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GEOTHERMAL FIELD DEVELOPMENTS IN ICELAND

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INTRODUCTION

Commercial exploitation of geothermal resources in Iceland dates back to the 1920's. The first district heating system, in the capital Reykjavík, began operation on a small scale in 1930 with the heating of a few buildings including a school house and a public swimming hall. The water, 15 kg/s, 93°C, was taken from shallow wells in what is now known as the Laugarnes field, which was at that time outside the town. In the 1940's the Reykjavík heating system was expanded considerably utilizing water issuing from wells less than 600 m deep in the Reykir geothermal field about 17 km away from the town. Rapid development followed, especially after the impetus given by the increase in oil prices during the 1970's. The main emphasis was on space heating, but other uses began to emerge at the same time. In 1976 the diatomite plant at Mývatn began operation using steam from the Námafjall field for drying. In 1969 a small non-condensing turbine was set up in the same place for generation of electricity. And about 1974 work started on the Krafla power plant which was to consist of two 30 MW units, of which only one has been operating yet. At the Svartsengi field which is used mainly for district heating, three small electric generating units of 8 MW total capacity have been installed. For more details on the utilization of geothermal energy the reader is referred to Gudmundsson (1982, 1983).

Today geothermal energy plays a relatively large role in the energy economy of Iceland. About 80% of the space heating requirements are met with geothermal energy at an average cost to the consumer which is about 18% of the cost of oil heating. The remaining needs are met with hydroelectricity (13%) and oil (7%). Space heating accounts for about 40% of the total energy consumption in Iceland. In terms of energy content geothermal provides about 40% of the total energy sold to users. In terms of oil equivalents the fraction is 27%. Fig. 1 shows how geothermal energy has steadily grown in importance relative to other primary energy sources in the past decades. At the present time the annual saving in imported oil due to the use of geothermal energy amounts to US$ 560 per capita.

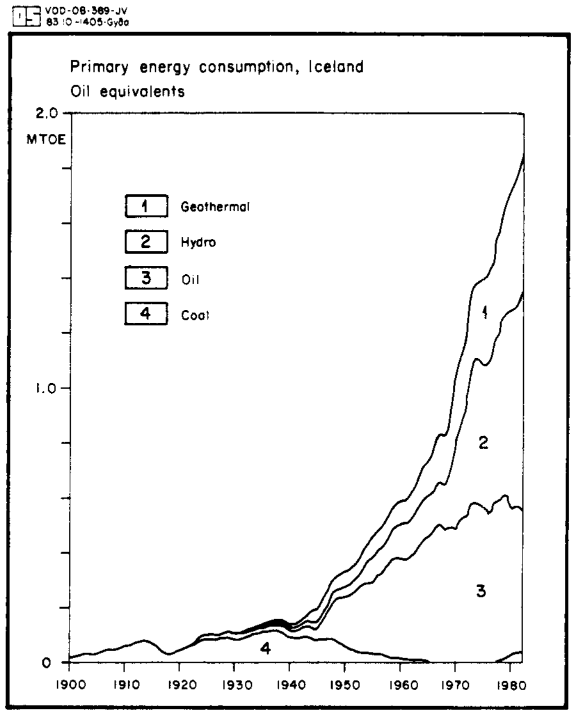

Fig. 1. The role of geothermal energy in the energy economy of Iceland, expressed in million tons of oil equivalents per year.

The exploration and research carried out in conjunction with the exploitation of the various geothermal fields has vastly deepened our 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. The purpose of the present paper is to review the present state of knowledge regarding the Icelandic geothermal systems, with emphasis on the production and reservoir engineering aspects.

ASSESSMENT OF THE GEOTHERMAL RESOURCES

The geothermal fields in Iceland have long been classified into high-temperature and low-temperature fields on the basis of the concept of base temperature (Bodvarsson, 1961). This division remains a useful one. The high-temperature fields are all within the active neovolcanic zones while the low-temperature activity occurs in flank areas where the crustal rocks are older and the temperature within the crust lower than in the neovolcanic zone.

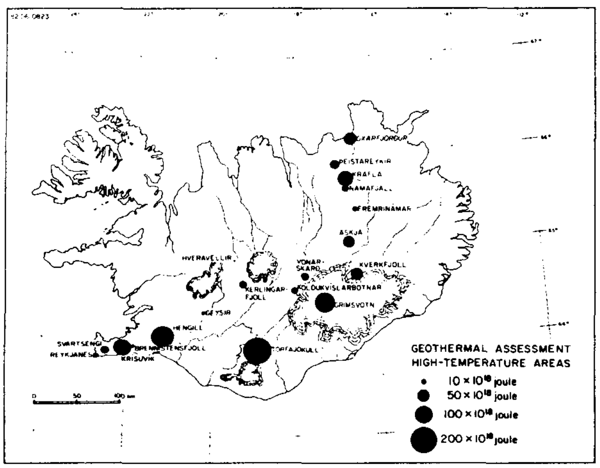

Fig. 2. A total stored-heat geothermal assessment of the high-temperature fields.

A revised assessment of the geothermal potential of the high-temperature fields has recently been made by the Geothermal Division of Orkustofnun (Pálmason, 1981). It is based on stored heat calculations and an assumed geothermal recovery factor of 20%. The area of the fields is estimated on the basis of surface manifestations and geophysical surface surveys where they are available. The reservoir thickness from which production can be obtained is assumed to be 3 km. The stored heat in the various high-temperature fields is shown in Fig. 2. The total available heat from these fields, taking into account recovery- and accessibility factors, is estimated to be 10^{20} Joule, or, when converted to electricity, 175,000 MWyrs. On the basis of geological considerations it seems possible that an additional potential of 2-3 times the above values may lie hidden without direct surface expression within the neovolcanic zone.

The assessment makes no predictions of the rate at which the energy can be withdrawn. Experience alone can add this dimension to the assessment. A considerable body of production data is gradually accumulating, both from high-temperature and low-temperature fields. Some of this is reviewed in the following.

THE REYKJAVÍK FIELDS

The Reykjavík Municipal District Heating Service utilizes geothermal water from low-temperature fields located within or relatively near to the city. These fields are (Fig. 3) Reykir, which supplies about 3/4 of the water used, Ellidaár and Laugarnes, which are located within the city. In addition, the Seltjarnarnes field which supplies the adjacent community of Seltjarnarnes with hot water is located within that community.

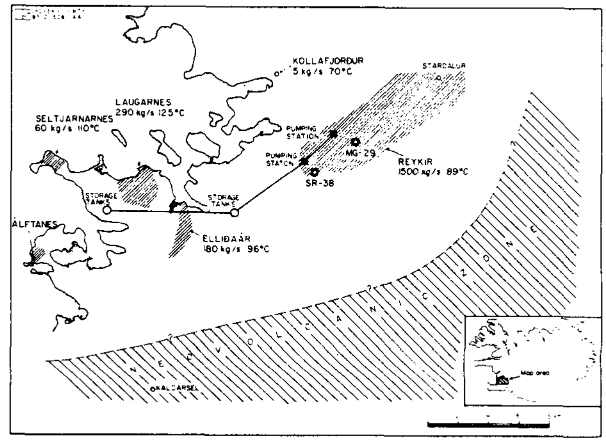

Fig. 3. A location map of the Reykjavík low-temperature fields. Also shown are maximum pumping rates from each field.

