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Geothermal District Heating in Eyjafjördur, N-Iceland; Eighty Years of Problems, Solutions and Success

Ólafur G. Flóvenz[1], Franz Arnason[2], Bjarni Gautason[3], Gudni Axelsson[1], Thorsteinn Egilson[3], Stefan H. Steindórsson[2] and Hjalti Steinn Gunnarsson[3]

[1]ISOR, Iceland GeoSurvey, Grensásvegi 9, 108 Reykjavik, Iceland

[2]Nordurorka, Rangárvöllum, 601 Akureyri, Iceland

[3]ISOR, Iceland GeoSurvey, Rangárvöllum, 601, Akureyri

olafur.flovenz@isor.is, bjarni.gautason@isor.is, gudni.axelsson@isor.is, thorsteinn.egilson@isor.is hjalti.steinn@isor.is

franz@no.is, stefan@no.is

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ABSTRACT

Since the first successful borehole, providing geothermal heat to the town of Akureyri was completed in 1975 this utility has been facing serious technical and geothermal problems that have been successively overcome by different technical and social measures. It currently produces geothermal heat in a sustainable way from several small but well managed reservoirs. The paper describes the history of the geothermal utility and how problems have been overcome. It includes complex history of exploration, reservoir assessment, reinjection of return water, anti-corrosion measures and description of the distribution system and its management.

1. INTRODUCTION

This paper deals with the development of the district heating systems constructed and operated by the company Nordurorka in the Eyjafjördur area in N-Iceland. The company is mostly owned by the municipality of Akureyri in N-Iceland. Previously it was named Hitaveita Akureyrar but after merging with the municipal electricity utility and the local waterworks it got the present name. Nordurorka is now running 4 independent district heating systems, one for the town of Akureyri from beginning in 1977 and the others for the villages at Ólafsfjördur since 2006, Grenivík since 2007 and Hrísey since 2004. The fifth system at Svalbardseyri was merged with Nordurorka in 2004 and connected to the system in Akureyri. In addition there are two other district heating systems in Eyjafjördur. The one is owned by the municipality in Dalvík serving the villages in Dalvik and Árskógsströnd with geothermal water from the fields at Hamar and Árskógsströnd. The other is a private system in Ytri-Vík serving a few houses. Thus all villages and the rural areas in a 70 km long district in Eyjafördur are heated by geothermal energy.

The district heating system in Akureyri was described by Flovenz et al in 1995. Since then big progress has been achieved. The purpose of this paper is to update the former paper and report the achievement.

2. THE GEOLOGY AND HOT SPRINGS

The outline of the geology of Eyjafjördur has been described by Björnsson and Saemundsson, (1975). The area is made of sequences of tertiary flood basalts, 6-10 m.y. old, called the Eyjafjördur basalts. It is interbedded with thin layers of scoria and soil remainders. The strike is almost E-W and the dip is general 3-7° but the strike turns to NNE south of Akureyri (Fig. 1).

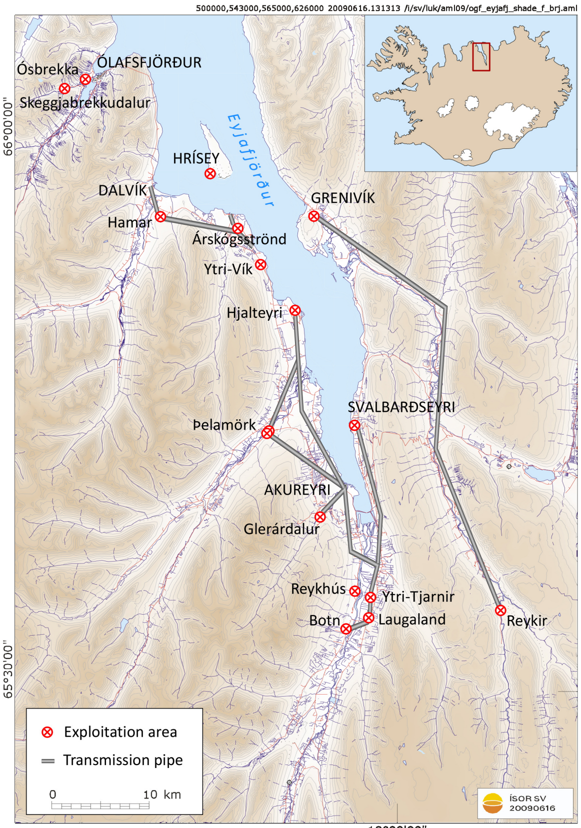

Figure 1: A map of Eyjafjördur and vicinity showing the harnessed geothermal fields, towns, villages and the main transmission pipelines for hot water

There is a marked flexure zone along the mountains east of Eyjafjördur. The strike of the Eyjafjördur basalts turns to N-S and the dip increases up to 20° where they disappear below gently eastward dipping 2 m.y. old flood basalts of different origin. In between series of sediments exist witnessing a gap in the geological history. The Eyjafördur basalts originate mainly in central volcanic systems of tertiary age in the area, like the Torfufell volcano (located just south of the map on Fig 1), and the Kaldbakur volcano north of Grenivik. Series of dikes and faults belonging to the volcanic systems intersect the flood basalt. The dykes are in most cases nearly perpendicular to the flood basalts and were mainly formed by intrusions and faulting during rifting periods in nearby volcanic centres at the time of the formation of the crust.

