Proceedings Seventh Workshop Geothermal Reservoir Engineering
Stanford, December 1981. SGP-TR-55.

THE REYKJANES GEOTHERMAL FIELD IN ICELAND: SUBSURFACE EXPLORATION AND WELL DISCHARGE CHARACTERISTICS

J. S. Gudmundsson
T. Hauksson
J. Tomasson

Geothermal Division, Orkustofnun
(Iceland Energy Authority)
Reykjavik

Introduction The exploration and development of the Reykjanes geothermal field dates back to about 1956 when the first well was drilled. This well was 162 m deep and had a maximum temperature of 185°C. The chloride concentration of the deep brine was about 25% higher than that of ordinary seawater. The well produced *3-4* kg/s of a steam-brine mixture for over 10 years without a noticeable change in chemical composition (Bjornsson et al. 1971). The fact that the fluid produced was of brine origin but not rainwater affected greatly the course of exploration and development of the Reykjanes field. Most high-temperature geothermal fields in Iceland produce fluids of rainwater origin.

The Reykjanes field was investigated extensively in the years 1968-1970 (Bjornsson et al. 1970, 1971, 1972). This was done in relation to plans to produce 250,000 tonnes/year of not only common salt but various other sea-chemicals for export (Lindal 1975). The investigation showed that the field would be suitable for development. However, the proposed sea-chemicals scheme did not materialize at that time and further geothermal work in Reykjanes was terminated. Four years ago a company was formed to consider again the production of common salt and other sea-chemicals in Reykjanes. Since that time it has conducted pilot plant and other studies to investigate the feasibility of salt production, mainly for the Icelandic market, which is currently about 60,000 tonnes/year. The building of a demonstration plant has now been decided. It is therefore anticipated that the Reykjanes field will come under development in the next few years.

From the time geothermal work was terminated in Reykjanes 10 years ago, two other high-temperature fields have been explored and developed in Iceland (Gudmundsson et al. 1981). These are the Krafla field (Stefansson 1981) in the northeast and the Svartsengi field (Thorhallsson 1979) in the southwest. These two fields are still being developed. While the Reykjanes field waited for development the one production well drilled was kept on discharge. The purpose of this test was to learn about the long-term discharge characteristics of the well/reservoir system. In 1980 extensive output measurements were done on this well, showing both flowrate and enthalpy at various wellhead conditions. The main purpose of the present paper is to report on the long-term discharge test and the more recent output measurements. An important feature of the salt-making in Reykjanes is that the geothermal brine itself will be the source of chemicals, so that the steam-brine mixture produced by the wells will supply both the energy and raw material to the process. The long-term chemical characteristics of the production wells is therefore of great importance. The emphasis of this paper will therefore be on reporting the geochemical nature of the Reykjanes field and the one production well operated for nearly a decade. To provide some background information, the reported subsurface exploration work will be discussed. The extensive surface exploration work of Bjornsson et al. (1970, 1971, 1972) will, however, not be discussed. It is hoped that the present paper may contribute something to the near future drilling and development activities in the Reykjanes field. At the same time it may provide reservoir engineering and other information for those not familiar with geothermal resource developments in Iceland.

Subsurface Exploration In 1968 and 1969 seven boreholes were drilled in the Reykjanes geothermal area. Four of the wells (2, 3, 4 and 8) were deep (301 m, 1165 m, 1036 m and 1754 m, respectively) and encountered both high temperatures and good aquifers, while three wells (5, 6 and 7) were relatively shallow (112 m, 572 m and 73 m) and did not penetrate the hot reservoir. The locations of all the boreholes are shown on Figure 1, which is the resistivity survey map of the area (Bjornsson et al. 1970, 1971, 1972). The surface area of the Reykjanes field has been estimated to be 1-2 km^2, which makes it one of the smallest in Iceland.

Drilling in the Reykjanes field proved to be difficult. Well 2 was never completed because it could not be controlled during drilling once the casing had been run to bottom-hole. Borehole 3 collapsed during initial discharge while well 4 produced for a few weeks before doing the same. This latter well was later

