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Geothermal Reservoir Engineering Experience in Iceland

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Geothermal reservoir engineering studies have been carried out in Iceland for years concurrently with the utilization of the various geothermal fields. This has been essential in order to understand the responses of the reservoirs to exploitation. The importance of geothermal energy has grown steadily in the past decades relative to other primary energy resources, providing at present about 40% of the total energy consumed in Iceland. In this article the experience gained from exploiting Icelandic geothermal reservoirs is reviewed. The geological setting of the hydrothermal system is described as well as geophysical exploration methods. Several field examples are presented, demonstrating the effects that exploitation has on the geothermal reservoir's response.

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, 92°C, was taken from shallow wells in what is 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

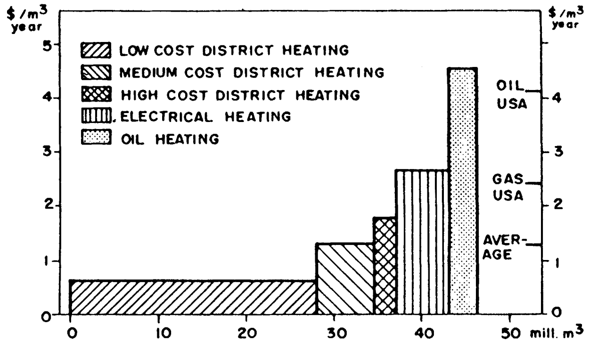

Fig. 1. Cost of heating in 1982.

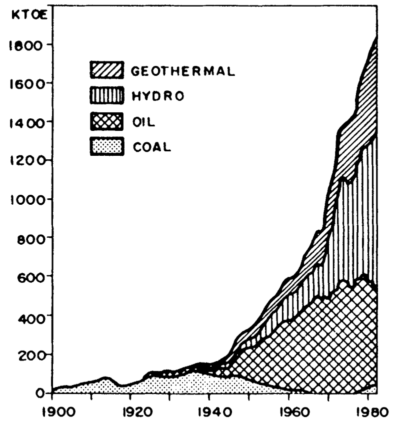

Fig. 2. Primary Energy consumption expressed in oil equivalents.

for drying. In 1969 a small non-condensing turbine was set up in the same place for generation of electricity. In 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, 1983a).

Today geothermal energy plays a relatively large role in the energy economy of Iceland. About 84% 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 oilheating, Fig. 1. The remaining needs are met with hydroelectricity (12%) and oil (4%). 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. 2 shows how geothermal energy has steadily grown in importance relative to other primary energy sources in the past decades. In 1983 the annual saving in imported oil due to the use of geothermal energy amounts to US $ 560 per capita.

As mentioned above 84% of the space heating requirements are met with geothermal energy. At present about 36 district heating services utilizing geothermal water are operating in the country, see Fig. 3 for location of the utilities.

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

Table 1 – Low-temperature geothermal fields.

Geothermal field	Utilization			Pressure * and Temperature						
	Start up year	Accum. volume Gl	Ave. flow l/s	Initial bar	Initial °C	Present bar	Present °C	Decay bar	Decay °C	Remarks
Blonduos	1978	7	23	29	71	17	71	12	0	
Dalvik	1969	–	45	–	–	–	–	–	–	
Deildartunga	1981	8	160	–	–	–	–	–	–	Free flow
Egilsstadir	1979	3	22	4	66	3	51	1	15	
Ellidaar	1968	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	16	51	19	95	–16	95	35	0	
Laugal. Holtum	1982	2	21	12	101	–2	101	14	0	
Laugarnes	1957	111	158	8	125	–6	–	14	–	
Olafsfjordur	1944	–	31	–	–	–	–	–	–	
Reykholar	1974	–	2	–	–	–	–	–	–	Free flow
Reykir	1944	590	982	8	86	–3	85	11	1	
Sauðarkrokur	1953	60	87	6	70	2	69	4	1	Free flow
Selfoss	1948	–	90	2	90	–4	81	6	9	
Seltjarnanes	1972	15	46	1	107	–4	107	5	0	
Siglufjordur	1975	7	25	16	67	–2	67	18	0	
Sudureyri	1977	–	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-	1974		210-220		
	Leirbotnar		14		178.2	
	Deeper-	1974		298-344		Decay 5 bars
	Sudurhliðar	1980	6	280-340	51.3	
	Hvitholar	1982	3	250-260	63.0	
Namafjall		1967	12	255-340	42.0	2 wells op.
Nesjavellir						
	North field	1965	7	255-284	98.0	Und.explor.
	South field	1982	3	278-295	56.9	Und.explor.
Svartsengi		1972	12	229-240	1060.0	Decay 9 bars
Reykjanes		1969	9		246.6	2 wells op.

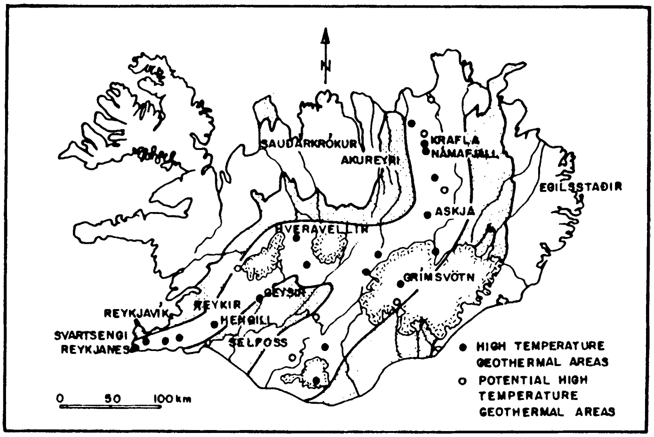

Fig. 3.
Location of geothermal fields and district heating services.

economical setting depth for the line shaft turbine pumps is 200-250 m. Thus, when the drawdown approaches this limit, a change over to a submergible pumping system will be neccessary 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 (8MWe). 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.

