

National Energy Authority  
Department for Natural Heat

THE UTILITY OF WATER FROM THE  
HIGH-TEMPERATURE AREAS IN ICELAND  
FOR SPACE HEATING AS DETERMINED BY  
THEIR CHEMICAL COMPOSITION

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Stefán Arnórsson, National Energy Authority  
and  
Sven Sigurdsson, Science Institute

### Abstract

Geothermal waters from the high-temperature areas in Iceland cannot, as a rule, be used directly for space heating or domestic purposes. It is the chemical composition of these waters which make them unsuitable for direct use and the components that are relevant include silica, hydrogen sulphide, carbon dioxide, calcium, and, for 3 high-temperature areas, too high salinity. In order to exploit the thermal energy from the high-temperature waters for space heating, this energy has to be transferred into fresh ground water by means of heat exchangers. Pilot plant tests and chemical thermodynamic calculations indicate that suitable thermal water for space heating can be produced by mixing steam, flashed from high-temperature waters, directly with fresh ground water. The fresh water must be heated to 110-130°C so it can be degassed by subsequent flashing to 100°C. The quality of the heated water formed by this method depends on the hydrogen sulphide and carbon dioxide content of the steam and the overall composition of the fresh water. The components in the fresh water that are particularly significant include total carbonate and pH. Fresh water heated directly with steam from the typical non-saline high-temperature hydrogen sulphide bearing waters would be too high in hydrogen sulphide to be suitable for domestic use as suggested by the thermodynamic calculations. Possibly the fresh water could be treated after heating to lower its hydrogen sulphide content to an acceptable level.

## Introduction

Geothermal energy is used extensively in Iceland for house heating. Presently, about 50 per cent of the inhabitants in the country use natural hot water for house heating and it is considered likely that this figure will reach about 70 per cent during the next five years. House heating by geothermal water plays an important economic role in Iceland, and presently, annual house heating costs by geothermal water are three to four times less than those by oil.

Until very recently, only waters from the low-temperature areas have been used in this respect but not waters from the high-temperature areas, but it is considered that there will be an increasing demand for the utilization of the water from the high-temperature areas in the near future. The waters from the low-temperature areas possess such a composition that they are quite suitable for direct use. They are not corrosive and no, or insignificant, scaling in pipes takes place. This is not so for waters from the high-temperature areas. They contain relatively high concentrations of silica and precipitation of calcite can also occur from these waters where flashing takes place. Flashing is mostly confined to drillholes. The waters from the high-temperature areas contain, typically, relatively high concentrations of hydrogen sulphide and carbon dioxide which makes them often totally unsuitable for domestic use. In three drilled high-temperature areas the thermal fluids are so saline that they cannot be used directly for space heating for that reason also.

Presently, waters from two high-temperature areas are used for space heating. They are Námafjall in northeast Iceland and Hengill in southwest Iceland (Fig. 1). By Námafjall a small community of about 250 inhabitants benefits from this geothermal water utilization. The village, Hveragerdi, with just about 1000 inhabitants, is heated by geothermal water from the Hengill high-temperature area. In Hveragerdi there is also extensive green house farming based on the geothermal energy. At Námafjall one drillhole provides the water for the space heating with a temperature of about 220°C, but in Hveragerdi two drillholes are used, both with a temperature close to 200°C. In both areas heat

exchangers are located in each house, where fresh water that feeds the central heating system, is heated up. The thermal water is used directly in taps. Water temperatures, on entering the houses, are 80° to 90°C. Precipitation of silica occurs on a small scale in the pipes and in the heat exchangers and, apparently, it needs removal from the heat exchangers every 6 months or so. Precipitation of silica has been observed in asbestous pipes above opal saturation temperatures. This silica appears to form chalcedony. It has been reported that some calcite precipitates in the drill-holes at Hveragerdi but not at Námafjall. Calcite has also been identified in scaling in pipes in Hveragerdi. It is necessary to remove the calcite precipitate from the holes in Hveragerdi to maintain sufficient output. Insufficient experience is available to say how often the calcite precipitate needs to be removed.

(Fig. 1)

A major research project was initiated in 1973 by the National Energy Authority in the Svartsengi high-temperature area in southwest Iceland (fig. 1). The aim of this project is to provide geothermal water for house heating for all the major communities in the Reykjanes peninsula. The water at Svartsengi possesses about 2/3 of the salinity of sea water and for that reason it cannot be used directly. Instead the energy from this water has to be transferred into exploitable fresh ground water by means of heat exchangers. Good quality heated water was produced by direct mixing of the cold water with steam and subsequent flashing of the heated water to degass it. The size of the heat exchange plant will be at least 30 megawatts (thermal), but may be as much as 100 megawatts if the international airport and the NATO base at Keflavík are included (see fig. 6). A geothermal energy plant of 30 megawatts produces about 180 litres per second of water at 100°C and suffices for house heating for a community of little less than 12000 inhabitants. The results obtained so far (September, 1974) indicate that no major technical difficulties are involved in designing the heat exchange plant.

The exploitation stage will be reached in 1976-1977.

In the following discussion a brief account is given of the compositional characteristics of the waters from the high-temperature areas with particular reference to those dissolved compounds which affect the quality of the hot water for space heating and domestic use. Subsequently, a description is given of the results of the heat exchange experiments at Svartsengi. It is clear that the major factors, in influencing the quality of the heated water, include the compositions of the steam and cold water respectively. Their compositions in future production wells may not be the same as in the present experiments at Svartsengi and for that reason the reliability of the experimental results depends to an extent on an understanding of how the quality of the heated water is affected by variation in the mentioned compositions. Accordingly, it was attempted to calculate the significant quality parameters of the heated water for different compositions of steam and fresh water and compare the calculated results with the experimental ones. The significant quality parameters include pH, total carbonate and total hydrogen sulphide. The calculations include also steam compositions which are typical for the low salinity hydrogen sulphide bearing waters of other high-temperature areas in Iceland.

Compositional characteristics of waters from the high-temperature areas

The classification of thermal areas in Iceland into high- and low-temperature types seems now to be firmly established (Bödvarsson, 1961; Arnórsson and Grönvold, 1974). The low-temperature areas are located in rocks of tertiary and lower quaternary age, but the high-temperature areas are all located within the belts of late quaternary and recent volcanism. Drillhole data indicate that temperatures are less than 150°C in the uppermost 1000 meters of the low-temperature areas but above 100°C in the uppermost 1000 meters of the high-temperature areas. Almost invariably the high-temperature areas are closely linked with central volcanic complexes which are characterised by differentiated volcanics and much intrusive activity as witnessed by their eroded tertiary analogues.

The bulk composition of thermal waters in Iceland appears to be largely influenced by underground temperatures in the geothermal areas. A major exception is to be found in two high-temperature areas, Svartsengi and Reykjanes, which are located on the Reykjanes peninsula in southwest Iceland (table 1). In these areas the water is rather saline and the salinity is considered to be due to impregnation of the sea water into the rocks underlying the Reykjanes peninsula. The rocks of which the peninsula is built up are lavas of recent age and lavas and hyaloclastites of late quaternary age. The rocks are extremely permeable. In the Reykjanes high-temperature area the water at depth below the zone of flashing has the same salinity as sea water (Björnsson et al., 1972). The salinity of the deep water at Svartsengi is about 2/3 that of sea water. The Reykjanes area is located on the southwest tip of the Reykjanes peninsula at low elevation, but Svartsengi is situated some 20 km to the east, about 6 km inland, at an elevation of 30 to 40 meters. Just east of Svartsengi the country reaches a height of 200 to 400 meters. It is considered that the salinity of the geothermal water at Svartsengi has resulted from mixing of fresh ground water and sea water in the downflow zone on the borders of, or just

outside, the geothermal area. It is known that fresh ground water of meteoric origin "floats" on top of the more dense sea water which impregnates the highly permeable rock formations in the Reykjanes peninsula. Due to the elevation, and therefore higher level of the ground water table, this fresh ground water lense is relative thick by Svartsengi, but practically non-existing around the Reykjanes geothermal area.

Thermal waters in other high-temperature areas, where sea water does not enter the ground water system, are typically low in dissolved solids. Analyses of fluids from drillholes in several high-temperature areas are given in table 1. Analyses of typical waters from the low-temperature areas are given for comparison. The analyses reported are those of the water entering the drillholes prior to steam formation by boiling. This water is termed "deep water". At the surface

(Table 1)

the drillholes issue two phases, a steam phase and a water phase. The steam formation is considered to be an adiabatic process. Therefore, during steam formation the water-steam mixture cools to an extent required to provide energy for vaporisation. The water phase contains all of the non-volatile dissolved matter in the deep water prior to flashing. Its concentrations have been increased to an extent determined by the degree of steam separation. The steam contains, on the other hand, most of the dissolved volatiles of the deep water. These volatiles are mostly carbon dioxide, hydrogen sulphide, hydrogen, and nitrogen. Due to substantial solubility of carbon dioxide and hydrogen sulphide in water, a portion of these volatiles remains dissolved in the water fraction issued from drillholes, their concentrations depending mostly of the pH of the water, their original concentration in the deep water, and the amount of steam that has separated from this water.

The concentrations of most of the dissolved solids in the deep water can be correlated with mineral solubilities and ion exchange equilibria with hydrothermal minerals. Thus the deep water seems to be, invariably saturated with calcite, anhydrite,



and fluorite. Dissolved silica is governed by the solubility of quartz. The ratio of sodium to potassium corresponds rather well with expected ratios from equilibria with alkali feldspars, according to data of Ellis and Mahon (1967) and Helgeson (1969). Magnesium concentrations are maintained at low concentrations in the water by ion exchange reactions with montmorillonite and/or chlorite. Probably the chloride and boron concentrations are governed by their extent of leaching from the rocks in those areas where impregnation of sea water into the hydrothermal system does not occur. Yet, the factors that really determine the concentrations of these elements in the waters have not been sufficiently revealed.

