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Exploration and Development of the Hveravellir Geothermal Field, N-Iceland

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ABSTRACT

The Hveravellir geothermal field, N-Iceland is one of Iceland's traditionally famous geothermal fields with its boiling hot springs and spouting geysers. The geothermal activity is mainly located on N-S trending lineaments, and limited to an area of 1600 m x 300 m. Total natural discharge from the geothermal field was 55-60 l/s prior to drilling. The largest hot spring is Ystihver, that discharged 17-19 l/s, prior to drilling, and has been reported to erupt to a height of 15-25 m for a period of 1/2 -1 minute.

According to geophysical data, the main fracture system in the area is a N-S trending one, involving several faults/fractures. Most of the surface geothermal activity is located along these faults, and the main hot springs found where they are intersected by structures or fractures of different trend, NW-SE, or NNE-SSW. The recharge towards the field appears to be from southeast. Geochemical data indicates reservoir temperatures close to 130°C.

In the late 1800s, Hveravellir or Reykir (the old name) became a centre for vegetable cultivation, and later a greenhouse industry, utilizing the benefits of the geothermal heat. In 1970, it was decided to develop the field further to provide hot water for space heating of Husavik, a town with a population of about 2500, located on the coast, about 18 km north of the geothermal field. An asbestos pipeline was constructed to connect the Husavik district heating system to the Hveravellir hot springs. Growing population and utilization called for more hot water, so in 1974, a 450 m deep well, HV-1 was drilled, that gave in free flow 44 l/s of 126°C hot water. Utilization was, however, limited to temperatures below 100°C due to the properties of the pipeline. In the late 1990s new ideas for utilization of geothermal water at Husavik, both for industrial purposes and electrical production, led to a new exploration effort, involving gradient wells and drilling of new production wells, HV-10 (61 l/s 124°C) and HV-16 (8 l/s 116°C). The total free flow from the three production wells is now 95 l/s of 124°C hot water. A new main steel pipeline and the new Husavik Energy Centre were completed in 2000, providing heat, steam and electricity, through a Kalina binary system, for the town of Husavik.

1. INTRODUCTION

The Hveravellir field in Reykjahverfi is the largest low-temperature geothermal field in N-Iceland, located on the western flank of the volcanic rift zone (Figure 1), and traditionally, the most famous one due to its large hot springs and spouting geysers. Historically, the geothermal field belonged to the Reykir farm and its crofts (reykir meaning steam or smoke), and was referred to as the Reykir or Storureykir field. The old Reykir farm was divided into several independent farms, with most of the major hot springs belonging to the Hveravellir greenhouse farm, which is its modern name.

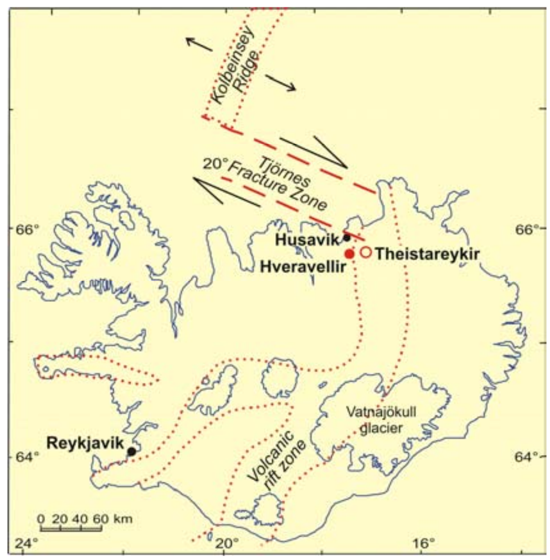

Figure 1: Location of the Hveravellir geothermal field, N-Iceland.

Due to the geyser activity travellers usually stopped at Reykir for observations and investigations. Thus, many descriptions of the geothermal activity by visitors in earlier centuries exist, the earliest from 1699. Utilization of the water was limited to washing, bathing and cooking, until late in the 19th century, when potato growing in warm ground near the hot springs started, later developing into the Hveravellir greenhouse farm. Now, the Hveravellir geothermal field does not only supply hot water to the greenhouse farm, the community centre and some 55 farms in the surrounding area, but also provides hot water for the town Husavik, located at the coast 18 km to the north, with a population of 2500. At the Husavik Energy Centre the hot water is used for electrical power production with a Kalina binary system, and distributed for district heating, bathing, snow melting, fish farming and industrial use in the town.

Scientific interest has several times been focussed on the Hveravellir geothermal field (Grönvold, 1973; Georgsson, 1977; Georgsson et al., 1982; Olafsson, 1999). The paper describes the geothermal activity and gives an overview of geothermal exploration, drilling, and utilization of the geothermal resource.

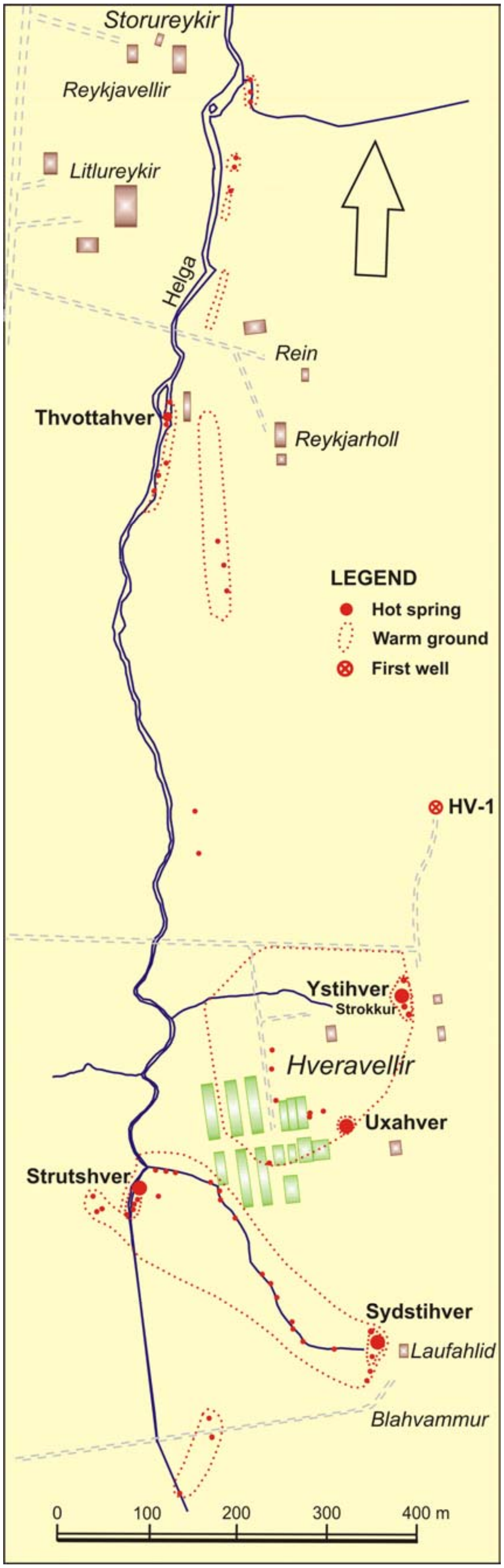

Figure 2: The Hveravellir geothermal field showing the locations of the geothermal manifestations.

