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A Quarterly Progress and Development Report
on the Direct Utilization of Geothermal Resources

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Cover: 1) The Pearl, a rotating restaurant built on the top of Reykavik’s geothermal water tanks; 2) Nesjavellir geothermal power plant supplies 150 MWt to Reykjavik; 3) Svartsengi geothermal power plant supplies 125 MWt and 16.4 MWe electric; and 4) Fish farm in NE-Iceland. (Photos coutesy of National Energy Authority and M.V. Lund)

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GEOTHERMAL ENERGY IN ICELAND

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INTRODUCTION

The annual primary energy supply in Iceland, which has a population of 268,000, is 98,000 TJ (T = 10^{12}) or 366 GJ per capita, which is among the highest in the world. Geothermal energy provides about 48.8% of the total, hydropower 17.2%, oil 31.5% and coal 2.5%. The main use of geothermal energy is for space heating. About 85% of all houses are heated with geothermal energy; the rest are heated mainly by electricity. So far, geothermal resources have only, to a limited extent, been used for electric power generation, because of the availability of relatively cheap hydropower resources. Of the total electricity production of 5,000 GWh in 1995, only 288 GWh or 5.8% came from geothermal energy, 94% from hydro and 0.2% from fuels.

Figure 1 shows the annual primary energy supply in the period 1940-1995, classified by energy sources. Direct uses of geothermal energy (Table 1) are calculated as used energy based on an estimated temperature drop for each utilization sector.

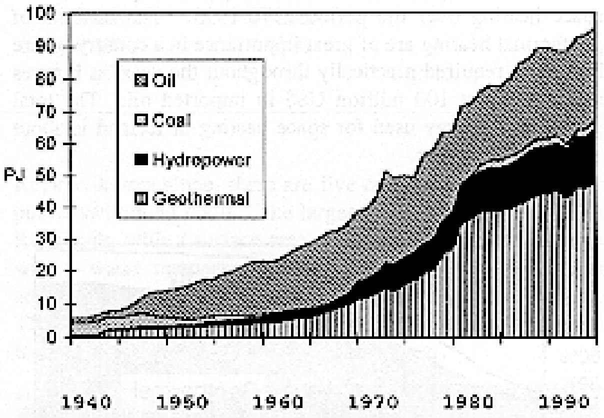

Figure 1. Primary energy supply in Iceland 1940-1995, classified by energy sources (excluding aircraft and ship refueling outside Iceland).

Table 1. Summary Table of Geothermal Direct Heat Uses

	Installed Thermal Power MW$_t$	Energy Use TJ/yr
Space Heating	1,150	16,300
Bathing and Swimming	60	1,000
Greenhouses	45	830
Fish and Other Animal Farming	25	630
Industrial Process Heat	105	2,000
Snow Melting	55	380
Subtotal	1,440	21,140
Heat Pumps	3	18
Total	1,443	21,158

SPACE HEATING

The main use of geothermal energy in Iceland is for space heating. In 1970 about 50% of the population was served by geothermal district heating systems. After the oil crisis in the 1970s, replacing imported oil with indigenous energy sources (geothermal and hydro) received high priority. Today about 85% of the space heating is by geothermal energy, the rest is by electricity (12%) and oil (3%). Figure 2 shows how geothermal energy has replaced imported oil for space heating over the period 1970-1995. The benefits of geothermal heating are of great importance in a country where heating is required practically throughout the year, as it saves annually about 100 million US$ in imported oil. The total geothermal energy used for space heating in Iceland is about 16,300 TJ per year.

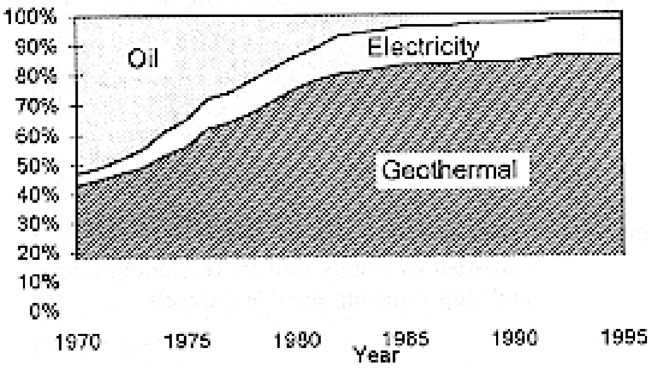

Figure 2. Space heating market by sources 1970-1995.

There are now 27 municipally-owned geothermal district heating services in Iceland. By far, the largest one is the Reykjavik Municipal District Heating (Hitaveita Reykjavikur) which had it's beginning in 1930. Today, it serves about 150,000 people, or 99.8% of the population in Reykjavik and five neighboring communities (see Table 2).

Table 2. Reykjavik Municipal District Heating Service 1995

Number of people served	147,740
Volume of houses served	39,478,000 m^3
Water temperature at user end	75°C
Number of wells in use	57
Installed capacity	640 MW$_t$
Total pipe length	1,179 km
Water delivered	59,650,000 m^3/year

The only Icelandic district heating system using heat pumps is in Akureyri. Two heat pumps, 1.3 MWth each, were installed in 1984. They extract heat from part of the return water from the district heating system at 35°C and boost another part of the return water to 80°. They provide about 5% of the total energy production. The 10-year experience with the heat pump units has shown them to be satisfactory, both from technical and economical points of view.

Over the last decade, many district heating systems have been built in rural areas with low-population densities. These single-pipe systems typically serve 10 to 20 farms that can be one to three kilometers apart. These systems serve about 4,000 inhabitants and the total pipe length is about 900 km, or 225 m per person, compared to 12 m in towns. In most cases, plastic pipes are used. They are made in Iceland of polypropylene or polybutylene and have diameters ranging from 25 to 110 mm. The insulation consists of 4-m long sections of polyurethane "sandwiches," which are strapped to the pipe in the field after unrolling the pipe. The installation of these pipelines is simple and is often performed by the farmers themselves. Each farmer receives a certain maximum flow, typically 15 liters per minute, that he can freely use throughout the year.

Experience in Iceland to date shows that plastic pipes can be used for moderate pressure water at temperatures up to at least 85°C. At higher temperatures, the risk of pipe damage increases considerably. It is important to keep the water pressure low, due to temperature and pressure limitations of the plastic, and to keep the pipe wall, and thereby material costs, as thin as possible. Compared to the traditional pre-insulated steel pipes, the main advantages of plastic pipes are the relatively low piping costs, easy installations and no corrosion effects on plastic pipes. The main disadvantages are the low limits on water pressure and temperature, rapid increase in pipe cost with increased pressure and pipe diameter, corrosion of radiators because of oxygen diffusing through the plastic pipe walls and high heat loss, especially during wet weather.

Two systems for selling the geothermal water are in general use, by water meter or by subscription. Most commonly, the user pays a fixed-annual charge and a price for each cubic meter of water used as measured by a water meter. The other system is based on maximum flow restriction; where, the user pays a fixed annual charge and a price related to the maximum flow rate that is equal to the expected demand during the coldest winter period. As most of the systems are direct through-flow systems, conventional energy metering is not suitable, because it would not encourage the users to maximize the heat extracted from the water before it goes to waste (the sewer system). Over the past few years, most of the systems which earlier used maximum flow restriction have changed their tariff systems to water meters. The main reason for this is that the old system did not encourage the users to cut back the flow outside the coldest winter months. Where this change of tariff system has been completed, it has resulted in 20-35% reduction in annual water consumption. As a result, the drawdown in the geothermal reservoir exploited has been reduced and money has been saved by delaying the need for additional drilling or development of new geothermal fields.

Increased attention has been paid to the influence of large-scale production of hot water or steam on the geothermal systems. In several geothermal systems, the water level

Table 3. Effects of Exploitation on Six Geothermal Reservoirs in Iceland

Geothermal Systems	Production Starts	Average Production kG/s	Water Temperature °C	Drawdown m	Cooling °C
Laugarnes	1930	160	127	130	0
Reykir	1944	920	64-100	100	0/13
Hamar	1970	24	64	35	0
Svartsengi	1976	260	240	210	0
S-Laugaland	1976	42	95	350	0
Urridavatn	1980	19	75	35	2/15

continues to drop and in other instances, cold water is starting to invade the systems. The latter may cause changes in both the temperature and the chemical content of the water produced. Lowering the water level and temperature are factors that limit the potential of a geothermal system. Table 3 gives a few examples of these effects on geothermal reservoirs being exploited.

As the effects of hot water production on the reservoirs have become clearer, the district heating services have paid more attention to monitoring of the geothermal fields. During the past five years, the National Energy Authority (NEA) has developed and installed data logging systems at 12 sites for field monitoring. The parameters logged are: water temperature, drawdown, and flow rate from each well. The data is automatically transferred to NEA where it is used for monitoring and for reservoir engineering studies.

Another area receiving increased attention in recent years is the environmental impact of geothermal projects. According to a new Icelandic environmental law, all geothermal development exceeding 25 MW_e gross production, or 10 MW_e net production, have to submit a detailed appraisal of the environmental impacts. The National Energy Authority has, since 1991, been working on a research project in this field in cooperation with some of the largest geothermal companies. A study of all the high-temperature geothermal areas under utilization has been initiated. Several unexploited areas are being studied for comparison. Pollution of air by hydrogen sulphide (H_2S) emission and the groundwater by power plant effluents are among the influences considered, as well as thermal pollution and land subsidence.

SWIMMING POOLS

From the time of settlement of Iceland some 1,100 years ago until early in this century, the utilization of geothermal resources in Iceland was limited to bathing, washing and cooking. Today, these uses are still important and heating of swimming pools is among the largest segments, after district heating. There are 120 public swimming pools heated by geothermal energy with a combined surface area of 25,000 m^2. Most of them are outdoors and in use throughout the year. They are both for recreational use and for swimming instruction, which is compulsory in the primary schools. In general, swimming is a very popular pastime in Iceland and in the Reykjavik area alone, there are five outdoor and three indoor public swimming pools. The largest pool is Laugardaslaug in Reykjavik, with a surface area of 1,500 m^2 and five hot tubs with a water temperature ranging from 35 to 42°C. The annual water consumption of Laugardaslaug is 460,000 m^3. The total geothermal energy used in swimming pools in Iceland is estimated to be 1,000 TJ per year.

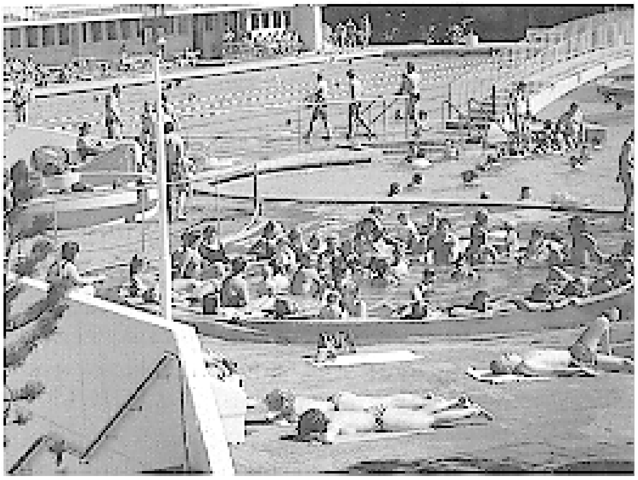

Figure 3. Laugardaslaug swimming pool in Reykjavik.

SNOW MELTING

The use of geothermal energy for snow melting has been widespread for the past 10-15 years. This kind of utilization gained popularity when plastic pipes for hot water were introduced in the market. Spent water from the houses, at about 35 °, is commonly used for deicing of sidewalks and parking spaces. During the last few years, the extension of snow melting systems has expanded considerably. The total area now covered by snow melting systems is estimated to be 350,000 m^2, of which about 250,000 m^2 are in Reykjavik. Extensive rehabilitation of the streets in downtown Reykjavik has been undertaken during the past five years. One improvement was to install snow melting systems, covering an area of 50,000 m^2, in the sidewalks and streets. This system is designed for a heat output of 180 W per m^2 surface area. The annual energy consumption is of course strongly dependent on the weather conditions. Measurements from Reykjavik's center has shown the energy consumption to be 250 kWh/m^2-375 kWh/m^2 (Jónsson, 1994). The total energy use for snow melting is estimated to be 380 TJ per year.

INDUSTRIAL USES

Kísilidjan, the Diatomite plant at Mývatn, near the Námafjall high-temperature field, is among the largest industrial users of geothermal steam in the world. The plant has been in operation since 1967, and the annual production has been between 20,000-30,000 tons of diatomite filter aid which is exported. The raw material is diatomaceous earth taken from deposits on the bottom of Lake Mývatn. After a period with decreasing production, the productivity of the factory has been increased considerably over the last three years. This resulted in a production of 28,100 tons in 1995, which is close to the capacity of the factory. The process requires about 220,000 tons annually of geothermal steam at 10 bar absolute (180^{o}C). This corresponds to an energy use of 515 TJ per year.

At Keykhólar, a seaweed processing plant uses geothermal water for drying. About 28 l/s of 107^o C hot water are used and cooled down to 55^{o}C. The annual use of geothermal energy in the plant is about 150 TJ.

On the Reykjarnes Peninsula, a salt pilot plant was in operation for more than twenty years, but was closed down in 1994 due to bankruptcy. From geothermal brine and sea water, the plant produced salt for the domestic fishing industry as well as low-sodium health salt for export. The annual use of steam was about 400,000 tons at 10 bar absolute (180^{o}C), which corresponds to an energy use of 813 TJ per year. Recently, this plant reopened and is now recrystallizing coarse salt into fine grain mineral salts used in bathing (Saga Salt).

Several small companies use geothermal water for industrial purposes, most of them buying their water from the district heating services around the country. A new survey indicates that 10% of the total energy delivered by the district heating services is used for industrial purposes, including space heating in the industry (Líndal, 1995).

GREENHOUSES

Heating of greenhouses with geothermal water began in 1920. Before that time, naturally warm soil had been used for growing of potatoes and other vegetables. Over the past few years, the use of artificial lighting has gained popularity and has extended the growing season to nine months. The total

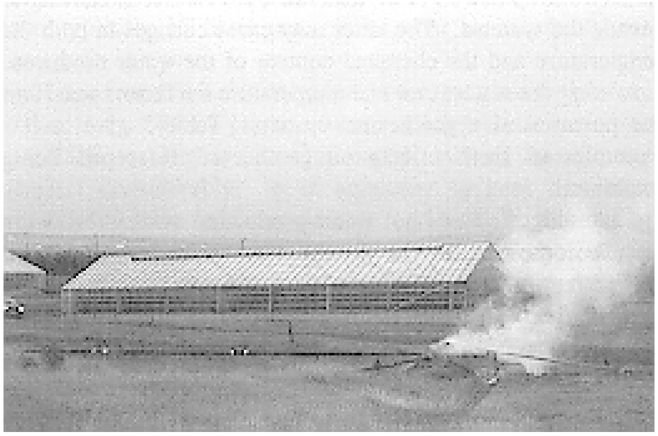

Figure 5. Greenhouse at Reykholt in western Iceland. Note heating pipes mounted on the wall.

Figure 4. The Kisilidjan diatomite plant is Iceland's largest industrial user of geothermal energy.

area under glass has increased over the years to 175,000 m^2, and 105,000 m^2 of soil is heated by pipes buried in the ground. Tomatoes, cucumbers, paprika, etc., are the most popular crops and greenhouses also supply most of the flowers for the domestic market. The total geothermal energy used in the greenhouse sector in Iceland is estimated to be 830 TJ per year.

FISH FARMING

In the middle of the 1980s, an explosive growth in fish farming took place and over 120 land-based aquaculture complexes were built. Salmon is the main species, but arctic char and trout have also been raised. This industry has had financial difficulties and many of the farms have gone into bankruptcy, mainly the large installations. Because of this, the anticipated increase in geothermal utilization in the fish-farming sector did not materialize. At present, there are 70 farms in operation. Many of them use geothermal hot water to heat 4-6°C freshwater to approximately 12°C, the ideal temperature for rapid development of fish smolt. The total geothermal energy used in the fish-farming sector in Iceland is estimated to be 630 TJ per year.

GEOTHERMAL ELECTRIC POWER GENERATION

Geothermal resources have only to a limited extent been used for electric power generation in Iceland, because of the availability of relatively cheap hydropower. Geothermal power is produced for the national grid at three high-temperature areas: Bjamarflag, Krafla and Svartsengi.

The first geothermal power plant was built in 1969 when a 3-MW$_e$ back-pressure turbine was installed in Bjamarflag (Námafjall field). This field also supplies steam to the Kísilidjan diatomite plant. The power plant has been operated successfully ever since the beginning 25 years ago. The reservoir temperature is about 280°C. Steam is separated from the water at 9.5 bar absolute to provide a steam flow rate of 12.5 kg/s to a single-flash turbine. The total electrical production of the Bjamarflag power plant in 1995 was 11.5 GWh.

The Krafla power plant, located about 10 km north of the Námafjall field, has been in operation since 1977. Two units, 30 MW$_e$ each, were purchased but only one of them was installed because of inadequate steam supply. The shortfall of steam was in part due to volcanic activity in the area. At the end of 1975, while the plant was under construction, a volcanic eruption started only 1-2 km from the drilling area. The immediate effect of the eruption was a contamination of the geothermal fluids by the volcanic gases. This caused operational problems in some of the production wells, mostly in the form of rapid scaling of complex iron silicates and also corrosion in the wells. Recent exploration drilling has shown that the concentration of magmatic gases in the steam has decreased drastically. Surface lava flows and earthquakes did not harm the installations. The plant has operated successfully with one unit in spite of nine eruptions, the last one in September 1984. Initially, the power production was 8 MW$_e$, but reached the present 30 MW$_e$ in 1982. The plant is shut down for four months every summer as there is abundant hydropower due to high river flows from snow melt. The production reservoir zone has a temperature of about 210°C. Steam is separated from the water in two stages, at 7.7 and 2.2 bar absolute, to provide 60 kg/s high-pressure steam and 15 kg/s of low-pressure steam. The installed unit has a double flash condensing turbine, which in 1995 had a total electrical production of 170 Gwh.

The Svartsengi power plant is a co-generation plant, which produces both hot water for district heating and electricity. It is located on the Reykjanes peninsula, about 40 km from Reykjavik. The system was commissioned 1976 and has the main purpose of providing the neighboring communities of about 15,5000 inhabitants and the airport at Keflavik with district heating. The geothermal reservoir fluid is a brine at 240°C and with a salinity of about two-thirds of seawater. The geothermal heat is transferred to freshwater in several heat exchangers. The effluent brine is disposed of into a surface pond called the Blue Lagoon, that is popular by tourists and people suffering from psoriasis and other forms of eczema, who seek therapeutic effects from the silica-rich brine.

Three single-flash back-pressure turbines were originally installed at Svarsengi: one 6 MW$_e$ and two 1 MW$_e$. In 1989, three Ormat units were installed, each of 1.3 MW$_e$. They are binary systems using low-pressure excess steam from the back-pressure units to produce electricity in a closed organic Rankine cycle. In 1992, four additional Ormat units were

Table 4. Utilization of Geothermal Energy for Electrical Generation in December 1995.