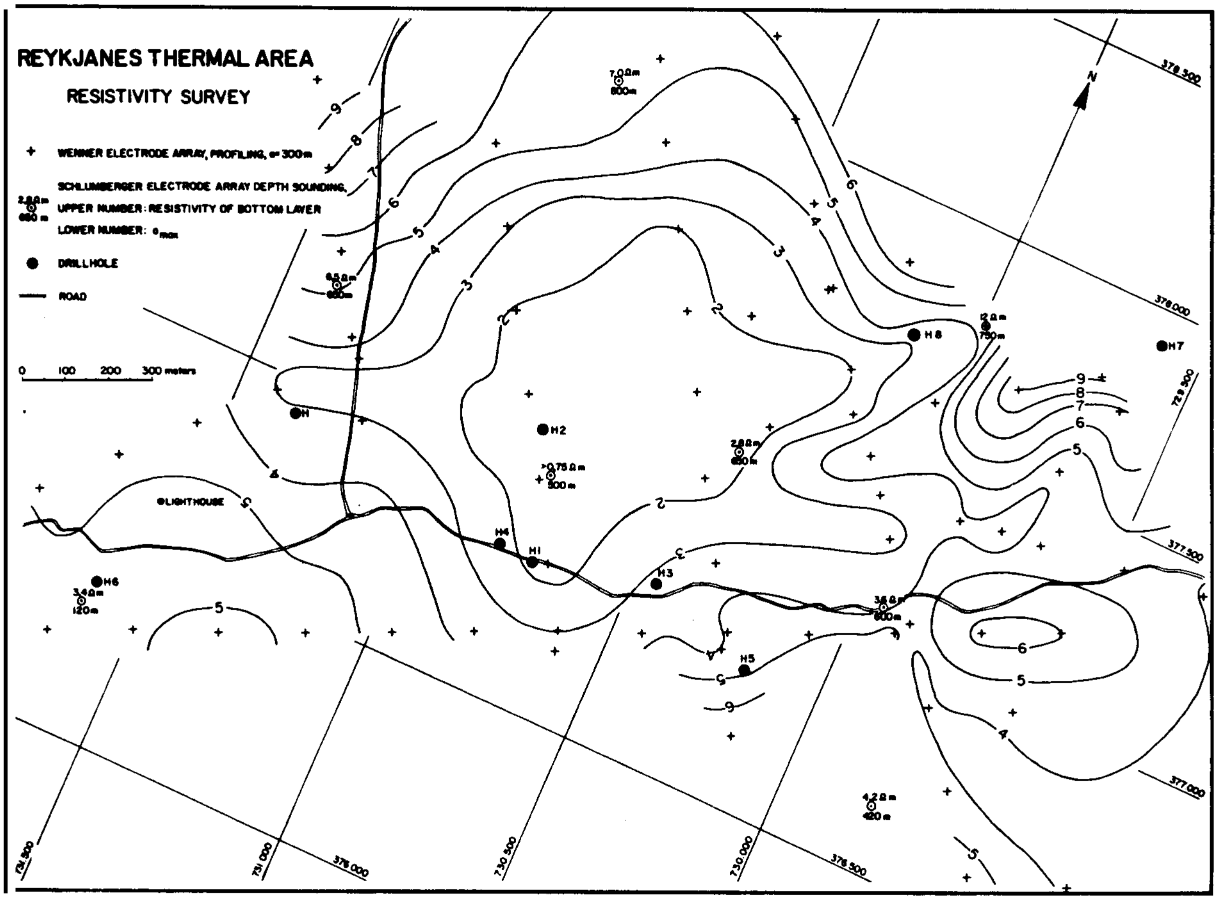

Figure 1: Resistivity survey map of the Reykjanes geothermal area, also showing the location of boreholes (Bjornsson et al. 1970, 1971, 1972).

abandoned after unsuccessful attempts to drill out the collapse. Because of the experiences with wells 3 and 4 it was decided to put a slotted liner to the bottom of well 8. It should be stated here that prior to 1968 it was not the practice in Iceland to put slotted liners in boreholes drilled in high-temperature areas. Until then open hole completion (without slotted liner) had been used with success in several fields. Well hole 8 turned out to be one of the best drilled in Iceland at that time. On initial discharge it delivered about 80 kg/s of a steam-brine mixture with an enthalpy of 1200 kJ/kg. Wells 2 and 4 delivered much less or about 30 kg/s and 20 kg/s, respectively.

The average concentrations of major elements in the deep brines feeding the geothermal wells in Reykjanes are shown in Table 1 (Hauksson 1981). The table shows that the brines are similar in total dissolved solids (TDS) to that of ordinary seawater. Also shown in Table 1 are the well depths and estimated inflow brine temperatures as derived from silica geothermometry. The chloride ion (Cl) concentration expresses salinity and is independent of water-rock thermal equilibria (Arnorsson 1978). It is clear from the table that salinity increases with decreasing well depth and therefore with decreasing brine temperature also. This increase is considered to be due to boiling of the geothermal brine as it rises toward the surface in the reservoir. It should be noted that while the total dissolved solids of the geothermal brines are similar to that of seawater, there are some differences in individual components. These differences are mainly due to ion exchange equilibria between rock and water. The geothermal brines are deficient in magnesium (Mg) and sulphate (SO_4) but enriched in potassium (K) and calcium (Ca). The change in sodium (Na) is not as marked, being less in well 8 than in seawater. The amount of silica (SiO_2) in the geothermal brines is an order of magnitude higher than in seawater, as would be expected from its increased solubility with temperature.

Table 1: Averaqe concentration (mg/kg) of chemical components in geothermal brine in Reykjanes and standard seawater. Also shorn are well depth and estimated brine temperature.