At present the northernmost part of the fiord is strongly affected by the Tjörnes fracture zone which is a transform fault connecting the volcanic rift zone in NE-Iceland and the Kolbeinsey Ridge north of Iceland. On land it appears as area of high seismicity (Fig. 2), the largest reported earthquake of magnitude 6 was in 1934 with epicentre almost within the village of Dalvik and caused severe damage there. The on-land faults connected to the transform zone are commonly short parallel north-south trending right lateral faults that probably reflect a sort of a "bookshelf" fracturing (Rognvaldsson et al., 1998).

The background heat flow is among the lowest found in Iceland, the regional temperature gradient being 40-60°C/km in the area which corresponds to 70-110 mW/m2 (Flovenz and Saemundsson, 1993). The regional gradient reflects the general crustal heat flow and can roughly be extrapolated up to the 700°C isothermal surface (Ágústsson and Flóvenz, 2005).

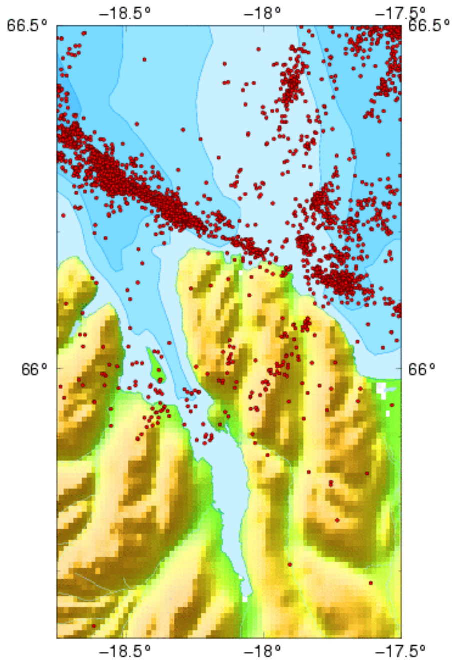

Figure 2: The location of Earthquakes in the Tjörnes fracture zone and Eyjafjördur in 1991-2003

3. THE GEOTHERMAL FIELDS

The lava pile in Eyjafjördur is relatively deeply eroded by glacial erosion, so the bedrocks presently at sea level are belonging to the mesolite/scolesite alteration zone (Palmason et al. 1978), with the lamontite zone starting at a depth of approximately 500m and the epidote zone at 3km depth. The primary permeability of the mesolite/scolestie zone is generally very low, and decreases with depth. Geothermal fields occurring in such environment must therefore owe their existence to recent tectonic fracturing that creates path for subsurface circulation of water.

Numerous hot springs exist in the Eyjafjördur area witnessing local geothermal fields. Their location is shown in figure 3. They are different in temperature, from 20°-90°C and the natural flow rate is usually quite low as well as the chemical content (Flovenz et al., 1995). Deep wells, 500-2800m, have been drilled into many of the fields. The temperature curves for all the geothermal fields show the same characteristics (Fig 4); very high near surface gradient that gradually lowers with depth and becomes nearly zero in many of the boreholes.

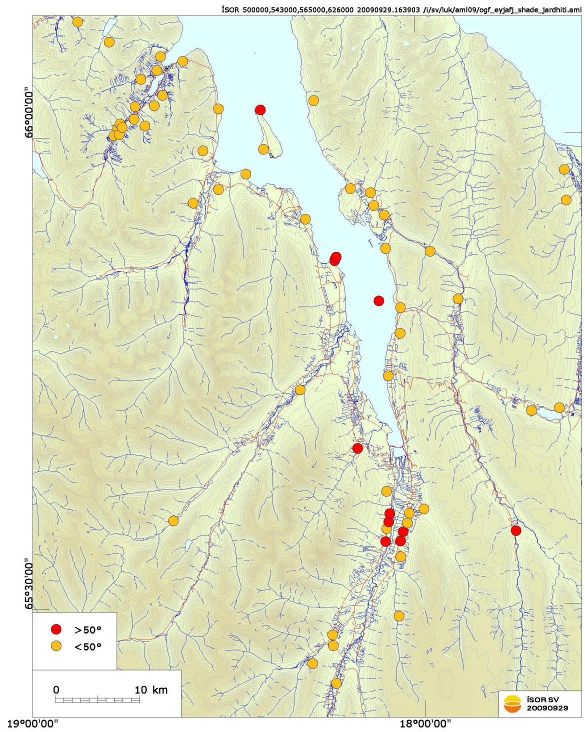

Figure 3: A geothermal map of Eyjafjördur. The dots shows the hot springs in the area and different colours refer to different temperatures

Compared to the regional gradient which is not disturbed by fluid flow the temperature within the geothermal fields is much higher at shallow depth but considerable cooler below some depth level. Such behaviour has been explained by fluid convection in a near vertical fracture system (Björnsson et al, 1990, Bödvarsson, 1982). From analysis of heat flow around vertical fractures (Milicevic, 1990) it can be concluded that the geothermal systems in Eyjafjördur have been active for several tens of thousands of years. During that time a self-sealing process has been active, closing the fractures at shallow depths by precipitation of secondary minerals during the cooling of the deeply originated fluid. At the same time it is likely that the process of downward propagation of the fractures (Bödvarsson et al., 1982) has maintained the convection.

