

DEPOSITION - THE GEOTHERMAL CONSTRAINT

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The world wide status of geothermal energy developments are reviewed and the opportunities for its utilisation emphasised.

Several different methods of recovering the energy contained in geothermal fluids are discussed briefly including; total flow systems, district heating, power generation, heat exchangers and desalination. The major obstacle in all applications appears to be the deposition of dissolved solids from the geothermal fluid onto surfaces. The paper discusses the relationship between underground and surface conditions on the solubility of dissolved salts and the effects upon utilisation of the energy. Disposal of these solids could represent a problem but at the same time could be overcome by providing a source of valuable raw material.

The paper outlines experimental work on the deposition of dissolved minerals from geothermal waters onto surfaces particularly as it affects energy transfer. The fouling of heat exchanger surfaces is shown to follow a linear relationship with time for low velocities. At higher flow rates the relationship appears to be asymptotic.

The main conclusion of the paper is that an understanding of the mechanism and quantitative data on deposition is essential for the successful utilisation of geothermal energy.

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INTRODUCTION

The rapid depletion of fossil fuels has stimulated interest in other forms of energy amongst which is the utilisation of the heat of the earth itself. The emphasis is on the effective exploration of known areas of geothermal activity and in the search for new locations of steam and hot water. More recently there has been an interest in the use of artificially created sources of steam and hot water.

The temperature of the earth increases with depth. Heat is being generated within the earth and conducted to the surface. The average temperature increase with depth (temperature gradient) is about $30^{\circ}\text{C}/\text{km}$ (1,2,3), and the average heat flux at the surface has been estimated as $0.06 \text{ W}/\text{m}^2$ (2,4).

The first electricity generating plant based on naturally occurring steam was built in 1904 at the Larderello field in Italy (5). Since that time there has been slow, but fruitful development in the technology of utilisation, and in 1970 the electrical output of the Larderello field had risen to about 400 MW. A number of other countries where geothermal activity occurs have also contributed to the developments in different applications including Hungary, Iceland, Indonesia, Japan, Mexico, New Zealand, the U.S.A. and U.S.S.R. The utilisation of the geothermal energy in Iceland has recently been outlined (7) demonstrating how it can be used for district heating, in horticulture, and for industry, in addition to the generation of electricity. The temperatures of the geothermal sources exploited by man range from above ambient to near critical (8). These temperatures arise in different geothermal systems for which several classifications have been suggested (2,9,10). These classifications may be either for geological or technological (or engineering) uses, the latter being of interest for the purposes of this paper.

There are two basic types of geothermal areas: convection and conduction. The convection areas occur where the rock is permeable to water. Cold water percolates down to hot regions and is heated before rising to shallower levels. These areas are termed hydrothermal convection systems and account for virtually all the geothermal energy utilised by man (1). Conduction areas occur where a thermal availability exists but the hot rock is not permeable to water. These areas are not well known and have not yet been exploited (2).

The hydrothermal areas may produce hot water, steam-water mixtures or superheated steam; traditionally these have been referred to as hot water, wet steam and dry steam fields respectively. From the point of view of utilisation it is convenient to classify geothermal areas according to Figure 1. The difference between steam and water dominated areas has been discussed by White et al (11) and the difference between high and low temperature water dominated areas by Bodvarsson (12). Low temperature water dominated areas are those with reservoir temperatures less than 150°C . High temperature water dominated areas are those with reservoir temperatures greater than 150°C but usually greater than 200°C . The steam dominated areas are those that produce predominantly steam from a reservoir temperature approximately 240°C , and they account for probably only 5 per cent of all geothermal systems with reservoir temperatures greater than 200°C (10).

It is suggested that the classification should include a reference to the solids content to draw attention to the practical difficulties of utilisation (see Figure 1). The classification reflects changing composition from geothermal waters with compositions similar to ground water through concentrations similar to sea water and up to highly concentrated brines.

The steam dominated fields are probably the easiest to exploit for two reasons:-

1. The enthalpy of one kilogramme of dry steam is higher than the heat content of one kilogramme of water at the same temperature and pressure.
2. The mineral content of the steam is small (or non-existent) although there is likely to be contamination from gases such as CO_2 and smaller amounts of H_2S , N_2 and NH_3 . The presence of these gases particularly those that are acidic in nature, can give rise to corrosion problems in the equipment handling the steam (13).

The use of water dominated fields present two major problems for the utilisation engineer, in addition to potential corrosion problems, which are directly related to the dissolved solids:-

1. The deposition of solids (possibly in conjunction with corrosion) in processing equipment and transfer lines with a resultant loss of operating efficiency.
2. The environmental problem of the rejection of hot waste waters usually containing suspended finely divided solids. Discharge to rivers may cause ecological difficulties or silting problems and rejection into the geothermal field itself may cause restricted activity due to 'plugging' of the porous rock structure.

The geological and chemical factors give rise to a spectrum of solutes and solute concentration that is extremely complex and the interaction of the factors will vary even within the same field and certainly in different parts of the world. Ellis (14) concludes that roughly two categories of dissolved solids may be defined:-

1. 'Soluble' elements (of which there are very few) including chloride, bromide, iodide, boron, cesium, lithium and ammonia under high temperature deep water conditions.
2. Elements with concentrations controlled by mineral equilibria constrained by the temperature and pressure conditions. For example the concentration of silica in water of known systems above about 150°C is controlled by the solubility of quartz (15). The ratio of sodium to potassium is considered to be associated with the feldspar equilibria (16).

In recent years there have been developments towards the use of the heat contained in 'dry rock' at great depths (3). In this technique heat energy is extracted by pumping down to the rock a heat transfer medium (say water) and returning it to the surface. The engineering developed for crude oil production can be adapted and holes of up to

9 km (17) have been drilled though 4-6 km is likely to be more acceptable and economic. The technique has problems additional to those associated with the use of 'natural' geothermal energy, particularly as far as the recovery of the heat is concerned since the deep rock, say granite, does not transfer heat effectively. Some additional technique of rock disintegration below ground may be required in order to improve the heat transfer effectiveness. Difficulties associated with dissolved solids can be anticipated just as with the use of 'natural' geothermal activity.