In the Laugarnes field, where exploitation was initiated in 1930, deep drilling (>1000 m) began in 1958, and soon after the first wells were connected to the district heating system in Reykjavík. The early production experience from this system has been reported by Thorsteinsson and Elíasson (1970). The main reservoir to a depth of 1250 m has a temperature of about 135°C, but the deepest well at that time, about 2200 m, encountered a deeper producing horizon with a temperature of about 145°C near its bottom. The water from this field is low in total dissolved solids, about 350 ppm, of which 35 ppm is chloride. Two deeper drillholes, to 2857 and 3085 m, were sunk in the production area in 1979 in order to explore possible deeper aquifers. Production was obtained all the way to the bottom, where the temperature was 155°C. In the deepest well the salinity of the water proved higher than in other wells in the Laugarnes field, with about 200 ppm of chloride (Gunnlaugsson, pers. comm.).

The permeability-thickness product in the Laugarnes field was estimated by Thorsteinsson and Elíasson (1970) on the basis of interference tests of 10-20 hours' duration to be about 110 darcy-m. Assuming a thickness of 1000 m for the producing reservoir, this gives a permeability of 110 millidarcys. A permeability of a few darcys was obtained by Bodvarsson (1978) on the basis of water level recovery data from one well. These values are rather high and may be affected by specific aquifer structures near the wells. On the basis of annual total production variations and accompanying water level changes, Pálmason (1967) estimated with a crude steady-state model a permeability of 35 millidarcys for the formations surrounding the production area. Bodvarsson (1978), using the same data and a more sophisticated model obtained a value of 10 millidarcys for the global permeability of the Laugarnes field. These estimates show wide discrepancies which need to be explained.

An opportunity for a pressure buildup test of the Laugarnes field as a whole presented itself in 1982, when pumping was temporarily discontinued from all the wells in the area for 4 months. The water level was monitored in several wells. The short-time buildup showed a proportionality to the square root of time (Fig. 4), indicating fracture permeability

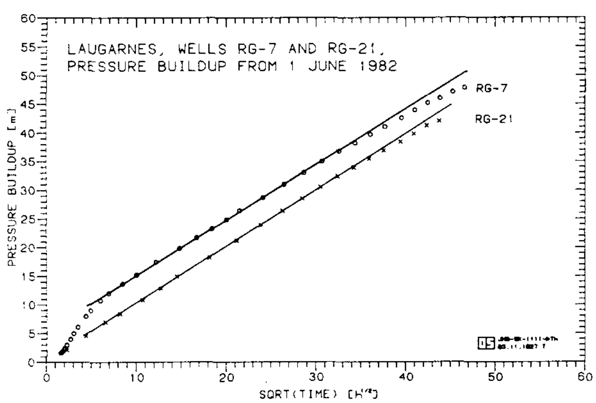

Fig. 4. Pressure buildup in the Laugarnes field, showing a linear change with the square root of time over a certain time interval.

(Gringarten et al., 1972a and b). The longer--time pressure buildup (Fig. 5) indicates a global permeability-thickness product of about 15 darcy-m. With a production zone thickness of about 1000 m this gives 15 millidarcys as a global permeability for the Laugarnes field.

The Reykir field was the principal source of thermal water for the Reykjavík District Heating Service from 1944 until 1959, when the redevelopment of the Laugarnes field began. In 1955 the production of 350 kg/s at an average temperature of 86°C was by free flow from 69 shallow wells. It was realized that the production could be increased by deeper drilling and by pumping from the wells. A redevelopment program was started in 1970, and by early 1975 29 new wells of 800-2040 m depth (average 1616 m) had been drilled. Well completions are of the open hole type. Prior to late 1973 production casing diameters were 9 5/8" up to 200 m depth, and hole size was 8 1/2". Later wells have 13 3/8" casings (200 m) and 12 1/4" hole size to 1400-1600 m. Typical pumping rates from the older wells are 30-40 kg/s but 90-100 kg/s from the later wells. The higher production rates are attributable to larger pumps and to improved productivity characteristics of the larger diameter wells.

The production history from 1971 to 1975 has been reported by Thorsteinsson (1976). In 1974 the annual discharge by pumping had reached 18.2 gigaliters, while the free flow from the older wells had ceased completely due to pressure drawdown in the reservoir. The average temperature of the pumped water was 83.5°C.

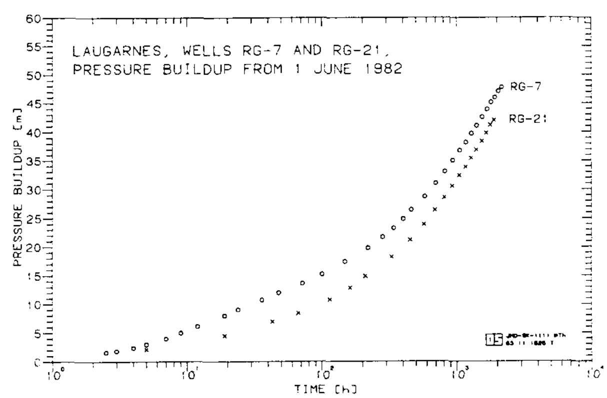

Fig. 5. Pressure buildup in the Laugarnes field, used for estimating the global permeability of the field.

On the basis of interference tests Thorsteinsson (1976) estimated the transmissivity in the Reykir production area to be in the range (0.48 - 2.7) x 10^{-2} m^2/s. With a 1000 m thickness of the producing reservoir this corresponds to a permeability range of 150 - 860 millidarcys. Since 1975 10 additional wells have been drilled in the Reykir field, expanding the production area considerably to the east, in the direction towards the neovolcanic zone. The production history for 1976--1982 and water levels from two observation wells is shown in Fig. 6. The pressure variations due to the seasonal variations in pumping rate are propagated over considerable distances as evidenced by the 204 m deep Stardalur observation well about 7 km to the northeast (Fig. 3), where 65% of the pressure amplitude in the production area is observed. The global permeability estimated from the long-term pressure decline is about 70 millidarcys, significantly lower than that obtained from the interference tests. This probably reflects similar conditions as in the Laugarnes field, although the permeabilities in general are higher in the Reykir field.

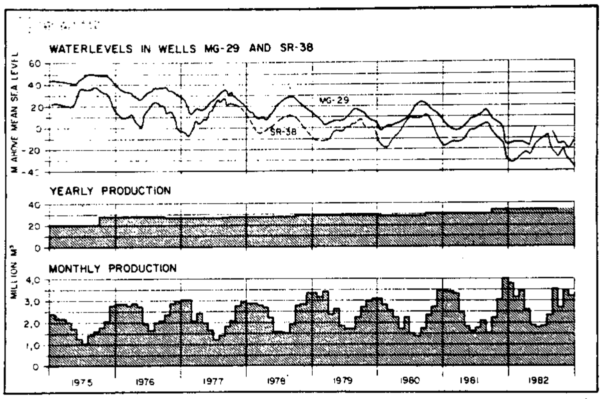

Fig. 6. The production history and pressure decline of the Reykir low-temperature field.

The water from the Reykir field is relatively low in dissolved solids, about 200 ppm, of which 10-15 ppm is chloride.

The Ellidaár field is relatively small, and was discovered in 1967 when the first well was drilled there. Although the field is only 2-3 km away from the Laugarnes field, its water is distinctly different, more dilute and of a lower temperature. It resembles more the Reykir water with regard to temperature, chemical and isotopic composition. The peak pumping rate from this area has been around 180 kg/s. Thorsteinsson (1976) has estimated the transmissivity within the production area to be 3.5×10^{-3} m^2/s on the basis of short-term interference tests. This indicates a permeability similar to that found for the Laugarnes field from similar tests.

