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Successful Utilization of Low-Temperature Geothermal Resources in Iceland for District Heating for 80 Years

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ABSTRACT

Geothermal energy provides at present about 2/3 of the primary energy supply in Iceland. Its principal use is for space heating, but other direct uses and electricity generation are also highly significant. About 90% of the space heating is currently by geothermal energy. The majority of the country's district heating services use energy from many of the numerous low-temperature geothermal systems, which are all located outside the volcanic zone. Many of the geothermal district heating services (hitaveitur) have been in operation for several decades, the oldest ones for more than 80 years and several others for 30 – 60 years. Much can be learned from their operation, in particular regarding long-term management of low-temperature geothermal resources. In most cases the utilization is through the operation of down-hole pumps, but there are examples of large-scale free-flow being maintained for up to 50 years. The production- and response (pressure, chemistry and temperature) histories of seven low-temperature geothermal systems are presented. Three of the systems are very productive and reach pressure equilibrium at constant production. Two are much less productive and don't attain pressure equilibrium. One of the systems is in-between these two. Only one of the systems is plagued by considerable cold ground-water inflow that has resulted in temperature decline and chemical changes. Several problems have faced the Icelandic low-temperature operations, such as overexploitation manifesting itself in excessive pressure draw-down as well as problems related to colder water inflow and sea water incursion. None of the district heating systems have ceased operation and solutions have been found to these problems. The solutions include improving the energy efficiency of the associated heating systems, deeper and more focussed drilling (e.g. directional drilling), finding new drilling targets (even new drilling areas), reinjection as well as technical solutions on surface. The long utilization case histories provide important information pertaining to sustainable management of geothermal resources. The future of all of these operations appears bright.

1. INTRODUCTION

Geothermal energy plays a major role in the energy economy of Iceland. At present it provides about 66% of the primary energy supply for the almost 320,000 inhabitants, or about 135 PJ (1 PJ = 10^{15} J; numbers for 2007). The principal use of geothermal energy in Iceland is for space heating. Currently about 89% of the space heating is by geothermal energy, having increased from about 45% in 1970 (see Fig. 1). Other uses of geothermal energy in Iceland include direct uses such as for industrial applications, swimming pools, snow melting, greenhouses and fish farming as well as indirect electricity generation (Ragnarsson, 2008).

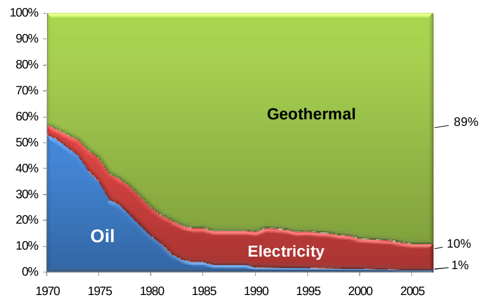

Figure 1: Energy sources used for space heating in Iceland 1970 – 2007 (Ragnarsson, 2008).

At the present there are 22 public, or municipally owned, geothermal heating companies in Iceland operating 62 separate district heating systems or networks. In Icelandic these are named *hitaveita* in the singular and *hitaveitur* in the plural. By far the largest one is the one serving the capital city of Reykjavik and five neighbouring communities. It is operated by Reykjavík Energy (www.re.is) and serves more than 180,000 inhabitants. Its energy use currently amounts to about 12 PJ/yr. Another two hitaveitur serve 18,000 – 20,000 inhabitants while the remaining 59 public hitaveitur are relatively small, serving communities with only a few households to a few thousand inhabitants each. Their annual energy use ranges from 5 to 500 TJ/yr. In addition, numerous small private district heating systems exist in rural areas, each typically serving ten to twenty farms. These systems presently serve about 4000 inhabitants.

Fifty-four of the public hitaveitur, and all of the rural ones, use energy from some of the numerous low-temperature geothermal systems found in Iceland. The low-temperature systems, which by definition have a reservoir temperature below 150°C, are all located outside the volcanic zone passing through the island. Actually, the Reykjavík hitaveita, mentioned above, utilizes four separate geothermal systems, three low-temperature systems and one high-temperature system. Most of the hitaveitur use the geothermal water directly.

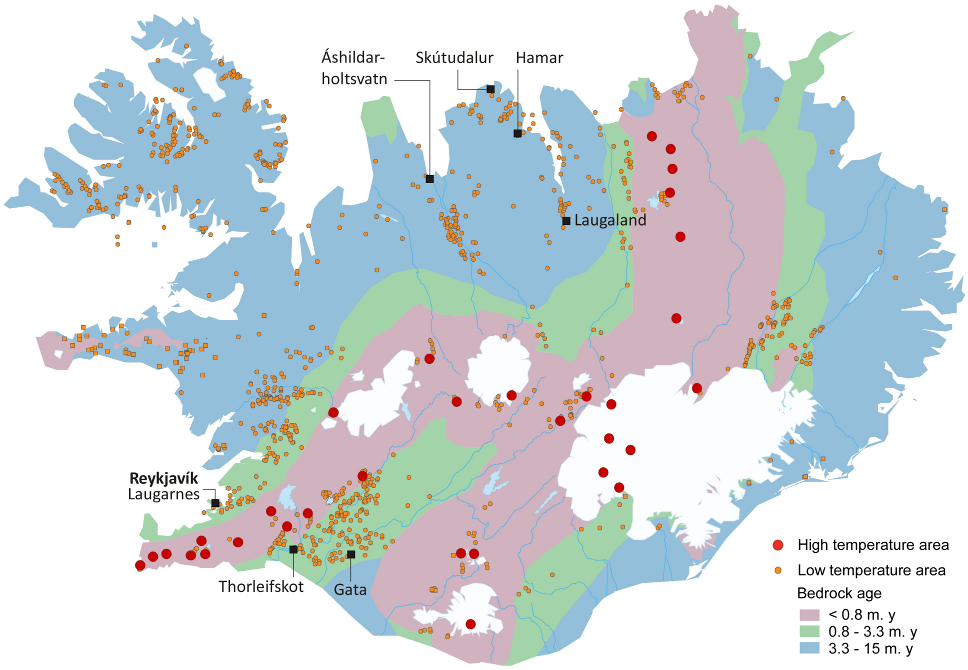

Figure 2: Map of Iceland showing the distribution of low-temperature and high-temperature systems relative to the volcanic zone passing through the island. The locations of the seven low-temperature geothermal systems presented in the paper are shown on the map.

