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STATUS OF GEOTHERMAL ELECTRIC POWER IN ICELAND 1980

J.S. Gudmundsson, S. Thórhallsson & K. Ragnars

Geothermal Division
Orkustofnun (Energy Authority)
Grensásvegur 9, Reykjavík, Iceland

INTRODUCTION

The main utilization of geothermal energy in Iceland is for thermal applications. There are many geothermal district heating systems that supply hot water to residential, commercial and industrial buildings. Geothermal water and steam are also used in greenhouses and for processing purposes in industry. The generation of geothermal electric power in Iceland is, however, limited because most of the electricity demand is met with hydro-power of which the country is relatively well endowed with. Until early this century, the use of geothermal energy in Iceland was limited to individual hot springs for bathing and washing. In 1928 drilling for geothermal energy in Iceland started. This was in a low-temperature field in Reykjavík where several shallow wells were drilled producing in total 15 l/s of 90-100°C water. Two years later in 1930 this water was piped 2.8 km to supply heating for about 70 homes, one school and a swimming pool. Since then great developments have taken place and now geothermal district heating plays a very important role in the economy of Iceland.

At about the same time as geothermal district heating was being introduced in Iceland, the generation of electric power using geothermal steam was already under discussion. In 1944 the first steam driven engine with a generator was installed in a high-temperature geothermal field in Iceland. This was near Hveragerdi, in the Hengill area, where several shallow boreholes had been drilled and were being used for various purposes. This first steam engine-generator was only run for a short time and produced sufficient electricity for just a few light bulbs. In 1946, also in Hveragerdi, the first steam turbine system was installed capable of generating 35 kW of electricity. This demonstration unit operated only for about one year until a much larger diesel generator was installed.

In this paper the development and status of geothermal electric power in Iceland will be discussed. Non-electrical applications will only be mentioned in passing.

RESOURCES

The geothermal areas in Iceland have traditionally been divided into low- and high-temperature areas. The high-temperature areas are in the active volcanic zone lying south-west to north-east across Iceland and the low-temperature areas on both sides of it. The two main low-temperature areas are in the south and west of Iceland at the periphery of the active volcanic zone, but other such areas are widely distributed. In the low-temperature areas the temperature of the reservoir fluid in the uppermost 100 m does generally not exceed 150°C while in the high-temperature areas it does and is usually 200°-350°C. It should be remembered that the water produced in low-temperature areas in Iceland is used in thermal applications only, being the back-bone of the district heating industry.

When it comes to the generation of geothermal electric power in Iceland, the high-temperature areas have to be used. There are 19 known high-temperature areas in Iceland and 9 potential areas. Figure 1 shows a map of Iceland and the location and name of these 28 high-temperature areas, most of which are within the active volcanic zone. Several geothermal assessment studies of the high-temperature areas have been conducted. The most comprehensive and recent is that of Pálmason (1981) and co-workers at Orkustofnun (Energy Authority). The study is based on the same methodology as used in the United States and Italy, but with several modifications to suit geological conditions in Iceland. The total size of all the high-temperature areas is about 600 km^2. An accessability factor of 0-1 was assigned to each of the 28 areas, the average value being about 0.6 for the 600 km^2. To arrive at an estimate of the electric power which the areas could possibly produce, it was assumed in the assessment study, that 20% of the accessable thermal energy of rock and water above 130°C down to a depth of 3 km is recoverable. This thermal energy is then converted to electricity with an efficiency of about 7-9% depending on the known or expected temperature of the fluids produced. It was estimated that 3,500 MW-electrical could be produced in total for a period of at least 50 years. About 3,000 MW-electrical would be in the 19 known high-temperature areas.

The hydro-power potential of Iceland has recently been up-dated by Tómasson (1981) and co-workers at Orkustofnun. The main result of this assessment is that the usable capability amounts to about 64 TWh/year with an associated installed capacity of 7,300 MW hydro-power. This usable electricity was divided into four groups that range from the most economical to marginal. In the decades to come the large hydro-schemes in the highlands (first group) will be most economic with a generating capability of about 30 TWh/year or almost 1/2 the total hydro-power potential of the country. The associated installed capacity corresponds to about 3,400 MW-electrical.

The total available geothermal electric power in Iceland may therefore amount to 3,500 MW for 50 years, while the hydro-power potential has been estimated more that double that value or 7,300 MW. When considering that hydro-power is more renewable than geothermal energy, which must also be viewed as higher risk technology, it seems most likely that the former will continue to supply the bulk of the electricity required in Iceland.

UTILIZATION

The energy market in Iceland is in many respects unusual when compared to many other countries. The main reason for this is the large amount of geothermal water sold for space heating purposes. In the last decade the percentage of Icelanders enjoying geothermal district heating has increased from about 40% to 70% (Gudmundsson 1976, Gudmundsson & Pálmason 1981). Another feature of the market is that for many years almost half the total energy consumption has been imported petroleum products, although the country has relatively great hydro-power and geothermal energy resources. Iceland is a sparsely populated country with about 230,000 people living in an area of 130,000 m^2. Most towns and villages are located on the coast with about half the population living in the south-west of the country in the Reykjavík area.

An overview will now be given of the electrical energy industry in Iceland in 1980. The total production of electricity amounted to 3,243 GWh of which 3,053 GWh or 97.2% was from hydro-power stations. Geothermal electric power stations produced 45 GWh (excluding own use) and oil-fired and diesel stations also 45 GWh. More that half the electricity was used in energy intensive industries and the rest for general purposes. At the end of 1980 the installed generating capacity of all public power stations was 670 MW of which 542 MW was hydro-power, 12 MW geothermal and 116 MW oil-oil-fired or diesel. The above geothermal value refers to the actual generating capacity but not the rated capacity at the end of the year (see later).

A few words about fuels imported to Iceland in 1980. The total fuel use amounted to 542,083 tonnes being 10.4% less than in 1979. Of this 43% was diesel fuel for fishing vessels mainly, but also for space heating, industrial use, transportation and the generation of electricity in small diesel stations. Heavy fuel was 32% being used for trawlers with large engines and also for industry. Gasoline for motor transport amounted to 16% while jet fuel, aviation gasoline and kerosene added up to 9%.