Despite the problems it is important to develop applications for the low enthalpy water as these can make a valuable contribution to the energy position in relation to domestic heating, horticulture, and possibly some industrial situations. Interest in the U.K. will probably be centred upon these applications (18).

Geothermal sources in the U.K. are limited to conduction (hot rock) and low temperature (hydrothermal) areas (2). In the low temperature Bath-Bristol area waters at temperatures approaching 50°C have been measured. There are indications that the reservoir temperature of the area might be higher. From warm springs in Derbyshire and Nottingham, waters close to 60°C could be available, and in Cheshire, Worcestershire and Hampshire waters near 100°C might be obtained. There are other potential low temperature water dominated areas in the U.K. Waters in the temperature range 60-100°C are probably most economically used for district heating or greenhouse heating. Geothermal areas of great interest in the U.K. are the potential conduction areas in Cornwall and Durham. These areas are not permeable to water. Any extraction of the heat contained in the dry hot rock must involve deep drilling, fracturing of rock and circulation of water through heat exchangers. The technology for hot rock exploitation is still being developed.

UTILISATION METHODS

Most of the geothermal energy extracted from the earth is used for generating electricity (1). Because geothermal sources occur usually remote from large centres of population, they have to be utilised locally for electrical generation. It is therefore, not surprising that 80 per cent of the extracted heat is used for producing electricity.

The estimated world generating capacity at the end of 1975 was about 14000 MW (6,10). About 70 per cent of the installed capacity is in steam-dominated areas. Although the steam areas have not been fully exploited, most future increases in the extraction of geothermal energy, must come from areas dominated by hot water. For future developments concentration of effort must be made in utilising hot water dominated areas.

Direct Flashing

In this technique the fluid is brought to the surface, flashed, and the steam produced is used for power generation in conjunction with a turbine.

The power plants generating electricity from geothermal areas producing steam-water mixtures are of three basic types as shown in Figure 2. In all the plants the geothermal steam is used directly in

the turbines. The simplest of these power plants is the non-condensing type; the steam leaving the turbines is exhausted to atmosphere. The plants are simple in operation but not very efficient. The more common power plant condenses the steam leaving the turbine and these plants are of two types: 'single-flash' and 'double-flash'. The designs are improvements on the non-condensing plant.

The reservoir temperature of the hot water areas utilised are in the range 200-300°C (8). At lower temperatures the amount of steam produced by flashing, to any reasonable turbine inlet pressure, is probably too small for economic generation of electricity. Presently, the lower limit is considered to be about 180°C (1,10).

If hot water at 200-300°C is flashed down to 150°C, the mass of steam produced will be in the range 10-30 per cent of the total fluid. In all the operational geothermal power plants utilising steam-water mixtures, the large quantities of hot water are discharged at 50-150°C without further use and the thermal efficiency of these plants is therefore very low. To improve the efficiency it is important to utilise the heat energy contained in the reject water. The operational temperature range of 50-150°C is also characteristic of the low temperature hydrothermal areas, as classified above. The use of the reject water from power plants operating in high temperature areas and the water produced by low temperature areas, may generally, be considered together.

Binary Cycles

The binary cycle (19) offers the possibility of generating electrical power from geothermal fluids with reservoir temperatures less than 200°C. The flow diagram of the cycle is shown in Figure 3 but power plants of this type have only been operated for experimental purposes. In the binary cycle a hydrocarbon working fluid is heated/evaporated/super-heated in heat exchangers and then expanded directly in a specially designed turbine. Isobutane has been suggested as a possible working fluid. Assuming a suitable fluid is available, the efficiency of this binary cycle depends largely on the heat exchange process. For a 50 MW binary cycle plant it has been estimated that 30-40 per cent of the cost will be for heat exchangers (20). The main exchangers, extracting the heat from the hot geothermal fluid, are estimated to account for about half the exchanger cost or 15-20 per cent of the total costs. An optimum heat exchanger design is therefore crucial in determining the viability of binary cycle power generation.

The need for optimisation is reflected in the search for suitable heat exchange methods, in order to reduce or eliminate the fouling problem. One solution involves a modified version of the concept of multistage flash as used in desalination (21). A different approach attempts to use direct contact heat exchange (20).

Total Flow

In high temperature areas the single flash and binary cycle power plants have similar efficiencies. For a geothermal area with reservoir temperature of 300°C the efficiency for conversion from thermal to electrical energy has been estimated as only 11 per cent (22). A power

cycle utilising most of the thermal energy of steam-water mixtures has been proposed (22); the total flow cycle, as shown in Figure 4. The steam-water mixture from the borehole is fed directly through a convergent-divergent nozzle and a specially designed turbine. For a geothermal reservoir temperature of 300°C the efficiency for conversion from thermal to electrical energy has been estimated as 26 per cent, or 60 per cent higher than the 11 per cent for flash and binary plants.

Fresh Water Production

Waters from high temperature areas need not be used for power generation only; they are ideal for desalination in arid areas providing power and fresh water at the same time (23) (24). The requirements as regards water salinity are similar for desalination and district utilities involving space heating and domestic hot water. In a high temperature area a novel method is being used to produce hot fresh water. The technique consists of a two stage flash separation down to 50°C with concentrated brine being rejected at that temperature. The steam is injected into the fresh water, the resulting hot water is degassed at approximately 100°C before being distributed (7).

THE SILICA CONSTRAINT

With most geothermal waters, corrosion is likely to occur. Standard methods may usually be employed to reduce the problem of corrosion such as is done in low temperature areas producing water for district heating (25,26).

The problem of deposition of dissolved constituents appears to be limited to high temperature areas. It has long been recognised that silica is the major substance giving rise to deposition and that other compounds present only a secondary problem. The behaviour of silica in geothermal waters may therefore be the major constraint on the utilisation of geothermal energy.