Component	Geyser	Well 1	Well 2	Well 4	Well 8	Seawater
SiO_2	569	414	355	452	588	6.0
Na	14,300	12,400	10,700	10,100	9 520	10,470
K	2,020	1,510	1,400	1,340	1 380	380
Ca	2,400	1,980	1,790	1,640	1 580	398
Mg	56	1.13	-	-	1.43	1,250
SO_4	155	82.2	75.6	74.5	40.8	2,630
Cl	28,900	23,700	20,500	19,800	19 200	18,800
F	0.25	0.15	-	-	0.15	1.26
TDS	50,900	-	34,800	33,800	33,300	33,900
CO_2	42.1	-	2,110	-	1,930	100
H_2S	-	-	43.1	-	36.5	-
H_2	-	-	-	-	0.24	-
Depth (m)	0	162	301	1,036	1,754	-
Temp. (^oC)	100	(220)	225	250	270	-

Subsurface stratigraphy of the Reykjanes field has been constructed by investigation of drill-cuttings and a few cores taken during the main exploration work from 1968-1970 (Tomasson and Kristmannsdottir 1972). It was found that hyaloclastic tuffs and breccias and tuffaceous sediments dominate in the uppermost 1000 m. At greater depths about half the rock is basalt and the rest tuffaceous rocks, mainly sediments. Although the hyaloclastite formation is highly porous, few good aquifers were encountered in the wells drilled. Numerous aquifers were, however, found in the interbeds of the deeper basalt formation. Contacts between lava flows and interbeds are expected to be porous and highly permeable. Faults and fissures seem also to form channels of substantial permeability.

The examination of the drill-cuttings showed that calcite ($CaCO_3$) was found throughout the rock. Although the amount of calcite varied with depth and location it was found to be most abundant in the uppermost *500-700* m. Calcite tends to precipitate out due to boiling when geothermal fluids flow toward the surface in boreholes and reservoirs. It seems likely that calcium rich rocks represent a region of initial boiling in the Reykjanes field. A further evidence for boiling in the upflow zone of the reservoir is the chloride concentration of the brine feeding the geyser and boreholes as shown in Table 1. The chloride concentration shows an increase between wells *8, 4* and *2* from 2% to 5% to 9% higher than that in seawater, the wells being *1754* m, 1036 m and 301 m deep, respectively. The corresponding values for well 1 are 26% and 162 m.

Tne Reykjanes Peninsula is rather flat. The Reykjanes geothermal field is about 20 m above sea-level while the Svartsengi field 15 km to the northeast is about *40* m above sea-level. The hydrostatic pressure on the Peninsula should therefore be rather uniform although there must be some regional gradient away from the hills and mountains to the east or northeast. The volcanic rocks that make up the bulk of the Reykjanes Peninsula are considered highly porous throughout. It is therefore not surprising to find that the ground is saturated with seawater even 30 km inland. Geohydrological studies have indicated that the bulk of the Peninsula is saturated with seawater which becomes more diluted as the hills and mountains are approached. On top of the seawater there is a freshwater lens which exhibits a classical freshwater-seawater interface of coastal aquifers. In the geothermal fields the freshwater lens does not exist because of the upflow of hot water and steam. It has been found that the water table within the Reykjanes field is similar to that of the groundwater table surrounding the system. It follows that there must be some boundary or separation that prevents the cold water from invading the field. It has been argued that accompanying the circulation of cold seawater toward the field and down into the ground, there must occur substantial precipitation of secondary minerals (mainly anhydrite) at the boundary of the thermal system, forming an impervious cap. This will lead to the separation of the hydrothermal system from the surrounding colder seawater. This separation is considered most advanced close to the surface and to decrease progressively downwards.

The amount of deuterium (D) in the deep brine in Reykjanes has been measured (Arnason 1976 and Olafsson and Riley 1978). It was found that the brine in well 8 contained about 23 o/oo less ($\delta D = -23$ o/oo) than standard seawater. Local rainwater contains about 48 o/oo less deuterium than seawater. The usual explanation for the low deuterium concentration of the Reykjanes brine has been that the reservoir fluid was a mixture of seawater and rainwater. The two would mix in near equal proportions (48% and 52%) to result in the measured deuterium value. But the chloride concentration of the geothermal brine is approximately the same as that of seawater as shown in Table 1. This "coincidence" has been attributed to continuous boiling and evaporation of the seawater/rainwater mixture. In the Svartsengi high-temperature field about 15 km away from Reykjanes, the deuterium concentration in the deep brine has been measured (Arnason 1976). Its value is also 23 o/oo less than that of seawater. Typical salinity (Cl) in the Svartsengi field is about 12,600 mg/kg (Thorhallsson 1979), which concentration has been explained as resulting from the mixture of 67% seawater and 33% rainwater (Kjaran et al. 1979). As in the Reykjanes field the 6 D = -23 o/oo value has been explained by continuous boiling and evaporation in the reservoir. However, the "coincidence" of both fields having 6 D = -23 o/oo but different salinities may require an explanation that also satisfies the "coincidence" previously mentioned. It is postulated here that the deuterium concentration in deep geothermal brines is mainly controlled by water-rock interactions. Deep brines are understood here to be geothermal fluids at depths greater than 1 km and which have not experienced evaporation in the main upflow zone of a geothermal field. It should be noted that hydrogen isotope fractionation between OH-bearing minerals and water have been demonstrated in the laboratory (O'Neil and Kharaka 1976, Suzuoki and Epstein 1976). The Reykjanes and Svartsengi fields are in similar geologic environments associated with interactions of seawater, basaltic rock and recent or active volcanism. The alteration minerals that form due to geothermal activity contain numerous hydroxyl (OH) groups that may take part in the proposed isotope interactions with circulating brine. This assumes that hydrothermal alteration progresses continuously during the lifetime of geothermal fields and that seawater behaves differently than freshwater. Seawater has higher ionic concentrations than freshwater so that chemical interaction processes are enhanced. This means that for the above postulate to hold the fractionation of deuterium between hydrothermally altered basaltic rock and geothermal brine could be chemically controlled. This tentative postulate could perhaps be examined by comparing the deuterium content of alteration minerals in Reykjanes with that found in high-temperature fields having water of rainwater origin.

