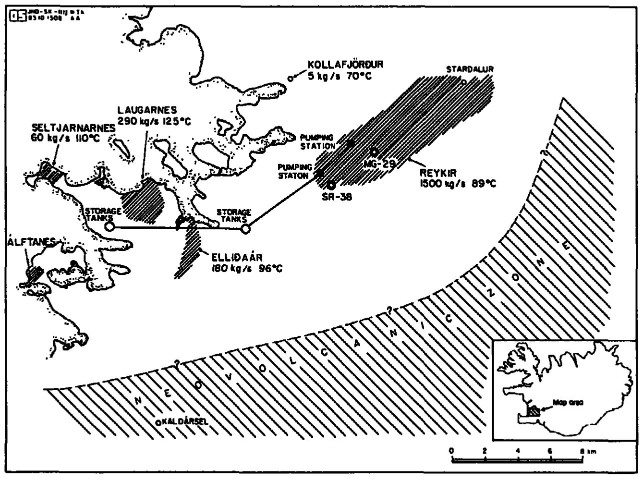

Figure 2. The low-temperature fields in Reykjavik and vicinity

Another example, but from a less developed field, is presented in Figure 4. The figure shows the changes in the discharge from the Saudarkrokur field (Ashildarholtsvatn) in the Skagafjordur valley in northern Iceland. When exploration drilling started there in 1948, the only surface sign of thermal potential was a tepid pit with a negligible discharge. A free flow of approximately 20 l/s was obtained, and maintained until 1965, by the drilling of eight

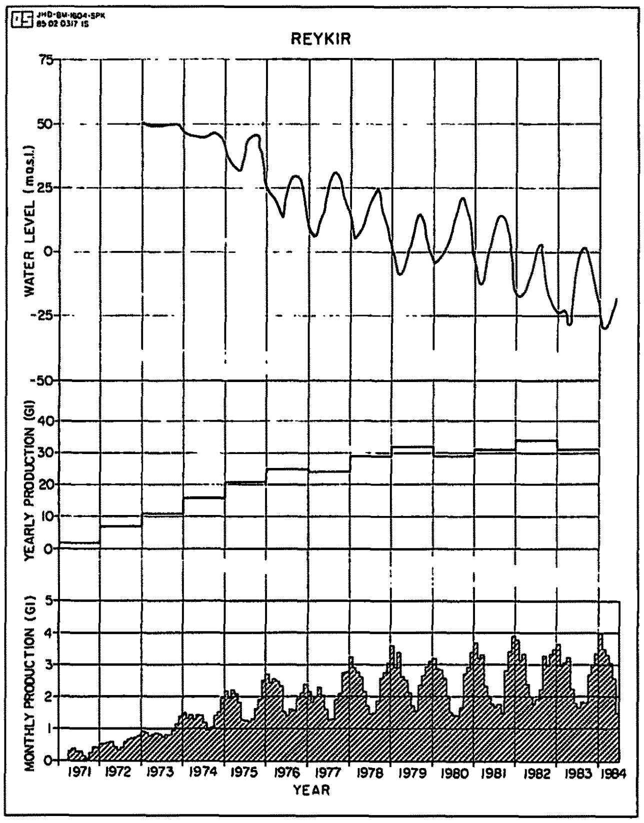

Figure 3. Production and drawdown history of the Reykir field from 1970

shallow wells 34 to 157 m). The sawtooth behavior of the discharge in Figure 4 shows how the free flow from the field was increased by the additional drilling of five deeper wells(379 to 669 m), and how, between drilling operations, the flow rate declined due to decreasing reservoir pressure (Thorsteinsson, 1984). To boost production from this field further, the drilling of a large diameter well is necessary as is the installation of pumps. Those measures could double the production, but the free flow would cease completely.

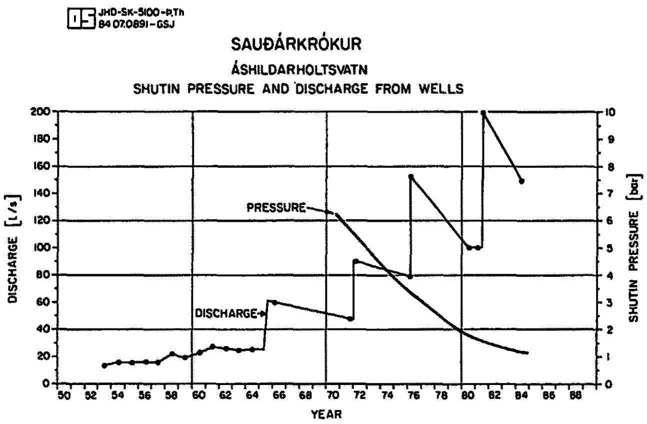

Figure 4. Discharge history and pressure decline of the Saudarkrokur low-temperature field

Initial Reservoir Responses

The pressure response of the reservoir to the initiation of production differs from one field to another. Two distinctive types of behavior are most frequently encountered, however. One type represents an infinite acting system and the other system of fractures or linear structures. The early response lasts until the limits of the reservoir are felt. It usually gives considerably higher transmissivities in the vicinity of the production area than the longer term production yields, which depends on the global response.

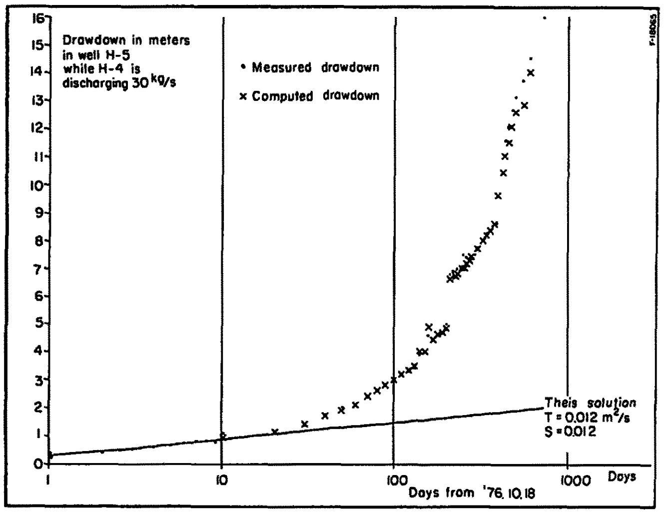

Figure 5. Early drawdown in well 5 at the Svartsengi field plotted vs. the logarithm of time

Figure 5 shows the drawdown behavior of the Svartsengi field on the Reykjanes peninsula from the start of production. The early response, which lasts for about 30 days, follows Thesis solution for infinite acting systems. After that, the boundaries of the field are felt. They control the long-term drawdown behavior of the field. The early effects indicate a transmissivity coefficient of 0.012 m^2/s and a storage coefficient of 0.012 (Kjaran and others, 1979).

Another example is shown in Figure 6. It shows the early drawdown in the Ytri-Tjarnir field adjacent to the Laugaland field in northern Iceland. The approximate proportionality of the drawdown to the square root of time indicates that the flow is mainly along fractures, in good agreement with what is expected on the basis of the geological structure in that area.

Reservoir Capacities

The production capacity of a reservoir depends on the global physical properties of the system. The limiting parameters are the global fluid transmissivity, the formation storage, and the recharge to the system. In its early state, a reservoir may behave like an infinite system for some limited period of time. This period depends on the extent of the production from the reservoir, being longer when the production is small in comparison with the potential of the reservoir. In Iceland such fields still exist, basically in areas with a small population (Stafholtstungur).

In the more populated areas, the demand for energy has brought the development of the fields to a stage where the limiting effects govern the reservoirs' responses.

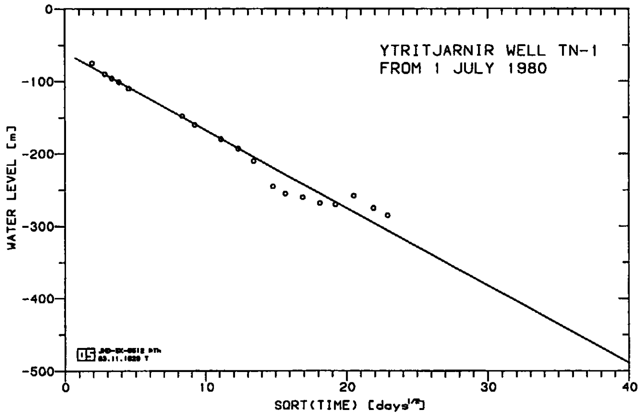

Figure 6. Early drawdown in the Ytri-Tjarnir field showing an approximately linear variation with the square root of time. The deviations from the line are due to changes in flow rate

A description of the developments in the Reykir field has already been presented. Prior to the redevelopment of the field in 1970, its free flow production capacity had been utilized for 25 years. In 1970 the free flow was 300 l/s and had reached a relatively steady state condition, meaning that the natural recharge to the system was about the same as the amount withdrawn. With increased production, especially after 1973, the discharge from the field has exceeded the recharge, resulting in an increasing drawdown. The increased discharge rate from 300 l/s to 980 l/s has not induced recharge to the system to the same extent. For the last 5 years the annual production has been relatively constant, causing the water level in the field to fall in a pseudosteady state manner, indicating a limited resource (Figure 3). At present, the water level is at about 70 m depth in the field, corresponding to an average yield of 12 l/s/m. But by comparing the seasonal fluctuation in the amplitude for the pumping rate to the water level, a yield of up to 25 l/s/m is obtained. This high yield clearly demonstrates the ability of the Reykir field to meet large variations in the annual energy demand.