2. THE GEOTHERMAL ACTIVITY

2.1 The Hveravellir geothermal field

The geothermal activity of the Hveravellir field is distributed over an area of 1600 m x 300 m, trending N-S. There are six major hot springs, but numerous smaller warm and hot springs are found in the area. Three of the hot springs have a long record of geyser activity (Thoroddsen, 1910; Thorkelsson, 1920). The northern part of the geothermal field follows a line trending N10°E. The distribution is more complicated in the southern part where the largest hot springs are found. The N10°E lineament is still active but here the three largest hot springs are located on a different N-S trending lineament, located 200-300 m to the east. Before drilling the total natural flow from the geothermal field is estimated to have been 55-60 l/s, with the six major hot springs yielding about 50 l/s. All the major hot springs are at the boiling point, or close to it. After drilling of production well HV-1 in 1974 the discharge from some of the hot springs diminished slightly, and the total discharge from the geothermal field was estimated to be about 50 l/s (Georgsson et al., 1982). The drilling in 1997-1998 again resulted in a decrease in the discharge from the major hot springs, their total flow now being between 35 and 40 l/s, while the wells are in production. Figure 2 shows a geothermal map of the field.

2.2 The major hot springs

The following are the major hot springs of the Hveravellir field (from north to south):

Thvottahver ("Laundry hot spring"). A circular pool on the bank of the Helga river. The temperature is 95°C and the flow 2-3 l/s. As the name indicates, it was used for laundry, and later for district heating of the surrounding farms. It is not utilized today.

Ystihver ("Northernmost hot spring.") is the largest hot spring in the field. It has formed a large circular bowl of silica deposits, roughly 10 m in diameter, around the opening (Figure 3). Fractures seen in the silica deposits trend N10°E, but also N30°E towards Uxahver. The temperature is at the boiling point. Before drilling the flow was measured at approx. 22 l/s. These measurements, however, include warm groundwater (3-5 l/s) collected around the hot spring, so the actual flow of Ystihver hot spring is believed to have been 17-19 l/s. After the drilling of well HV-1, 200 m to the north the flow was reduced to about 15 l/s. Drilling of new production wells in 1997-1998 again affected the flow from Ystihver, reducing it to about 13 l/s. The water flowing from Ystihver is collected into a concrete channel for utilization.

Figure 3: The Ystihver hot spring and its large circular bowl of silica deposits (photo from 1982 by L.S. Georgsson).

Ystihver is now the main geyser at Hveravellir, and the biggest one found in low-temperature fields in Iceland (Figure 4). In the 1700´s and 1800´s it rarely erupted and only ahead of major changes in weather (coming of a low-pressure zone). The height of the eruption column is cited as approximately 4-5 m. In 1904, the water level in the hot spring's bowl was lowered by about 25 cm, resulting in much larger and more frequent eruptions. The highest eruption columns have been estimated to reach 15-25 m, and the eruptions lasting 30-60 seconds. With the utilization of the water from Ystihver in 1970, the water level was increased again to prevent eruptions. However, Ystihver can still erupt with the assistance of some soap inserted into it. It did so with vigour when tested in July of 2004, at a time when discharge from the wells was at a minimum, due to maintenance in Husavik Energy Centre.

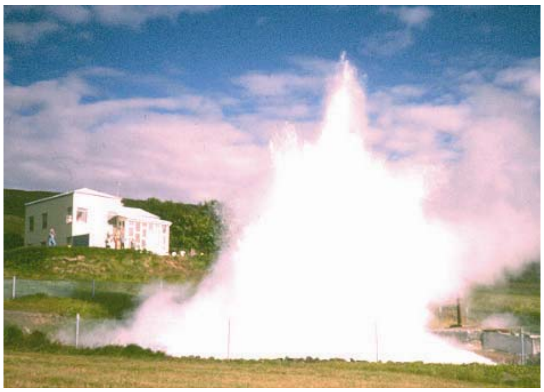

Figure 4: Ystihver erupting in 1996. The height of the eruption column is 8-10 m. The concrete cistern covering Strokkur is seen in the lower right corner (photo by L.S. Georgsson).

Strokkur ("the Churn") is about 3 m south of the Ystihver bowl. It has also formed a bowl of silica (2x3 m). The temperature is at the boiling point and the flow is about 2 l/s. A covered concrete cistern has been built around Strokkur so the bowl can not be seen today. The water from Strokkur has been used for the local swimming pool and community centre.

Uxahver ("Ox hot spring"). A large hot spring that has also formed a large silica bowl, elliptical in shape and with the dimensions 2.5x3.5 m. The temperature is at boiling point and the flow 8-9 l/s. In 1970, the hot spring was covered with a concrete cistern to aid the utilization of the water. Drilling may have reduced the flow from Uxahver slightly, but its exact discharge has not been measured recently.

Uxahver was in earlier centuries the most famous geyser in N-Iceland (Figure 5). Most accounts mention frequent, 10-20 feet high eruption columns, up to a maximum of 30 feet around 1870 (Thoroddsen, 1910). Eruptions were usually accompanied by a rumbling noise that may have been the reason for the name, referring to the bellow of an ox. After the large earthquakes in the Husavik area in 1872, no eruptions were recorded for several years. But around 1900, Uxahver had started erupting again and in 1904 to about 3 m every 5 minutes (Thorkelsson, 1920). The water level was lowered by about 25 cm in 1904 by deepening the outflow channel. This resulted in lowering of the eruption columns to about 2 m but increased the frequency of the eruptions. At the time of covering (1970), the status was similar. It is probable that geyser action can be restored if the hot spring would be uncovered.

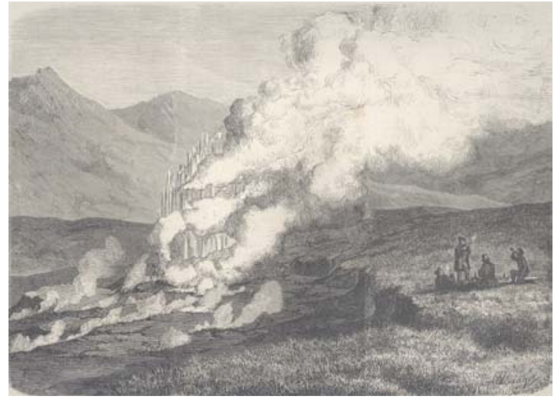

Figure 5: Eruption in Uxahver around 1860 (drawing by Carl Baagoe).