Locality	Power Plant Name	Year Commissioned	No. of Units	Type of Units	Unit Rating MW$_e$	Total Installed Capacity MW$_e$	Annual Energy Prod. 1995 GWH/yr
Krafla	Krafla	1997	1	2-Flash	30	30	170
Námafjall	Námafjall	1969	1	1-Flash	3	3	11
Svartsengi	Svartsengi	1978	2	1-Flash	1	2	13
Svartsengi	Svartsengi	1981	1	1-Flash	6	6	39
Svartsengi	Svartsengi	1989/92	7	Binary	1.2	8.4	55
Total			12			49.4	288

installed bringing the total installed capacity to 17.1 MW_e. The electrical production of Svartsengi power plant in 1995 was 107 GWh.

At the salt plant on the Reykjanes peninsula, a small back-pressure turbine of 0.5 MW_e is installed and provides electricity for local needs only.

At the Nesjavellir high-temperature field, Reykjavik Municipal District Heating has built a co-generation power plant, which was commissioned in 1990. The primary purpose of the plant is to provide hot water for the Reykjavik area 27 km away. It supplements the water from the low-temperature fields in the vicinity of Reykjavik which are fully exploited. Freshwater is heated by geothermal steam in heat exchangers in a similar way as in the Svartsengi power plant. The first phase of the plant was a hot water production of the capacity 100 MW_t. The second phase, which was for another 50 MW_t, went into operation in 1992. The ultimate goal is to produce 400 MW_t for space heating and 80 MW_e for electric generation.

EXPLORATION ACTIVITIES

The National Energy Authority, in cooperation with the National Power Company, Reykjavik Municipal Heating and Sudurnes District Heating, has since 1991 been working on a project, which involves exploration of high-temperature geothermal areas with respect to their potential for electricity generation. The project is based on the principle of conducting investigations simultaneously in more than one geothermal area and harnessing the area in relatively small steps. As a part of this project, surface explorations have been carried out in several geothermal fields. Many smaller studies have also been carried out in a number of low-temperature fields for district heating services.

DRILLING ACTIVITIES

Drilling activity has been slow in Iceland for the past five years, with only two wells drilled in high-temperature areas. A good number of low-temperature wells have been drilled in this period, mainly for new projects in rural areas and for fish farms. Drilling of shallow-temperature gradient wells for exploration has also increased in recent years.

FUTURE PLANS

About 50% of the electricity production in Iceland is consumed by energy intensive industry. An expansion of the aluminum smelter at Straumsvik, which is now under construction, will increase the total electricity demand in the country by 1000 GWh or 20%. Other possibilities for new energy intensive industry are now under consideration. They include other aluminum smelters and magnesium plant. To meet the increased demand, the second turbine unit is now being installed at Krafla power plant. This will bring the capacity of the plant up to 60 MW_e. Also it has been decided to start electricity production at Nesjavellir co-generation power plant in late-1998. The capacity of the plant will be 60 MW_e. Additional generation capacity at Svartsengi is also under consideration and a plant at Bjarnarflag is now undergoing environmental assessment. The geothermally produced electricity in the country will, thus, probably triple from the present level in a few years time.

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HITAVEITA REYKJAVIKUR AND THE NESJAVELLIR GEOTHERMAL CO-GENERATION POWER PLANT

Edited by John W. Lund
Geo-Heat Center

BACKGROUND

When Ingólfur Arnarson sighted land on the voyage which would make him the first settler in Iceland, he threw the pillars of his high seat overboard and relied on the gods to direct him to where he should settle. His slaves found them washed ashore in a bay where "smoke" rose out of the ground. Therefore, they call if Reykjavik, "Smoky Bay." But the smoke after which Iceland's capital is named was not the result of a fire, but was rather steam rising from hot springs.

Ancient records only mention the use of geothermal springs for washing and bathing. The best known examples are the Thvottalaugar (Washing pools) in what is now Laugardalur in Reykjavik, and the hot pool where saga writer Snorri Sturluson bathed at his farm in Reykholt in western Iceland.

The first trial wells for hot water were sunk by two pioneers of the natural sciences in Iceland, Eggert Ólafsson and Bjarni Pálsson, at Thvottalaugar in Reykjavik and in Krísuvík on the southwest peninsula, in 1755-1756. Further wells were sunk at Thvottalaugar in 1928 through 1930 in search of hot water for space heating. They yielded 14 liters per second at a temperature of 87°C, which in November 1930 was piped three kilometers to Austurbejarskóli, a school in Reykjavik which was the first building to be heated by geothermal water. Soon thereafter, more public buildings in that area of the city as well as about 60 private houses were connected to the geothermal pipeline from Thvottalaugar.

The results of this district heating project were so encouraging that other geothermal fields began to be explored in the vicinity of Reykjavik in Mosfellssveit, by Laugavegur (a main street in Reykjavik) and by Ellidaár, the salmon river flowing at that time outside the city but now well within its eastern limits. Results of this exploration were good. A total of 52 wells in these areas are now producing 2,400 litres per second of water at a temperature of 62-132°C.

Hitaveita Reykjavikur (Reykjavik District Heating) supplies Reykjavik and several neighboring communities with geothermal water. There are about 150,000 inhabitants in that area, living in about 35,000 houses. This is well over half the population of Iceland. Total harnessed power of the utility's geothermal fields, including the Nesjavellir plant, amounts to 600 MW_t and its distribution system carries an annual flow of 55 million cubic meters of water.

INTRODUCTION

The maximum capacity of the low-temperate fields in 1990 was about 460 MW_t. Therefore, Hitaveita Reykjavikur needed a further 140 MW_t in order to meet peak power demands, as can be seen in Tables 1 and 2. It was not possible

Table 1. The Main Characteristics of the System

Peak power demand	600	MW_t
Annual production	3,000	GWh
Storage tanks	72,000	m^3
Volume of connected buildings	32	Mm^3
Population served	144,000	
Consumer price	0.662	US\$/m^3
Energy price	0.013	US\$/kWh

Table 2. Production Data for the Low-Temperature Fields

Reservoir	Max. Production (mM^3/h)	Temperature (°C)	Number of Wells	Capacity (>40°C) (MW_t)
Laugarnes	1,033	128	10	106
Ellidaar	826	89	8	47
Reykir	5,600	87	35	306
Total geothermal capacity	459			
Peak power boilers, oil-fired	96			
Maximum output capacity	555			

to increase production from the then existing geothermal fields. They were fully-exploited and their production capacity had declined by about 4% annually over the past few years due to extensive pressure drop in the reservoirs. Temperature decrease and scaling due to changes in fluid chemistry had been observed in a few production wells so their utilization were stopped.

Hitaveita Reykjavikur carried out detailed geothermal exploration in the vicinity of Reykjavik in search of new exploitable low-temperature reservoirs. No usable reservoirs had been discovered so far. Exploration was also carried out at Nesjavellir and Kolvidarholl, which belong to the Hengill high-temperature area situated some 20-30 km east of Reykjavik. Nesjavellir was found to be the most economical alternative to increase the geothermal production capacity of Hitaveita Reykjavikur.

New connections to the distribution system were increasing by 3-4% a year on average. During the past few years, this had been met by increasing storage capacity from 18,000 m^3 to 72,000 m^3 and by the installation of additional oil-fired boilers.

The City Council of Reykjavik decided on 20 November 1986 to begin construction of a geothermal power plant at Nesjavellir. The first stage in this development was a thermal power plant with a capacity of 100 MW^t. The plant went into operation in September 1990.

GEOTHERMAL ENERGY AT NESJAVELLIR

General studies conducted in the Hengill geothermal area in 1947-49 included research into the thermal field of Nesjavellir. Studies and drilling of wells continued intermittently until 1986.

The greatest geothermal activity at surface level was found to be south of Nesjavellir. Exploration by drilling was, therefore, focused on that area. The extent of the area of geothermal distribution was also studied at a depth of 1-2 kilometers to the east, west and north. Extensive geological, geochemical and geophysical studies were also conducted at Nesjavellir.

Since 1972, all exploratory wells have been designed so as to function as production wells later. Results have been good. On average, each well has a thermal power of 60 MW_t, which would yield a net output of 30 MW_t from a thermal power plant. This would be sufficient to supply space heating for a community with 7,500 inhabitants.

Of 18 wells drilled so far at Nesjavellir, 13 are production wells.

Five of them (>2000 kJ/kg enthalpy) have so far been activated to allow the Nesjavellir plant to produce a total thermal power of 150 MW_t. The plant is designed for a maximum capacity of 400 MW_t.

THE HEATING PROCESS

Heat Exchangers

Hitaveita Reykjavikur operated a pilot heating plant at Nesjavellir during 1974-1990. Various types of heat exchanger were tested. Conventional plate heat exchangers are used for the condensation of steam from the separators and to cool the condensate. They are equipped with EPDM-gaskets and made of titanium plates to avoid stress corrosion; as, it is not possible to guarantee problem-free operation if stainless steel plates were used.

Conventional heat exchangers cannot be used for the separated water due to the high content of dissolved solids (TDS 1200 ppm) which would cause severe scaling of silica. A new type of heat exchanger, in the geothermal context, was tested successfully in the pilot plant. These are the so-called "fluidized-bed heat exchangers," or FBHX made by Eskla Heat Exchangers BV in the Netherlands. They are shell-and-tube heat exchangers operating in a vertical position (Figure 1). Stainless steel balls, 1.5 mm in diameter, circulate in the flow stream of the separated water. They impact continuously against the pipe surfaces and remove any scaling that may form. A mechanical device is fitted to the inlet and outlet of the heat exchangers to keep the steel balls evenly distributed in the flow stream. The FBHX heat exchangers make possible the direct utilization of the heat in the water from the separators and contribute to the overall economy of the heating process.

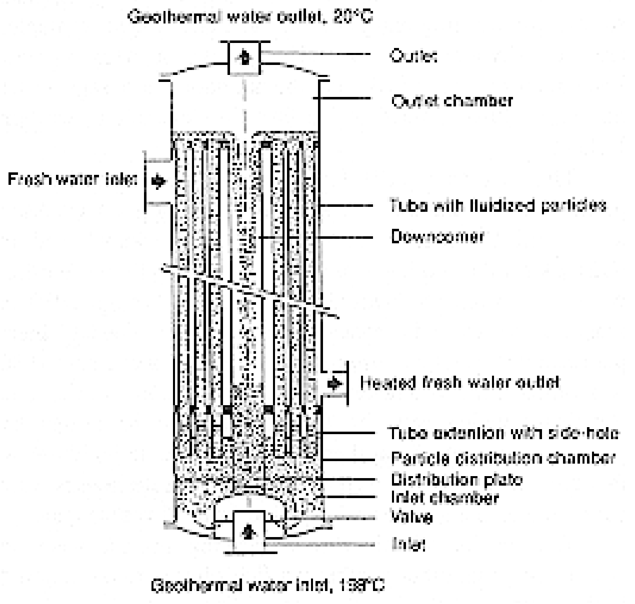

Figure 1. A schematic drawing of a "fluidized-bed heat exchanger" (FBHX).

Recently, the FBHX was dismantled as the well enthalpy and dissolved silica content of the fluid has changed. Thus, ordinary shell-and-tube plate heat exchangers now appear satisfactory.

De-aeration

The cold groundwater is saturated with dissolved oxygen and becomes very corrosive when heated. A conventional thermal de-aeration method is used where the groundwater is boiled under vacuum after heating to remove the oxygen. The cold groundwater has pH value of 7.5-8.5. It is partially degassed through boiling after heating (at 86ºC under a vacuum). Small pieces of plastic are introduced to provide contact surface to release the O_2. This raises the pH value to 9.0-9.5 and the oxygen content is reduced down to about 50 ppb. The remaining dissolved oxygen is removed through injection of small amounts of geothermal steam that contains acid gases (H_2S and CO_2). Hydrogen sulphide gas reacts rapidly with the dissolved oxygen, and contains 0.5-2.0 ppm of H_2S. The remaining H_2S gas reacts against any oxygen absorption in accumulators and ensures that the "pleasant smell," which the users of geothermal water in Iceland have become accustomed to, is retained.

Amorphous Mg-Si scaling was formed in the distribution system in Reykjavik during the first months of operation of the plant, due to the high pH value of the mixture of the geothermal water from the low-temperature fields, and the heated groundwater from Nesjavellir. Different ratios of these two water types control the pH value. Scaling can only be avoided by reducing the amount of geothermal water in the mixture below 10-15%. Therefore, the original plan of mixing these two water types in the distribution network has been abandoned. They are now used separately, with each system providing heat to a separate area of Reykjavik.

The Waste Geothermal Water

Geothermal heating plants in high-temperature fields only utilize the thermal energy of the geothermal fluid; which, after use in heat exchangers, must be disposed of with minimum risk to the environment. This disposal can be performed in two different ways (i.e., at surface or into subsurface aquifers). Surface disposal can be carried out in a similar way to the natural disposal of flow from the hot springs (i.e., into the brook in the Nesjavellir valley, which disappears into a lava field before reaching Lake Thingvallavatn). Subsurface disposal requires that the waste water is pumped back into the geothermal reservoir. This latter method is obviously more friendly to the environment, but more expensive. It can also be more difficult to operate due to scaling in the reinjection wells and their aquifers.

There are two important features of the waste water from high-temperature fields that may have a negative effect on the environment. These are the raised temperature of surface waters and groundwater aquifers, and the presence of hazardous chemicals in the waste water (i.e., arsenic, mercury, boron, etc.). Extensive research has been carried out at Nesjavellir with respect to disposal of the waste water. Chemical and biological measurements have been carried out at Lake Thingvallavatn since 1979 to define the preexploitation value for future reference. All the wells at Nesjavellir were flow tested in 1984-1987 as a part of the exploration program. Large amounts of geothermal water were disposed of at the surface during these tests without any apparent effects on water chemistry at the shoreline of the lake. This is in agreement with the prediction of a groundwater model that simulates fluid flow and distribution of chemicals in the groundwater system at Nesjavellir.

Chemical analysis of the geothermal fluid show that dangerous chemicals, which may be expected from the condensate of the steam phase, are almost absent.

All arguments seem to indicate that surface disposal of the waste water can be used for the geothermal power plant at Nesjavellir.

PLANT OPERATION

A mixture of steam and geothermal brine is transported from the wells to a central-separation station at 200ºC and 14 bar. After being separated from the brine, the steam is piped through moisture separators to steam heat exchangers inside the plant building. The steam can be piped to steam turbines for co-generation of electricity. Unutilized steam is released through a steam exhaust.

In the steam heat exchangers consisting of 295 titanium plates, the 120ºC steam is cooled under pressure into condensate whose heat is then transferred to cold fresh water in condensate heat exchangers. The condensate cools down in the process to 20ºC.

Separated geothermal brine has its heat transferred to cold fresh water by geothermal brine heat exchangers.

Cold water at 4ºC is pumped from wells at Grámelur, near the shore of Lake Thingvallavatn, to a storage tank by the power house. From there, it is pumped to the steam heat exchangers where its temperature is raised to 85-90ºC.

Since the fresh water is saturated with dissolved oxygen that would cause corrosion after being heated, it is passed through de-aerators where it is boiled at low vacuum pressure to remove the dissolved oxygen and other gases, cooling it to 82-85ºC as described earlier.

Finally, a small amount of geothermal steam containing acidic gases is injected into the water to rid it of any remaining oxygen and lower its pH, thereby preventing corrosion and scaling.

A flow diagram of the process is shown in Figure 2.

DISTRIBUTION

The Nesjavellir power station is situated at an elevation of 177 meters above sea level. The water is pumped by three 900-kW (1250-hp) pumps through a main pipeline of 900 millimeters in diameter to a 2000-m^3 storage tank in the Hengill area at an elevation of 406 meters.

From there, the water flows by gravity, through a pipeline which is 800 millimeters in diameter, to storage tanks on Reynisvatnheidi and Grafarholt on the eastern outskirts of Reykjavik (Figure 3). Those tanks are at an elevation of 140 meters above sea level, and have control valves to regulate the flow of water through the pipeline and maintain a constant water level in the tank in the Hengill area.

From the storage tank, near Reykjavik, the water is fed through pipelines to the communities which are served by Hitaveita Reykjavikur.

From Nesjavellir to Grafarholt, the transmission pipe measures about 27 kilometers in length, and has fixed and expansion points every 200 m. It is designed to carry water at up to 96ºC, with a transmission rate of 1,870 liters per second. During phase one of the project, its flow rate was around 560 liters per second; whereby, the water took seven hours to run the length of the pipe and cooled by 2ºC on the way. Good

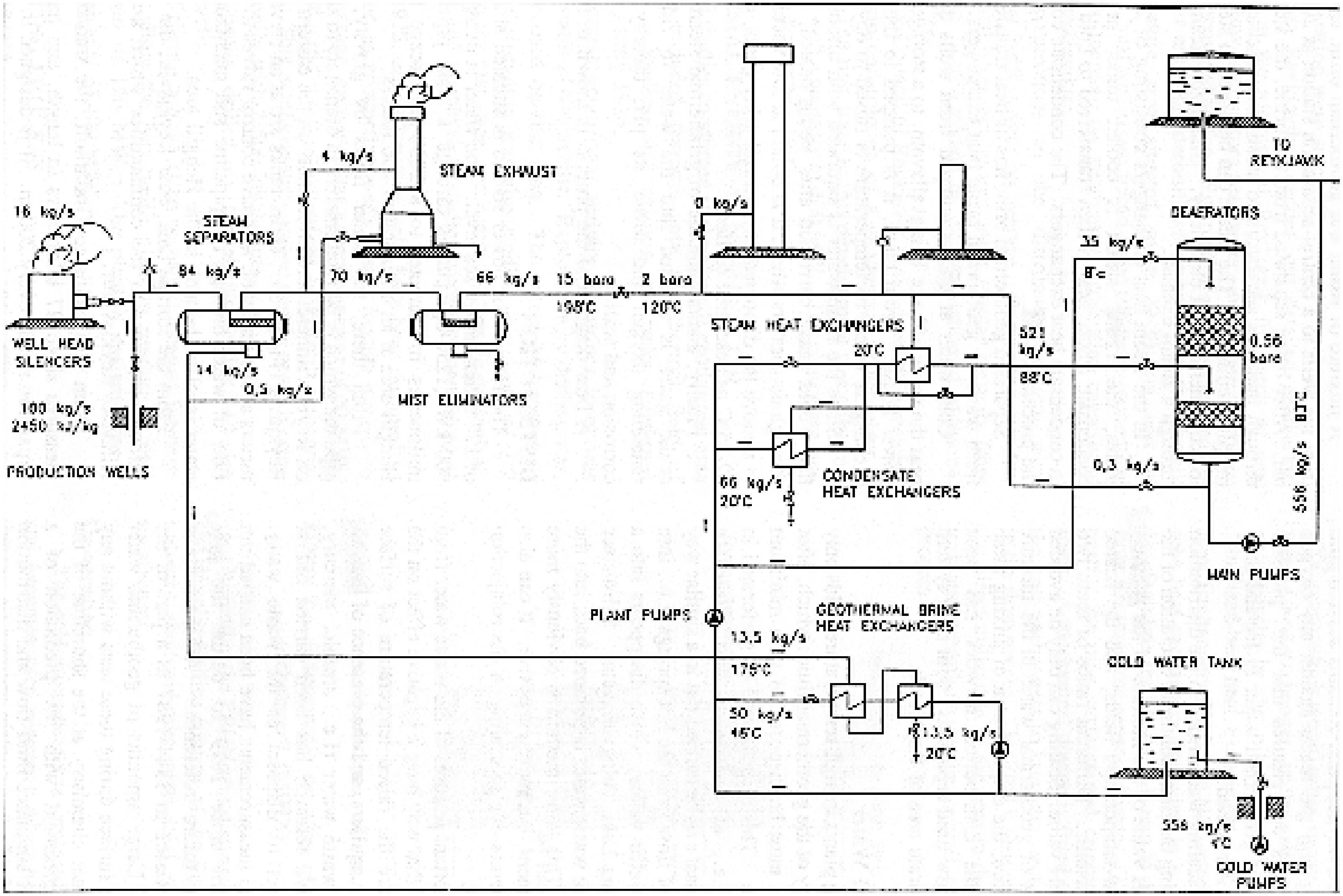

Figure 2. A flow diagram for the Nesjavellir power plant. The first phase is 100 MW_t.