Some cooling, up to 10°C, has been observed in wells in the Ellidaár field. It is believed to be caused by infiltration of colder water from the surroundings or by downflow of colder groundwater in non-producing wells. This phenomenon is presently under study.

The Seltjarnarnes field which is located 3-4 km west of the Laugarnes field has five wells, 860-2000 m deep, of which three are producing. The peak pumping rate is 60 kg/s and the reservoir temperature is 80-125°C. Interference tests indicate a permeability about one half that of the Laugarnes field. The water is distinctly more mineralized than the Laugarnes water, with about 1600 ppm total dissolved solids of which 670 ppm is chloride. Because of the high salinity and corrosive nature of this water heat exchangers have to be used.

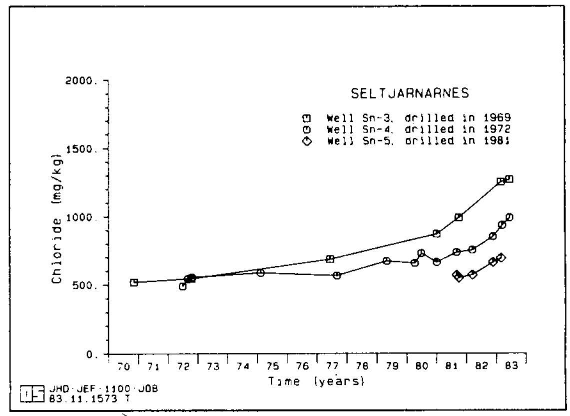

Fig. 7. Changes in chloride content of water from wells in the Seltjarnarnes low-temperature field.

In recent years the salinity of the water pumped from the Seltjarnarnes field has increased considerably (Fig. 7), while the temperature has remained constant. A possible explanation of this is that mixing with a few percent of sea-water is taking place.

Besides the four main low-temperature fields described above there are indications from exploration work that other fields may exist in the Reykjavík area. One of them is the Álfta-

TABLE 1. TRANSMISSIVITIES AND PERMEABILITIES IN THE REYKJAVÍK LOW-TEMPERATURE GEOTHERMAL FIELDS

Field	Short time interference tests (1 - 4 days)		Long time values	
	Transmissivity m^2/s	Permeability millidarcy	Transmissivity m^2/s	Permeability millidarcy
Laugarnes	6.0×10^{-3}	110	7.4×10^{-4}	14
Ellidaár	3.5×10^{-3}	100		
Reykir	4.8×10^{-3}-2.7×10^{-2}	150 - 860	2.2×10^{-3}	70
Seltjarnarnes	2.5×10^{-3}	50		

nes field shown in Fig. 3. Little is known, however, about the production characteristics outside the fields presently being exploited.

Table 1 summarizes the transmissivities and permeabilities that have been deduced for the Reykjavík fields.

THE SVARTSENGI HIGH-TEMPERATURE FIELD

The existence of the Svartsengi field was proved in 1971 by the first well drilled in that area to a depth of 240 m. The field is located within the axial zone of the Mid-Atlantic Ridge on the Reykjanes peninsula. The field is exploited by the Sudurnes Regional Heating service which was established in 1975 to provide district heating to several communities on the Reykjanes peninsula (Thórhallsson, 1979). Electricity is also generated by 3 small turbine units of 8 MW total capacity.

Eleven holes have been drilled in an area of about 1.5 km^2 to depths of 240-1998 m. The hydrothermal system in its natural state is liquid-dominated with a reservoir temperature of 240°C. The geothermal fluid is a brine with a salinity of 2/3 that of seawater(12500 ppm Cl).

Production data, including fluid discharge rate, pressure drawdown, downhole pressure, dissolved solids and gas, and downhole temperature, have been collected regularly since the beginning of the operations. Annual fluid production has been increased steadily reaching about 8.7 million tons in 1981 and 1982 (Fig. 8). The used fluid has been disposed of by surface drainage in the surrounding lava field, causing substantial silica deposition in the disposal pond. Reinjection experiments have been started (Gudmundsson 1983a) and will be continued.

Short-time interference tests have been made between wells spaced about 200 m apart. They have given rather high values of permeability, about 1 darcy. The drawdown history of the field (Figs. 8 and 9) suggests that the high permeability zone may be bounded by rather impermeable walls in one or more directions, and model studies have been made with this assumption (Kjaran et al., 1979). By analogy with the Laugarnes field described earlier one might also suspect that the short-time interference tests are primarily affected by fractures in the vicinity of the wells and that the longer-time drawdown behavior is controlled by lower global permeability values in the rocks surrounding the production area.

The geological strata in the Svartsengi wells consist of alternating suites of basalt lavas and hyaloclastites (Franzson, 1983). Below about 800 m depth 20-40% of the succession are basaltic intrusives. A comparison between aquifer occurrences and geological structures reveals that aquifers in the upper 600 m are largely due to primary permeability along stratification boundaries, whereas below that depth, i.e. within the reservoir proper, the aquifers are associated with intrusives and near vertical fractures, but there the primary pores have largely been filled with secondary minerals.

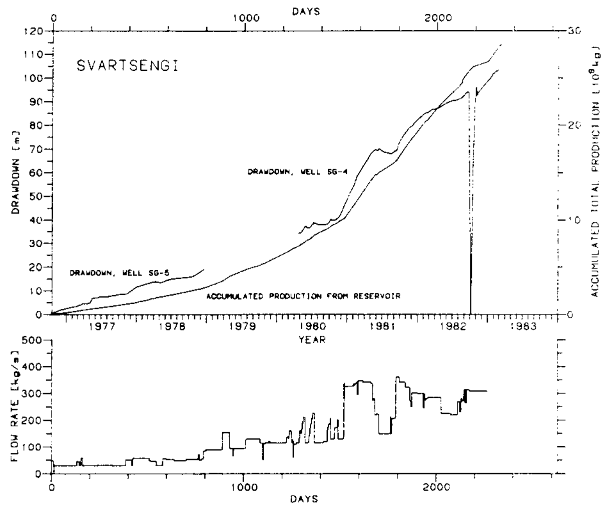

Fig. 8. Production history and pressure decline of the Svartsengi high-temperature field.

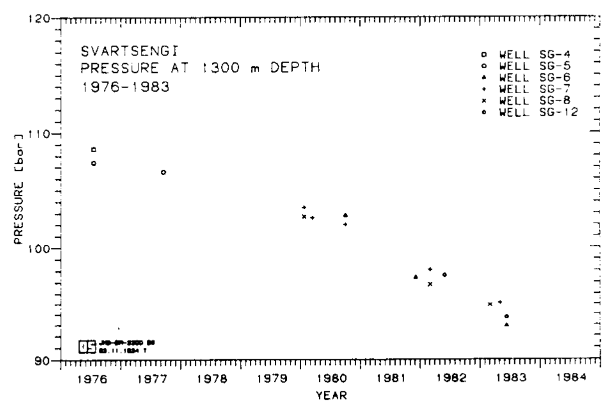

Fig. 9. Downhole pressure measurements in the Svartsengi wells.