Strutshver ("Conic hot spring"). A large boiling hot spring in the Helga river, with two main openings and no silica deposits. The main flow is from the northern one, about 8 l/s, that has now been covered with a concrete cistern for utilization. Strutshver does not seem to have been affected much by drilling, probably due to its low elevation.

Sydstihver ("Southernmost hot spring"). There are two openings in one large pool but no silica deposits. The temperature is at the boiling point and the flow was 11 l/s before drilling, and did not change much after the drilling of well HV-1 in 1974. It was covered with a concrete cistern in 1970. In the early 1990's, the level of the water was heightened, probably resulting in the considerable decrease of flow that was experienced in the 1990's down to about 5 l/s. The drilling of well HV-16 in 1998 led to a further reduction of the flow from Sydstihver, to 2-2.5 l/s.

Sydstihver was a geyser, with frequent eruptions of either of the openings or both simultaneously, to a height of 1-3 m. Eruptions seem to have stopped after major earthquakes in 1872, and no younger accounts exist of them.

3. GEOTHERMAL EXPLORATION AND PRODUCTION DRILLING

3.1 Geological setting

The Hveravellir geothermal field is located at an elevation of 150-160 m a.s.l. in a shallow valley in Reykjahverfi, North-Iceland. The valley is asymmetric. The eastern side comprises the 300 m high Mt. Reykjafjall which is made up of early Quaternary strata which dip 3-4° to the east. The western side is less than 50 m high consisting of a late Quaternary valley filling. At Nes 4 km west of Hveravellir it was found by drilling to extend 300 m below sea level. Half of this is a single eruptive unit formed by the hyaloclastite and lavas of Hvammsheidi. Figure 6 shows the main geological structures of the Reykjahverfi area and its surroundings.

The N-S trending active volcanic rift zone is 7-8 km to the east and the Tjörnes Fracture Zone 12 km to the northeast (Figure 1). In the active rift zone faults, ground fissures and eruptive fissures trend on average N5°E. These belong to the Theistareykir volcanic system (Figure 6). The core area of this system hosts a high-temperature geothermal field which is elongated east-west. Its westernmost outlier of altered rock is found in eastern Lambafjöll mountains, 9 km to the east of Hveravellir. Faults of the Tjörnes Fracture Zone trend primarily NW-SE and N-S. They are strike slip or oblique faults. South of the main faults at the southern margin of the Tjörnes Fracture Zone NW-SE faults are found across Lambafjöll, but they have not been traced across the 300-400 m high plateau west of them to Hveravellir.

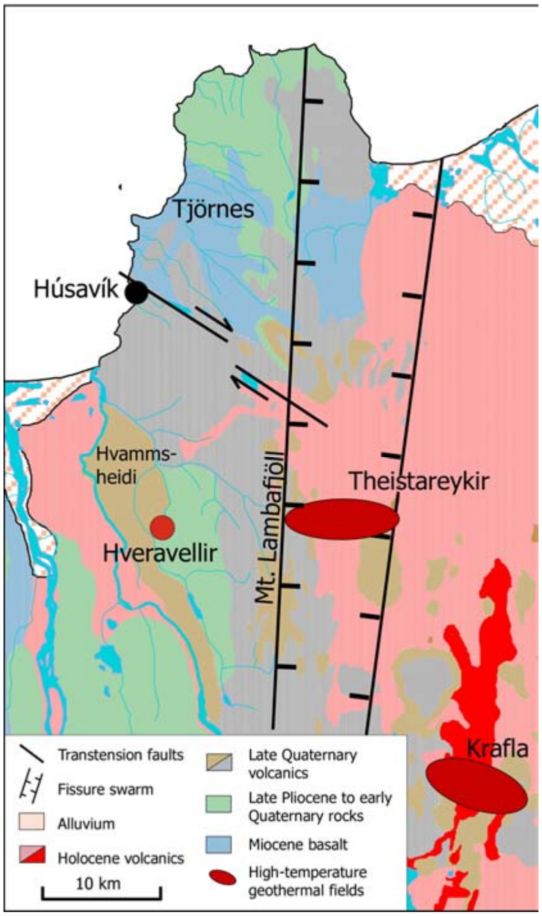

Figure 6: The main geological structures in the Reykjahverfi area and its surroundings.

The rocks of Reykjafjall consist of basalt flows, hyaloclastites and sedimentary beds. They are transected by dykes and faults, that trend about N10°E. Zeolitization of the near surface volcanic pile is distinctly of a type that correlates with the chabazite-thomsonite zone, which means that primary permeability of the rock is already strongly reduced. The rock sequence increases in age with depth. Common averages for Iceland would indicate about 1 million years per 1000 m of rock. At the same time secondary alteration increases to a degree that primary permeability gradually becomes negligible. This is clearly seen from borehole logs from the area (Fridleifsson, 1998).

The area is seismically very active as the name Skjalfandafloi (Figure 7) or "the Bay of Quakes" infers. The last destructive earthquakes date from the late 1800's. In 1872, large earthquakes associated with movement along the Tjörnes Fracture Zone hit the Husavik area. Many houses were destroyed or damaged, and large surface fractures opened with widths up to 1 m. The Husavik earthquakes appear to have had a significant effect on the Hveravellir geothermal field. Sydstihver stopped erupting and Uxahver ceased to erupt for some years. The area was trembling again in 1884-1885. This time it was the Theistareykir fissure swarm (Figure 6) that was undergoing a rifting episode. During the 1900's a few minor seismic events have hit the Husavik area, but not with the same force as those of the 1800's.

