National Energy Authority
Reykjavík, Iceland.

OSJHD 7527

EXPLOITATION OF SALINE HIGH-TEMPERATURE WATER FOR SPACE HEATING.

Stefán Arnórsson; Karl Ragnars; Sigurður Benediktsson; Gestur Gíslason; Sverrir Thórhallsson; National Energy Authority, Reykjavík, Iceland; Sveinbjörn Björnsson; Science Institute, Reykjavík, Iceland; Karl Grönvold; Nordic Volcanological Institute, Reykjavík, Iceland; Baldur Líndal; consulting engineer, Reykjavík, Iceland.

Second United Nations Symposium on the Development and Use of Geothermal Resources, San Francisco, U.S.A., May 20-29, 1975.

EXPLOITATION OF SALINE HIGH-TEMPERATURE WATER FOR SPACE HEATING

Arnórsson, Stefán; Ragnars, Karl; Benediktsson, Sigurdur; Gíslason, Gestur; Thórhallsson, Sverrir; National Energy Authority, Reykjavík, Iceland; Björnsson, Sveinbjörn, Science Institute, Reykjavík, Iceland; Grönvold, Karl; Nordic Volcanological Institute, Reykjavík, Iceland; Líndal, Baldur; consulting engineer, Reykjavík, Iceland.

ABSTRACT

Pilot plant tests carried out in the Svartsengi high-temperature area, SW Iceland, show that direct heating of fresh water with steam derived from the 235°C saline geothermal water, yields hot water with good qualities for space heating and domestic use. The fresh water is heated to 110-120°C and flashed at 1 atmosphere pressure to degas it. During degassing, O_2, that was originally in the fresh water, is removed, and CO_2 and H_2S, which are derived from the steam, are substantially lowered. At the same time the pH is raised. Other heat exchange methods were tested but the direct heating method is no doubt most economical and technically superior. Flashing of the heated water in steps would still improve the effective energy utilization.

It is the chemical composition of the steam and fresh water respectively that determine the quality of the heated water, and the extent of the degassing. It seems likely that the direct heating method could be applied generally, when, otherwise unsuitable, geothermal fluids are intended for space heating.

It is planned to exploit the saline high-temperature water in Svartsengi for house heating for all the larger communities in the western part of the Reykjanes Peninsula and the international airport at Keflavík. The estimated energy consumption is about 80 MW (thermal). Exploratory drilling has been completed and 4 wells are available for utilization with a total capacity of 70-80 MW. The exploitation stage will be reached in 1976-77.

INTRODUCTION

In 1971 two shallow wells (240 and 400 meters) were drilled in the Svartsengi high-temperature area on the Reykjanes Peninsula with the aim of recovering hot water for space heating for the neighbouring village, Grindavík, 5 kilometers to the south. Both wells proved to be highly productive having total mass flow of about 130 kg/sec with a feeding temperature of 210° and 230°C. The water in these wells was quite saline, or about 2/3 the salinity of sea water. This had been suspected by comparison with the Reykjanes thermal brine area, which is located about 20 kilometers to the west (see Björnsson et al., 1972). Bedrock resistivity was very low (less than about 5Ωm) in the area, also suggesting saline hot water. It was evident after this drilling that the high-temperature water could not be used directly for space heating because of its salinity. Transfer of the geothermal heat into fresh water was required for such exploitation.

In early 1973 a feasibility report, including plans for heat exchange pilot plant tests, was submitted by the National Energy Authority (Björnsson and Ragnars, 1973). In this report space heating of all the major towns and villages, including the international airport and NATO base at Keflavík, was taken into consideration assuming that a heat exchange plant would be located at Svartsengi and the heated fresh water piped at 100°C to these communities (fig. 1). The energy comsumption is estimated at 80 MW thermal referring to cooling of the water from 80° to 40°C in the central heating systems. 80 MW thermal corresponds to about 480 liters per sec of hot water.

The pilot plant tests were carried out in 1974 and a heat exchange method was developed that involves direct mixing of fresh water with the geothermal steam. This method is evidently the most economical of those tested.

Two deep wells were drilled in 1974, being about 1500 meters and 1700 meters deep. Both proved to be highly productive each yielding about 80 kg/sec of water and steam with a feeding temperature of about 235°C. The four wells in the area yield sufficient steam for an 80 MW heat exchange plant, but it is to be expected that the output of the wells will decrease at the initation of continued production so a production capacity in the long run corresponding to 55 MW thermal seems to be a reasonable estimate.

Detailed design of the heat exchange plant is now under way as well as the design of main and distribution pipelines. It is planned to have a 4 MW heat exchange plant errected by the end of 1975, which suffices for the village of Grindavík to the south, and gain experience in operating the heat exchange plant before construction in full dimension will be initiated about one year later. Thus it is planned that all the major communties will benefit from the exploitation of the Svartsengi geothermal field by 1977. This exploitation is a matter of high economic importance since space heating by oil is estimated to cost about 3 times that by the geothermal energy.