Some aspects of the developments of the Icelandic geothermal fields have been presented by Sigurdsson *et al.* (1985) and by Palmason *et al.* (1983).

Geology

Iceland lies astride the Mid-Atlantic Ridge. The axial rift zones, which are divided into two parallel branches in southern Iceland (Fig 3), 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-temperature 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.

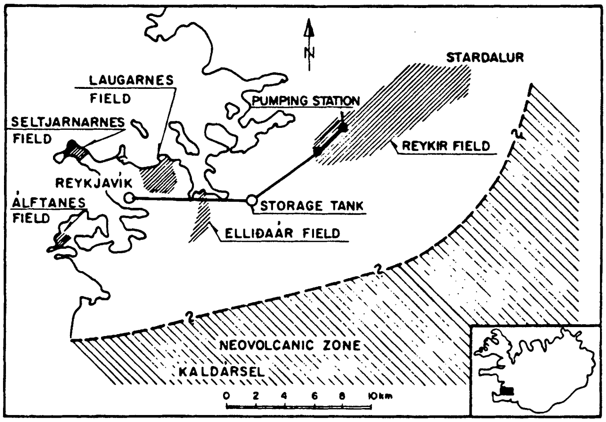

Fig. 4.
The low-temperature fields in Reykjavik and vicinity.

Geophysics

During the last decades, Schlumberger and dipole-dipole equatorial resistivity soundings have been the most powerful geophysical tools for geothermal exploration and description of reservoir boundaries. The following two examples show the usefulness of the geophysical methods. The first example is from the geothermal low-temperature fields in Reykjavik shown in Fig 4.

Surface thermal gradients measured in shallow drillholes in Reykjavik and vicinity are shown in Fig 5.

Four areas of thermal maxima are apparent from the isothermal lines in the figure, that is the Alftanes, Seltjarnanes, Laugarnes and Ellidaar fields. Only the latter three have been exploited and hydrological (Thorsteinsson and Eliasson

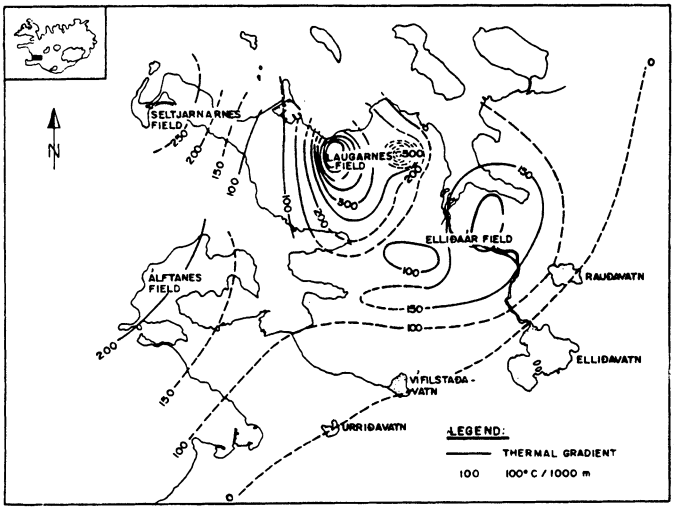

Fig. 5.
Surface thermal gradients in Reykjavik and vicinity.

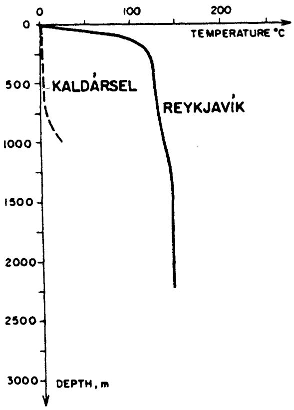

Fig. 6. Temperature profile in drillholes.

1970), thermal, chemical and isotropic data (Arnason and Tomasson 1970) indicate that these areas constitute separate hydrothermal systems. Estimated location of the zero surface thermal gradient is shown in the figure. This fact is also demonstrated by the temperature profile in the well at Kaldarssel as shown in Fig 6, which location is according to Fig 4.

These conditions correspond to heavy infiltration of cold water at the outskirts of the volcanic zone. This evidence is supported by the results of the resistivity measurement as shown in Fig 7. The high resistivity values to the south indicate the infiltration area but the high resistivity to the north is evidence of tighter formations.

Gravity measurements in the Reykjavík area were carried out by Einarsson (1954). The Bouguer anomalies obtained are shown in Fig 8.

The old central volcanoes Kjalarnes and Stardalur are marked by positive gravity anomalies which reflect the intensity of intrusions in the strata. The Reykjavik

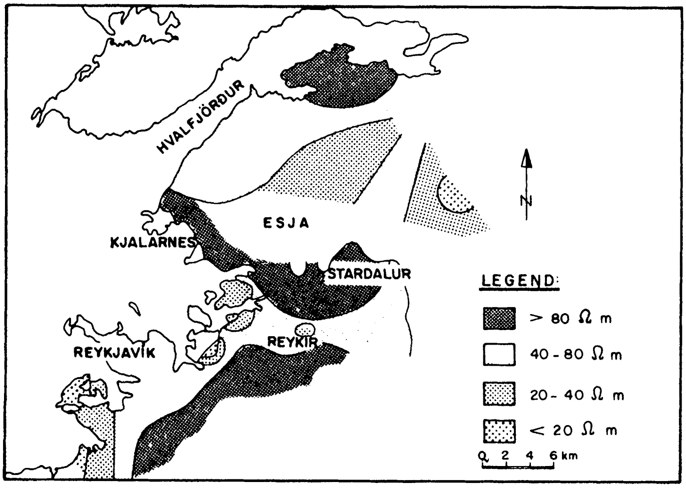

Fig. 7.
Resistivity map in Reykjavik and vicinity.