Production Well The feasibility of most geothermal projects depends heavily on the success of drilling. The cost, deliverability and longevity of wells is therefore of major importance. Well 8 in Reykjanes is the only borehole there that has discharged for any length of time. An examination of the experience gained from the 12 years of its operation should therefore be most relevant to the future development of the Reykjanes geothermal field. Also to be considered is what information borehole measurements can contribute to our understanding of the reservoir/well system. Because the geothermal brine in Reykjanes will be put to direct process use as well as for energy purposes, in the production of salt, its chemical as well as other characteristics are of concern.

Well 8 was drilled to a depth of 1754 m. It has a 13 3/8" anchor casing down to 89 m and a 9 5/8" production casing to 297 m, both cemented. It has a 7 5/8" liner from 260 m to a depth of 1685. This liner was placed in the well about one year after drilling. The liner is slotted at four intervals 984-1037 m (49 m), 1122-1308 m (186 m), 1484-1535 m (50 m) and 1624-1685 m (61 m). These intervals were selected because circulation losses had been encountered there during drilling.

The drilling of well 8 was completed on November 28, 1969. Its temperature was measured both during and after drilling. Figure 2 shows a few of these measurements. The temperature log from November 9, 1969, indicated aquifers at depths of about 360 m (300-450 m) and 820 m (750-900 m). The well was first discharged about one year after drilling on October 24, 1970. At that time the bottom-hole temperature was 250-260°C and about 230°C at 750-850 m. On initial discharge the well was kept on a 10" critical lip-pressure nozzle for about two months until January 1971 when it was shut-down. On February 3, 1971, its temperature was measured as shown on Figure 2. The bottom-hole temperature had clearly increased to 280-290°C.

The temperature log taken after the first 2 months of production (February 3, 1971) is of particular interest as it may indicate where flashing starts in the well during discharge. If two straight lines are drawn through the temperature profile, they intersect at a depth of about 910 m. It must be remembered here that the first slots of the liner start at 984 m such that the total flowrate of the well had been developed at that point. The straight line below 910 m may represent the flow of liquid brine at about 290°C from near bottom, being mixed with colder brine as it passes the liner slots. The point of flashing represents the saturation temperature of the brine mixture from the various aquifers. Figure 2 shows this temperature to be about 270°C, the same as indicated in Table 1. Above 910 m the steam-brine mixture flashes continuously and cools

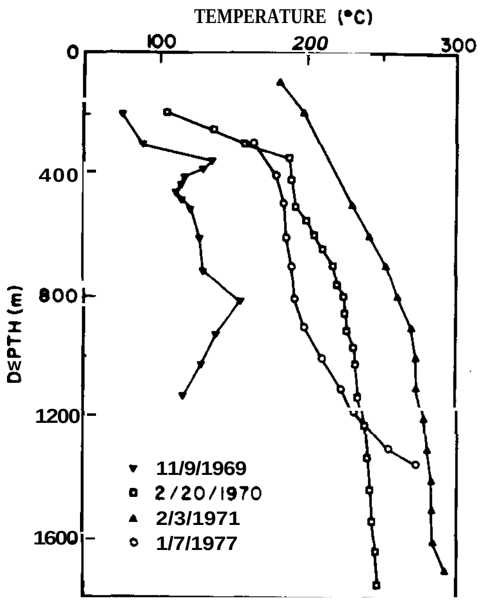

Figure 2: Temperature measurements in well 8 in Reykjanes

as it flows up the borehole. It should be noted that the temperature log of February 3, 1971, was not a flowing survey, but measured shortly after the well had been shut-in. Because the well had produced for a long time and reached stable thermal conditions, the temperature of its immediate surroundings may have approached the temperature profile existing in the well during discharge. It would be of great interest to compare the flashing point estimated above to theoretical borehole calculations for pressure drop and other characteristics of steam-water flows in geothermal wells.