3.2 Regional resistivity

A number of Schlumberger soundings measured in the Reykjahverfi and Adaldalur region in the late 1970's show the main resistivity distribution (Georgsson et al., 1976; Georgsson, 1977). Figure 7 is a resistivity map of the area at 500 m depth below sea level. A striking low-resistivity anomaly is associated with the geothermal field at Hveravellir, with a resistivity of 13-25 ohm-m that stretches for 4-6 kilometres north and south from Hveravellir. The boundaries are fairly sharp, except in the east towards Mt. Reykjafjall and the volcanic rift zone, for which no data

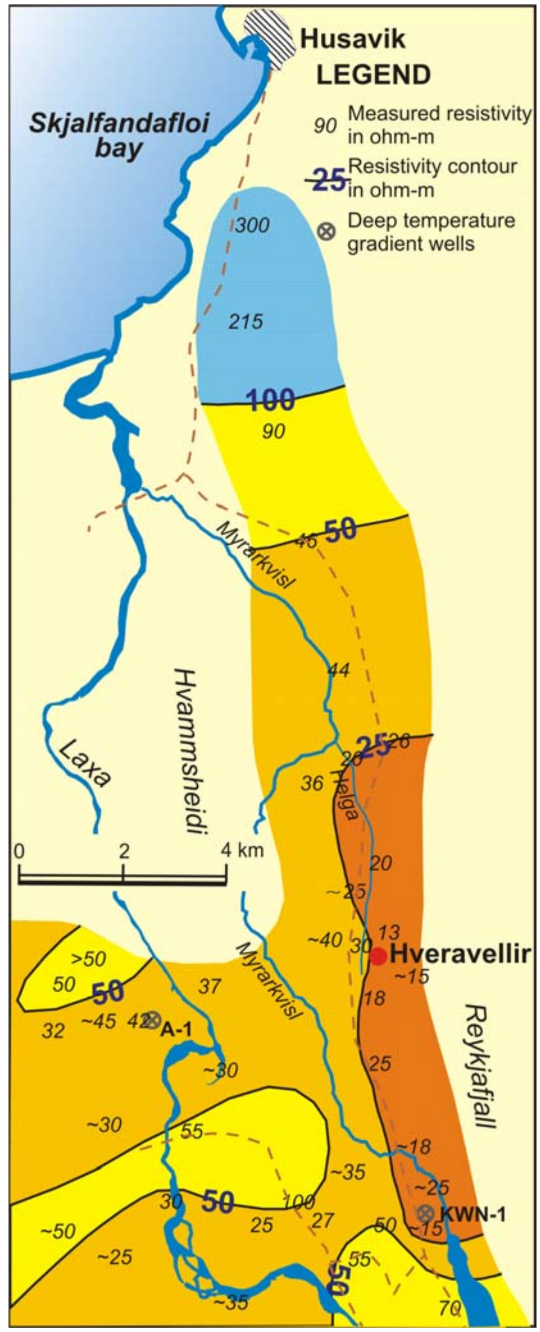

Figure 7: Resistivity map of the Reykjahverfi and Adaldalur region at 500 m below sea level.

exist. The low resistivity can be compared to resistivities ofat least 30-60 ohm-m outside the anomalous area. At 500-600 m b.s.l. the resistivity increases to 50-100 ohm-m.

The simplest interpretation of the low-resistivity anomaly is that it defines an area with alteration in the smectite-zeolite zone and high thermal gradient, probably combined with high (secondary) permeability. The higher resistivity at deeper levels might reflect different alteration status or less permeability. The low-resistivity layer is found at gradually deeper levels to the south and disappears about 10 km south of Hveravellir.

3.3 Magnetic measurements

The total magnetic field was measured with a proton magnetometer at 2.5 m height above the ground. Profiles with 5 m between measuring stations were taken with an interval of 20 m between the parallel lines. The area covered was 0.8 km^2 and included all significant surface manifestations of geothermal activity. The results of the magnetic measurements do not show as clear linear anomalies as might have been expected from the linear distribution of the geothermal manifestations, but many weak and somewhat irregular anomalies are seen. Some are more easy to follow in a profile map. Filtering of short wavelengths with upward enhancement assisted in enhancing the main features, and the vertical gradient in exaggerating minor features of shallow origin. Interpretation of the magnetic map is summarized as follows:

- Several northerly trending lineaments can be seen most of which are probably related to minor faults or fractures.
- Two exceptions are seen from the northerly trend, a lineament trending approx. N30°E between Ystihver and Uxahver as indicated in fractures at Ystihver, and a shallow magnetic low trending about N60°W between Strutshver and Sydstihver.
- Irregular features on the western side are caused by the normally magnetized Hvammsheidi formation that borders the geothermal field to the west.

The main lineaments deduced from the magnetic measurement results are shown on the map in Figure 8. It is concluded that several minor northerly trending faults or fractures dissect the geothermal field and that the major hot springs seem to be associated with intersections between the northerly trending faults/fractures and faults/fractures of different directions.

3.4 Chemical evidence

Table 1 shows results of chemical analyses of samples collected from the production wells in 1998 and an older analysis from Strokkur hot spring. The chemical composition of all the samples is similar, except that the silica concentrations of the HV-1 and Strokkur samples are slightly higher than those of the rest, a feature that is reflected in higher chalcedony temperatures. The chalcedony temperature (Fournier, 1977; Bjarnason, 1994) of the samples from the wells is calculated to be about 130°C, and thus in good agreement with highest measured temperature in the wells, 128°C. Thus, we can state that the base temperature in the geothermal system at Hveravellir is around 130°C (Olafsson, 1999). The low deuterium content of the water indicates that its origin is in the central highlands in the NW-Vatnajökull area (Figure 1), and it may be quite old.

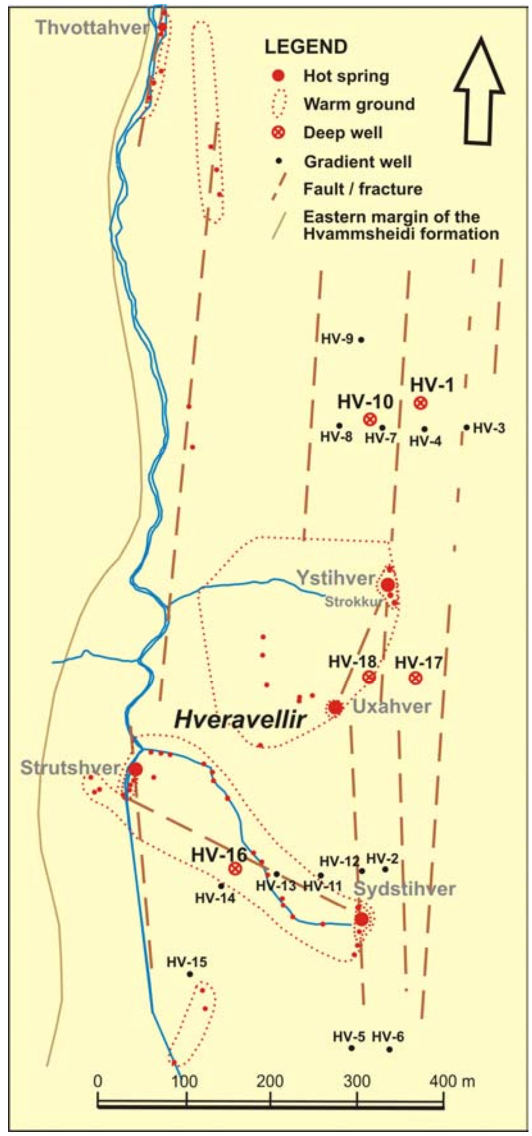

Figure 8: Main fractures/faults observed by magnetic measurements and locations of wells at Hveravellir.