The geothermal fluid composition has been monitored in all the wells. There are irregular variations with time but no long-term trends are visible. The gas content is more variable. In most wells it is about 0.2% by weight of the steam but in the shallow wells it reaches about 2%. Calcite scaling takes place inside the production casing where flashing occurs (Arnórsson, 1978), and the deposits are cleaned regularly by drilling.

The production characteristics of the Svartsengi wells are typical of high-permeability liquid-dominated reservoirs. The maximum wellhead pressure is about 20 bar, and the maximum flow depends primarily on the well diameter. The older wells 4,5 and 6 had a 9 5/8" production casing and a typical mass flow of 60 kg/s (at 10-15 bar , WHP), while the later wells have a 13 3/8" casing and a typical mass flow of 120 kg/s. Delivery curves for wells 4 and 10, showing the benefits of the larger casing program, are shown in Fig. 10.

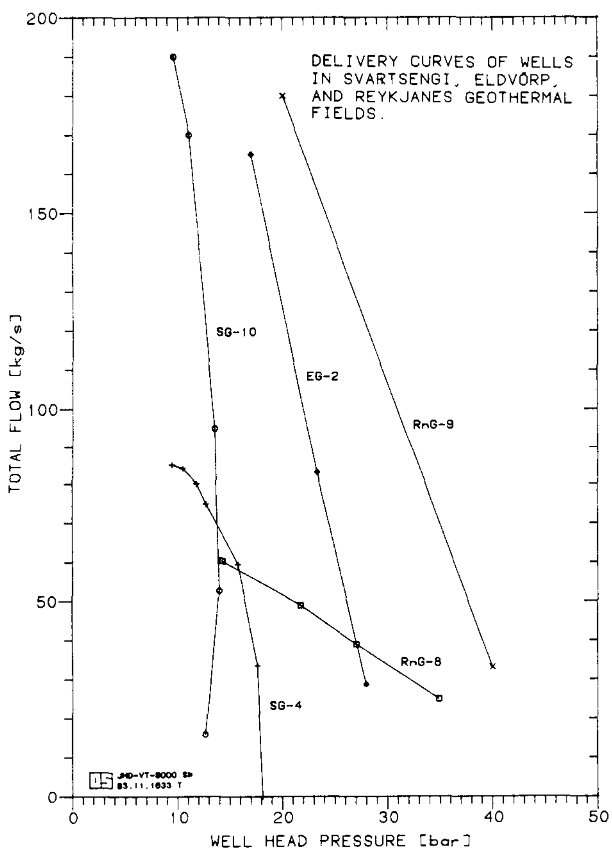

Fig. 10. Delivery curves of wells in the Svartsengi (SG-4, SG-10), Eldvörp (EG-2) and Reykjanes (RnG-8, RnG-9) fields.

The Eldvörp area, about 6 km southwest of the Svartsengi production area, is probably a part of the Svartsengi field, as indicated by electrical resistivity measurements (Georgsson, 1981). The first well was drilled in 1983 to a depth of 1265 m. It is of the same design as the newer Svartsengi wells with 13 3/8" production casing. First tests indicate that the well will be a good producer, similar to the Svartsengi wells.

THE REYKJANES HIGH-TEMPERATURE FIELD

The Reykjanes field is located on the south--western tip of the Reykjanes peninsula, about 8 km southwest of the Eldvörp area. Early exploration of the field has been described by Björnsson et al. (1972). Additional work on the well discharge characteristics was reported by Gudmundsson et al. (1981). The field is at present exploited by a sea-chemicals production company, which operates a small-scale plant for the production of salt, as well as for generating electricity for its own use. A fish-meal plant is under construction in the area. It will purchase geothermal steam from the sea-chemicals company for process heating.

Several wells were drilled in the Reykjanes field in 1968 and 1969, to a maximum depth of 1754 m. In 1983 an additional well (No. 9) was drilled to a depth of 1445 m. It was of the same design (13 3/8" production casing) as the recent Svartsengi wells. The delivery curves of wells 8 and 9 are shown in Fig. 10, demonstrating clearly the increased output for the larger diameter well.

The Reykjanes field is liquid-dominated as the other nearby fields on the Reykjanes peninsula. The geothermal fluid is a brine, considered to originate as mostly seawater, although other possibilities have been suggested (e.g. Gudmundsson et al., 1981). The total dissolved solids content is similar to that of seawater. Individual components differ from seawater, in particular magnesium, sulfate, potassium and calcium, which are determined by ionic exchange equilibria between rock and water. The silica content is determined by the temperature, which in the Reykjanes reservoir is 270-290°C.

The main reservoir is capped by a zone of heavy calcite deposition between 500 and 700 m depth. The strata consist of alternating sequences of lavas, hyaloclastites and tuffaceous sediments. Intrusives are rare. Aquifers appear to correlate mostly with horizontal stratification boundaries as well as with (near vertical) fracture planes.

THE KRAFLA HIGH-TEMPERATURE FIELD

The development of the Krafla field in the northern part of the neovolcanic zone was started in 1974, with a view to generating 60 MW of electricity. A detailed description of the field development up to 1979 is given by Stefánsson (1981). Further details are given by Ármannsson et al (1981), Stefánsson and Steingrímsson (1980), G.S. Bodvarsson et al (1981, 1982, 1983a, 1983b, 1983c), Pruess et al (1983), Kristmannsdóttir (1981).

At the end of 1983 23 wells have been drilled in the Krafla field. They are located in three drilling areas, which are here termed Leirbotnar, Southern Slopes and Hvíthóll. Their location is shown in Fig. 11.

In the beginning of the development (1975) in Leirbotnar it seemed that the reservoir was boiling, giving a saturation pressure and temperature with depth. In 1976 it was found that the reservoir was divided into an upper zone (down to 1000 m depth) of single phase 210°C water and a lower zone (beneath 1100 m depth) which is boiling and with a temperature in the range 300-350°C. Late in 1975 magmatic activity started about 2 km from the drilling area resulting in substantial influence on the geothermal reservoir. The effect of the magmatic gases on the reservoir fluid resulted in severe deposits in wells (Ármannsson et al.,

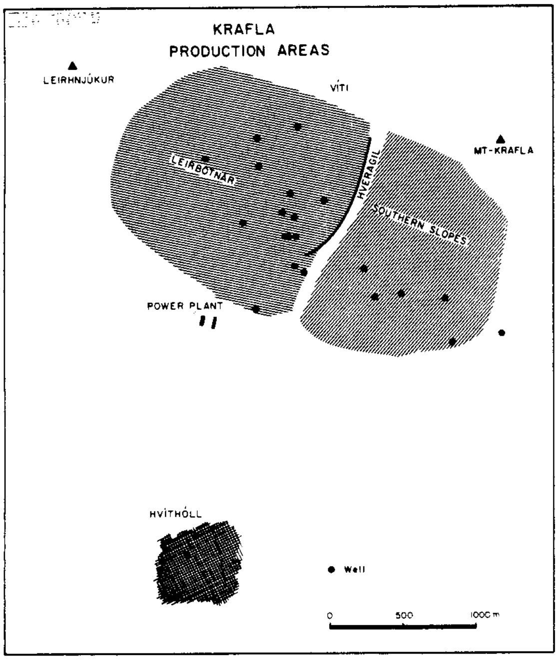

Fig. 11. A location map of the Krafla production areas, showing also the distribution of wells. Leirhnjúkur, on the eruptive fissure swarm, is in the upper left hand corner.