Many hitaveitur have been in operation for several decades, the oldest ones for more than 80 years and several others for 30 – 60 years. Much can be learned from their operation, in particular regarding long-term management of low-temperature geothermal resources. This experience also provides valuable input into discussions and studies related to the renewability of geothermal energy and the possible contribution of geothermal energy to sustainable development (Axelsson *et al.*, 2005a). Several problems have faced these operations, however, such as overexploitation manifesting itself in excessive pressure draw-down as well as problems related to colder water inflow and sea water incursion. None of the district heating systems have ceased operation and solutions have been found to these problems.

The purpose of this paper is to present some of the longest Icelandic low-temperature utilization case histories and to summarize the lessons learned from the associated long-lasting experience. At first the current understanding of the nature of the low-temperature activity is reviewed. Following that the overall experience is reviewed along with a presentation of seven long and well-documented case histories. Then some of the problems encountered will be discussed along with the solutions applied. The paper is concluded by some general observations and recommendations.

2. LOW-TEMPERATURE SYSTEMS IN ICELAND

The low-temperature systems, which by definition have a reservoir temperature below 150°C, are all located outside the volcanic zone passing through Iceland (see Fig. 2). The largest such systems are located in SW-Iceland on the flanks of the volcanic zone, but smaller systems are found throughout the country. The surface manifestations of the low-temperature activity are in most cases hot or boiling springs, while a few such systems have no surface manifestations. Spring flow rates range from almost zero to a maximum of 180 L/s from a single spring.

The heat-source for the low-temperature activity is believed to be the abnormally hot crust of Iceland, but faults and fractures, which are kept open by the continuously ongoing tectonic activity also play an essential role by providing the channels for the water circulating through the systems and mining the heat. The geothermal gradient in Iceland varies from about 50°C/km to about 150°C/km, outside the volcanic zone. The nature of the low-temperature activity has been discussed by several authors during this century (Einarsson, 1942; Arnason, 1976; Bödvarsson, 1982; Björnsson *et al.*, 1990; Arnórsson, 1995; Arnórsson *et al.*, 2008). A highly simplified conceptual model may be described as follows: Precipitation, mostly falling in the highlands, percolates down into the bedrock to a depth of a few km (1-3) where it takes up heat from the hot rock and ascends subsequently, towards the surface, because of reduced density. Some of the systems may simply be deep-rooted ground-water systems, of great horizontal extent, but most of the systems are believed to be more localized convection systems, wherein heat is transported from depth to shallower formations (Bödvarsson, 1982; Björnsson *et al.*, 1990). The former may constitute practically steady-state phenomena, whereas the latter must in essence be transient.

A steady-state process can't explain the high natural heat output of the largest low-temperature systems in Iceland, which may be of the order of 200 MW_t. Therefore, Bödvarsson (1982, 1983) proposed a model for the heat-source mechanism of the activity, which can explain the high heat output. This model appears to be consistent with the data now available on most of the major low-temperature systems (Björnsson *et al.*, 1990). According to his model, presented in Fig. 3, the recharge to a low-temperature system is shallow ground water flow from the highlands to the lowlands. Inside a geothermal area the water sinks through an open fracture, or along a dike, to a depth of a few km where it takes up heat and ascends. In the model the fracture is closed at depth, but opens up and continuously migrates downward during the heat mining process by cooling and contraction of the adjacent rock.

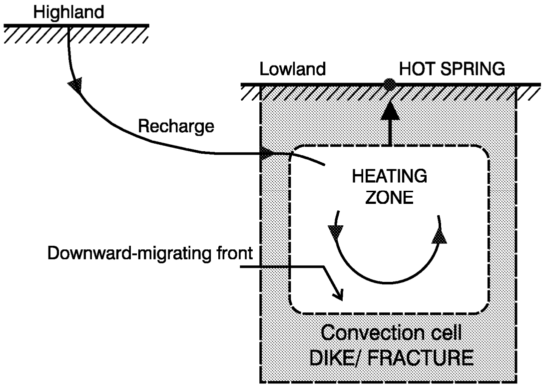

Figure 3: Model of the heat-source mechanism of the more powerful low-temperature systems in Iceland. Based on Bödvarsson (1983).

Theoretical calculations based on Bödvarsson's model (Axelsson, 1985) indicate that the existence and heat output of such low-temperature systems is controlled by the temperature and stress conditions in the crust. In particular, the local stress field, which controls whether open fractures are available for the heat mining process and how fast these fractures can migrate downward. Given the abnormal thermal conditions in the crust of Iceland it appears, therefore, that the regional tectonics and the resulting local stress field are the main factors controlling the low-temperature activity.

A number of low-temperature systems have been discovered in recent years in areas devoid of surface manifestations, many already in use for space heating in nearby towns and villages. They were all discovered after intense surface exploration. The nature and properties of some of these systems have been studied and compared with that of other low-temperature systems in Iceland having surface manifestations. The results indicate that the characteristics of these systems fall within the range observed for other systems, except perhaps for systems that appears to have abnormally closed boundaries and limited recharge (Axelsson *et al.*, 2005b).