METHODS OF HEAT EXCHANGE

Four methods of heat exchange were considered when designing the pilot plant. They are: (1) direct heating of fresh water with steam, (2) indirect heating with steam, (3) indirect heating with water, and (4) indirect heating with the application of water as a heat transfer medium in a closed system. The pilot plant was designed in such a way that all these methods could be tested separately and in different combinations. Besides, a barometric condenser was fitted to the plant so steam could be produced by flashing to low pressures and used directly or indirectly for heating. The fresh water used for the tests was obtained from one of the water supply wells of Grindavík. The steam was derived from one of the shallower geothermal wells. The composition of both is presented in tables 1 and 2.

Indirect heating by the water fraction from the geothermal well 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 70°C. Substantial silica scaling had formed during this period of time. Therefore, it was clear that this heat exchange method was inadequate. Silica is poor conductor of heat and any deposition will significantly reduce the efficiency of the heat exchanger. The temperature of the water feeding the geothermal well used in the experiment is about 230°C. The concentration of the dissolved silica in the feeding water is governed by quartz solubility but precipitation of silica from the flashed water is not expected until opal saturation is reached. This occurs at about 125°C (fig. 2). Indeed no silica scaling was observed in the above mentioned experiment nearest to the entrance point of the 140°C geothermal water. In general it may be stated that indirect heating with high-temperature geothermal water is not feasible due to silica scaling. It depends on the feeding temperature of the geothermal water and the pH of the flashed water fraction at what temperature opal saturation is reached. Due to the relatively high salinity of the Svartsengi high-temperature water and therefore rather low pH, flashing does not cause sufficient rise in pH to bring about any ionization of the dissolved silica. The ionized silica does not participate in the equilibrium with the solid phase and a rise in pH, which brings about such ionization, lowers the opal saturation temperature. It seems conceivable to use the flashed water of high-temperature fluids for indirect heating of fresh water if the outlet temperatures are above the opal saturation point but for most geothermal waters this would imply an ineffective energy recovery.

Indirect heating with steam was not tested for a long period. Upon condensation of the steam, the carbon dioxide, which accompanies it, will partly dissolve in the condensate and render it acid and corrosive to ordinary steel. A pH of 3-5 has been measured in the condensate and the carbon dioxide is in the range of 500-1000 ppm. Indirect heating with the application of water as a heat exchange medium in a closed system was not tested.

Direct heating of the fresh water with steam derived from the geothermal water yields hot water that proved to have good quality for space heating. The direct heating involved mixing of steam and fresh water in two steps and, after final heating to more than 100°C in the second step, flashing in an open tank to degas the hot water. In the first step steam at about 50°C, derived from the separator joined to the barometric condenser, is mixed with the fresh water, which is preheated in the process to about 40-45°C. This preheated water is subsequently mixed with steam derived directly from the separator on the wellhead. In the degassing tank most of the carbon dioxide and the hydrogen sulphide, which accompanies the steam, is removed from the water and into the steam which forms. At the same time the pH of the heated water is substantially raised. If no degassing occurs, the pH of the heated water is in the range of 6-7 depending on the extent of geothermal steam in the mixture. During degassing the pH is raised to as much as 9. The final pH value depends on the extent of the degassing which is expressed by the amount of flashing in the tank and determined by the temperature, or more precisely the enthalpy, of the finally heated fresh water. The construction of the degassing tank is also of importance. Blocks of basaltic scoria were placed in the tank to facilitate the degassing.

The oxygen which is originally in the fresh water is all removed during the degassing. Indeed most of it is removed during the preheating in the barometric condenser and it seems possible to remove practically all of it at this stage in the heating process by heating the water very close to its boiling point at the pressure existing in the barometric condenser. The preheated water, if containing some oxygen, is obviously highly corrosive.

The steam that is formed through the flashing in the degassing tank contained some 2000 ppm of carbon dioxide, 30 ppm of hydrogen sulphide, 40 ppm of oxygen and had a pH of about 2. All these values depend of course on the extent of steam formation. Yet, it seems certain, due to the corrosive character of the steam, that it may not be feasible to use it for indirect heating. Therefore, thermal energy, which corresponds to the steam formation in the degassing tank is wasted. A compromise between the quality of the heated water and the effective energy utilization has therefore to be found since both are determined by the extent of flashing but in opposide ways. It would be advantageous to let the flashing occur in steps to get more effective degassing for a given amount of steam separation. According to thermodynamic calculations flashing in two equal steps from 105°C to 100°C causes equal degassing as flashing in one step from 135°C to 100°C.