More details will now be given about the geothermal energy market in Iceland in 1980. Figure 2 shows the utilization of geothermal energy in Iceland. At the end of 1980, high-temperature geothermal energy was used in four areas in Iceland, excluding small experimental units. Table 1 shows these high-temperature geothermal areas and the main details. For each area there is shown the number of boreholes drilled and how many are capable of production. The thermal power is divided into installed and used. The former represents the maximum thermal power which the production boreholes are capable of delivering at present back pressures or lower. This thermal power is calculated on the basis of condensing all the steam and cooling the total borehole discharge (steam and water) to 100°C. The used thermal power, on the other hand, is the actual thermal power consumed in the relevant direct application. At Svartsengi it is the maximum thermal power consumed for space heating, in Hengill it is the thermal power used for space (10 MW) and greenhouse (15 MW) heating in Hveragerdi, while the Námafjall application is for industrial drying. The last column in Table 1 shows the rated (or name-plate) capacity of the 3 geothermal electric power stations in Iceland. The geothermal steam used for these power plants is included in the installed thermal power shown in the table.

It is of interest to estimate the thermal power associated with all direct applications in Iceland. Gudmundsson & Pálmason (1981) have reported the utilization of low-temperature geothermal fluids in Iceland and the rest of the world. Experience in Iceland shows that low-temperature waters used for space heating are discharged at 35-40°C on average. Table 2 shows the total thermal power used in direct applications from low- and high-temperature geothermal areas in Iceland in 1980. The reference temperature is taken as 35°C, amounting to 818 MW-thermal. The steam used in electric power generation is not included in this tabulation. The main use is space heating, being 85% of the total. Assuming a load factor of 50% the amount of thermal energy used in direct applications becomes about 13,000 TJ or 3,600 GWh in 1980.

DEVELOPMENT

Extensive geothermal studies and drilling were carried out in the 1950's in the Hengill and Krísuvík high-temperature geothermal areas in the south-west of Iceland. In 1950 a pre-feasibility study had been carried out for a 30 MW geothermal electric power plant to be located near the town of Hveragerdi in the Hengill area. It was estimated that the geothermal electricity would cost 40-50% more to produce than in a similar sized hydro-power station. Subsequently it was decided to build a second hydro-power station in the river Sog to serve the electricity market of the south-west of Iceland, particularly Reykjavík.

Great advancement was made in the exploration and exploitation of geothermal energy in 1958 when a rotary drilling rig, with a depth capability of 2000 m, was brought to Iceland. In the years that followed it was e.g. used to drill 8 boreholes 800-1200 m deep near Hveragerdi. By 1961 the project design of a 15 MW (net output) geothermal electric power plant was completed (Einarsson 1961). It was concluded that the capital cost per installed kW was similar to that of hydro-power stations in Iceland of under 40 MW in output. The generation cost of electricity from both types of stations was considered comparable. These plans to build a small geothermal power station were pushed aside in 1965-1966 when it was decided to build a 210 MW hydro-power plant at Búrfell in the river Thjórsá. Simultaneously an agreement was signed with an international aluminium company to build a large smelter not far from Reykjavík. Further work on the Hveragerdi project was abandoned. Additional reasons for the lack of interest in the Hveragerdi scheme, were problems of both geothermal and technical nature. The enthalpy of the steam-water mixture produced in the boreholes was rather low, corresponding to a reservoir temperature of about 215°C. This meant that a large quantity of steam and water had to be produced to generate the electricity, resulting in a disposal problem. This, and expected calcium carbonate deposition in the boreholes, did not favour building a power plant near Hveragerdi. The interest in geothermal electric power in Iceland was, however, aroused again when temperatures of 260-280°C were encountered when drilling in the Námafjall high-temperature area 1965-1966.

There are now 3 geothermal electric power plants in Iceland. These are at Námafjall and Krafla in the north-east and at Svartsengi in the south-west. The Námafjall and Krafla stations are not far from each other, only 7-8 km. The Svartsengi station is on the Reykjanes peninsula where there are several high-temperature areas.

NÁMAFJALL

The development of the Námafjall high-temperature area has been described by Ragnars et al. (1970). Drilling in the west section of the Námafjall area was started in 1963 and in 1966 the first production well was drilled. It supplied steam to the diatomite processing and drying plant that was commissioned in late 1967. At that time a pre-feasibility study indicated, that building a 5-10 MW non-condensing geothermal electric power station in Námafjall, would be an attractive way of meeting the increased load in the north-east part of Iceland, in smaller steps than would be economically feasible in hydro-power stations. An important consideration at that time was also the felt need of gaining experience in operating a geothermal electric power plant. In 1968 it was decided to build a small atmospheric exhaust plant in Námafjall and in 1969 it became operational. By 1971 enough steam had been secured for both the power plant and the diatomite plant and then onwards the Námafjall station was in full operation.

The main technical specifications of the Námafjall (and Krafla and Svartsengi) geothermal electric power station are presented in Table 3. The turbine-alternator is a British Thompson Houston (BTH) industrial set built in 1932. It was bought second-hand, but some alterations were made on it in 1968 when it was installed. The steam turbine itself is of the simplest possible type with one Curtis wheel. In 1971 the wheel was replaced with a new one to increase the output and to change the material of construction to make it more suitable for geothermal steam. The rated capacity is now 3 MW and the material used 12-14% Cr-steel. Every year some silica deposits have to be cleaned from the inlet nozzles of the steam turbine. This has been caused by some carry-over of water from the steam-water separators. After almost a decade of operation, the condition of the steam turbine at Námafjall is good. There has been some pitting corrosion and erosion of the first row of blades, but not serious.

Ten boreholes had been drilled in Námafjall by the end of 1975. They ranged in depth from 340 to 1800 m and were spaced at about 100 m apart. At that time wells 4-9 were productive. In 1979-1980 two more boreholes were drilled. By then most of the older boreholes had been destroyed due to tectonic activity. It appears that magma from the fissure swarm extending from Krafla to Námafjall caused the increased surface activity. At the end of 1980 two new wells (11 and 12) produced high-pressure steam for the diatomite plant and the Námafjall power station. Borehole 11 produced 29 kg/s at 19 bar-g pressure of steam-water mixture with an enthalpy of 2400 kJ/kg. Borehole 12 produced 22 kg/s at 16 bar-g pressure of steam-water mixture with an enthalpy of 2300 kJ/kg. Borehole 4 is the only old well that still produces. In total it is capable of producing about 10 kg/s of steam-water at enthalpy close to 1000 kJ/kg. The steam from this borehole is used to heat directly fresh water for district heating in the Reykjahlíd village by Lake Mývatn. Table 4 shows the estimated gas composition of the saturated steam produced from borehole 11 in Námafjall (N-11) when allowed to flash down to 180°C or 10 bar-g pressure. The total gas content is estimated as 0.2% by weight.