It is worth considering the water balance for the Reykir field. The cumulative production from the field over the period 1970 to 1983 is 292 gigaliters (Gl), which corresponds to about 180 Gl increase over the free flow situation. Assuming a storage coefficient of less than $5\ 10^{-3}$ results in an estimated areal extension of 500 km^2 for the reservoir. This is an area of considerable but not unreasonable size, since over 65 percent of the seasonal pressure variation in the production area is observed in a well located at a distance of more than 7 km.

Several hydrothermal systems are located in the valley of Eyjafjordur in northern Iceland. They are utilized by the town of Akureyri District Heating Service (Figure 7).The major field is the Laugaland field where exploitation started in 1976. The geology is characterized by gently dipping Tertiary plateau basalts, cut by numerous dikes, trending approximately north-south. The production horizons seem to be associated with some of the dikes and

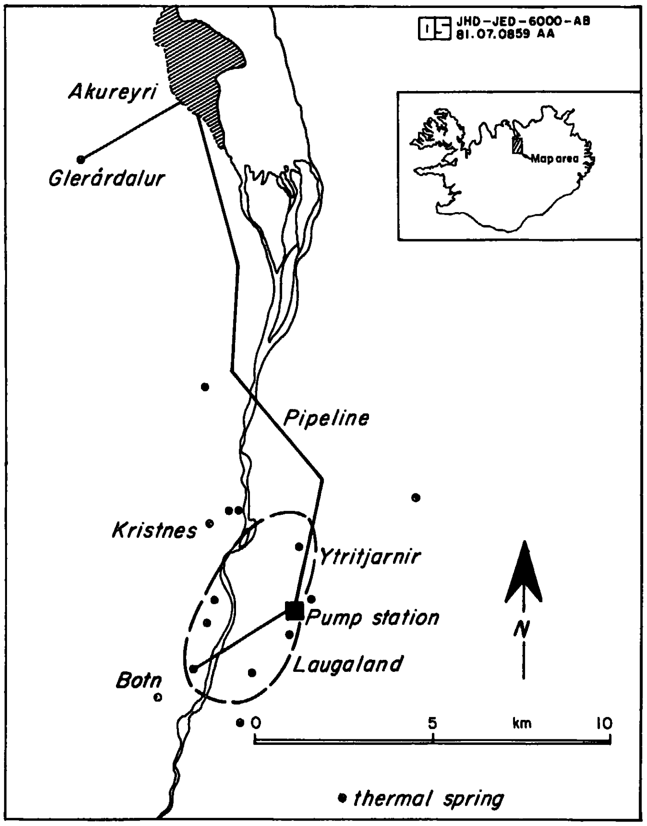

Figure 7. The low-temperature fields in the Eyjafjordur valley near the town Akureyri. The dashed curve encloses a low-resistivity area.

and with interlayers between lavas. The best horizons occur at intersections between these two kinds of permeable structures. At present 17 deep wells (1000 to 2800 m) have been sunk into the area. Of these, eight are situated at the Laugaland field, four at the Ytri-Tjarnir field, one at the Botnslaug field and four in other localities. Due to the geological nature of the region, nonproductive wells are common, bringing the success ratio down to about 50 percent for this area (Bjornsson, 1981).

Figure 8 shows the annual production rate and the corresponding drawdown of the Laugaland field. The initial reservoir corresponded to a water level of +187 m relative to the top of well LN-10, while 6 years later the level was down to about -180 m, a decline of 370 m. In Figure 9 the effects of the seasonal fluctuations in production rate have been filtered out. The agreement between the measured water level and the calculated curves for different production rates shows clearly the proportionality of the drawdown to the square root of time, indicating fracture dominated behavior of the reservoir (Flovenz and Thorsteinsson, 1984). This is typical behavior for a fractured reservoir in a rock formation of low permeability.

Phase Changes

The response of high-temperature fields to exploitation is often different from that of low-temperature fields. This difference is attributed to the change in the physical state of the fluid as the system evolves from being liquid-dominated to being vapor-dominated. While the reservoir is liquid-dominated the pressure decline is similar to that of

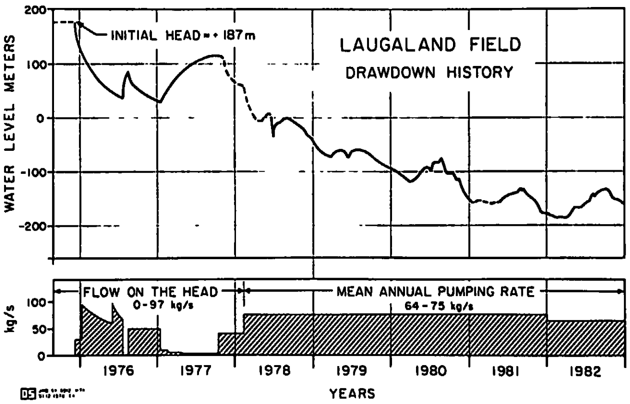

Figure 8. Production and drawdown history of the Laugaland field

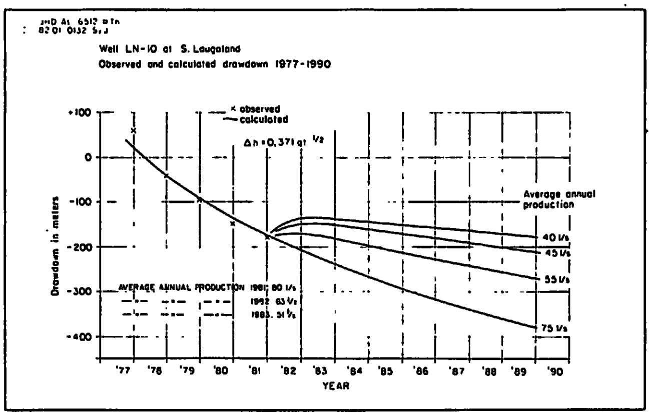

Figure 9. The mean water level of well LN-10 in the Laugaland field compared to calculated drawdown for different production rates, indicating its proportionality with the square root of time

low-temperature fields. As the pressure declines, however, boiling can occur locally, in wells or in the surrounding formation. As the boiling area grows with increasing mass withdrawal the pressure declines at a slower rate until the whole system has reached vapor saturation. Then the pressure falls rapidly to its economical limit (Bodvarsson, Pruess, Stefansson, and Eliasson, 1984).

As an example of this is the Svartsengi field located within the axial rift zone on the Reykjanes peninsula. Exploratory drilling began in 1970, but the field has been in production since 1976 (Thorhallsson, 1979). Eleven production wells and one reinjection well have been sunk into an area of about 1.5 km^2 to depths of 240 to 1998 m (Figure 10). The hydrothermal system in its natural state is liquid-dominated with a reservoir temperature of 240°C. The geothermal fluid is a brine with salinity 2/3 that of seawater. The brine, which is primarily utilized for domestic heating by several communities on the peninsula, is exploited by means of heat exchangers.

