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COMBINED USE OF GEOTHERMAL ENERGY IN SERIES AND PARALLEL

Eyob Easwaran Narayan

Geothermal Training Programme
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Eyob Easwaran Narayan
UNU Geothermal Training Programme
National Energy Authority
Grensásvegur 9
108 Reykjavík
Iceland

Permanent Address:
Ethiopian Institute of Geological Surveys
Geothermal Exploration Project
P.O. Box 40069
Addis Ababa
Ethiopia

ABSTRACT

The combined use (generation of electricity and district heating) or the direct use (industrial application) of geothermal energy is more efficient from the thermal point of view than that of only generating electricity. Examples generation of electricity and industrial applications in Iceland such as: fish drying and geochemicals extraction at the Reykjanes peninsula, the power plant at Svartsengi and the diatomite plant at Namafjall.

The utilization of geothermal energy for combined use (generation of electricity and drying) both for a production in series and in parallel are analyzed. Two types of rotary dryers, one which is air heated and the other an indirect-heat-rotary-steam-tube dryer are considered for both types of productions and compared. The production in series with the use of a back-pressure turbine and an indirect-heat-rotary-steam-tube dryer is the most advantageous from the total thermal efficiency point of view.

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1. INTRODUCTION

The earth is a great reservoir of heat, but most of its heat is buried too deeply or spread too diffusely to be utilized economically for thermal energy. The observed thermal gradient of the outer crust averages about 33°C/km, which means that water found at depth of 2-3 km can be used for space heating, agricultural, or various industrial purposes.

In certain regions of the earth much steeper temperature gradients occur; sometimes these gradients are as much as one order of magnitude larger. These regions are most commonly associated with volcanic activities and earthquakes. The most important of these zones follows the periphery of the Pacific Ocean along island groups of the mid-Atlantic ridge, and with an easterly branch which passes through the Mediterranean basin across Asia to the Pacific Ocean. Yet another zone approximately follows the direction of the African Rift and the Red Sea. All these zones are interconnected except for a small isolated zone on the Hawaiian Islands.

Geothermal areas are sources of energy which in many cases can be be claimed at a low cost, buy are characterized by relatively low temperatures (80-300°C). Moreover the heat dissipates rapidly and transportation costs are relatively high. Therefore the thermal energy cannot be used far from the point of recovery. Thses properties are fundamental for any consideration of the utilization of geothermal resources. Individual thermal areas are characterized by the reservoir temperature (or enthalpy). This term indicates the upper limit of the fluid temperature that can be produced by drilling. The production temperature will, in fact, always be below the reservoir temperature.

Geothermal energy like solar-, wind- and wave energy are often called alternative sources of energy compared to the use of conventional fuel. Geothermal energy has been used traditionally in the past for various purposes including bathing and washing. Nowadays it is being utilized on a much larger scale and broad purposes including generation of electricity, district heating systems, process heating or drying, greenhouse heating and aquaculture which can be mentioned among the major forms of uses.

The many uses of geothermal energy are easily illustrated in a diagram called the Lindal Diagram (Lindal, 1973; Gudmundsson et al, 1985). The diagram shows examples of current and potential uses of geothermal energy in terms of application temperature (see Figure 1). The Lindal digram depicts a range of application temperatures and emphasizes two opposing aspects of the nature of utilization (Gudmundsson and Lund, 1987): (1) cascading and combined uses offer the possibility of enhancing the feasibility of geothermal projects, (2) the resource temperature may limit the kind of uses possible. However, design modification of existing conventional thermal processes can in some instances make them suitable for use with geothermal fluids.

Geothermal energy is very site specific and this factor affects the utilization energy. Thus, the characteristics of a particular geothermal site must be matched to appropriate energy conversion alternatives. For geothermal regions which are far from inhabited areas, the only possible method of utilization is to convert the thermal energy into electric power. The energy can then be transported and distributed throughout the power-transmisson grid. Conversion to electricity represents a practical means of transferring energy from remote areas to population centers. However, the price of conversion is a substantial loss of energy, where only about 10% of the energy is converted and 90% is lost. In addition electricity cannot be stored easily, which means that a power system must be built to meet peak demand. Because of these unfavorable factors, direct utilization of geothermal heat in such applications as space heating, direct industrial processing, agriculture or aquaculture seem to be the options for utilizing this energy on a much efficient basis. The combined use for electric generation and direct utilization would be a better approach.