4. THE HISTORY

4.1 Forty Five Years of Unsuccessful Exploration

The first attempts to explore for geothermal energy for the town of Akureyri dates back to the year 1930 when the first borehole in the area was drilled at the hot springs in Glerárdalur. It was unsuccessful but in 1933 explosives were used to increase the flow rate from the hot springs in Glerárdalur and the water was piped to a swimming pool in Akureyri. (Flóvenz et al., 1983). Drilling was continued in many of the hot-spring areas in Eyjafjördur now and then over the next decades but without any considerable results. Only for the village of Ólafsfjördur drilling was successful at Skekkjabrekkudalur and hot water was piped 3 km to the village where geothermal heating started in 1944. In 1970 it was a general opinion that the geothermal fields close to Akureyri were too small to allow for large scale utilization that could satisfy the needs for thermal energy in Akureyri (Gudmundsson and Sæmundsson, 1972).

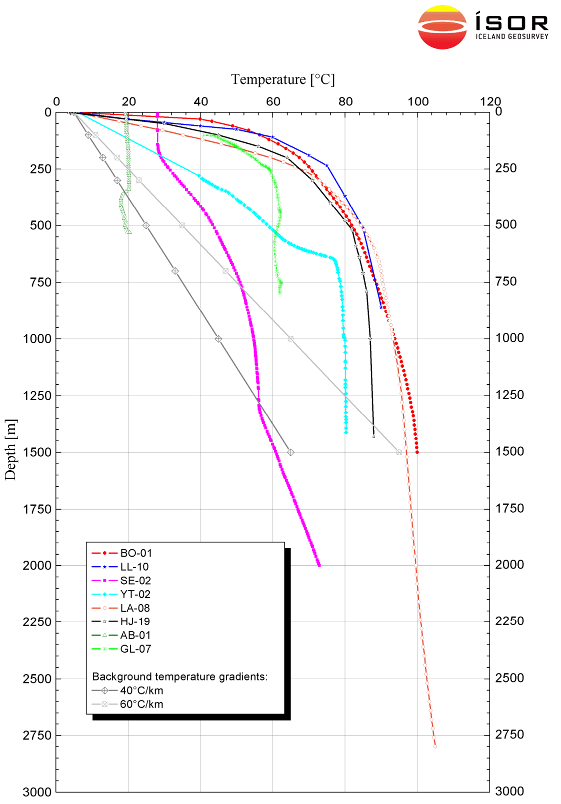

Figure 4: Temperature profiles from 8 different geothermal fields in the Eyjafjördur area. The straight lines show temperature gradients of 40 and 60 °C/km which are the upper and lower limits for the background temperature gradient in the area

4.2 The Final Attempt and Surprising Results

During the first oil crisis in 1973 the cost of house heating increased dramatically in Akureyri since the town was mostly oil-heated. In 1975 it was decided to get rid of the oil either by geothermal energy or by electricity from hydropower. Since the heating by geothermal is generally cheaper than by electricity it was decided to make a final attempt to explore for sustainable geothermal resources in the vicinity of Akureyri. If that would fail the next alternative was to pipe hot water roughly 70-100km distance over 600m high mountains to Akureyri from known geothermal areas close to the volcanic rift zone.

The exploration work was carried out by the Geothermal division of Orkustofnun, the predecessor of ISOR. It was based on DC resistivity soundings, mostly with Schlumberger arrangement. They revealed a clear resistivity low at Laugaland 13 km south of Akureyri (Björnsson and Sæmundsson, 1975). Drilling of a full size geothermal well into the low resistivity anomaly led to surprising results in December 1975 when around 100 L/s of free flow of 95°C water came from the well. It was about one-third of the expected energy demand in Akureyri. Based on these good results it was decided to establish a municipal district heating system in Akureyri and it was assumed that it would not be difficult to find enough hot water to fulfil the hot water demand.