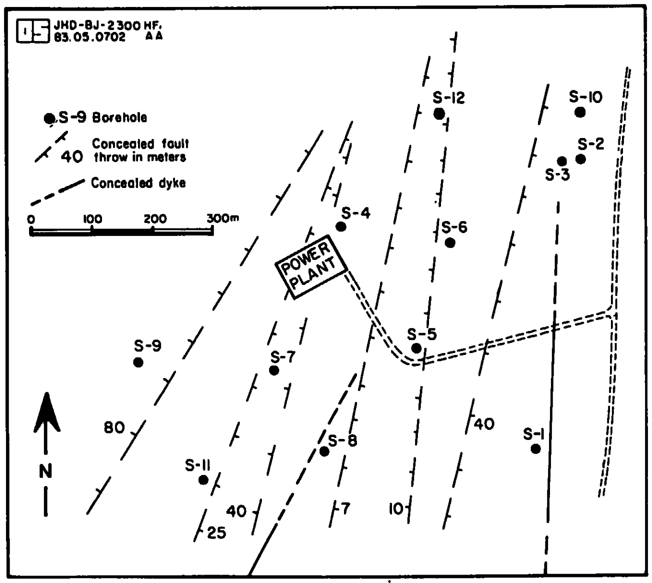

Figure 10. Location of wells, faults (exact projection uncertain) and dykes at the Svartsengi field

The production history and pressure decline of the field is shown in Figures 11 and 12. The annual production has been steadily increasing, reaching about 8.7 million tons in 1982. The cumulative production is 28 million tons. At present there is no indication of a recharge to the field, and with the present production of 300 kg/s a drawdown of

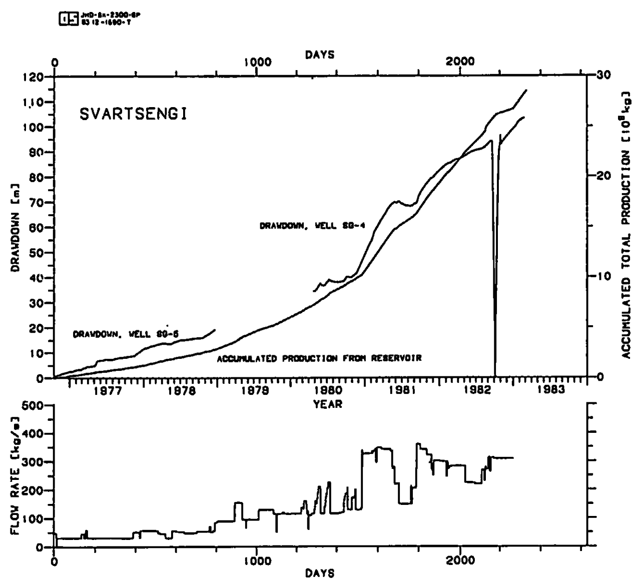

Figure 11. Production and drawdown history of the Svartsengi field

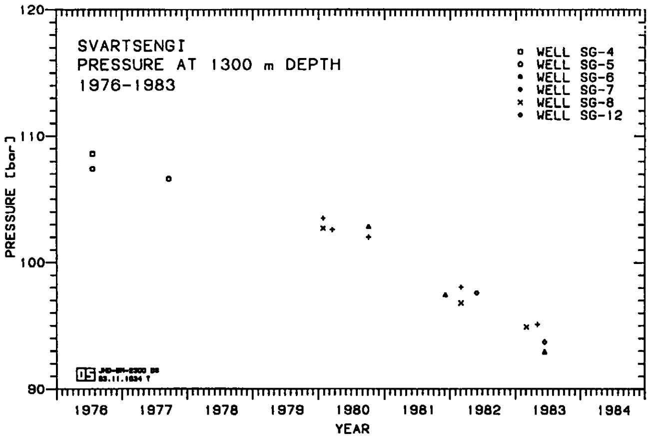

Figure 12. Downhole pressure measurements in the Svartsengi wells

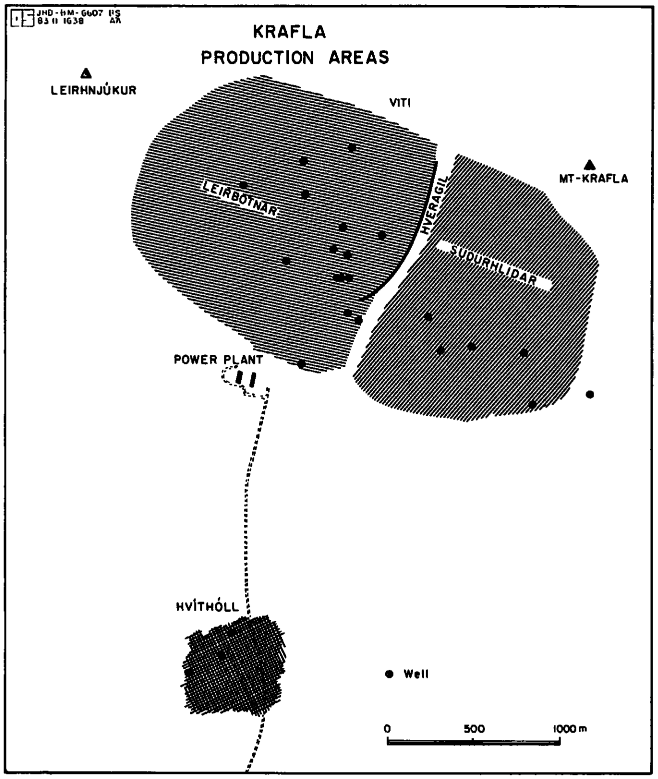

Figure 13. Production areas of the Krafla field, also showing the distribution of wells. Leirhnjukur, on the eruptive fissure swarm, is in the upper left hand corner.

250 m will be reached in 15 years. A quarter drawdown is not desirable due to calcite deposition, which is preferably kept inside the production casing (600 m). A lumped parameter model that simulates the production history has been constructed (Kjaran and others, 1979). It gives a reservoir area of 23 km^2 and an estimate of 0.012 for the storage coefficient. The high value for the storage coefficient indicates a free surface effect rather than elastic storage. This suggestion is strengthened by evidence of an incipient steam cap in the main production area, allowing free surface storage at the boiling surface.

The Krafla high-temperature field is another example. Development of the Krafla field, which is located on the axial rift zone in northeastern Iceland, started in 1974 (Stefansson, 1981). To date, 23 wells have been drilled in three drilling areas, called Leirbotnar, Sudurhlidar and Hvitholar. Their locations in relation to the power plant are shown in Figure 13.

In the Leirbotnar field, pressure, temperature, and chemistry data indicate the presence of two reservoirs. The upper one contains only liquid water, but the deeper one is a two-phase reservoir with temperatures and pressures corresponding to the boiling curve with depth. These reservoirs are separated by a confining layer at a depth of 1100 to 1300 m. This division into upper and deeper reservoirs does not extend across the Hveragil gully, and in the Sudurhlidar field only the two-phase liquid-dominated reservoir seems to be present. The reservoirs in the Leirbotnar-Sudurhlidar fields seem to be connected near the Hveragil gully (Bodvarsson, Benson, Sigurdsson, Stefansson, and Eliasson, 1984). The area tested in the Hvitholar field shows an inverted temperature profile and is liquid dominated.

Production characteristics of wells tapping a two-phase reservoir differ greatly from those of a single-phase reservoir. An example is given by well KJ-14 in Krafla (Figure 14). It shows that it may take weeks for the flow and enthalpy to stabilize. The reason is that in two-phase reservoirs a large local drawdown is created around the well, and this drawdown propagates very slowly into the reservoir due to the high compressibility of the two-phase system. When stable conditions are reached, the flow rate and enthalpy remain relatively constant. This is also reflected in the delivery curves, which contrast sharply with similar curves for single-phase reservoirs. As shown in

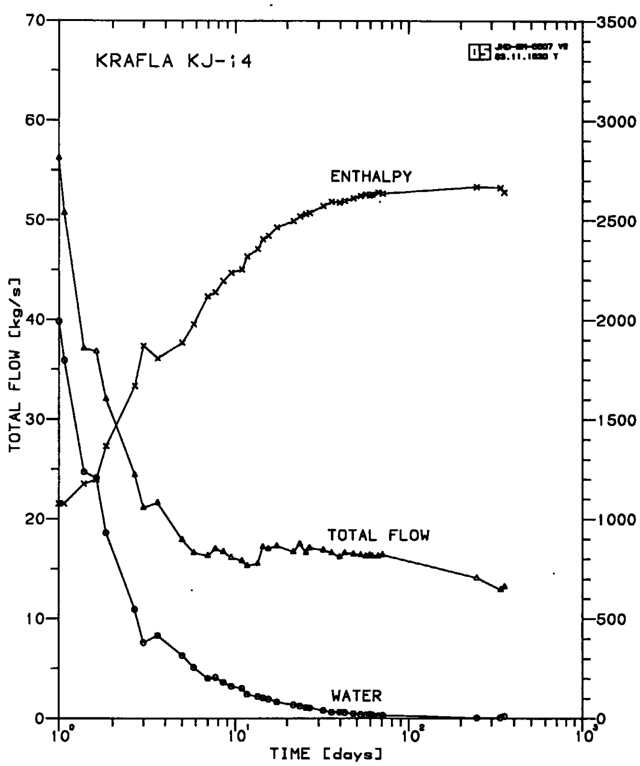

Figure 14. Production history of well KJ-14 in the Krafla field

Figure 15 the flow is almost independent of the wellhead pressure. The enthalpy, however, is usually high, in the range 2000 to 2700 kJ/kg. A peculiar behavior is found for well KJ-11 (Figure 15), which is open to both the upper and deeper Leirbotnar reservoirs. At low wellhead pressures the upper, single-phase water zone controls the flow, giving a delivery curve that changes considerably with wellhead pressure. At higher pressures, the deeper feed zone is activated, resulting in flow that is almost independent of wellhead pressure.