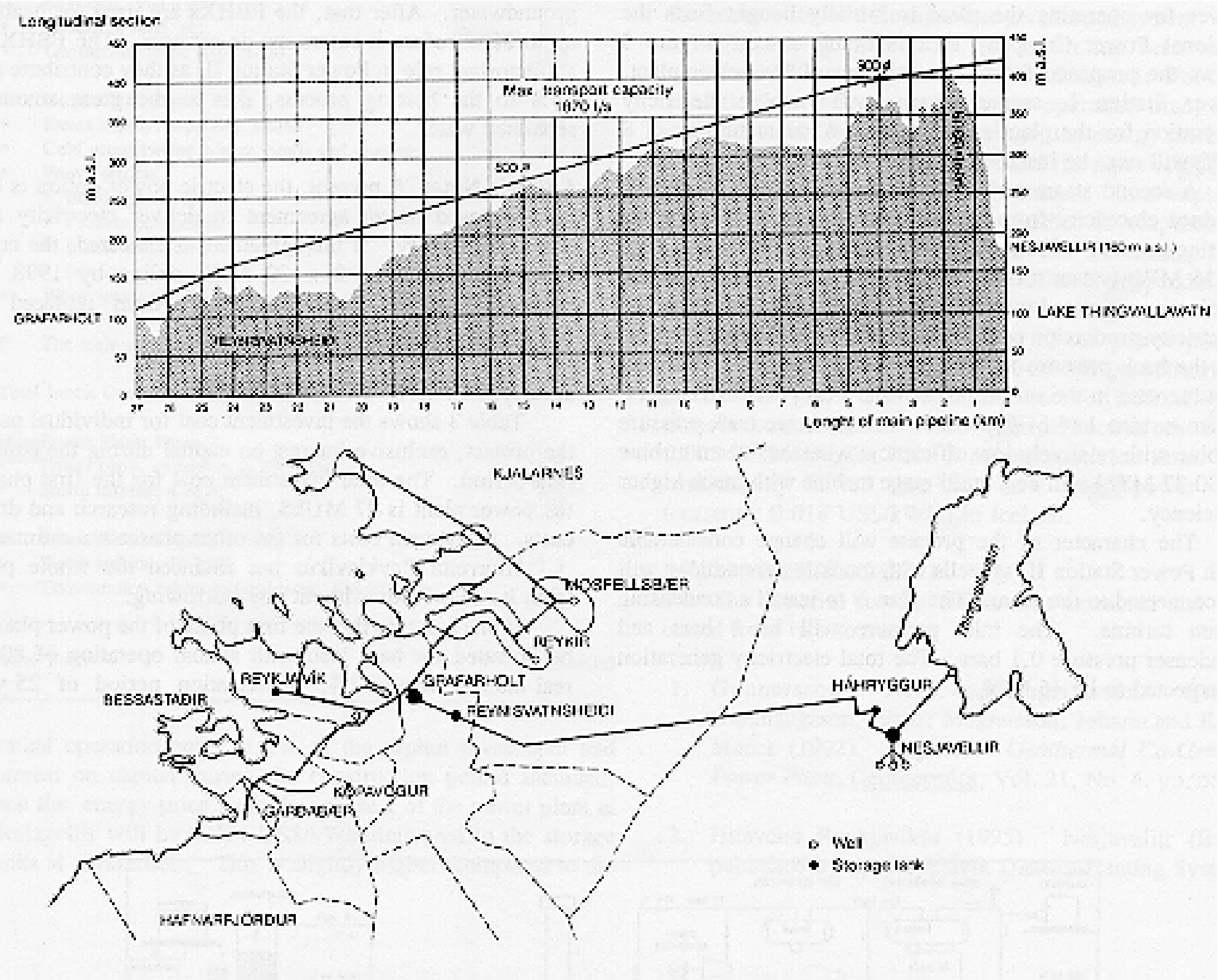

Figure 3. The hot water pipeline from Nesjavellir to Reykjavik.

insulation and a high volume of water are the most crucial factors contributing to this low heat loss. At later construction stages at Nesjavellir, the flow rate will be tripled, reducing the heat loss to less than 1ºC.

The 8- to 10-mm thick steel pipe is insulated with 100 mm of rockwool and covered with aluminum sheets, where it lies above the ground, and insulated with polyethylene and covered with PEH plastic where it lies underground. A corrugated plastic vapor barrier is located under the aluminum skin to keep the rockwool insulation dry. Drip holes are provided at bearing plates to remove any condensation. Its high insulative properties are shown by the fact that snow does not melt on the part that lies above the surface. For environmental and traffic reasons, a 5-kilometer section of the pipe is underground. The surface section also runs under automobile crossings at several points which have been well marked. Provisions are also provided for snowmobile crossings in winter.

Figure 4. The 800-mm diameter pipeline with a snowmobile crossing.

FUTURE DEVELOPMENTS

It can be seen from Figure 2, that the first phase of the power plant involves no generation of electricity. Electrical power for operating the plant is initially bought from the National Power Company at a favorable price. Figure 5 shows the proposed future development of the power plant. Power Station I, second phase, will involve electricity generation for the plant's own need. A steam turbine of 8 MW_e will next be installed in phase 2.

A second steam turbine is planned for phase 3. It will produce electricity from all the steam that is needed for the heating process. The total generation of electricity will then be 36 MW_e (steam turbine 1 included). The pressure in the turbines is estimated to drop from 15 to 2 bara. However, the electricity production could be increased to 43 MW_e by lowering the back pressure to 1.2 bara. This requires a considerable increase in the surface area of the steam heat exchangers. Steam turbine 1 (8 MW_e) will be a single-stage back pressure turbine with relatively low efficiency; whereas, steam turbine 2 (30-37 MW_e) will be a multi-stage turbine with much higher efficiency.

The character of the process will change considerable with Power Station II, as wells with much lower enthalpy will be connected to the plant. The plan is to install a condensing steam turbine. The inlet pressure will be 8 bara and condenser pressure 0.1 bara. The total electricity generation is expected to be 46 $_{Mwe}$.

The steam is condensed in an indirect condenser at a temperature of 46°C and the condensate rejected with the waste water. The condensation heat is utilized to heat up cold groundwater. After that, the FBHXs are used for heating it up to 88°C before it enters the de-aerators. The FBHX play an important role in Power Station II, as they contribute about 43% to the heating process, due to the great amount of separated water.

Editor's Note: A present, the electric power option is being revised based on an agreement to deliver electricity to an aluminum factory. If the agreement is finalized, the current schedule is to have 2 x 30 MW_e online by 1998. As mentioned earlier, the FBHX have been replaced with conventional heat exchangers.

ECONOMY AND INVESTMENT

Table 3 shows the investment cost for individual parts of the project, exclusive interest on capital during the construction period. The total investment cost for the first phase of the power plant is 97 MUS$, including research and drilling costs. Investment costs for the other phases are estimated.

Hitaveita Reykjavikur has financed the whole project from its own funds without any borrowing.

If one assumes that the first phase of the power plant will be operated for base load with annual operation of 8000 h, real interest rate of 7%, depreciation period of 25 years, annual

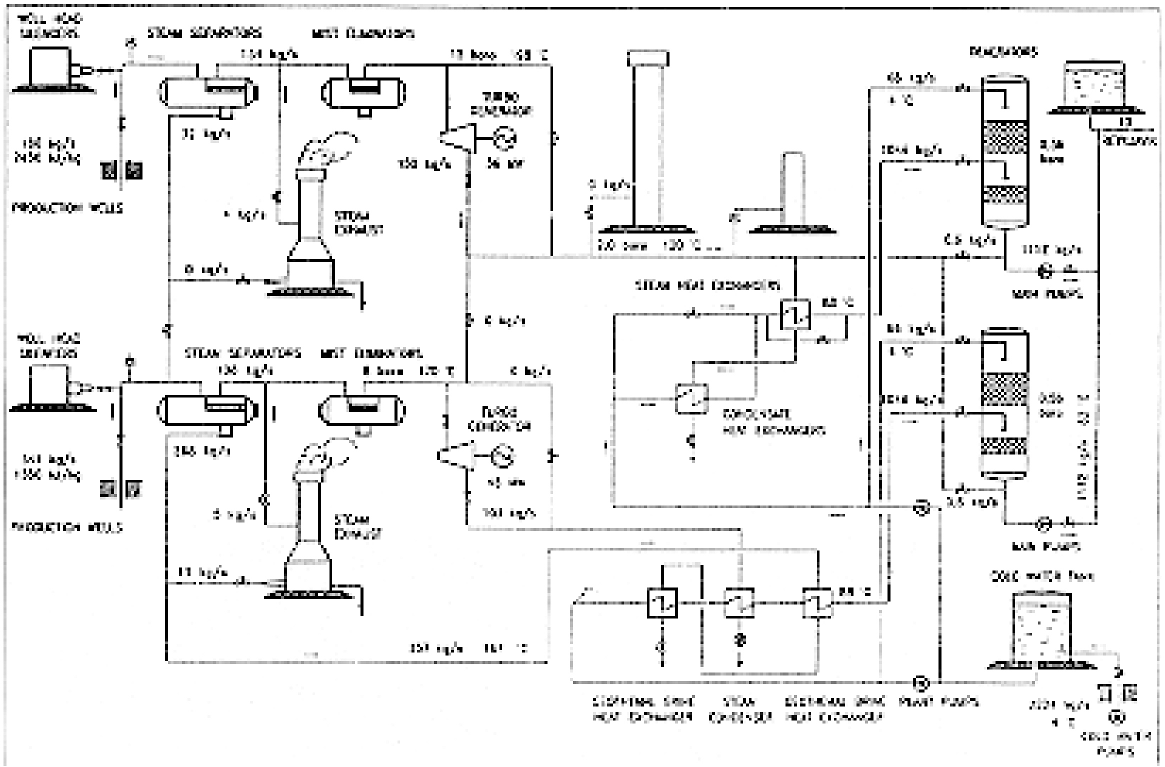

Figure 5. Flow diagram for the power plant fully developed to 400 MW_t.

Table 3. Investment Costs for Nesjavellir

	MUS$
A. Research 1964-1986	
- Research, land, etc.	8.1
- Geothermal wells (No. 6-18)	18.5
	26.6
B. Nesjavellir - Power Plant	
- Steam supply, separator station	6.0
- Cold groundwater system, wells and pipelines	5.3
- Power station	
- Buildings	9.3
- Process equipment	9.4
- Instrumentation	2.3
- Interior	0.6
- Waste water system	0.2
	37.1
C. The main transmission pipeline to Reykjavik	33.6
Total Invest Costs for Phase 1	97.3
D. Power Plant, Phase 2	
- Power plant, extension to 200 MW_t	6.8
- Steam turbine, 8 MW_e	4.3
	11.1
E. Power Plant, Phase 3	
- Steam turbine, 30 $_{Mwe}$	11.3
- Transmission cables to Reykjavik, 132 kV	3.6
	14.9
Grand Total	123.3 MUS$

operation costs of 2% of the capital investment and interest on capital during the construction period included, then the energy price from the phase 1 of the power plant at Nesjavellir will be 0.014 US$/$kWh_t$ delivered to the storage tanks at Grafarholt. This is slightly higher compared to the current consumer price of heat from Hitaveita Reykjavikur, which is 0.013 US$/$kWh_t$. The Nesjavellir system provides 23% of the total power, and 20 to 25% of the sales of heat in the entire Hitaveita Reykjavikur geothermal system.

The energy price from Nesjavellir has been calculated with the addition of phase 2 of Power Station 1. For the same conditions as above, apart from the operation time, which is expected to be 7000 h/yr on average, the energy price will be 0.008 US$/$kWh_t$. The buildings and the pipes of phase 1 are ready to accommodate the later phases. This explains the great drop in energy price with further development of the plant. The most important fact is that the main pipeline is designed for a power plant of 300-400 MW_t, depending on the temperature of the produced district heating water.

In addition to the first phase of the power plant (200 MW_t), it is possible to generate 30-37 MW_e of electricity for the national grid. The investment cost for a 30 MW_e power plant is estimated at 15 MUS$. The production cost would be 0.008 US$/$kWh_e$ for 7000 h annual operation time. This is considerably lower than for new hydro-power stations (currently 0.018 US$/$kWh_e$) in Iceland.

ACKNOWLEDGEMENT

The material for the article was extracted and slightly edited from two sources:

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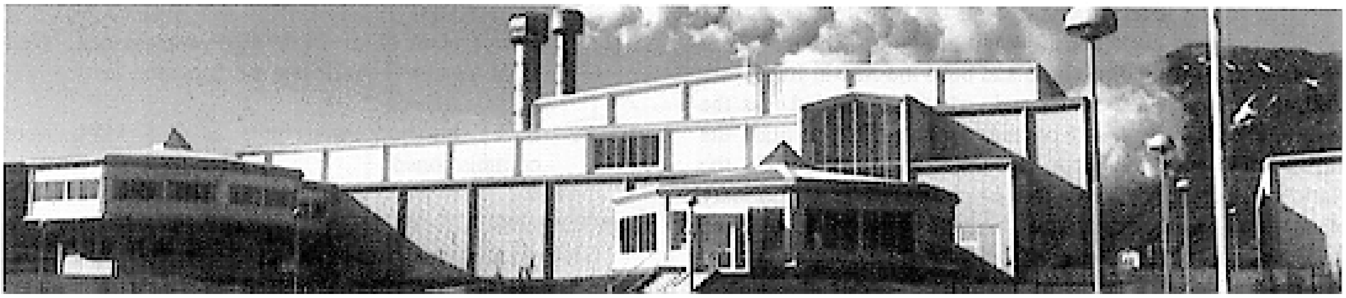

Figure 6. The Nesjavellir power station.

SUDURNES REGIONAL HEATING CORP.

Edited by Paul J. Lienau
Geo-Heat Center

INTRODUCTION

The Svartsengi geothermal area is close to the town of Grindavik on the Rekjanes peninsula and is part of an active fissure swarm, lined with crater-rows and open fissures and faults. The high-temperature area has an area of 2 sq. km and shows only limited signs of geothermal activity at the surface. The reservoir, however, contains lots of energy and at least 8 wells supply the Svartsengi Power Plant with steam. The steam is not useable for domestic heating purposes so that heat exchangers are used to heat cold groundwater with the steam. Some steam is also used for producing 16.4 MW_e of electrical power. Figure 1 shows the distribution system piping hot water to nine towns and the Keflavik International Airport. The effluent brine from the Svartsengi Plant is disposed of into a surface pond, called the Blue Lagoon, popular to tourists and people suffering from psoriasis and other forms of eczema seeking therapeutic effects from the silica rich brine. This combined power plant and regional district heating system (co-generation) is an interesting and unique design for the application of geothermal energy.

In 1969, the Grindavik municipal council decided to have a study made of harnessing geothermal energy in the Svartsengi area to heat houses in the village. The wells drilled at that time, 240 and 430 m deep, looked very promising, while there was some disappointment as they revealed that:

- this was a high-temperature geothermal area (i.e. with temperatures rising to more than 200°C at less than 1000 m depth, and
-
- the geothermal reservoir contained water with about two thirds of the salinity of the sea.

Due to the level of salinity and the high temperature of the water, it was clear that it would not be possible to utilize the geothermal fluid directly as had been the case in Reykjavik and most other places in Iceland; what was needed was the development of a method of heat exchange to facilitate the utilization of the geothermal power. In January 1973 the National Energy Authority (NEA) completed its preliminary plans for a geothermal plant in the Svartsengi area. The results of these plans were very encouraging, urging further research, which the Authority undertook for the entire area. Two wells were drilled, 1,713 m and 1,519 m deep and a resistivity survey made to ascertain the size of the geothermal areas. These measurements revealed that the size of the hot-water reservoir at a depth of about 600 m was roughly 400 hectares. By 1993, a total of 14 high-temperature wells were drilled in the Svartsengi area, totaling 13.6 km in depth, the deepest one being about 2,000 m; two of the wells were never productive, four have become inactive, and the drilling of one was only preliminary. A summary of the project development follows:

1971-72	The first two wells drilled. They disclosed a reservoir temperature of about 235°C and highly saline water with total dissolved solids of about 20,000 to 30,000 ppm, which could not be used directly in a district heating system.
1972-73	National Energy Authority published a feasibility report for a district heating system. Production cost of geothermal energy estimated at about 1/3 that of oil-fired heating.
1974	A pilot plant was built by NEA. Two wells drilled (HSH-4/1713 m; HSH-5/1519 m). Sudurnes Regional Heating Company (SRHC) established, owned 60% by the regional communities and 40% by the Icelandic state.
1976-77	A preliminary power plant of 3 MW_t commissioned. Power plant I of 12.5 MW_t was commissioned.
1978	First 1 MW_e turbogenerator commissioned. Second unit of power plant I of 12.5 MW_t commissioned. Well HSH-6 drilled (1734 m).
1979-80	Third and fourth units of power plant I of 2 x 12.5 MW_t commissioned. Second 1 MW_e and third 6 MW_e turbogenerator units commissioned. Wells HSH-7 (1438), HSH-8 (1603 m), HSH-9 (994 m), HSH-10 (425 m) and HSH-11 (1141 m) drilled.
1981	Power plant II of 75 MW_t commissioned. Well HSH-12 (1488 m) drilled for injection tests.
1989-92	Seven binary power units of 8.4 MW_e were commissioned.

PROCESSING METHOD

Geothermal brine cannot be used directly for heating because of its high mineral content. On cooling, it releases great quantities of hard deposits (silica) which lodge themselves onto pipes and other equipment, making such equipment inoperable after a short time.