The discharge history of well 8 has been presented by Thorhallsson (1977). Figure 3 shows the well discharge in the first four years of production, from October 1970 to October 1974. When the well was shut-down after the first two months the 10" nozzle was removed and replaced by an 8" one to carry out a deliverability test as discussed below. When this test was over, the well was again shht-down and fitted with a 4" nozzle. The well discharged through this nozzle for long periods but was temporarily (few hours) shut-domi and fitted with the 8" nozzle (critical lip-pressure) for all subsequent (instantaneous) flowrate measurements.

The initial discharge of well 8 was about 85 kg/s through the 10" nozzle to the atmosphere. When it was fitted with the 8" nozzle, two months later, its maximum flowrate was about 70 kg/s (deliverability test January 1971) whereas by 1974 this had decreased just below 60 kg/s, the well-head pressure being about 6 bar-a. Thorhallsson (1977) estimated that the long-term discharge of the well with the 4" nozzle may have been 45-55 kg/s during the first four years shown in Figure 3. The well was shut-in for three years from October 1974 to October 1977.

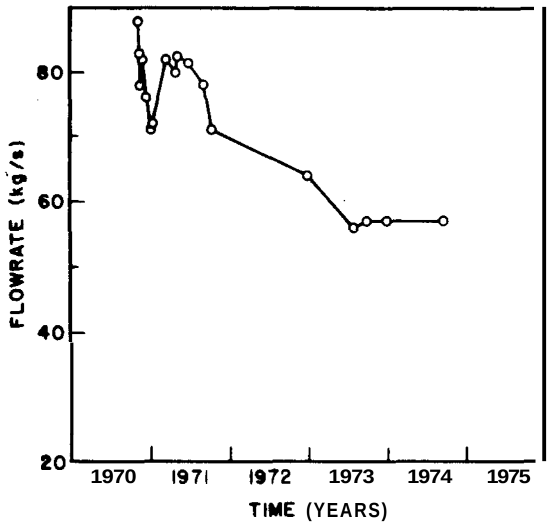

Figure 3: Discharge history of well 8 in Reykjanes

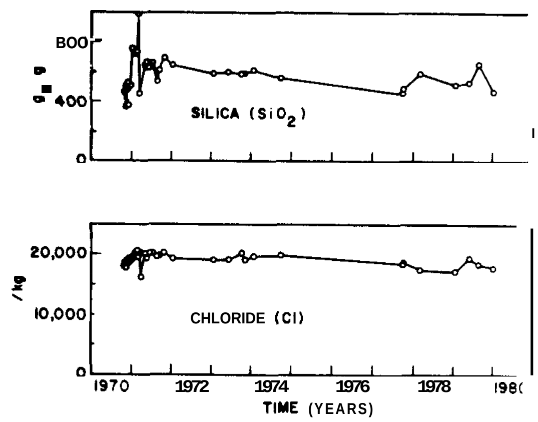

Figure 4: Silica and chloride concentration with time in the deep brine of well 8 in Reykjanes

The discharge history curve of well 8 in Figure 3 shows several features of interest. Before considering these the corresponding changes in deep brine chemistry will be examined. Figure 4 shows the silica (SiO_2) and chloride (Cl) concentrations with time, not only the first four years, but also later measurements (Hauksson 1981). The silica concentration changed from about 470 mg/kg in October 1970 to about 730 mg/kg in February 1971.

This corresponds to an apparent increase in deep brine temperature from about 250°C to over 280°C according to silica geothermometry. During the same period the chloride concentration increased from about 18,000 mg/kg to 20,000 mg/kg. From the time of initial discharge the concentration of most major elements in the deep brine have however been found to remain fairly constant (Hauksson 1981). It is perhaps of interest to note that the same conclusion had been arrived at from the monitoring of well 1 from 1956 to 1966.

During the first two months of full discharge the flowrate of well 8 decreased from about 85 kg/s to 70 kg/s. At the same time the silica concentration of the deep brine increased, indicating a temperature increase from about 250°C to 280°C. There appear to be two main explanations why the flowrate decreased and the indicated temperature increased during initial discharge. The first is that the well initially may have produced fluids that were influenced by cold water injected when the slotted liner was placed in the well. It must be remembered, however, that the slotted liner was run into the well about one year after the drilling finished. The second explanation is that the deeper feed zones (aquifers) of the well are more permeable than the upper feed zones. Therefore, when the well starts discharging at high flowrates (70-80 kg/s), there occurs greater drawdown in the upper feed zones compared to the deeper zones. The result of this would be that the contribution of the upper feed zones to the total well flowrate would decrease more rapidly with time than that of the deeper and hotter feed zones.