Of the several forms of silica that exist in equilibrium with water, quartz is the most stable and amorphous silica the least stable. Quartz is therefore the least soluble and amorphous silica the most soluble (27). In high temperature areas the amount of silica dissolved in the reservoir fluid depends on the solubility of quartz (15,28). It has, however, been demonstrated that amorphous silica is the form which precipitates from geothermal and other aqueous solutions on concentration and cooling (27-30). The solubility of quartz and amorphous silica in water is shown in Figure 5 (31).

The principal form of dissolved silica in water is monosilicic acid H_4SiO_4 which is a weak acid and therefore practically undissociated in neutral solutions (32). In basic solutions when the $pH > 9$, however, the acid dissociates and increases the total solubility of silica considerably (33). The solubilities shown in Figure 5 are for neutral conditions.

When a solution saturated with silica is cooled, the excess silicic acid will polymerize until a new equilibrium is reached (27, 31, 34-36). In an alkaline solution the polymerization gives rise to negatively charged colloids (34,35). Geothermal waters are usually neutral or

basic (28).

Excess silicic acid will also deposit and form hard scales. The reaction involved is one of dehydration as is the polymerization process (34,35). In geothermal solutions supersaturated with silicic acid, there are therefore two competing removal processes; polymerization and deposition. The role of colloidal silica in deposition is not clear. It has, however, been suggested that colloidal silica does not form a hard scale and that the problem of silica scaling might be reduced by allowing supersaturated solutions to polymerize before passing through pipes and equipment where deposition occurs (37). This can only reduce the problem if the geothermal water is not to be cooled further during utilisation, which is unlikely to happen.

The reservoir temperature of geothermal areas utilised for power generation is in the range 200-300°C (8). The composition of geothermal waters involving say the concentration of dissolved silica, depends to a large extent on mineral equilibria with water (14). The reservoir temperature will therefore determine the amount of silica present in the water. It is fortunate that silica precipitates out as amorphous silica, but not as quartz, because the water can be brought to the surface and allowed to flash and cool before reaching the solubility limit where deposition occurs. The reservoir temperature will effectively set the lowest temperature the geothermal waters may be used without deposition being a problem.

Geothermal waters in high temperature areas may be brought to the surface in two ways; by allowing the fluid to flow by pressure reduction and partial flashing, or by pumping with a 'down-hole' pump and maintaining the reservoir pressure. In all geothermal areas used for generating electricity the former method is used. Because steam is being formed when geothermal water flashes in a borehole, the temperature at which deposition from the residual water is likely to occur will be higher than had the water been kept under pressure during cooling. This is illustrated in Figure 5 for a reservoir temperature of 250°C where sensible cooling leads to deposition at about 103°C with flashing at 140°C. The possible effect of flashing on the pH value and therefore total solubility, has not been included. This demonstrates clearly the constraint put on geothermal development by the deposition of silica.

In all the power plants generating electricity from geothermal steam in high temperature water dominated areas, the residual hot water is discharged into rivers, the sea and cooling ponds. This can lead to environmental problems. A possible solution would be to reinject the residual water into the ground by pumping it down a borehole. This would replenish the reservoir fluid being withdrawn and prevent such problems as land subsidence. Waters supersaturated with silica, however, are not easily reinjected into porous rock because of deposition. Reinjection wells are likely to block up rapidly, requiring frequent and costly replacements. Before reinjection the silica must therefore be separated out. The settled silica could provide a raw material for such processes as sodium and potassium silicate manufacture or other silica chemicals, thereby helping to improve the economics of the overall process.

DEPOSITION STUDIES

Recognising that deposition is likely to be a major constraint in the utilisation of geothermal energy it is important to study deposition effects. The results obtained for any particular geothermal water will be directly related to the field of origin and it would be difficult to draw generalised conclusions from specific tests. Nevertheless specific data are of considerable value in guiding developments and demonstrating the potential effects of differing parameters. Foremost attention to problems relating to heat transfer is necessary but the effects of deposition on pressure loss in flowing systems is also of importance.

Some Published Results

Some small scale tests to evaluate a shell and tube heat exchanger extracting heat from a geothermal brine at Heber in California have been reported by Lombard (38). The geothermal brine inlet temperature to the tubes of the exchanger was about 180°C and it contained 14,500 ppm of dissolved solids. Scale deposited in the tubes reduced the overall heat transfer coefficient with time. Three tube materials were tested including carbon steel, titanium and a 90% copper - 10% nickel alloy. Tests were conducted in a range of brine velocities between 1.52 and 6.10 m/s (5-20ft/sec) inside the tubes. As the brine velocity increased over the range the rate of decline in the heat transfer coefficient increased suggesting that the scale deposition is a function of brine velocity (and heat flux) over the time of exposure which was up to 600 hours.

Optimum brine velocities for this particular system were in the range 1.52 - 2.13 m/s (5-7 ft/sec). Pressure drop changes were negligible over the period of the test.

In addition to the effects of velocity and heat flux scale formation also seemed dependent upon the material from which the tubes were made; the copper-nickel alloy appeared to scale much more rapidly than the carbon steel or the titanium tubes which resembled each other in performance. It is possible that the scaling is directly related to the effects of corrosion. There was no evidence of corrosion with the titanium tubes after 560 hours of test and the carbon steel showed only mild corrosion over a similar period. On the other hand corrosion of the copper-nickel alloy was evident after an exposure of 200 hours and they appear to corrode much faster than the carbon steel under similar conditions.

Some effects due to temperature were apparent; as the brine temperature fell to around 65°C deposition increased.

Experimental Work

A plate heat exchanger and simulated tubular heat exchangers were used in experimental investigations on geothermal water in Iceland. Deposition and fouling studies were carried out at Svartsengi and Hveragerdi, both situated in the south-west of Iceland. These geothermal areas are within the active volcanic zone lying across Iceland and produce steam/water mixtures (7). At Hveragerdi the geothermal fluid is of rain water origin but at Svartsengi the fluid originates from

sea water.