3 QUALITY OF HOT WATER OBTAINED BY DIRECT MIXING OF FRESH WATER WITH GEOTHERMAL STEAM

The quality for space heating of the fresh water heated directly with geothermal steam is determined by the chemical composition of the fresh water and steam respectively, and the flashing in the degassing tank. The important quality parameters are taken to be pH and carbon dioxide and hydrogen sulphide concentrations. In evaluating the reliability of the pilot plant tests the possibility had to be taken into account that the compositions of the geothermal steam and the fresh water would be different in future production wells compared to those used in the tests. The geothermal well used for the pilot plant tests is about 400 meters deep and much shallower than was planned for production wells. Aquifers feeding 1500-2000 meters deep wells could be expected to have compositions different from shallow aquifers close to or in the flashing zone, particularly with respect to their volatile content. (Deep drilling in the summer of 1974 showed that this was not the case, table 1.) It was also clear that the fresh water from the supply well in Grindavík, used in the tests, could not be assumed to be representative for waters from future production wells. The fresh water in the Reykjanes Peninsula forms a lense, which floats on top of a more dense sea water. The sea water percolates into the bedrock as a result of its extremely high permeability. Diffusion of dissolved solids from the underlying saline water into the fresh water lense causes considerable variation in the dissolved solids content of the latter. The available data indicate a concentration of several hundred ppm of chlorine by the coast where the lense is very thin but several tens of ppm in the central part of the peninsula where the ground water table is about 4 meters above sea level and therefore some 140 meters thick (table 2). Apparently, the largest ground water shed in the western part of the peninsula occurs to the northwest of the geothermal field (see fig. 1), where the ground is also relatively low (30 meters above sea level) and it is planned to locate fresh water production wells here.

The evaluation of the applicability of the pilot plant tests involved calculation of the pH of heated fresh water and its carbon dioxide and hydrogen sulphide contents from known fresh water and steam compositions. Detailed account of these calculations have been given by Arnórsson and Sigurdsson (1975). Their calculated results compare rather well with those of the experimentally determined values obtained during the pilot plant tests (fig. 3), suggesting that the calculations can be relied upon to some extent in predicting what tolerance is acceptable in fresh water and steam compositions for production of heated water by the direct mixing method. The results of Arnórsson and Sigurdsson (1975) indicate that the water feeding the geothermal wells may contain as much as 3000 ppm of carbon dioxide and few tens of ppm of hydrogen sulphide without a significant effect upon the quality of the heated fresh water. The water feeding the well used in the tests at Svartsengi contains about 160 ppm of carbon dioxide and about 4 ppm of hydrogen sulphide. Expected variations in pH and the silica content of fresh water is 6-8 and 10-40 ppm respectively. This variation was not detected in the calculated results. The concentration of carbon dioxide has, on the other hand, some effect on the final pH of the heated water. Thus, lowering of CO_2 from 44 ppm to 22 ppm produced a calculated lowering of the pH of the heated by about 0.2 pH units. This pH lowering is hardly significant. It was, therefore, concluded from the mentioned calculations that direct heating of fresh water with geothermal steam at Svartsengi will produce good quality hot water for space heating as regards expected limits of fresh ground water and geothermal water compositons. The calculations indicate that flashing in steps in a series of degassing tank demands much less steam separation than one flashing step does for production of good quality hot water (see fig. 3). Step flashing presents therefore one way of improving the effective energy utilization of the geothermal fluid.

It is emphasized that direct heating of fresh water with steam derived from high-temperature geothermal water may be applied generally where hot water is required for space heating, but it is well known that such geothermal waters cannot be used directly, mostly due to silica scaling, which sets in after sufficient cooling of the geothermal water has occurred to reach opal saturation. The salinity of the geothermal water will, as a rule, not be significant for the success of the direct heating method although degassing of very dilute geothermal waters upon flashing is only partial. Geothermal waters containing high concentrations of hydrogen sulphide, such as all the low-salinity high-temperature waters in Iceland, will always yield hot water, which is produced by the direct mixing method, that contains substantial concentrations of this compound (5-20 ppm) or well above accepted limits for domestic use. These hydrogen sulphide waters will, however, be acceptable for space heating.

EFFECTIVE ENERGY UTILIZATION OF THE DIRECT HEATING METHOD

A flow diagram is presented in figure 4 which describes in outline the proposed arrangement of the heat exchange plant. A separator will be located on top of each well, and the water and steam phases emerging from these separators are piped separately to the plant. The water fraction from all the geothermal wells is piped to one major separator where steam, that has formed through the pressure drop during transport, is separated from the aqueous phase. The high pressure steam from the separator on the wellhead is partly used in a gas ejector and in a turbo-generator. It is estimated that the electric consumption of the heat exchange plant, mostly for pumping, is 10 KW for each MW thermal produced. The steam emerging from the turbo-generator is again mixed with the rest of the high pressure steam and the steam from the main separator. This mixture is piped to the steam injector where it is used in the final step of heating the fresh water.

The water fraction from the main separator is piped to a low pressure (0.20 ata) separator attached to a barometric condenser. The steam that forms is led to the barometric condenser where it condenses in the cold fresh water and preheats it to about 53°C. The 60°C water fraction from the low pressure separator is discharged.