### Dissolved chemical components unsuitable for exploitation

The dissolved components that render waters from the high-temperature areas unsuitable for exploitation for house heating or comparable use, apart from salinity, are silica, hydrogen sulphide, carbon dioxide, and calcium. Calcium is relevant only if calcite precipitation occurs. The extent of the unsuitability of the water increases as the concentrations of the mentioned compounds increase, but as a rule increasing concentrations accompany increased deep water temperatures. In general terms, it may be stated that waters with temperatures of less than about 150°C contain so low concentrations of the compounds in question that they are suitable for direct use, as has indeed been mentioned before in the case of the geothermal waters from the low-temperature areas. At temperatures above about 250°C the waters are totally unsuitable for direct domestic use or space heating. For the exploitation of the thermal energy from such waters, an exchange of heat into fresh water is needed.

It has been well established that the concentrations of silica in the deep water of the high-temperature areas in Iceland are governed by the solubility of quartz (Arnórsson, 1970; Arnórsson, 1974). Similar results have been obtained in high-temperature fields outside Iceland (Mahon, 1966; Fournier and Rowe, 1966). The solubility of quartz increases in the relevant temperature range (fig. 2). Rapid cooling by adiabatic flashing, which occurs as high-temperature waters ascend drillholes, results therefore in quartz supersaturation. Steam separation increases the concentration of the dissolved silica in the water phase and thus adds to the supersaturation

(Fig. 2)

caused by the adiabatic flashing. Such an increase in silica is shown in fig. 2 for three different temperatures of the deep water. Precipitation of quartz in drillholes does not take place, however, due to the extremely sluggish formation of quartz crystals. Former experience has indicated that silica will only be precipitated if opal saturation is reached.

The solubility of opal is much greater than that of quartz as can be seen from fig. 2. It has, however, been observed recently in Hveragerdi that silica precipitates from the water at temperatures well above the opal saturation point, apparently to form chalcedony. It may be that external conditions in the pipes aid formation of chalcedony. The high pH (9.7 when measured at 20°C) of the flashed water may also favour chalcedony formation.

Silica in solution behaves like a weak acid (fig. 3). Experimental work of Alexander et al. (1954) showed that it is only the undissociated fraction of silica in solution that is involved in equilibrium with the solid phase, whether it is

(Fig. 3)

quartz or opal. Through steam separation in drillholes and simultaneous removal of carbon dioxide and hydrogen sulphide from the water fraction, the pH of this water is raised. In the case of the non-saline high-temperature waters the pH is sufficiently raised to cause substantial part of the silica to become dissociated. The effect of raised pH through flashing causes therefore opal saturation to be reached at lower temperatures than would be the case otherwise. The pH of the water fraction of the saline high temperature waters in Svartsengi and Reykjanes are not raised sufficiently during flashing to cause any significant dissociation of the dissolved silica.

(Fig. 4)

In fig. 4 is shown the relation between the temperature (and corresponding pressure of saturated steam) of opal saturation and the temperature of the deep water. In this figure it was assumed that the pH was not raised sufficiently through the flashing to cause any significant dissociation of silica. Such assumption holds well for the saline waters in Svartsengi and Reykjanes.

(Fig. 5)

Often about one third of the dissolved silica in non-saline high-temperature waters has become dissociated, after flashing, to temperature below some 200°C. Fig. 5 shows the relationship between deep water temperatures and opal saturation temperatures when one third of the silica in the solution is dissociated. Comparison between figures 4 and 5 shows that the effect of increased pH through flashing is quite significant in lowering opal saturation temperatures. Since precipitation of opal is a slow process, only a slight fraction of the dissolved silica, in excess of saturation, is precipitated and the rate of precipitation cannot be predicted quantitatively. External conditions, such as salinity, the degree of supersaturation, saturation temperature, and turbulence flow, aid precipitation. The material in the pipes or other constructions, with which the water comes into contact, also influences the rate of precipitation. Thus, opal precipitates much faster from solution if it is in contact with galvanized steel or polythene as compared with ordinary steel.

Precipitation of silica in pipes and valves may interfere with exploitation. Precipitation is particularly serious if it occurs in the valve on the wellhead, since such precipitation can render the valve inoperative. For a given temperature of the deep water feeding a drillhole, the pressure on its wellhead should be kept high enough to prevent silica precipitation. Since operational pressures on wellheads are generally not less than 6 ata, silica precipitation is unlikely to occur in drillholes issuing non-saline high temperature waters (see fig. 5). This may not be so for the saline high temperature waters at Svartsengi and Reykjanes (see fig. 4). Maximum temperatures recorded in drillholes in Iceland are about 290°C.

The transfer of carbon dioxide and hydrogen sulphide into the steam phase, upon flashing of the deep water, may cause the steam to become unsuitable for direct heating of fresh water. Whether this method of heat exchange is acceptable or not depends mostly on the concentrations of the two gases in the steam. Their concentrations in the steam are governed by their concentrations in the deep water, the temperature of this water, and the pressure of separation of steam and water. The concentrations in the steam phase can be decreased to a minimum by flashing the deep water in steps to low temperatures,

say 50°C. Relatively insignificant steam formation leads to transfer of a large part of the dissolved gas from the water. Therefore, early separation of steam at high pressure allows formation of less contaminated steam by further flashing to lower temperatures. The transfer of the gas from the water into the steam is highly effective in the case of saline deep waters because of the low solubility of the gases in such waters. It is, therefore, relatively easy to produce pure steam from such waters, as is the case for Svartsengi. By contrast, pure steam cannot be produced from the non-saline high-temperature waters and for two reasons. Firstly, the gases are somewhat soluble in these waters and, secondly, their pH is relatively high, so a large part of the gases are dissolved in dissociated form as bicarbonate and bisulphide.

The bulk composition of the high temperature waters influences their content of hydrogen sulphide. Thus, the saline waters are low in hydrogen sulphide (4 to 32 ppm) as compared with the non-saline waters (30 to 240 ppm). Direct heating of fresh water by steam to more than 100°C and subsequent flashing to 100°C may suffice to remove most of the gas from the heated water and make it suitable for use. Whether this is possible or not depends mostly on the carbon dioxide content of the fresh water, but also on its silica and pH, and the carbon dioxide and hydrogen sulphide content of the steam.

Indirect heating of fresh water by the water fraction from a high-temperature drillhole raises difficulties because of precipitation of silica on the surface of the material that conducts the heat into the fresh water. Silica is a poor conductor of heat. Its precipitation would, therefore, reduce the efficiency of the heat exchangers. Indirect heating by steam may also be troublesome. When the steam condenses, substantial part of the carbon dioxide and hydrogen sulphide that accompany it dissolve in the condensate and render it quite acid (pH 3 to 5). The acid condensate is expected to be highly corrosive. It appears that no single mechanism can be developed for heat exchange from chemically unsuitable high-temperature water into fresh water. The mechanism selected in each case will, little doubt, depend mostly on

the composition of the high-temperature water and, possibly, also to an extent on the composition of available fresh ground water.

Results of tests in heat exchange pilot plant in Svartsengi

In 1973 a heat exchange pilot plant was erected in the Svartsengi high-temperature area, southwest Iceland, in order to devise a method for transferring the thermal energy from the high-temperature saline water of this area into exploitable fresh water. Presently, the geothermal field is being explored by drilling and investigations are under way regarding provision of fresh ground water for the future heat exchange plant. This research is concerned with provision of thermal water for house heating for all the larger villages and towns in the Reykjanes peninsula (fig. 6).

(Fig. 6)

In 1971 and 1972 two holes were drilled in Svartsengi being about 240 and 400 meters deep. One aquifer was penetrated near the bottom of each hole, its temperature in the shallower hole being about 200°C and in the deeper hole about 230°C. The water in these holes was saline (table 1) and it was evident that this water could not be used directly for house heating. Four methods of transferring the thermal energy from the saline water into fresh exploitable ground water have been considered (Björnsson and Ragnars, 1973). They are: (1) direct heating with steam, (2) indirect heating with water, (3) indirect heating with steam, and (4) indirect heating with the application of water in a closed system as a heat exchange medium. Of course, all combinations of these four methods are possible. The heat exchange pilot plant was devised in such a way that all these four methods could be tested. Besides, a barometric condenser was fitted to the plant, so steam could be produced by flashing to low pressure and used directly or indirectly for heating.

Indirect heating by the water fraction from the drill-hole was tested for about three weeks. On entering the heat exchanger, the temperature of the water was about 140°C, but on leaving it, the temperature had dropped to about 70°C. Substantial deposition of silica had formed in this period of time and, for that reason, it was clear that this method

was inadequate. The temperature of the water feeding the drillhole used for this test is about 230°C. Accordingly, opal saturation is expected to be reached at about 125°C (figs. 2 and 4). Indeed, no silica precipitation was observed in the heat exchanger nearest to the entering point of the thermal water. Inspection of fig. 4 indicates that high-temperature thermal waters cannot, as a rule, be used for indirect heating of fresh water, since deposition of opal will always be troublesome, unless this water is only cooled insignificantly or to the opal saturation point.

Inadequate information is available on tests of indirect heating with steam. The pH of the condensed steam in the tests is about 4 and its content of carbon dioxide some 500-1000 ppm (depending on separation pressure) so it is expected that this condensate will be corrosive.

Direct heating with steam from the separator by the barometric condenser and the separator on the wellhead yields good quality water. This success can be attributed to relatively low content of carbon dioxide in the deep water and, therefore, the steam, negligible hydrogen sulphide in the steam, and flashing of the heated water to 100°C after an initial heating to 110-135°C. The set-up for this test is shown in fig. 7. First, the fresh water is preheated to about

(Fig. 7)

50°C by mixing it with steam from the separator by the barometric condenser and then heated to as much as 135°C by mixing it with steam from the separator on the wellhead. The heated water is finally degassed by flashing to 100°C in a tank containing blocks of basaltic scoria, which are thought to facilitate the degassing. The compositions of the steam and the fresh water used for heating are given in tables 1 and 2 respectively. The steam from the separator by the barometric condenser does not contain any detectable carbon dioxide nor hydrogen sulphide. The water, that is flashed in this separator, is derived from the separator on the wellhead.