For this reason, the geothermal brine is made to boil twice and the heat from the steam thus formed is utilized, while deposits from the steam are minimal. As shown in Figure 1 high-pressure geothermal steam (5.2-5.5 bars) is

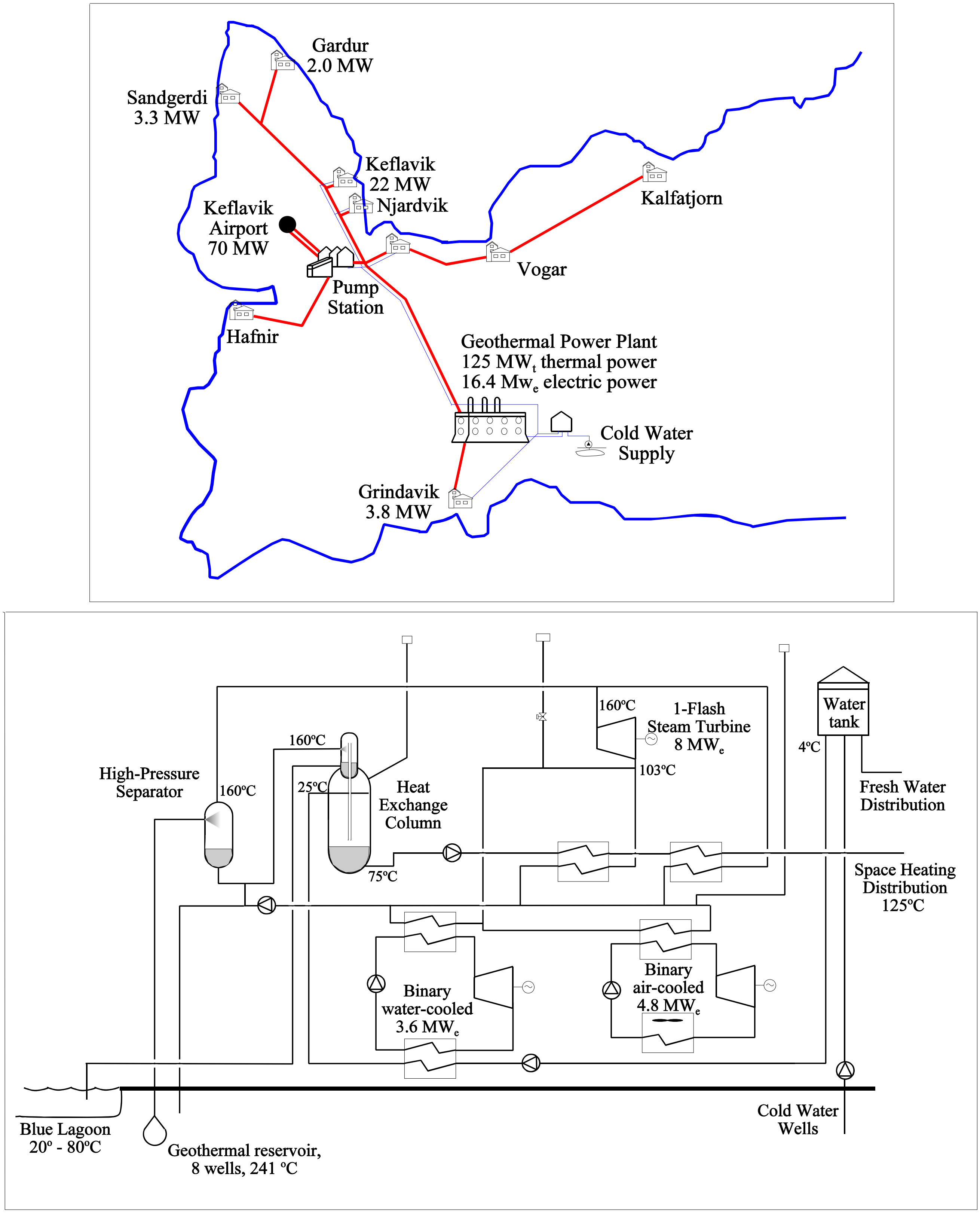

Figure 1. The Sudurnes Regional Heating System layout and flow diagram for Svartsengi Power Plant.

harnessed in steam turbines for the generation of electricity (8 MW_e), and for the final heating of the utility water (100° -120°C). Low-pressure geothermal steam (80° -104°C) is used for the direct warm-up of fresh water (preheating) and for the generation of electricity (8.4 MW_e) in ORMAT binary generators.

Thus, fresh water is warmed up (from 4°C to 25°C) in the ORMAT generators, de-gassed and heated with low-pressure steam to about 75°C in direct-contact heat exchangers. Then it is heated to about 100°C in a plate heat exchanger with 105° -110°C hot steam coming out of the exhaust from steam turbines; and finally, the water is superheated with high-pressure steam to about 100° -125°C in a plate heat exchanger.

The power generated by the power station amounts to 125 MW_t in the form of hot water, assuming the water is 125°C on leaving the power station and 40°C hot when discarded by the end users, and 16.4 MW_e of electricity.

DISTRIBUTION SYSTEM

The distribution system of the SRHC covers all the local government areas in the district, in addition to Keflavik Airport (Figure 1). In 1993, the total length of the distribution system and supply systems comes to about 340 km. There is only a single piping system in the local government areas, but at Keflavik Airport there is a closed-circuit system, enabling the utility to return the back flow to a pumping station. Supply lines from Svartsengi and collection pipes from production wells at Svartsengi are located above ground, insulated with mineral wool, which is covered with a dimple plastic sheet and clad with aluminum sheets. All other pipes are located underground inside the boundaries of built-up areas; thus, they do not constitute any hindrance or an eyesore in the landscape.

Water from the power station is at two temperatures. Water pumped to Grindavik leaves the power station at 83°C and arrives at the village boundary at about 80°C, while water piped to the pumping station at Fitjar leaves at 105° -120°C, as this water is mixed with back-flow water from the airport area and then pumped to the end users at 83°C, and 90°C to the airport area. It is expected that the end users utilize the heat in the water down to 35° -40°C, and then the water runs out to the sea through the sewer systems of the local government areas.

A large quantity of cold water, up to 330 L/s, is extracted from a perched aquifer at Gja and other places. Water extraction for the water works averages about 190 L/s. However, there is thought to be little risk of the water extraction rate being too high, as the average precipitation in an area of 10-15 km^2 is expected to equal the entire water supply of the SRHC; the total area of the Reykjanes peninsula is about 580 km^2.

ELECTRICITY GENERATION

At the power station, high-pressure steam has been used to generate electricity almost from the beginning; thus, in 1978, two 1-MW_e geothermal steam turbines were installed for the purpose of generating electricity for use at the power station and pumping station themselves. In December 1980, a 6-MW_e Fuji steam turbine was put into operation, generating electricity for the grid. During the next few years the three turbines generated about 40 GWh per year, including about 10 GWh for the stations. Through the merger of the power distribution systems in 1985, it became possible to utilize the turbines better, increasing the production to about 60 GWh per year.

On 8th September 1989, the next step was taken with the start up of three 1.2-MW_e binary ORMAT turbines (water-cooled), utilizing steam which had previously flowed unharnessed from the chimneys of the power station. The production went up to about 90 GWh per year, including about 15 GWh for the stations. The latest increase in electricity generation came on the 5th of March 1993, when four additional 1.2-MW_e binary turbines (air-cooled) were put into operation. Installed power at the station then rose to 16.4 MW_e, and production is expected to rise in stages during the next few years to 110 GWh, including 17 GWh for the plant's own use.

THE BLUE LAGOON

In 1981, people suffering from psoriasis tried bathing in the Blue Lagoon with fairly promising results. This encouraged interest in the Lagoon and several studies have since been made of its healing properties. In the light of increased attendance, the SRHC in 1986 decided to construct a bathhouse by the Lagoon. The building was then enlarged in 1988 as attendance kept increasing steadily. The Grindavik municipality took over the operation of the bathing facility in 1992 and erected an annex to the building, which has come in good stead as the number of guests came to more than 133,000 in 1993, including 108,000 actual bathers.

Great efforts are being made to work on further development and utilization of the possibilities offered by the Blue Lagoon. Preliminary plans have been made for the construction of a new lagoon under the western slopes of the mountain Thorbjorn, at a distance of about 2 km from the present one, where there are plans to construct extensive health and tourist facilities. Although some people prefer the present location next to the power plant, which provides an additional attraction. The Health Company by the Blue Lagoon Ltd has prepared special bathing facilities for psoriasis patients. Studies of the healing powers of the lagoon are being made there under the strict supervision of dermatologists. Furthermore, the company has started experiments in preparing lotions, creams, etc., containing silica and salts from the Lagoon; algae living in the Lagoon are being cultivated at a special research facility.

There are hopes that these activities, along with other possibilities connected to the Blue Lagoon, will prove to be the mainstay of the economy of the area in the future.

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HITAVEITA (DISTRICT HEATING) IN AKUREYRI

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INTRODUCTION

Akureyri is a town of 15,000 inhabitants located in central N-Iceland (Figure 1). It has been heated by geothermal energy since the end of the seventies. Prior to that, it was partly heated by electricity, but mainly with oil burners, located within individual buildings. During the period 1928-1970, several attempts were made to exploit known hot spring areas in the vicinity of Akureyri. These attempts failed. Following the jump in energy price during the oil crisis of 1973, considerable effort was put into further exploration. Based on resistivity soundings, the Laugaland field was selected for deep drilling. In 1975, this resulted in the discovery of a big feed zone, which initially yielded around 100 l/s of 90°C hot water by free flow. Two years later another big feed zone was located at the Ytri-Tjarnir geothermal field initially yielding 50 l/s of 80°C water. Based on short-term pump tests, and simulations by the Theis model, it was estimated that these two fields together could yield 240 l/s with a water level drawdown to 190 m below the surface (Björnsson, et al., 1979). This was expected to satisfy the energy need for space heating in Akureyri. In 1977, Hitaveita Akureyrar (Akureyri District Heating) was, therefore, established. Construction of the district heating system was initiated in 1976 and most of the town had been connected in 1979.

Soon after pumping from the fields began, it became evident that the drawdown would be much greater than had been predicted. Since pump design limited the drawdown to 240 m at Laugaland and 330 m at Ytri-Tjarnir, the average annual production declined rapidly with time. After a few years in operation, the annual average production from these fields was reduced to 75 l/s. This unforeseen decline was answered by an almost desperate exploration for more geothermal water, mainly by drilling, but later by careful surface exploration followed by drilling. This resulted in the discovery of productive feed zones at three different geothermal fields: Botn in 1980, Glerardalur in 1981 and Thelamörk in 1992. These new fields together with heat pumps, electric boilers and energy saving efforts have ensured enough geothermal energy in Akureyri and will do so for the next decade or so. However, the over-investment due to the initial over-estimate of productivity and hot water demand, along with other reasons, have led to much higher energy prices than expected. At the moment, the price is close to the oil price; but, it is expected to drop slowly over the next decade or so.

This paper, a shortened version of the original (Flóvenz, et al., 1995a), describes the structure of the district heating system in Akureyri, both reservoir characteristics and installations for distributing the water as well as how the system is operated and monitored.

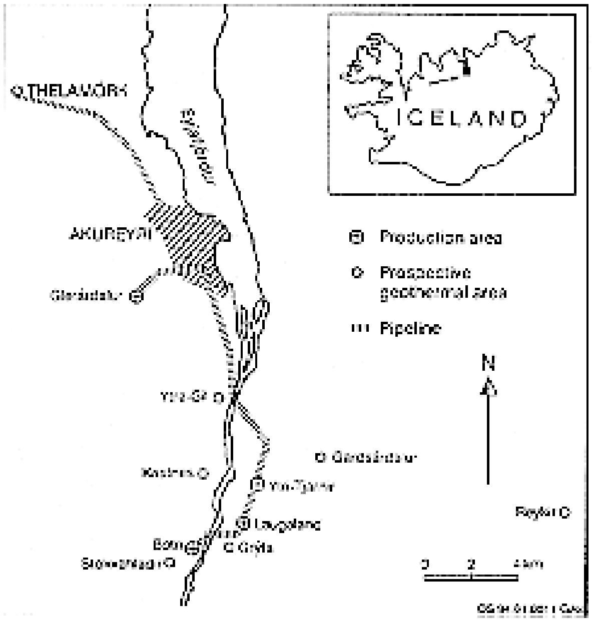

Figure 1. A map of Akureyri and the nearby geothermal fields.

THE DISTRICT HEATING SYSTEM

Figure 2 shows a schematic picture of the district heating system. Hot water is pumped from three different locations towards Akureyri, from the Eyjafjördur geothermal fields 12-14 km south of the town, from Glerardalur 2 km west of the town and from Thelamörk 10 km north of the town. Eyjafjördur geothermal fields are a synonym for three separate geothermal fields: Laugaland, Ytri-Tjarnir and Botn. In Eyjafjördur and at Thelamörk, a part of the hot water is used for local consumption; but, the main part is pumped to Akureyri. In Glerardalur and at Thelamörk, the water is pumped directly from the boreholes to Akureyri. In Eyjafjördur, the water from the three different fields is first collected at the Laugaland Pumping Station (LPS) from which it is pumped along the transmission pipe to Akureyri.

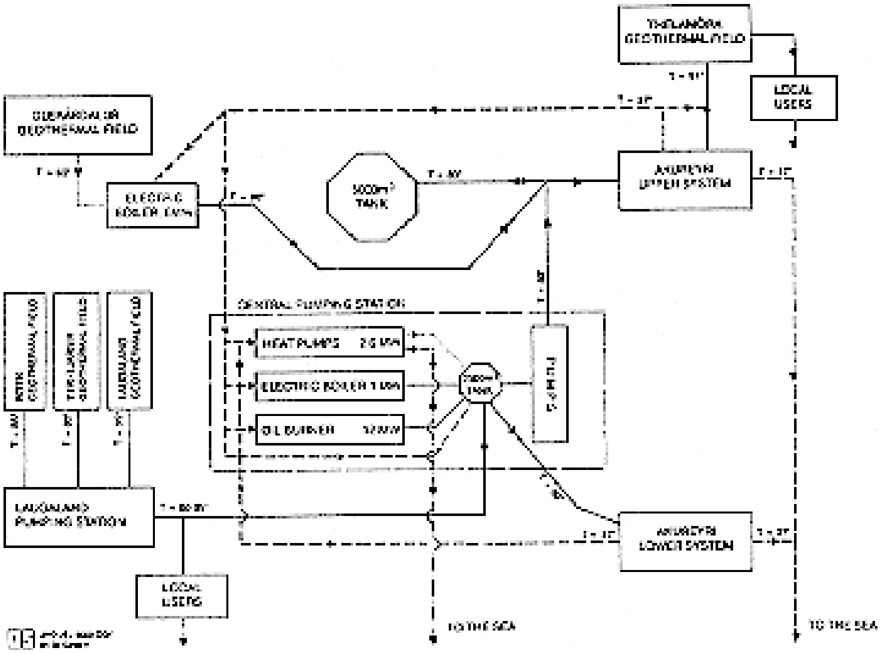

Figure 2. A schematic picture of the Akureyri district heating system.

There it enters the Akureyri Central Pumping Station (CPS); where, it is mixed with some return water that has been reheated in two 1.3-MW heat pumps. In addition, a 1-MW electric boiler at the CPS is used together with the 27°C return water to regulate the outlet temperature from the CPS to 73-80°C.

At Akureyri, the 60°C hot water from Glerardalur is heated to 73°-80°C by a 6-MW electric boiler before it is mixed with water from the CPS and sent to the upper distribution system.

The total length of pipelines of the distribution network in Akureyri is 215 km and the distance from the pumping station to the most distant users is about 5.3 km. The inlet temperature to the houses is quite variable, depending on the distance from the pumping station and the rate of consumption. It is usually in the range of 65-75°C; but in extreme cases, it may fall to 45°C during hot summer days.

Because of elevation differences within the town, the distribution system is divided into two separate parts: the upper and lower distribution systems. About 30% of the hot water that is sent to the consumers is recollected, especially from those parts of Akureyri with the highest population density. The average temperature of the return water is 27°C. Of the total consumption, 90% is for space heating, but 10% for bathing, washing and other purposes.

Within the buildings, the water enters a substation which includes back-pressure control valve, a no-return control valve, flowmeter, thermometer and a shut-off valve (Figure 3). The water is sold to the consumers according to volumetric measurements; but, corrections are made if the water temperature is below certain limits at maximum load.

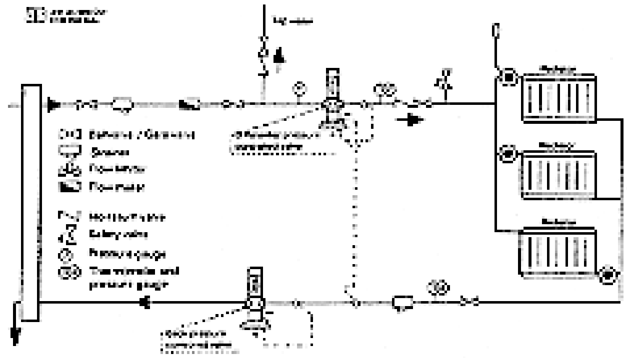

Figure 3. A typical house substation in Akureyri.

THE GEOTHERMAL FIELDS

The crust around Akureyri is made of 6-10 m year old flood basalts inter-bedded with thin layers of sediments. The lava pile typically tilts a few degrees towards the active riftzone. The lava pile is intersected by numerous near-vertical dykes and normal faults, which appear in swarms. The lava pile has suffered low-grade alteration which together with precipitation of alteration minerals has drastically reduced the primary permeability. In recent geological times, crustal movements have caused formation of tectronic fractures, which often coincide with older dykes or faults. Many of the low-temperature geothermal fields in Iceland are local convection systems situated in such fracture zones. Thus, the low-temperature geothermal systems of Iceland are, in most cases, fracture-dominated convection systems surrounded by almost impermeable rock. This is the case for all five

Table 1. Productivity of Geothermal Reservoirs Utilized by Hitaveita Akureyrar.

Area	Initial Pressure[1] (bars)	Maximum Pump Depth (m)	Productivity[2] (l/s)	Water Temperature (ºC)
Botn	17.5	250	30	85
Laugaland	19.8	250	46	95
Ytri-Tjarnir	5.7	400[3]	33	80
Glerardalur	6.3	250	15	60
Thelamörk	1.9	250	17	90

[1] Wellhead [2] Until the year 2005 [3] A submersible-motor downhole pump

geothermal systems utilized by Hitaveita Akureyrar. The low-permeability and small volumes lead to a great pressure drawdown and limited productivity for all the systems. The productivity of the five systems, estimated on the basis of lumped modeling, is presented in Table 1. The Laugaland reservoir is far the most productive, because of the relatively greater volume and permeability. For further details on the geology of the systems, we refer to Flóvenz, et al. (1995).

Chemical Aspects

Generally, the water is very low in chemical content (TDS = 180 - 290 ppm) and direct use should be possible without any problems. 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 in geothermal water is usually harmless as oxygen reacts with hydrogen sulphide in geothermal water to form sulphate. But since the water utilized in Akureyri is extremely low in H_2S, it is necessary to mix sodium sulphide (Na_2SO_3) into the water to remove the oxygen. This mixing is not sufficient, however, to allow the use of the storage tank. The reaction is too slow to remove all oxygen before the water enters the houses closest to the tank.

TRANSMISSION PIPELINES AND PUMPS

Borehole Design

Borehole design has varied with time since the late seventies, as well as drilling technology. Reservoir temperatures in Eyjafjördur are up to 100ºC and the maximum observed wellhead pressure is 20 bar. In most cases, the pressure is, however, much lower and the water level can be as low as 200 below the wellhead if the wells are connected to production wells in use.