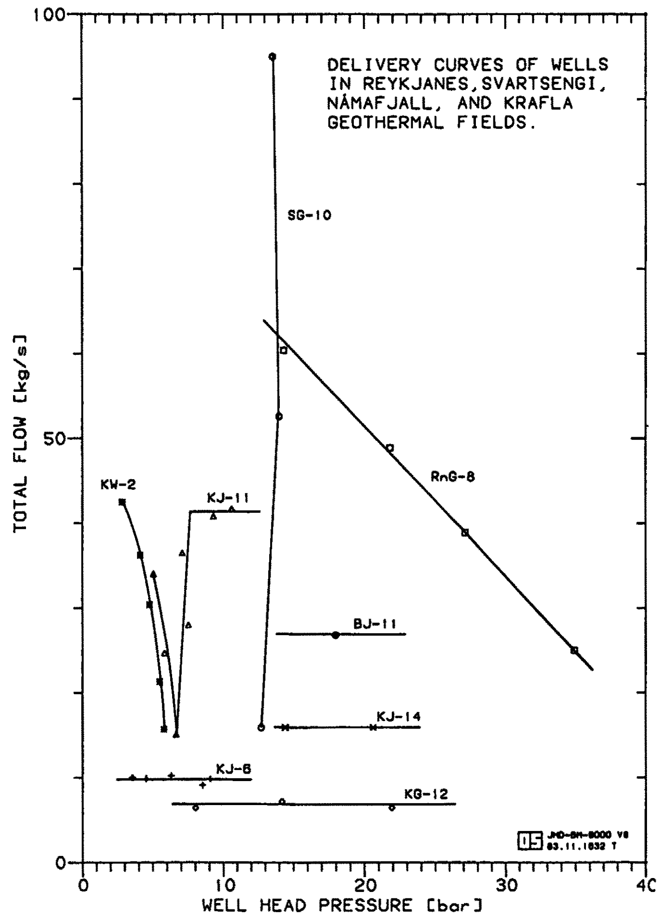

Figure 15. Delivery curves of wells in the Krafla (KW-2, KJ-6, KJ-11, KG-12, KJ-14) and the Namafjall (BJ-11) fields. For comparison two wells from the Svartsengi (SG-10) and the Reykjanes (RnG-8) fields are shown.

An opportunity for a pressure recovery test of the Leirbotnar and the Sudurhlidar fields presented itself in 1984, when production from most of the wells in the fields was discontinued for 3 months. The buildup test revealed the flow capacity behavior of the wells and gave a fieldwide estimation of the reservoir pressure. It indicated that no measurable drawdown had occurred after 3 years of production in the Sudurhlidar reservoir. A localized drawdown of 5 bars was, however, estimated for the deeper Leirbotnar reservoir after 7 years of production (Sigurdsson, Steingrimsson, and Stefansson, 1985). This is in agreement with theory, that a very small pressure decline is observed in reservoirs while they are in two-phase condition and pressure is maintained by boiling.

THERMAL EFFECTS DUE TO EXPLOITATION

Effects of Cold Water Recharge

Due to the nature of geothermal systems in Iceland, many geothermal fields show evidence of recharge whose rate may even approach that of the production itself. The temperature of the recharging fluid is usually lower than that of the initial reservoir fluid. The recharge thus cools the reservoir and lowers the energy content of the fluid produced. If the recharging water reaches the wells quickly, the useful life of the reservoir may be shortened appreciably. This is expecially noticeable in small fields that show considerable recharge. On the other hand, if there is a relatively long time lag between the entrance of the recharging fluid into the system and its subsequent discharge by the wells, the useful life of the reservoir may be increased so as to exceed that of a closed reservoir. Reinjection of spent fluid is one form of recharge that is mainly aimed at maintaining the pressure in the geothermal system, while at the same time disposing of the fluid.

The Ellidaar low-temperature field is an example of how cooling takes place in a geothermal reservoir. The Ellidaar field, located inside Reykjavik, is relatively small. It was discovered in 1967, when the first well was drilled there (Figure 2). The field has since been one of the sources of thermal water for the Reykjavik Municipal District Heating Service. Figure 16 shows the production and drawdown history of the field. At the end of 1981 the annual discharge by pumping had reached 4 Gl and the cumulative production from 1968 was 50 Gl. A drawdown of 105 m from the 1968 level was observed, corresponding to a yield of 1.25 l/s/m. When compared to the 25 l/s/m for the Reykir field mentioned above, this indicates how much less the Ellidaar field is able to meet large variation in the annual energy demand. A unit response function representing the drawdown is shown in Figure 17. It indicates that a steady state has been reached. Thus the production has induced a recharge into the field equaling the current

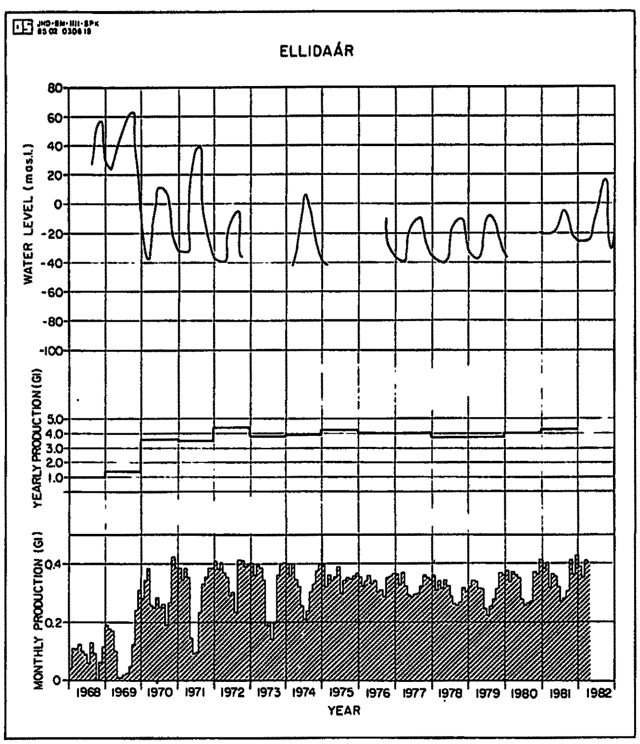

Figure 16. Production and drawdown history of the Ellidaar field

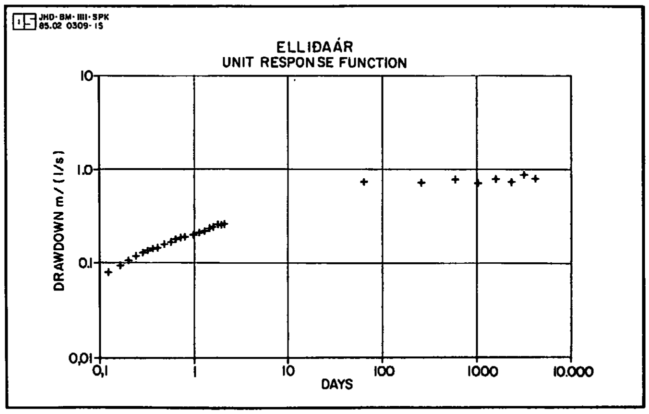

Figure 17. A unit response function for the Ellidaar field, showing that it has reached a relatively steady-state condition

production rate. The recharge water is cold and has cooled the reservoir as indicated in Figure 18, which shows changes in chemistry and temperature of the produced fluid.

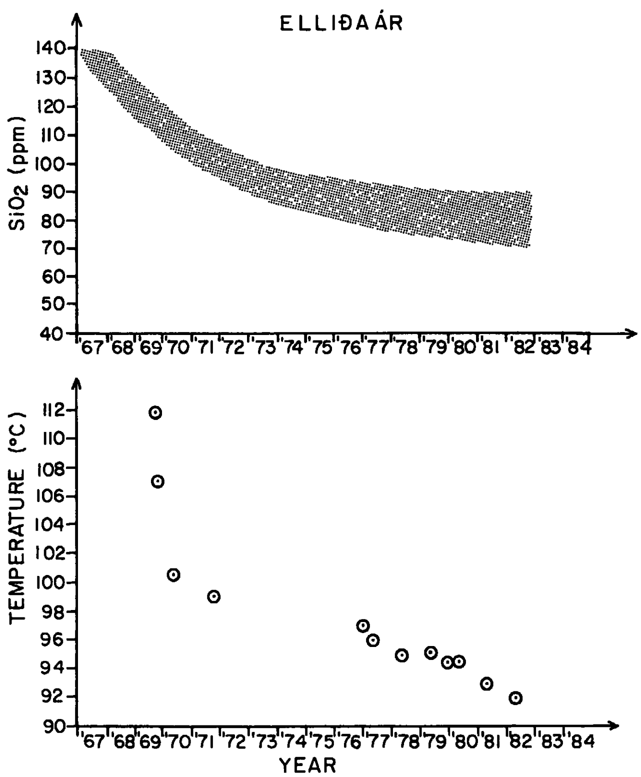

Figure 18. Temperature and chemical changes in the Ellidaar field

The Urridavatn low-temperature field in the Tertiary plateau basalt of eastern Iceland also provides a good example of cooling. It is utilized for district heating in the nearby town of Egilsstadir. Surface manifestations of thermal activity were limited to gas bubbles emanating from the bottom of lake Urridavatn through holes in the winter ice (Einarsson and others, 1983). The strata, which dip gently (4 to 6 degrees) to the southwest are traversed by a fissure and fault swarm of an ancient central volcano to the south, which was active about 8.5 million years ago.