The steam-water mixture from the boreholes is piped in two-phase flow to two cyclonic separators. These have (safety) valves that are adjusted to open if the pressure increases above the operating pressure of 11-12 bar-g. In this way the excess steam produced is vented to the atmosphere. The separated water is discharged to concrete silencers and to a surface pond where it percolates into the ground.

KRAFLA

The Krafla Power Station is the first major geothermal electric power project in Iceland. Exploration of the Krafla high-temperature area was initiated in 1970. This work was not done with any specific utilization in mind, but in 1972 a preliminary project report was published by Orkustofnun on the feasibility of constructing a 8 MW, 12 MW or 16 MW geothermal electric power plant in either Námafjall or Krafla. The results were considered sufficiently encouraging to warrant further study and in 1973 a feasibility report was again published by Orkustofnun on the above sized stations and also a 55 MW station.

By late 1973 it was considered that the electricity supply situation in north-east Iceland would shortly become critical because a planned hydro-power scheme in the river Laxá had to be restricted for environmental reasons. The preliminary and tentative plans for a geothermal electric power station in Námafjall or Krafla were therefore suddenly the subject of great interest. In 1974 the construction of a 55 MW power plant to be located in Námafjall or Krafla was authorized and an ad-hoc committee was formed by the Ministry for Industry (and energy), known as the Krafla Project Executive Committee. The committee was to be responsible for the construction of the power plant, while the State Geothermal Steam Supply at Orkustofnun was to develop the field and produce the steam. The State Electric Power Works were given the responsibility of building the switchyard and the 132 kV transmission line to the town Akureyri. Formally, all the organization involved reported to the Ministry for Industry. The events that followed developed differently than imagined and the Krafla geothermal power project became one of the most controversial issuesin Iceland for years.

The first issue that had to be resolved was to decide where to build the power plant. The Námafjall area was already well known, but no drilling had yet been done in Krafla. The State Drilling Contractors at Orkustofnun were contracted to drill two 1200 m deep exploration boreholes in 1974 and the Geothermal Division of Orkustofnun was engaged to carry out the geoscientific work. In 1975 the Geothermal Division reported on the exploration drilling and concluded that the Krafla geothermal field would be able to produce the required amount of steam for a 50-60 MW power station. Because the Krafla geothermal area is much larger than Námafjall area, the former was favoured as the site for the power plant. It was also the view of the Environmental Protection Board of Iceland that the Krafla site would be a better choice. It was subsequently decided to build the proposed power station in Krafla. Reporting the drilling history and exploration of the Krafla geothermal field requires more space than is available here. Stefánsson (1981) has made a report on the development and status of the project in late 1978. Stefánsson & Benediktsson (1980) have also reported on the geothermal fields in Krafla and Námafjall. Three boreholes (1300-200 m deep) were drilled in the summer of 1975, six (1300-2200 m deep) in 1976, one (2200 m deep) in 1978 and three (2000-2100 m deep) in 1980.

The power station in Krafla was built by the Krafla Project Executive Committee. Table 3 shows the main technical specifications of the station. The station was to have two 30 MW turbine-generators, but only one of them has been installed. The station has never operated on full load because sufficient high-pressure steam has not been available. Its maximum load was initally 6-8 MW but has now reached 11-12 MW. Elíasson et al. (1980) have reported in detail about the Krafla Power Station. The station was commissioned in early 1978.

The flow diagram for the one 30 MW unit of the Krafla Power Station is shown in Figure 3. The steam-water flow from the boreholes is piped in two-phase flow to the separator building which contains all high-pressure and low-pressure separators for one unit. The high-pressure separators operate at 8.7 bar-a pressure. The high-pressure steam is manifolded from the separators into a single pipeline which brings the steam to the power station. A second flash steam separator is used to boil off and separate all the water from the high-pressure separator at a pressure of 2.2 bar-a. The primary steam enters the turbine at 7.2 bar-a pressure and the secondary steam at 2.0 bar-a pressure between the second and third stages. The turbine is a single-cylinder, double-flow, dual-admission unit with 5 stages. It is manufactured by Mitsubishi Heavy Industries (MHI) in Japan. It has an underlying direct contact jet condencer operated at 0.12 bar-a. The high-pressure steam contains 1.5-1.7% of non-condensable gases at the present time.

At the end of 1980 eight boreholes of the 15 drilled could produce steam as shown in Table 1. Most of these are located within 500 m of the separator station, spaced 100-300 m apart. The high- and low-pressure steam are piped to the power station about 500 m from the separator station. The total production of the field in late 1980 was 168 kg/s of steam-water from 11 boreholes of which 88 kg/s came from the 8 that were connected with pipelines. The 4 boreholes not producing were either damaged or not completed. The enthalpy of the steam-water mixture discharged from the 8 boreholes utilized is in the range 1100-2900 kJ/kg. These boreholes produce in total 53 kg/s of high-pressure steam (8.7 bar-a in separator) of which about 1/2 comes from only two boreholes. Table 4 shows the estimated concentration of non-condensables when the steam-water mixture from these two boreholes (K-9 & K-14) is allowed to flash at 175°C which corresponds roughly to the separator pressure of 8.7 bar-a. The gas content is about 1.9%, which is an order of magnitude greater than in Námafjall and Svartsengi.

In December 1975 a volcanic eruption occurred about 2 km away from the Krafla Power Station. This volcanic eruption was the beginning of a rifting episode in the fissure swarm intersecting the Krafla caldera. During the last 5 years this volcanic activity has continued with 12 rifting episodes, 6 of which have resulted in volcanic eruptions. The magmatic activity has influenced the production characteristics of the Krafla geothermal field and given rise to several difficulties experienced in its utilization. Volcanic activity is still going on in the Krafla area affecting the boreholes and reservoir properties in both the Krafla and Námafjall geothermal fields.

SVARTSENGI

The exploration of the Svartsengi high-temperature geothermal area started more than 10 years ago. The first two boreholes were drilled in 1971-1972 and it was discovered that the hot water produced was saline with a concentration about 2/3 of seawater. The reason for exploration work in the Svartsengi area was the possibility of building a heating system for the nearby town of Grindavík.

The exploration and early drilling in Svartsengi were successful, but the problem was that the high-temperature brine could not be used directly for district heating purposes. It was clear that a novel method had to be developed if the high-temperature brine was to be used for district heating. Extensive pilot plant studies were carried out to test several methods of heating fresh cold water using the geothermal steam-brine mixture produced in Svartsengi. Arnórsson et al. (1975) have reported some of the early results.