4.3 Twenty Five Years of Struggle for Survival

In 1977 Hitaveita Akureyrar (Akureyri District Heating) was established. Construction of the district heating system was initiated in 1976 and most of the town had been connected in 1979. Drilling was continued at Laugaland but the results were disappointing, only 3 out of 8 deep boreholes were successful and these were connected to the same fracture zone. In 1977 drilling at Ytri-Tjarnir, 2 km north of Laugaland yielded 50 L/s of 80°C water. Based on short term pumping tests, and simulations by the Theis model, it was estimated that these two fields together could yield 240 L/s with a water level draw-down to 190 m below the surface (Bjömsson et al., 1979). This was expected to satisfy the energy need for space heating in Akureyri. Soon after pumping from the fields began, it became evident that the down-draw would be much greater than had been predicted. Since the pump design limited the down-draw to 240 m at Laugaland and 330 m at Ytri-Tjamir the average annual production declined rapidly with time. After few years in operation the total annual average production from these fields was reduced to 75 L/s. This unforeseen decline was answered by almost desperate exploration for more geothermal water, by drilling but, later by careful surface exploration followed by deep drilling. This resulted in the discovery of productive feed zones at 3 different geothermal fields; in Botn 1980, in Glerárdalur 1981 and in Thelamörk 1992. In addition two heat pumps, electric boilers and oil burner were installed, strong energy saving efforts made (Flóvenz et al., 1995) and in 1998 a permanent reinjection of return water started at Laugland which substantially improved the productivity there (Axelsson et al., 2000, 2001). By all these efforts it was possible to provide enough geothermal energy for space heating in Akureyri but every winter was associated with the challenge to be able to cover the heating demands during the coldest periods.

4.4 The Ultimate Success

During the struggling years all exploration attempts were concentrated on the area south of Akureyri. The reason was the investment in the big transmission pipeline and other installations at Laugaland and the fact that utilizing possible geothermal fields north of Akureyri would require considerable additional investment in pipelines and other infrastructure. However, the step to harness the Thelamörk area in the early nineties was first taken when it was almost a desperate need to get more geothermal water and all further exploration attempts south of Akureyri had failed.

On the western part of Eyjafjördur, there were no signs of geothermal activity all the way from Thelamörk to Hamar near Dalvik (see Fig. 2) and no geothermal exploration had taken place there. During the middle-nineties two new hidden geothermal fields were discovered in the northern part of the area, in YtriVík and Árskógsströnd (Flóvenz et al., 2000). In 1999 a shallow well was drilled to obtain sediment-filtered seawater for flatfish-farming practises. It was drilled through the sediments and into the underlying bedrock and showed a geothermal gradient of 100 to 110°C/km compared to regional gradient of 50 to 60°C/km in this region (Gautason et al., 2005) Following this the municipality of the small village at Hjalteyri hired ISOR to search for the origin of the thermal anomaly. This resulted in the discovery of a well defined thermal anomaly about 1 km away from the original well. At this stage Nordurorka overtook the project by an agreement with the local municipality and bought the exploitation rights from the landowners. The surface exploration was completed and a deep well were drilled in 2002 with great success. According to a conservative (pessimistic) estimate, based on predictions by a closed version of the lumped parameter model for Hjalteyri, the production potential of the reservoir is of the order of 200 L/s assuming down-hole pumps at depth above 250 m (Gautason et al, 2005).

Following this, in 2003 a pipeline to Akureyri was constructed from the Hjalteyri field that has since then been the main provider of geothermal energy in Akureyri.

Figure 5 shows the energy use in Akureyri by year from 1981 to 2008 and the relative contribution from the individual resources as well as the total annual average generating capacity for the geothermal fields in operation. Note the following from the figure:

- The big decline in the production from the Laugaland and Ytri-Tjarnir fields in 1981-1987 due to the pressure decline in the systems.
- The reduction in the energy use by installing flow meters instead of selling fixed amount (see Flovenz et al., 1995).
- The dramatic change in the generating capacity after the discovery of the Hjalteyri geothermal field.

The last item show the drastic change in the availability of geothermal water for Akureyri. The present demand is around 400 GWh per year while the total generating capacity is of the order of 730 GWh/year corresponding to 83MW of average power. Since Hjalteyri came into production it has been the main production area for Akureyri allowing the other geothermal fields to recover from long lasting intensive and non-sustainable production.

5. THE DRILLING SUCCESS RATE

It is of interest to consider the drilling success rate in Eyjafjördur and how it varies with time. Geothermal boreholes in Eyjafjördur fall in two main categories; shallow exploration boreholes and wells that are intended to be production wells. We define here all wells deeper than 500m to be production wells and also shallower boreholes that have definitely be intended to become production wells. All other wells are regarded as shallow exploratory wells.

We define a production well to be successful if it either has been used as a production well or it did intersect a feed zone that could yield at least 10 l/s of water by pumping with reasonable down draw.

In the table we also distinguish between wells drilled in the period 1970 to 1980 and wells drilled from 1981 to 2008.

The reason for this selection is that after 1980 more emphasis were put on surface exploration before drilling production wells and new exploration methods were introduced, including head-on resistivity profiling and drilling of cheap shallow temperature gradient wells.

The results of our analysis are shown in Table 1. It is striking how much the success ratio did increase after 1980; it rose from 41% to 88% showing clearly the importance of the application of good exploration methods. Of the total of 26 successful wells for the whole period 4 have not been utilised. Two of the wells were accidentally destroyed by drilling failure after success was obtained and two were regarded too cold for utilisation. Of the 22 remaining successful wells 16 are still used as main production wells, four as backup wells and two wells with very low productivity have been abandoned.