After the drilling of two very shallow exploratory wells in 1963 and a deeper one in 1975, the first production well was sited out in the lake and drilled to a depth of 1600 m in 1978. Producing zones were encountered at the shallow depths of 150 to 300 m and well tests indicated a leakage into this aquifer. Production of 65° C water at the rate of 12 l/s began in late 1979, and a year later a second well producing 13 l/s at 55° C was brought into operation. Temperature remained stable at first, but soon a decrease in the concentration of dissolved chemicals, especially chloride, heralded imminent cooling of the thermal water (Figure 19). The rate of cooling was 2° C/year at first, but had increased to 4° C/year in 1981-1983 (Benjaminsson, 1984).

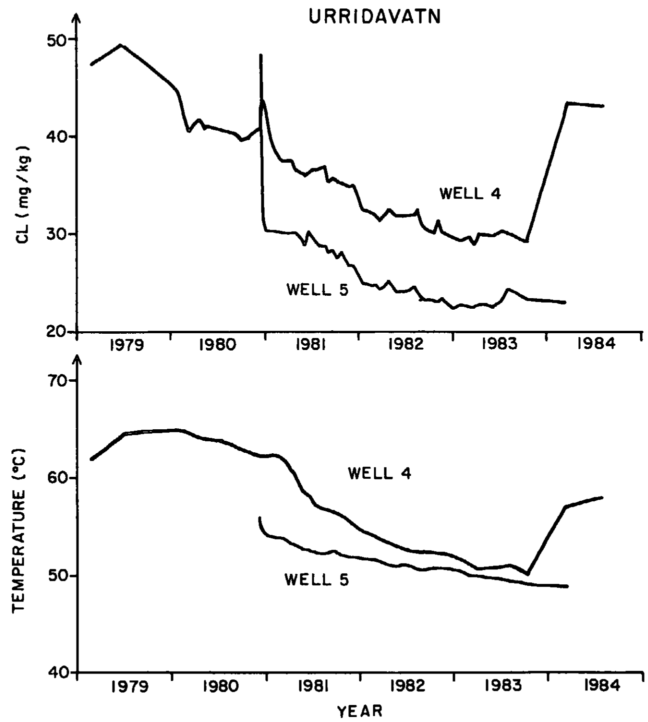

Figure 19. Variation of temperature and chloride content of water from wells 4 and 5 in the Urridavatn field

A tracer survey done by depositing fluorescein dye on the lake bottom in the vicinity of the production wells confirmed leakage through the lake bottom to the shallow producing aquifer within 50 hours (Benjaminsson, 1985). A head-on resistivity survey indicated the presence of a near-vertical geological feature of anomalously low resistivity striking northeast below the lake bottom. This geological feature, assumed to be a fractured zone was subsequently intersected by a new well at 600 to 900 m depth. Production capacity of the new well is 30 l/s of 76°C water. During its first year of production the temperature and the chemical composition of the water have remained stable.

Effects of Boiling

Boiling in geothermal wells or reservoirs occurs when exploitation has reduced the pressure down to the boiling point pressure for the prevailing temperature in the system. Geothermal systems in their natural state can also be two-phase, with temperatures and pressures corresponding to the boiling point curve with depth. The boiling will initiate convection in wells or segregation in reservoirs and heat the column above the boiling surface until the temperature reaches the boiling point everywhere. This is especially true where the boiling water temperature is above 235 °C, the temperature of maximum enthalpy for saturated steam (Stefansson and Bjornsson, 1982). The enthalpy of the boiled two-phase water is higher than that of the source water. This means that in order to sustain boiling, heat must be extracted from the remaining water and the reservoir formation, which in turn are cooled.

Boiling has a pronounced effect on the discharging behavior of wells. Some of the main features are displayed in Figure 20 for the Namafjall field and in Figure 14 for the Krafla field. The discharge history may be divided into two different stages (Stefansson and Steingrimsson, 1980). In the first stage, which covers the first weeks of discharge, the water phase decreases continuously, whearas the steam flow is fairly constant. This occurs while the water level is being drawn down in the vicinity of the well. The accompanying increase in enthalpy is a consequence of the different mobilities of the steam and water phases in the two-phase reservoir, and of nonadiabatic flashing in the vicinity of the well. Further development of the well seems to depend on whether the water flow decreases to zero or not. If it does, the second stage is characterized by a nearly constant total discharge and enthalpy (Figure 14). Figure 20 shows the other case. Here the water flow from well BJ-11 has stabilized at a nonzero value in the second stage, but the steam flow and enthalpy are increasing. Similar behavior is also observed in well NG-6 in the Nesjavellir field. The increase in flow rate is attributed to increased permeability in the rock matrix close to the well due to thermal contraction. Temperature logs taken after discharge have demonstrated a drop of more than 100° C from the undisturbed formation temperature in the two-phase production zone.

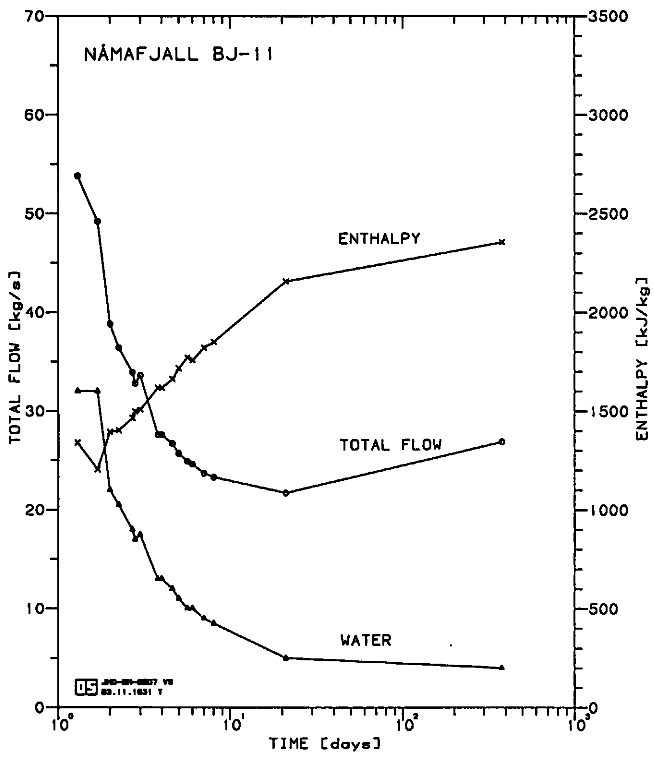

Figure 20. Production history of well BJ-11 in the Namafjall field

Sporadic Cooling

Sporadic changes are changes that occur suddenly and irregularly in a considerable part of the hydrothermal system, and whose effect diminishes with time. They are very often consequences of geological events, such as earthquakes or volcanic eruptions. The effect on the hydrothermal system may be cooling, heating, and changes in chemistry and pressure. Examples of all these phenomena are available and some will be discussed below.

In September 1977 a rifting episode with associated earthquakes occurred in the fissure swarm crossing the Namafjall high-temperature field. This event caused disturbances of the geological strata, opening of fractures, and movements along faults. The opening of fractures up to the surface released pressure from the hydrothermal system, resulting in boiling that cooled the geothermal system down to depth of at least 500 m.

The temperature logs from well SG-11 in Svartsengi provide another example of cooling. Figure 21 shows that a cooling of 12°C occurred between two consecutive measurements, but in a later measurement the temperature had recovered to its previous level. The cause of this is not known, but it is speculated that tectonic events in the axial rift zone may have led to the opening of fractures, causing a burst of cold water to enter the system.