As the Svartsengi project was developing from exploration to pilot-plant studies, the price of oil suddenly quadrupled. At the turn of 1974/1975 a company was formed to exploit the Svartsengi high-temperature field for district heating in the Sudurnes region, which consists of seven separate towns and villages on the Reykjanes peninsula. The main function of the power plant in Svartsengi is therefore the production of hot water for district heating.

The novel heat exchange process used in the Svartsengi power plant has been described by Thórhallsson (1979). The flow diagram of the power plant is shown in Fugure 4, illustrating the main equipment and associated flowrates, temperatures and pressures. There are four parallel flow streams in power plant I. Two of these are as shown while two have additional heat exchangers that can cool the deaerated water from about 100°C to 85°C. This water is pumped directly to Grindavík while the 125°C water is pumped (in the opposite direction) to the rest of the towns using the hot water.

The geothermal steam-brine mixture is piped in two-phase flow from the wells to a flash plant located by the power house. (See Figure 4). Two centrifugal steam separators in series produce the high-pressure (5.4 bar-a) and low-pressure (0.25-.039 bar-a) steam. The water level in the high-pressure separator is controlled and the spent brine discharged from the barometric leg of the low-pressure separator is presently discharged into a large pond by the generation of electricity in a back-pressure turbine before being condensed in a plate heat exchanger. The low-pressure steam is piped to a direct contact condenser where it heats the fresh cold water from 5°C to 65°C and removes 90% of the dissolved gases from the fresh water. This water is pumped, in two of the flow-streams, to the turbine condenser mentioned above. In the other two flow-streams there is the possibility of pumping the water first through heat exchangers as mentioned above to produce 85°C water for the town of Grindavík. In the turbine condenser the water is heated to 105-110°C before it enters the atmoshperic deaerator. At this point the hot water is heated further by high-pressure steam in a plate heat exchanger to 125°C for pumping to the main district heating market in the area of the town of Keflavík.

The design of power plant I is based on a steam-brine production of 60 kg/s from each borehole, an output which is split between two flow-streams. The power plant has four flow-streams such that two boreholes are required on-stream at any one time. Each flow-stream produces sufficient hot water to satisfy a 12.5 MW thermal load at the consumer, the rated capacity of the power plant therefore being 50 MW thermal.

Power plant II is presently under construction. It is being built for the purpose of supplying district heating water to the Keflavík International Airport and NATO Military Base. Initially it is to have 2-3 flow-streams of a new design, each with a rated thermal capacity of 25 MW.

There are two AEG-Kanis 1 MW back-pressure steam turbines in power plant I. Table 3 shows their main technical specifications. The amount of steam expanding through the turbine in Figure 4 is sufficient to generate about 0.6 MW of electricity. The high-pressure steam associated with two flow-streams in power plant I is used for each turbine-generator. The first 1 MW turbine was commissioned in late April 1978, the second one in 1979. Both units have operated as required since that time. The main purpose of these turbines is to provide the power plant with electricity for pumps and other equipment. In December 1980 the third turbine-generator was installed in Svartsengi, a 6 MW Fuji Electric package-type unit (see Table 3). The unit is located in power plant II and generates electricity for general demand in the Sudurnes region.

At the end of 1980 ten geothermal boreholes had been drilled in Svartsengi (see Table 1). The boreholes are of three basic designs: a) 2, 3 and 10 are shallow 239 m, 402 m and 424 m closely spaced 35-105 m, b) 4, 5 and 6 are deep 1713 m and 1734 m with 9 5/8" production casing and c) 7, 8, 9 and 11 are deep 1438 m, 1603 m, 994 m and 1141 m with 13 3/8" production casing. All boreholes have slotted liners except 7 which is "barefoot". Boreholes 5-11 are spaced 200-250 m apart while 2, 3 and 10 are much closer to each other. The output of the boreholes with 9 5/8" production casing is 60 kg/s but the 13 3/8" boreholes have an output of 120 kg/s.

Flowrate (and enthalpy) measurements have been done on all the Svartsengi boreholes. Figure 5 shows some of the results. Borehole S-4, being 9 5/8", produces 60-80 kg/s at 10-15 bar-a well head pressure, while S-8 and S-11, being 13 3/8", produce 120-180 kg/s. Well S-10, shallow 13 3/8", is capable of similar production as the other wide holes. Borehole S-7, which is "barefoot", has typical 13 3/8" characteristics but has been tested to only 80 kg/s. The large diameter boreholes in Svartsengi are probably among the best producers in the world. The enthalpy of the steam-brine mixture in all the boreholes corresponds to water at 235-240°C. It has remained constant since the start of production as has the fluid composition.

There has been experienced calcium carbonate deposition in some of the boreholes in Svartsengi. These deposits are formed at the depth where flashing starts and have to be cleaned every 7-8 months with a drill-rig. It was partly because of the calcium carbonate problem that it was decided to drill wider boreholes and use 13 3/8" production casing instead of the 9 5/8". Of the 10 production boreholes drilled in Svartsengi, one has suffered casing failure and is no longer useful as a production hole.

The amount of non-condensable gases in Svartsengi is low being typically 0.1-0.3% wt. Table 4 shows the estimated non-condensable content in high-pressure steam produced in borehole 6, when the steam-brine mixture is separated at about 155°C (5.4 bar-a), which corresponds to normal operating conditions.

DRILLING

The boreholes drilled in Námafjall 1979-1980 are similar to the most recent wells drilled in Krafla. Ragnars & Benediktsson (1981) have described the drilling of a typical 2000 m deep borehole in Námafjall. They have also given the actual cost of drilling well 11 in Námafjall in the middle of 1979. The borehole is 1923 m deep, cased with 13 3/8" to 280 m and 9 5/8" to 620 m. The 7" slotted liner extends to the bottom. The drilling time was 33 days and the total cost 702,700 U.S. dollars or 265 $/m. The drill-rig used was a Gardner Denver 700E. It must, however, be appreciated that the total drilling cost can vary appreciably between geothermal fields. The boreholes drilled in Krafla are more expensive than in Námafjall, with a total cost of almost one million U.S. dollars. It takes longer time to drill in Krafla because the conditions there are more difficult.

In the south-west of Iceland in Svartsengi, the boreholes are less expensive than in Námafjall and Krafla. Borehole 8 in Svartsengi is typical for the deep wells with a 13 3/8" production casing. It was drilled to 1603 m in 1979 and cost about 650,000 U.S. dollars or 350 $/m. The drilling time was 35 days and the drill-rig used was Oilwell 52. The 13 3/8" production casing is to 600 m and the 9 5/8" liner to bottom.

ENVIRONMENT

The utilization of high-temperature geothermal energy in Iceland is both limited and recent in comparison to low-temperature waters. In the 12 years since the first major utilization of high-temperature geothermal energy started, there have not been any significant environmental problems. There has, however, been expressed concern over topographical and visual matters.