The low-temperature systems in Iceland have been studied extensively during the last half a century or so. First through resource exploration and later through, reservoir engineering studies, resource assessment and monitoring. Axelsson and Gunnlaugsson (2000) and Axelsson *et al.* (2005b) review the associated research and experience. Axelsson (2008) discusses the factors that control the production capacity of geothermal systems and presents Icelandic as well as worldwide examples. Axelsson *et al.* (2005c) furthermore discuss a method of lumped parameter modelling which has been used successfully to simulate the pressure changes in the Icelandic low-temperature geothermal systems during production.

3. LONG CASE HISTORIES

3.1 General

Some of the low-temperature hitaveitur (geothermal district heating services) have been in operation for more than half a century and several others for more than three decades. Several of the associated low-temperature systems are listed in Table 1 at the end of the paper. Seven of these, distributed throughout the country, are discussed briefly below. Also listed in the table are the Mosfellssveit system, which is utilized by the hitaveita operated by Reykjavík Energy along with the Laugarnes system discussed below and the Ellidaár system. Gunnlaugsson and Ívarsson (2010) present the history of the Reykjavík Energy low-temperature geothermal systems in more detail.

In addition the table lists the geothermal systems utilized by two of the oldest hitaveitur in Iceland. These are the Laugar (in Reykjadalur) and Laugavatn low-temperature systems, in N-Iceland and S-Iceland, respectively, serving the relatively small communities with the same names. The utilization of both systems started more than 80 years ago and is still continuing. Also included in the table is the tiny Brautarholt hitaveita in S-Iceland, which has been in operation since 1950.

Initially (from the 1930’s through the 1960’s) the utilization of many of these systems was through free-flow from relatively shallow wells and in some cases from hot springs. Today the utilization is in most cases through the operation of down-hole pumps, which has enabled production at rates considerably greater than the free-flow rates (see the Laugarnes case below). There are still examples, however, of large-scale free-flow being maintained for more than half a century (see the Áshildarholtsvatns case below).

In most of the Icelandic low-temperature systems utilized, such as most the cases presented below, semi-equilibrium between mass extraction and pressure decline has been reached. In a few systems a continuously increasing pressure draw-down has been observed at constant yearly production, however. This has been attributed to more limited recharge than in the systems where semi-equilibrium has been reached. In most cases reservoir pressure changes are monitored through water-level changes in production wells or specific monitoring wells. Changes in temperature and chemistry have, furthermore, been minimal, except in a very few exceptional cases, such as in the Thorleifskot system discussed below.

3.2 Laugarnes in Reykjavík

The Laugarnes geothermal system is located near the center of Reykjavík, the capital city of Iceland. It’s embedded in relatively young and hot crust about 20 km NW of the active zone of spreading. It is believed to be associated with the intersection of SW-NE trending faults and fractures and the caldera rim of an extinct central volcano (Gunnlaugsson *et al.*, 2000). It’s exploitation for space heating started in 1930 with the utilization of free-flowing 87°C water from a number of shallow wells (the deepest being 246 m).

In 1958 further drilling of both deeper and larger diameter wells commenced in the field. This together with the introduction of large capacity down-hole pumps enabled the hot water production in Laugarnes to be increased by an order of magnitude (Axelsson and Gunnlaugsson, 2000). Ten production wells are in operation today in the field with the deepest one extending down to 2700 m depth. The reservoir temperature in the Laugarnes system is about 120 – 140°C and the last four years the average production has been more than 150 L/s (Gunnlaugsson *et al.*, 2010).

Fig. 4 shows the production and water-level history of the field. It shows how the production increase in the 1960’s resulted in a reservoir pressure drop corresponding to about 120 m water level drop. Production and water level have, however, remained relatively stable during the last four decades. This indicates that the reservoir has found a new semi-equilibrium, with ten times the natural recharge.

Laugarnes is among the more productive low-temperature systems utilized in Iceland.

During the middle 1980's, when production was at a maximum, an inflow of slightly saline ground-water was detected in a few wells. This, however, was reversed when production was reduced again in the 1990's (Gunnlaugsson *et al.*, 2000).

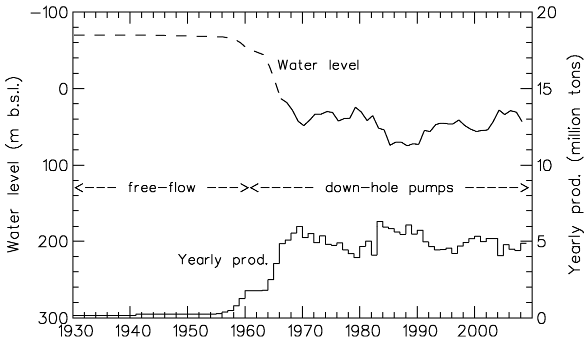

Figure 4: Production and water-level (winter minima) history of the Laugarnes low-temperature geo-thermal system within Reykjavík, SW-Iceland, from 1930 to 2008. The broken line indicates estimated water-level.

3.3 Áshildarholtsvatn in Skagafjördur

The Áshildarholtsvatn low-temperature geothermal system is located in the Skagafjördur region in central N-Iceland. This region is geothermally quite active because of its proximity to an extinct segment of the N-Iceland spreading axis and considerable tectonic activity. The Áshildarholt area is a few km SE of the town of Saudárkrókur and geothermal energy from the system is used for space heating of the town and neighbouring farms. Today this heating system is connected to a smaller heating system from Varmahlíd, located further south resulting in an integrated system extending about 30 km.