3.5 Gradient wells

In the late 1990's, a renewed exploration effort led to the drilling of several shallow gradient wells in order to try to learn more about the active structures, and then drilling of new production wells. A total of 13 shallow wells was drilled, most of them 60-70 m deep. Locations are shown in Figure 8. Most of the wells did not give true gradient or rock temperature except near the bottom and where water entered them. The westernmost wells, HV-13, 14 and 15 yielded water in excess of 100°C from the subsoil and late Quaternary strata, and had an instant effect on the flow from Sydstihver hot spring. The wells provided valuable information for the locations of wells HV-10 and HV-16, but did not prove to be a sure key to success.

The thermal gradient in the 1704 m deep well KWN-1 close to Lake Langavatn, 6 km to the south of Hveravellir, is about 90-95 °C/km and in the 1250 m deep well A-1, at Nes, 4 km to the west, it is about 80°C/km (location of the wells is shown in Figure 7). Thus, we can expect the regional gradient around Hveravellir to be about 90°C.

Table 1: Chemical composition of waters from hot springs and wells at Hveravellir (mg/l) (Olafsson, 1999; and personal comm.).

Location	Strokkur	HV-1	HV-10	HV-16
No.	87-0213	98-0372	98-0371	98-0548
Date	87-11-02	98-06-21	98-06-21	98-11-07
Temperature (°C)	96.0	100.5	102.2	112.0
Pressure (bar-g)		2.1	2.0	5.4
pH (/°C)	9.46/19	9.32/24.8	9.32/24.4	9.40/21.3
CO_2	32.1	37.0	39.0	36.7
H_2S	0.92	1.70	1.30	1.33
SiO_2	178.3	179.8	170.7	166.1
Na	57.2	58.0	57.9	58.0
K	2.7	2.46	2.29	1.90
Mg	0.070	0.005	0.006	0.004
Ca	1.6	1.56	1.72	1.91
F	0.98	0.80	0.84	0.98
Cl	12.1	11.1	10.8	11.4
SO_4	29.3	28.8	26.7	29.7
Al	-	0.214	0.189	0.128
Fe	<0.025	0.0053	0.0056	0.0032
Mn	-	0.0001	0.0002	0.0001
TDS	335	305	322	282
O_2	0	0	0	0
δD (%oSMOW)	-	-101.7	-101.7	-103.1
$\delta^{18}O$ (%oSMOW)	13.59	-13.79	-13.81	-14.02
T-chalcedony*	132	134	130	129
T-well measured		128	124	116

3.6 Production wells

Five deep wells have been drilled at Hveravellir to depths of 450-1027 m. The locations of the wells are shown in Figure 8 and some of their main characteristics are listed in Table 2. Temperature logs from all the deep wells are shown in Figure 9.

The first production well HV-1 was drilled in 1974, when the need for hot water at Husavik had exceeded the water available from hot springs. The well is located about 200 m north of Ystihver and proved very successful. The drillrig hit water at such force at 448-450 m depth that drilling could not be continued. The well became the main supplier of hot water for Husavik District Heating for the next 25 years, yielding 44 l/s of 126°C hot water in free flow, and is still a good producer.

The extensive plans in the late 1990's for further utilization of the hot water resulted in the drilling of several production wells. The first one was well HV-10 in 1997. Based on the results from the gradient wells, the well was located about 60 m west of HV-1 and was targeted to intersect similar structures. It was drilled down to 652 m. Once again the drilling proved extremely successful with the well producing at the end of drilling 80-90 l/s of 124°C hot water in free flow with the main aquifer at 638 m. As expected there was some interference with well HV-1 and Ystihver hot spring. Well HV-10 has a diameter of 216 mm in its production part compared to 173 mm in HV-1 which may, at least partially, explain its larger discharge.

With the gradual forming of innovative ideas for a new Energy Centre at Husavik, drilling was continued in 1998, with both additional shallow gradient wells, and new production wells. Well HV-16 was located midway between Strutshver and Sydstihver aiming at the northwesterly fractures assumed to be there (Figure 8). It became the deepest well in the field to date, 1027 m. After the big producers HV-1 and HV-10, the result was somewhat disappointing, with the well yielding about 15 l/s of 114°C hot water in free flow.

Drilling was still continued and 2 additional deep wells drilled northeast of Uxahver hot spring. The intention was to intersect similar structures as in HV-1 and HV-10. Well HV-17 is located 100 m east-northeast of Uxahver, and became 792 m deep, and well HV-18 is located 60 m northeast of Uxahver and became 481 m deep. Both wells are relatively hot (127-128°C), but the results were very disappointing with only minor aquifers found. Neither well can be used as a producer.

Current discharge from the wells at Hveravellir is at 2.5 bar-a pressure, with wells HV-1, HV-10 and HV-16 producing in all 95 l/s of 124°C hot water (Hjartarson et al., 2003).

Geological logging of the deep wells at Hveravellir has not given any conclusive clues to the connection between the aquifers and geological structures. No clear vertical structures (dykes or faults > 10 m) were seen in association with the main aquifers, controlling the upflow of hot water. However, this does not disprove the existence of minor faults, such as those revealed by the magnetic measurements, or tectonic fractures as the main controllers of the flow to the surface (Fridleifsson, 1998).

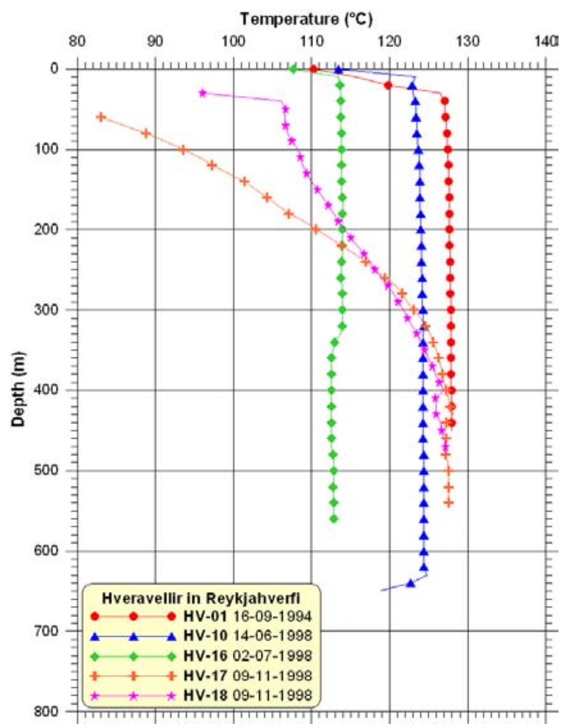

Figure 9: Temperature profiles for the deep wells at Hveravellir.