The figures presented in figure 4 indicate the amount of steam, geothermal water and fresh water involved in the various stages of heating for production of 6 l/sec of hot water at 100°C. For temperature drop from 80°C to 40°C 6 l/sec correspond to 1 MW thermal. This temperature drop corresponds to that of central heating systems where geothermal water is used in the heating.

Maximum thermal efficiency of the proposed heat exchange plant limits the maximum permissibe pressure in the main separator. The steam pressure in this separator determines the ratio of steam piped to the injector and water piped to the low pressure (0.20 ata) separator. Too high pressure in the main separator results in excess production of low pressure steam used in preheating the fresh water. This in turn leads to too much preheating in the barometric condenser, which means higher pressure and less effective energy utilization of the water feeding the low pressure separator. The pressure in the main separator should not be lowered so much that the water reaches opal saturation. If so, silica scaling is expected to occur.

Figure 5 demonstrates equilibrium between low pressure and main separators for different feeding temperatures of the geothermal wells and different thermal efficiency. It is assumed that the fresh water is heated to 110°C before degassing. A roof is put to this relationship by the opal saturation curve. The application of figure 5 is demonstrated by an example where the feeding temperature of the geothermal wells is taken to be 230°C. Equilibrium conditions for maximum thermal efficiency between low pressure and main separators are given in figure 6, when feeding temperature is 230°C.

REFERENCES

Arnórsson, S. and Sigurdsson, Sv., 1975, The utility of water from the high-temperature areas in Iceland for space heating as determined by their chemical composition, Geothermics, in press.

Björnsson, Sv., Arnórsson, S., and Tómasson, J., 1972, Economic evaluation of the Reykjanes thermal brine area, Iceland, Bull. Amer. Ass. Petrol. Geologists, v. 56, p. 2380.

Björnsson, Sv. and Ragnars, K., 1973, District heating supply from Svartsengi, unpublished report to the National Energy Authority, Reykjavík, in Icelandic.

CAPTION TO FIGURES

1. Location of towns and villages in the Reykjanes Peninsula that will benefit from the exploitation of the Svartsengi geothermal field. When the heat exchange plant will reach full capacity, it will produce hot water for space heating amounting to 180 MW thermal or about 480 liters per sec of water at 100°C.

2. 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 the flashing brings about no significant ionization of the dissolved silica.

3. Variation in pH and total carbonate with temperature of fresh water heated directly with steam. If the fresh water was heated above 100°C, it was subsequently flashed to 100°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 compositions of fresh water and steam used in the experiments are given in table 2. Calculated variation in pH and total carbonate is given for comparison.

4. A flow diagram for the heat exchange plant where cold water is heated by mixing with steam in two steps, or steam from the low pressure separator by the barometric condenser and steam form the main separator.

5. A diagrammatic illustration of the effective use of heat from the geothermal fluid (of various temperatures) for different separation pressures in main separator and low pressure separator.

   The temperature difference between low pressure separtor and barometric condenser is taken to be 7°C. The fresh water is heated from 5°C to 110°C and subsequently flashed to 100°C.

   Example: Feeding temperature of the geothermal well is 230°C. Temp./pressure in low pressure separator is fixed at 60°C/0.20 ata. Temp./pressure will then be 143°C/3 atg in the main separator and the effective use of heat in the geothermal fluid 0.815 for a feading temperature of 230°C and cooling to 40°C. In this case 1 kg/sec of geothermal fluid yields (237 - 40) kcal/kg. 0.815 = 160.5 kcal/sec. This is sufficient to produce 1.69 kg/sec of fresh water at 100°C. For cooling from 80° to 40°C 6 kg/sec of heated water corresponds to 1 MW. Hence, a market requiring 1 MW thermal for space heating needs 6·1.69 = 3.55 kg/sec of geothermal fluid.

6. Relation between temperature/pressure in main separator, low pressure separator and temperature of heated water before flashing to 100°C in the degassing tank. The effective use (η) of the geothermal fluid is also shown for a feeding temperature of 230°C and cooling to 40°C.

TABLE 1

The composition of water feedings wells in the Svartsengi high-temperature area. Concentrations in ppm.

	well 3 (400 m deep)	well 5 (1515 m deep)
Temp. °C	235	238
pH/°C	-	6.15/238
SiO_2	420	438
B	7.8	-
Na^+	6448	6008
K^+	1032	958
Ca^{++}	924	924
Mg^{++}	1.3	7.3
CO_2(total)$^+$	163.3	443.0
SO_4^{--}	31.4	32.5
H_2S(total)$^+$	4.4	2.5
Cl	12888	11433
F^-	0.1	0.16
CO_2 in steam^x	486.1	1288.0
H_2S in steam^x	12.1	7.3