The Áshildarholtsvatn system has been utilized since 1948, all the time by free-flow from a number of wells. Today 4 production wells, ranging in depth from 520 to 670 m, are utilized. The reservoir temperature is of the order of 70°C and the average production has been of the order of 70 L/s the last few years. Fig. 5 shows the production and pressure change history of the system, the pressure changes being monitored as well-head pressure changes of a special observation well.

Like the Laugarnes system, the Áshildarholtsvatn system is one of the more powerful low-temperature systems in Iceland, even though the reservoir temperature is considerably lower than in Laugarnes. This is reflected in relatively small pressure changes, both annually and long-term. The Áshildarholt system appears to have found a new semi-equilibrium just as the Laugarnes system. The Áshildarholt system is, furthermore, one of a very few Icelandic low-temperature systems were all the production is by free-flow, i.e. artesian.

It is of interest to note that a relatively pronounced peak in well-head pressure in 2000 is partly due to the pressure increase effect of two major (both M_S = 6.6) earthquakes that occurred in S-Iceland at a 200 km distance that summer, but not only due to the annual production minimum.

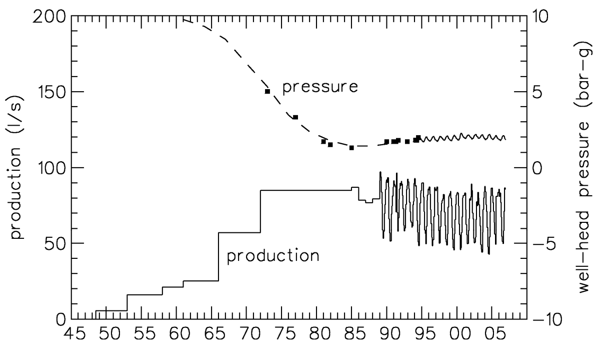

Figure 5: Production and pressure history of the Áshildarholtsvatn low-temperature geothermal system near the town of Saudárkrókur in N-Iceland from 1948 (the hitaveita started operation in 1953) to 2006. The figure shows yearly average production up to 1989. The broken line indicates estimated reservoir pressure and the dots isolated pressure readings.

3.4 Skútudalur in Siglufjördur

The Skútudalur low-temperature system is located on the east side of the Siglufjördur fjord in central N-Iceland and serves the town of Siglufjördur on the west side of the fjord. It is in a region of relatively old crust that is tectonically quite active, explaining the low-temperature activity in the region. The system has a reservoir temperature of approximately 70°C and has been utilized since 1975. Fig. 5 shows the production and water-level history of the Skútudalur system.

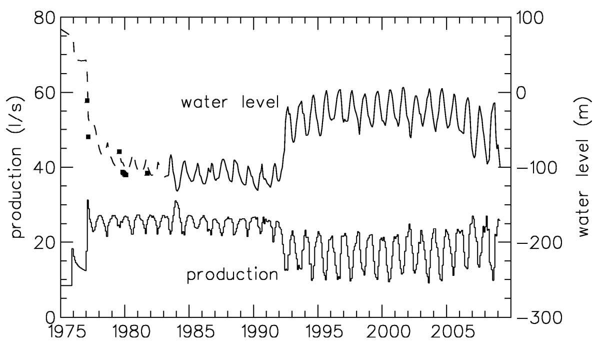

Figure 5: Production and water-level history of the Skútudalur low-temperature geothermal system in Siglufjördur, N-Iceland, from 1975 to 2008. The broken line indicates estimated water-level and the dots isolated water-level readings.

The Skútudalur system is not a highly productive system, but it does reach equilibrium during constant production as Fig. 6 shows. It is noteworthy that the water level appears to drop more the last few years than would be expected on basis of the production. It has been speculated that this may be attributed to a recently constructed road-tunnel through the mountains above Skútudalur. This is being studied, but would not be surprising since the road-tunnel drains water from, and lowers pressure in, the ground-water system in the mountains, which supposedly also provides recharge for the Skútudalur geothermal system.

3.5 Hamar near Dalvík

The Hamar low-temperature geothermal system is discussed by Axelsson *et al.* (2005a). It is located on the western side of the Eyjafjördur fjord in central N-Iceland, a little over 20 km SE of Skútudalur, The basaltic lava-pile hosting it is relatively permeable because of recent tectonic activity (Flóvenz *et al.*, 2000). The western edge of the fjord is in fact particularly active as is demonstrated by the 6.2 (Richter-scale) Dalvík earthquake in 1932, which occurred a few km east of the Hamar system.

The Hamar system has been utilized for space heating in the near-by town of Dalvík since 1969. In recent years the average yearly production from the field has been close to 40 kg/s. Two production wells, with feed-zones between depths of 500 and 800 m, in the basaltic lava-pile, are currently in use and the reservoir temperature is about 65°C. The production and water-level history of the field is presented in Fig. 6. The production has caused a very modest pressure decline of about 3 bar (30 m).

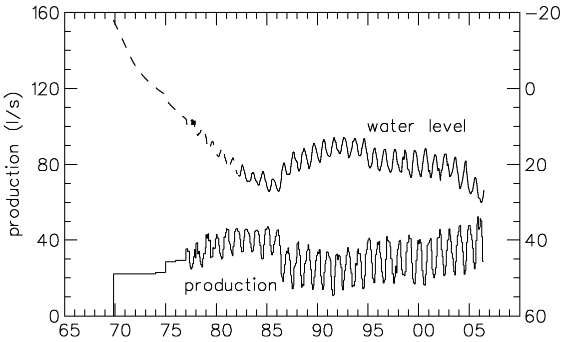

Figure 6: Production and water-level history of the Hamar low-temperature geothermal system near the town of Dalvík in N-Iceland from 1969 to 2006. The broken line indicates estimated water-level and the dots isolated water-level readings.

