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.

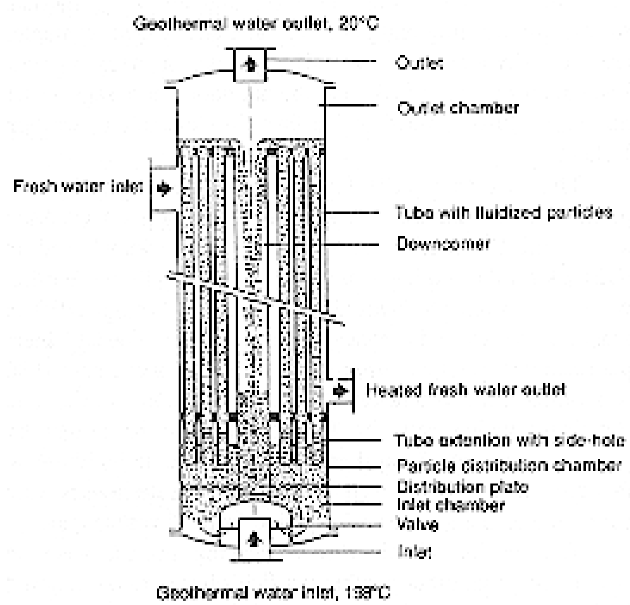

Figure 1. A schematic drawing of a "fluidized-bed heat exchanger" (FBHX).

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 86°C 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