(Table 2)



The reason for the absence of carbon dioxide and hydrogen sulphide in this secondary steam lies in the fact that these gases are almost quantitatively transferred from the saline water into the primarily formed steam in the separator on the wellhead, as a result of their low solubility in such water. Because the steam used in the preheating does not contain any detectable carbon dioxide, the pH is not changed during the preheating. By contrast, during the final heating, considerable amount of carbon dioxide and a little hydrogen sulphide is introduced into this water from the steam and, as a result, the pH of the water is lowered. When the heated water is flashed in the degassing tank, most of its hydrogen sulphide and carbon dioxide is transferred into the steam. Simultaneously the pH of the remaining water is raised to 8-9 depending on the extent of the flashing. The relation between the temperature of the heated water and its measured content of total carbonate and pH is shown in fig. 8.

The fresh water drillhole that was used for the pilot plant tests is located about 2 kilometers south of the pilot plant near the boundary of the thermal field. Its composition with respect to silica and total carbonate is somewhat

(Figs 8 and 9)

different from fresh ground waters in the Reykjanes peninsula. The concentration of these compounds are higher than the average (see table 2). In all likelihood, production wells for fresh water will be located few kilometers northwest of the thermal field. As mentioned before, the fresh water in the western part of the Reykjanes peninsula "floats" on top of sea water which impregnates the rock formations as a result of their very high permeability. The compositional range of this fresh water lense varies considerably (table 2). It appears that the content of dissolved solids in this water decreases inland. For that reason it is rather expected that the composition of the fresh water in the future production wells will, in composition, fall close to the lower concentration range reported in table 2 for ground waters in the Reykjanes peninsula. The content of carbon dioxide and hydro-

gen sulphide may also be higher in deep production wells that will be exploited for the future heat exchange plant, than in the shallow well used for the pilot plant tests.

The quality of the heated water formed by direct mixing of steam and cold fresh water and subsequent flashing depends on the composition of steam and fresh water respectively. Since the water in future production cold and thermal water wells may not have the same composition as those used in the tests in Svartsengi, it was attempted to calculate the pH and the CO<sub>2</sub> and H<sub>2</sub>S contents of the heated water in order to evaluate the general significance of the results in Svartsengi.

Calculation of the pH, CO<sub>2</sub>, and H<sub>2</sub>S contents in water heated directly with CO<sub>2</sub>-H<sub>2</sub>S bearing steam

In this section it is demonstrated how the pH, CO<sub>2</sub>, and H<sub>2</sub>S contents of the heated water may be calculated from knowledge of the composition of the fresh water and the steam respectively and their enthalpy. The compositional components that are relevant are pH, total carbonate, and silica in the fresh water and carbon dioxide and hydrogen sulphide in the steam.

In the calculations it is assumed that concentrations are equal to activities. This is a reasonable assumption because the ionic strength of the fresh waters is very low.

In the discussion below the suffices w, g, and m refer to the fresh water, steam, and their mixture respectively. m<sub>w</sub> and m<sub>g</sub> refer to the water and steam phase of the mixture after flashing.

The enthalpy of the heated water, h<sub>m</sub>, is determined by the enthalpy of the steam, h<sub>g</sub>, (determined by the separation pressure on the wellhead), the enthalpy of the fresh water, h<sub>w</sub>, and the fraction of steam in the mixture, Y:

$$h_m = Yh_g + (1-Y) h_w \quad (1a)$$

Conversely, if h<sub>m</sub>, h<sub>g</sub>, and h<sub>w</sub> are known:

$$Y = \frac{h_m - h_w}{h_g - h_w} \quad (1b)$$

The concentration of carbonate in the heated water, which is derived both from the fresh water and the steam, is expressed by the equation:

$$(CO_2)_m = Y(CO_2)_g + (1-Y)(CO_2)_w. \quad (2)$$

Similarity for hydrogen sulphide and silica:

$$(H_2S)_m = Y \cdot (H_2S)_g \quad (3)$$

$$(SiO_2)_m = (1-Y)(SiO_2)_w \quad (4)$$

noting that these compounds are only derived from the steam and the fresh water respectively.

The increase in pH of the heated water, which occurs when it is flashed, is governed by the transfer of carbon dioxide and hydrogen sulphide into the steam that forms and the buffering action of the remainder of these compounds in the water phase. The silica from the fresh water may also exert a buffer influence upon the final pH of the heated water. The initial pH of the fresh water is also relevant. The following equations describe the equilibrium between hydrogen ions and the relevant weak acids and their anions:

$$\frac{(\text{H}^+)(\text{HCO}_3^-)}{(\text{H}_2\text{CO}_3)} = K_1 = 10^{-6.35} (10^{-6.46}) \text{ at } 20^\circ\text{C} (100^\circ\text{C}) \quad (5)$$

$$\frac{(\text{H}^+)(\text{CO}_3^{--})}{(\text{HCO}_3^-)} = K_2 = 10^{-10.33} (10^{-10.16}) \text{ at } 20^\circ\text{C} (100^\circ\text{C}) \quad (6)$$

$$\frac{(\text{H}^+)(\text{HS}^-)}{(\text{H}_2\text{S})} = K_3 = 10^{-7.00} (10^{-6.63}) \text{ at } 20^\circ\text{C} (100^\circ\text{C}) \quad (7)$$

$$\frac{(\text{H}^+)(\text{S}^{--})}{(\text{HS}^-)} = K_4 = 10^{-15.30} (10^{-13.60}) \text{ at } 20^\circ\text{C} (100^\circ\text{C}) \quad (8)$$

$$\frac{(\text{H}^+)(\text{H}_3\text{SiO}_4^-)}{(\text{H}_4\text{SiO}_4)} = K_5 = 10^{-9.98} (10^{-8.86}) \text{ at } 20^\circ\text{C} (100^\circ\text{C}). \quad (9)$$

Dissolved silica is presented as  $(\text{H}_4\text{SiO}_4)$  in equation (9). It is considered that this expression presents the true form of silica in solution (see Arnórsson (1974)). The values of the equilibrium constants ( $K_1$  to  $K_5$ ) at different temperatures have been obtained from Helgeson (1969), Rizenko (1967), and Dickson (1966).

The distribution of carbon dioxide and hydrogen sulphide between the water and steam phases are described by the following equilibria:

$$\frac{(H_2CO_3)}{CO_{2g}} = K_6 = 10^{-3.56} \text{ at } 100^\circ C \quad (10)$$

$$\frac{(H_2S)}{H_2S_g} = K_7 = 10^{-3.18} \text{ at } 100^\circ C \quad (11)$$

$(H_2CO_3)$  and  $(H_2S)$  represent the concentrations in the water phase but  $CO_{2g}$  and  $H_2S_g$  the concentrations in the steam phase. The values for  $K_6$  and  $K_7$  at different temperatures have been obtained from Ellis (1959) and Helgeson (1969).

The mass of total carbonate, total hydrogen sulphide, and total silica, which is split between the water and steam phases during flashing, must be conserved. Thus it follows that:

$$(CO_2)_m = X (CO_2)_{m_g} + (1-X)((H_2CO_3) + (HCO_3^-) + (CO_3^{--}))_{m_w} \quad (12)$$

$$(H_2S)_m = X(H_2S)_{m_g} + (1-X)((H_2S) + (HS^-) + (S^{--}))_{m_w} \quad (13)$$

$$(SiO_2)_m = (1-X)((H_4SiO_4) + (H_3SiO_4^-))_{m_w} \quad (14)$$

noting that the silica will not be present in the steam phase. On the left hand side in equations (12) to (14) are expressed known values from equations (2), (3), and (4).  $X$  denotes the fraction of steam that has separated from the water during the flashing. This fraction is determined if adiabatic cooling to  $100^\circ C$  is assumed. Then the enthalpy of the heated water,  $h_m$ , becomes split between the steam,  $G_{100^\circ}$ , and the remaining water,  $h_{100^\circ}$ :

$$h_m = X \cdot G_{100^\circ} + (1-X)h_{100^\circ}. \quad (15)$$

Since  $G_{100^\circ} = h_{100^\circ} + L_{100^\circ}$ , where  $L$  is the latent heat of vaporisation, it follows that

$$h_m = X \cdot L_{100^\circ} + h_{100^\circ} \quad (16a)$$

or

$$X = \frac{h_m - h_{100^\circ}}{L_{100^\circ}} \quad (16b)$$

From equations (5) (6), and (10)  $(\text{HCO}_3^-)_{m_w}$ ,  $(\text{CO}_3^{--})_{m_w}$ , and  $(\text{CO}_2)_{m_g}$  can be determined in terms of only  $(\text{H}^+)_{m_w}$  and  $(\text{H}_2\text{CO}_3)_{m_w}$ . Subsequent substitution into equation (12) allows determination of  $(\text{H}_2\text{CO}_3)_{m_w}$  in terms of only  $(\text{H}^+)_{m_w}$  and the known  $(\text{CO}_2)_m$ . Similarly, from equations (7), (8), (11), and (13)  $(\text{H}_2\text{S})_{m_w}$ ,  $(\text{HS}^-)_{m_w}$ , and  $(\text{S}^{--})_{m_w}$  can be determined in terms of only  $(\text{H}^+)_{m_w}$  and  $(\text{H}_2\text{S})_m$ , and from equations (9) and (14)  $(\text{H}_4\text{SiO}_4)_{m_w}$  and  $(\text{H}_3\text{SiO}_4^-)_{m_w}$  can be determined in terms of only  $(\text{H}^+)_{m_w}$  and  $(\text{SiO}_2)_m$ .