The Hamar system is a small, but productive, low-temperature system, as witnessed by the modest pressure drop. It appears to reach semi-equilibrium when production is constant. The reservoir pressure has been declining since 1995, however, due to constantly increasing production. Axelsson *et al.* (2005c) present the results of a modelling study aimed at estimating the sustainable potential of the Hamar system. They conclude that the long-term (200 years) production potential of the system is limited by energy-content rather than pressure decline (lack of water). The sustainable rate of production at Hamar is estimated to be greater than 40 kg/s, corresponding to more than 11 MW_{th}.

3.6 Laugaland in Eyjafjördur

The Laugaland low-temperature system is located in the Eyjafjördur valley south of the Eyjafjördur fjord in central N-Iceland already mentioned. It is the second largest of six low-temperature geothermal fields utilized by Nordurorka for space heating in the town of Akureyri at the bottom of the fjord (Flóvenz *et al.*, 1995 and 2010). The Laugaland system has been utilized since late 1977 following a testing period in 1976. The name Laugaland actually means land, or farm, of hot-springs.

The Laugaland geothermal system is a typical fracture controlled system, embedded in 6-10 Myrs old flood basalt, wherein the hot water flows along open fractures in otherwise low-permeability rocks. Twelve wells have been drilled in the Laugland area, but only three of them are sufficiently productive to be used as production wells. The reservoir temperature at Laugaland is of the order of 100°C. The Laugaland system is drastically less permeable than the Hamar system presented above, even though both systems are in the same region. The reason is believed to be the fact that the Eyjafjördur valley, where Laugaland is located, is much less tectonically active than the western side of the Eyjafjördur fjord, where Hamar is located. The distance between the fields is about 50 km.

Fig. 7 shows the production and water-level history of the Laugaland system. Hot water production from the field has varied between 0.9 and 2.5 million tons annually and today the average production from the field is of the order of 30-40 L/s. Because of the low overall permeability, and apparently limited recharge, this modest production has lead to a great pressure drawdown. It continues to increase with time if constant rate production is maintained. In the early eighties the draw-down reached about 400 m, which forced the production from the field to be reduced by about 50%.

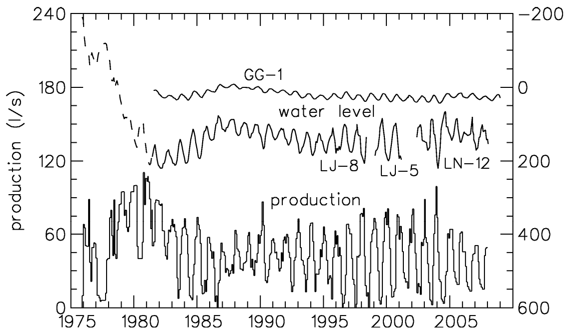

Figure 7: Production and water-level history of the Laugaland low-temperature geothermal system south of Akureyri in N-Iceland from 1976 to 2007. The broken line indicates estimated water-level. Wells LJ-5, LJ-8 and LN-12 are inside the field while well GG-1 is 2 km from the fields centre.

Because of the drastic pressure draw-down, and limited recharge, reinjection had for long been considered a possible way to improve the productivity of the Laugaland system. Therefore, a comprehensive 2-year reinjection experiment was conducted in the field at the end of the 20th century (Axelsson *et al.*, 2001). Since then reinjection, corresponding to about 25% of the mass extraction, has been part of the management of the Laugaland geothermal system. It has helped to stabilize the pressure decline in the system.

3.7 Gata in the Holt District

The Gata (or Laugaland) system has been discussed briefly by Axelsson *et al.* (1995) and Zhang (2003). It is located in the Holt district of the south Iceland lowlands, a few km south of the highly active S-Iceland seismic zone. In spite of its proximity to the seismic zone, the permeability of the Gata system is unusually low and the system poorly productive. It may be mentioned that numerous, permeable, low-temperature systems are located inside, and north of, the seismic zone while hardly any systems are found south of the zone.

The Gata geothermal system has been utilized since 1946, up to 1982 for local heating and a swimming pool, but after 1982 for a hitaveita for the towns of Hella and Hvolsvöllur east of Gata. The geothermal system has a reservoir temperature of 100-105°C. The production and water-level history of the system is presented in Fig. 8. The average yearly production rate has varied between 10 and 22 L/s, the last few years it has been of the order of 15 L/s. One primary production well, 1000 m deep, has been in use since 1982.

Fig. 8 shows how the water level declined continuously up to early 2000 indicating very limited recharge to the Gata geothermal system. Therefore a new production area was hooked up to the Hella/Hvolsvöllur hitaveita in early 2000, which enabled a drastic reduction in production. This is the Kaldárholt system described by Zhang (2003). It is a very productive system, but with a reservoir temperature of only 65-70°C. At the same time limited (10-20% of the production) reinjection was started at Gata. During the last few years production at Gata has started to increase again causing the water level to decline once more.

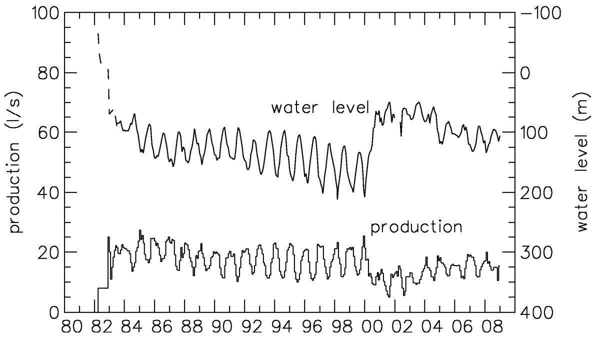

Figure 8: Production and water level history of the Gata low-temperature geothermal system in the Holt district of S-Iceland from 1982 to 2008. The broken line indicates estimated water-level.