The brine used at Svartsengi came from a 402 m borehole with a base temperature of 212°C. The steam/brine mixture was separated in a cyclonic separator with a small fraction of the brine used in the plate heat exchanger and tubular heat exchanger experiments. The exchangers were on the same site as the borehole and separator such that the brine, supersaturated with silica, passed through the exchangers seconds after being separated. The brine fed to the tube heat exchangers was obtained by flashing off the geothermal steam/brine mixture at 100°C, whereas the fluid entering the plate heat exchanger resulted from flashing at 150°C. Since both streams were from the same boreholes, the dissolved solids content of the brine to the tube heat exchanger was greater, as shown in Table 1.

TABLE 1 - Composition of Geothermal Waters used in the Experiments

Measurement	SVARTSENGI		HVERAGERDI
	Plate Heat Exchanger	Simulated Heat Exchanger Tubes	Simulated Heat Exchanger Tubes
pH/°C	7.65/20	7.50/25	9.46/23
SiO ₂	569.5	581	305
Na ⁺	8100	9700	155.4
K ⁺	1630	1385	12.9
Ca ⁺⁺	1182	1227.4	3.21
Mg ⁺⁺	1.3	5.93	0.25
Cl ⁻	15920	16125	126.2
F ⁻	0.1	0.16	2.3
SO ₄ ⁻⁻⁻	33.3	37.6	54.9
CO ₂ [*]	22.7	19.3	119.2
H ₂ S ^{**}	0.1	0.1	4.74
Dissolved Solids	27856	29642	777.0

* H₂CO₃ + HCO₃⁻ + CO₃⁻⁻⁻

** H₂S + HS⁻ + S⁻⁻⁻

All concentrations in ppm.

At Hveragerdi the geothermal water was taken from the district heating mains. The water comes from two boreholes about 500 m outside the town. These boreholes are 400 and 695 m deep, both with a base temperature of about 200°C. The steam/water mixture from the boreholes is separated at atmospheric pressure, the water fraction being piped to the town and arriving in the experimental heat exchangers some 20-30 minutes later. Simulated tubular heat exchangers were used at Hveragerdi.

The tubular heat exchangers were manufactured from 316 stainless steel with a 0.048 in thick wall. The main tube of the exchangers was 0.5 in O.D. tube 2 m long. The first 50 cm acted as an entry section and a further 150 cm was surrounded by a 0.75 in O.D. cooling jacket. The exchangers were thermally insulated. The tubes were mounted vertically and operated in a co-current mode at Svartsengi but in a counter-current mode at Hveragerdi. At the inlet and outlet of all streams temperatures were measured by mercury in glass thermometers. From the heat exchanger tubes all streams were fed to a weighing tank and drain.

At Svartsengi the geothermal brine was fed directly from the cyclonic separator to the tubular heat exchangers. Similarly, the cooling water was fed directly from the water mains. At Hveragerdi, however, considerable fluctuations existed in the hot and cold water mains. Automatic pressure regulators were therefore installed at the hot and cold water inlets to the exchangers. With the passage of time there was a tendency for the flowrate of the geothermal waters, at both locations, to decrease gradually due to increased pressure drop resulting from deposition in the pipelines and exchangers. To overcome the problem flowrates were adjusted each day to the required value. The flowrate of the cooling waters remained constant during the experiments.

The plate heat exchanger used at Svartsengi was an Alfa-Laval P22 exchanger. The exchanger had 13 plates made of 316 stainless steel and 0.51 mm thick. Each plate had a developed heat transfer area of 0.12 m², making the total heat transfer area 1.32 m². The plate heat exchanger operated in counter-current mode.

Temperatures of all streams entering and leaving the exchanger were measured by mercury-in-glass thermometers. Inlet and outlet pressures of the brine were measured. From the plate heat exchanger both brine and cooling water were fed to a weighing tank and drain.

The heat exchanger tubes were used as received, as was the plate heat exchanger. The experimental method consisted of regular adjustment of the flowrates to the required values and measuring the inlet and outlet temperatures. Adjustments were made at least once every day, sometimes more often. The composition of the geothermal waters used in the experiments is given in Table 1. The experimental conditions used in the deposition and fouling studies are summarised in Table 2.

The results obtained under the different conditions were quite different in nature. At Svartsengi it is considered that the equipment arrangement was such that the silica was present in molecular form. At Hveragerdi however, some colloidal silica might have been present because there was a possibility that sufficient time had elapsed for silicic acid in solution to polymerize and form colloidal particles.

TABLE 2 - Summary of the Experimental Conditions

Run No.	Average inlet bulk Temperature of geothermal brine (°C)	Solubility limit (°C)	Reynolds number of geothermal brine inside tube
Svartsengi 2	90	143	44293
Svartsengi 3	90	143	39036
Svartsengi 4	150	140	6673
Hveragerdi 1	80	74	43650
Hveragerdi 2	80	74	22605
Hveragerdi 3	80	74	7299

As a measure of the inefficiencies created by the fouling effects it is sufficient to note the changes in the estimated fouling resistance. Visual observations after the tests revealed that the deposition had in fact occurred on the geothermal water side only, which means that the change in fouling resistance is directly related to the silica deposition.

Figure 6 shows the fouling resistance for both the plate and tube heat exchangers increases linearly with time. Even after 1000 and 800 hours respectively there is no change in the rate of increase in the fouling resistance. There are insufficient data to enable conclusions as to the direct effects of velocity to be made.

Figure 7 shows results obtained at Hveragerdi. For the tests at the two higher Reynolds numbers the apparent fouling resistance actually decreases for a period after the commencement of the tests reaching a minimum at about 300 hours. After this initial decrease the fouling resistance increased with time and was still increasing when the tests were stopped at 2000 hours from the beginning of the experiment.