In order to obtain the pH of the heated water,  $-\log (\text{H}^+)_{m_w}$ , use is made of the fact that during the flashing, when carbon dioxide and hydrogen sulphide become distributed between the two phases, the sum of the negative charges, that is the equivalent sum of the anions of the weak acids, will remain constant apart from the small increase which is determined by the extent of the steam separation. The value of this equivalent sum, A, before flashing in the heated water, is determined by the pH of the fresh water, its total content of carbonate and silica, and the fraction Y (see equation (1)):

$$\begin{aligned} A &= (1-Y)((\text{HCO}_3^-)_w + 2(\text{CO}_3^{--})_w + (\text{H}_3\text{SiO}_4^-)_w) \\ &= (1-Y)\left(\frac{K_1}{(\text{H}^+)_w} \left(1 + \frac{2K_2}{(\text{H}^+)_w}\right)(\text{CO}_2)_w + \frac{K_5}{(\text{H}^+)_w} (\text{SiO}_2)_w\right) \quad (17) \end{aligned}$$

using equations (5), (6), and (9), and noting that the anions  $\text{HCO}_3^-$ ,  $\text{CO}_3^{--}$ , and  $\text{H}_3\text{SiO}_4^-$  are not present in the steam.

However, since hydrogen sulphide may be present in the steam in considerable concentrations, some hydrogen sulphide will be in the heated water and this hydrogen sulphide will be partly dissociated into  $\text{HS}^-$  and  $\text{S}^{--}$ , replacing the preexisting  $\text{HCO}_3^-$ ,  $\text{CO}_3^{--}$  and  $\text{H}_3\text{SiO}_4^-$  to some extent. Thus, after flashing the constant sum of the charges of the anions will be given by:

$$\frac{A}{1-X} = ((\text{HCO}_3^-) + 2(\text{CO}_3^{--}) + (\text{HS}^-) + 2(\text{S}^{--}) + (\text{H}_3\text{SiO}_4^-))_{m_w} \quad (18)$$

where X is the fraction of steam that has separated from the water. Now, reexpressing the right hand side of equation (18) in terms of  $(\text{H}^+)_{m_w}$ ,  $(\text{CO}_2)_m$ ,  $(\text{H}_2\text{S})_m$ , and  $(\text{SiO}_2)_m$  in the way indicated after equation (16), the following equation is obtained:

$$A = \frac{(\text{CO}_2)_m ((\text{H}^+)_{m_w} + 2K_2)}{(1 + \frac{X}{(1-X)K_6}) \frac{(\text{H}^+)_{m_w}^2}{K_1} + (\text{H}^+)_{m_w} + K_2} + \frac{(\text{H}_2\text{S})_m ((\text{H}^+)_{m_w} + 2K_4)}{(1 + \frac{X}{(1-X)K_7}) \frac{(\text{H}^+)_{m_w}^2}{K_3} + (\text{H}^+)_{m_w} + K_4} + \frac{(\text{SiO}_2)_m K_5}{(\text{H}^+)_{m_w} + K_5} \quad (19)$$

From this equation  $(\text{H}^+)_{m_w}$  can be determined for known values of A (see equations (17)),  $(\text{CO}_2)_m$ ,  $(\text{H}_2\text{S})_m$ ,  $(\text{SiO}_2)_m$  (see equations (2), (3), and (4)), and X (see equation (16)), by a suitable iterative method. The pH value thus determined will be the pH value of the heated water at 100°C after flashing,

so the values of the equilibrium constants  $K_i$   $i = 1, 2, \dots, 7$ , must be chosen for that temperature.

Once this pH value has been obtained, one can determine the total carbonate content,  $(CO_2)_{m_w}$ , the total hydrogen sulphide content,  $(H_2S)_{m_w}$ , and the total silica content,  $(SiO_2)_{m_w}$ , in the heated water after flashing:

$$\begin{aligned} (CO_2)_{m_w} &= ((H_2CO_3) + (HCO_3^-) + (CO_3^{--}))_{m_w} \\ &= (CO_2)_m / \left( \frac{X(H^+)_{m_w}^2}{(H^+)_{m_w}^2 + K_1 K_6 \left( \frac{X(H^+)_{m_w}^2}{K_1} + (H^+)_{m_w} + K_2 \right)} + (1-X) \right) \end{aligned} \quad (20)$$

$$\begin{aligned} (H_2S)_{m_w} &= ((H_2S) + (HS^-) + (S^{--}))_{m_w} \\ &= (H_2S)_m / \left( \frac{X(H^+)_{m_w}^2}{(H^+)_{m_w}^2 + K_3 K_7 \left( \frac{X(H^+)_{m_w}^2}{K_3} + (H^+)_{m_w} + K_4 \right)} + (1-X) \right) \end{aligned} \quad (21)$$

$$(SiO_2)_{m_w} = ((H_4SiO_4) + (H_3SiO_4^-))_{m_w} = (SiO_2)_m / (1-X) \quad (22)$$

where in the derivation of equations (20) and (21) similar substitutions are used as in equation (19). In equation (21)  $(H_2S)_{m_w}$  denotes the total  $H_2S$  content on the left hand side but the undissociated fraction on the right hand side. The pH value of the heated water can be obtained at any temperature below  $100^\circ C$  by replacing the values of  $(CO_2)_m$ ,  $(H_2S)_m$ , and  $(SiO_2)_m$  in equation (19) by their expression in equations (20), (21), and (22) respectively and setting X equal to zero before solving for  $(H^+)_{m_w}$ . The values of the equilibrium

constants  $K_i$ ,  $i = 1, 2, \dots, 5$ , must then also be chosen for the given temperature.



Similarly, in the special case, when the temperature of the heated water does not reach 100°C and, therefore, no flashing takes place, the pH of this water can still be found from equation (19) by setting X equal to zero. The values of  $(\text{CO}_2)_m$ ,  $(\text{H}_2\text{S})_m$ , and  $(\text{SiO}_2)_m$  will be those of equations (2), (3), and (4) respectively.

A FORTRAN II program was developed for the present study. In this program the pH value of the heated water at 100°C and 20°C and its total carbonate and hydrogen sulphide content are calculated for given values of  $h_w$ ,  $h_g$ ,  $h_m$ ,  $(\text{CO}_2)_g$ ,  $(\text{CO}_2)_w$ ,  $(\text{H}_2\text{S})_g$ , and  $(\text{SiO}_2)_w$ . In the program an allowance is made for the possibility of flashing in K steps to 100°C at boiling temperatures  $t_i$ ,  $i = 1, 2, \dots, K$ ,  $t_1 t_2 \dots t_k = 100^\circ\text{C}$ , where it is assumed that the water is degassed after each flashing stage. In this case equation (19) is solved K times for successively decreasing boiling temperatures in order to obtain the pH value of the heated water at 100° after the final flashing. After each solution the values of  $(\text{CO}_2)_m$ ,  $(\text{H}_2\text{S})_m$ , and  $(\text{SiO}_2)_m$  are modified according to equations (20), (21), and (22) and the values of the equilibrium coefficients adjusted to the new boiling temperature. The value for X in the first solution is  $\frac{h_m - h_{t_1}}{L_{t_1}}$  (see equation (16b)) and success-

ive solutions  $\frac{h_{t_i} - h_{t_{i+1}}}{L_{t_{i+1}}}$ ,  $i = 1, 2, \dots, K-1$ .

Equation (19) is solved by a modification, suggested recently by Anderson and Björck (1973), of the well known regula-falsi iterative method. Using this method, and taking [4, 10] as a starting interval for the pH value, a final value with two correct decimals is in general obtained within 12 iterations.

## Discussion

The values of pH and carbonate calculated from the analysed compositions of fresh water and steam used in the tests in Svartsengi compare rather well with the actually measured values in the heated water as is indicated in fig. 8. However, when heated above 100°C, the calculated pH values are, systematically, approximately 0.2 to 0.5 pH units higher than the measured ones. This may be so because equilibrium has not been established for the distribution of carbon dioxide between the water and steam phases. It is also possible that the mentioned bias in calculated and measured pH values stems from inaccurate values of some of the equilibrium constants used in the calculations. The dimension of the degassing tank relative to the flow rate of heated water into it and the effect of the scoria blocks are thought to be the determining factors in establishing equilibrium of carbon dioxide between the water and steam phases. The difference between theory and experiment with respect to pH, when the fresh water was heated to temperatures of less than 100°C, is, at least partly, due to the fact that in the experiment the fresh water was initially preheated to about 40°C with pure steam from the separator by the barometric condenser.

The rather good comparison between theory and the experiments at Svartsengi, which is demonstrated in fig. 8, suggests that the calculations can be relied upon. Satisfactory heated water will accordingly be produced even if the thermal water in deep production wells contains as much as 2000 - 3000 ppm of carbon dioxide and few tens of ppm of hydrogen sulphide. The composition of the fresh water is not likely to affect the quality of the heated water. Lowering of silica from about 30 ppm to 10 ppm is not detectable. Lowering of total carbonate from 44 ppm to 22 ppm produces a little lower pH in the heated water (about 0.2 pH units), but this is hardly significant regarding the quality of the produced heated water. It is, therefore, concluded that direct heating of fresh water with steam in a heat exchange plant at Svartsengi will produce good quality water for house heating as regards expected limits of fresh ground water and thermal water

compositions in that area.

The composition of the thermal water in the Svartsengi field is unusual in comparison with thermal fluids from other high-temperature areas in Iceland. As discussed previously, the high-temperature waters are typically low in total dissolved solids and contain substantial amount of hydrogen sulphide (table 1). It is of interest to know if the thermal energy of the hydrogen sulphide bearing water can be used for space heating and domestic purposes through direct heating of fresh water with steam derived from this thermal water by flashing. As at Svartsengi, the critical parameter regarding the quality of the heated water is taken to be pH, but its hydrogen sulphide content is also significant. A concentration of 0.5 - 1.0 ppm is considered to be an upper limit for hydrogen sulphide in thermal water used for domestic purposes.