In Námafjall and Krafla the boiling water from the separators is discharged into a disposal pond and a small stream, respectively. The hot water percolates into the highly fractured lava and mixes with the ground water. There are no indications that the disposal water causes environmental problems.

At Svartsengi there is, however, a disposal problem of a sort. The geothermal brine from the low-pressure separators is highly supersaturated with silica which polymerizes quickly to form colloidal silica that deposits in the disposal pond. The silica particles gradually seal the surface lava when percolating into the ground, with the result that the disposal pond increases relatively rapidly in size. In the future the plan is to reinject the waste brine and condensate and presently work is underway to bring that about. Other work at Svartsengi relevant to environmental matters are detailed studies of ground-water hydrology, land subsidence (levelling and gravity measurements) and seismicity. Similar studies are carried out in the Krafla-Námafjall region.

CONCLUSION

In this paper the development and present status of geothermal electric power in Iceland have been discussed. The main "competitor" of geothermal electric power in Iceland is the relatively abundant and cheap hydropower, while geothermal energy has no "rival" when it comes to thermal applications such as district heating. In the years to come the role of geothermal energy in electricity generation is not clear. Because of the Krafla experience there is limited confidence in Iceland in geothermal electric power.

The success at Svartsengi has, however, done a lot of good for the geothermal industry in Iceland. It was provided the counterbalance to Krafla and shown that high-temperature geothermal energy is viable and that Námafjall is not the exception. The novelty of the Svartsengi power plant has created great interest and for the first time in Iceland there has been generated electricity and thermal power in the same plant. Co-generation will undoubtedly be widely practiced in the geothermal power and processing plants built in the future.

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TABLE 1

High-temperature geothermal energy used in Iceland in 1980.

Name of area	Boreholes		Thermal power (MW)		Electric Power
	Drilled	Production	Installed[a]	Used	(MW)
Svartsengi	10	9	520	50[b]	8
Hengill	>25	19	135	25[b]	0
Námafjall	12	3	100	35[a]	3
Krafla	15	8	140	0	30
Total	>62	39	895	110	41

a: Above 100°C condensate.
b: Space heating above 35-40°C.

TABLE 2

Approximate thermal power used in 1980 in Iceland from low- and high-temperature geothermal areas. The steam used for geothermal electric power generation is not included in this tabulation.

Type of use	Thermal power >35°C (MW)			(%)
	Low	High	Total	
Space heating	634	60	694	84.9
Greenhouses	36	15	51	6.2
Swimming pools	21	0	21	2.6
Industrial	15	35	50	6.1
Fish culture	2	0	2	0.2
Total	708	110	818	100.0

TABLE 3

Main technical specifications of geothermal electric power stations in Iceland (Thórhallsson et al. 1979).

Specification	Námafjall	Krafla	Svartsengi	Svartsengi
Manufacturer	BTH	MHI	AEG-KANIS	Fuji
Installed (year)	1968	1978	1978/1979	1980
Rated capacity (MW)	3	30	2 x 1	6
Speed (rpm)	3000	3000	4479	3000
Inlet pressure (bar-a)	9-10	7.2/2.0	5.4	5
Steam flowrate (kg/s)	~14	53.2/19.6	8.9	37.2
Exhaust pressure bar-a)	~1.1	0.12	1.7	1.2
Type/Stages	C	5	C	C

TABLE 4

Estimated non-condensable gas composition in geothermal steam (Compiled by G. Gíslason & T. Hauksson).

Concentration (mg/kg)	Námafjall	Krafla	Krafla	Svartsengi
Borehole number	N-11	K-9	K-14	S-6
Date of sample	20.09.80	25.11.80	28.11.80	15.05.80
Enthalpy mixture (kJ/kg)	2,355	1,055	2,634	1,030
Steam fraction	0.79	0.15	0.93	0.18
Temperature[a] (°C)	180	175[b]	175[b]	155
CO_2	799	18,080	11,660	2,540
H_2S	1070	642	751	34.5
H_2	93	6.4	35.9	0.03
CH_4	1.17	6.6	0.84	0.50
N_2	5.8	0.0	0.0	33.6
Total	1,969 (~0.2%)	18,735 (~1.9%)	12,448 (~1.2%)	2,609 (~0.3%)

a: Temperature corresponding to saturation pressure of steam-water separation.
b: Separators are presently operated at 6-7 bar-a but not the design pressure 8-9 bar-a.