3.7 The structure of the geothermal field

The Hveravellir geothermal water originates as precipitation in the central highlands, probably in the northwest part of Vatnajökull glacier. From there the groundwater flows along permeable structures inside the volcanic rift zone towards north.

The influence of the earthquakes of 1872 on the geothermal field shows that the Tjörnes fracture zone with its northwesterly fractures may have a major influence in the field. Here it is postulated that the main local flow towards the field is from the southeast probably along hidden NW-SE trending faults belonging to the Tjörnes Fracture Zone. The field is also expected to rely on the interaction between hot crust, and the active tectonics that keep the fractures open for deep heat mining beneath the highlands to the southeast of Hveravellir, possibly associated with old intrusive activity on the western flank of the Theistareykir volcanic system. At the lower elevations at the foot of Mt. Reykjafjall northerly trending faults/fractures seem to open the way up for the water with the major hot springs found at their intersection with fractures with other directions.

The main upflow at Hveravellir seems to be confined to a northerly trending structure near the eastern border of the geothermal field, and minor upflow is associated with another northerly trending structure at its western border. The structure near the eastern border is poorly defined so far but most likely it is a fault or a fracture zone. The alignment of the large hot springs Ystihver and Sydstihver and fractures seen through the basin of Ystihver indicates that its main trend is close to N-S (355-5°) and this can be used as its definition. The hottest wells (HV-1, HV-17 and HV-18), that all reach 127-128°C temperature, are close to this structure. However, HV-1 has a large inflow while HV-17 and HV-18 between Ystihver and Uxahver are almost dry apart from an insignificant stratabound feed zone at about 400 m depth. Drilling of the five 450-1027 m deep wells showed that the rock is generally of low primary permeability and success depends on the intersection of fractures. Wells HV-1 and HV-10 are 60 m apart (Figure 8) with one large inflow each at 450 and 635 m depth, respectively, possibly from the same fracture. If both intersect such a fracture, its dip would be about 55° to the west and intersection with the surface over 300 m east of HV-1. However, it is more likely that the permeable fractures are related to a steeply dipping fracture zone, at least 60 m wide. HV-17 east of the largest hot springs Ystihver and Uxahver did not intersect any permeable fractures nor did HV-18 which is in the middle of the upflow zone as defined by the hot springs and the successful HV-1 and HV-10 wells. Probably well HV-17 (792 m) is too far away from the active fracture zone to intersect it, and horizontal permeability too low for significant aquifers, while HV-18 might not be deep enough.

The subsurface temperature distribution from the deeper wells (Figure 9) indicates a very effective flow with little temperature loss towards north from the area of Ystihver and Uxahver and a less pronounced flow from the area of Sydstihver towards northwest with a considerable temperature loss. The channels feeding the upflow are unknown and probably out of reach as targets for drilling. The best choice for drilling additional production wells still seems to be in the general area around Ystihver and Uxahver. As a first step deepening of HV-18 might be considered. Directional drilling has not been considered so far. None of the existing wells seems a good candidate for that. The best site for such a well would be northwest of Uxahver with the borehole transecting the admittedly poorly defined fault zone at 400-1200 m depth over some 200-300 m interval to the east. Then again the area near wells HV-1 and HV-10 has proven very yielding.

Reservoir assessment of the Hveravellir field (Axelsson, 1998) indicates that it might be able to sustain a production of at least 190 l/s of 120-130°C water in free flow from wells. At present the production from wells is 95 l/s of 124°C hot water and from the hot springs 35-40 l/s of mainly boiling water. So there is still scope for increased production in free flow even though it will certainly lead to a further decrease of flow from the hot springs.

The hot springs at Hveravellir in Reykjahverfi undoubtedly have a significant historical and environmental value, especially the Ystihver geyser that is the only active geyser in N-Iceland, and the biggest geyser in the low-temperature geothermal fields in Iceland, even though some soap is needed to trigger its eruptions today. Its bowl of silica deposits is also worth preserving. Therefore a balance needs to be found between the production from wells and the activity of the hot springs at Hveravellir. The Ystihver geyser will be missed if more wells continue to drain hot water from its feed zone.

4. UTILIZATION

4.1 The Hveravellir greenhouse farm

Systematic utilization of geothermal energy at Hveravellir dates from the end of the 19th century. In 1878 potato growing in warm ground proved successful, gradually leading to extensive cultivating of potatoes and vegetables by the farmers in the area. This led to the formation of a limited company of local farmers and investors called Gardraektarfelag Reykhverfinga (Reykjahverfi Horticultural Association) in 1904 that bought the land around the major hot springs and the rights to utilize the hot water. In 1920 this became the Hveravellir farm. Heating of houses was first tried successfully in 1924 with steam from Strokkur and in 1933 the first geothermal greenhouse was built (Reykjahverfi Horticultural Association, 1979). Today, Hveravellir is a thriving greenhouse farm and company, with 6,900 m^2 under glass, producing tomatoes in a large quantity, but also cucumbers and green peppers, and vegetables and summer flowers in warm ground around the greenhouses, servicing a large part of N-Iceland.

Strokkur was for some years mainly utilized for the heating of a swimming pool that was built at Hveravellir by the local sports club. Gardraektarfelag Reykhverfinga donated land and the right to use Strokkur to the local community with the building of the Heidarbaer community and sports centre (1962-1978) located about 1 km northwest of Hveravellir. The swimming pool was rebuilt in 1986. From 1970, the water for heating was supplied through the main pipeline to Husavik to avoid costs of pumping. But from the year 2000, Strokkur has again been directly connected to Heidarbaer to provide the community centre and the swimming pool with hot water.

4.2 Husavik district heating system

In 1970, the town of Husavik bought the rights to utilize hot water from Hveravellir for a district heating system at Husavik. At the start, Husavik utilized the water from Ystihver, Strutshver and Sydstihver (and Strokkur) a total of about 40 l/s, with Uxahver providing the water for heating the local greenhouse farm. The Husavik district heating system was connected to Hveravellir with an 18 km long pipeline (Figure 10) with a diameter of 250 mm made of asbestos-reinforced concrete, covered, and thus insulated, with earth. When more water was needed for Husavik Town the successful well HV-1 was drilled in 1974. Only a minor reduction was seen in the flow from hot springs (5 l/s), but the total free flow from the geothermal system increased to about 95 l/s. Well HV-1 became the main supplier for the Husavik district heating, together with Ystihver and Sydstihver, but use of hot water from Strutshver was stopped as the water needed to be pumped up to the local storage tank. Use of asbestos in the main pipeline meant that the water could only be used below 100°C, and thus about 74 l/s of 100°C, were available for Husavik District Heating. Additional 15°C were lost due to cooling in the pipeline, with the water arriving at about 85°C at Husavik (Hjartarson et al., 2003). No pumping was needed as the difference in altitude is around 100 m. In the early 1980's a new 300 mm asbestos pipeline was laid along the first 12 km to increase the reliability of the system.