Calculated results for direct heating with hydrogen sulphide bearing steam are presented in fig. 9. For these calculations the compositions of 3 wells from 3 high-temperature areas were selected, namely, well 4 at Námafjall, well 5 at Nesjavellir, and well 4 in Hveragerdi. The compositions of the fluids from these wells are given in table 1. The selected fresh water composition is based on available knowledge of cold ground water compositions in Iceland and fits well with the composition of the most commonly occurring waters. For the calculations it was assumed that all the carbon dioxide and all the hydrogen sulphide would be transferred from the water phase into the steam, that is used to heat the fresh water. This is a reasonable assumption, if steam is produced by flashing to low pressures, say to 50°C. Still, some of the gases in question will remain in the water phase. It is therefore, expected that a little less carbon dioxide and hydrogen sulphide will be transferred into the heated water in reality than was assumed for the calculations. If the difference between theory and tests at Svartsengi, which is demonstrated in fig. 8, is due to a lack of establishment of equilibrium in the degassing tank, it is also expected that the actual pH of heated fresh water with hydrogen sulphide bearing steam will yield somewhat lower pH values than the calculated ones.

The content of hydrogen sulphide in the heated water, presented in fig. 9, varies from about 3 ppm to about 9 ppm. These concentrations are too high to be acceptable for domestic use. Another snag with the heated water, apart from too high hydrogen sulphide content, is rather low pH. The final pH of the heated water at Nesjavellir depends considerably on the total carbonate content of the fresh water although this does not appear to be the case at Svartsengi. For example final heating to 120°C yields a pH of 7.25 as compared with 7.65 referring to 22 ppm and 44 ppm total carbonate in the fresh water respectively.

Direct heating of fresh water to more than 100°C and subsequent flashing to 100°C produces steam that would be desirable to exploit for its thermal energy. This steam is, however, difficult to use because of its high acidity (pH of about 2 in the tests at Svartsengi) and its relatively high content of oxygen (few tens of ppm) and carbon dioxide (as much as few thousand ppm). The oxygen and carbon dioxide contents of the steam would depend on the degree of flashing. If the energy required to heat the water above 100°C has to be wasted, it is desirable to let the flashing occur in steps to 100°C by joining together a series of degassing tanks. In this way it would not be necessary to flash over as large a temperature interval as would be the case for flashing in one step in order to obtain the same pH value of the heated water. The calculated pH values of the heated water at Svartsengi, after flashing in four equal steps over the temperature interval 110 - 100°C, are plotted in fig. 8. Such flashing produces considerably higher pH than flashing in one step from as much as 140°C.

The hydrogen sulphide content and pH value have been similarly calculated for well 5 at Nesjavellir. The results have been plotted in fig. 9. They indicate that flashing in steps is critical in yielding high-pH heated waters, and therefore non-corrosive, by direct heating of fresh water with steam high in carbon dioxide and hydrogen sulphide. Flashing in steps does not yield much lower hydrogen sulphide content in the heated water than flashing in just one step, or 6 - 7 ppm as compared with 8 - 10 ppm for well 5 at Nesja-

vellir. It appears, therefore, that direct heating of hydrogen sulphide bearing steam will not yield acceptable water for domestic use, although it is usable for space heating, unless the hydrogen sulphide content of this water can be lowered by some means after heating. It may well be, that such a treatment is desirable economically, because direct heating of the fresh water is much less costly than indirect heating. It should be mentioned that the calculated and measured concentrations of hydrogen sulphide in the heated water in the tests at Svartsengi do not compare well. The calculated values are a few times higher or 0.7 ppm as compared with 0.24 ppm. This may be due to erroneous value of the equilibrium constant used in describing the distribution of hydrogen sulphide between the water and steam phases. If so, it is to be expected that the actual content of hydrogen sulphide in water heated directly with H<sub>2</sub>S rich steam will be lower than the computed H<sub>2</sub>S content.

The ratio of hydrogen sulphide to sulphate in the heated water will be grossly different from the same ratio in naturally occurring thermal waters with similar temperature. Fresh ground waters in Iceland contain typically less than about 5 ppm of sulphate whereas thermal waters with temperatures near 100°C contain typically 50 - 100 ppm of sulphate and less than 1 - 2 ppm of hydrogen sulphide. The content of hydrogen sulphide and sulphate in naturally occurring thermal waters can be related to their redox potential. Therefore, it could be expected that the redox potential of the heated water would be somewhat raised and the hydrogen sulphide content lowered, if this water flowed through a body of fragmented rock after it had been heated. On these grounds it is tentatively postulated that acceptable heated water for domestic use might be obtained by direct heating with hydrogen sulphide bearing steam, if, after heating, this water was allowed to flow through a tank containing blocks of basaltic scoria or other suitable material. If the oxidising reaction proves to be too slow, it may be possible to add some of the oxygen to it, which was derived from the fresh water during preheating. A part of the oxygen would react with the sulphide to form sulphate or sulphur. The remainder would have to be removed by flashing at a later stage.

## Conclusions

Geothermal fluids from the high-temperature areas in Iceland cannot be used directly for space heating because of their chemical composition. It appears, that the same would apply to fluids from other high-temperature areas in the world.

The pilot plant tests carried out in the Svartsengi high-temperature area, SW-Iceland, indicated that good quality heated water can be produced by direct mixing of fresh water with the geothermal steam of that area and subsequent flashing of the heated water in order to degass it. Oxygen, which was originally present in the fresh water, is removed from the heated water by the flashing, but its content of carbon dioxide and hydrogen sulphide is also greatly reduced. These two compounds are mostly derived from the geothermal steam.

Together with the pilot plant tests, chemical thermodynamic calculations indicate that it is the composition of the fresh water and steam respectively, that determines the quality of the heated water with respect to space heating and domestic use. The only significant components in the steam include carbon dioxide and hydrogen sulphide. In the fresh water, the most significant components include total carbonate, silica, and pH. The salinity of the geothermal water does not influence the quality of the heated water.

There is much observed variation in the composition of fresh ground water and geothermal steam from drillholes in Iceland. Yet it appears that good quality heated water for space heating can be obtained by the mentioned heat exchange method for the observed compositional limits. This may also be so for geothermal steam from the majority of geothermal fields in other parts of the world. If this is so, this heat exchange method may be of general use, where it is desired to exploit high-temperature geothermal fluids for space heating, say green house farming.

The majority of high-temperature geothermal fields in Iceland contain low salinity water, which is high in hydrogen sulphide and yields, therefore, hydrogen sulphide rich steam upon flashing. This steam, when mixed with fresh water, yields heated water too high in hydrogen sulphide to be

acceptable for domestic use. This heat exchange method, may, therefore, not be acceptable for such use, if the hydrogen sulphide content of the heated water cannot be lowered by some treatment.

Due to the high gas content, including oxygen, of the steam formed by the flashing of the heated water, it appears that this steam has to be waisted. Flashing of the heated water in steps to degass it, facilitates the degassing and would, therefore, improve the effective energy utilization of the geothermal fluid. For example, final heating to 130°C might be required for degassing by flashing in one step to 100°C, whereas, if flashing occurred in three steps, final heating to no more than 105-110°C would be required.

### Acknowledgements

The National Energy Authority was responsible for the pilot plant tests in Svartsengi. The present paper describes only a part of the results of these tests and does not include technical and engineering aspects. Many experts contributed to the project including S. Benediktsson, Sv. Björnsson, K. Grönvold, B. Líndal, K. Ragnars, and Sv. Thórhallsson. Special acknowledgement is due to these experts for their cooperation in executing the project. The computer work related to the chemical thermodynamic calculations was carried out at the Science Institute, University of Iceland. G. Pálma-son is acknowledged for reading the manuscript and helpful suggestions.



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Legend to figures

- Fig. 1 Distribution of high-temperature areas in Iceland.
- Fig. 2 The solubility of quartz and opal along the three phase curve solid + water + steam. Silica concentrations are shown for residual water attained by adiabatically cooling solutions initially in equilibrium with quartz and at 200<sup>o</sup>, 230<sup>o</sup>, and 280<sup>o</sup>C.
- Fig. 3 Variation in the first dissociation constant of silicic acid with temperature. From B.N. Ryzhenko (1967).
- Fig. 4 Relation between opal saturation temperature (and corresponding pressure of saturated steam) and the temperature of non-flashed high temperature water, which is in equilibrium with quartz. It is assumed that the increase in pH caused by flashing does not bring about any significant dissociation of dissolved silica. Such dissociation lowers the opal saturation temperature.
- Fig. 5 Relation between opal saturation temperature (and corresponding pressure of saturated steam) and the temperature of non-flashed high temperature water, which is in equilibrium with quartz. In this figure the flashing is considered to cause sufficient increase in pH to bring about dissociation of one third of the dissolved silica resulting in substantial lowering of the opal saturation temperature.
- Fig. 6 Location of villages and towns in the Reykjanes peninsula that will be able to exploit the high-temperature field at Svartsengi for house heating.
- Fig. 7 Flow diagram demonstrating the set up for direct heating of fresh water with steam derived from the saline high-temperature water at Svartsengi.
- Fig. 8 Variation in pH and total carbonate with temperature of fresh water heated directly with steam. If the fresh water was heated above 100<sup>o</sup>C, it was subsequently flashed to 100<sup>o</sup>C in a degassing tank

and the reported pH is that of the water after flashing. The effect of the degassing is quite pronounced in raising the pH and lowering total carbonate. The composition of the fresh water that was heated is given in table 2 (1). Calculated variation in pH and total carbonate with the temperature of the heated water is given for comparison.

Fig. 9 Calculated variation in pH and total hydrogen sulphide with temperature of fresh water heated directly with steam. If the water was heated above 100°C, it was subsequently flashed to 100°C and the reported pH is that of the water after flashing. The fresh water composition selected corresponds well with common composition of ground water in Iceland (see table 2 (4), (5)). The hydrogen sulphide content of the steam was selected from analyses 3 to 5 in table 1. The calculated values indicate that good quality thermal water for house heating cannot be produced by direct heating with steam derived from flashing of the typical non-saline hydrogen sulphide bearing high-temperature waters in Iceland. It is desirable that the hydrogen sulphide content does not exceed about 0.5 ppm and the pH should be  $>8$ .