$^+$ Includes dissociated as well as undissociated carbonate and sulphide

^{x} These concentrations refer to complete transfer of these volatiles to the steam phase, which is a fair apporximation when steam is produced by flashing to temperatures as low as 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)	Reykjanes peninsula range (6)	Reykjanes peninsula average (9 anal.)
pH/°C	7.39/20	7.50/20	8.03/20	7.08 - 7.72	7.47/20
SiO_2	32.8	28.1	26.1	10.7 - 31.8	19.3
Na^+	95.2		79.8	28.7 - 232.4	21.3
K^+	4.7		4.0	1.7 - 22.9	6.6
Ca^{++}	19.6		16.1	6.6 - 33.1	17.9
Mg^{++}	17.4		14.0	1.4 - 32.1	16.5
Co_2 total	47.1	44.5	30.0	15.9 - 73.5	33.2
SO_4^{--}	29.6		27.6	11.9 - 60.9	29.4
H_2S total	<0.1	<0.1	0.24	<0.1	<0.1
Cl	206.0		172.5	53.5 - 434.5	231.0
F^-	0.15		0.20	<0.1 - 0.15	0.1

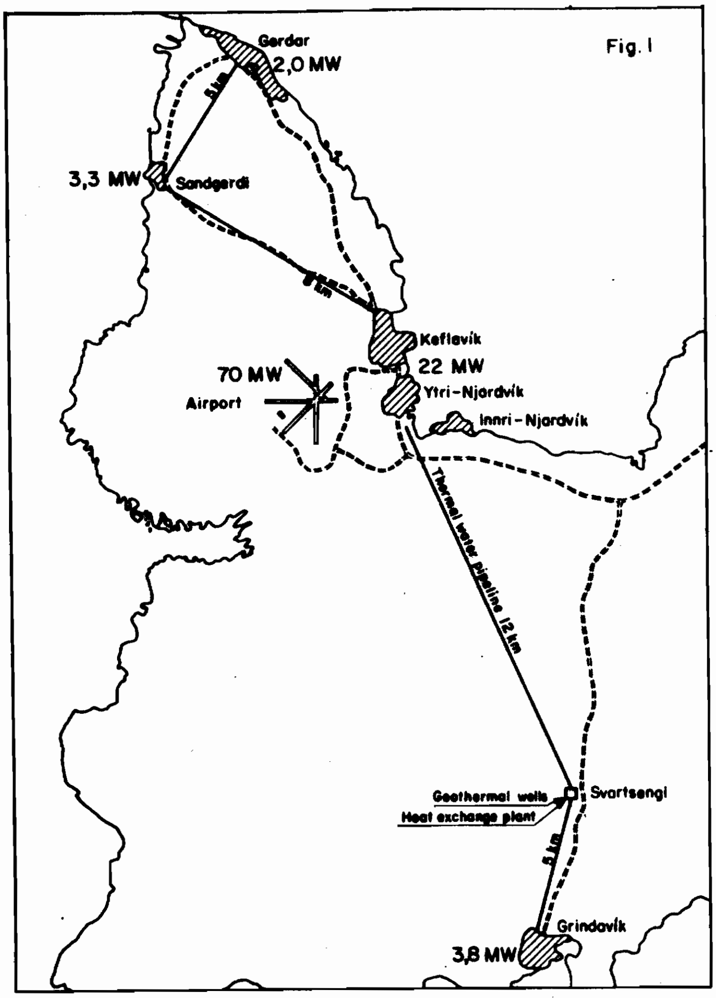


Fig. 1

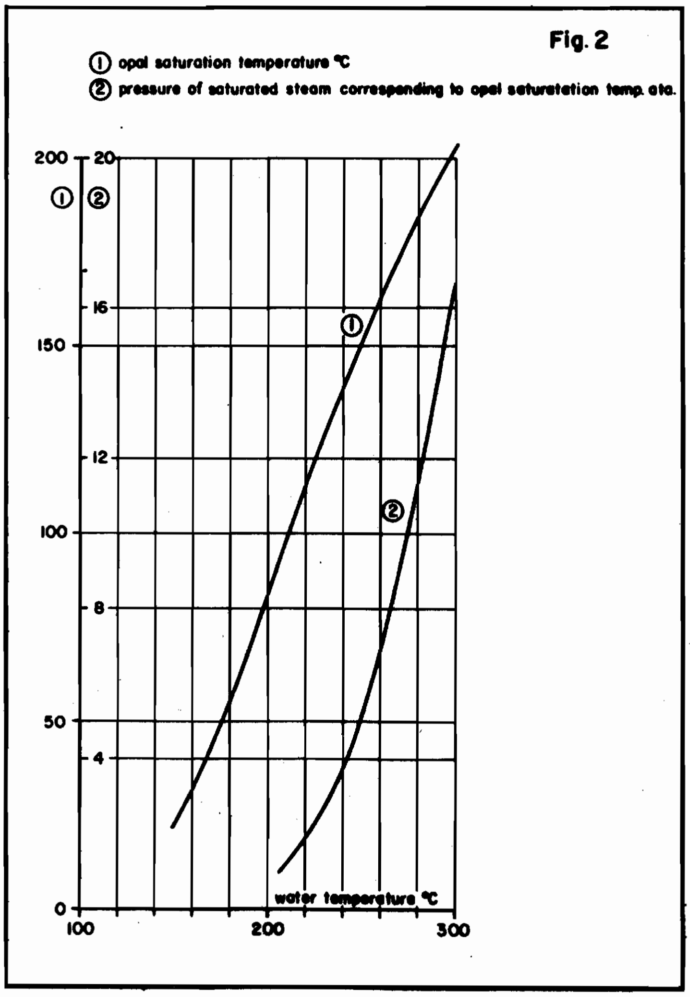


Fig. 2

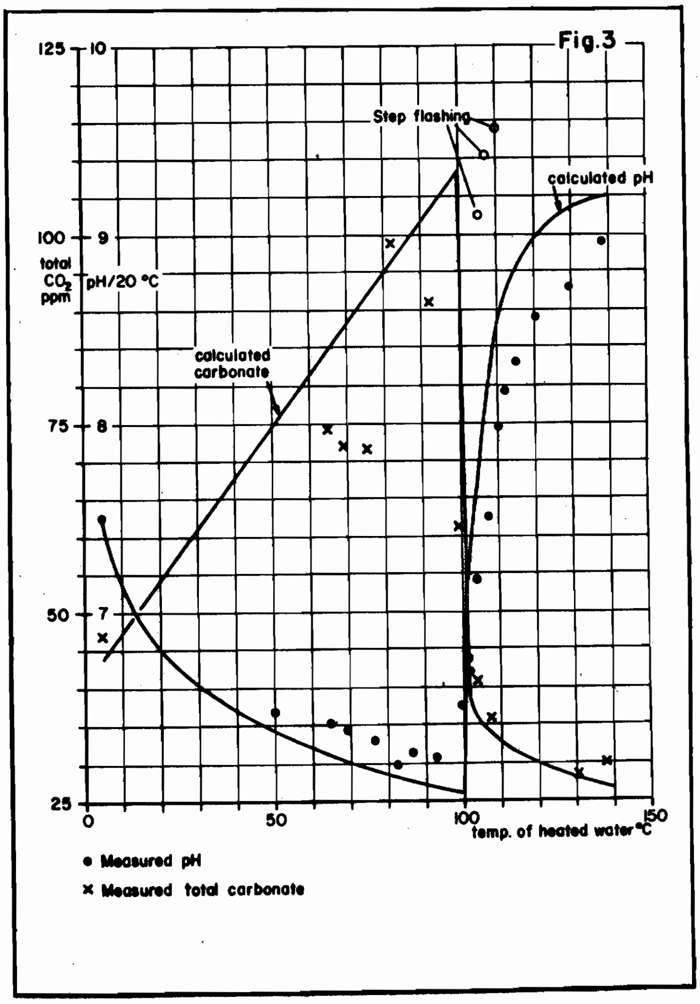


Fig. 3

FIG.4