#en well 8 was put on long-term discharge through the 4" nozzle to the atmosphere in January 1971, the total long-term steam-brine flowrate decreased from the 70-85 kg/s in the initial period to the estimated 45-55 kg/s, as mentioned above. When the well was measured in March 1971 the total (instantaneous) flowrate through the 8" nozzle was 80 kg/s or about 10 kg/s greater than that measured with the 10" nozzle at the end of the initial two months' discharge period. The problem at hand is to explain why the flowrate increased. The silica concentration of the inflow brine seemed also to have decreased to a value at which it remained after that. A possible explanation is that at the lower long-term flowrate of 45-55 kg/s, as compared to 70-85 kg/s, there is less drawdown in the aquifers feeding the well. Each 8" nozzle test lasted a day or two during which time further drawdown presumably did not develop to affect the discharge flowrate. An instantaneous measurement using the 8" nozzle should therefore result in a higher flowrate than at conditions of greater drawdown when discharging for two months through the 10" nozzle.

From 1971 to 1974 the 8" nozzle (instantaneous) flowrate of well 8 decreased from over 80 kg/s to under 60 kg/s. The long-term flowrate (between each measurement) was much lower or 45-55 kg/s. An examination of Figure 3 shows that the total flowrate declines in a fashion where drawdown is increasing. It should be noted that the total flowrate declines smoothly with time, also, that the rate of decline 1971-1974 (flow 45-55 kg/s) is much lower than 1970 (flow 70-85 kg/s). There is some other evidence to support the above suggestion that drawdown in well 8 has increased with time. In 1970 the water level in the well was at about 40 m while in 1979 it was at 109 m (Bjornsson et al. 1971 and Gudmundsson 1980). In both instances the well was in near thermal equilibrium with the reservoir, i.e., not filled with cold water after drilling.

In the autumn of 1977 the wellhead of borehole 8 was overhauled after three years of shutdown (Thorhallsson 1977). The temperature in the well was measured as shown in Figure 2. It was found that the well was blocked at a depth of about 1370 m and that the temperature was very different from that measured before. The temperature profile had assumed an s-type curve with an inflection point at about 820 in depth. Several simple caliper (wire frame) measurements were made in the 7 5/8" slotted liner. It was found that in addition to a blockage at 1369 m, there appeared to be a minor restriction at 704 m and a major one at 841-845 m. The well was discharged on October 3, 1977, through an 8" nozzle. After two days the total flowrate was measured (critical lip-pressure method) to be 43 kg/s and the wellhead pressure 4 bar-a. On October 5, 1977, the well was shut-down temporarily and fitted with a 4" nozzle to produce 37 kg/s at a well-head pressure of 17 bar-a the following day. The discharge rate was therefore almost independent of wellhead pressure, indicating some restriction (choking) in the wellbore. #en the well was shut-in three years earlier the discharge through the 8" nozzle had been just under 60 kg/s so that the flowrate had decreased by about 1/3. It seems that this loss of production could be attributed to the wellbore blockages. Silica geothermometry of samples collected at the time of the above discharge measurements indicated deep brine temperatures just above 270°C as before. Because of the blockages found in well 8 in 1977, a difficulty arises with respect to the flowrate decline during 1971-1974 shown in Figure 3. It is possible that all or some of the decline was due to gradual wellbore blockage rather than drawdown in the main feed zones of the well. For the time being, however, it will be assumed that the two are separate because the flowrate decline is gradual while casing/liner failures are likely to occur suddenly, for example, when wells are put on discharge after long standing periods. Well 8 was again shut-down in July 1978 for further simple caliper measurements which confirmed earlier results. The well was then kept on production until November 1978 when it was shut-down for repair in the following December. This repair or work-over was done with a 6 3/8" drill-bit down to about 750 m and then a 6" drill-bit to bottomhole. The detailed results of this work-over are not yet well understood. After the work-over the well may have no liner at depths of 630–725 m and where the two main blockages were found as indicated above.

The deliverability of geothermal wells expresses their total flowrate against back pressure Two main deliverability measurements have been carried out on well 8, the first in 1971 and the second in 1980. The former was done using the critical lip-pressure method where the brine enthalpy was determined by silica geothermometry (Bjornsson et al. 1971). The latter was similarly based on the critical lip-pressure method but involved also the determination of the brine flowrate when the total mixture had flashed at atmospheric conditions. By this improved method the enthalpy of the steam-brine mixture could be determined independently (Gudmundsson 1980). The two deliverability tests are shown in Figure 5. The measurements in 1971 were carried out in one dav at the end of the initial discharge period (see above), The well was fitted with an 8" nozzle and the flowrate was adjusted by *e* valve, the readings being taken one or two hours later. The measurements in 1980 were taken over a period of four days. The well had been discharging almost continuously for one year with a wellhead pressure of 20-30 bar. The conditions under which the two deliverability tests were taken were therefore quite different. The 1980 test was carried out using 3", 5" and 7" nozzles. When changing nozzles the flow was directed through a by-pass line to minimize all pressure and temperature transients in the reservoir-well system. Each nozzle was allowed at least one day to adjust to stable wellhead pressure and flowrate values. Two sets of measurements were taken for each nozzle, the first after one day of adjustment and the second about 2 hours after decreasing the flowrate by a valve When using the 7" nozzle, however, two more sets of measurements were taken, also two hours after adjusting the flowrate.