4.3 The rural district heating systems

The drilling of well HV-1 opened up new possibilities in the utilization of the hot water for the rural areas. The Reykir farms just north of Hveravellir had been using the water from the local hot spring Thvottahver for space heating. With this well, Husavik District Heating could provide hot water for all the 20 farms located between Hveravellir and Husavik and they were soon connected to the main pipeline using the water for heating and drying of hay.

Several years later, the farmers in the rural area to the southwest of Hveravellir formed a company with the aim of buying hot water from Hveravellir for heating. For that purpose utilization of hot water from Strutshver started again in 1989-1990, providing water for the Adaldalur and Kinn rural district heating system. It is one of the largest of systems of its type in Iceland, providing hot water for about 35 farms and sites distributed over an area of more than 50 km^2. The pipeline is made of polybutylene and insulated with polyurethane. The total length of the pipeline is about 50 km, and the diameter varies from 25 mm at the users end to 125 mm in the main pipes. About 8 l/s are taken from Strutshver at 100°C (maximum temperature permitted for polybutylene is 85°C). The water is pumped onwards and reaches the furthest lying farms at about 50°C. However, most farms receive the water at temperatures of 60-80°C. The large pressure change caused by the 100 m elevation change from the Hvammsheidi formation to the lower lying farms in the west, together with the high initial temperature of the water has caused some difficulties and will shorten the normal lifetime of the initial part of the pipeline, and already a part of the first few kilometres has been replaced with pre-insulated steel pipes. Even so, the connection to the geothermal district heating system has been a major benefit to the rural population. Figure 10 shows most of the area with the pipeline with farms and sites connected.

4.4 Husavik Energy Centre

In the 1990's, new plans for the utilization of hot water were discussed and planned at Husavik, such as for industrial use and electrical production, with multiple and/or cascaded use of the water. However, this required an increased amount of hot water with temperatures above 120°C and preferably in free flow, to save on costs associated with pumping of the water. This led to an exploration effort and the drilling of new production wells in 1997-1998. The reservoir assessment of the Hveravellir field (Axelsson, 1998) showed that it might be able to sustain more production in free flow, thus giving the plans for the new Husavik Energy Centre a good support.

The extensive project plans were initiated in 1998-2001. This included renewal of the main supply pipeline from Hveravellir to be able to use the full energy content of the geothermal water. A new pre-insulated steel pipeline with 400 mm diameter was laid from Hveravellir to Husavik and carries 95 l/s of 124°C water to Husavik with only 3°C

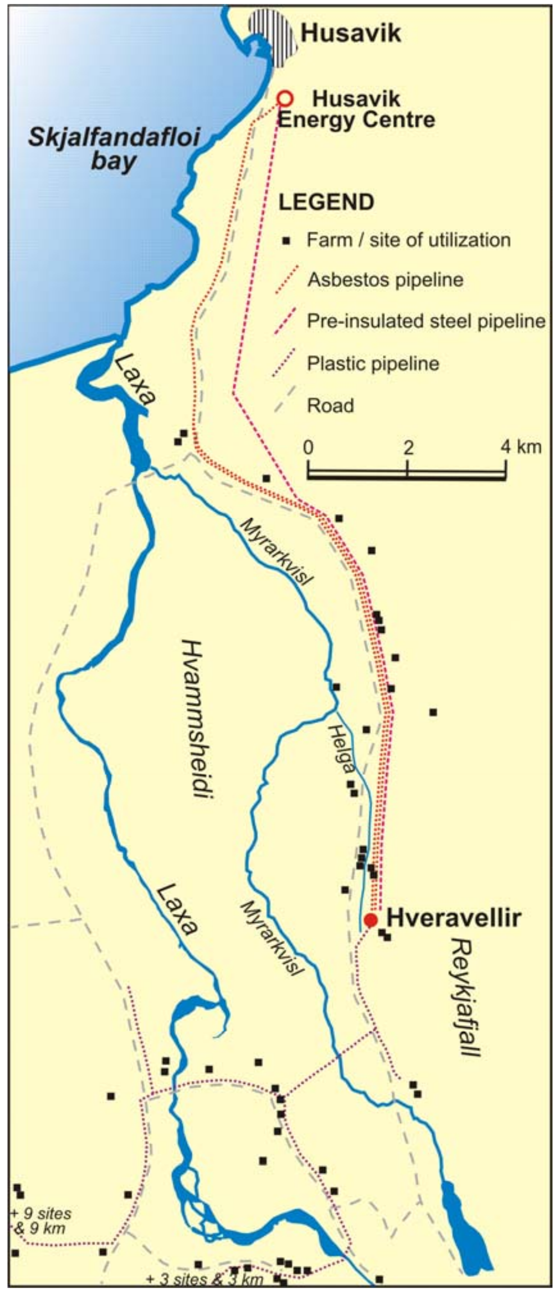

Figure 10: The geothermal pipelines in the Reykjahverfi and Adaldalur region.

cooling under way (Hjartarson et al., 2003). The old asbestos pipeline was, however, not abandoned but is used for water from the hot springs (Ystihver and Sydstihver), a total of about 16 l/s of 100°C water. Of this 3 l/s are used by the farms along the way, and the rest mainly for fish farming (Hjartarson et al., 2003). The project benefited from a generous grant from the 4th framework programme of the European Union.

With the steel pipeline new aspects of the use of the geothermal energy opened, both for industrial utilization and direct use and even production of electricity. The flexible cascade system built included a binary power plant based on the Kalina power cycle (e.g. Valdimarsson, 2003), with an initial installed capacity of 1.6 MWe that uses the power from the hot water upon cooling it from 121° to

80°C. The electrical production was designed to supply about 2/3 of Husavik's needs for electricity. During the years 2000-2004, the average annual production has been about 9.4 GWh/a, very close to the designed values. Water and steam can also be supplied for industrial use at temperatures up to 121°C. At temperature from 80 to 35°C the main utilization continues to be district heating at Husavik and at lower temperatures the water is used for bathing, snow melting and fish farming (Hjartarson et al., 2003). Figure 11 shows the Husavik Energy Centre and the utilization of the geothermal water schematically.

Initial difficulties were experienced in the material selection for the Kalina power system leading to some corrosion. Improvements carried out in July-August, 2004, including instalment of a new turbine made of special corrosion-resistant titanium have put this right. The modified Kalina plant is running at 2.0 MWe and supplies 90% of Husavik's needs for electricity. The Kalina binary plant at Husavik is now producing about 30% more power than conventional ORC binary plants for the available temperature interval.