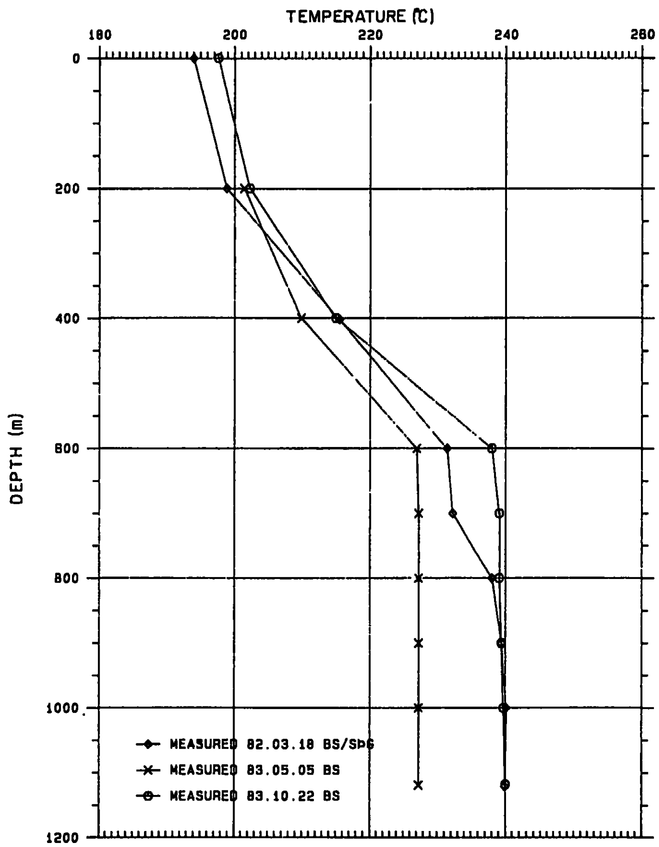

Figure 21. Temperature changes in well SG-11 in the Svartsengi field

An interesting phenomenon is a pressure pulse that was observed in well KG-5 in the Krafla field at the beginning of a volcanic eruption about 3 km away (Figure 22). A few other pulses have been observed in this well, which is mainly open to the upper single-phase Leirbotnar reservoir. They are believed to have been caused by flashing in the confined reservoir, when magma rose from the magma chamber up to the surface, resulting in a response that is similar to an instantaneous point-like pressure change (Sigurdsson and Tiab, 1983). These pulses were not observed in the two-phase reservoir due to the high fluid compressibility.

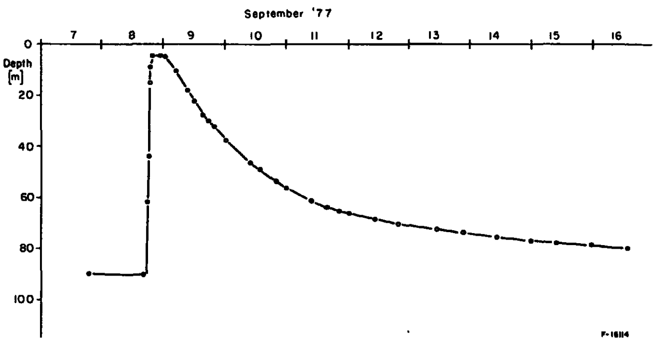

Figure 22. A pressure pulse in well KG-5 in Leirbotnar caused by volcanic activity about 3 km away. The vertical scale shows depth to the water level.

Indication from Chemical Effects

Changes in the chemical composition of the fluid issued from geothermal reservoirs are often an early indicator of important future developments. Many of these are undesirable for the utilization of the hydrothermal system but can, in some instances, be rectified or delayed with changed production strategy or different completion techniques.

An example is the Seltjarnarnes low-temperature field, located 3 to 4 km west of the Laugarnes field (Figure 2). Six wells have been drilled in the field, 860 to 2700 m deep, three of which are currently used for district heating. The peak pumping rate is 60 kg/s and the reservoir temperature is 80 to 125°C. The water is distinctly more mineralized than the water in the nearby Laugarnes field, originally containing about 1600 ppm total dissolved solids, including 570 ppm chloride. In recent years, the salinity of the water pumped from the Seltjarnarnes field has increased considerably (Figure 23), while the temperature has remained constant. A possible explanation of this is that mixing with a few percent of seawater is taking place. This can therefore be an early sign of a cooling in the reservoir that will become more noticeable in the future.

The thermal water in the Selfoss low-temperature field, situated in south Iceland, has a relatively high chloride content, 430 to 520 ppm (Figure 24). The chloride is believed to originate in sediments laid at the time the area was covered by the sea in the early postglacial period (Tomasson and Halldorsson, 1981). Exploitation of the field started in 1948 by the pumping of shallow wells. When pumping of the geothermal water started, progressive cooling was observed, so that these wells had to be abandoned after 3 years. Between 1950 and 1952 five wells

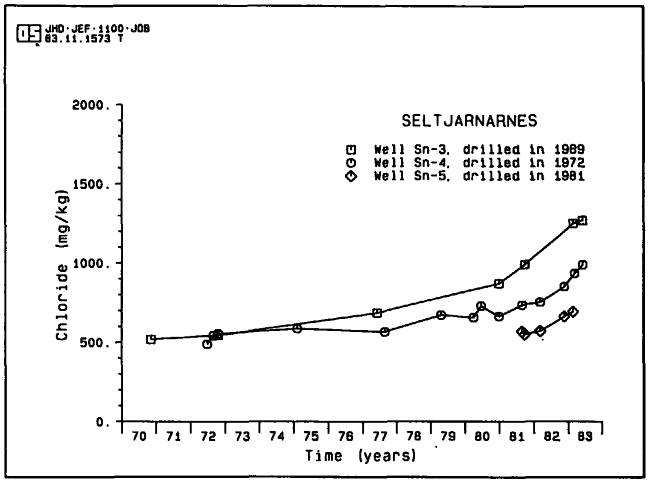

Figure 23. Changes in chloride content of water from wells in the Seltjarnarnes field

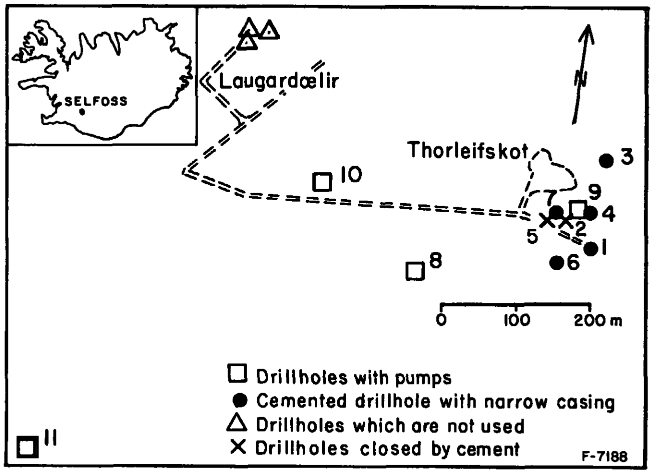

Figure 24. Location of wells at the Selfoss field

were drilled, 150 to 350 m deep, and three additional wells, 450 to 500 m deep, between 1963 and 1966, all with casings down to about 50 m deep. With increased pumping, however, the cooling accelerated and the chloride concentration of the water decreased. This was a clear indication of intrusion into the thermal system of cold fresh water with low chloride content. The groundwater in the area has a chloride concentration of less than one-tenth that of the thermal water. It was concluded that groundwater leaked into the geothermal system through drillholes with shallow or cracked casings as well as by vertical seepage through the surface formations. This problem was partly solved in 1976-1977, when most of the old wells were abandoned and blocked with cement. Others were deepened and cased to greater depths (>200 m). These measures raised the temperature of the water produced and have decelerated the cooling of the hydrothermal system. Today, five wells, 784 to 2000 m deep, with casings down to 365 m depth, are producing.

The magmatic activity that started in 1975 in the vicinity of Leirhnjukur, northwest of the Krafla drilling area (Figure 13), has affected the geothermal reservoirs in various ways. The magmatic activity has strongly influenced the chemical composition of the reservoir fluid, especially in the Leirbotnar field, causing many problems in production-well management and fluid utilization. Figure 25 shows the CO_2/H_2S ratio in the discharge from wells KG-3 and KJ-6 in Leirbotnar during the period 1975-1983. An increase by a factor of 100 was observed at the beginning of the magmatic activity, but at present the effect seems to be fading out, with the CO_2 concentration only about five times higher than before the magmatic episode. This could indicate that problems associated with these chemical changes may be coming to an end and that the exploitation of larger areas of the Leirbotnar field is now again becoming feasible.