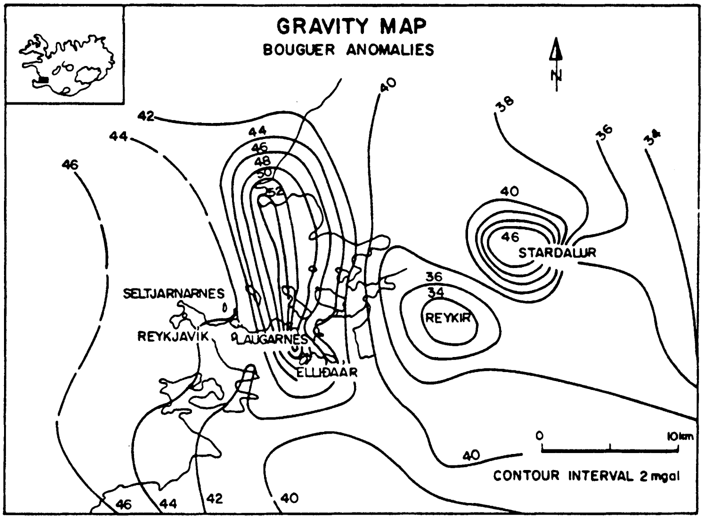

Fig. 8. Gravity map in Reykjavik and vicinity.

thermal fields are situated on the southern margin of the Kjalarnes central volcano, and the Reykir field is between the central volcanoes, but closer to the southwestern margin of the Stardalur volcano. The low-temperature thermal fields are thus superimposed on the margins of extinct, eroded high-temperature fields, which act as impermeable boundaries to the geothermal fields. The geological structure at the outskirt of the calderas makes it possible to have flow anisotropy direction along the boundaries. Geological mapping of the whole area reveals anisotropy in north-north-easterly direction. Fig. 9 shows the low-temperature fields in the Quaternary strata in Reykjavík and vicinity.

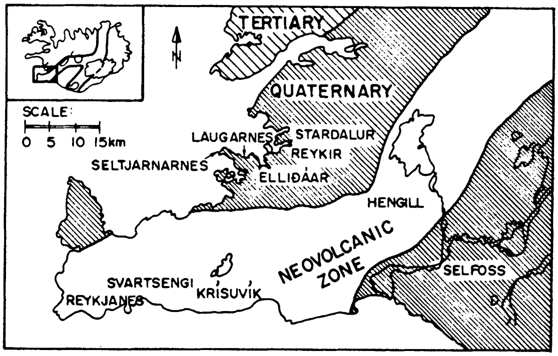

Fig. 9. Low-temperature fields in quaternary strata.

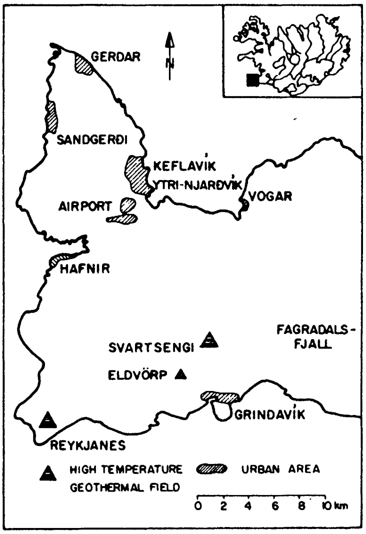

Fig. 10. Location of the Svartsengi high-temperature field.

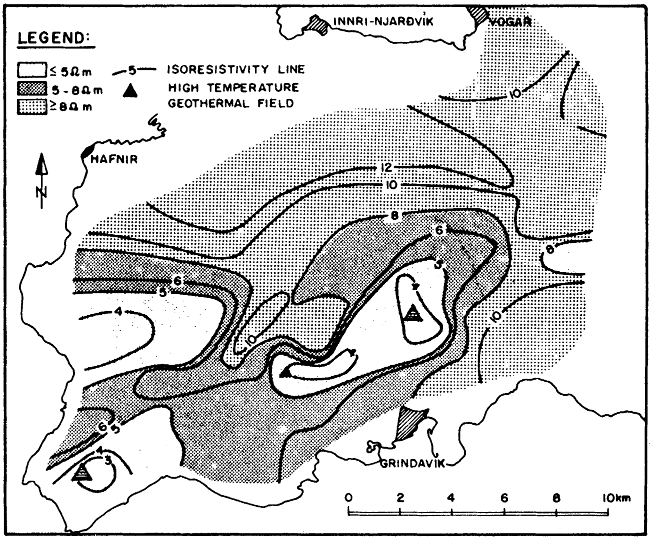

Fig. 11.
Resistivity map at 600 m b.s.l. in Svartsengi.

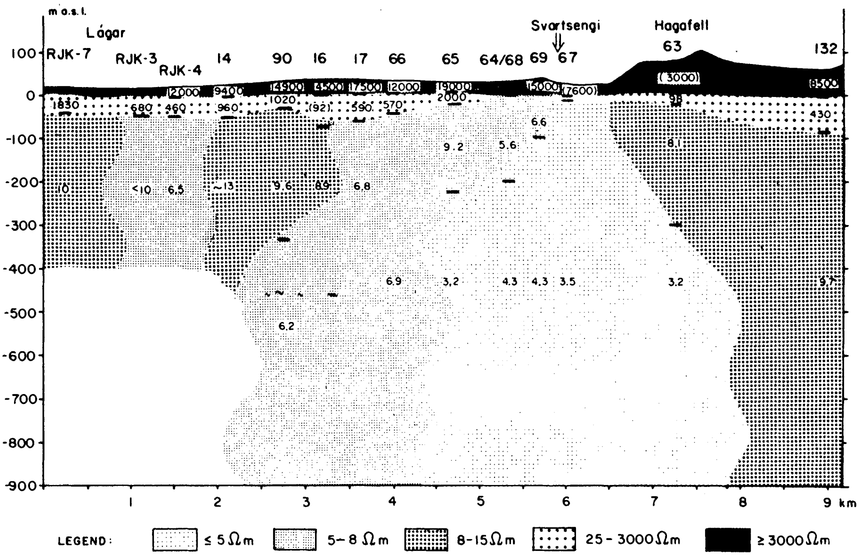

Fig. 12. Resistivity cross-section through the Svartsengi field.