Most of the recent wells are cased with a 14-in. surface casing down into the bedrock, which is typically at 10-30 m depth. Below that depth, air drilling is commonly applied with an 8 ½-in. downhole hammer. The air drilling is often used down to 200-400 m depth or as deep as is possible because of water inflow and compressor limitations. Below that depth, conventional rotational drilling is used with water as circulation media. Typical drilling rates are 8-10 m/hr during air drilling, but 3-5 m/hr during rotational drilling. In case of circulation loss in under-pressurized feed zones, all the drill cuttings will settle into the feed zones. To avoid that, air is commonly mixed into the circulation water to lower the weight of the fluid column in the borehole.

Usually, the well is drilled to its final depth before it is cased with production casing. A cement plug is put into the well just below the desired casing depth and the well is widened to 12 ½ inches by rotational or air drilling, and then cased with 10-3/4-cemented steel casing. Typical depth of the production casing is 250 m and typical borehole depth is 1000-1800 m. Liners are usually not necessary; the wells are usually barefoot below 250 m depth.

Borehole Pumps

Basically, two types of downhole pumps are used by Hitaveita Akureyrar. A pump with submersible motor is used at Ytri-Tjarnir; but in the other fields, rotary-shaft pumps are used. Five types of rotary-shaft pumps manufactured by the Floway Company are used. They have 6-15 stages each, the performance is 12-60 l/s and with motors of 50-300 hp, all with a rotational speed of 300 rpm. Hot water is used as lubrication. When the pumps are not in use, the shafts are kept warm by pumping down a small amount of hot water. The submersible pump is a Reda M-520 with a 215 hp motor and a rotational speed of 2915 rpm. The performance is 32-33 l/s. Experience shows that the lifetime of the rotary-shaft pumps is about nine years with the same motors running from the beginning of operation of Hitaveita Akureyrar. The lifetime of the submersible pumps has been 2-3 years.

Pipelines and Pumping Stations

At the Laugaland Pumping Station (LPS), the water from the Eyjafjördur geothermal fields passes through a degasser, which is a 300 m^2 insulated storage tank before being pumped towards Akureyri by two Floway 14FKH pumps. They have six stages each, 300 hp motors and rotational speed of 1450 rpm. Their performance is 170 l/s. Under normal load, only one of the pumps is used; the second serving as a peak and reserve pump. During the winter time, electrical system failure may occur, especially in bad weather when snow and ice break the electrical power lines. To account for this, a 1500-kVA power station has been installed at the LPS. Therefore, the pumping from the Eyjafjördur fields towards Akureyri is not dependent on external electrical power. In addition, sodium sulphide is mixed with the water at the LPS to remove the oxygen contamination.

The transmission pipeline is a 508-mm diameter steel pipe, insulated with water resistant rockwool and covered with a thin aluminum cover. Only about 1.3 km of the 12 km pipeline is buried in a concrete tunnel; while, most of it rests on 1-2 m high concrete columns, with 9 m spacing. The pipeline can move freely on the concrete columns except at every tenth column where it is either a fixed point or an expansion unit to take up thermal expansion in the pipeline. The cooling in the 12-km pipeline is close to 2°C for a flow of 100 l/s.

The transmission pipelines from the fields at Glerardalur and Thelamörk are of a different construction. Since Glerardalur is located just 2 km outside Akureyri, and at an elevation of 220 m, the water is pumped directly from the borehole through a small degassing tank and to the CPS at Akureyri.

At the Thelamörk field, the production borehole is equipped with a frequency regulated downhole pump allowing time-dependent regulation of the production without variations in the valve pressure. The water is pumped from the borehole to a 20-m^2 degassing tank and then by three 18-kW Grundfos pumps along the 10.1 km long pipeline to Akureyri. In the northern part of the town, it is mixed with return water to adjust the temperature to the desired value.

The transmission pipeline from Thelamörk to Akureyri consists of a 4.5-mm thick steel pipe, 193.7 mm in diameter and with a 60-mm thick polyurethane insulation, covered with a polyethylene coat. The estimated temperature loss along the pipeline is 6°C. This is a subsurface pipeline without expansion units or loops; the thermal expansion is taken up by stresses in the buried pipeline.

The Central Pumping Station

The Akureyri Central Pumping Station is located in the southern part of the town. There the water from the Eyjafjördur and Glerardalur fields, as well as a part of the return water is blended in a 2500 m^2 storage tank before it is pumped to the customers. This is done by two 14 DOH Floway pumps with four stages. One of them is frequency regulated with a 150-hp, 1450 rpm motor and a maximum performance of 120 l/s at 55 Hz. The other pump has a 100-hp motor and a performance of 95 l/s. The distribution system is divided into two parts due to elevation differences within the town. The water from the storage tank at the CPS flows directly into the lower part of the system; while, pumping from the CPS is needed to fee the upper part, either directly or through a 5000-m^2 storage tank located at 115 m above sea level.

At the CPS, the heat pumps, the 1-MW electrical boiler and the oil burner are located.

Heat Pumps

In 1984, two 1.3-MW heat pumps were installed at the CPS. The purpose of the installation was to extract more energy from the geothermal water instead of discarding 27°C hot return water. In the system, a part of the return water is cooled down to approximately 15°C and the heat is transferred to what remains of the recollected return water. The coefficient of performance is between 3 and 4. The heat pumps have now been in operation for 11 years without any serious problems, and average operation time is 5500 hrs/year.

From 1997, the return water from the heat pumps will be recirculated to the Laugaland field and injected there.

Electrical Boilers and Oil Burner

The smaller one of two electrical boilers, which have been installed at Akureyri, is located at the CPS. The bigger one (6 MW) is run in co-operation with a dairy plant, and is located a short distance from the upper storage tank. The boilers make use of cheap surplus electricity that is available in Iceland at the present, throughout most of the year. The 1-MW boiler is used to regulate the temperature of water from the CPS; while, the 6-MW boiler is used to elevate the temperature of the water from Glerardalur from 60°C to the system temperature. By using surplus energy in that way, the lifetime of the present geothermal field is prolonged and an investment in a new field is delayed.

The 12-MW oil burner uses heavy fuel oil. It is primarily used in emergency cases, such as cases of major system failure. It has also occasionally been used over short and extremely cold periods in the winter time when more power is required than can be extracted from the geothermal fields.

Storage Tanks

Two storage tanks have been built at Akureyri: a 2500-m^2 tank at the CPS and a 5000-m^2 tank for the upper system. The purpose of the tanks was to filter out short-term changes in consumption and to have some reserve water available at all times in case of a system failure. To avoid oxygen contamination, a blanket of steam, produced by the 6-MW boiler, is used to cover the water surface in the larger tank. Both the tanks are make of steel and insulated by rockwool.

ENERGY CONSUMPTION AND PREDICTIONS

The first houses were connected to Hitaveita Akureyrar in November 1977. In the three years that followed, most of the town was connected to the system and the energy consumption increased rapidly to nearly 300 GWh/year in 1982 (Figure 4). The long-term generating capacity of the four geothermal fields that had been harnessed in 1982 was only around 250 GWh/year. Therefore, the geothermal fields were heavily overexploited, especially Laugaland and Ytri-Tjarnir. An almost desperate exploration effort, mainly by intensive

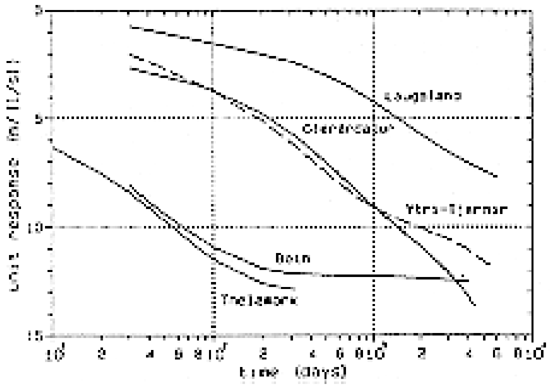

Figure 4. Unit response of the geothermal systems utilized by Hitaveita Akureyrar.

deep drilling in 1978-1980 yielded relatively poor results, yet increased the total investment considerably. The over-exploitation resulted in rapidly increasing drawdown in wells and in 1982, a constantly increasing energy production by the oil burner was foreseen. For three reasons this was not very attractive. Firstly, the distribution system was originally designed as a no-return system (i.e., the return water was not collected). It became, therefore, necessary to reconstruct a part of the system to recollect return water from the most densely populated parts of the town. This increased the investment cost further. Secondly, the oil price was still very high and the purpose of building the district heating service was to avoid oil as fuel. Thirdly, a lack of electricity in Iceland at that time kept the price of electricity relatively high.

In 1981-84, Hitaveita Akureyrar increased the energy price dramatically. The price actually approached the price of oil heating. The price increase, together with energy saving efforts, led to about 15% reduction in energy consumption (45 GWh/y) from 1982 to 1985 and at the same time, the generating capacity was increased by 15 GWh/y by installing the two heat pumps. However, in late-1985, the most radical energy saving effort took place. It involved a change in the mode of selling the water. Instead of selling it through a flow limiter, where the users paid for the maximum installed power instead of energy used, the price became based on volumetric measurement of the consumption. This led to a further 15% (40 GWh) decrease in energy consumption. At the same time, the tariff was adjusted so that the total income of Hitaveita Akureyrar was not reduced. The explanation for the dramatic effect of the sales mode on the energy consumption lies in the behavior of the users. When they buy the water according to a preset flow limiter value, they try to select as low a value as possible. By this, they minimize their cost of heating; but, often they buy less than is necessary to keep a comfortable indoor temperature during the coldest days of the year. But they don't care how much energy they use. The users pay the same regardless if they just open the windows on warmer days or whether they turn off their radiators.

The 30% reduction in energy consumption from 1982 to 1987 had a very positive effect on the energy budget of Hitaveita Akureyrar (Figure 5). Instead of over-exploitation of the geothermal fields, there has been enough geothermal energy available from 1985 to 1995. It has, therefore, not been necessary to use the oil burner except in emergency cases. This has provided a reasonably long period to explore other potential geothermal fields in the vicinity of Akureyri. This resulted in the Thelamörk field being harnessed since late-1994 (Flóvenz, et al., 1995b), which together with the new 6-MW electric boiler will ensure enough energy for the next decade or so.

SYSTEM CONTROL AND MONITORING

Daily Control

To account for changes in consumption rate, the water level in the degassing tank at Laugaland is monitored and automatically kept constant. This is done by frequency regulation of the main pumps at the Laugaland Pumping Station. The water level in the smaller storage tank at Akureyri is also monitored and kept within a selected range by switching selected borehole pumps at Laugaland and Botn

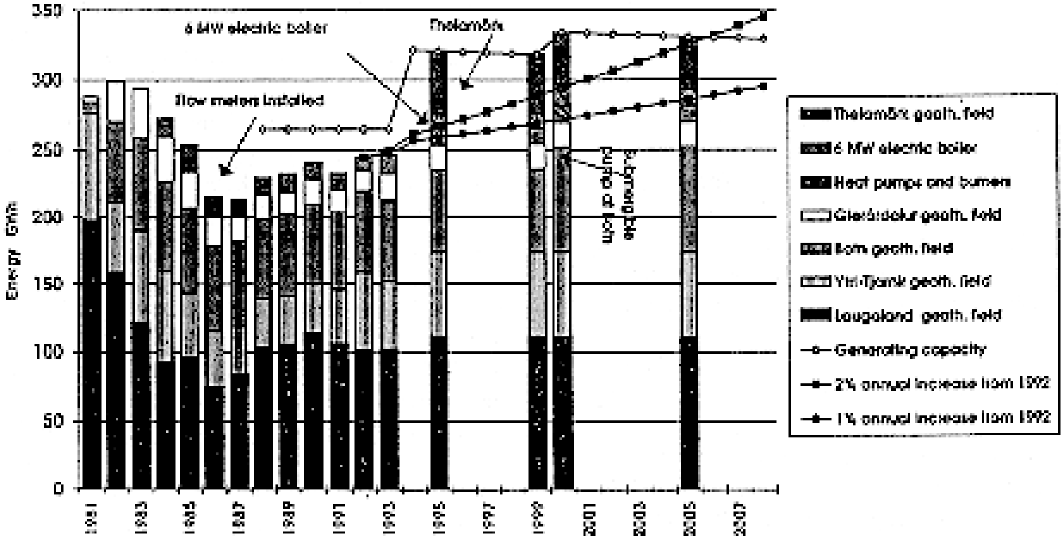

Figure 5. Energy consumption, future demand and generating capacity of Hitaveita Akureyrar.

automatically on and off. The submersible pump at Ytri-Tjarnir is, however, always kept at a constant production rate, since its lifetime seems to be reduced considerably by frequently turning it on and off.

The two heat pumps are in operation when enough return water is available. They have an automatic internal control. The outlet temperature from the CPS is manually controlled by selecting which boreholes are in operation (they have different reservoir temperatures), by varying the mixing of return water and by use of the 1-MW electric boiler.

Monitoring of the Geothermal Systems

Careful monitoring of the geothermal field is critical in the management of the system. It provides information used to estimate the productivity of individual fields and wells, and its variations with time. Information on production rate and water level in individual production wells as well as water level in surrounding observation boreholes is used for modeling the geothermal reservoirs and to make predictions on future trends in water level for the desired production. The predictions are usually done by lumped parameter modeling of the data (Axelsson, 1989). Under ordinary circumstances, these parameters are measured once a week along with the water temperature and the electrical conductivity of the water.

Once a year, a complete chemical analysis is done for water from all the boreholes to monitor possible chemical changes. Generally, chemical changes have been very small, except for the Botn field where significant changes have been observed. These changes together with most other available data have been used as the basis for detailed three-dimensional modeling of Botn (Axelsson and Björnsson, 1993). To monitor possible sudden chemical changes in the geothermal water, the electrical conductivity of the water is measured weekly. The sensitivity of the conductivity measurements corresponds to a change of +/- 0.5 ppm of a NaCl equivalent solution. The conductivity measurements are believed to be suitable for giving indications if sudden changes in chemical content occur. In addition, the content of dissolved oxygen and $NaSO_2$ is frequently measured to ensure efficient removal of oxygen by sulphite mixing.

FUTURE ENERGY POLICY

The great investment in the district heating service at Akureyri, together with high interest rates in the eighties have led to a relatively high price for the hot water. The consumer price is now about 32 mills/kWh, which is similar to the governmentally subsidized price for electricity for space heating. This can be compared to the average geothermal price of 11 mills/kWh in Iceland or 42 mills/kWh in the case of oil burning.

The generating capacity of Hitaveita Akureyrar is now estimated to satisfy the energy consumption until at least the year 2005, provided that the average annual increase will not exceed 2%. In this period, no major investment is expected such that the big debts which now plague the company will be reduced considerably. This is expected to open the way for a lower energy price in the future. However, care must be taken in price reduction as it will most likely lead to an increase in consumption and, therefore, call for additional new investment in energy production sooner than otherwise.

During the next ten years, geothermal exploration will be continued. There are still several known but unexploited geothermal resources in the vicinity of Akureyri which could give additional energy when needed. Furthermore, reinjection of return water or possibly injection of cold water into the geothermal field is likely to prolong the lifetime of the present geothermal fields and increase their generating capacity (Axelsson, et al., 1995).

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HIGH TECHNOLOGY IN GEOTHERMAL FISH FARMING AT SILFURSTJARNAN LTD., NE-ICELAND

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INTRODUCTION

Land-based fish farming in Iceland relies on good resources of freshwater and seawater with thermal energy to warm it up. In Öxarfjördur, NE-Iceland plentiful cold groundwater exists and geothermal manifestations are found at many locations. Seawater resources are, apart from the unstable sand shore, limited to a pillow lava formation close to the shore. During 1986-1990, Orkustofnun - the National Energy Authority of Iceland joined with local authorities in Öxarfjördur to study the potential of the area for fish farming. The project led to the forming of the company Silfurstjarnan Ltd., which built and presently runs a fish farm in Núpsmýri in Öxarfjördur. Fridleifsson, et al. (1995) have described the fish farm in its initial phase and the research project. While the present article is based on that paper, here we focus on the present status and future possibilities and expand on some of the technological aspects.

The Öxarfjördur region, at the coast of NE-Iceland, is within the active zone of rifting and volcanism which crosses Iceland from southwest to northeast. Three northerly trending fissure swarms, parts of active volcanic systems further inland, cross the region. While most of the volcanic zone is characterized by volcanic products of some sort, the Öxarfjördur delta is chiefly a graben zone filled by shallow marine fjord sediments and glacial outwash from Jökulsá river. The sedimentary thickness in the central outer part of the graben approaches 1 km (Georgsson, et al., 1989; 1993a and Ólafsson, et al., 1993).

Groundwater from a large area drains into the Öxarfjördur basin, where the three fissure swarms play a key role in the flow and distribution of springs. In all, about 40 m^3/s surface within them at the margin between the porous post-glacial lava horizons and the sedimentary basin (Georgsson, et al., 1989).

Most of the surface geothermal activity is confined to the gravel plain and the Krafla fissure swarm. During the Krafla volcanic and tectonic episode in 1975-1984, geothermal activity increased considerably, but is now slowly decreasing again. Resistivity survey delineated a low-resistivity area of about 10 km^2 within the Krafla fissure swarm which is explained by the existence of a high-temperature geothermal area (Georgsson, et al., 1993a; 1993b). Another geothermal area is at Skógalón, close to the coast (Figure 1). There, results from shallow exploration wells lead to the drilling of the production well AE-3 in 1988 (Figure 1), which yields 40 - 50 l/s of 96ºC hot water in free flow (Georgsson, et al., 1989; 1993a). This well is now utilized by the Öxarfjördur Heating Services.

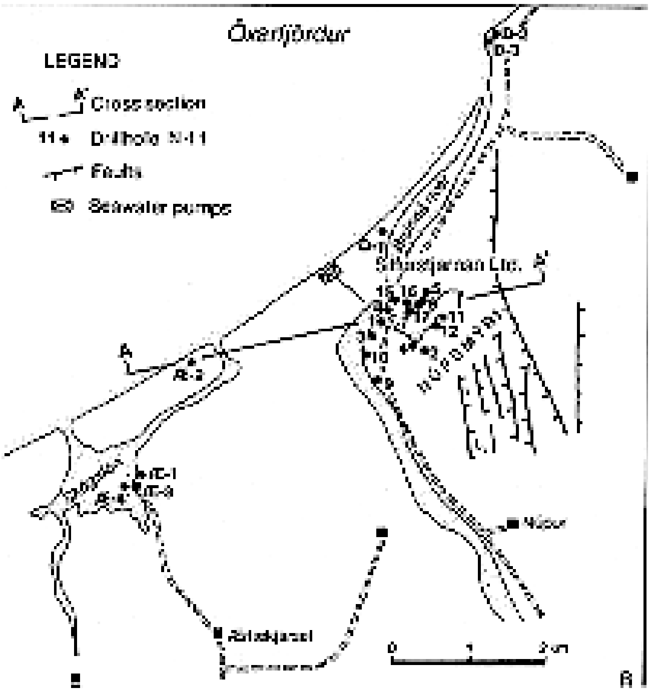


Figure 1. a) The Öxarfjördur region and the geothermal pipeline of the Öxarfjördur Heating Services, and b) The location of drill holes and the Silfurstjarnan Ltd. fish farm.