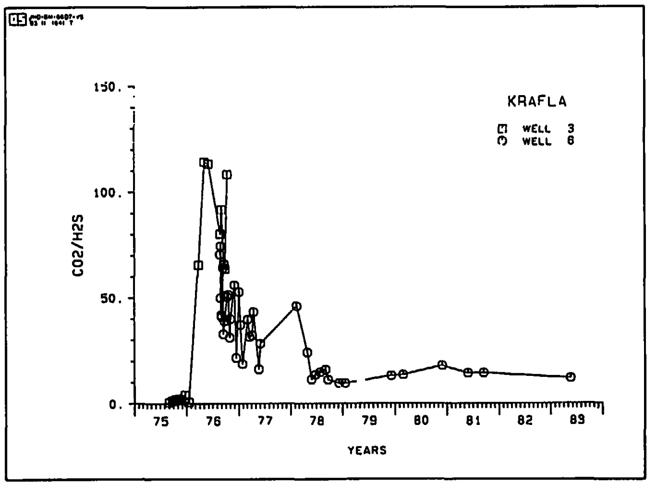

Figure 25. Variation of gas content in wells in Leirbotnar, due to nearby magmatic activity

Reinjection

Reinjection tests have been performed in the Svartsengi high-temperature field. The first test was carried out in September 1982 when cold fresh water was injected for 24 days into well SG-12. The thermal fluid is a brine of high salinity as mentioned before (Gudmundsson, 1983b). A second test of about 3 months duration started in late July 1984. The test involved the injection of a brine-condensate mixture (80/20 percent) from the Svartsengi power plant, with two chemical tracers added at an early stage (Gudmundsson and others, 1984). The objectives of the tests were to investigate the connectivity between injection and production wells, and to observe the effects on the output of the production wells and the drawdown behavior of the reservoir. The long-term goal of the tests is the injection of the spent brine from the power plant to extend the life of the reservoir. Preliminary results from the tests indicate rapid tracer breakthrough (90 hr) to well SG-6 about 200 m south of the injector, possibly along a fracture (Figure 10). Wells about 500 m south of the injector, but slightly to the west of well SG-6, show tracer breakthrough in less than 6 weeks. No tracer was observed in the western-most wells. No perceptible changes were observed in the output of any well during the test period.

Reinjection into the Krafla reservoirs has not been tried yet, but an unintentional interference was observed when cold water was injected for about 3 days during a drillout operation in well KJ-7. Two days after the start of injection the flow characteristics of the nearby well KJ-13 changed as shown in Figure 26. The enthalpy of the flow decreased and the water phase in the discharge increased, while the steam phase remained more or less constant. Numerical studies of the effect of injection into the Krafla reservoirs have given results similar to those observed in well KJ-13 (Pruess and others, 1984). Reinjection into two-phase reservoirs will not increase the steam flow from existing wells, but it will extend the life of the reservoirs considerably. This is also true of single-phase reservoirs.

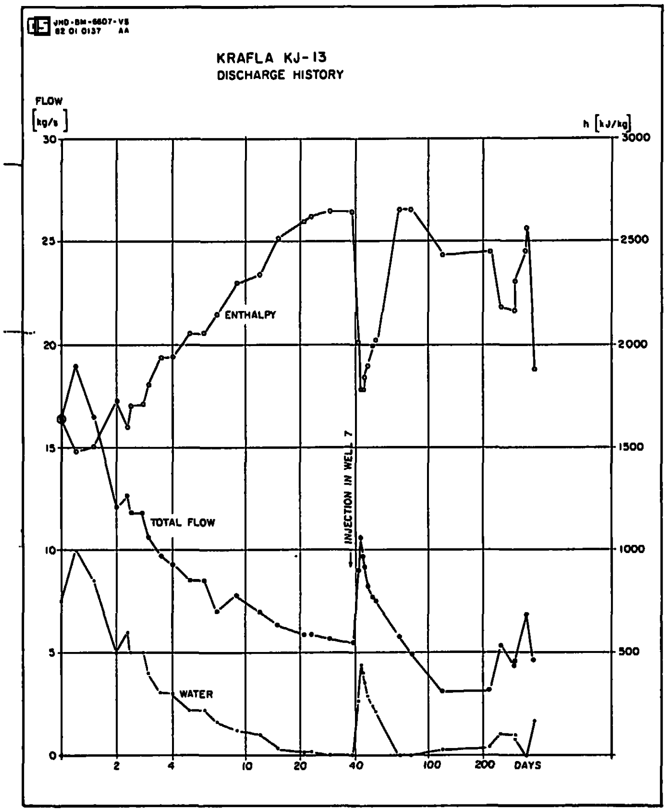

Figure 26. Production history of well KJ-13 in the Krafla field showing the effect of a cold water injection during a drillout operation in a nearby well

DISCUSSION

Regular reservoir engineering studies in Iceland began in the 1960s after several wells had been drilled into the low-temperature fields. On the basis of their outcome the production from the Laugarnes and Reykir fields has been increased substantially, and district heating services have been established in many of the rural parts of the country. When a sufficient number of wells became available in high-temperature areas, especially in the Svartsengi and Krafla fields, reservoir studies of these were also initiated. The collective experience from exploitation of geothermal

Table 1. Low-temperature geothermal fields

Geothermal field	Utilization Start up year	Duration years	Accum. volume Gl	Ave. flow l/s	Pressure * and Temperature: Initial bar	Initial °C	Present bar	Present °C	Decay bar	Decay °C	Remarks
Blonduos	1978	7	7	23	29	71	17	71	12	0	
Dalvik	1969	—	—	45	—	—	—	—	—		
Deildartunga	1981	3	8	160	—	—	—	—	—		Free flow
Egilsstadir	1979	4	3	22	4	66	3	51	1	15	
Ellidaar	1968	16	58	127	7	102	-4	92	11	10	
Hrisey	1973		—	6	1	68	1	59	0	9	
Husavik	1970		—	50	—	—	—	—	—	—	Free flow
Hvammstangi	1973		—	21	—	—	—	—	—	—	
Laugaland	1977	6	16	51	19	95	-16	95	35	0	
Laugal. Holtum	1982	2	2	21	12	101	-2	101	14	0	
Laugarnes	1957	26	111	158	8	125	-6	—	14	—	
Olafsfjordur	1944		—	31	—	—	—	—	—	—	
Reykholar	1974		—	2	—	—	—	—	—	—	Free flow
Reykir	1944	39	590	982	8	86	-3	85	11	1	
Saudarkrokur	1953	31	60	87	6	70	2	69	4	1	Free flow
Selfoss	1948	36	—	90	2	90	-4	81	6	9	
Seltjarnarnes	1972	14	15	46	1	107	-4	107	5	0	
Siglufjordur	1975	9	7	25	16	67	-2	67	18	0	
Sudureyri	1977	7	—	12	3	63	0	63	3	0	
Thorlakshofn	1979			21	3	135	3	135	0	0	Free flow

*Reference to mean sea level

Table 2. High-temperature geothermal fields

Geothermal Field	Reservoir	Start drill. year	No. of wells	Max. temp. °C	Total avail. flow rate kg/s	Remarks
Eldvorp		1983	1	260	165.0	Exploration
Krafla	Upper-Leirbotnar	1974	14	210-220	178.2	
	Deeper-	1974		298-344		Decay 5 bars
	Sudurhlidar	1980	6	280-340	51.3	
	Hvitholar	1982	3	250-260	63.0	
Namafjall		1967	12	255-340	42.0	2 wells operating
Nesjavellir						
	North field	1965	7	255-284	98.0	Under exploration
	South field	1982	3	278-295	56.9	Under exploration
Svartsengi		1972	12	229-240	1060.0	Decay 9 bars
Reykjanes		1969	9		246.6	2 wells operating

fields in Iceland is reviewed in this paper and examples from selected fields cites. Many other fields that have been exploited, though not mentioned here, are of interest from the reservoir engineering point of view and show how diverse these fields can be.

In Iceland, geothermal energy is primarily used for space heating, supplying over 80 percent of its requirements. At present, about 36 district heating services utilizing geothermal water are operating in the country. In Table 1 the effect of utilization is summarized for some of the major low-temperature fields used by the heating services. The data on many of the fields is incomplete. Most of them had natural discharge as thermal springs before utilization started. Where free flow has ceased, downhole turbine pumps are used. The most frequently used design for the pumping system has the motor at the surface and an axle connection to the turbine, which hangs in the discharge tubing. The economical setting depth for the line shaft turbine pumps is 200 to 250 m. Thus, when the drawdown approaches this limit, a change over to a submergible pumping system will be necessary to extend the life of the fields. This means that in the next decade a redevelopment program has to be initiated for many of the currently exploited fields in order to meet the demand for energy.