The result of the geophysical measurements indicate that the neovolcanic zone could act as a constant head boundary condition for the geothermal fields and no flow boundary conditions are reached by approaching the tighter tertiary formations.

The second example is from the Svartsengi high-temperature field, Fig. 10.

Fig. 11 shows the resistivity at 600 m depth below sea level. The Svartsengi high-temperature field is found within the 4 Ωm contour line. Outside the low-resistivity zone regional resistivity is 10-12 Ωm.

The northwest-southeast resistivity cross-section through the Svartsengi field, see Fig. 12, clearly shows the low-resistivity anomaly at the Svartsengi field. The resistivity map has been converted to a map showing the temperature distribution (Georgsson 1984). The Svartsengi field is located inside the 200°C contour line. The resistivity data has been useful for hydrological modelling to indicate location of the geothermal field and its boundaries.

Reservoir Engineering

Geothermal energy in Iceland is primarily used for space heating. Most of the geothermal fields (mainly low-temperature) 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 used for space heating. 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 exeeded 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. Finally the pumps cannot be lowered anymore. This situation defines the lifetime of the geothermal reservoir. 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 lifetime of the reservoir may be shortened appreciably. This is especially 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 lifetime of the reservoir may be increased so as to exceed that of a closed reservoir. Reinjection of 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.

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.

In the following examples of these effects will be given.

Drawdown Effects

A classical example of the evolution of a typical low-temperature field in Iceland is the Reykir field. The 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 (Fig. 4). 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 1970-1977, 37 large-gauge wells of 800-2,040 m depth were drilled. The well completions were of the open hole type with production casing diameters up to 13 3/8″ (200m) and hole size up to 12 1/4″ to 1,400-1,600 m. Improved productivity characteristics are attributed to the larger diameter wells. The production history for the field after 1970 is shown in Fig. 13.

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.

At present, the water level is at about 70 m depth, 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 field. The cumulative production 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% of the seasonal pressure variation in the production area is observed in a well located at a distance of more than 7 km. It is however more likely that the field is showing some double porosity or delayed yield effects, where the initial storage coefficient is small corresponding to the elastic properties but the long term storage coefficient corresponds to the porosity of the system.

Due to the increasing drawdown pumps have to be lowered, and before very long time has elapsed we have reached the drawdown limit corresponding to the pumpcapacity defining the lifetime of the Reykir field.

The exploitation of the geothermal energy resources in the Reykir field have made it very clear that our geothermal energy is only partly a renewable energy source but could rather be defined as a mining process.

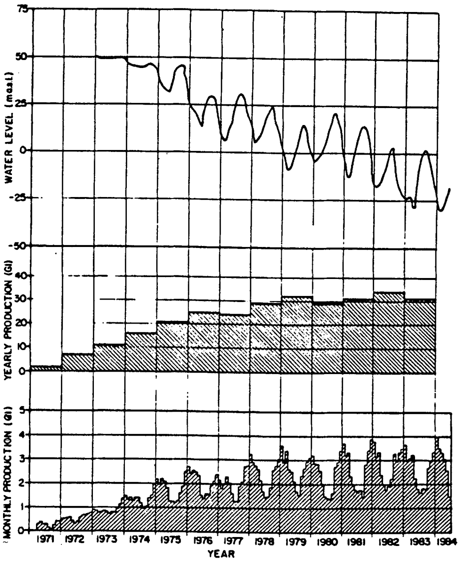

Fig. 13. Reykir field, production history and drawdown.

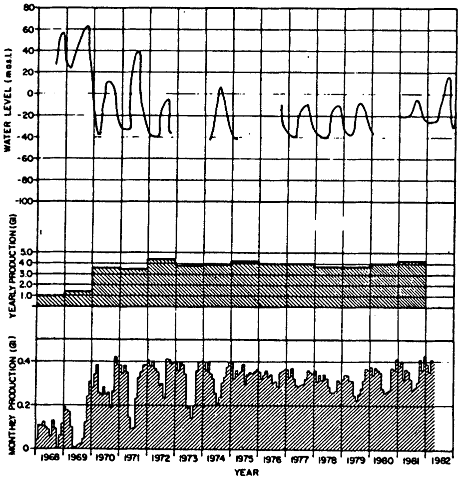

Fig. 14. Ellidaar field, production history and drawdown.

Effects of Cold Water Recharge

The Ellidaar field is an example of how cooling takes place in a geothermal reservoir. The field, located inside Reykjavik, is relatively small. It was discovered in 1967, when the first well was drilled there (Fig 4). Fig. 14 shows the production and drawdown history of the field.

At the end of 1981 the annual discharge by pumping had reached 4 G1 and the cumulative production from 1968 was 50 G1. 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 1/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. An unit response function representing the drawdown is shown in Fig. 15. It indicates that a steady state has been reached. Thus the production has induced a recharge into the field equaling the current production rate. The recharge water is cold and has cooled the reservoir as indicated in Fig. 16, which shows changes in chemistry and temperature of the produced fluid.

Example from the Laugarnes Low-Temperature Field

A more detailed example will now be given of the Laugarnes field, Fig. 4. The field is an example of how drawdown and chemistry affect the lifetime of the geothermal reservoir.