Table 1. The composition of some thermal waters in Iceland. The analyses reported for drillholes with temperatures above 100°C are those of the water before flashing. Concentrations are in ppm.

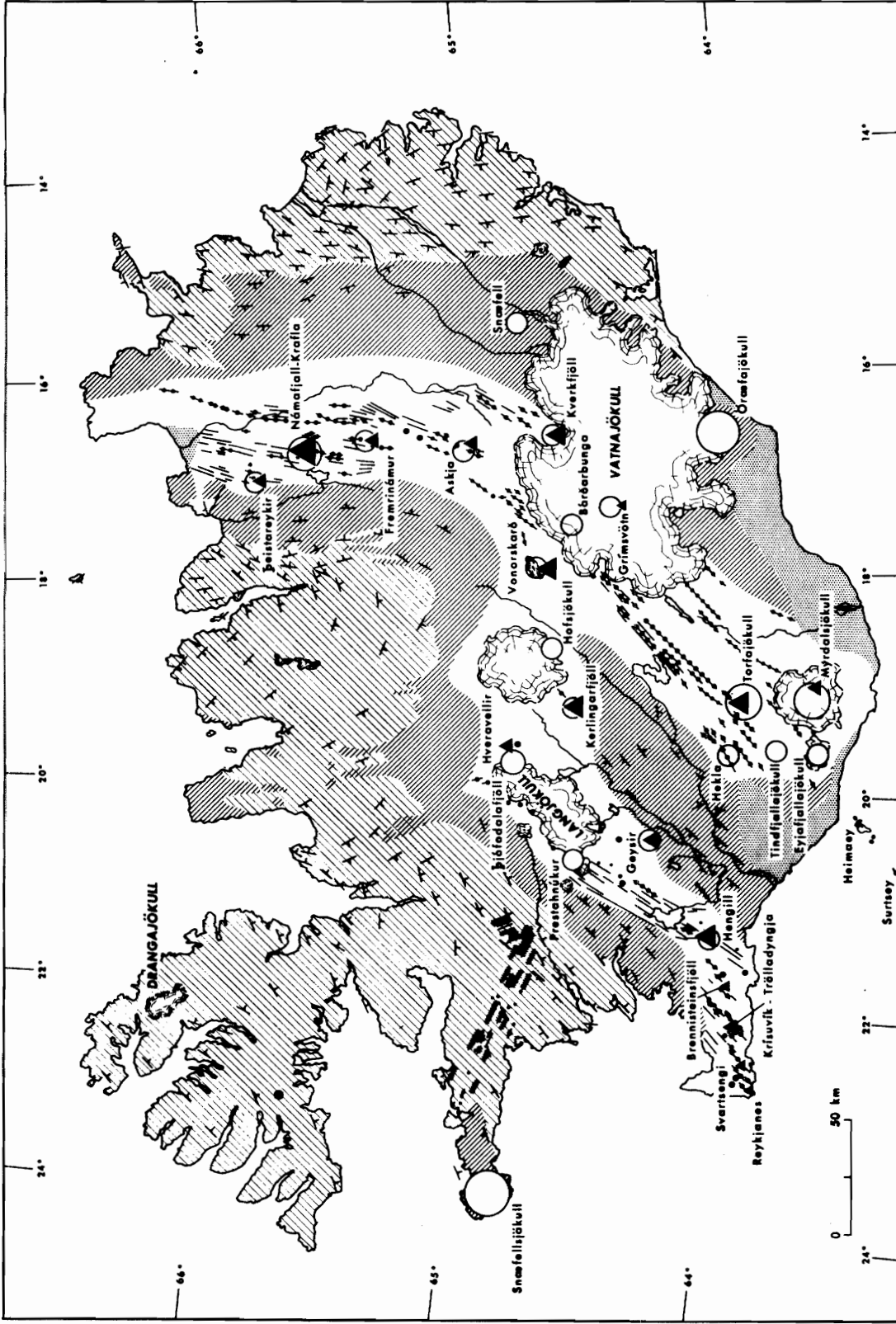
	Svartseugi well 3	Reykjanes well 8	Hveragerdi well 4	Nesjavellir well 5	Námafjall well 4	Reykir Mosfellss. well 10	Ystihver Reykjahverfi
Temp. °C	235	274	199	262	257	77	99
pH/°C	-	6.27/274	7.59/199	7.59/262	7.68/257	9.51/21	9.50/15
SiO <sub>2</sub>	420	610	265	553	537	82	196
B	7.78	8.26	0.72	0.92	0.61	-	0.15
Na <sup>+</sup>	6448	10150	142.0	139.1	129.9	40.4	65.0
K <sup>+</sup>	1032	1433	11.4	24.5	22.5	1.0	3.2
Ca <sup>++</sup>	924	1577	1.8	0.9	1.2	2.7	1.9
Mg <sup>++</sup>	1.3	1.21	0.10	0.07	0.04	0.26	0.04
CO <sub>2</sub> (total) <sup>+</sup>	163.3	1480	210.1	857.5	82.8	28.2	33.0
SO <sub>4</sub> <sup>--</sup>	31.4	29.6	50.2	49.5	58.0	16.5	34.5
H <sub>2</sub> S (total) <sup>+</sup>	4.4	32.4	30.1	238.4	158.1	0.1	0.65
Cl <sup>-</sup>	12888	19392	97.7	14.0	20.7	13.2	14.7
F <sup>-</sup>	0.1	0.1	1.8	1.8	1.4	0.7	1.0
CO <sub>2</sub> in steam <sup>x</sup>	486.1		781.0	2181.9	218.2		
H <sub>2</sub> S in steam <sup>x</sup>	12.1		111.9	606.6	409.9		

<sup>+</sup> Includes undissociated as well as dissociated carbonate and sulphide.

<sup>x</sup> These concentrations refer to complete transfer of these compounds to the steam phase, which is a fair approximation when steam is produced by flashing to temperatures as low as about 50°C.



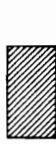




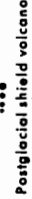



Table 2. The composition of cold and heated ground waters. Concentrations in ppm.

	Svartsengi cold water 5°C (1)	Svartsengi preheated water 40°C (2)	Svartsengi heated water 125°C (3)	Þthlídharraun S. Iceland ground water (4)	Svelgshraun W. Iceland ground water (5)	Reykjanes peninsula range (6)	Reykjanes peninsula average (9 anal.) (7)
pH/°C	7.39/20	7.50/20	8.03/20	7.72/20	6.94/20	7.08 - 7.72	7.47/20
SiO <sub>2</sub>	32.8	28.1	26.1	17.9	9.7	10.7 - 31.8	19.3
Na <sup>+</sup>	95.2		79.8	7.1	5.1	28.7 - 232.4	121.3
K <sup>+</sup>	4.7		4.0	0.5	0.6	1.7 - 22.9	6.6
Ca <sup>++</sup>	19.6		16.1	6.2	2.8	6.6 - 33.1	17.9
Mg <sup>++</sup>	17.4		14.0	1.5	1.4	1.4 - 32.1	16.5
Co <sub>2</sub> total	47.1	44.5	30.0	18.9	9.4	15.9 - 73.5	33.2
SO <sub>4</sub> <sup>---</sup>	29.6		27.6	33.3	3.5	11.9 - 60.9	29.4
H <sub>2</sub> S total	< 0.1	< 0.1	0.24	< 0.1	< 0.1	< 0.1	< 0.1
Cl	206.0		172.5	6.0	7.9	53.5 - 434.5	231.0
F <sup>-</sup>	0.15		0.20	< 0.1	< 0.1	< 0.1 - 0.15	0.1



Compiled by Kristján Samundsson  
National Energy Authority (Iceland)  
September, 1973

**LEGEND:**

-  Bedrock covered by alluvial deposits and lava flows
-  Active zones of rifting and volcanism
-  Quaternary flood basalts
-  Tertiary flood basalts
-  Strike/slip
-  Faults within Snæfellsnes volcanic zones
-  Postglacial fissure eruption
-  Postglacial shield volcano or single crater
-  Open fissure
-  Late Quaternary or Holocene silicic center
-  High temperature area