A major earthquake (M_s = 6.6) shook the Holt district on June 17th 2000, only a few km north of Gata, followed by another one a few days later further to the west (see discussion on Áshildarholtsvatn above). It caused drastic changes in reservoir conditions in hydrological systems all over the southern lowlands of Iceland (Jónsson *et al.*, 2003). A modelling study for the Gata system indicates that the observed water level after the earthquake(s) is, in fact, 40 – 80 m higher than the modelled level (Axelsson *et al.*, 2005c). This is believed to be the result of reservoir permeability at Gata, as well as fluid recharge, having increased in conjunction with the earthquake(s).

3.8 Thorleifskot near Selfoss

The Thorleifskot low-temperature geothermal system is on the outskirts of the town of Selfoss in S-Iceland. Along with the Ósabotnar low-temperature system it is used by the Selfossveitur hitaveita for district heating in the Árborg community, which encompassed the towns of Selfoss, Eyrarbakki and Stokkseyri as well as surrounding rural areas (Ólafsson *et al.*, 2005). The Thorleifskot system has been utilized for space heating since 1948 and currently the average yearly production is 70-80 L/s.

The Thorleifskot system is inside the S-Iceland seismic zone mentioned above and is, hence, highly permeable. Initially the hot water production was by pumping from a few shallow wells, but these had to be abandoned one by one because of inflow of cold groundwater through some of the open seismic fractures. Later deeper wells were drilled that were also cased to greater depth, but many of these have also been affected by the inflow (Tómasson *et al.*, 1981). Today four production wells are utilized at Thorleifskot. They were all drilled from 1979 to 1999 and range in depth from about 1400 m to about 2400 m. They have casings that are from 310 – 630 m deep. The last few years average production at Thorleifskot has been about 70-80 L/s. Reservoir temperature in the Thorleifskot system is unusually variable, ranging from about 60°C to more than 120°C.

Fig. 9 presents water temperature and silica content data from two of the main production wells. The figure shows clearly that cold ground-water inflow continues to plague geothermal production at Thorleifskot in spite of the deep casings. Well 10 has cooled down dramatically, in particular after the S-Iceland earthquakes, which affected the geothermal system drastically. Changes in well 13 are much less pronounced and the earthquakes even seem to have caused the production temperature of the well to have increased slightly. The difference between the two wells may be attributed to different casing depths.

Drastic changes in production temperature as observed at Thorleifskot are really an exception for low-temperature systems utilized in Iceland. No such changes have e.g. been observed in the other systems discussed in this paper. Other cooling examples are limited to particular wells with very short casings or wells located on the outer boundaries of particular systems (Axelsson and Gunnlaugsson, 2000). In the case of the Árborg hitaveita this problem has been resolved by adding a new low-temperature geothermal system to the hitaveita. It may be mentioned that temperatures are quite high in the deeper parts (> 1000 m) of the Thorleifskot system, or above 120°C. Feed-zones with sufficient permeability have not been found there in-spite of a few drilling attempts. It's hoped, however, that in the future this deeper part of the system will provide more energy for the Árborg hitaveita.

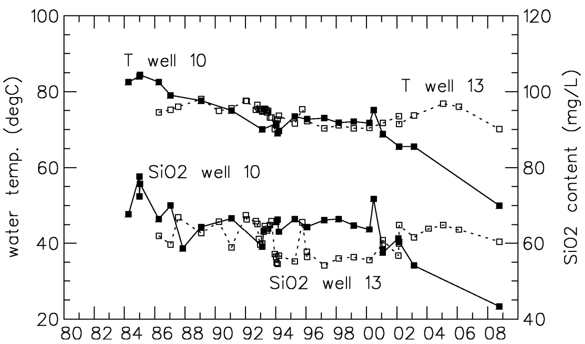

Figure 9: Changes in water temperature and silica (SiO_2) content for two of the main production wells in the Thorleifskot field near Selfoss in S-Iceland from 1984 to 2008.

4. PROBLEMS AND SOLUTIONS

Several problems and/or challenges have faced the district heating operations discussed above and other district heating operations in Iceland. The most common ones are (some already mentioned above):

(A) Overexploitation manifesting itself in excessive pressure draw-down.
(B) Problems related to colder water inflow, such as production well cooling and changes in chemical composition.
(C) Sea water incursion.
(D) Changes in reservoir conditions due to earthquake-activity.
(E) Corrosion and scaling.
(F) Technical problems associated with wells (casings), pumps, etc.

Solutions have been found to these problems and none of the district heating systems have ceased operation as of yet. The solutions include:

(1) Improving the energy efficiency of the associated heating systems.

(2) Deeper and more focussed drilling (e.g. directional drilling).
(3) Finding new revised drilling targets or new drilling areas.
(4) Return water reinjection.
(5) Use of scaling- and corrosion inhibitors.
(6) Technical solutions to surface hardware problems.

Solutions (1) and (3) aim at reducing production from a given low-temperature system. Figures 5 and 6 show clear examples of this (i.e. reduced production and water-level recovery). Solutions (2) and (4) aim at transferring a part of the production from overexploited zones.

The operation problems and solutions associated with the Reykjavík low-temperature systems are discussed in more detail by (Gunnlaugsson and Ívarsson, 2010).