Exploitation of the Laugarnes field was initiated in 1930 and deep drilling (>1,000 m) began in 1958, and soon after the first wells were connected to the

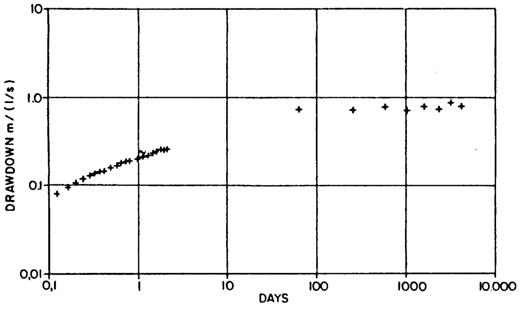

Fig. 15. Ellidaar field, unit response function.

district heating system, in Reykjavik. The early production experience from this system has been reported by Thorsteinsson and Eliasson (1970). The main reservoir to a depth of 1,250 m has a temperature of about 135°C, but the deepest well at that time, about 2,200 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 2,857 and 3,085 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. The annual production from the Laugarnes field is shown in Fig. 17. Average annual withdrawal is about 5 Gl. The cumulative withdrawal from 1963-1985 is 116 G1.

The seasonal variations in the flow rate are great as can be seen from Fig. 18. The waterlevel in one observation well is in Fig. 19. The initial water level was 70 m a.s.l, a total drawdown of about 115 m has thus been observed at the end of 1985. This corresponds to an average yield of 1.3 l/s/m. But by comparing the seasonal fluctuation in the amplitude for the pumping rate to the waterlevel, a yield of 3.3 l/s/m is obtained.

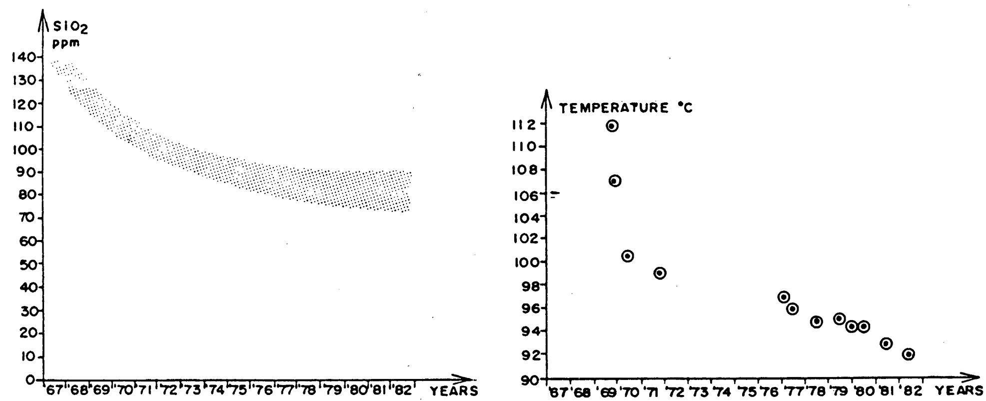

Fig. 16. Ellidaar field, changes in chemistry and temperature.

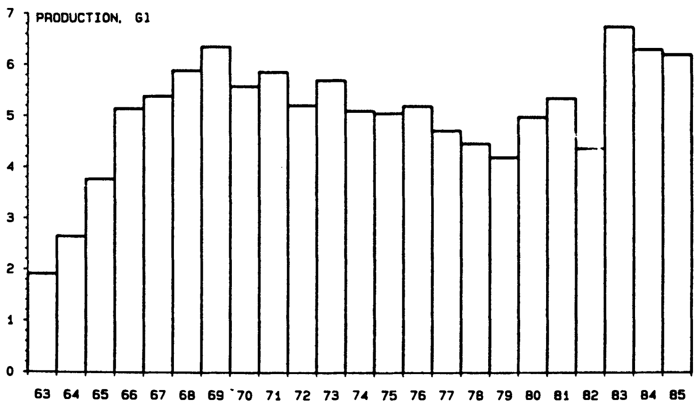

Fig. 17.
Laugarnes field,
annual production

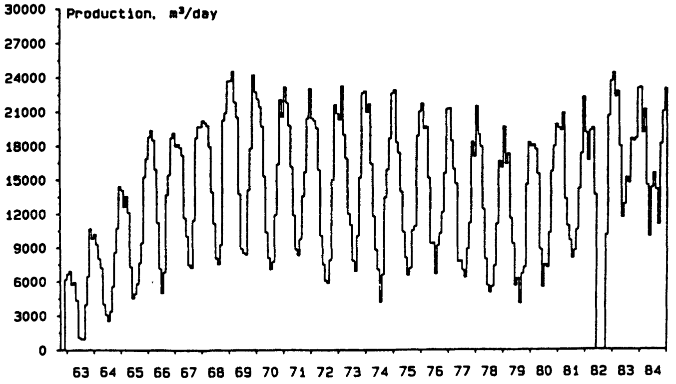

Fig. 18.
Laugarnes field,
seasonal variation
in flow rate.

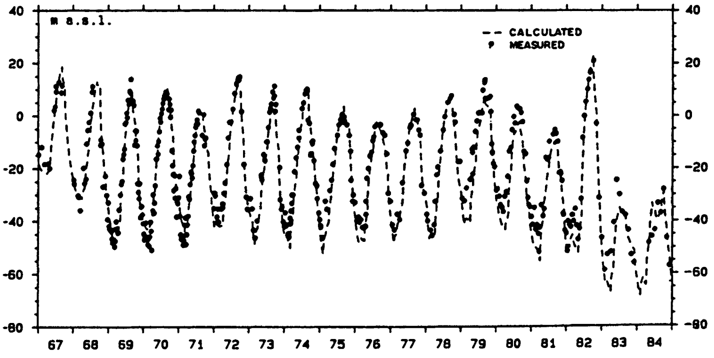

Fig. 19.
Laugarnes field,
measured and calculated waterlevel.

As mentioned before the cumulative production from 1963 to 1985 is 115 Gl corresponding to 115 m drawdown. Assuming an elastic storage coefficient of 10^{-4} results in an estimated areal extension of 10,000 km^2 for the reservoir. It is thus obvious that delayed yield effects must dominate the long term behavior of the reservoir. For an average porosity of 1 % the necessary reservoir area would just be 100 km^2.