The enthalpy of the steam-brine mixture was measured in the 1980 deliverability test. A chemical sample was also taken (January 8, 1980) and the temperature of the deep brine estimated from silica geothermometry. All these measurements are shown in Figure 6. The enthalpv of the steam-brine mixture was found *to* depend on the wellhead pressure and decreasing flowrate. This seems to indicate that the upper aquifers feeding the borehole are not as permeable as the deeper aquifers. Two measurements were taken for each nozzle/valve setting. When the wellhead pressure was increased the first time, for all the nozzles, the enthalpy did not change. However, after the second and third wellhead pressure changes when using the 7" nozzle, the enthalpy decreased. This may indicate that the pressure and thermal conditions in the reservoir-well system had not reached stable conditions. The deep brine temperature estimated from silica geothermometry is shown in Figure 6. It indicates basically the same enthalpy as obtained from the direct measurements. The saturation curve for steam-water is shown in Figure 6 for reference.

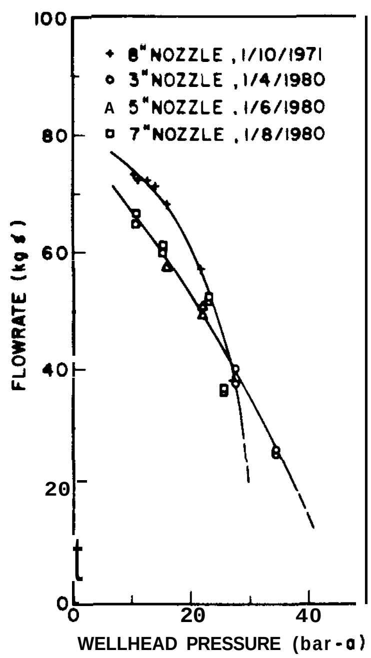

Figure 5: Deliverability measurements of well 8 in Reykjanes

<u>Concluding Remarks</u> Twenty-five years have now passed since the first exploration was initiated in the Reykjanes field. The main exploration work was, however, carried out about 10 years ago so that the early work (25 years ago) is mainly of historic interest. Nevertheless an important issue must be how the example of Reykjanes reflects on the future development of geothermal energy. In addition 'to what has already been stated above, the following aspects may be considered: (1) The results of the first exploration work influenced the way in which the resource may be used; (2) The pioneering nature of the sea chemicals scheme, as proposed about 15 years ago, was an important reason for the lack of development of the Reykjanes field; (3) Although the main

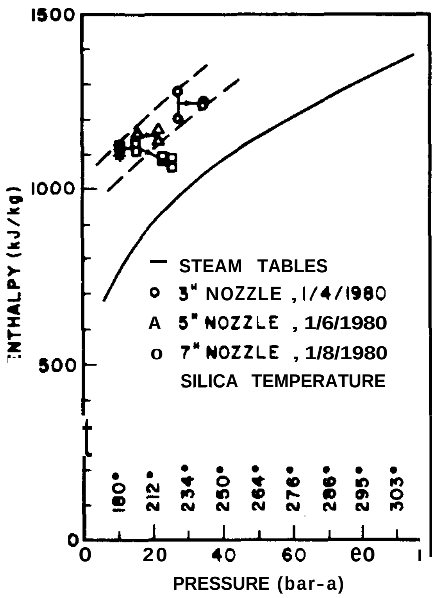

Figure 6: Enthalpy measurements of well 8 in Reykjanes

exploration phase (ten years ago) lasted only 3 years the basic results are still considered valid. There have, however, been advances in several areas of geothermal exploration and evaluation that should be applied to the field now.

The problems experienced in the drilling and discharging of the Reykjanes wells were new in Iceland. They had not been met in other fields and indicated that perhaps each geothermal area should be treated as unique. This view was, however, not arrived at until much later when further experience from other fields showed that experience gained in one geothermal field was not necessarily applicable to others.

Drilling in geothermal fields provides direct access to the energy resource in the ground. In exploration it should give information about the nature of the reservoir with respect to the translation of thermal energy into power. An important consideration in this translation must be the natural circulation of fluids in the geothermal reservoir. Geochemistry, both that of the water and the rock, has the potential of providing such information. It is well established that the Reykjanes field produces a deep brine having salinity similar to that of seawater. The origin of the geothermal brine is, however, still a subject of discussion. The isotope chemistry of the brine has puzzled investigators and will probably continue to do so for some time yet. In this paper a hypothesis is set forth as to the origin of the deep brine. It is suggested that water-rock interactions influence the deuterium content of the deep brine. This is very much a tentative suggestion but should nevertheless warrant consideration.