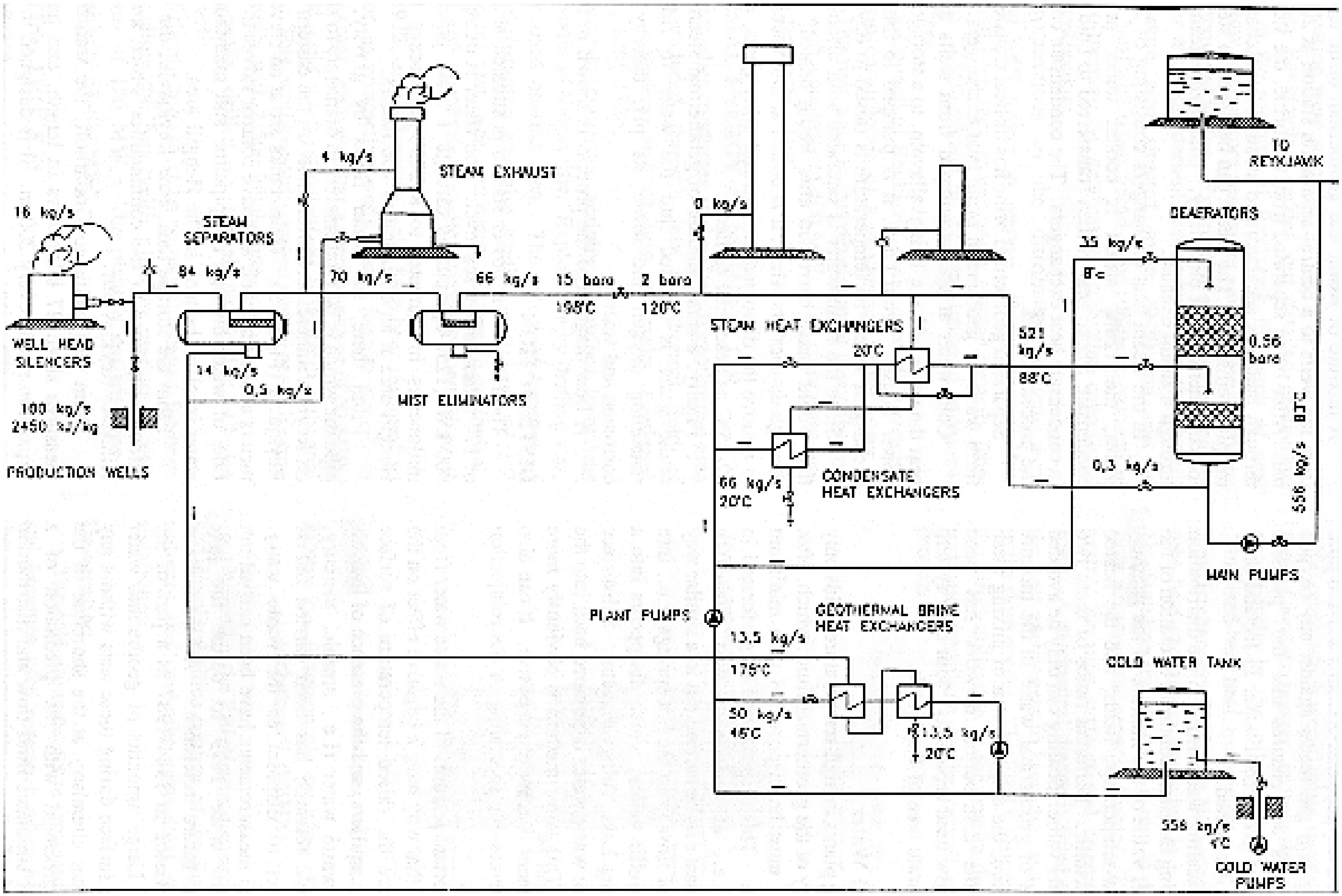

Figure 2. A flow diagram for the Nesjavellir power plant. The first phase is 100 MW_t.

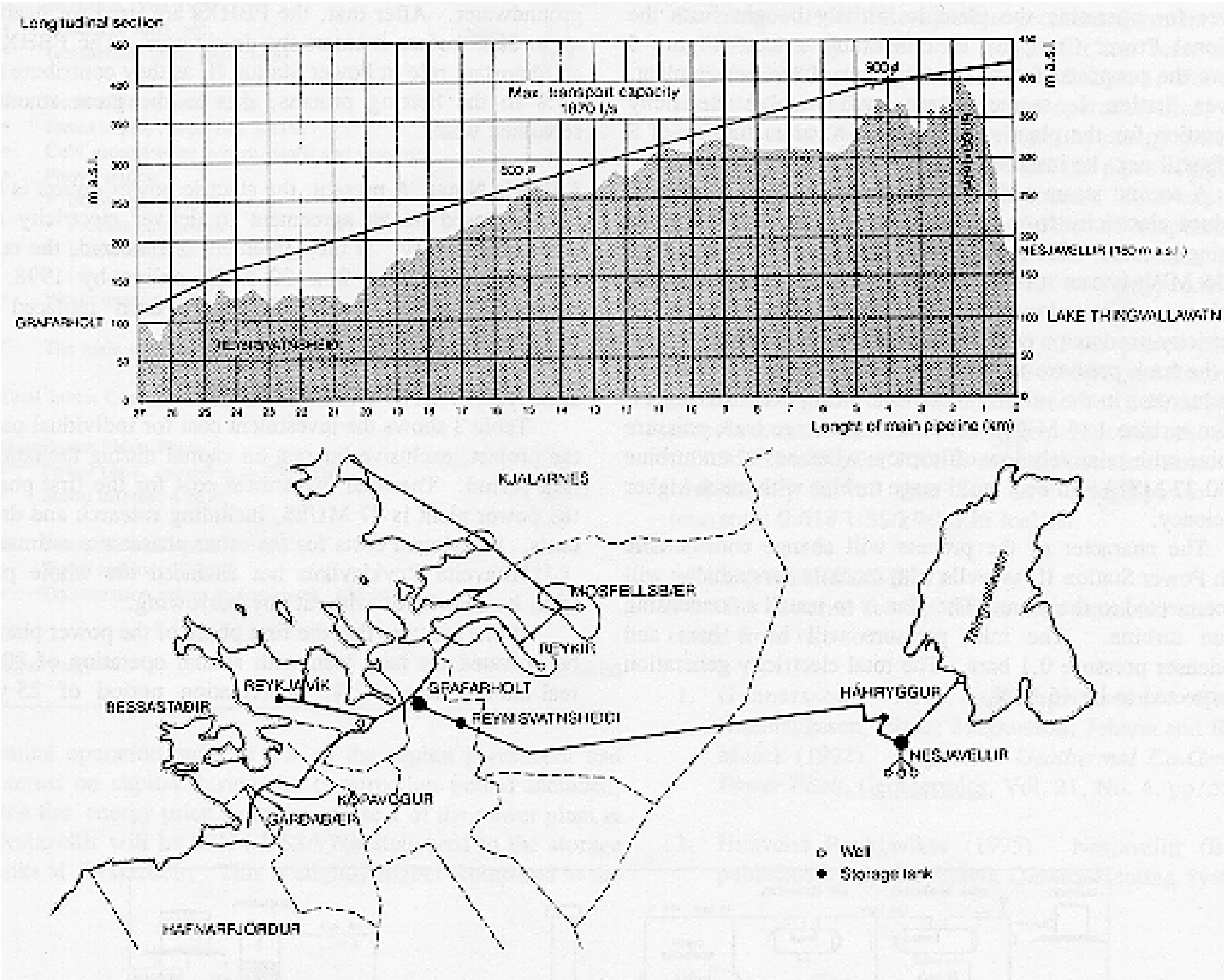

Figure 3. The hot water pipeline from Nesjavellir to Reykjavik.