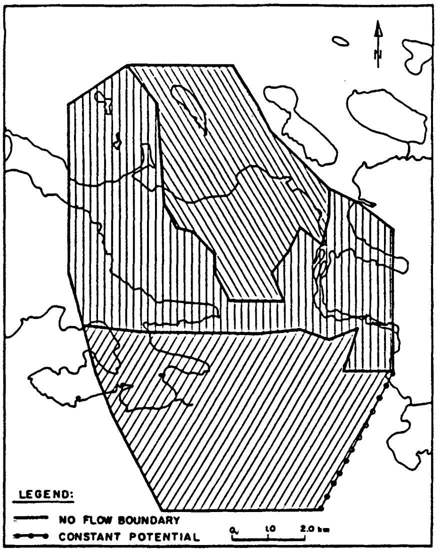

Fig. 20. Simulation area and anisotropy directions.

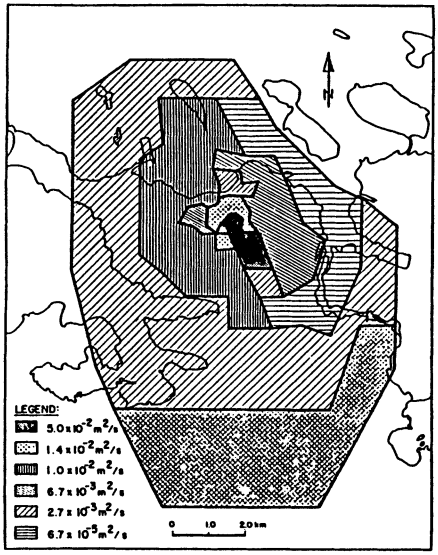

Fig. 21. Map of transmissivities.

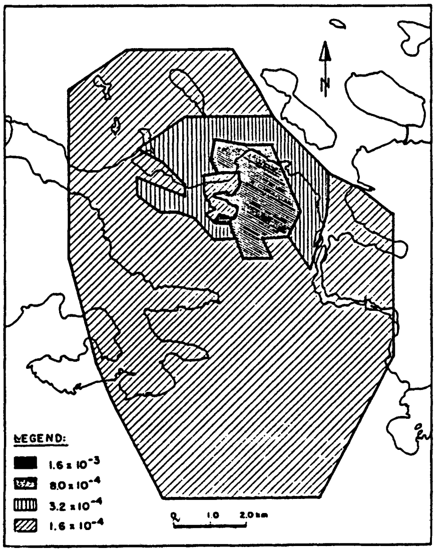

Fig. 22. Map of storage coefficients.

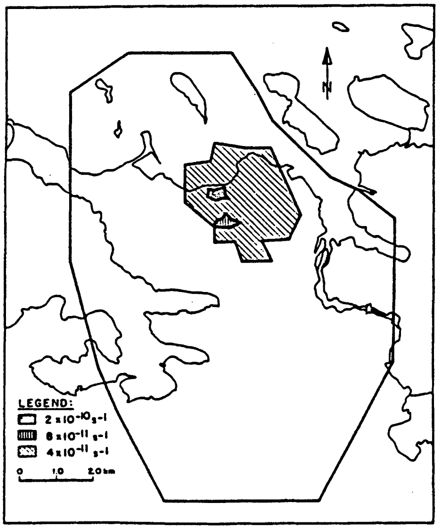

Fig. 23. Map of leakage coefficients.

In order to predict future behavior of the geothermal reservoir a numerical flow model is used. The model is a Galerkin finite element model with triangular elements in space but a finite difference scheme is used for the time derivative. Both the flow equations and the equations for the transport of mass and heat are solved

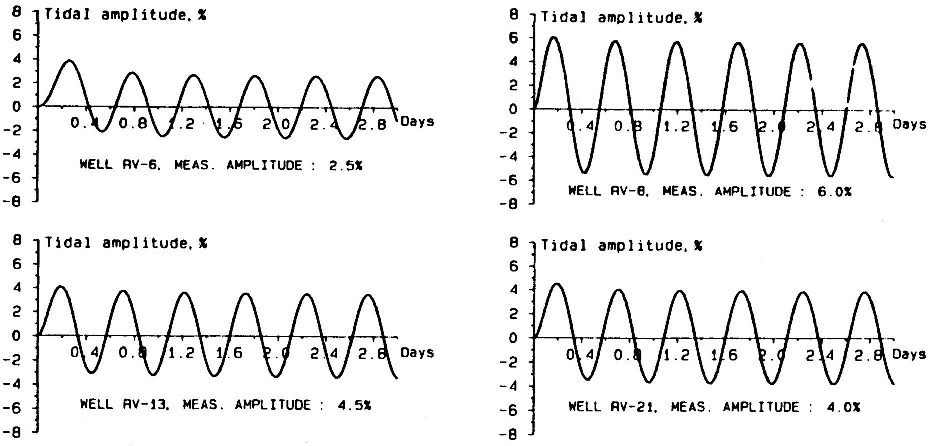

Fig. 24. Measured and calculated tidal response.

in this way.

According to the discussion in the section on geophysics the boundary conditions and the simulation area are shown in Fig. 20. We have everywhere no-flow boundaries except in the infiltration area where constant potential is assumed. From geological mapping and the gravity survey mentioned before the anisotropy directions are determined and shown in Fig. 20. The transmissivities, storage coefficients and leakage coefficients are determined by matching observed and calculated reservoir response. By using waterlevel measurements as shown in Fig. 19 and tidal response measurements in Fig. 24 the reservoir parameters are determined and shown in Figs. 21-23.

Measured and calculated values can be compared in Figs. 19 and 24.

The resulting response function for 200 l/s production rate is shown in Fig. 25. It

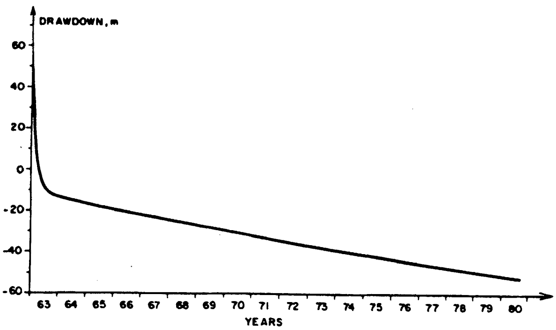

Fig. 25. Response function for 200 l/s production rate.