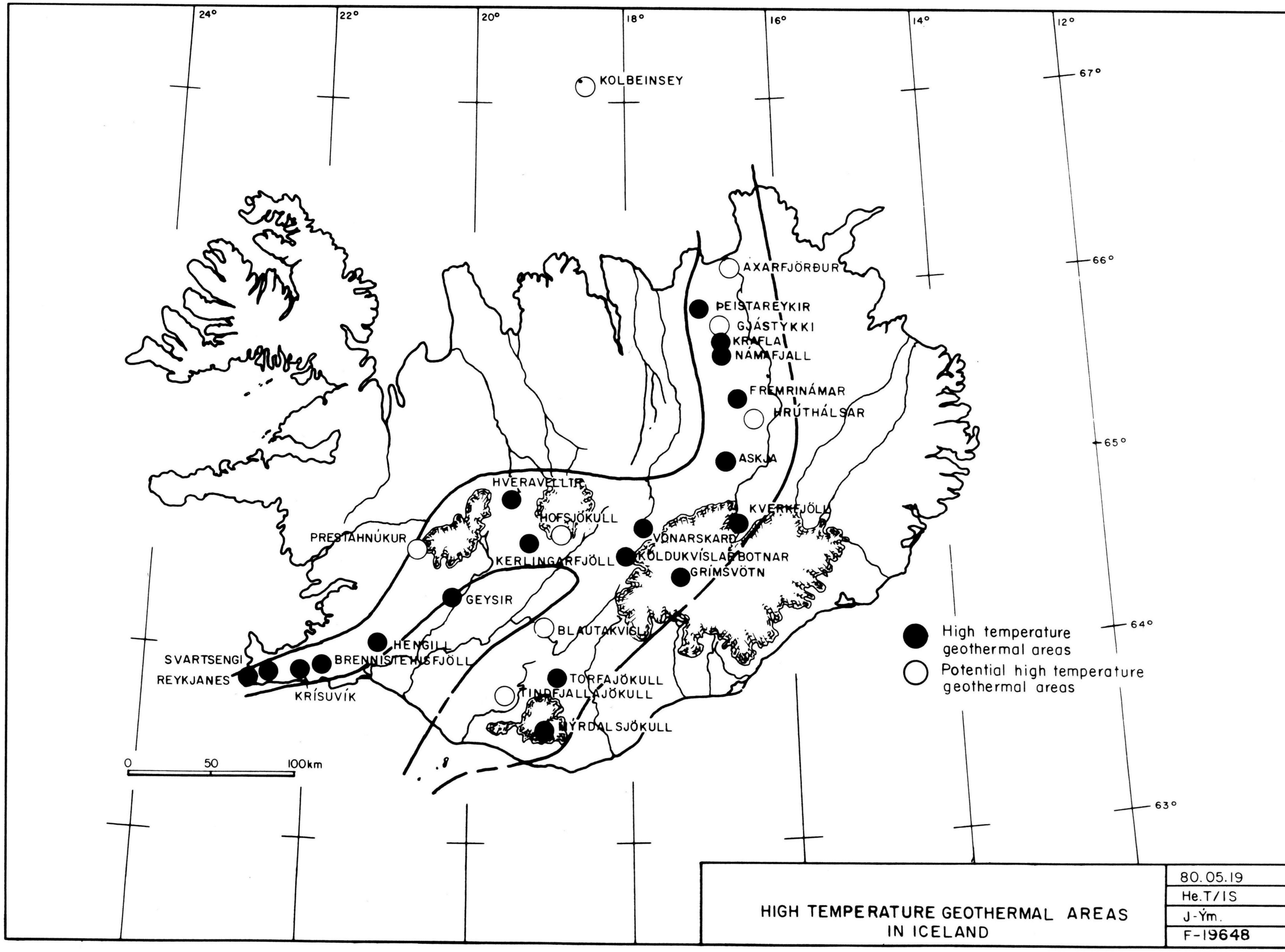


FIGURE 1. High-temperature geothermal areas in Iceland, known and potential.

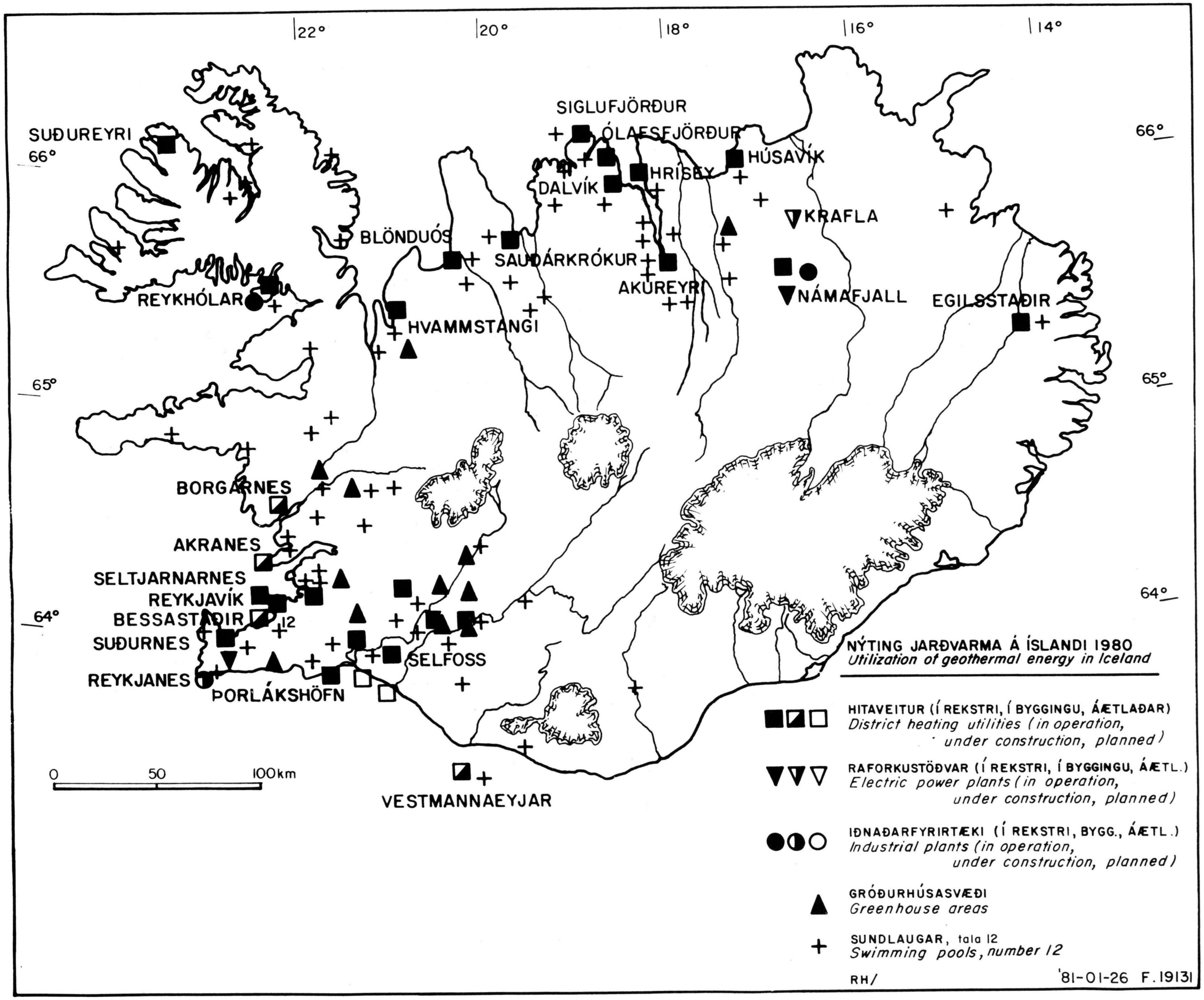
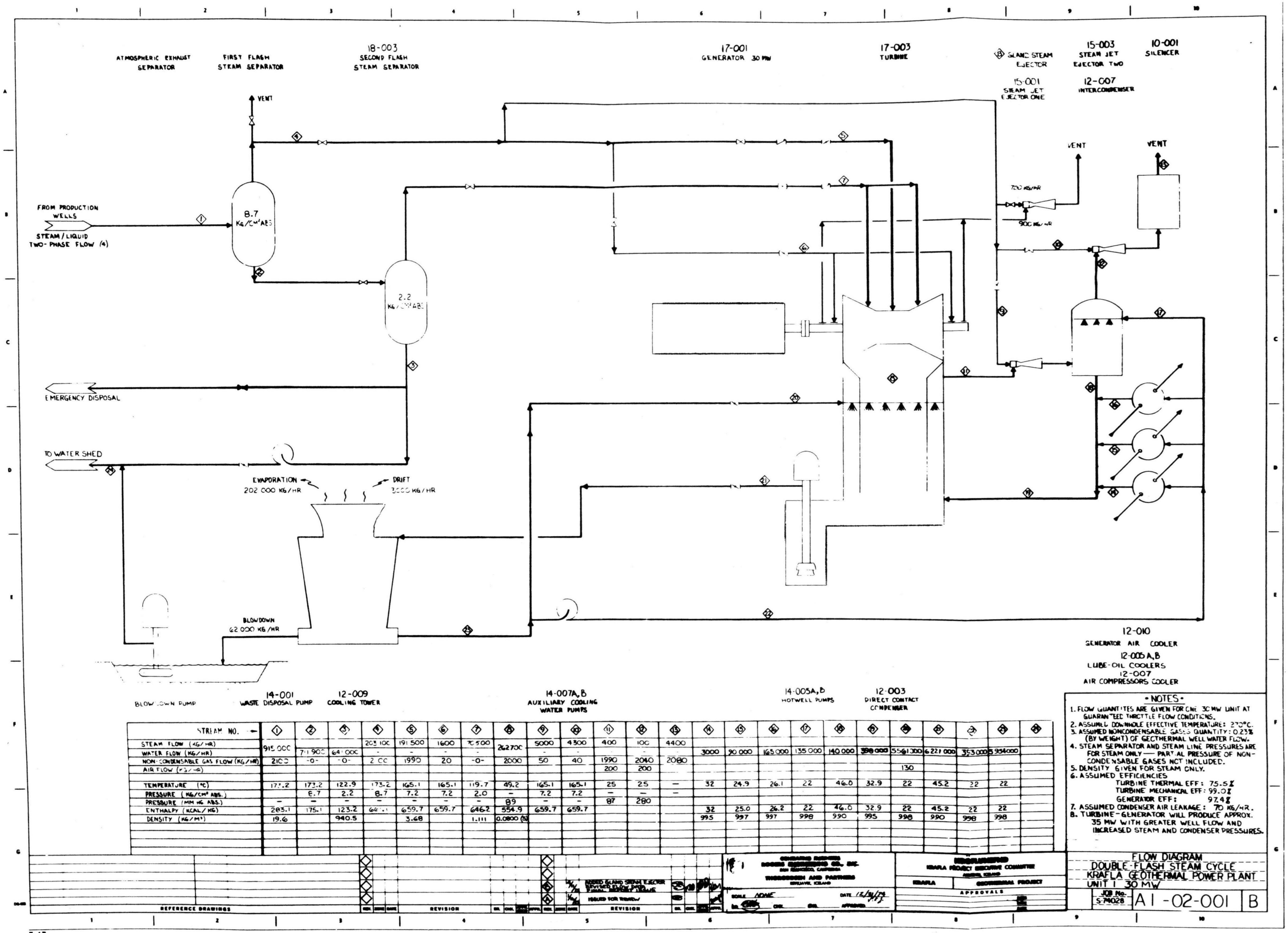