Results of drilling at Skógalón were encouraging, and concentrated the research for a suitable site for the fish farm on the coastline east of Skógalón. Drilling of exploration wells at the coast confirmed that seawater had to be collected at or close to the surface, but unexpectedly led to the discovery of warm groundwater. Further drilling revealed a large reservoir of brackish 35 - 36ºC warm water at 60 - 200 m depth in Núpsmýri close to the coast, at the eastern margin of the sedimentary basin. Furthermore, it turned out that from the same Núpsmýri field at least 400 l/s of cold groundwater could be pumped form the uppermost 50 - 60 m with only a minor drawdown (Fridleifsson, 1989; Georgsson, et al., 1989). The quality of this water proved excellent for fish farming. When experiments with shallow drainpipes dug into the sand at the seashore, showed that seawater of good quality could safely be collected, Núpsmýri was chosen as the site for the Silfurstjarnan fish farm (Figure 1).

THE NATURAL CONDITIONS

The main results of the research on natural conditions for fish farming were that both cold freshwater and warm brackish water could be harnessed from the Núpsmýri field. Altogether, 17 wells have been drilled in the field. The location of the wells is shown in Figure 1. The fish farm was built on top of the reservoir, neatly located close to the main road in NE-Iceland. One branch of the Jökulsá river also runs close by, and is used for disposing effluent water from the fish farm.

The water reservoir is composed of very porous and permeable pillow lava breccia which is a part of a subglacially formed hyaloclastite ridge of late-Pleistocene age covered by a 20 - 60 m thick blanket of sediments in Núpsmýri. Beneath a thin layer of sandy soil, the sediments are composed of a river delta and eolian sand in the upper part, and a beach sand and shallow marine mud in the lower part, which cap the pillow lava reservoir formation (Figure 2). All water is pumped from the wells with a fixed 1 - 2 m drawdown, yielding 60 - 230 l/s per well (200 - 830 m^3/h) depending on pump size and well width.

The natural state of the thermally- and chemically-layered water reservoir is such that cold freshwater (5 - 7°C) extends to a depth of about 100 m in the eastern part of the well field, the freshwater lens there being about 60 - 80 m thick (Figure 2). West of the fish farm only brackish warm water (>30°C) was met, from below 60 m to at least 220 m depth. A fault control is inferred for the warm water (Figure 2).

The salinity of the cold water is <1 ppt (parts per thousand) above 100 m depth, appears brackish (3 - 6 ppt) from there to 120 - 130 m, and strongly saline (>25 ppt) approaching seawater salinity below that depth. The warm water in the western part of the reservoir, on the other hand, is brackish (4 - 8 ppt) from 60 m down to about 120 m depth, below which depth the salinity increases sharply to above 25 ppt (Figure 2). An example of the chemistry of different waters from the area is shown in Table 1.

Table 1. Chemical Composition of Representative Water Types (mg/l)

Water Type Well No.	Cold N-6	Brackish N-12	Warm N-1	Seawater Drainage	Hot AE-3
Temperature (°C)	5.4	7.6	34.2	2.3	96
pH/°C	9.6/16	8.8/25	7.8/15	8.6/24	7.9/24
Diss. oxygen (O_2)	9	-	0.1	-	0
Carbonate (CO_2)	42.5	42.9	58.6	50.9	24.3
Sulphide (H_2S)	<0.03	<0.03	<0.03	<0.03	0.07
Silica (SiO_2)	18.3	16.1	36.5	2.4	129.1
Sodium (Na)	64	1790	1865	7940	833
Potassium (K)	3.7	63	86	295	44
Magnesium (Mg)	1.3	173	60	905	0.42
Calcium (Ca)	1.4	103	152	301	154
Iron (Fe)	0.025	-	0.1	-	<0.02
Manganese (Mn)	<0.05	-	0.2	-	-
Sulphate(SO_4)	11.2	477	390	1930	97
Chloride (Cl)	48.1	3490	3937	14300	1534
Fluoride (F)	0.2	0.25	0.36	0.8	0.27
TDS	174	6859	4430	27765	2709
Salinity (ppt)	0.09	6.3	5.3	25.8	2.8

The lack of a large saline groundwater reservoir was solved in a unique manner by installing a drainage system into the sandy sea bottom at the shore in Öxarfjördur. The best results were reached by digging 12-m long, 254-mm slotted steel pipes into the sea bottom on the lowest tide to a depth of

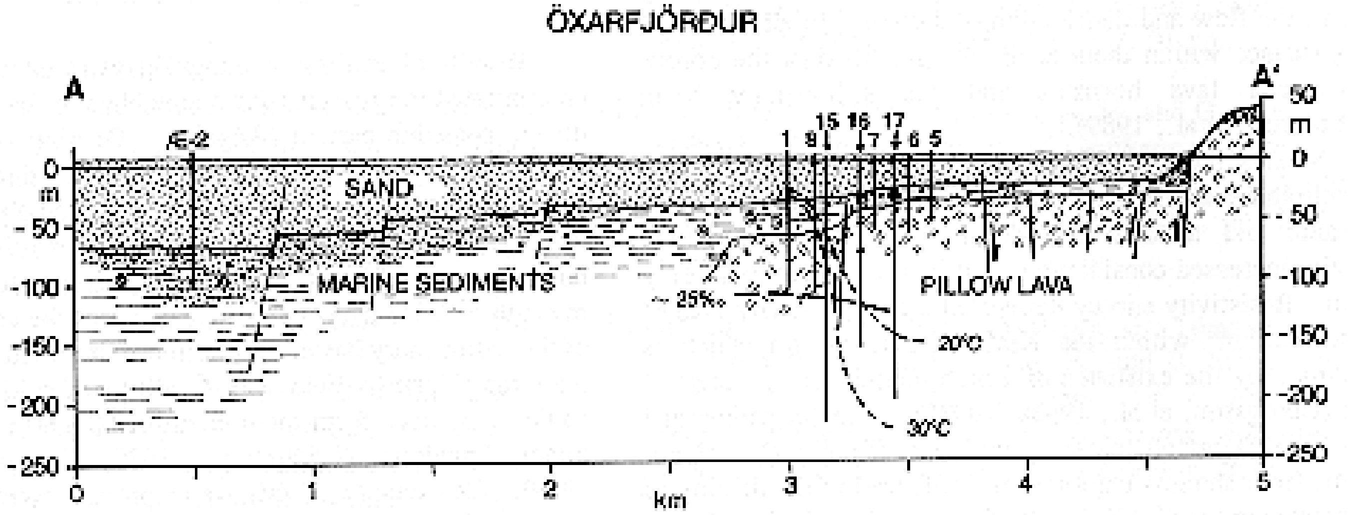


Figure 2. The geological cross-section A-A' through the Núpsmýri drill field (location see Figure 1); also shown are isotherms and the 25 ppt salinity isoline.

1.5 - 2 m. Seven such slotted liners are now connected with plastic pipes to seven centrifugal pumps. With this system, a constant amount of about 800 l/s of clean seawater can be pumped towards the fish farm, about 1 km inland. The temperature ranges from about 1°C in January to 8 - 9°C in July/ August. Consequently, the need for hot water increases in the winter as the rearing water needs to be kept at a constant temperature of about 10°C the year round.

Extra geothermal energy for house heating is now provided by Hitaveita Öxarfjördur or the Öxarfjördur Heating Services, which started operation in late-1995. Then, geothermal water replaced electricity as the main energy source for house heating in the region. The first phase of construction involved a pipeline from well AE-3 at Skógalón to the village of Kópasker with about 170 people, located at the coast about 19 km north of Skóglón (Figure 1), providing geothermal water for its inhabitants and the farms, and minor industries along the way, such as the Silfurstjarnan fish farm. The free-flowing 96 - 98°C water from the well is pumped towards Kópasker through a 4 ½-in. polybutylene pipeline, insulated with polyurethane and asphaltic paper cover, which can carry about 7 l/s. The initial part (1.2 km) of the pipeline is not insulated to reduce the temperature, which is slightly too high for the polybutylene. On the way, the water cools to 79 - 82°C; but, at Silfurstjarnan, it arrives 88 - 90°C warm. Due to its salinity (Table 1), plate heat exchangers are necessary to avoid corrosion in the radiators. The second phase will include a pipeline south, to the school village at Lundur, farms close by, and further south towards Ásbyrgi (Figure 1).

THE SILFURSTJARNAN FISH FARM

The Silfurstjarnan fish farm is a land-based system where fish are reared in a number of individual tanks of various sizes. Construction began during the autumn of 1988. Building of the fish tanks was more or less completed a year later. A small hatchery for arctic char was built elsewhere in Öxarfjördur in the same year. At the hatchery, artesian cold and hot waters from springs or drill holes are used. The temperature can be adjusted to increase or reduce the fish growth, which is important in order to secure delivery of the same size fish product throughout the year. Early on, the company hired an additional hatchery for salmon in S-Iceland with similar conditions. Now, the salmon smolt is bought from Stofnfiskur Ltd., where a breeding research programme based on Norwegian stocks has produced the best salmon stock in Iceland for fish farming. The main fish farm now consists of the following utilities (Figure 3):

Freshwater supply
Warm water supply
Oxygenation system
Effluent/filtering system
Monitoring/control and alarm system
Fish handling and grading system
Seawater supply
Aeration system
Tank rearing system
Feeding system
Electrical supply and emergency back-up system
Fish processing and packing plant

Water is pumped from the boreholes by downhole submersed pumps of 80 - 300 l/s capacity. Seawater is pumped by standard horizontal centrifugal pumps of 125 l/s each. Pumping head is variable, generally in the range of 20 -30 m. Presently, about 700 l/s of seawater are mixed with about 700 - 800 l/s of cold groundwater and 100 - 200 l/s of warm water, yielding a total of 1500 - 1600 l/s (5400 - 5700 m^3/h) for the main fish farm of the Silfurstjarnan Ltd. in Öxarfjördur. Electricity cost is high; at present, about 800 kW are required. The fish farm is equipped with two reserve diesel engines, both with the capacity to produce 750 kW in case of electrical failure.

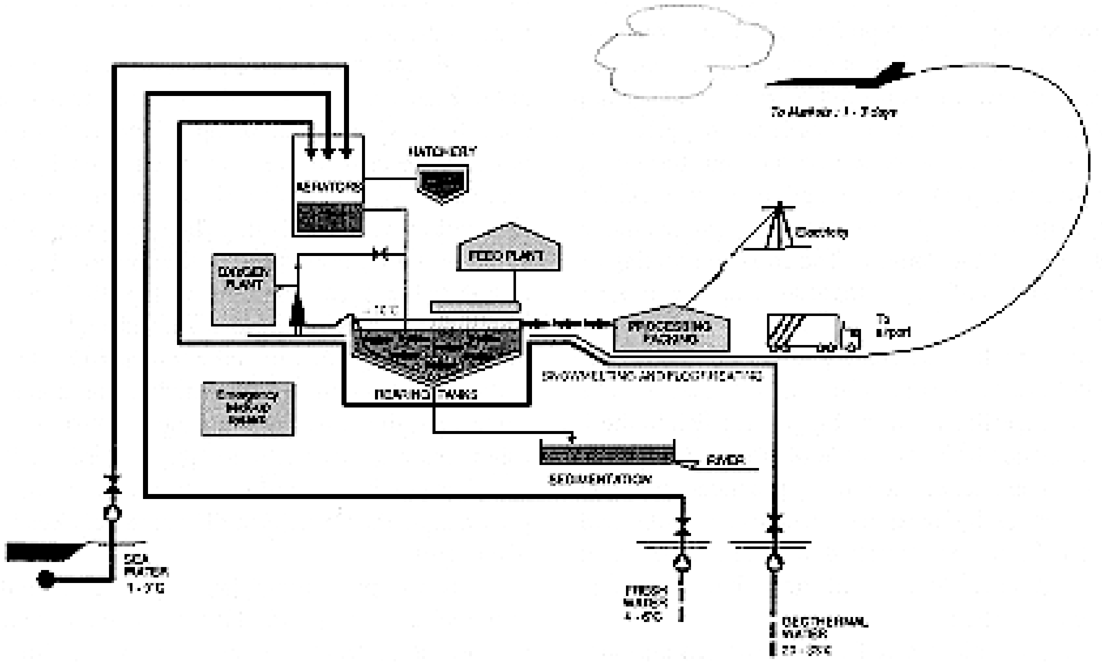


Figure 3. A schematic diagram of the Silfurstjarnan Ltd. Fish farm in Öxarfjördur, NE-Iceland.

Whereas, only about 10% of the water resources are of geothermal origin, a cascaded usage of the warm water is of interest. The hottest water (35 - 37ºC) is first used for domestic heating in the floors of the fish farm. For heating the houses, only a minor addition of heat from external sources is required, now provided by geothermal water from well AE-3. The hot water pipes then extend into a dense pipeline network in concrete pavement between the outdoor fish tanks, where it serves for snow-melting before being mixed with the water used for the fish.

Water is connected to the farm through several mains, made of PEH plastic pipes. On arrival to the farm, the three basic water types (cold/fresh, warm/geothermal and cold/sea water) are mixed in different ways to suit the different fish sizes/types. Before the mixtures are admitted to the tanks, de-aeration/aeration takes place in order to equalize nitrogen, which otherwise would reach supersaturation due to the mixing with warm water. Nitrogen in supersaturation may kill fish. Following de-aeration, water flows by gravity to the tanks. Flow rate to each tank is adjusted by valves to suit the respective biomass; this being primarily governed by the oxygen needs, but also by other factors such as CO_2 level, self-rinsing of fish excrements and food leftovers, suitable water velocities for proper swimming exercise, etc.

In nature, fish is generally offered oxygen saturated waters. In tank farming, this is not possible, and certainly not without separate oxygenation. Since oxygen is the key factor, total water pumping can be reduced if oxygen levels, and thereby, reducing stress which again improves fish health and growth rate. The oxygen is partially produced on site by molecular sieves and partially bought liquified in bottles. The oxygen generating plant has a total capacity of 70.8 Nm^3/h. The oxygen is introduced to the tank water mainly by pressure injection in the water supply prior to admittance to the tank. The principle behind is the following. The pressure on part of the water to the tank is increased by sending the water through a narrow port by an extra pump. The 2-in. port is at a top of a fiberglass cone with a 1.2-m diameter at the bottom. The water is released into the cone and oxygen blended into it at the top. With the pressure fail the water and oxygen mix. The water is then led from the cone into the tank through a 110-mm plastic pipe with a minimum length of 18 m to ensure complete mixing. In some of the smaller tanks, the oxygen is introduced by defusers at the bottom. The complete mixing of the oxygen in the water is of major importance for the optimal growth of the fish.

The tanks are circular, different in diameter and depth, from few m^3 in volume up to some 1500 m^3, the smaller tanks generally used for fingerlings and the biggest for fish in the 1 - 5 kg size. The smaller tanks are made of fiberglass; whereas, the bigger ones are assembled from precasted concrete elements, held together by tensional steel cable girths and surrounding soil (Figure 4). Installed fish tank capacity at present is about 15,000 m^3 in the mail plant; but, additional tanks are under construction.

By introducing the inlet water from the oxygen injectors in a tangential direction and at variable rates with depth, water movement is optimized in order to provide a suitable swimming velocity and also a self-rinsing effect, where the bottom velocity is high enough as to sweep fish excrements towards the centrally located outlet, without stirring up the water. Tank effluent flows by gravity through traditional sewage piping system towards a settling pond, where the bulk of fish excrements and food leftovers settle for periodic removal. From the settling pond, effluent is channeled to the nearby Jökulsá glacial river.

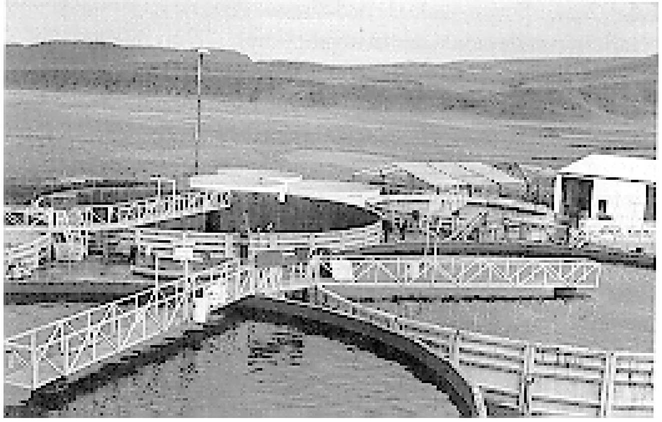


Figure 4. Some of the larger fish tanks at Silfurstjarnan fish farm (photo by G. Ó. Fridleifsson).

Fish feed, partly made on site from fish trash, fish oil, vitamins and binding agents, and partly purchased ready-made, is dispersed in the form of pellets over the water level. Pellet size is chosen to suit fish size. About 85% of the feeding is automatic through feeders programmed to feed the fish at proper rate and at selected times of the day. The remaining 15% is done by hand depending on the appetite of the fish, which varies with weather and daylight, preferably at sunrise and sunset. Thus, it is possible to maximize the growth rate of the fish and at the same time, decrease the feed waste and water pollution.

Fish are transported from the smaller tanks to the bigger ones as size increases, usually every two months. This is done by a special fish pump which is basically a pressure vessel connected to the tank in question by a flexible tube. The vessel is then subjected to vacuum; whereby, water and fish will eventually fill it. Then the process is reversed, the vessel is now pressurized, a suction valve closes and a discharge valve opens for flow in the discharge tube, through which the fish is piped to a second tank, generally passing through a fish grader, or if the time is right, towards the finals at the processing plant. The graders are connected directly to computers, thus ensuring automatic control on the fish growth. The tanks are cleaned thoroughly before smaller fish are put into them again. One of the advantages of the 90ºC hot water provided by the Öxarfjördur Heating Services is in rinsing and disinfecting.

The fish processing plant is 450 m^2, including the offices of the Silfurstjarnan Ltd. Here the fish are slaughtered, gutted and processed (filet) for the needs of the different customers and packed with ice in styrofoam boxes before being sent to the markets. The ice is produced at the site.

Emergency alarms are connected to the most sensitive parameters for the fish to avoid accidents. Oxygen levels in the outlet water from each tank are monitored continuously, raising alarm if the values deviate out of present boundaries. Alarms are connected to the water system indicating if pumps go out. Every oxygen pressure injector is monitored continuously and the alarm is raised if it is not working properly. Finally, the temperature of the inlet water to the tanks is monitored raising alarm if it becomes too high.

THE PRODUCTION OF THE SILFURSTJARNAN LTD.

Two main species have been raised from the beginning: Atlantic salmon (Salmo Salar) and arctic char (Salvelinus Alpinus). The farming temperature is kept more or less constant the year around and accordingly, the demand for hot water diminishes during summers. The optimal temperature for salmon are at 8 - 10°C varying with size (Figure 5). The arctic char starts in colder water, 6°C, but is later on reared in the same 10°C water. It is worth mentioning that a small number of arctic char is kept in the tanks with the salmon (7% of the total fish number). In this form of cohabitation, the arctic charr lies at the bottom and lives mainly on leftover fish feed. Thus, the waste of fish feed is minimized. The salinity of the farming water is kept constant throughout the year at about 10 - 12 ppt (Figure 5), which is an increase from the 8 -10 ppt salinity used before. The increased salinity is one of the factors that has allowed steadily increased biomass per m^3. The process from hatch to the market takes 30 - 35 months. Average weight of the salmon product is now close to 4 kg gutted weight (gutted and in some cases, filet fish), and the arctic charr product is about 1 kg. Hitherto, the plant has been free of any kind of fish disease, which to some extent relates to the superb water quality for fish farming. So far, not a single dose of medicine has been used. The fish is slaughtered four times a week, about 50 weeks a year (Figure 6).