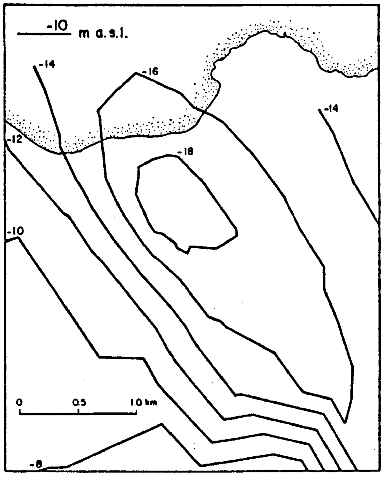

Fig. 26. Calculated waterlevel in October 1985.

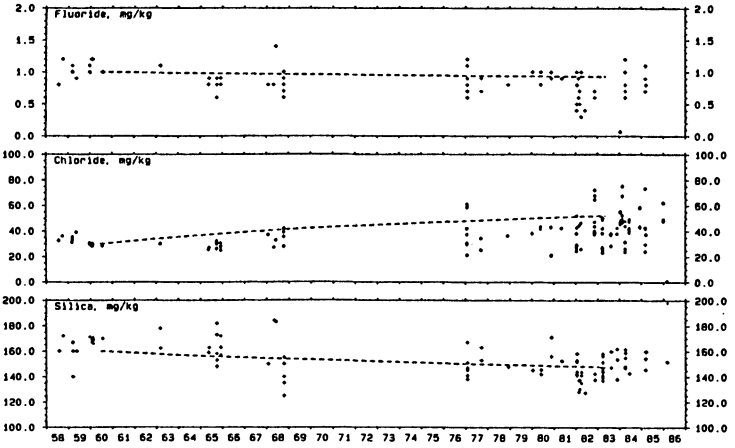

Fig. 27.
Measured and calculated concentration.

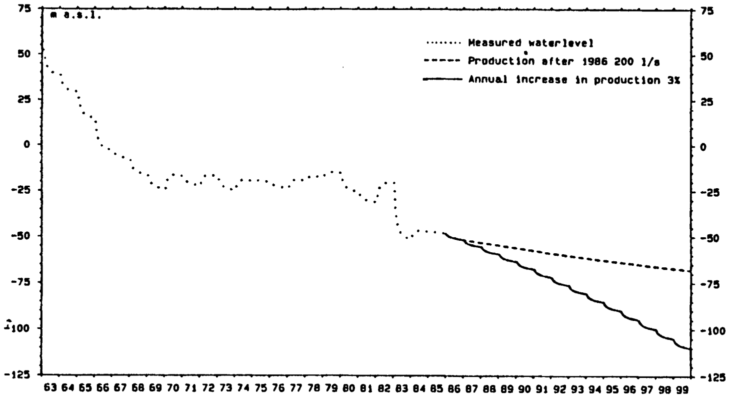

Fig. 28.
Prediction of drawdown until year 2000.

is evident from the figure that there are two storage coefficients dominating the reservoir response, according to the effects of delayed yield. Within the first year of production the elastic storage coefficient controls the reservoir behaviour but the long term drawdown is determined by the porosity of the reservoir.

Fig. 26 shows an example of calculated waterlevel in October 1985. It is clear from the figure how the lines are stretching in the anisotropy direction.

Results for calculations of concentration are shown in Fig. 27. Results are shown for fluoride, chloride and silica as an average concentration for the whole reservoir. Measured and calculated values of the concentration can be compared in the figure. No cooling has been observed.

The model has now been calibrated and can be used to simulate future performance of the reservoir. Predictions of drawdown is shown in Fig. 28 until year 2000.

To calculate actual drawdown in a pumping well the drawdown due to the seasonal variations in the flow rate and the turbulent pressuredrop must be added.

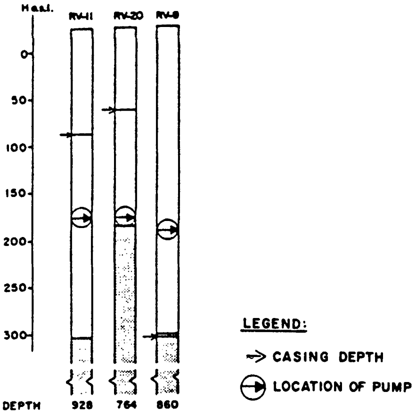

Fig. 29. Location of waterlevel and pumps in production wells in year 2000.

Examples of such results for three pumping wells are shown in Fig. 29 for the year 2000.

The figure indicates the waterlevel in the pumping wells the year 2000 and the present location of the pumps. It is therefore clear from the figure how much each individual pump must be lowered. Significant changes in chemistry are predicted. Increased chloride content causes scaling problems which is very serious for the exploitation of the Laugarnes field. Some of these problems might be diminished by deeper casings. Predicted temperature changes are insignificant.

Example from 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, Figs. 9 and 10. 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 (Thorhallsson 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 240-1,998 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 (12,500 ppm Cl^-).

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 had a 9 5/8″ 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.