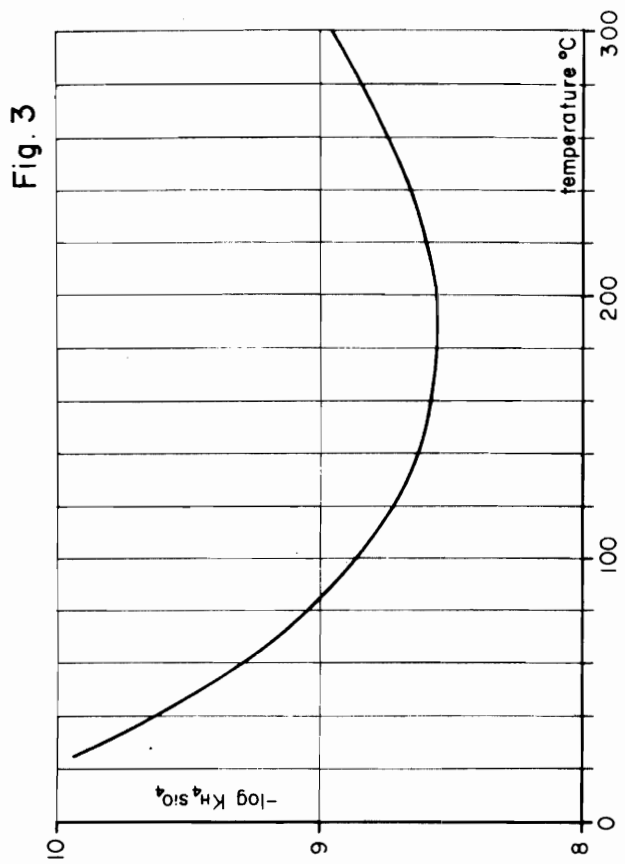
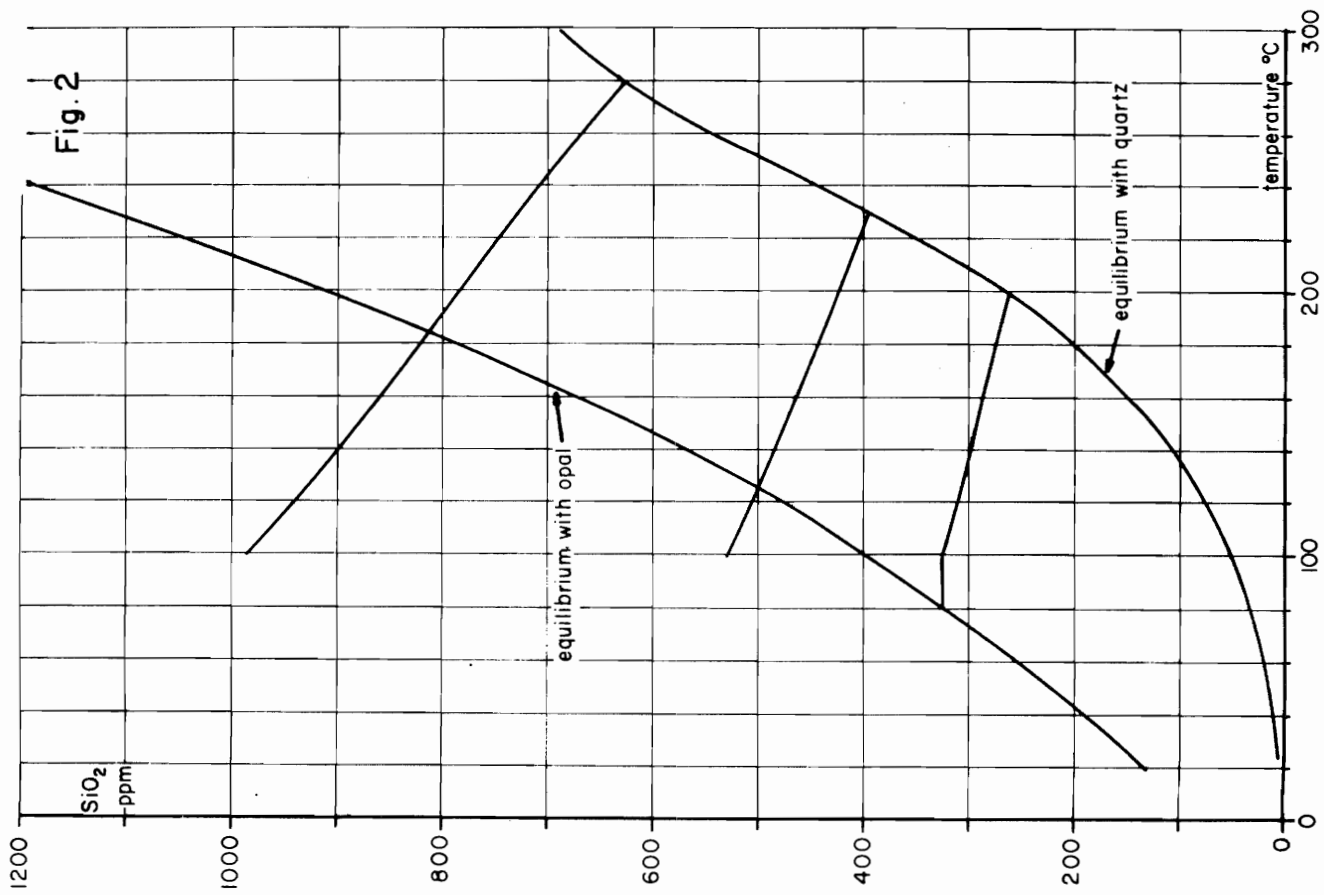




Fig. 4

- ① opal saturation temperature °C
- ② pressure of saturated steam corresponding to opal saturation temp. ata.

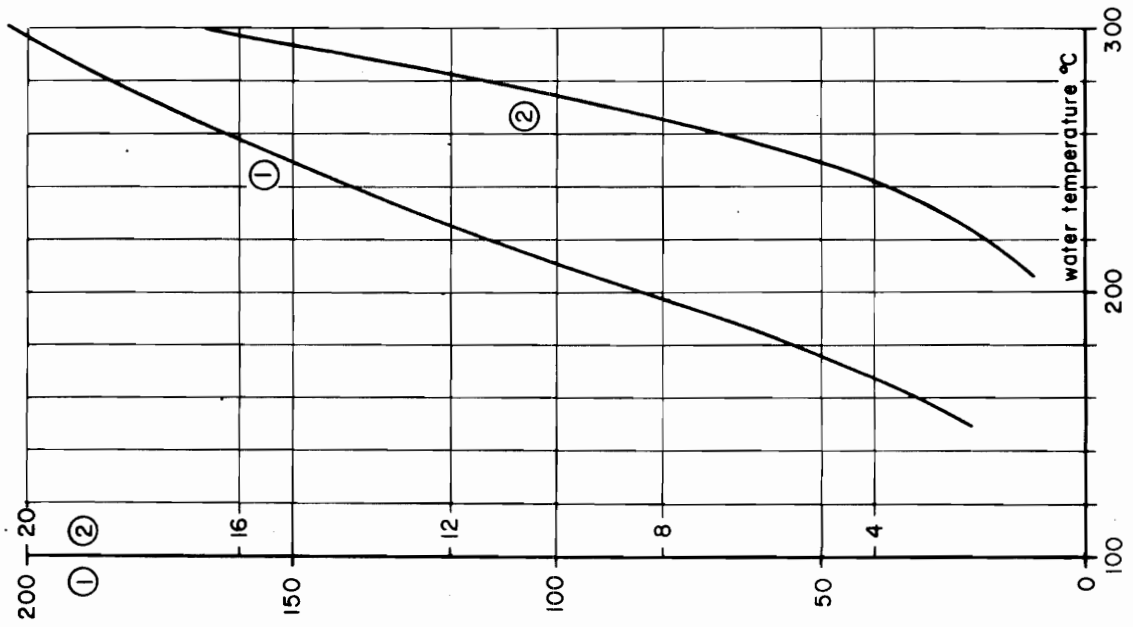
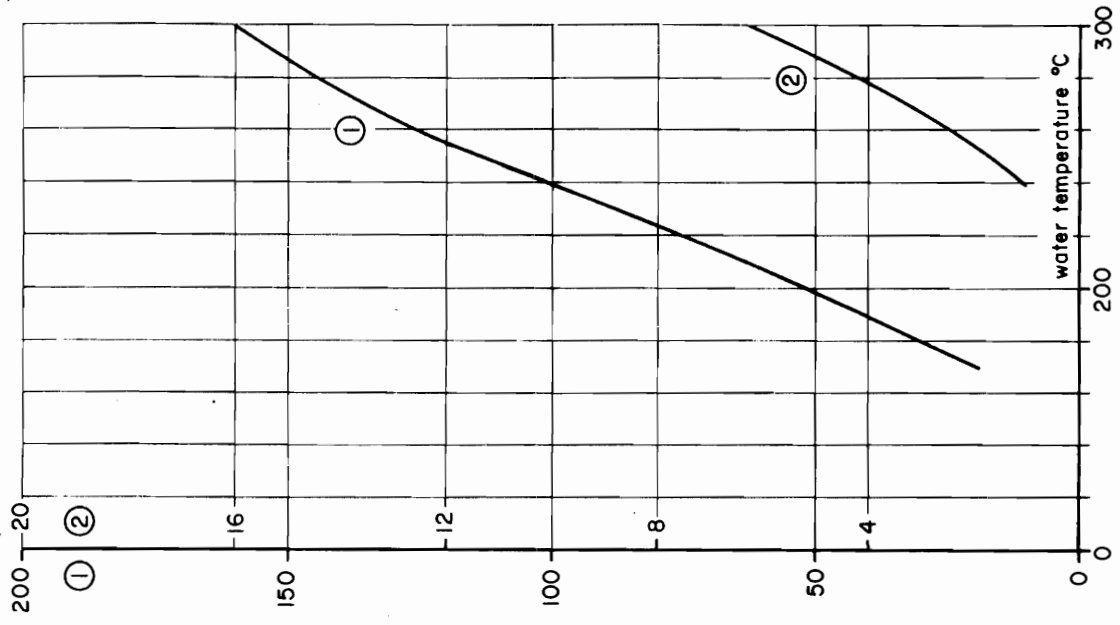


Fig. 5

- ① opal saturation temperature °C
- ② pressure of saturated steam corresponding to opal saturation temp. ata.