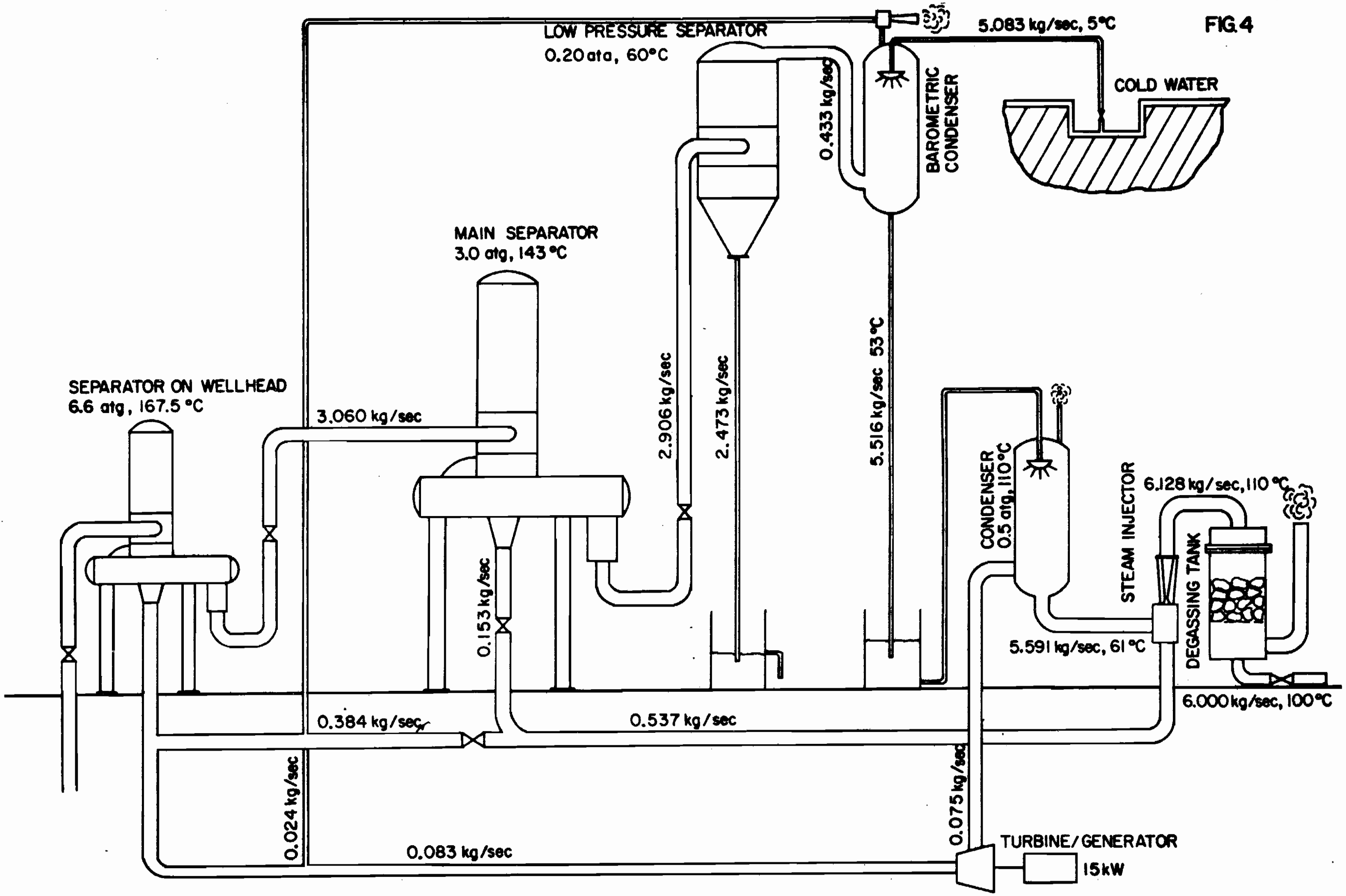

LOW PRESSURE SEPARATOR
0.20 ata, 60°C
5.083 kg/sec, 5°C
COLD WATER
BAROMETRIC CONDENSER
0.433 kg/sec
MAIN SEPARATOR
3.0 atg, 143°C
SEPARATOR ON WELLHEAD
6.6 atg, 167.5°C
3.060 kg/sec
2.906 kg/sec
2.473 kg/sec
5.516 kg/sec 53°C
CONDENSER
0.5 atg, 110°C
STEAM INJECTOR
6.128 kg/sec, 110°C
DEGASSING TANK
5.591 kg/sec, 61°C
6.000 kg/sec, 100°C
0.153 kg/sec
0.384 kg/sec
0.537 kg/sec
0.024 kg/sec
0.083 kg/sec
0.075 kg/sec
TURBINE/GENERATOR
15 kW