Production data, including fluid discharge rate, drawdown, downhole pressure, dissolved solids and gas, and downhole temperature have been collected regularly since the beginning of the operations. 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

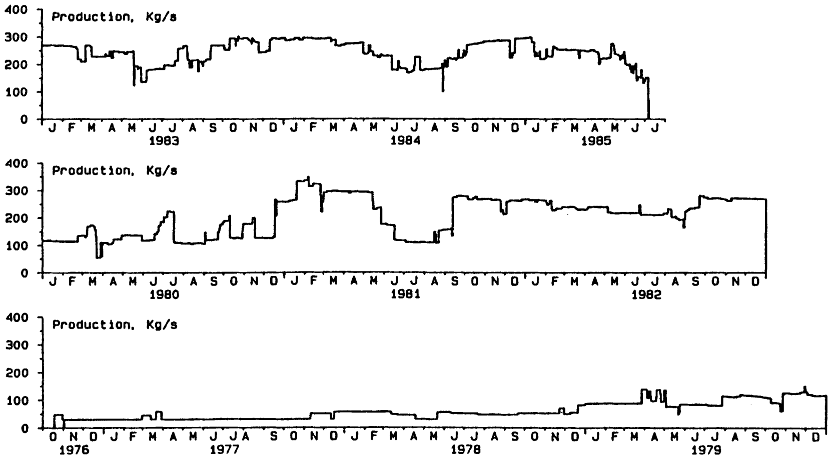

Fig. 30. Svartsengi field, production history.

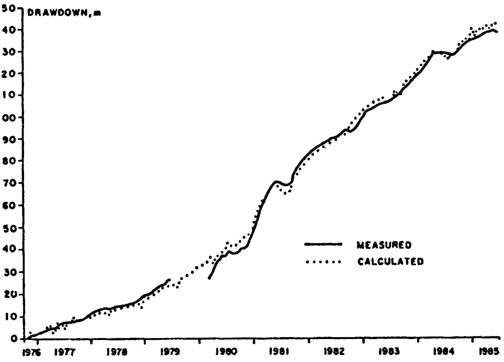

Fig. 31. Measured and calculated drawdown.

1983b) and will be continued.

The production history for the Svartsengi field is shown in Fig. 30. Annual fluid production has been increasing steadily and the cumulative production reached about 45 million tons in 1985.

The waterlevel in an observation well is shown in Fig. 31. The present drawdown is about 140 m.

The pressure response of a geothermal reservoir to the initiation of production differs from one field to another. However two distinctive types of behavior are most frequently encountered. One type represents an infinite acting system and the other a 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.

Fig. 32 shows the drawdown behavior of the Svarteengi field for the first three production years.

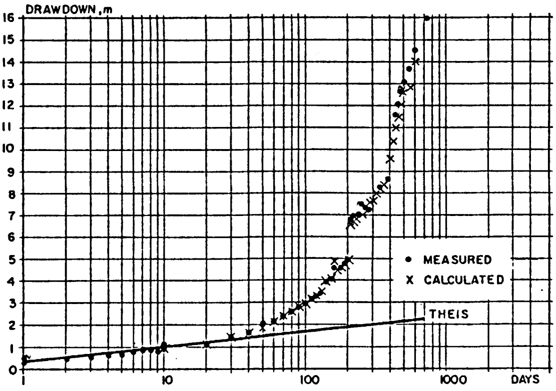

Fig. 32. Measured and calculated initial response.

The early response, which lasts for about 30 days, follows Theis 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 *et al.* 1979). This high value of the storage coefficient clearly indicates delayed yield effects in the Svartsengi reservoir, where this coefficient is the long term value due to the porosity of the reservoir. The Svartsengi reservoir thus behaves like an infinite reservoir for the first few days with the elastic storage coefficient, then it still acts like an infinite reservoir for some weeks with the storage coefficient equal to the reservoir porosity, after that the reservoir boundaries take over and the response is dominated by the boundaries. This example demonstrates how important it is to have continuous registration of the water level (pressure).

According to the geophysical measurements mentioned before and the hydrological evidence above, it is likely that the Svartsengi reservoir behaves like a linear

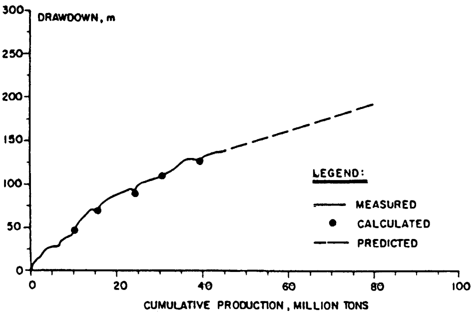

Fig. 33. Drawdown vs. cumulative production.

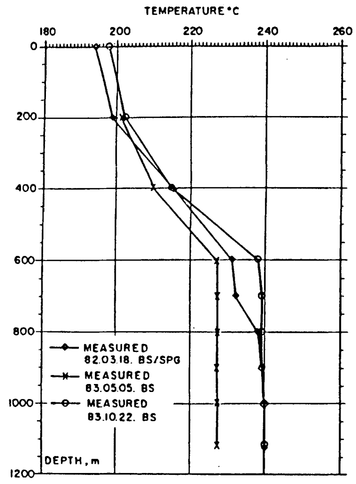

Fig. 34. Measured temperature profile in well SF-11.

structure. The pressure behavior of the system is modelled by an analytical, linear model. The results are shown in Figs. 31, 32 and 33, where measured and calculated drawdown can be compared. Future predictions are shown in Fig. 33.

Calcite scaling takes place inside the production casing where flashing occurs in the production wells, and the deposits are cleaned regularly by drilling. It is important to keep the flashing inside the casing. The present casing depth is about 650 m and the initial flashlevel was at a depth of 400 m so the maximum permissible drawdown is 250 m. According to Fig. 33 this situation is reached when the cumulative production becomes 100 million tons.

Until now no prediction of enthalpy changes have been made. This is due to the fact that no detectable changes in reservoir temperature have been observed. Fig. 34 shows however recent temperature logs from one well in Svartsengi.

The figure 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. The reservoir is clearly more sensitive to events of this kind. Because of large drawdown reinjection into the geothermal reservoir is necessary in the near future in order to recover the reservoir pressure.

The injected water is much cooler than the reservoir fluid so large enthalpy changes can occur. Reinjection experiments have therefore been performed in Svartsengi and now the next step in the research program is to calculate enthalpy variations due to cooling and reinjection.

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