FIGURE 2. Utilization of geothermal energy in Iceland in 1980.



STREAM NO.	1	2	3	4	5	6	7	8	9	10	11	12
STEAM FLOW (KG/HR)	915 000			203 100	191 500	1600	70 500	262700	5000	4300	400	100
WATER FLOW (KG/HR)		711 900	641 000	-	-	-	-		-	-	-	-
NON-CONDENSABLE GAS FLOW (KG/HR)	2100	-0-	-0-	[illegible]	1990	20	-0-	2000	50	40	1990	2040
AIR FLOW (KG/HR)											200	200
TEMPERATURE (°C)	173.2	173.2	122.9	173.2	165.1	165.1	119.7	49.2	165.1	165.1	25	25
PRESSURE (KG/CM² ABS.)		8.7	2.2	8.7	7.2	7.2	2.0	—	7.2	7.2	—	—
PRESSURE (MM HG ABS.)	—	—	—	—	—	—	—	89	—	—	87	280
ENTHALPY (KCAL/KG)	283.1	175.1	123.2	[illegible]	659.7	659.7	646.2	554.9	659.7	659.7		
DENSITY (KG/M³)	19.6		940.5		3.68		1.111	0.0800 (5)				

STREAM NO.	13	14	15	16	17	18	19	20	21	22	23	24
STEAM FLOW (KG/HR)	4400											
WATER FLOW (KG/HR)	-	3000	90 000	165 000	135 000	140 000	398 000	5 561 300	6 221 000	353 000	5 954 000	
NON-CONDENSABLE GAS FLOW (KG/HR)	2080											
AIR FLOW (KG/HR)								130				
TEMPERATURE (°C)	—	32	24.9	26.1	22	46.0	32.9	22	45.2	22	22	
PRESSURE (KG/CM² ABS.)	—											
PRESSURE (MM HG ABS.)												
ENTHALPY (KCAL/KG)		32	25.0	26.2	22	46.0	32.9	22	45.2	22	22	
DENSITY (KG/M³)		995	997	997	998	990	995	998	990	998	998	

FIGURE 3. Flow diagram for one 30 MW unit in the Krafla Power Station.