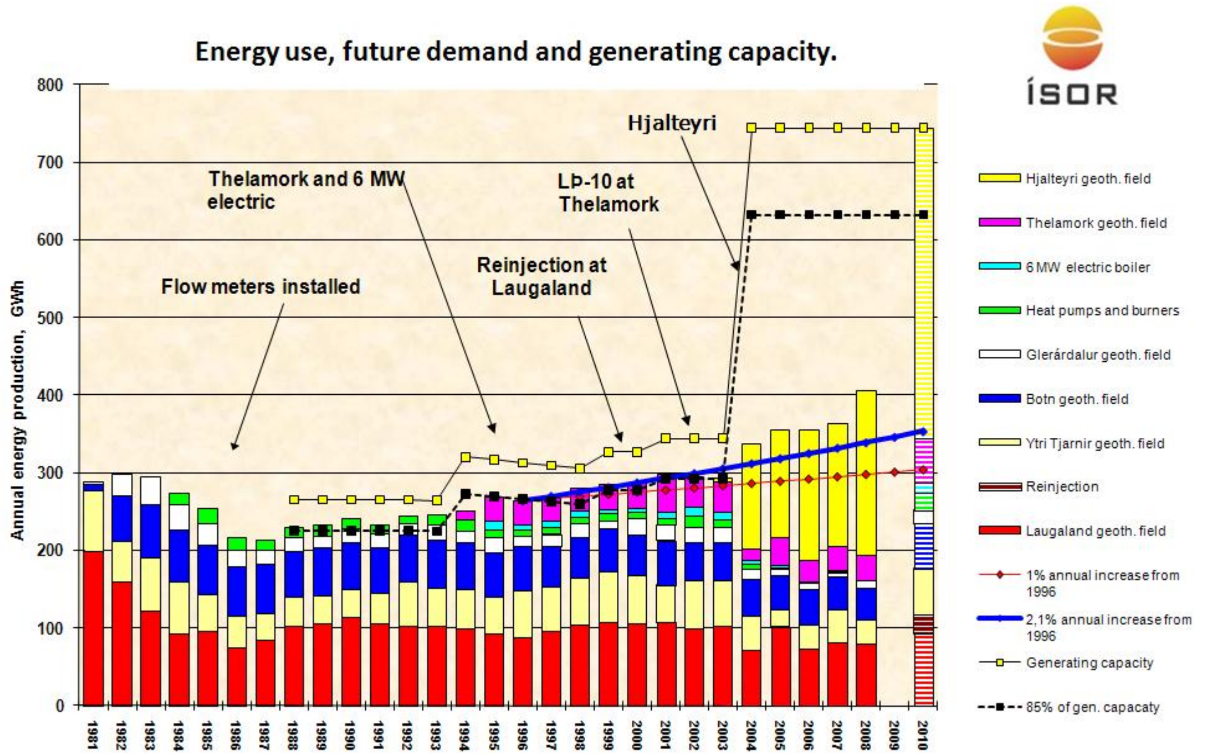

Figure 5: Energy use in the Akureyri district heating system from 1981 to 2008. The different colours denote different energy sources. The line with the yellow points shows the estimated annual generating capacity and the line with the black points shows 85% of that. The blue and red lines show 2% and 1% annual increase from 1995

Table 1. Overview of the Drilling Success of Production Wells in Eyjafjördur

	Year of drilling		
	1970-1980	1981-2008	Total
Number of production wells	29	16	45
Unsucessful wells	17	2	19
Sucessful wells	12	14	26
Wells that have been utilized	9	13	22
Wells in production in 2008	5	11	16
Backup wells	2	2	4
Abandoned wells	1	0	2
Sucess ratio	41%	88%	58%
Ratio of utilized wells	31%	81%	49%

6. THE DISTRICT HEATING SYSTEMS

Nordurorka is to-day operating 10 independent geothermal fields. Six of them, Laugaland, Ytri-Tjarnir, Botn, Glerárdalur, Thelamörk and Hjalteyri are supplying water for the Akureyri system, two for Ólafsfjördur, one for Hrísey and one for Grenivík. Table 2 shows a list of these fields with their production characteristics. A short description of the four different systems is given in the following sections.

6.1 The Akureyri System

The largest district heating system operated in Eyjafjördur is the Akureyri district heating system. It serves about 19,000 people, in the town of Akureyri and the rural areas on the both sides of Eyjafjördur and the valley south of Akureyri. The total distance between the farthest points of the system is about 35km. This system was described by Flovenz et al in 1995 and the basic system is still the same but with some modifications. Figure 6 shows a schematic and simplified picture of the present system. The changes since 1995 are mainly the commissioning of the production at Hjalteyri and the extension of the system to Svalbardseyri. Because of the strongly increase generating capacity from the geothermal fields it was not any more need for the smaller electric boiler and the heat pumps that were decommissioned and sold to another facilities. The 6 MW electrical boiler is still in use to provide a steam blanket over the water-table in the main storage tank to prevent oxygen contamination. The oil burner is also kept for safety reasons and can be used in case of emergency. The fact that the town is now supplied by hot water by two major transmission pipelines, one from north and another from south strongly increases the security of the hot water supply so the probability of emergency cases where the oil burner would be needed are very low.