The negative value of the estimated fouling resistance at the beginning of the tests is due to the inadequacies of the correlations used in the calculations which do not take full account of the true hydrodynamic conditions.

At the low Reynolds number of 7299 for the geothermal water flow, no large reduction of the fouling resistance is observed but for a period of about 800 hours the resistance remains reasonably steady and then begins to increase as time passes.

The improvement of the overall heat transfer coefficient emphasised by the apparent decrease of the fouling resistance in the initial stages of the tests at Hveragerdi is attributed to increased roughness produced by the deposit of silica. The increased roughness would produce a greater degree of turbulence and hence an improved heat transfer

coefficient on the geothermal water side, which could not be allowed for in the calculations of the fouling resistance. Examination of the surface of the deposit from run No. 1 at Hveragerdi showed narrow ridges rising above a relatively uniform rough area, transverse to the direction of water flow. Similarly rippled deposits have been observed in quite different systems such as iron oxide and alkaline scales (39).

CONCLUDING REMARKS

The future expansion in the utilisation of geothermal energy will most likely come from the hot water dominated areas (high and low temperature). The present technology of utilisation has not needed to be particularly efficient, but as the world's fossil fuel reserves continue to decrease it will be important to raise the efficiency of geothermal energy applications.

The major constraints in improving efficiency are the effects which result from deposition from hot geothermal waters. The improvement of efficiency will therefore, depend upon solving the deposition and scaling problems. As far as silica scale is concerned it is indeed fortunate that in effect, there is a time delay factor in the formation of particles potentially available to cause fouling problems. Despite this advantage there is still the need to concentrate on providing a solution to the fouling problem which could account for an increase of up to 40% or more in the heat transfer area and hence in the capital cost of the process plant. Maintenance costs are also likely to be high under these fouling conditions. Even if some secondary medium is used, such as a liquid hydrocarbon, for the transfer of energy to reduce fouling problems, the lower heat transfer coefficients involved will still represent an increase in heat transfer area requirement over that theoretically possible with clean water systems. It is imperative to be in a position to utilise geothermal water directly in any energy recovery system.

Further urgent investigation of the solubility and complex chemical kinetics of solute substances (e.g. silica) is required together with examinations of the mechanism of deposition on surfaces. The use of additives to the water may also reduce its fouling characteristics. It is through a thorough understanding of all aspects that geothermal resources may be fully utilised.

A bonus may accrue from these studies with the possibility of providing chemical raw materials based on the precipitated solutes.

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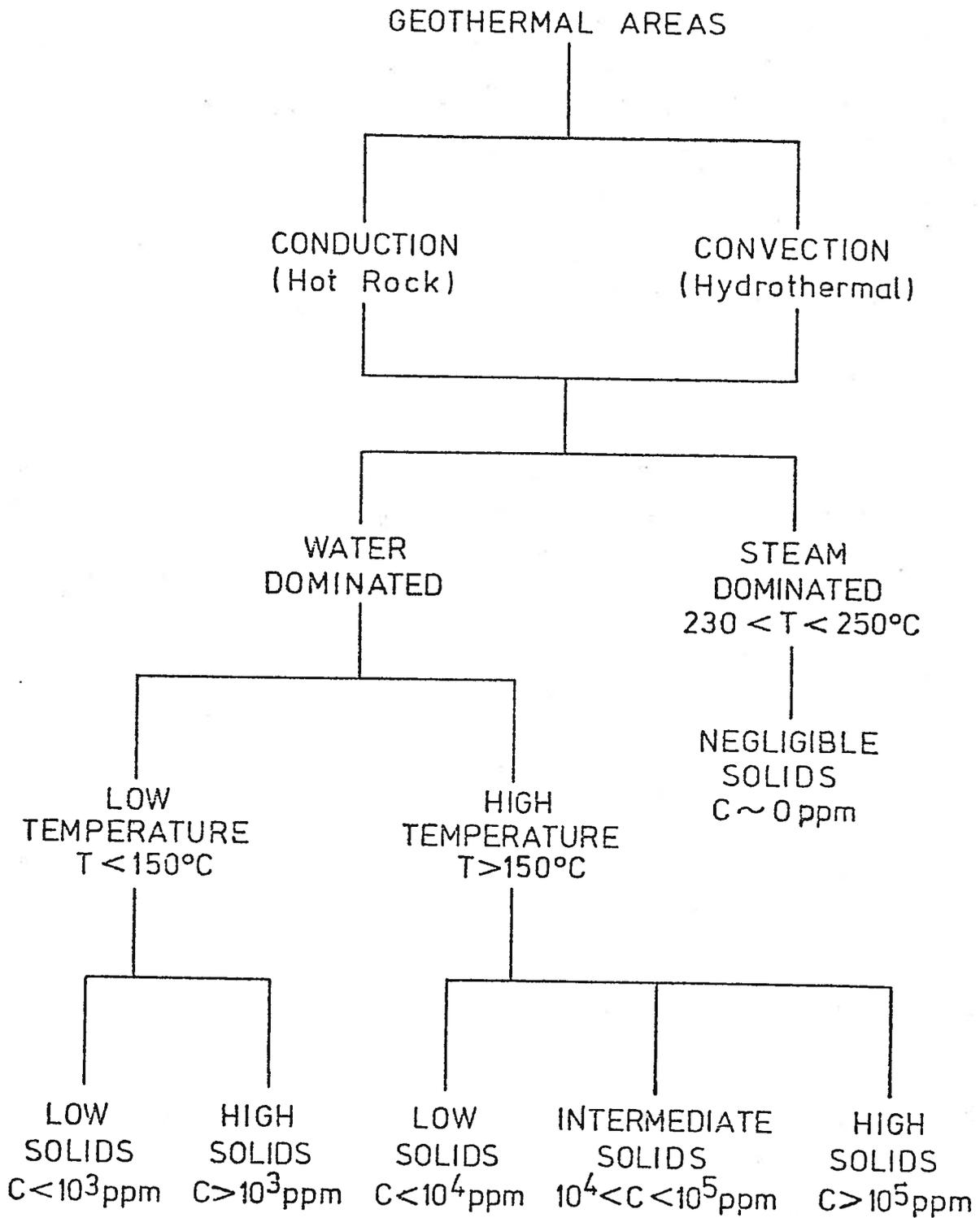
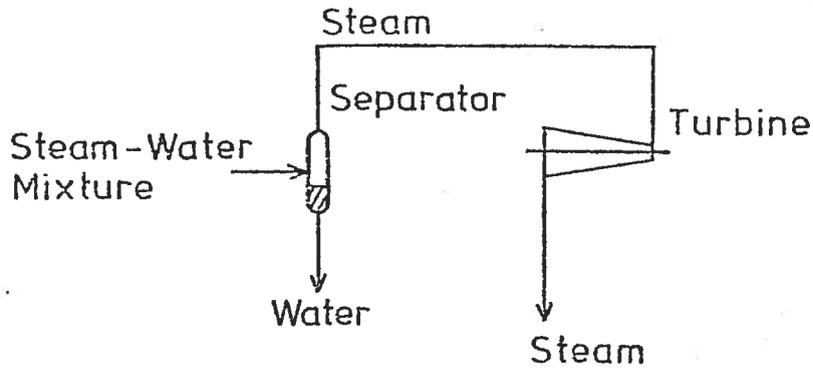
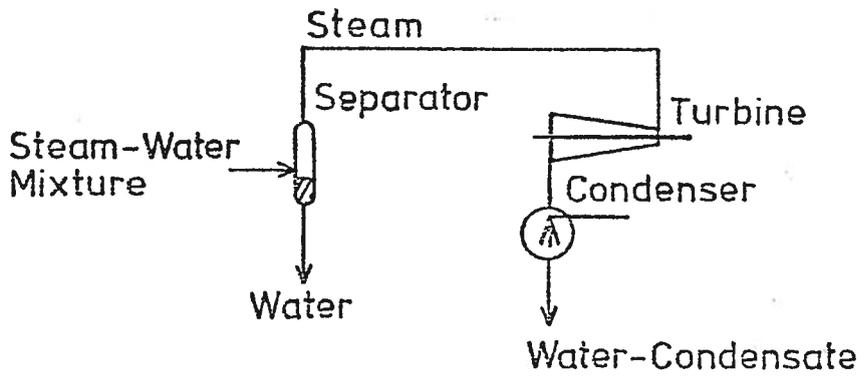