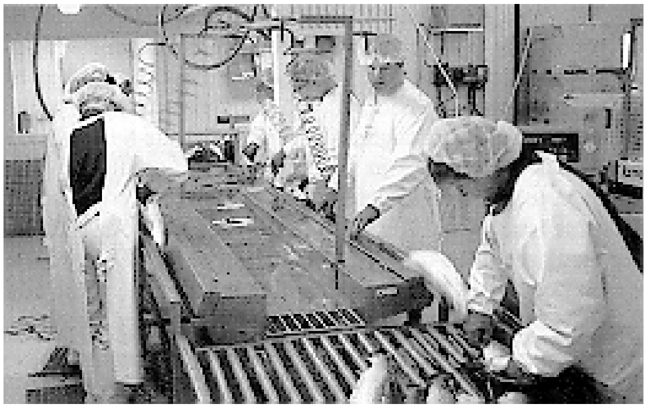
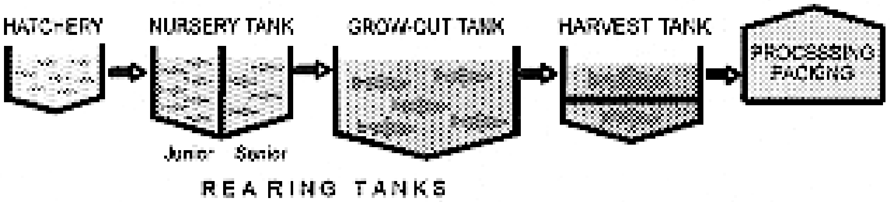


Figure 6. Slaughtering of fully grown salmon in the processing plant (photo by G. Ó. Fridlefsson).

Presently, the annual production is 900 - 950 tonnes or 50 - 60 kg/m^3, which is a record production. Of this, salmon is about 80%. The steadily increasing production strongly relates to the stability in rearing conditions that can be held due to the geothermal energy, which the siting of the fish farm was based on. Not only the temperature control, but also the purity of the groundwater and the salinity control are of fundamental importance to that can be added successful experiments in increasing the oxygen level in the farming water. These optimal growing conditions are manifested in various ways, such as the exceptionally high yield where only 1.05 kg of fish feed are needed to produce 1.00 kg of salmon. These figures do not include the arctic char kept with the salmon (about 2% of the fish weight in the tanks).



ARCTIC CHARR					1 kg
Temperature °C	6	10	10	9	
Salinity ‰	0	12	12	12	
Year	0.4	1.2	1.2	0.03	

SALMON					4 kg
Temperature °C	8	10	10	9	
Salinity ‰	0	12	12	12	
Year	0.5	1	1	0.03	

Figure 5. A schematic layout of conditions and fish growth at Silfurstjarnan Ltd.

Marketing is done by the company itself. About 90% of the product is exported, mainly as a fresh fish product; but, some is marketed smoked. Most of the customers make use of the fish farm's capability of delivering the same size of fish in similar quantity throughout the year. Despite fierce competition, this has resulted in fairly high prices for the product, which in turn directly relates to the use of geothermal water.

The transport of fresh fish to the markets in America and Europe needs to be quick, and therefore, most of the product is exported by air. From slaughtering in this remote fish farm in NE-Iceland to the markets, the iced and packed product is driven about 700 km by trucks overnight to Keflavik airport in SW-Iceland, to be air-freighted to the markets the same day. The whole process only requiring about 1.5 days, up to 3 days at the most.

FUTURE DEVELOPMENT

Products from the Silfurstjarnan fish farm have many advantages for its customers. The biggest salmon producers today are the Norwegians where fish farming is based on pen-rearing. The ever increasing competition has led to prices being at a minimum to be able to pay off investment costs. Construction is now underway on additional fish tanks with a capacity of about 6,000 m^3. With their completion in July 1997, the annual production is scheduled to increase to 1,200 -1,300 tn. In these new tanks, the water from the older tanks will be reused. Results of experiments show that by filtering food particles from the water, full production capacity can be kept by mixing it with some new water. The amount of re-used water needs to be kept below 80%, else the growth rate can only be kept up with addition of chemicals which would be against the principles of the Silfurstjarnan fish farm. The increased production will definitely help the Silfurstjarnan fish farm towards economical stability as it is to a large extent based on existing investment.

The Silfurstjarnan Ltd. has always been ready to participate in development of new methods for fish farming. One of these projects, in cooperation with several partners, was an experiment with CO_2 exhaust system with the purpose of increasing the live mass per m^3. This is of fundamental importance, as each ton of live mass at each time results in 2 tons production at each time. The results were not up to expectations. However, they provided vital information that led to the ongoing plans for the expansion of the fish farm.

Experiments on growing rainbow trout (Salmo Gairdneri) are now done at the hired Arlax hatchery in the South-Öxarfjördur region. This hatchery uses local 12 - 14°C warm groundwater for breeding. Breeding of arctic charr there did not prove economical due to high content of protozoan ectoparasites in these relatively warm waters, resulting in slow growth. However, the first results of the new breeding programme indicate that this water is good for breeding of rainbow trout, at low costs.

Further experiments are on the drawing table. One of them is the development of an advanced control equipment for oxygen. The oxygen use of the fish is quite variable, and to some extent, associated with the feeding. The idea is that by precise monitoring of the outlet water from the tanks, the oxygen injection into the inlet water can be optimized, which is very feasible economically.

Another experiment involves adding sea bass (Dicentranchus Labrax) into the breeding programme. The sea bass requires about 23 - 24°C water. It is adaptable to very variable salinity though about 50% of seawater salinity is preferred. It will be located at the start of the breeding programme, using mainly the brackish warm water, before it is used for the salmon and arctic charr. At optimal conditions, the growth rate of the sea bass is about double that of salmon and the current prices are about 70 - 80% higher. Experiments on this will start in 1997. Thus, rainbow trout and sea bass may become important products of the Silfurstjarnan Ltd. in the future.

ACKNOWLEDGEMENTS

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GEOTHERMAL TRAINING IN ICELAND 1979-1996

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INTRODUCTION

The Geothermal Training Programme of the United Nations University (UNU) was established in Iceland in 1979. Since then, a group of scientists and engineers from energy agencies and research organizations, and in a few instances, universities in the developing countries, have come to Iceland every spring to spend six months in high-specialized studies and on-the-job training in geothermal science and engineering. All of them are university graduates with practical experience in geothermal work in their home countries. The training is tailor-made to the individual and the needs of his institution/country. In all, 181 participants from 33 countries completed the six-month course during 1979-1996. Table 1 shows the number of participants per country and the specialized courses they have taken during 1979-1996.

The Training Programme operates within the Geothermal Division of Orkustofnun, the National Energy Authority (NEA) of Iceland. It is academically governed by a Studies Board, which is composed of experts responsible for each of the eight specialized courses that are offered, and a chairman who is the director of the Training Programme. The present members of the Studies Board are Kristjan Saemundsson (Geological Exploration), Hjalti Franzson (Borehole Geology), Olafur Flovenz (Geophysical Exploration), Benedikt Steingrimsson (Borehole Geophysics), and Sverrir Thorhallssson (Drilling Technology) from the NEA; Stefan Armorsson (Chemistry of Thermal Fluids) and Valdimar K. Jonsson (Geothermal Utilization) from the University of Iceland, and Snorri Pall Kjaran (Reservoir Engineering) from the Vatnaskil Consulting Engineers Ltd. Ingvar Birgir Fridleifsson has been the director of the Training Programme from the beginning except for one training season in 1981 when Hjalti Franzson served as director, and three training sessions in 1986-1988 when Jon Steinar Gudmundsson served as director. Ludvik S. Georgsson has been the deputy-director since 1990.

The NEA became an Associated Institution of the UNU in 1979. It is the only Associated Institution of the UNU offering training in geothermal energy science and technology. The cost of the operations of the Training Programme in Reykjavik is shared by the Government of Iceland (80%) and the United Nations University (20%). The Icelandic contribution is a part of the development aid of the Government of Iceland. There is a great demand for the type of specialized training offered. It is, therefore, planned to continue with the same type of training in the near future.

THE TRAINING

The approximate time schedule of the Training Programme is shown in Table 2. The duration is 6 months. In general, all participants are expected to attend an introductory lecture course that last 4-5 weeks (three lectures and a practical each day). The aim of the lecture course is to provide a background knowledge on most aspects of geothermal energy resources and technology, and to generate an appreciation for the inter-relationship between the various disciplines necessary in geothermal projects from the initial exploration to the stages of implementation and utilization. Participants have to take two written tests during the introductory lecture course. The lecture course is followed by practical training in a specialized field and the execution of a research project that is concluded with an extensive project report. Study tours are arranged to all the main geothermal fields under exploration and utilization in Iceland.

All participants receive training in using PC-computers for word processing and interpretation of data. Experience has shown that most trainees have access to PC-computers at home, and they can take their diskettes home and continue to work there. Thus, there has been a considerable transfer of computer technology from Reykjavik to geothermal institutions in the developing countries. Participants having access to large computers at home are allowed to work on the main frame computer at the NEA.

The main emphasis of the training is to provide the participants with sufficient understanding and practical experience to permit the independent execution of projects within a selected discipline in their home countries. Eight specialized lines of training are offered (Table 2). Each participant is meant to follow only one line of training; but within each line, there is considerable flexibility. A significant part of the practical training is done in connection with the research projects of the Fellows. In many cases, the participants bring with them data from geothermal projects in their home countries; but sometimes, the research projects are integrated with geothermal exploration or utilization projects that are in progress in Iceland at the time of training. The project topic is always selected with respect to the conditions of the home country of the participant. Many of the project reports are written in such a way that they serve as manuals for performing certain measurements or interpretations dealt with in respective reports. All the project reports are published by the Training Programme. Copies can be obtained upon request. The reports are mailed regularly to many of the

Table 1. Participation in the UNU Geothermal Training Programme in Iceland, 1979-1996

Country	Geological Exploration	Borehole Geology	Geophysical Exploration	Borehole Geophysics	Reservoir Engineering	Chemistry of Thermal Fluids	Geothermal Utilization	Drilling Technology	Total
Algeria	1					1	1		3
Bulgaria				1	2	2			5
Burundi	1								1
Costa Rica	1	1	2		1		1		6
China		3	1	2	10	6	9	1	32
Djbouti		1							1
Egypt		1			1	1			3
El Salvador	1	1	1	2	3			2	10
Ethiopia		1	2	1	2	2	1	1	10
Greece			1				2		3
Guatemala			1				1		2
Honduras		1	1						2
Indonesia		3	3	2	2			1	11
Iran	1								1
Jordan				1	1				2
Kenya	1	4	7		3	4	1	2	22
Lithuania							1		1
Macedonia						1			1
Mexico	1		1		2				4
Nepal						1	1		2
Nicaragua					3	1			4
Pakistan	1								1
Philippines		3	3	4	7	5	3		25
Poland		1			2				3
Romania							4		4
Russia				1					1
Serbia				1	1	1			3
Slovakia				1	1				2
Tanzania	1								1
Thailand		1		2		1	1		5
Turkey		1			1		1		3
Uganda	2	1	1			1			5
Viet Nam					1	1			2
Total	11	23	24	18	42	29	26	7	181

Table 2. UNU Geothermal Training Programme in Iceland

Week	Geological Exploration	Borehole Geology	Geophysical Exploration	Borehole Geophysics	Reservoir Engineering	Chemistry of Thermal Fluids	Geothermal Utilization	Drilling Technology	Week
1 2 3 4 5	Lecture course on all main aspects of goethermal energy exploration and utilization, practicals and short field excursions								1 2 3 4 5
6 7	Field Geology Maps and Photos	Drilling Petrological logging	Theoretical studies	Course on well logging and reservoir engineering		Sampling of fluids and gas Scaling and corrosion		Drilling equipment Drilling procedures	6 7
8 9 10	Structure analysis Hydrogeology		Field Work	Logging and well test practises Data analysis Reservoir properties Well performance Reservoir simulation		Analytical methods Thermdynamics	Course on heat transfer and fluid flow	Safety Well design Management	8 9 10
11 12	Excursion to the main geothermal fields of Iceland								11 12
13 14 15 16	Field work in deeply eroded strata and recent volcanic fields	Alteration mineralogy Aquifers Modeling	Data processing techniques and tools	Logging methods Data evaluation	Well testing Reservoir simulation Responses to exploitation	Chemical geothermometers Water rock interaction	Design of plants systems	Rig operations Cementing Completion	13 14 15 16
17 18 19 20 21 22 23 24 25 26	Project and Report	Project and Report	Project and Report	Project and Report	Project and Report	Project and Report	Project and Report	Project and Report	17 18 19 20 21 22 23 24 25 26

leading geothermal institutions in the developing countries. The titles of the reports from 1979-1984, 1985-1989, and 1990-1994 are listed by author in Fridleifsson (1985), Fridleifsson (1990) and Fridleifsson (1995) respectively. These lists also give the names of all participants who have completed the six-month course during 1979-1989.

THE SPECIALIZED COURSES

The geological exploration course offers practical training in basic geological mapping, which is commonly the first step in the geothermal exploration of an area. Participants analyze the geological structure of an area with regard to siting drill holes, both thermal gradient and production wells. Many of the participants have also been trained in mapping surface geothermal manifestations, including shallow temperature surveys and measurement of flow rates of springs. The field work is commonly conducted both in active geothermal and volcanic areas and in deeply eroded areas where the roots of extinct volcanoes and hydrothermal systems can be inspected. Participants should have a degree in geology.

The **borehole geology** course gives training in making geological logs, analyses of drill cuttings and cores, and in some cases, fluid inclusions. The identification of alteration minerals (microscope and x-ray diffraction) and the interpretation of the alteration mineralogy forms an integral part of the course. Many of the participants receive training in collecting and interpreting data on aquifers and in making geological models of geothermal reservoirs based on their own data and data from other disciplines. Participants should have a degree in geology.

The **geophysical exploration** course is for practical training in conducting geophysical surveys of geothermal areas and/or interpretation of such data. The essentials of heat flow surveys, magnetic and gravity surveys, as well as resistivity depth soundings and profiling are covered. During the latter half of the training, a selection can be made between further specialization in electric survey (Schlumberger, dipole, head-on profiling, TEM, MT, AMT, SP), magnetic surveys and gravity surveys. Emphasis is laid on the application of computers in the interpretation of geophysical data. Participants should have a degree in physics, geophysics or engineering.

The course in **borehole geophysics** covers the essentials of geophysical measurements in boreholes used for geothermal investigations, with the main emphasis on temperature and pressure measurements, but including lithology logs such as electrical resistivity, caliper, porosity and density logs, and well completion logs such as CCL, CBL, inclination and spinner logs. The participants undertake well measurements; but, most of the time is devoted to the interpretation of logging data. Participants should have a degree in physics, geophysics or engineering.

The **reservoir engineering** course covers the methodology needed to obtain information on the hydrological characteristics of geothermal reservoirs and to forecast the long-term response of the reservoirs to exploitation. Both surface and downhole measurements are considered and the interpretation of flow tests of wells, injection tests and interference tests. It is also possible to specialize in production engineering of geothermal fields. The course requires a sound background in mathematics. Participants should have a degree in engineering, physics, geophysics, mathematics or hydrogeology.

The course on **chemistry of thermal fluids** gives an insight into the role of thermal fluid chemistry in geothermal exploration and exploitation, including sampling, analysis of major constituents and the interpretation of results. Much emphasis is placed on the application of chemical thermometers and the calculation of mixing models. Environmental aspects of the thermal fluids are also considered. The participants need a solid background in chemistry. They should have a degree in chemistry, geochemistry or chemical engineering.

The course in **geothermal utilization** deals with the civil, mechanical and chemical engineering aspects of geothermal fluids in pipes, equipment and plants. The feasibility of projects and environmental factors are also considered. Due to the wide spectrum covered by geothermal engineering, the participants have to be very selective in their specialization. Most of the participants specialize in the design and/or feasibility studies of district heating systems and/or in the application of geothermal steam and water in industry. One specialization is the selection, installment and operation of downhole pumps in geothermal wells. Participants should have a degree in engineering.

The course in **drilling technology** provides engineers with the information and on-site training necessary to prepare them for the work of drilling engineers or supervisors. The course is thus, training in the planning and supervision of drilling and not in the task of drilling itself. The course deals with the selection of drilling equipment, the design of wells and casing programs, as well as cementing techniques. The cleaning and repairs of production wells is also covered. Participants should have a degree in engineering.

TEACHING MATERIAL

Most the teaching is done by tutorials and practical work where the teacher works with two or three trainees, and use is made of available textbooks and articles in journals as appropriate. In some instances, however, a special effort has been required to compile text material and manuals as teaching material for the training. Most of this work has been done by the regular teachers of the Training Programme, who are mostly staff members of the National Energy Authority and the University of Iceland. Some texts have also been written by visiting scholars from other countries. Some of the teaching material has been published in reports, and is available from the Training Programme. Examples include the texts on hydrogeology (Sigurdsson, 1987), geophysical exploration (Hersir and Bjornsson, 1991), geothermal logging (Kjaran and Eliasson, 1983), geothermal reservoir physics (Bodvarsson, 1987), geothermal district heating (Karlsson, 1982), direct use of geothermal energy (Lund, 1987 and 1996), and one dimensional inversion of Schlumberger resistivity soundings (Arnason and Hersir, 1988). This last report contains the description of a computer program, user's guide and a diskette for a PC-computer. A few of the teaching texts are already into their second and third edition.

One guest lecturer with an international reputation is invited every year as a UNU Visiting Lecturer to give a lecture series and to lead discussions with the trainees. The UNU Visiting Lecturers have stayed from about two weeks to two months in Reykjavik. The following have been UNU Visiting Lecturers:

1979	Donald E. White	USA
1980	Christopher Armstead	UK
1981	Derek H. Freeston	New Zealand
1982	Stanley H. Ward	USA
1983	Patrick Browne	New Zealand
1984	Enrico Barbier	Italy
1985	Bernardo Tolentino	Philippines
1986	Russel James	New Zealand
1987	Robert Harrison	UK
1988	Robert O. Fournier	USA
1989	Peter Ottlik	Hungary
1990	Andre Menjoz	France
1991	Wang Ji-yang	P.R. China
1992	Patrick Muffler	USA
1993	Zosimo F. Sarmiento	Philippines
1994	Ladislaus Rybach	Switzerland
1995	Gudmundur Bodvarsson	USA
1996	John W. Lund	USA

Most of the lecturers of the UNU Visiting Lecturers have been published by the Training Programme and are listed by author in Fridleifsson (1995). Some of these have served as important teaching material. Copies of the publications are available on request.

BUILDING OF SPECIALIST GROUPS AND EVALUATION

Table 1 lists the countries of origin of the participants during 1979-1996 and their specialized courses. The largest groups have come from three countries: China (32), Kenya (22), and the Philippines (25). Ten other countries have sent 4-10 participants. The aim of the UNU Geothermal Training Programme is to concentrate its training efforts so as to assist in building up groups of specialists in the geothermal departments of selected countries with significant geothermal potential. Priority for training is given to candidates from carefully selected institutions from developing countries where geothermal exploration and development is already underway. The limiting factor is, in some cases, the availability of sufficiently qualified staff in the recipient institutions. The fact that participants must speak English fluently has, for example, hampered participation from certain parts of the world such as Latin America.