6.2 The Grenivik System

The construction of the Grenivik district heating system was completed in 2007. It serves a small fishing village with 250 inhabitants as well as farms and clusters of summerhouses along the pipeline. The 90°C hot water is piped along 54 km long transmission pipeline from the production field at Reykir in Fnjóskadal. The transmission pipe is a 150 mm steel pipe in 280 mm casing for the first 12 km and 125mm steel pipe in 250 mm casing the rest of the way. It is insulated with polyurethane foam. The flow rate is 10-14 L/s to Grenivík depending on the season and the temperature loss underway is 38°C.

Table 2. Production Properties of the Different Geothermal Fields Operated by Nordurorka.

Area	Initial whp[1] (bar)	Max. pump depth (m)	T (°C)	Prod capacity[5] (l/s)	Thermal power capacity[7] (MW_{th})
Botn	17.0	250	85	29	6.5
Laugaland	20.5	250	95	41 / 48[6]	10.7 / 12.6[6]
Ytri-Tjarnir	5.7	400[3]	80	29	5.9
Glerárdalur	5.8	250	60	15	1.9
Thelamörk	1.9	250	100	20	5.6
Hjalteyri	0.8	250	90	200	49
Hrísey	–[2]	ff[4]	80	(15)	3.1
Ósbrekka	5.8	100	70	30	4.9
Skeggjabr.	–	ff	55	28	2.9
Reykir	~0	100	90	50	12

1) Estimated well-head pressure, usually not measured directly.
2) Unknown.
3) A submersible motor down-hole pump.
4) Artesian flow / free flow.
5) Mostly based on lumped parameter pressure response modelling.
6) Without reinjection / with 10 l/s average reinjection.
7) Based on a reference temperature of 30°C.

6.3 The Hrísey System

Hrísey is a small fishing village with 200 inhabitants located on an island in Eyjafjördur. In 1973 a district heating system was installed in the village. Six wells were drill from 1966 to 1982 close to a hot spring at the beach about 1 km away from the village. The deepest well was 1055m. Hot water was only found in a horizontal layer at around 100m depth but no major feed zones were found deeper. The water was initially 64°C but cooled slowly down and became oxygen contaminated due to inflow of fresh groundwater and severe calcite scaling and corrosion occurred in the distribution system. In 1984 a head-on resistivity profiling was carried out to map the vertical feed zone of the system. (Björnsson and Flóvenz, 1985). Based on the results three 150-250m boreholes were drilled to map the temperature beneath the horizontal layer and then a 330m deep production well which did cut the fracture feeding the horizontal layer. That well has since been used for the district heating system giving 77°C hot water without oxygen and serious scaling problems. The district heating system was run by the municipality of Hrísey until 2003 when it was merged with Akureyri and Nordurorka took over the system.

6.4 The Ólafsfjördur System

Ólafsfjördur is a fishing village of 850 people which has the oldest district heating system in the Eyjafjördur area. It was established in 1944 and used 50°C hot water from hot springs at Skeggabrekkudalur (Pálmason, 2005) and later from shallow boreholes close to the hot springs. In 1975 a new field, Ósbrekka, closer to the village was developed and it gives now 65°C hot water from two wells, 1168m and 1484m deep respectively (Karlsdóttir and Helgason, 1978).