1981). Further drilling was carried out east of Leirbotnar, in the second production area, the Southern Slopes of Mt. Krafla. The chemical properties turned out to be favorable, but this second production area was found to be too small for the 60 MW power plant.

A third production area at Hvíthóll was tested in 1982 and 1983. In this case, the chemical characteristics turned out to be favorable also, but the reservoir system is apparently too small. The presently available steam from the three areas suffices for 35 MW, of which 25 MW is connected.

The experience in Krafla has shown that this is one of the most complex geothermal systems described in the literature. Not only are the conditions complex but the production characteristics vary considerably within the geothermal system. Fig. 12 shows the temperature distribution within the three production areas so far tested in the Krafla field. The usual classification of reservoirs into vapor-dominated, liquid-dominated and two-phase boiling reservoirs does not seem to apply for the geothermal system as a whole, as in the Krafla field we might have all three cases present in one geothermal system.

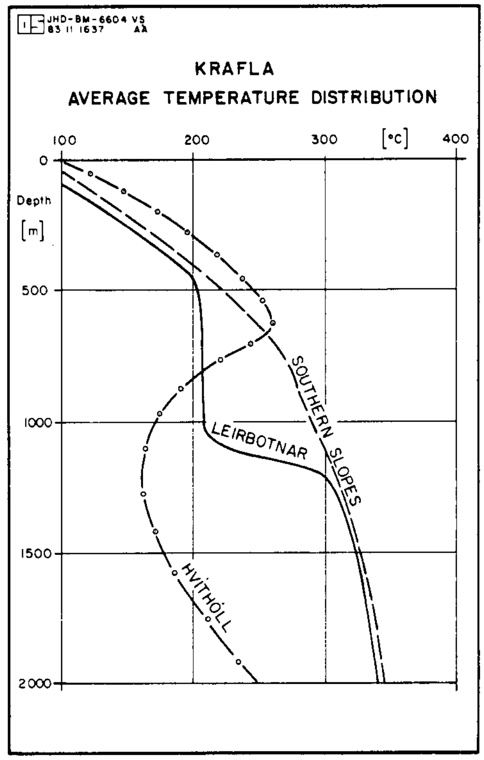

Fig. 12. Average temperature distribution in the three production areas in the Krafla field.

Most of the wells in the Krafla field produce from a boiling reservoir with a temperature of 300-350°C. The delivery curves of these wells contrast sharply with similar curves for single-phase reservoirs, e.g. Svartsengi. The flow is almost constant regardless of the wellhead pressure (Fig. 13). The enthalpy on the other hand is high, usually in the range 2000-2700 kJ/kg. A peculiar behavior is found for well KJ-11 (Fig. 13), which is open to two types of reservoirs, an upper liquid-dominated zone and a lower boiling zone. For certain conditions of pressure at the wellhead the upper zone controls the flow giving a delivery curve which changes considerably with wellhead pressure. For other pressure conditions the lower feed zone is activated giving a flow that is almost constant with varying wellhead pressure.

The wells tapping the two-phase reservoir in Krafla do not reach stable conditions of flow and enthalpy until after weeks or months of production. An example is given by well KJ-14 in Krafla (Fig. 14). The reason for this behavior is that in two-phase reservoirs a very large local drawdown is created around the well, which propagates very slowly in the reservoir due to the high compressibility of the system. When stable conditions are reached in in the reservoir the flow rate and the enthalpy remain relatively constant.

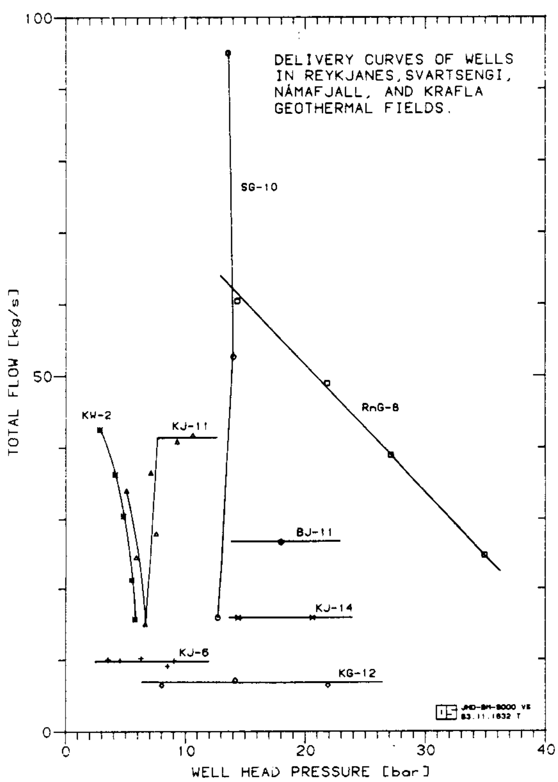

Fig. 13. Delivery curves of wells in the Krafla (KW-2), KJ-6, KJ-11, KG-12, KJ-14) and Námafjall (BJ-11) fields. For comparison two wells from the Svartsengi and Reykjanes fields are shown.

Reinjection into the Krafla reservoir has not been carried out yet. Fig. 15 shows the effect of an unintentional interference test, when during cleaning operations cold water was injected into a well for about 3 days. Two days after the start of the injection the flow characteristics of the nearby well KJ-13 changed as shown in Fig. 15. The flowing enthalpy decreased and the water phase in the discharge increased, while the steam phase remained more or less constant.

Numerical studies of the effect of reinjection into the Krafla reservoir (Pruess et al., 1983) have given similar results to those observed in well KJ-13. Reinjection into two-phase reservoirs will not increase the steam flow from existing wells, but will increase the longevity of the reservoir considerably as is also the case for single-phase reservoirs.

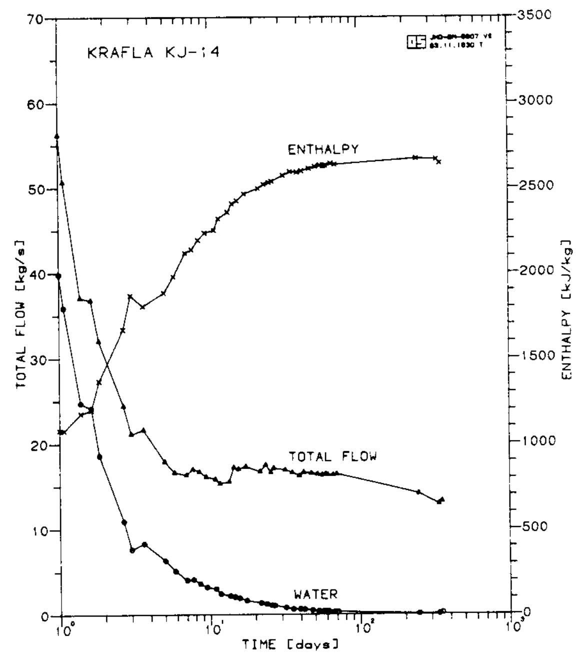

Fig. 14. Production history of well KJ-14 in Krafla.