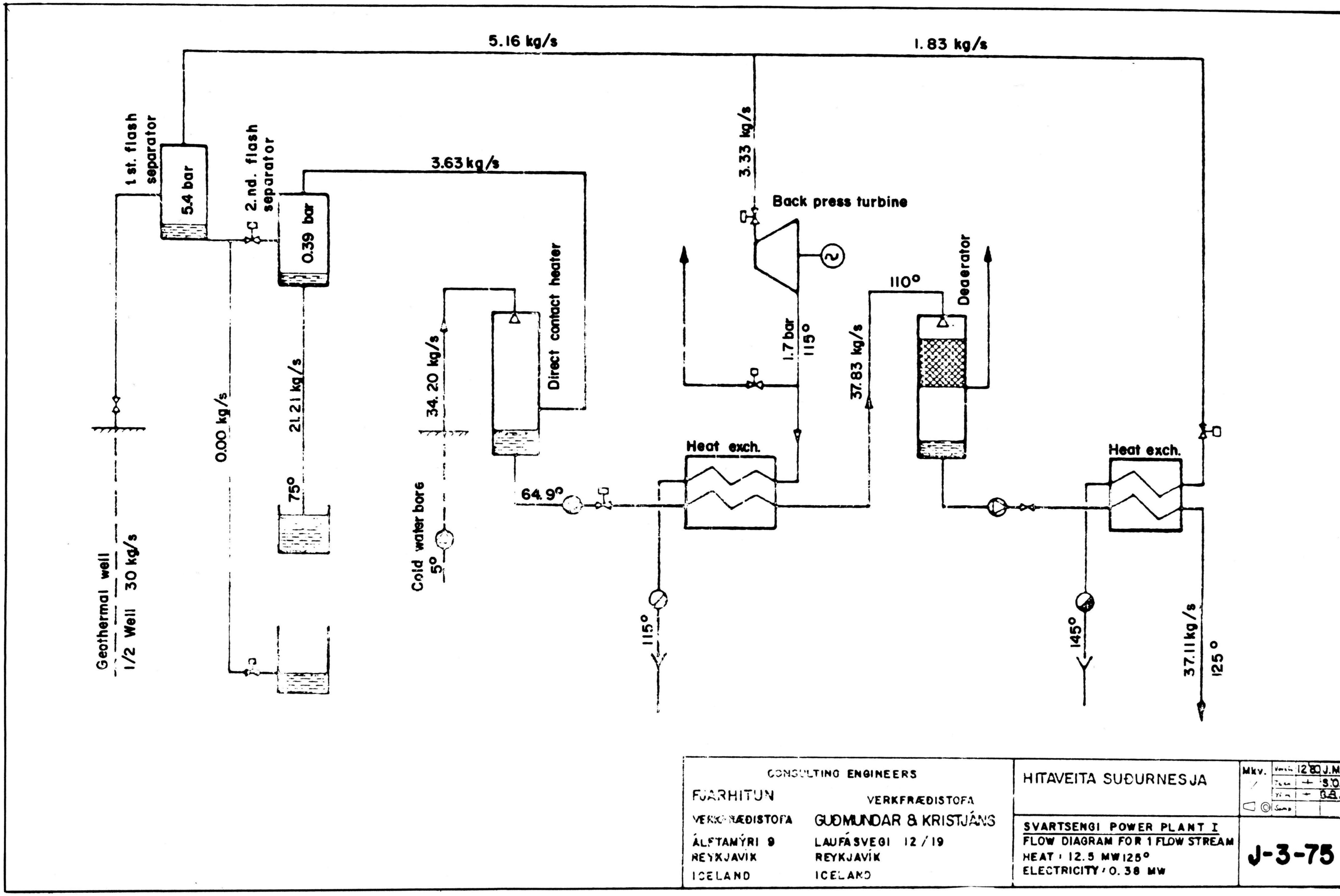


FIGURE 4. Flow diagram for one flow stream (12.5 MW-thermal) in the Svartsengi power plant.

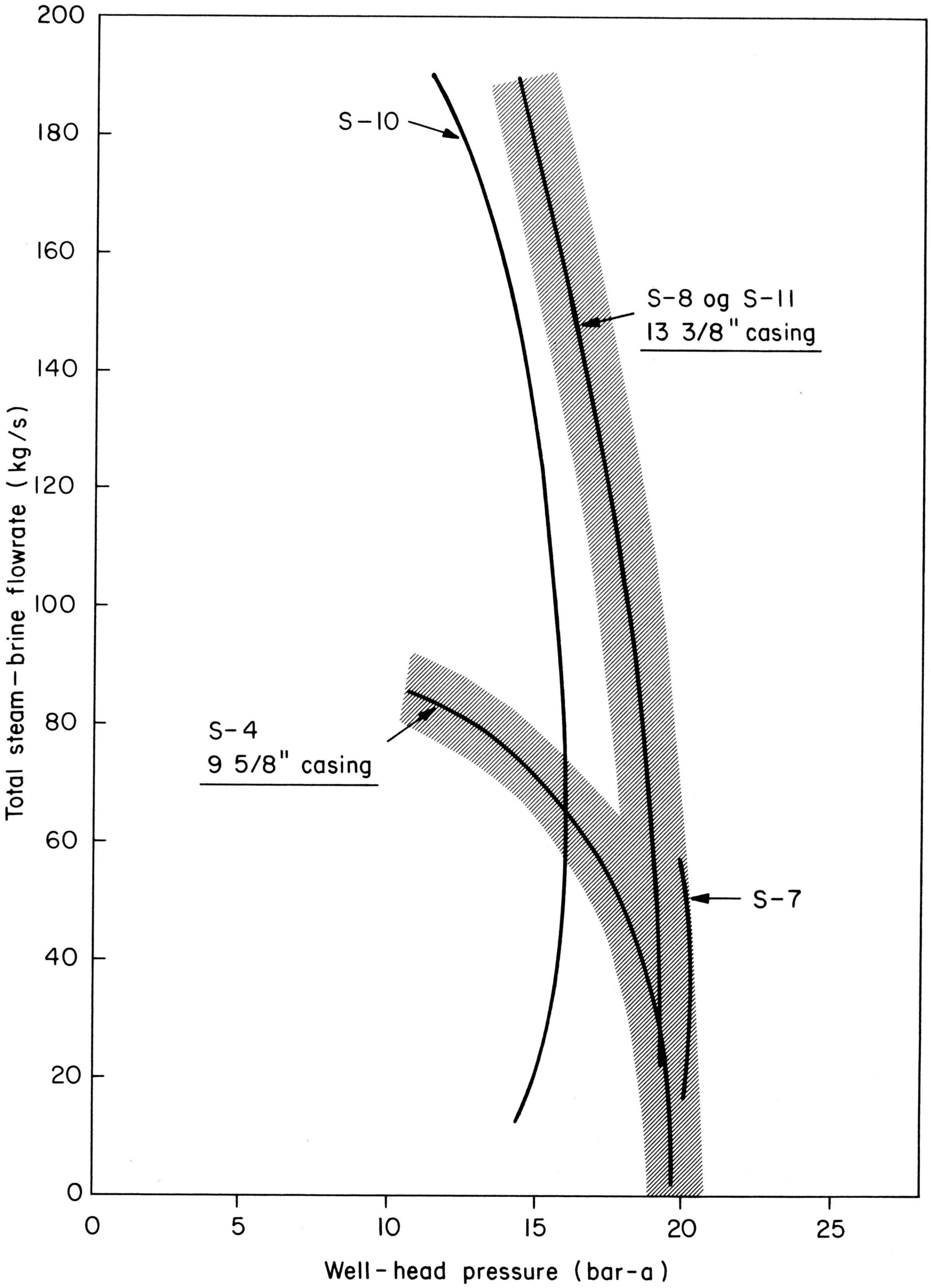


FIGURE 5. Flowrate measurements of boreholes in Svartsengi.