Assessment of the training has mainly taken the form of interviews with former trainees and their directors. A representative of the Training Programme visits the main recipient countries every few years, and meetings are also arranged in connection with international geothermal conferences. Some changes have been made in the detailed contents of some of the specialized courses based on the feedback from the trainees and their institutions. But generally speaking, the fact that the training is tailor-made to the abilities of the individual and the needs of the recipient country/institution seems to have been very successful. The number of fully-qualified applicants each year is normally much greater than the number of scholarships available. All the participants are selected after private interviews with staff members of the Training Programme and on the recommendation of the recipient institutions. It is, therefore, not surprising that many of the former trainees have become the leading specialists in their countries in their given fields. Our records indicate that about 85% of all our trainees are still working in the geothermal sector.

SELECTION OF PARTICIPANTS

Specialized practical training is considerably more expensive than group training because of the high teacher-to-student ratio. On average, a full-time teacher takes care of three students during the intensive training. The total cost of training per student in Reykjavik (including international travel and per diem) is over US$ 30,000. Much care is, therefore, taken in selecting the participants. The selection procedures of the UNU are adhered to, which involve site visits by representatives of the Training Programme to the countries of potential candidates and personal interviews with all candidates. The potential role of geothermal energy, within the energy plans of the respective country is assessed, and an evaluation made of the institutional capacities in the field of geothermal research and utilization. Based on this, the training needs of the country are assessed and recipient institutions selected.

The candidates must have a university degree in science or engineering, a minimum of one-year practical experience in geothermal work, speak English fluently, and have a permanent position at a government energy company, research institution, or university. The directors of such institutions are invited to nominate candidates for training in the specialized fields that are considered most relevant to promote geothermal development in the respective country. Nominations, including the curriculum vitae of the candidates, should be sent to the Training Programme in Iceland. Training starts in late-April and ends in late-October each year. Nominations must be received in Reykjavik before 1st August each year for participation in the training staring the following year. Due to the high cost of international travel, site visits for interviewing candidates cannot be held in all requesting countries every year. Therefore, interviews are held in aheld in a given country for candidates for two or three years at a time. Participants from developing countries normally receive scholarships financed by the Government of Iceland and the UNU or UNDP that cover international travel, tuition fees and per diem in Iceland. The participants, therefore, do not need other funds for their training. Qualified participants from industrialized countries can also be accepted on condition that they obtain similar scholarships from their own institutions/countries.

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GEOTHERMAL STAMPS OF ICELAND

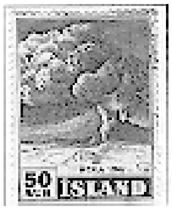
John W. Lund
Geo-Heat Center

Iceland, a leader in the use of geothermal energy, is also a leader in issuing stamps depicting various geothermal manifestations such as geysers, volcanic eruptions and methods of utilizing the energy. Some of the earlier issues were described and shown in Vol. 5, No. 1 (Lund, 1980). In my recent visit to Iceland as the visiting lecturer for the UNU geothermal program, I was able to collect some of the more current issues. A review of the older issues and most of the new ones are described and shown below.

In historical times, since AD 850-900, more than 250 volcanic eruptions have occurred in Iceland--an average of one every four years! Four volcanic events have had a major impact on Iceland, and are thus, reflected in many of their stamps: (1) Hekla, has erupted 20 times since Iceland was settled. The 1947 eruption, lasting 13 months, produced almost 800 million m^3 of lava and 210 million m^3 of tephra and sent falling ash as far away as Finland. (2) The Laki eruptions (Skaftareldur episode) in 1783 produced lava flows of 800 m^3 per second and resulted in 14 to 15 km^3 of volume covering almost 600 km^2. The gas and acid rain and the resulting pollution killed 50% of the domestic animals and 20% of the population in Moduhardindi (Haze Famine). (3) Surtsey Island, of the southwest coast, was first formed in 1963 from an underwater eruption along the mid-Atlantic spreading ridge. By 1967, an island of 2.7 km^2 had been formed. It is used for biological and geological research. (4) Heimaey, another one of the Westmann Islands (Vestmannaeyjar), was partially engulfed by an eruption from Eldfell volcano in 1973. Nearly 200 houses were burned by lava; however, the lava flow was stopped from closing the harbor by spraying it with seawater to slow its advance.

Finally, another volcanic phenomena that is world famous is Geysir, the geyser that once erupted to heights over 60 meters. It has been dormant for the past 30 years; but, the nearby Strokkur (the Churn), erupts every few minutes to the delight of tourists.

An example of the series (8 stamps) from 1938-47 showing the world famous Geysir from which we get the word geyser.



An example of the series (7 stamps) from 1948 showing the 1947 eruption of Hekla, lasting 13 months.

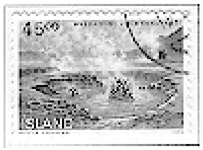
The formation of the island Sutsey--erupting from the Atlantic Ocean starting in 1963 (3 stamps).

The eruption on Heimaey January 23, 1973 (2 stamps).

Hot spring utilization (honoring sports and health).

Geothermal steam and valve (3 stamps).

Bicentenary of the Skaftareldar (Laki) volcanic eruption (1783) causing extensive devastation.



Hot spring and mud pot at Hverarönd near Namaskard (between Myvatn and the Krafla power plant).

Eruption of the geyser Strokkur (the Churn) next to the now dormant Geysir.

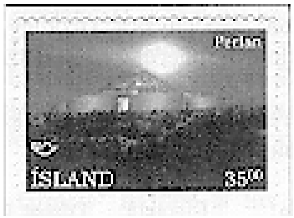
Painting of women washing clothes in Thvottalangar hot springs at Laugardalur (Reykjavik).

Another version of women washing clothes in Thvottalaugar (Washing Springs) at Laugardalur.

Based on Latin description of Irish monks (st. Brendon?) approaching Iceland in the 6th century seeing a volcano.

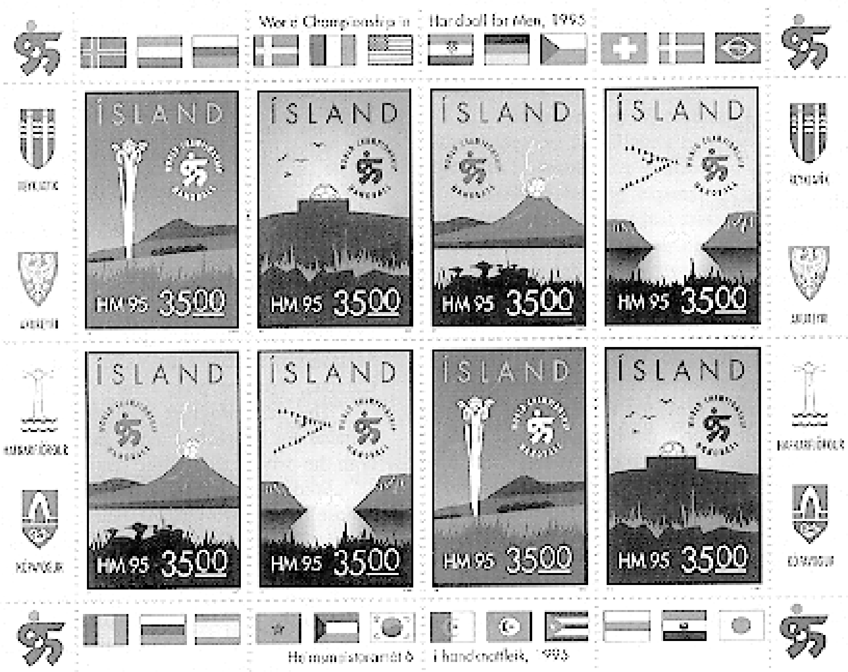
The following two stamps show recent tourist attractions associated with geothermal energy.

The Blue Lagoon, a swimming pond sealed with silica from the effluent of the Sudurnes heating facility.



The "Pearl" restaurant sitting on top of the four 1.2-million gal. hot water storage tanks used in the Reykjavik district heating system.

The next series were issued for the World Championship in Handball for men held in Iceland in 1995. Note the ball on top of the geyser, the "Pearl" and a volcano. The non-geothermal one shows the ball as the setting sun.



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GEOTHERMAL PIPELINE
Progress and Development Update
from the Geothermal Progress Monitor

MEETING ANNOUNCEMENTS

Eighteenth New Zealand Geothermal Workshop, 6-8 November 1996

The Geothermal Institute and the New Zealand Geothermal Association will host the 18th New Zealand Geothermal Workshop at the University of Auckland on 6-8 November 1996. The meeting will provide a forum to exchange information on all aspects of the exploration, development and use of geothermal resources worldwide. Topics will include:

- Exploration: Geophysics, Geology, Geochemistry, Site Investigation, Epithermal Mineralization
- Field Development: Drilling, Reservoir Engineering, Reinjection, Mineral Deposition
- Utilization: Electric, Direct-Use, Optimization, Environmental Consequences, Preventive Maintenance
- Applications: Materials, Standards, Environmental, Economic, Legal
- Case Studies: Geothermal Field or Plant--for example, Make-up Drilling and Reinjection Strategies

For more information contact:

Geothermal Institute
The University of Auckland
Private Bag 92019
Auckland, New Zealand
Fax: 64-9-373-7436

22nd Stanford Workshop on Geothermal Reservoir Engineering, 27-29 January 1997

The Stanford Geothermal Program will organize the workshop, whose aims are: to bring together engineers, scientists and managers involved in geothermal reservoir studies and developments, to provide a forum for the exchange of ideas on the exploration, development and use of geothermal resources, and to enable, promote and open reporting of progress. Topics to be covered will include:

- Case Studies: Reservoir Response to Production, Effects of Injection, Scaling Characteristics
- Engineering Techniques: Reservoir Stimulation, Empirical Methods, Well Tests, Tracers
- Field Management: Strategies for Exploitation, Injection, Scale Inhibition
- Exploration: Geophysics, Geochemistry, Geology, Heat Flow Studies, Outflows
- Drilling and Well Bore Flows: Well Stimulation, Bare Flow Modeling, Hydro-Fracturing, Scaling
- Low-Enthalpy Systems: Applications of Heat Pumps, Hot-Dry Rock Technology
- Geosciences: Application of Geophysics, Geochemistry, Thermodynamics and Fluid Mechanics

For more information contact:

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COLORADO

New San Luis Valley Aquaculture Training Program

The commemorative "signing of the lease" between the State Board of Community Colleges and Occupational Education and Mrs. Ilene O. Kerr occurred on Thursday, August 1, at Kerr's Aquafarm location in Colorado's beautiful San Luis Valley.

In addition to the lease signing, the unveiling of a new sign dedicated Kerr's aquafarm as the James G. Kerr Educational Center for the Advancement of Aquaculture, Agriculture, Wildlife, and Water Conservation in honor of Ilene's late husband.

The aquafarm will be used entirely for instructional and production purposes in the new Aquaculture Technician Program being offered for the first time this 1996 Fall Semester by the San Luis Valley Educational Center, Alamosa Campus, Trinidad State Junior College.

The new program will strive to address the growing demand for properly trained farm and hatchery technicians: both the private and public sectors.

Students currently enrolled in the new program may choose from a two-year Associate of Applied Science Degree or a 1-year Occupational Certificate upon successful completion of either program. The student will understand and be able to perform the duties and responsibilities as they relate to the propagation, feeding, care, transfer/harvest and sales of fish and other aquacultural products.

The Aquaculture Technician Program will be taught with a hands-on emphasis by utilizing a combination of classroom, lab/field and industry exposures.

Kerr's Aquafarm will provide the program with an excellent opportunity to introduce technology and to train students in the various types of culture practices and techniques currently employed in today's aquaculture industry.

The facilities at the farm include a geothermal well with a constant temperature of 97 degrees Fahrenheit for year-round fish production.

The artesian water resource, adjudicated for fish culture use, flows at a rate of 1,050 gallons per minute. The well supplies water to 30 acres of existing ponds, raceways, tanks and a greenhouse.

There is also a cold water well available on site. The nutrient enriched effluent from the fish farm is then reused to irrigate potatoes as well as award-winning Coor's Barley, which took first place at the Colorado State Fair last year.

In addition, the aquafarm and surrounding wetlands serve as a wildlife refuge for migratory geese, ducks, cranes and other waterfowl by providing habitat to sustain their seasonal activities and needs. This tremendous resource is now secured in a long-term lease to ensure all students will be involved in a rich educational experience.

For more information on the program, please contact: Aquaculture Technician Program, The San Luis Valley Educational Center at 1-800-411-8382. (Source: *Aquaculture News*, September 1996)

IDAHO

Fish and Alligator Ranching in Idaho

In the stifling, humid darkness, sweat pops out on your body. Through the murk all around you gleam the cold eyes of dozens of alligators. But this is not midnight in the Everglades. This is mid-afternoon in southern Idaho.

Though it might seem odd to be surrounded by alligators in rural Idaho, Leo Ray of Buhl finds it perfectly reasonable.

Leo is a commercial fish farmer. He studied under Dr. Howard Clemens, the dean of modern fish farming, at the University of Oklahoma. After completing his studies, he and his wife, Judith, opened their first fish farm in 1968, in California.

But when Leo visited the area around Buhl, on the Snake River, the hot artesian wells caught his interest. He thought that if all that pure, hot geothermal water could be mixed with cold surface water for an optimum temperature of 78° to 80° F, he could grow the finest fish around!

"Idaho is a desert," Leo quips, "and its most abundant resource is water. A fish is like a sponge, and absorbs the flavor of the water it's in."

If kept moving, water this pure would eliminate any off-flavors in fish.

In 1973, the Rays bought a hillside site on the bank of the Snake River, collected the water from eight artesian wells and began building a complicated series of concrete raceways and ditches cascading down the hillside. Although catfish had never been successfully raised in concrete raceways before, Leo did it.

Then he added tilapia, an Asian food fish, in raceways down the hill below the catfish. He branched out into trout at another site. Soon the family company--Fish Breeders of Idaho, Inc.--was turning out tons of fish a year, shipping them to Alaska, throughout the Pacific Northwest and even to Hawaii.

There was only one little problem.

When you raise hundreds of thousands of fish at a time, some will inevitably die, and others have to be culled out in the packing shed. What to do with these "mortalities" becomes a considerable headache. How do you dispose of all those dead fish?

The obvious answer--obvious to Leo, that is--was alligators. The big reptiles were already being farmed in Florida; but, he saw no reason he couldn't raise them in Idaho.

"What made it economical is that we had free food and free heat," he says. Last year he ordered a couple of hundred alligator hatchlings from Florida--at $25 to $28 a head--and built a sunken, circular pool, heated with flowing geothermal water, and with a domed roof made of spray-on insulation foam.

Florida "gator farmers" scoffed at his design. They recommended a rectangular structure, with square pens. So Leo built one of those and put more hatchlings in it. It turned out that the alligators actually did worse in a square pen. When spooked, they tend to pile up in the corners, like turkeys.

In Leo's round pit, the first batch of alligators--fed on a diet of cull fish--grew rapidly. At 18 months old, they weigh 50 pounds apiece and are six feet long--about the right size for commercial harvest for luxury leather products and meat for specialty restaurants.

But Leo is backing off on that. He says that it's because of the rising cost for alligator hatchlings; but, one suspects he might also be developing an affection for these scaly monsters.

Why keep buying expensive hatchlings, Leo explains reasonably, when he can just raise his first crop of 'gators to maturity, and start breeding his own? After all, alligators reach breeding age in only five to seven years, and the bigger they grow, the more waste fish they eat.

It's all economy of scale--or scaly economy.

So *now*, every day, Leo and his assistants visit the alligator pits with buckets of trout. The big alligators--thriving in the tropic heat of their circular den--continue to gorge and grow. And whenever someone enters the rectangular shed, the "small" gators--a mere two or three feet long--scramble out of the water expectantly, making a peculiar noise between a chirp and a croak, seizing thrown fish and wrestling each other for prize treats.

It's a scene straight out of the age of dinosaurs, and one Leo Ray watches with satisfaction.

After all, not every farmer can raise livestock like these. (Source: *Ruralite*, August 1996)

OREGON

Blowing Off Steam At Newberry Volcano

The decision by California Energy Co. to mothball its geothermal drilling operation at Newberry Crater is not only disappointing, it may be premature.

No one can blame the developers for being discouraged when two large-size production wells and two small-core test wells haven't yielded sufficient resources to support an economically viable plant.

But what California Energy learned about its leases by no means should foreclose further geothermal development in the Newberry Crater area.

The Newberry Volcano, in the Deschutes National Forest near Bend, has been toured by geologists for a quarter of a century as the Northwest's best hope for an economically-feasible geothermal plant.

In 1983, BPA contracted for a detailed assessment of geothermal power in the region and determined that 1,200 potentially hot sites existed. Ninety-nine sites were chosen as the most promising for further analysis. the Newberry site ranked No. 1.

The question that the Bonneville Power Administration, which pledged to buy 20 megawatts from the proposed 30-megawatt plant, should be asking is whether the developers looking for hot steam and rock fractures in precisely the right place.

The point of messing with geothermal energy at all is to establish its viability for the future. Most everyone in the energy business knows that geothermal energy today is not competitive with market prices for electricity.

In the current deregulated power market, in which natural gas seems to be getting cheaper by the day, the cost of geothermal is way off the charts.

So what to do?

BPA should encourage California Energy to reconsider its proposal to mothball the Newberry operation. Failing that, the agency should consider other proposals for the Newberry Crater area that are more promising.

The agency no doubt prefers a third option--getting out of the geothermal demonstration business altogether.

That may make a lot of sense to ratepayers for the rest of this century. But in the year 2010, when conventional thermal energy rates could be out of control, we could be very sorry we didn't give Newberry Crater more of a chance to blow off steam. (Source: *Oregonian*, September 6, 1996)

UTAH

Australian Red Claw Lobster Raised at Belmont Hot Springs, Utah

Near Fielding, Utah, north of Salt Lake City at the intersection of Interstates 84 and 15, Belmont Hot Springs is supplying heat to aquaculture ponds, a swimming pool, hot tubs and four homes. The 125° F hot spring, consisting of four big springs, produces 4000 gpm.

Red Claw Lobsters are raised in ten 60 ft x 20 ft and twenty 40 ft x 15 ft ponds and a channel 3/4 mile long, 50 ft wide and 10 ft deep maintained at 80° F. The lobsters are harvested at 1/4 in. to 9 in. in length and shipped live to various markets. In addition to the lobsters, the ponds also contain tropical fish.

A 200,000-gallon swimming pool and three 16 ft hot tubs are also supplied by the springs. Four homes utilize the geothermal water in a radiant-floor type heating system.

A unique application for one of the springs, which has a depth of 35 ft and a temperature of 92° F, is scuba diving during winter months from September through May. The spring is too hot to use during the summer months.

Owner and operator of the facility is Scott Holmgren, Belmont Hot Springs, Box 36, Fielding, UT 84311, Ph: 801-458-3200.