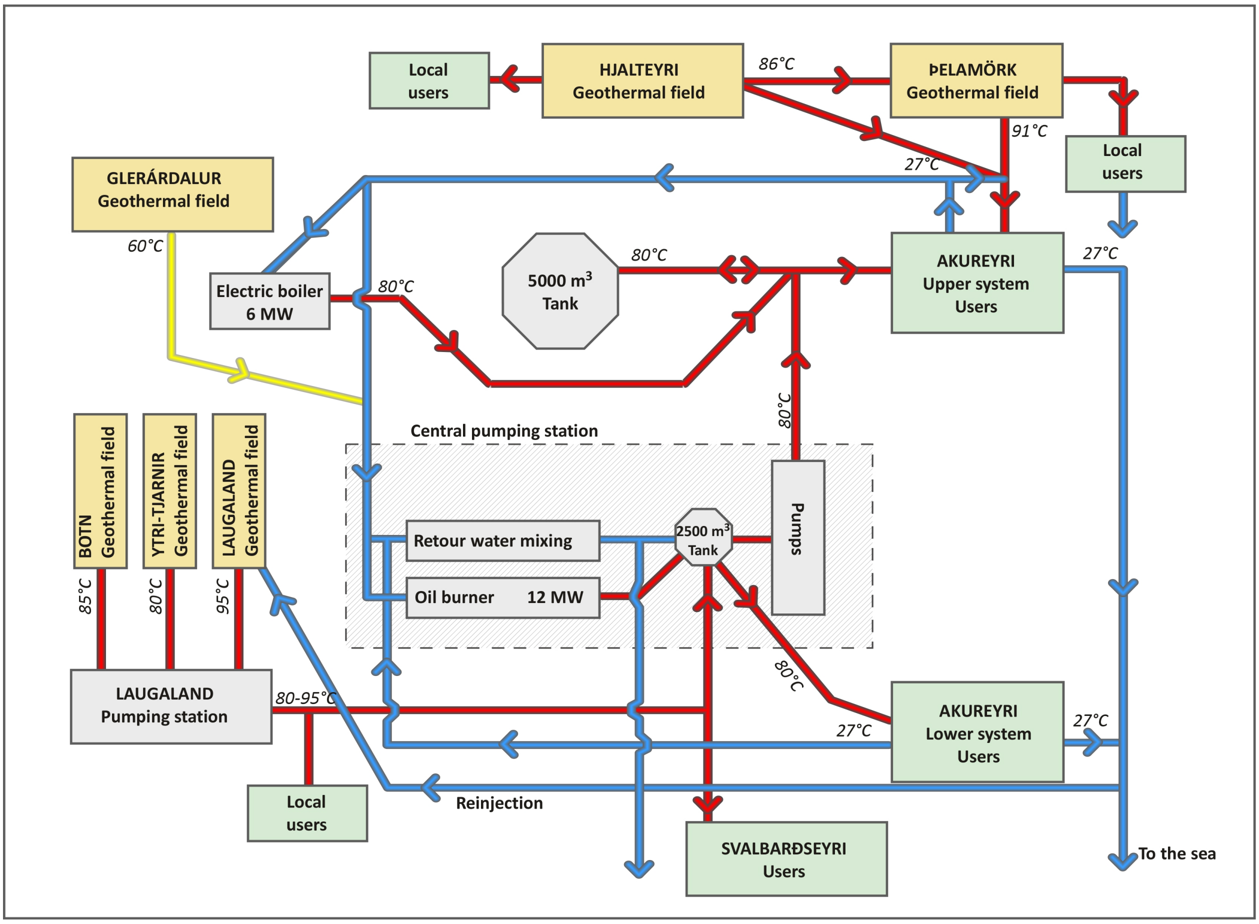

Figure 6:A simplified schematic overview of the district heating system in Akureyri. The location of the production fields is shown in Figure 1

7. RESERVOIR PROPERTIES

The reservoir characteristics of the ten geothermal systems utilized by Nordurorka today have been derived by careful analysis of available data on the production response of the systems. Long-term monitoring data have been most important, but other data, such as shorter-term well-test data have also been used. The production response histories, ranging from 2 to 30 years, of all the systems except Hrísey and Skeggjabrekkudalur have been successfully simulated by lumped parameter models (Axelsson, 1991; Axelsson *et al.*, 1999; Axelsson *et al.*, 2000; Hjartarson *et al.*, 2002; Axelsson *et al.*, 2005a; Axelsson *et al.*, 2006). The modelling method is reviewed by Axelsson *et al.* (2005b). In addition the Botn and Laugaland system have been simulated by detailed three-dimensional numerical model (Axelsson and Björnsson, 1993; Axelsson *et al.*, 2000).

Most of the geothermal systems have low average permeability. One the basis of interference test data and lumped parameter modelling the permeability-thicknesses (kh) of the Botn, Laugaland, Ytri-Tjarnir, Glerárdalur and Thelamörk systems has been estimated at 1 – 10 Dm (10^{-12} m^3). A permeability-thickness of this order is comparable to the lowest such values estimated for geothermal systems utilized in Iceland. The permeability-thicknesses of the more productive systems, Hjalteyri, Laugarengi and Reykir, are considerably greater with Hjalteyri having the highest average kh-value of 110 Dm.

The low-permeability systems are also small in volume, with volume-estimates of the order of a few km^3. The Glerárdalur and Thelamörk systems appear to be the smallest, while Laugaland system appears to be the largest, of the low-permeability systems. In contrast the Hjalteyri system is estimated to be an order of magnitude larger in volume. The low permeability and small volumes of the Botn, Laugaland, Ytri-Ttjarnir, Glerárdalur and Thelamörk systems lead to a great pressure down-draw and limited productivity for the systems while the Hjalteyri, Laugarengi and Reykir systems have greater productivity.

The Hjalteyri system is by far the most productive of the geothermal systems utilized by Nordurorka and its production capacity is comparable to that of the most productive low-temperature systems in Iceland (Axelsson *et al.*, 2005a). The reason why it is so much more productive than the systems around Akureyri is believed to be the fact that the northern part of Eyjafjördur is much more tectonically active than the region further south, where the other systems are located. The production properties of the systems utilized by Nordurorka, in most cases estimated on the basis of lumped parameter modelling, are summarized in Table 2 below.