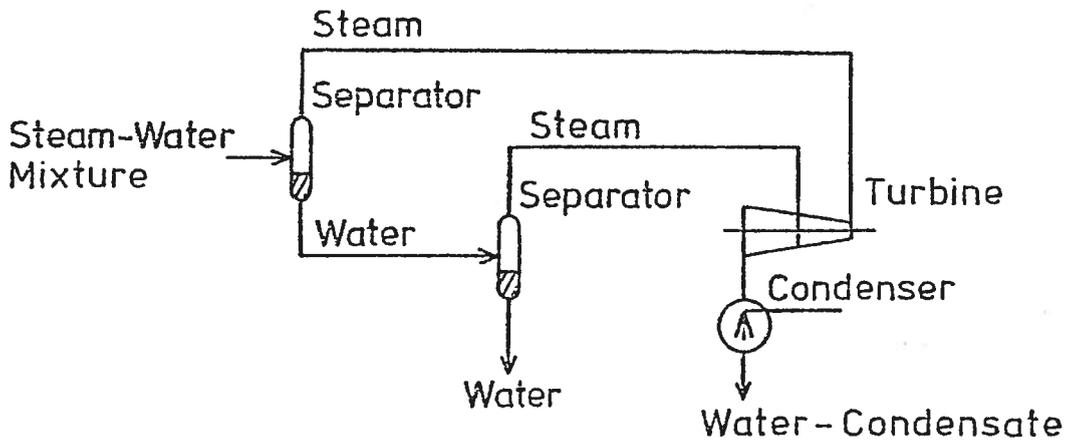
Fig. 1. - Classification of Geothermal Areas



(a)



(b)



(c)

Fig. 2. — Direct flashing power generation, (a) non-condensing, (b) condensing single-stage, (c) condensing double-stage.

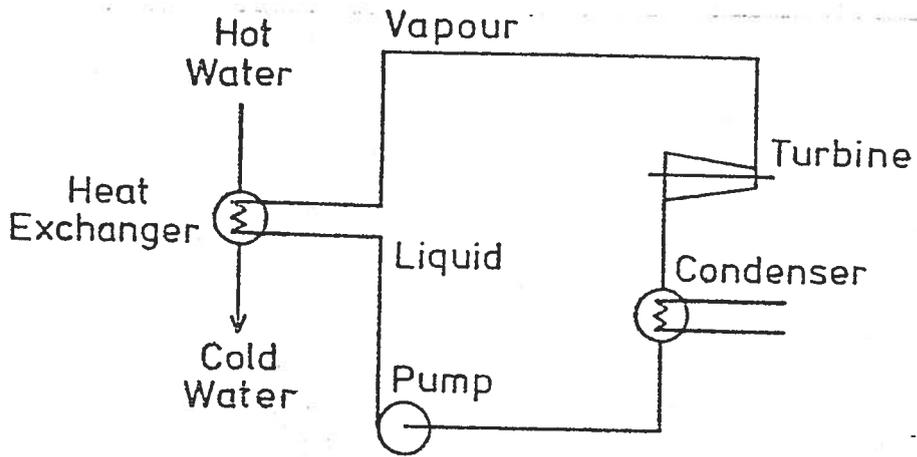


Fig. 3. - Binary cycle power generation.