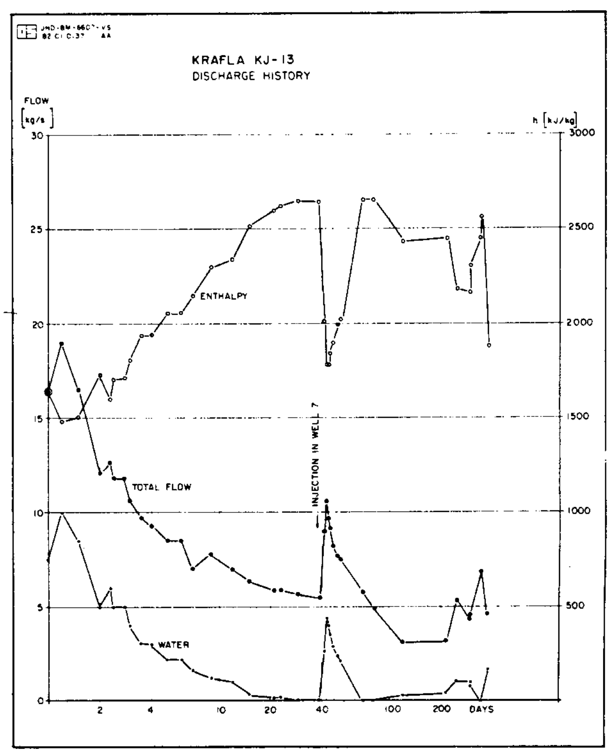

Fig. 15. Production history of well KJ-13 in Krafla, showing the effect of a cold water injection into a nearby well.

The magmatic activity which started in 1975 in the vicinity of Leirhnjúkur (Fig. 11) northwest of the drilling area has influenced the geothermal reservoir in various ways, and has provided an opportunity to study some interrelationships between the two kinds of phenomena. On the basis of attenuation of seismic S-waves a magma chamber has been inferred at a depth of approximately 3-7 km beneath the Krafla caldera (Einarsson, 1978). Large changes in the ground surface elevation have taken place over a period of 5-6 years. They have reflected the pressure variations associated with the movement of magma beneath the Krafla fissure swarm where the volcanic activity was concentrated (Björnsson et al., 1979).

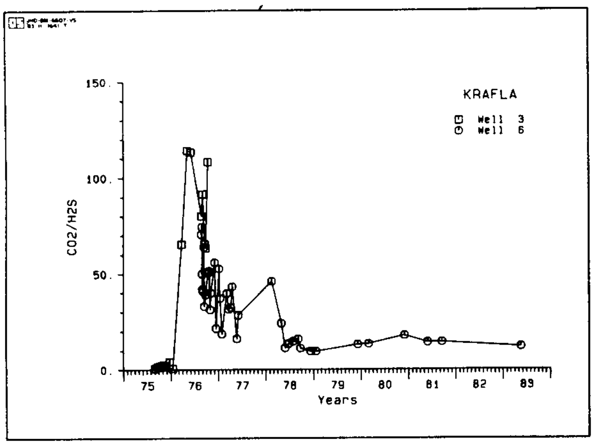

Fig. 16. The variation of gas content in wells in Leirbotnar, due to the nearby magmatic activity.

The chemical composition of the reservoir fluid in Krafla has been strongly influenced by the magmatic activity. Fig. 16 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 in the beginning of the magmatic activity, but the effect seems to be fading out at present. The concentration of CO_2 is now (1983) only about five times higher than before the magmatic episode.

An interesting phenomenon from a reservoir engineering point of view was a pressure pulse which was observed in well KG-5 at the beginning of a volcanic eruption about 5 km away (Fig. 17). The well is mainly open to the single-phase upper part of the reservoir, and the pulse seems to be an example of the response of a confined reservoir to an instanteneous point like pressure change. The average transmissivity deduced from the pulse for the single-phase upper zone of the reservoir, $kh/\mu=1.7\times10^{-8}$ $m^3/Pa.s$ (Sigurdsson and Tiab, 1983), is in good agreement with

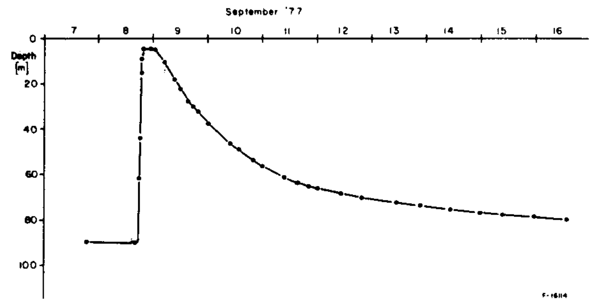

Fig. 17. A pressure pulse in well KG-5 in Leirbotnar caused by volcanic activity about 5 km away. The vertical scale shows depth to the water level.

what is obtained from injection tests of individual wells (Sigurdsson, 1978).

THE NÁMAFJALL HIGH-TEMPERATURE FIELD

The Námafjall field supplies steam for process heating in a diatomite plant and for the generation of electricity in a 3 MW noncondensing station. Its exploitation began in 1967,

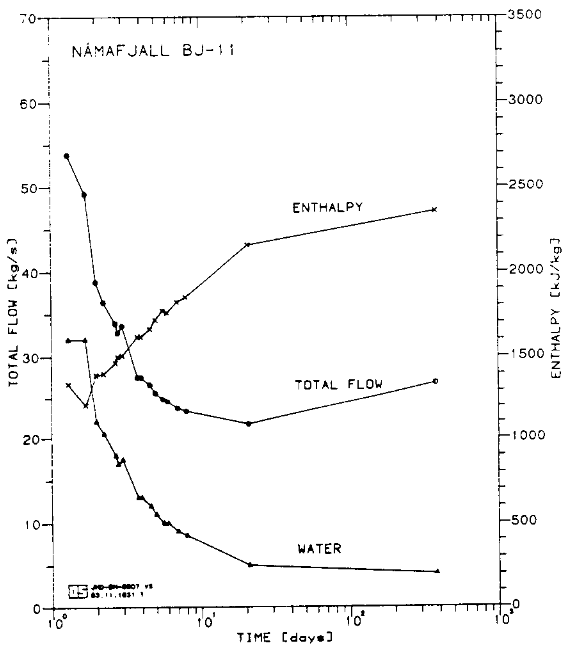

Fig. 18. Production history of well BJ-11 at Námafjall.

and to date 12 wells have been drilled. Changes in the chemistry of the discharged fluid in 1970-1976 have been reported by Arnórsson (1977).

The field which is located about 8 km south of the Krafla field was affected to some degree by the volcanic activity which began in 1975.

Some of the older wells were damaged by movement on faults. Two new wells were drilled in 1979 and 1980 to depths of 1923 and 1999 m. They show in many ways similar characteristics as some of the Krafla wells. The reservoir is boiling and a steady state production is not reached until after several weeks. Fig. 18 shows the production history of well BJ-11. An interesting feature is the increase in flow rate with time. This is believed to be caused by thermal contraction associated with a cooling of the reservoir rock under boiling conditions.