Varmaveita Suðurnesja

Fig. 6

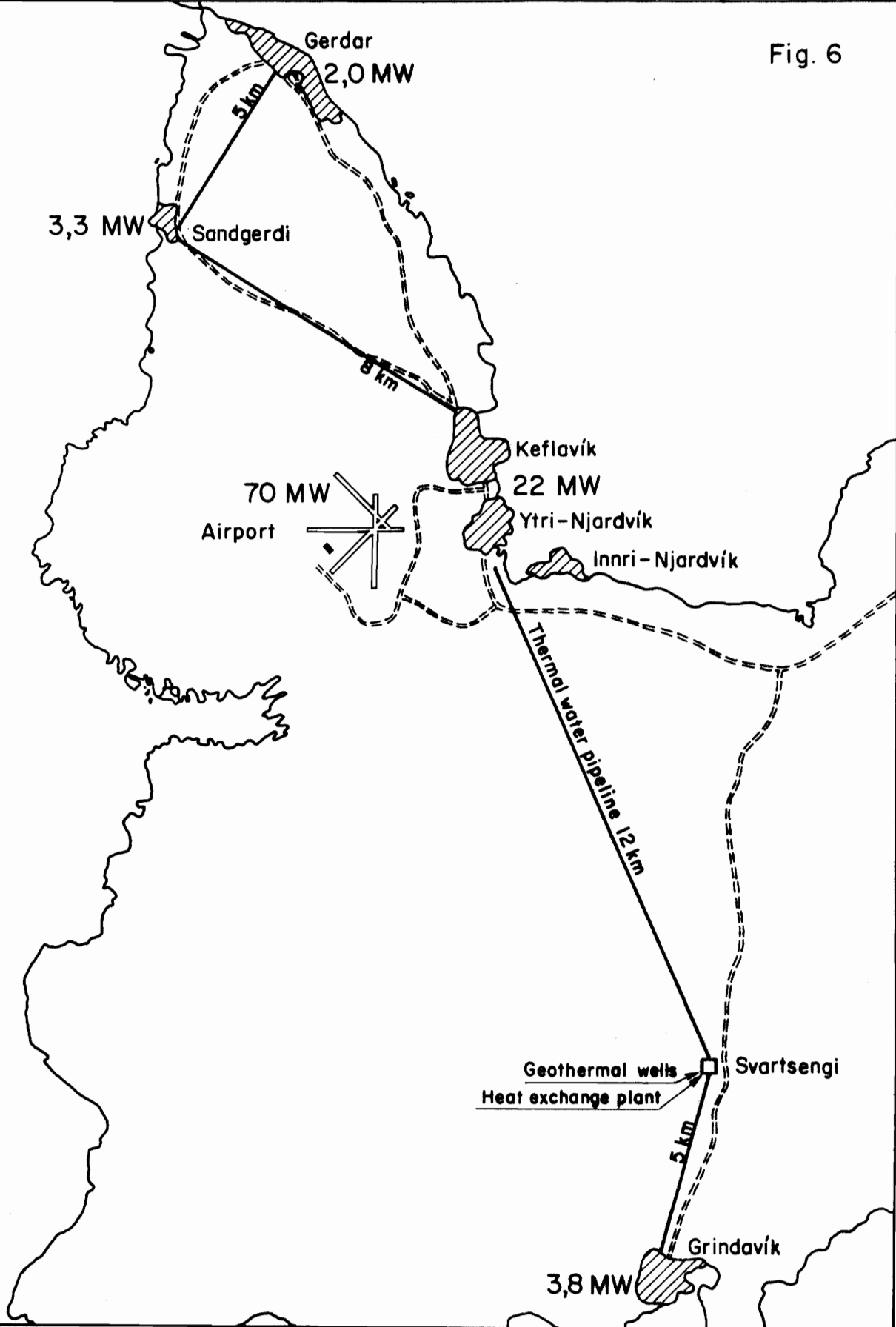


Fig. 7

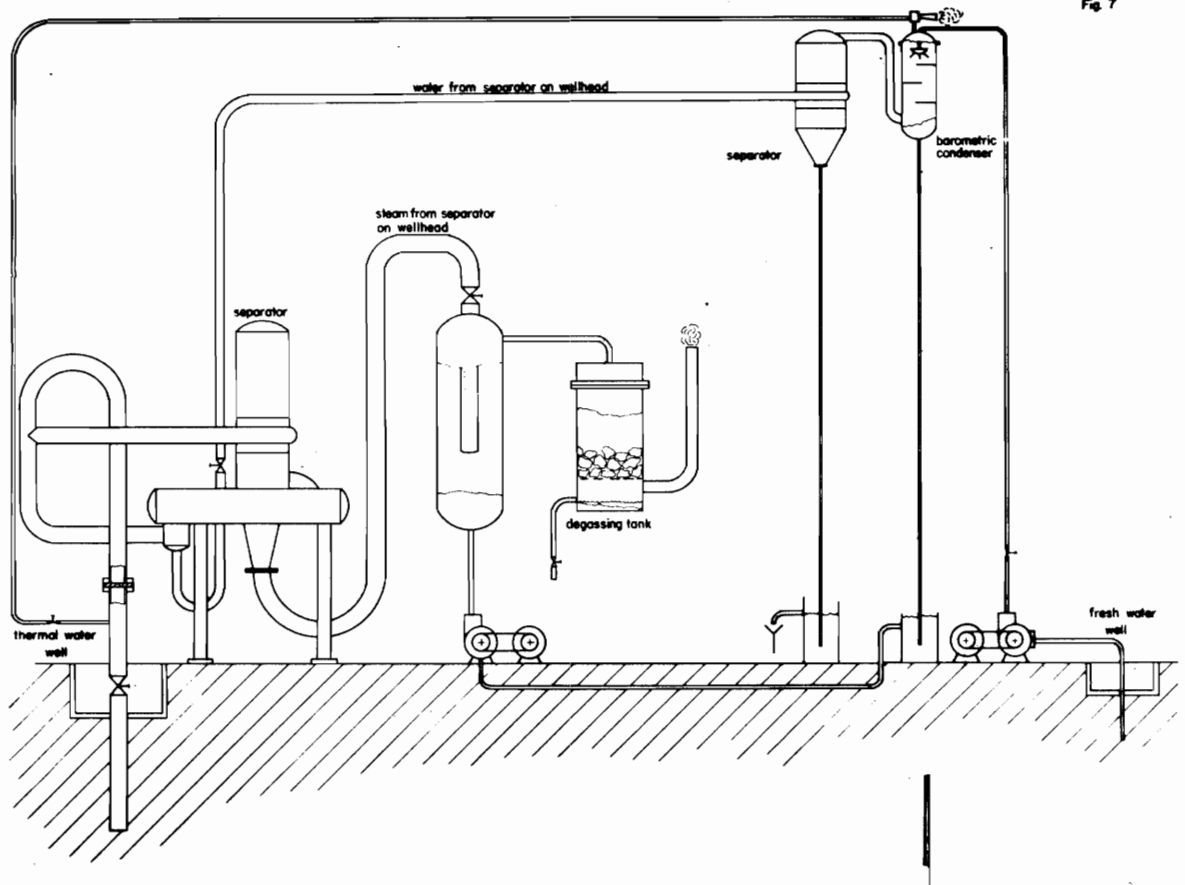


Fig. 9

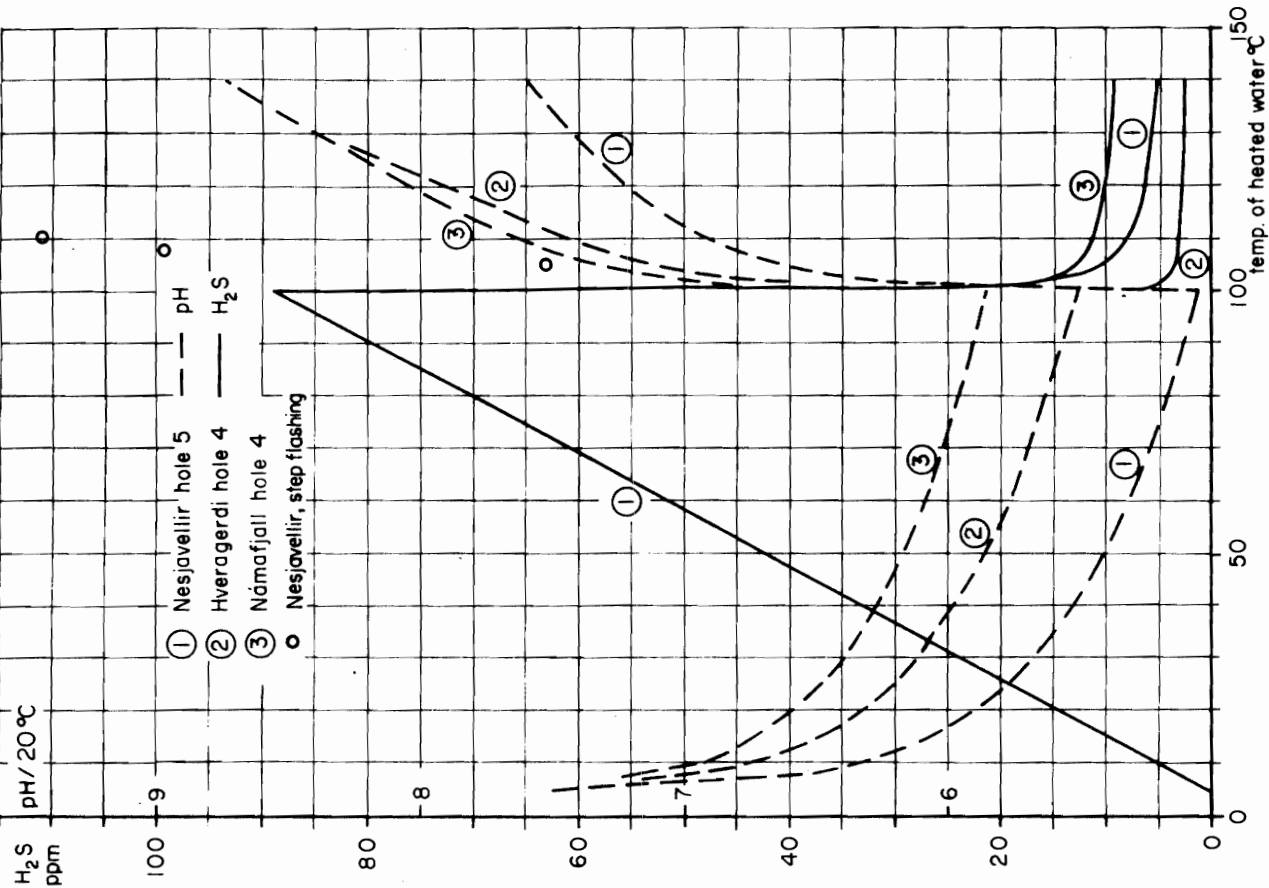


Fig. 8