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 $_{\mathrm{Mwe}}$.

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

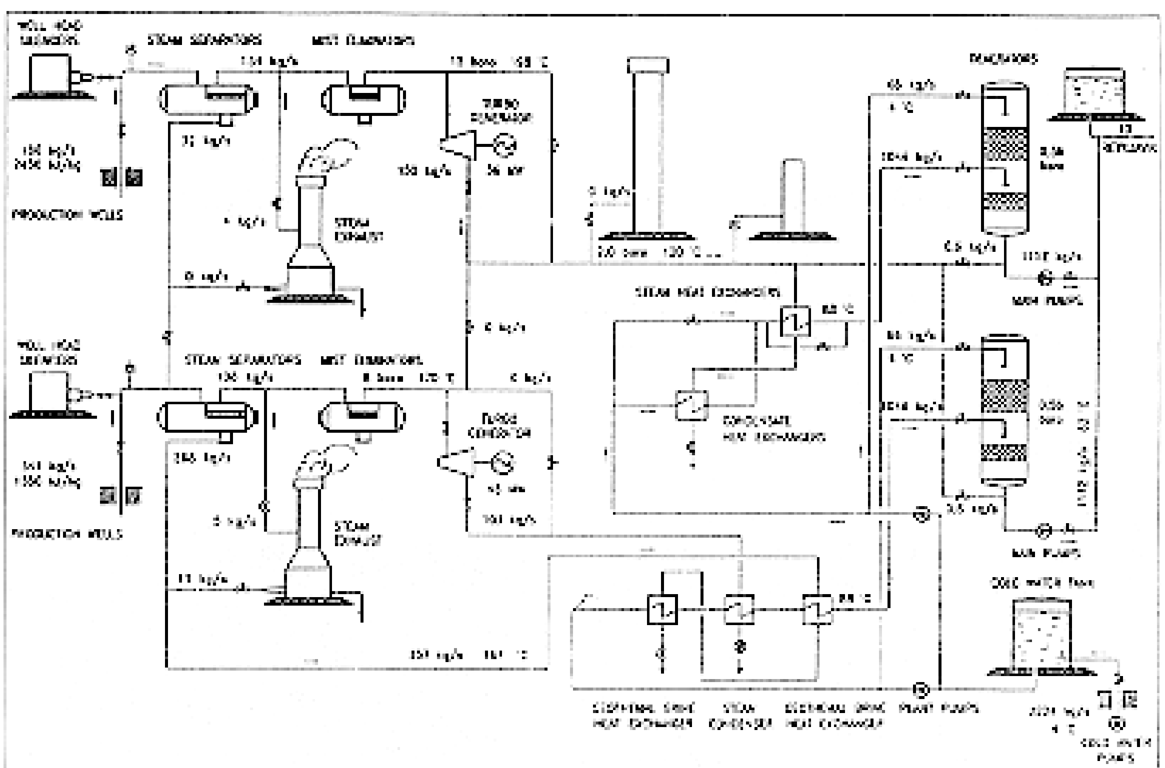

Figure 5. Flow diagram for the power plant fully developed to 400 MW_t.

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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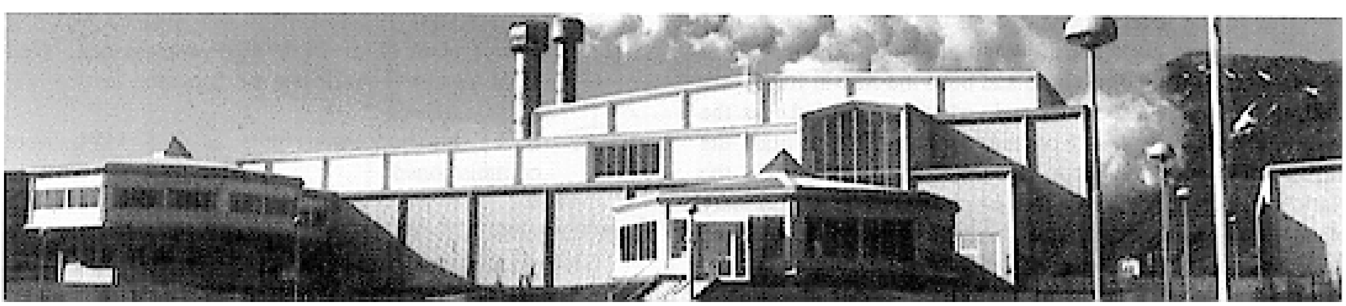

Figure 6. The Nesjavellir power station.