The feasibility of geothermal projects depends greatly on the success of drilling. Factors of importance in this success are the cost of drilling and also the deliverability and lifetime of boreholes. These two latter issues are explored in this paper by way of well 8 in Reykjanes as an example. The lifetime of boreholes, as the term is used here, concerns their mechanical condition mainly. It is evident that geothermal wells will generally experience difficult temperature and pressure transients. These may lead to failures resulting in permanent damage. The experience gained from well 8 in Reykjanes shows that great care is called for in the operation of high-temperature boreholes. The cementing of casings appears to be one of the most important factors in prolonging the lifetime of geothermal wells. Avoiding severe temperature transients in wells will aid in their successful operation In addition to casing and liner failures, problems may arise due to the deposition of calcite ($CaCO_3$) and other materials in the wellbore. Such problems tend to be field specific, while their solution (cleaning) usually involves drilling. Such workover operations will inevitably put strain on boreholes and may lead to failures as already mentioned.

Measurements of the deliverability of geothermal wells (well characteristics) are used for three main purposes: To specify steam-water transmission lines/equipment and power plants; To aid in the exploration for good production fields in geothermal areas, and; To monitor the performance of wells with time once under production. Such tests do not require the shut-down of wells and should therefore not introduce great temperature transients downhole. Deliverability tests will continue to provide the reservoir engineer with firsthand measurements of some of the dynamic fluid and heat flow processes taking place underground.

Acknowledgment

The authors would like to thank V. Stefansson, B. Steingrimsson and B. Lindal for reading the draft of this paper.

References

Arnason, B., 1976: Groundwater Systems in Iceland Traced by Deuterium, Soc. Sci. Isl., Pub. No. 42, 236 pp.

Arnorsson, S., 1978: Major Element Chemistry of the Geothermal Sea-water at Reykjanes and Svartsengi, Iceland, Mineral Mag., 42, 209-220.

Bjornsson, S., Arnorsson, S., and Tomasson, J., 1970: Exploration of the Reykjanes Thermal Brine Area, Proceedings, U.N. Symp. Development Utilization Geothermal Resources, 2, (2), 1640-1650.

Bjornsson, S., Arnorsson, S., Tomasson, J., Olafsdottir, B., Jonsson, J., and Sigurmundsson, S. G., 1971: Reykjanes--Final Report on Exploration, Iceland Energy Authority, 122 pp. (In Icelandic).

Bjornsson, S., Arnorsson, S., and Tomasson, J., 1972: Economic Evaluation of Revkianes Thermal Brine Area, Iceland, Am. Assoc. Pet. Geol. Bull., 56, (12), 2380-2391.

Georgsson, L. S., 1981: A Resistivity Survey on the Plate Boundaries in the Western Revkjanes Peninsula, Iceland, Geoth. Resources Council Trans., 5, 75-78.

Gudmundsson, J. S., 1980: Discharge Measurements of Well 8 in Reykjanes, Iceland Energy Authority, Note JSG-80/01, 16 pp. (In Icelandic).

Gudmundsson, J. S., Thorhallsson, S., and Ragnars, K., 1981: Status of Geothermal Electric Power in Iceland 1980, Proc. Fifth E.P.R.I. Annual Geoth. Conf. Workshop, 7/52-7/65.

Hauksson, T., 1981: Reykjanes--Concentration of Chemicals in Geothermal Brine, Iceland Energy Authority, Note TH-81/04, 53 pp. (In Icelandic).

Kjaran, S. P., Halldorsson, G. K., Thorhallsson, S., and Eliasson, J., 1971: Reservoir Engineering Aspects of Svartsengi Geothermal Area, Geoth. Resources Council Trans., 3, 337-339.

Lindal, B., 1975: Development of Industry Based on Geothermal Energy, Geothermal Brine and Sea Water in the Reykjanes Peninsula, Iceland, Proc. Second U. N. Symp. Development Use Geothermal Resources, 3, 2223-2228.

Olafsson, J., and Riley, J. P., 1978: Geochemical Studies on the Thermal Brines from Reykianes (Iceland), Chem. Geol., 21, 219-237.

O'Neil, J. R., and Kharaka, Y. K., 1976: Hydrogen and Oxygen Isotope Exchange Reactions Between Clay Minerals and Water, Geochimica et Cosmochimica Acta, 40, 241-246.

Stefansson, V., 1981: The Krafla Geothermal Field, Northeast Iceland. Ryback, L., and Muffler, L.J.P. (eds.), Geothermal Systems, Wiley, 273-294.

Suzuoki, T., and Epstein, S., 1976: Hydrogen Isotope Fractionation Between OH-bearing Minerals and Water, Geochimica et Cosmochimica Acta, 40, 1229-1240.

Thorhallsson, S., 1977: Well 8 in Reykjanee, Iceland Energy Authority, Note OS-JHD-7730, 9 pp. (In Icelandic).

Thorhallsson, S., 1979: Combined Generation of Heat and Electricity from a Geothermal Brine at Svartsengi in S.W. Iceland, Geoth. Resources Council Trans., 3, 733-736.

Tomasson, J., and Kristmannsdottir, H., 1972: High Temperature Alteration Minerals and Thermal Brines, Reykjanes, Iceland, Contr. Mineral. Petrol., 36, 123-134,