THE AKUREYRI LOW-TEMPERATURE FIELDS

Several hydrothermal systems in the valley of Eyjafjörður in northern Iceland are here termed the Akureyri fields (Fig. 19), because they are utilized for district heating in the town of Akureyri (13,000 inh.). The first successful drilling was carried out in Laugaland in 1976, and at the present time a total of 19 wells, 800 to 2800 m deep, have been

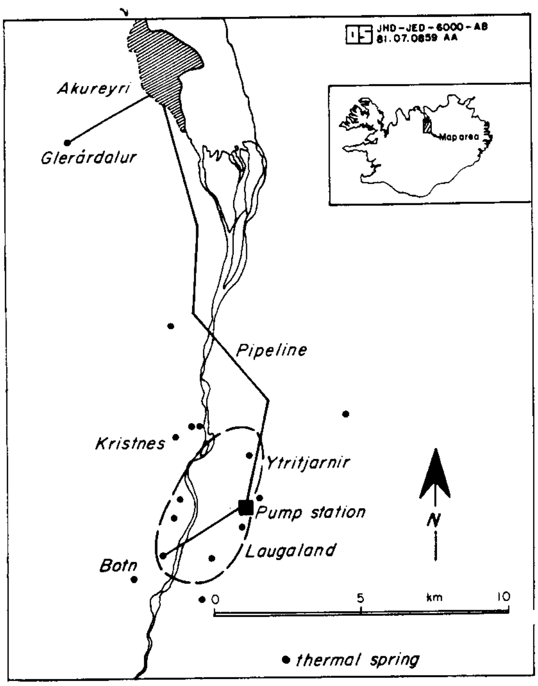

Fig. 19. A location map of the Akureyri low-temperature fields. The dashed curve encloses a low resistivity area.

drilled in the Akureyri fields. The development in these fields to 1981 has been described by Björnsson (1981).

The reservoir temperature is mostly in the range 80-100°C, and the water is low in dissolved solids, 200-300 ppm, of which 10-15 ppm is chloride. The aquifers are found in the depth range 300-2500 m.

The reservoir rocks are gently dipping (5-7°) plateau basalts of Tertiary age (8-10 Myrs). They are cut by numerous dikes, trending approximately north-south. The aquifers seem to be associated with some of the dikes and with interlayers between lavas, the best aquifers occurring at intersections between these two kinds of permeable structures. Because of the nature of the aquifers, non-productive wells are relatively common in these fields, the success ratio being rather low, about 50% of all drilled wells.

Because of the low overall permeability of the reservoirs the pressure drawdown is relatively high. Fig. 20 shows the drawdown for the Laugaland system as measured in several wells.

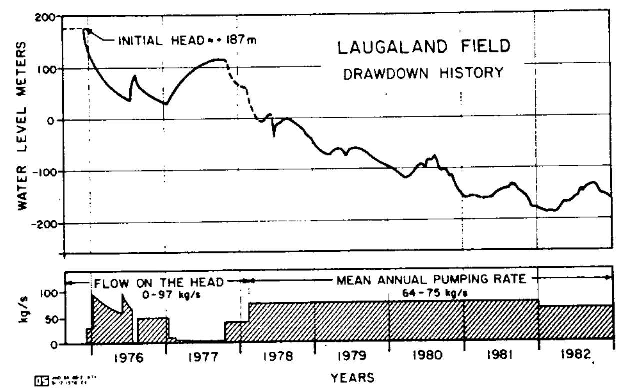

Fig. 20. Production history and pressure decline of the Laugaland low-temperature field.

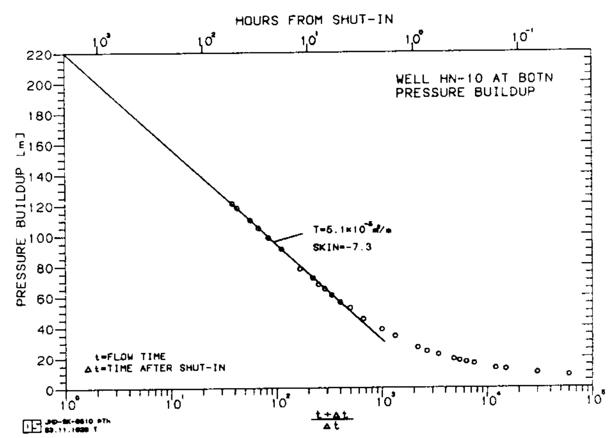

Fig. 21. A Horner diagram of pressure buildup at the Botn low-temperature field.

Original pressure corresponded to +187 m water level relative to the top of well LN-10, while six years later the level was down to about -180 m, a total decline of about 370 m. The total accumulated flow from the field at the end of 1981 was about 12 gigaliters. Seasonal variations in production rate are reflected in the drawdown diagrams.

An example of a Horner diagram from a pressure buildup test at the Botn field adjacent to the Laugaland field is shown in Fig. 21. The calculated permeability-thickness product is 1.8 darcy-m, corresponding to about 2 millidarcys, which is significantly lower than in most other exploited fields in Iceland.

Fig. 22 shows the drawdown in the Ytritjarnir field just north of the Laugaland field, due to a production of 46 kg/s. The approximate proportionality 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 the area.

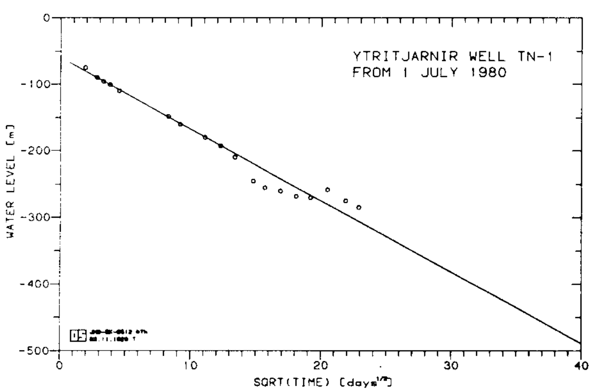

Fig. 22. Pressure drawdown in the Ytritjarnir field, showing an approximately linear variation with the square root of time. The deviations from the line are due to changes in flow rate.

THE NESJAVELLIR HIGH-TEMPERATURE FIELD

The Nesjavellir field is located in the northern part of the Hengill geothermal area (Bodvarsson 1951, Árnason et al., 1969). It is being explored with a view to a possible use for district heating in Reykjavík and for generation of electricity. Drilling started in the sixties and was resumed in 1982 after about 10 years' h^lt in development.

Well NG-6 which was drilled in 1982 has indicated the possibility of a 300°C steam zone at 800-1000 m depth. Fig. 23 shows the interpreted pressure profile in the reservoir at the location of this well. The reservoir seems to be overpressured to approximately 800 m depth, but the main feeder at 1085 m has an undisturbed pressure of 86 bar. The pressure profile in the reservoir thus indicates a steam zone of 86 bar pressure and 300°C temperature in the depth range 800-1000 m.

So far, vapor-dominated reservoirs have generally been found to have steam zones of about 240°C temperature and 32 bar pressure. The results from well NG-6 at Nesjavellir seem to indicate that steam zones outside the magical numbers of 240°C, 32 bar are possible in Nature. Further drilling, which is planned in the Nesjavellir field, will probably throw further light on this question.

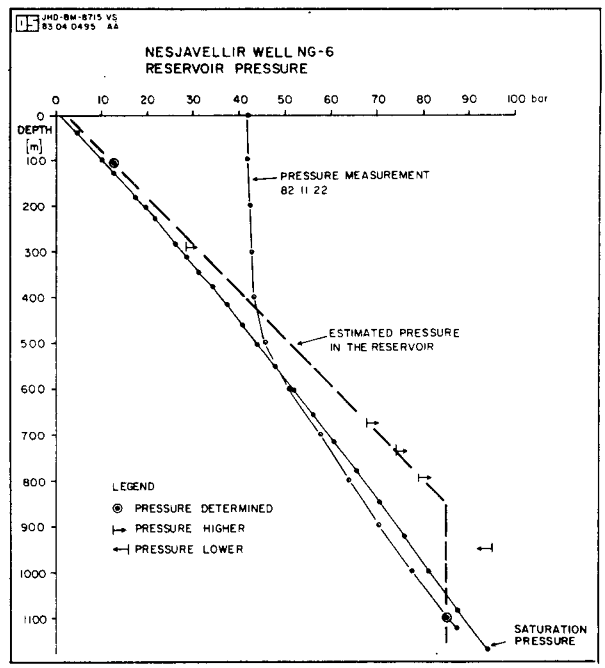

Fig. 23. A pressure profile in well NG-6 at Nesjavellir, indicating a 300°C steam zone at 800-1000 m depth.