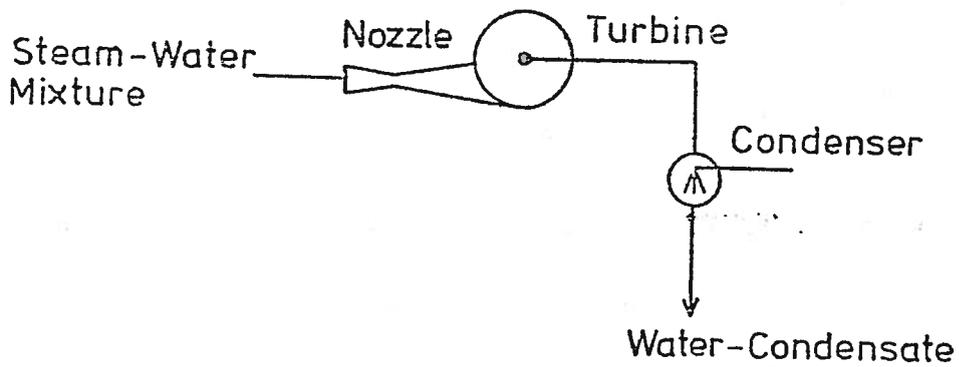


Fig. 4. - Total flow power generation.

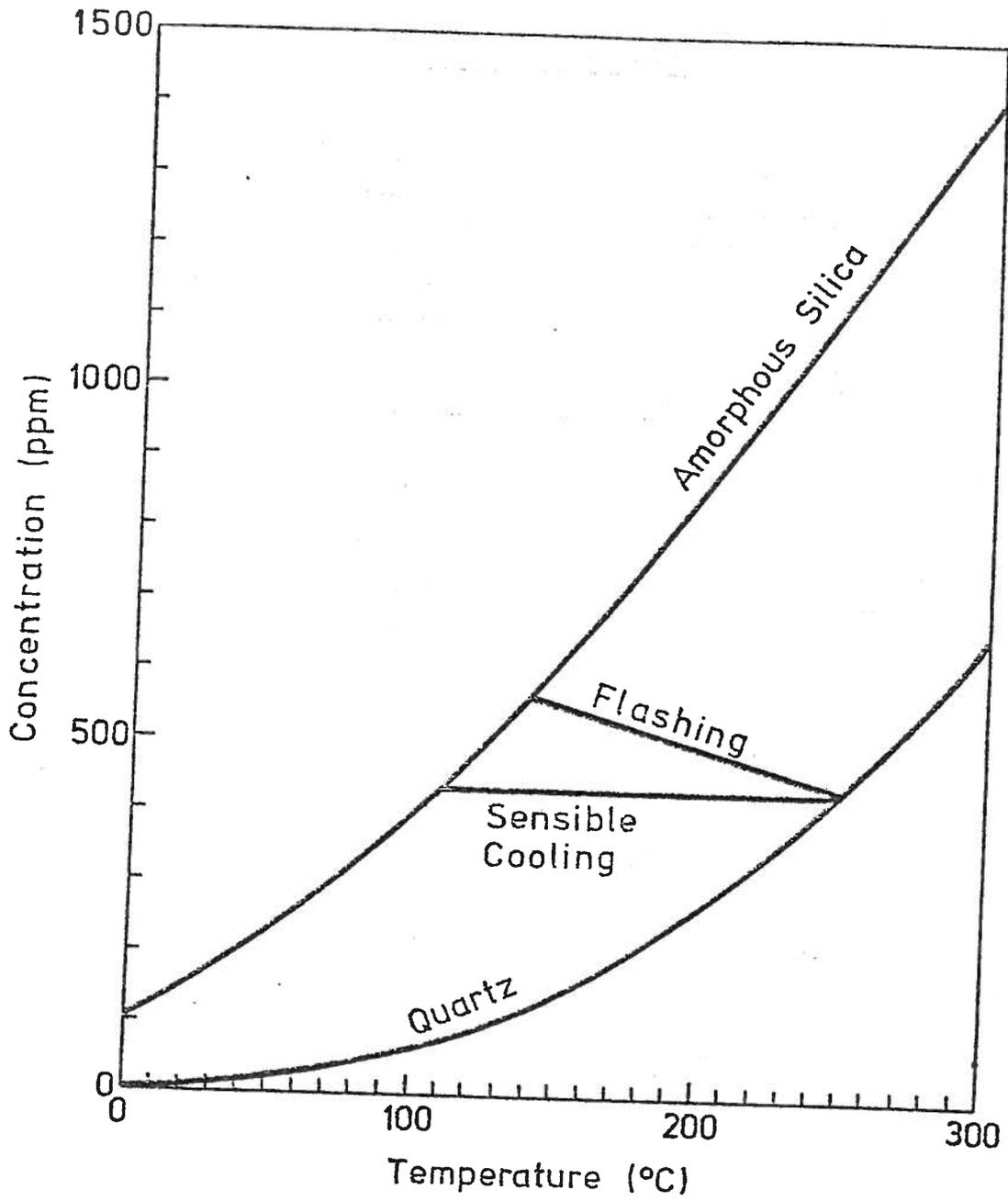


Fig. 5. - Solubility of quartz and amorphous silica (31)