5. RESULTS AND CONCLUSIONS

This paper has reviewed the long experience available in Iceland on utilizing low-temperature geothermal systems for direct use, such as space heating. The longest case histories presented are more than 80 years long while the shortest history presented is 33 years. These, and other comparable histories, encompass extremely valuable information on the nature of the geothermal systems. The associated experiences are also beneficial as guidance for the long-term management of other low-temperature geothermal systems, in Iceland and worldwide.

The seven low-temperature geothermal systems presented as case histories here are quite variable in terms of size, nature and production capacity. Three of them are very productive, because of favourable permeability and boundary conditions, and reach equilibrium at constant production. Two of them are much less productive and don't attain equilibrium, while one has low permeability but favourable boundary conditions (is in-between the other two types). Only one of the systems, which is albeit highly productive, is plagued by considerable cold ground-water inflow that has resulted in temperature decline and chemical changes. In spite of such inflow being negative, one must keep in mind that it helps extract more energy from the reservoir rocks than would be otherwise. Such a system classification is along the lines proposed by Axelsson (2008).

Table 1 presents the total volume of water extracted from 7 of the 11 systems listed in the table during their entire production histories (only since 1971 for the Mosfellssveit system, however). These range from 0.014 to 1.1 km^3. It is of interest to compare these volumes with the pore-space volumes of the systems involved. This is, however, beyond the scope of this work. The pore-space volumes are in addition poorly known. Yet, two examples are mentioned:

(i) The volume of the Laugarnes system is believed to be of the order of 10 km^3 and its porosity approximately 10% (partly based on Björnsson *et al.*, 2000). A rough estimate of its pore-space volume is, therefore, about 1 km^3. The total volume extracted from the system (0.25 km^3) corresponds thus to about 25% of the total volume of water in-place in the Laugarnes system prior to production.
(ii) The volume of the Hamar system is believed to be at least 0.5 km^3 and its porosity approximately 10% (see Axelsson *et al.*, 2005a). A rough estimate of its pore-space volume is, therefore, more than 0.05 km^3. The total volume extracted from the system (0.039 km^3) corresponds thus to less than 80% of the total volume of water in-place in the system prior to production.

In both cases the volume extracted is less than the initial water in-place in the systems, in-spite of the long production histories. This is important for understanding the long-term behaviour of such systems and may explain why no noticeable chemical- or temperature changes have been detected during the utilization histories of these systems, and most other Icelandic low-temperature systems being utilized.

Various problems, differing in nature and severity, have faced many of the Icelandic low-temperature based hitaveitur. Some continue operation without any immediate action being required while a variety of solutions have been found for other problems. One solution may involve revised, or new, drilling targets within a geothermal system being utilized while the solutions for systems where a reduction in production has been required may involve reinjection or transferring part of the production to other geothermal systems. None of the hitaveitur discussed here, or any other low-temperature hitaveitur in Iceland for that matter, have ceased operation and the future of all of the operations appears bright.

The data available associated with the long utilization case histories presented here are extremely valuable for the study of the renewability of geothermal resources. A comprehensive study of this aspect of low-temperature resources in Iceland has not been conducted so far, but the data presented here are available for such studies. They also demonstrate that the low-temperature resources can be utilized in a sustainable manner, along the lines presented by Axelsson *et al.* (2005) and provide important information pertaining to sustainable management of geothermal resources. This is clear for the systems attaining equilibrium discussed above while systems with limited recharge require reinjection for their sustainable utilization.

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REFERENCES

Árnason, B., 1976: Groundwater systems in Iceland traced by deuterium. *Soc. Sci. Islandica*, **42**, 236pp.

Arnórsson, S., 1995: Geothermal systems in Iceland: Structure and conceptual models-II. Low-temperature areas. *Geothermics*, **24**(5/6), 603-629.

Arnórsson, S., G. Axelsson and K. Saemundsson, 2008: Geothermal systems in Iceland. *Jökull*, **58**, 269-302.

Axelsson, G., 2008: Production capacity of geothermal systems. *Proceedings of the Workshop for Decision Makers on the Direct Heating Use of Geothermal Resources in Asia*, Tianjin, China, May 2008, 14 pp.

Axelsson, G., 1985: Hydrology and thermomechanics of liquid-dominated hydrothermal systems in Iceland. Ph.D. Thesis, Oregon State University, Corvallis, Oregon, 291pp.

Axelsson, G. and E. Gunnlaugsson (convenors), 2000: Long-term Monitoring of High- and Low-enthalpy Fields under Exploitation. International Geothermal Association, World Geothermal Congress 2000 Short Course, Kokonoe, Kyushu District, Japan, May 2000, 226pp.

Axelsson, G., V. Stefánsson and G. Björnsson, 2005a: Sustainable utilization of geothermal resources for 100

– 300 years. *Proceedings World Geothermal Congress 2005*, Antalya, Turkey, April 2005, 8 pp.

Axelsson, G., G. Björnsson, Th. Egilson, Ó.G. Flóvenz, B. Gautason, S. Hauksdóttir, M. Ólafsson, Ó.B. Smárason and K. Sæmundsson, 2005b: Nature and properties of recently discovered hidden low-temperature geothermal reservoirs in Iceland. *Proceedings World Geothermal Congress 2005*, Antalya, Turkey, April 2005, 10 pp.

Axelsson, G., G. Björnsson and J.E. Quijano, 2005c: Reliability of lumped parameter modelling of pressure changes in geothermal reservoirs. *Proceedings World Geothermal Congress 2005*, Antalya, Turkey, April 2005, 8 pp.

Axelsson, G., Ó.G. Flóvenz, S. Hauksdóttir, A. Hjartarson and J. Liu, 2001: Analysis of tracer test data, and injection-induced cooling, in the Laugaland geothermal field, N-Iceland. *Geothermics*, **30**, 697-725.