DISCUSSION

The exploitation of geothermal fields in Iceland for a large variety of uses, especially in the past 2-3 decades, has provided a wealth of new data on the reservoir properties of the hydrothermal systems, and has shown that they are more diverse than previously thought.

Reservoir engineering studies were initiated in the Laugarnes low-temperature field in the middle 1960's, after several wells had been drilled in that area to depths of 1000-2000 m. When a sufficient number of wells became available in high-temperature fields, especially in the Svartsengi and Krafla fields, reservoir studies were also started in these fields. The main results of this work are reviewed in this paper. Several fields which have been exploited on a smaller scale, have not been mentioned, although they are of interest from the reservoir engineering point of view. These include the Selfoss low-temperature field (Tómasson and Halldórsson, 1981) in southern Iceland, and the Urridavatn low-temperature field in the Tertiary plateau basalts of eastern Iceland, both of which are used for district heating.

TABLE 2. PRODUCTION DATA FOR WELLS IN HIGH-TEMPERATURE FIELDS

Field	Well*) No	Year meas.	P_o (bar)	Tot.flow (kg/s)	Enthalpy (kJ/kg)	Steam (6 bar) (kg/s)	Power**) (MW_e)
Reykjanes	8	71	10	80	1100	16.5	7.5
	8	83	10	66.6	1102	13.8	6.3
	9	83	21	180	1300	54.4	24.7
Eldvörp	2	83	18	165	1270	47.5	21.6
Svartsengi	(2)	72	7.0	50	850	4.3	2.0
	3	72	7.5	72	990	11.1	5.0
	(4)	74	11.0	85	1040	15.1	6.9
	5	79	15	72	1040	12.8	5.8
	6	79	6.8	84	1040	14.9	6.8
	7	80	18.4	57	1040	10.1	4.6
	8	80	16.0	160	1040	28.4	12.9
	9	80	16.0	160	1040	28.4	12.9
	10	80	14.0	160	1000	25.3	11.5
	11	80	16.0	160	1040	28.4	12.9
Nesjavellir (N-Hengill)	5	77	7.0	33	1130	7.3	3.3
	6	83	9.1	26.7	2005	17.1	7.8
Hveragerði (S-Hengill)	6	79	6.7	58	1000	9.2	4.2
	7	79	3.4	32	870	3.1	1.4
	8	61	8.0	97	1140	21.9	10.0
Krafla	(1)	74	-	17.2	1675	8.3	3.8
	(3)	75	8.5	68	1100	14.0	6.4
	6	76	8.2	16.2	1486	6.3	2.9
	6	83	2.5	6.7	1248	1.9	0.9
	7	76	10.7	13.4	1780	7.1	3.2
	7	83	9.0	8.1	1214	2.1	1.0
	9	77	18.0	42.2	1230	11.3	5.1
	9	83	10.0	22.5	988	3.4	1.5
	(10)	76	23	52	1360	17.2	7.8
	11	77	10	44.2	1300	13.4	6.1
	11	83	10.4	4.6	1816	2.5	1.1
	12	79	7.9	6.5	>2676	6.4	2.9
	12	83	12.4	3.6	>2676	3.5	1.6
	13	83	8.5	9.2	2393	7.6	3.5
	14	83	11.9	12.7	2642	12.0	5.5
	15	83	7.6	3.5	2676	3.4	1.5
	16	83	3.8	8.0	1515	3.2	1.5
	17	83	14.2	10.7	1340	3.4	1.5
	19	83	12.2	8.9	2626	8.3	3.8
	20	83	12.9	10.0	1941	6.1	2.8
	21	83	20.3	27.4	1652	12.9	5.9
	22	83	5.3	30.9	1103	6.4	2.9
Námafjall	(4)	77	10.2	-	-	7.0	3.2
	(6)	77	9.0	-	-	3.8	1.7
	(7)	77	11.4	52.3	1288	15.5	7.0
	(8)	77	29.0	44.4	1093	9.0	4.1
	(10)	77	28.0	89.2	1270	25.7	11.7
	11	83	16.2	25.3	2320	20.0	9.1
	12	83	18.2	16.9	2260	12.9	5.9

*)Wells in parenthesis are damaged.
**)Calculated electric power based on 1 MW_e = 2.2 kg/s steam at 6 bar.

The temperatures encountered in the geothermal reservoirs range from less than 100°C in the low-temperature fields to over 300°C in some of the high-temperature fields. The geothermal fluids are usually low in dissolved solids and gases. An exception is the fields on the outer part of the Reykjanes peninsula, where seawater circulates in the neovolcanic zone which connects with the submarine axial zone of the Mid-Atlantic Ridge.

An interesting recent result of the work in the low-temperature fields, especially Laugarnes and Akureyri, is that the pressure buildup (drawdown) behavior supports strongly the assumption that the flow is mainly associated with fracture permeability. This result is not unexpected on geological grounds as surface outflow from hydrothermal systems is often observed to be along dikes, faults or boundaries between lava flows. There are some indications that similar conditions may exist in the high-temperature fields as well.

Permeabilities have been estimated for the various reservoirs exploited to date. These show wide variations between fields, and also within fields depending on the method used. Great care is needed in interpreting data from fractured reservoirs. Short-time interference tests usually give much higher permeabilities than longer-time tests, which probably reflects the nature of the flow along mostly linear fractures.

Overall global permeabilities for the various fields have been estimated using a thickness of 1000 m for the production reservoir, as most of the production wells are 1000-2000 m deep. The highest permeability, some 100 millidarcys, is found in the Reykir low-temperature field and in the Svartsengi high-temperature field. The lowest values, some 2 millidarcys, are found in the Akureyri fields. In Krafla, permeabilities of some 1-10 milli-darcys are indicated. Intermediate values are found e.g. in the Laugarnes field, about 15 millidarcys.

The physical state of the high-temperature hydrothermal systems varies from one field to another, and also within one and the same field. The fields on the Reykjanes peninsula (Svartsengi, Eldvörp, Reykjanes) are liquid-dominated in their natural state, but the experience from Krafla, Námafjall and Nesjavellir shows that two-phase boiling systems may be just as common. The difference in well production characteristics from the two kinds of reservoirs is clearly demonstrated in Figs. 10 and 13. In the single-phase systems the well total flow is usually large and primarily controlled by the diameter of the well, while in the two-phase systems the total flow is smaller and is governed by conditions within the reservoir outside the well, and largely unaffected by the wellhead pressure. Some production data from individual wells in the various high-temperature fields have been compiled and are given in Table 2.

Another difference between the single- and the two-phase reservoirs concerns the changes in flow with time. In single-phase reservoirs the decrease in flow with time is primarily governed by the overall drawdown in the reservoir, and the flowing enthalpy remains constant. In two-phase reservoirs both mass flow and enthalpy change initially with time (Figs. 14, 15 and 18), while the long-term decline depends more on local conditions around each well.

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