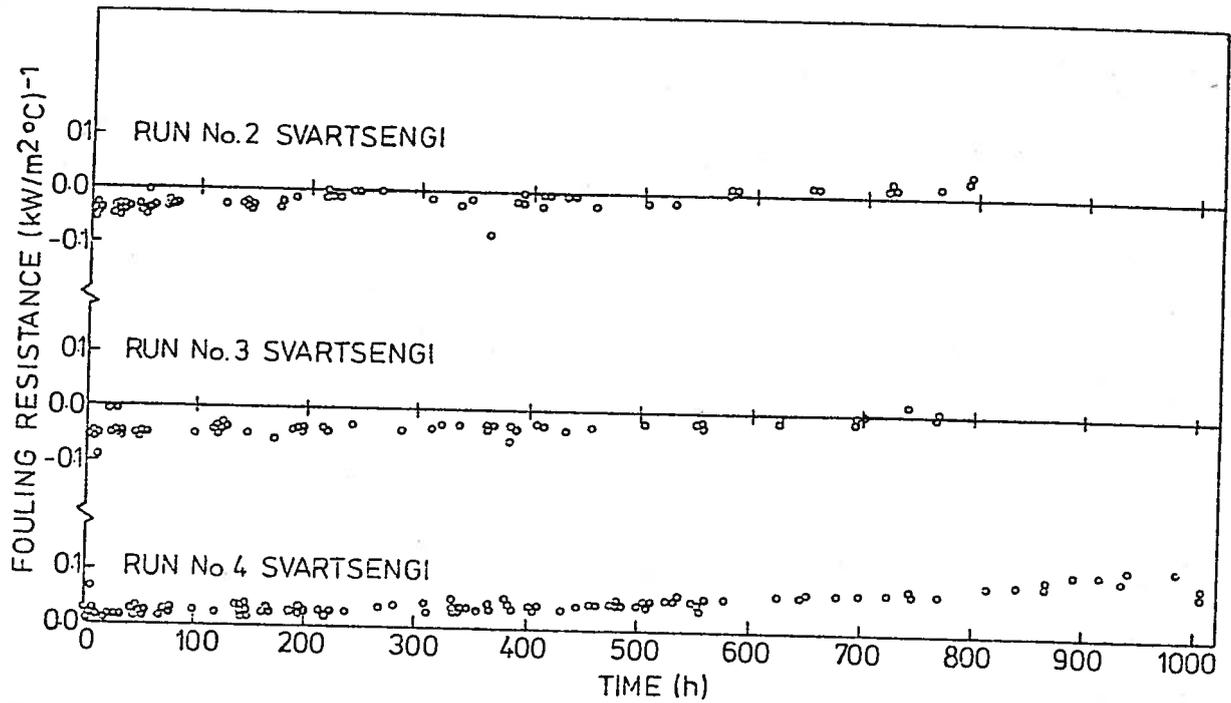


Fig. 6. Change in Fouling Resistance for Tube (Run 2 and 3) and Plate (Run 4) Heat Exchangers with Time.

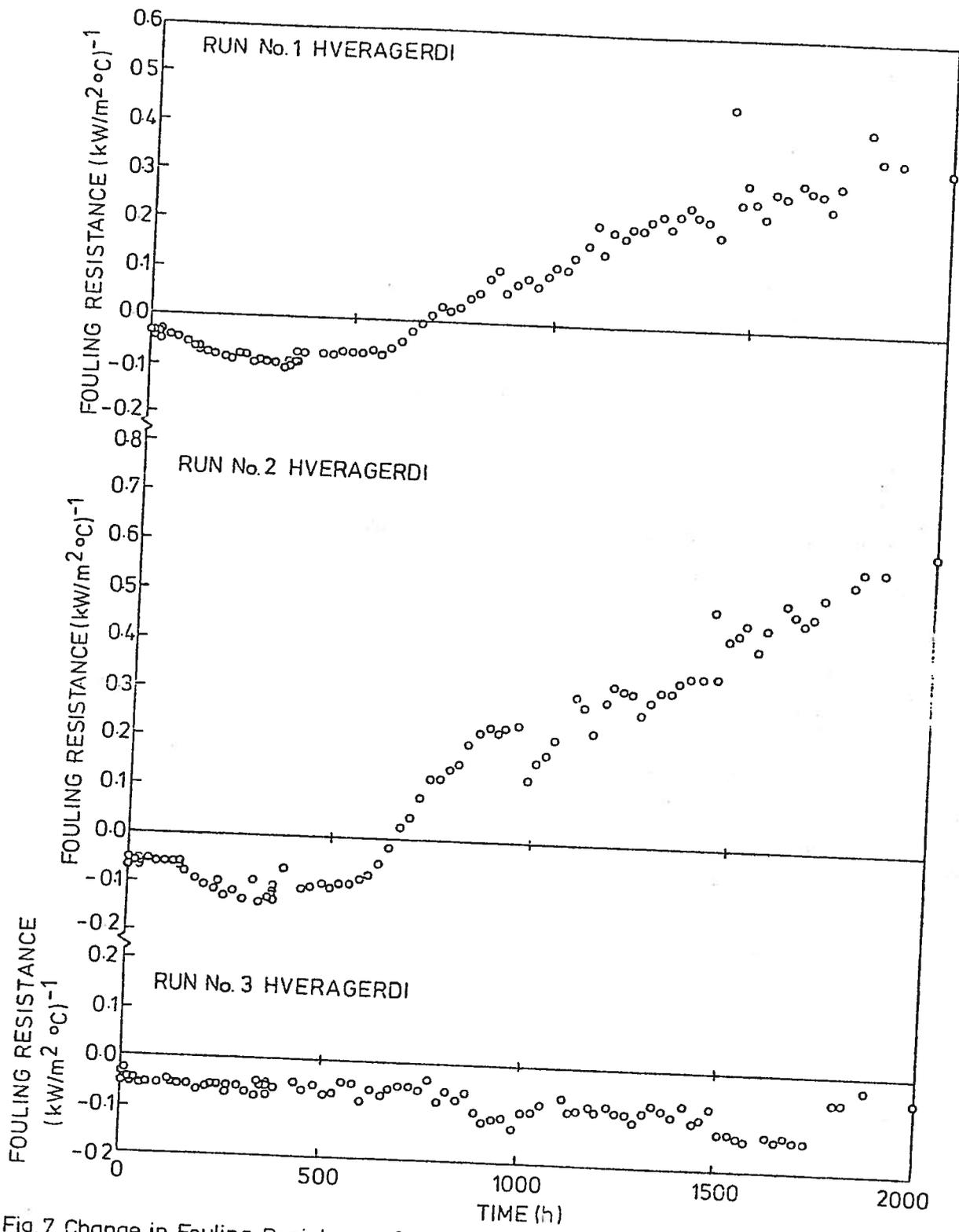


Fig 7. Change in Fouling Resistance for Tube Heat Exchangers with Time.