The responses of the different systems to long-term production may be compared by calculating their unit responses, which is simply the response to a constant production of a unit volume (or mass) per unit time. The results for seven of the systems are presented in Fig. 7. It shows the greatest draw-down in the Botn and Thelamörk systems and by far the the smallest draw-down in Hjalteyri system, reflecting the differences in permeability and volume discussed above. The responses of the Laugaland, Ytri-Tjarnir and Glerárdalur systems show a draw-down continuously increasing with time. This indicates that these systems are mostly closed, or with a limited recharge (see Axelsson, 2008). The other systems appear to reach partial, or full, equilibrium indicating open boundary conditions. This applies in particular to the Botn and Laugarengi systems, and most likely also to the Hjalteyri system, while the production history of that system is still too short to determine that.

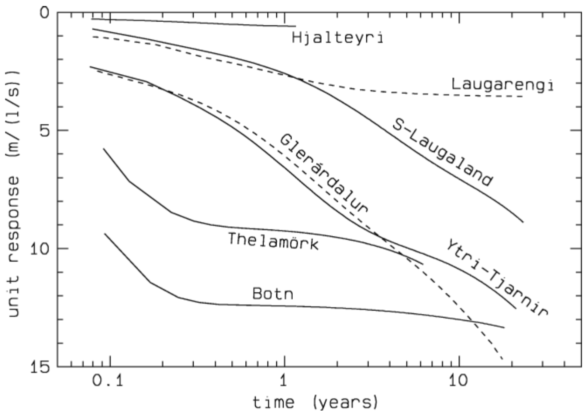

Figure 7: Unit water-level response of the geothermal systems utilized by Nordurorka

7.2 The Fluid Chemistry, Problems and Solutions

The chemical content of the water from the different geothermal fields is rather similar. Generally, the water is very low in chemical content and direct use should be possible without any problems. The total dissolved solid is ranging from 180 to 300 ppm. Yet, corrosion problems, especially in radiators, were encountered after a few years of operation. The corrosion was caused by oxygen contamination, mainly originating in the storage tank, but partly in degassers. A minor oxygen contamination will make the water corrosive (Kristmannsdóttir, 1991). Therefore its concentration should be kept below 10 ppb. A minor oxygen contamination is usually harmless in geothermal water as oxygen reacts with hydrogen sulphide in geothermal water to form sulphate. But since the water from most of the geothermal fields utilized in Akureyri is extremely low in H_2S it is necessary to mix sodium sulphide into the water to remove the oxygen. This mixing was not sufficient, however, to prevent oxygen uptake in the storage tank without special measures. The reaction rate is to slow to remove all oxygen before the water enters the houses closest to the tank. Therefore an electrical boiler is used to produce pure steam that is injected into the airspace above the water-table in the storage tank and prevents oxygen to enter the space. Thus, when the water level in the tank lowers, hot steam in injected into the tank but when the water level rise the steam is flowing out of the tank through an one-way valve. Apart from these problems, the district heating system in Akureyri has been practically without serious chemical problems.

8. GEOTHERMAL ENERGY PRICES IN AKUREYRI

Figure 8 shows the evolution of the consumer price for geothermal energy for house heating in Akureyri. In the beginning it was rather low but increased after the problems of finding enough geothermal water grew. It was at maximum in 1985 when the system of selling was changed from selling power through a flow limiter to selling the energy through a flow meter. Each household pays a fixed price per cubic meter of used water which usually is 76°C hot. Thus roughly, one cubic meter contains about 50 kWh of thermal energy.

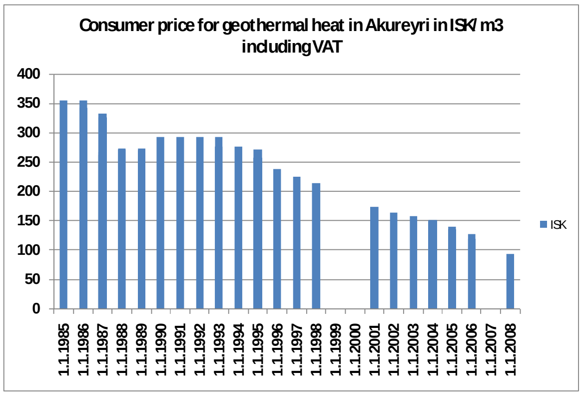

Figure 8: Consumer price for one cubic meter of geothermal water in Akureyri from 1985 to 2008. The price is in Icelandic "krónur" (ISK) and index adjusted for inflation with reference in 2008. By the end of the year 2008 1 ISK was roughly equal to 1 US cent. One cubic meter contains roughly 50 KWh

The figure clearly shows the lowering of the price with time as the initial investment was paid back. By the end of the year it was only about 25% of the price in 1985. Due to the unstable value of the Icelandic "króna" during the past year it is difficult to convert the price to US dollars, but to give some idea 1 ISK might be set equal to 1 US cent. This means that the consumer price in Akureyri by the end of the year 2008 was close to 1 US cent per cubic meter or 2 US cent per kWh.

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