5. MAIN CONCLUSIONS

With its large hot springs and spouting geysers and its historical background, the geothermal field at Hveravellir in Reykjahverfi, has a special place among the low-temperature geothermal fields of Iceland.

The recharge to the geothermal field is assumed to be from southeast, probably along hidden NW-SE trending faults associated with the Tjörnes Fracture Zone. Interaction between the active faults and hot crust keeps the fractures open for deep heat mining beneath the highlands to the southeast of Hveravellir, possibly associated with old intrusive activity at the western flank of the Theistareykir volcanic system. At the lower elevations at the foot of Mt. Reykjafjall the hot water reaches the surface.

The main upflow at Hveravellir seems to be confined to a northerly trending structure, a fault or a fracture zone, near the eastern border of the geothermal field. The alignment of the large hot springs Ystihver and Sydstihver and fractures seen through the basin of Ystihver indicate that its main trend is close to N-S. Lineaments seen in the results of magnetic measurements support this. Wells HV-1 and HV-10 intersect permeable fractures that belong to this fracture zone. Minor upflow is associated with another N-S trending structure at the western border of the geothermal field

Utilization of the hot water from Hveravellir is a major benefit to the region. The Hveravellir greenhouse farm services a large part of N-Iceland with tomatoes, cucumbers and other vegetables. About 55 rural farms in a large area to the north, south and west of Hveravellir are supplied with hot water for heating and bathing. At the coast, 18 km north of Hveravellir, the Husavik town is supplied with electricity from a Kalina binary power plant and hot water for district heating, bathing, fish farming and snow melting, and hot water or steam for industrial use, through the flexible cascaded system of the Husavik Energy Centre.

Utilization of the geothermal field is based on free flow from wells and hot springs with new production wells causing gradual decline of the major hot springs. Currently, 95 l/s of 124°C hot water are produced from wells, while the major hot springs are discharging 35-40 l/s of 95-100°C hot water. The field is expected to be able to sustain additional production from wells in free flow. A first choice for a new production well would be the deepening of well HV-18 between Ystihver and Uxahver or a directional well located northwest of Uxahver aimed at transecting the N-S trending fracture to the east.

Significant increase in production from wells is, however, in conflict with the desireable preservation of Ystihver geyser, at present the only geyser in N-Iceland, and the biggest geyser of low-temperature geothermal fields in Iceland. Therefore some balance needs to be defined between the production from wells and the activity of the hot springs at Hveravellir.

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Table 2: Main characteristics of the deep wells at Hveravellir

Well no.	Drilled (year)	Depth (m)	Elevation (m)	Initial discharge (l/s)	Pres.disch. at 2.5 bar-a (l/s)	Tmax in well (°C)	Twellhead (°C)	Tbottom of well (°C)	Main aquifers (m)
HV-1	1974	450	160	44	26	128	126	128	422-**448**
HV-10	1997	652	152	80-90	61	124	123	119	330-**638**
HV-16	1998	1027		15	8	116	114	?	330-758-804
HV-17	1998	792		-	0	128		>121	435
HV-18	1998	481		-	0	127		127	410

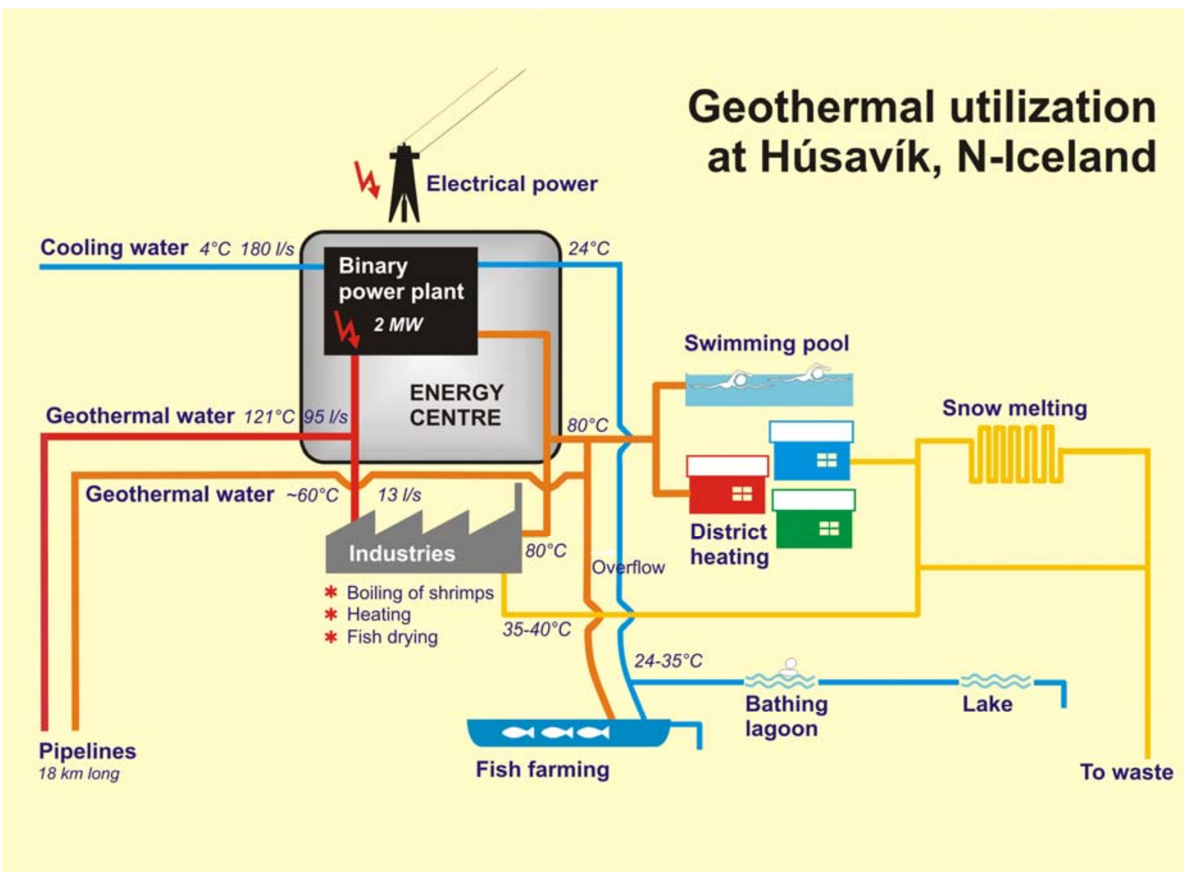

Figure 11: Schematic of the Husavik Energy Centre and utilization of hot water at Husavik (modified from Husavik Energy, 1998; and Hjartarson et al., 2003)