Table 2 summarizes the available production from some of the explored high-temperature fields. The utilization of these fields varies. The Krafla field is used for electricity generation. The presently available steam suffices for 35 MWe, of which 30 MWe is connected. The Svartsengi field is used for domestic heating and generation of electricity (8 MWe). The same is intended for the Nesjavellir field, but there a 400 MWt and up to 70 MWe are planned in the near future. The Namafjall and Reykjanes fields are used for process heating and small-scale electrical generation, and the latter for sea-chemicals production as well. A few other high- temperature fields not mentioned in Table 2 are under exploration. Activity in the exploration for and development of geothermal energy is at present high in Iceland, and the outlook for the advancement of geothermal knowledge is bright.

ACKNOWLEDGEMENTS

We thank the State Electric Power Works, Krafla Division and the District Heating Services of Reykjavik, Sudurnes, Akureyri, Egilsstadir, Saudarkrokur, Seltjarnarnes, and Selfoss for permission to use data from their fields. We also thank our colleagues and personnel at Orkustofnun for their contributions and preparation of many of the figures. Special thanks are extended to Dr. Jon O. Bjarnason for reviewing the manuscript and suggesting many improvements. We would further like to express our gratitude to Orkustofnun and Vatnaskil Consulting Engineers for the time to prepare this paper.

REFERENCES

Armannsson, H., Gislason, G., and Hauksson, T., 1982, Magmatic gases in well fluids and the mapping of the flow pattern in a geothermal system: Geochimica et Cosmochimica Acta, v. 46, p. 167-177.

Arnason, B., 1976, Groundwater systems in Iceland traced by deuterium: Societas Scientiarum Islandica, v. 42, 236 p.

Barth, T.F.W., 1950, Volcanic geology, hot springs and geysers of Iceland: Carnegie Institute, Washington, D.C.

Benjaminsson, J., 1984, Jardhitasvaedid Urridavatni, Varmavinnsla og Efnainnihald Vatns: Report OS-84114/JHD-50B in Icelandic, National Energy Authority, Reykjavik, Iceland.

Benjaminsson, J., 1985, Jardhitasvaedid Urridavatni, Ferlunarprofanir 1983: Report OS-85011/JHD-03 in Icelandic, National Energy Authority, Reykjavik, Iceland.

Bjornsson, A., 1981, Exploration and exploitation of low-temperature geothermal fields for district heating in Akureyri, north Iceland: Geothermal Resources Council, Transactions, v. 5, p. 495-498.

Bjornsson, A., and Hersir, G.P., 1981, Geophysical reconnaissance study of the Hengill high-temperature geothermal area, SW-Iceland; Geothermal Resources Council, Transactions, v. 5, p. 55-58.

Bodvarsson, G., 1961, Physical characteristics of natural heat resources in Iceland: Jokull, v. 11, p. 29-38.

Bodvarsson, G.S., Benson, S.M., Sigurdsson, O., Stefansson, V., and Eliasson, E.T., 1984, The Krafla geothermal field, Iceland: 1. Analysis of well test data: Water Resources Research, v. 20, no. 11, p. 1515-1530.

Bodvarsson, G.S., Pruess, K., Stefansson, V., and Eliasson, E.T., 1984, The Krafla geothermal field, Iceland: 3. The generating capacity of the field: Water Resources Research, v. 20, no. 11, p. 1545-1559.

Cheng, Y.W., 1980, Location of nearsurface faults in geothermal prospects by the "Combined head-on resistivity profiling method:" Proceedings New Zealand Geothermal Workshop, p. 163-166.

Einarsson, S., Kjartansdottir, M., Eyjolfsson, B., and Flovenz, O.G., 1983, Jardhitasvaedid i Urridavatni; Jardfraedi- og Jardedlisfraedirannsoknir 1978-1982: Report OS-83005/JHD-03 in Icelandic, National Energy Authority, Reykjavik, Iceland.

Einarsson, T., 1942, Uber das Wesen der heissen Quellen Islands: Societas Scientiarum Islandica, v. 26, Reykjavik, 91 p.

Flovenz, O.G., and Georgsson, L.S., 1982, Prospecting for near vertical aquifers in low temperature geothermal areas in Iceland: Geothermal Resources Council, Transactions, v. 6, p. 19-22.

Flovenz, O.G., and Thorsteinsson, Th., 1984, Vatnsoflun Hitaveitu Akureyrar; Stada og Horfur i Arslok 1983: Report OS-84031/JHD-02 in Icelandic, National Energy Authority, Reykjavik, Iceland.

Gudmundsson, J.S., 1982, Low-temperature geothermal energy use in Iceland: Geothermics, v. 11, p. 59-68.

Gudmundsson, J.S., 1983a, Geothermal electric power in Iceland: Development in Perspective: Energy, v. 8, p. 491-513.

Gudmundsson, J.S., 1983b, Injection testing in 1982 at the Svartsengi high-temperature field in Iceland: Geothermal Resources Council, Transactions, v. 7, p. 423-428.

Gudmundsson, J.S., Hauksson, T., Thorhallsson, S., Albertsson, A., and Thorolfsson, G., 1984, Injection and tracer testing in Svartsenqi field, Iceland: Presented at the Sixth New Zealand Geothermal Workshop, Auckland, New Zealand, November 7-9.

Kjaran, S.P., Halldorsson, G.K., Thorhallsson, S., and Eliasson, J., 1979, Reservoir engineering aspects of Svartsengi geothermal area: Geothermal Resources Council, Transactions, v. 3, p. 337-339.

Orkustofnun Annual Report, 1982, (in Icelandic), National Energy Authority, Reykjavik, Iceland.

Palmason, G., 1973, Kinematics and heat flow in a volcanic rifting zone, with application to Iceland: Royal Astronomical Society Geophysics Journals, v. 33, p. 451-481.

Palmason, G., 1980, Geothermal energy: Natturufraedingurinn, v. 50, p. 147-156, (in Icelandic with English summary).

Palmason, G., Stefansson, V., Thorhallsson, S. and Thorsteinsson, Th., 1983, Geothermal field development in Iceland: Proceedings Nineth Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, p. 37-51.

Pruess, K., Bodvarsson, G.S., Stefansson, V., and Eliasson, E.T., 1984, The Krafla geothermal field, Iceland: 4. History match and prediction of individual well performance: Water Resources Research, v. 20, no. 11, p. 1561-1584.

Saemundsson, K., 1978: Fissure swarms and central volcanoes of the neovolcanic zones of Iceland: Geological Journal, v. 10, p. 415-432.

Saemundsson, K. and Fridleifsson, I.B., 1980, Application of geology in geothermal research in Iceland: Natturufraedingurinn, v. 50, p. 157-188, (in Icelandic with English summary).

Sigurdsson, O., Steingrimsson, B.S. and Stefansson, V. 1985: Pressure Buildup Monitoring of the Krafla Geothermal Field, Iceland, Proceedings 10th Workshop on Geothermal Reservoir Engineering, Stnford University, Stanford, California, (in press).

Sigurdsson, O., and Tiab, D., 1983, Analysis of pressure pulses resulting from magmatic activity in the vicinity of geothermal wells: Paper SPE-11751, Proceedings Society of Petroleum Engineers 53rd Annual California Regional Meeting, March 23-25, p. 775-782.

Stefansson, V., 1980, Geothermal drilling and investigations of wells: Natturufraedingurinn, v. 50, p. 250-270, (in Icelandic with English summary).

Stefansson, V., 1981, The Krafla geothermal field, northeast Iceland, *in* Rybach, L., and Muffler, L.J.P. (eds.), Geothermal systems: Principles and case histories: John Wiley and Son Ltd., p. 273-294.

Stefansson, V., and Bjornsson, S., 1982, Physical aspects of hydrothermal systems, *in* Palmason, G. (ed.), Continental and Oceanic Rifts: Geodynamics Series, v. 8, American Geophysical Union, p. 123-145.

Stefansson, V., and Steingrimsson, B., 1980, Production characteristics of wells tapping two phase reservoirs at Krafla and Namafjall: Proceedings Sixth Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, p. 49-59.

Thorhallson, S., 1979, Combined generation of heat and electricity from a geothermal brine at Svartsengi in S.W. Iceland: Geothermal Resources Council, Transactions, v. 3, p. 733-736.

Thorsteinsson, Th., 1975, Redevelopment of the Reykir hydrothermal system in southwest Iceland: Proceedings Second United Nations Symposium on the Development and Use of Geothermal Resources, San Francisco, May 1975, v. 3, p. 2173-2180.

Thorsteinsson, Th., 1984, Aukning Vatnsvinnslu a Vinnslusvaedi Hitavietu Saudarkroks vid Ashildarholtsvatn: Report OS/JHD-B in Icelandic, National Energy Authority, Reykjavik, Iceland.

Tomasson, J., and Halldorsson, G.K., 1981, The cooling of the Selfoss geothermal area, S-Iceland: Geothermal Resources Council, Transactions, v. 5, p. 209-212.