FIG.5

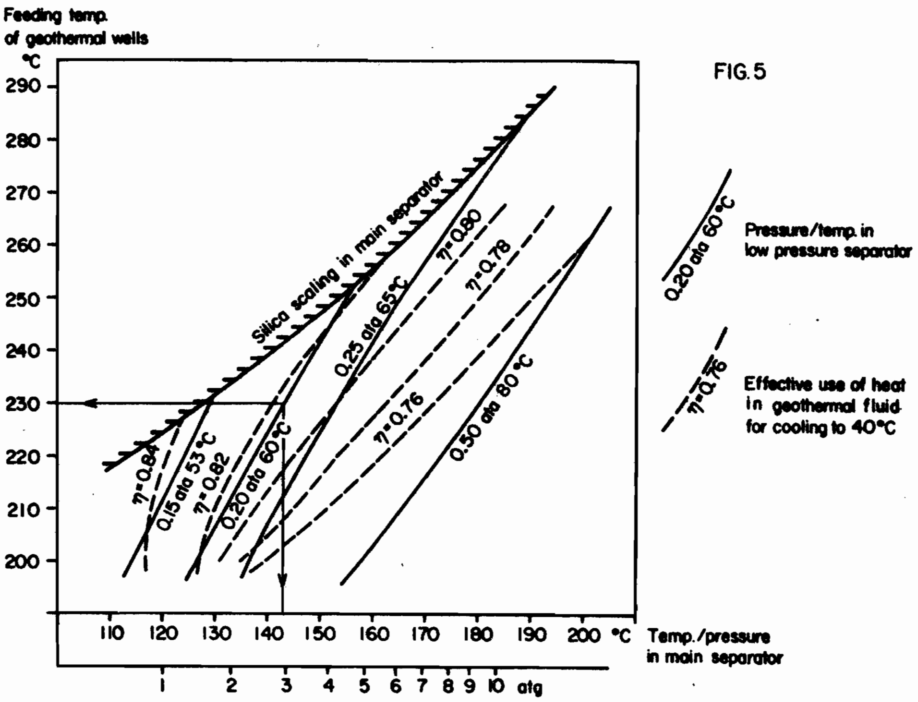
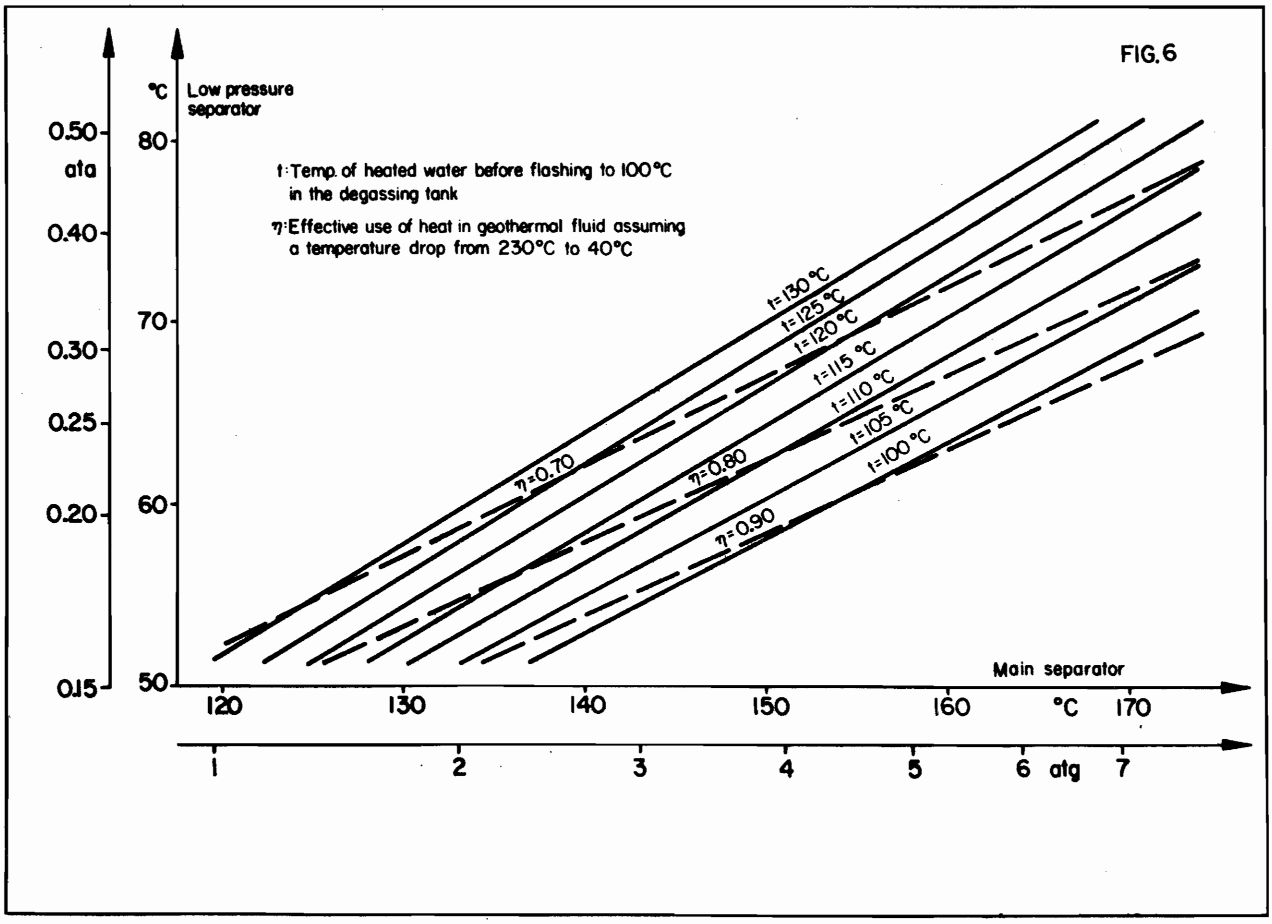

Feeding temp. of geothermal wells
°C
290
280
270
260
250
240
230
220
210
200
Silica scaling in main separator
η=0.84
0.15 ata 53 °C
η=0.82
0.20 ata 60 °C
0.25 ata 65 °C
η=0.80
η=0.78
η=0.76
0.50 ata 80 °C
110 120 130 140 150 160 170 180 190 200 °C
Temp./pressure in main separator
1 2 3 4 5 6 7 8 9 10 atg
0.20 ata 60 °C
Pressure/temp. in low pressure separator
η=0.76
Effective use of heat in geothermal fluid for cooling to 40 °C

FIG.6


0.50
ata
0.40
0.30
0.25
0.20
0.15
°C
80
70
60
50
Low pressure separator
t: Temp. of heated water before flashing to 100 °C in the degassing tank
η: Effective use of heat in geothermal fluid assuming a temperature drop from 230 °C to 40 °C
t=130 °C
t=125 °C
t=120 °C
t=115 °C
t=110 °C
t=105 °C
t=100 °C
η=0.70
η=0.80
η=0.90
Main separator
120 130 140 150 160 °C 170
1 2 3 4 5 6 atg 7