Axelsson G., G. Björnsson, Ó.G. Flóvenz, H. Kristmannsdóttir and G. Sverrisdóttir, 1995: Injection experiments in low-temperature geothermal areas in Iceland. *Proceedings of the World Geothermal Congress 1995*, Florence, Italy, 1991-1996.

Björnsson, G., S. Thordarson and B. Steingrímsson, 2000: Temperature distribution and conceptual reservoir model for geothermal fields in and around the city of Reykjavík, Iceland. *Proceedings of the 25th Workshop on Geothermal Reservoir Engineering*, Stanford University, California, January 2000, 7 pp.

Björnsson, A., G. Axelsson and Ó.G. Flóvenz, 1990: The nature of hot spring systems in Iceland (in Icelandic/ English abstract). *Náttúrufraedingurinn*, **60**, 15-38.

Bödvarsson, G., 1983: Temperature/flow statistics and thermomechanics of low-temperature geothermal systems in Iceland. *J. Volcanol. Geothermal Res.*, **19**, 255-280.

Bödvarsson, G., 1982: Glaciation and geothermal processes in Iceland. *Jokull*, **32**, 21-28.

Einarsson, T., 1942: Uber das Wesen der Heissen Quellen Islands (The nature of the hot springs in Iceland, in German). *Soc. Sci. Islandica*, **42**, 91pp.

Flóvenz, Ó.G, F. Árnason, B. Gautason, G. Axelsson, Th. Egilson and S.H. Steindórsson, 2010: The district heating of the town of Akureyri, N-Iceland; 35 years of problems, solutions and success. Paper submitted to the World Geothermal Congress 2010.

Flóvenz, Ó.G., R. Karlsdóttir, K. Sæmundsson, Ó.B. Smárason, H. Eysteinsson, G. Björnsson, M. Ólafsson and Th. Bjornsson, 2000: Geothermal exploration in Arskogsstrond, N-Iceland. *Proceedings of the World Geothermal Congress 2000*, Kyushu-Tohoku, Japan, May-June 2000, 1133-1138.

Flóvenz, Ó.G., F. Arnason, M. Finnson and G. Axelsson, 1995:. Direct utilization of geothermal water for space-heating in Akureyri, N-Iceland. *Proceedings of the World Geothermal Congress 1995*, Florence, Italy, May 1995, 2233-2238.

Gunnlaugsson, E., and G. Ívarsson, 2010: Direct use of geothermal water for district heating in Reykjavík and other towns and communities in SW-Iceland. Paper submitted to the World Geothermal Congress 2010.

Gunnlaugsson, E., G. Gíslason, G. Ívarsson and S.P. Kjaran, 2000: Low-temperature geothermal fields utilized for district heating in Reykjavík, Iceland. *Proceedings of the World Geothermal Congress 2000*, Kyushu – Tohaka, Japan, May – June 2000, 831-835.

Jónsson, S., P. Segall, R. Pedersen and G. Björnsson, 2003: Post-earthquake ground movements correlated to pore pressure transients. *Nature*, **424**, 179-183.

Ólafsson, M., S. Hauksdóttir, S. Thórhallsson and Th. Snorrason, 2005: Calcite scaling at Selfossveitur hitaveita, S-Iceland, when mixing waters of different chemical composition. *Proceedings World Geothermal Congress 2005*, Antalya, Turkey, April 2005, 6 pp.

Ragnarsson, Á., 2008: Utilization of geothermal energy in Iceland. *Proceedings of the 14thBuilding Services, Mechanical and Building Industry Days*, Debrecen, Hungary, October, 9 pp.

Tómasson, J. and G.K. Halldórsson, 1981: The cooling of the Selfoss geothermal area, S-Iceland, *Geothermal Resources Council, Transactions*, **5**, 209-212.

Zhang, Y., 2003: Assessment of the Kaldárholt geothermal system and associated reinjection into the nearby Laugaland system, S-Iceland. *UNU Geothermal Training Programme, Reports 2003*, report 22, Reykjavik, 527-552.

Table 1: Low-temperature geothermal areas in Iceland utilized by some of the oldest public hitaveitur (district heating services). The areas are listed in a clockwise manner around the country (Fig. 2). The areas in bold are discussed in the paper.

Area	Utilized since	Reservoir temp. (°C)	Number of prod. wells	Average prod. 2005 – 2008 (L/s)	Inhabitants served	Total volume extracted (km^3)
Laugarnes (SW-Iceland)	1930	120-140	10	156	183000[2)]	0.25
Mosfellssveit (SW-Iceland)	1943	80-90	34	877	183000[2)]	1.1[5)]
Áshildarholtsvatn (N-Iceland)	1953	70	4	71	2600	0.11
Skútudalur (N-Iceland)	1975	70	2	26	1200	0.024
Hamar (N-Iceland)	1969	65	2	38	1400	0.039
Laugaland (N-Iceland)	1977	90-100	3	36	18000[3)]	0.046
Laugar/Reykjadalur (N-Iceland)	1924	65	1	<10	300	–
Gata (S-Iceland)	1946	90-100	1	15	1900[4)]	0.014
Brautarholt (S-Iceland)	1950	75	1	3	40	–
Laugarvatn (S-Iceland)	1928	100	spring	–[1)]	200	–
Thorleifskot (S-Iceland)	1948	60-130	4	76	7300[3)]	–

1) Data not available.
2) One of three low-temperature areas, and two high-temperature areas, serving the corresponding hitaveita.
3) One of six low-temperature areas serving the corresponding hitaveita
4) One of two low-temperature areas serving the corresponding hitaveita.
5) Since 1971.