The chemistry of geothermal waters is also an important factor to take into account. Most geothermal waters contain dissolved solids. The total amount of dissolved solids is in the range of 300-1500 ppm (parts per million), and of which silica amounts to some 25-50% (Jónsson, 1976). The dominant ions are sodium, chloride and sulphate. In some areas saline geothermal waters occur resulting from seawater perculating into the bedrock and mixing with fresh water of meteoric origin in various portions. Where seawater does not enter geothermal systems, variations in the thermal-fluids composition can be related to reservoir temperature and be correlated with mineral solubilities and ion-exchange equilibria with hydrothermal minerals. Geothermal water also contains some dissolved gases such as carbon dioxide, hydrogen sulphide, and to a lesser extent hydrogen and ammonia. The transfer of carbon dioxide and hydrogen sulphide into the steam phase, upon flashing, may cause some harmful effects to some materials. When the steam condenses, substantial amounts of the carbon dioxide and hydrogen sulphide are dissolved in the condensate and render it quite acidic (pH 3-5),; the acid condensate is highly corrosive. Thus, the chemistry of geothermal waters should be given high priority before reaching the utilization stage in order to avoid problems due to scaling and to make a good selection of corrosion resistant materials for the plant to be setup.

2. ELECTRICAL PRODUCTION

The various possibilties of harnessing and converting geothermal energy into mechanical and then electrical energy are listed in Figure 2. The coventional method is to separate the fluids and use the steam to drive the turbine either with a condenser or by exhausting the steam to the atmosphere. There also exists the possibility of using a binary cycle using low-boiling working fluids such as Freons or isobutane, in a closed circuit heated by geothermal effluents in a heat exchanger especially at low geothermal temperatures.

2.1 Back-pressure Turbine

The flow diagram of a back pressure unit is shown in Figure 3. As can be seen the geothermal steam after being separated in the separator goes to the turbine where it expands and converts to mechanical energy rotating the generator and producing electricity by magnetic induction. The fluid exit is flows out at atmospheric pressure or a bit above and can be thrown away or used further for heating or drying processes. These type of turbines are also advantageous when the content of non-condensible gases in the steam is very high, because of the high power required to extract thes gases from a condenser.

2.2 Single Flash Cycle

It is common in the case of unpumped geothermal wells for the well head product to consist of a two-phase mixture of liquid and vapor. The quality of the mixture (i.e.,the mass fraction of the vapor phase) depends on reservoir properties and well-head pressure. It is not difficult to separate the phases, say, at each wellhead, at centrally located stations, or at the powerhouse. Plants using a single stage of steam are called separated-steam plants (DiPippo, 1980).

In all likelihood the fluid condition in the reservoir is that of a compressed liquid at elevated temperature. As the fluid comes to the surface under a falling pressure, it flashes into steam and attains a wellhead quality ranging from about 10 % to 50 % for individual wells. Because of the flashing process, such plants are called flash-steam or single flash steam plants, eventhough the flashing takes place in the well or in the reservoir formation. The flow diagram of the single flash cycle is shown in Figure 4. It is of importance having a float-ball check valve to prevent massive ingestion of liquid to the turbine in the event of a backup in the separator or by other means such as moisture separators located at the power station in conjunction with a liquid level indicator on the separator which will control the shut-down in case of emergency.

2.3 Double Flash Cycle

The flow diagram in Figure 5 is similar to that in Figure 4, except that a flash vessel is included to generate additional steam from the hot water separated from the wellhead mixture. The added steam from the flasher at state 4 is admitted to the turbine via a plenum, where it mixes with the primary steam before expanding through the low-pressure stages. The term "double flash" arises from the fact that two flashes occur, one below the surface and one above the surface in the specially designed flash tank. The main point of interest is that a two-stage process of steam generation and utilization is employed, the second stage capturing a portion of the energy otherwise wasted in a one stage system. Thus, the efficiency of the double flash system is higher than that of the single flash system. In practical systems, where economic considerations generally outweigh thermodynamic reasoning, the number of flash stages will be limited to two.

The selection of flash temperatures is, of course, a function of several factors which include well productivity, turbine specific output per unit of well flow and economic considerations. Conditions which produce optimum productivity in terms of available energy and flow rate are not necessarily those which produce maximum turbine output.

2.4 Binary Fluid cycle

Much thought has been, and is being, given to the use of refrigerant fluids of very low boiling point, such as freons, isobutane, propane and others in a closed turbine-feed-boiler cycle as shown in Figure 6. The theoretical advantages of the binary cycle are (Armstead, 1983):

a) It enables more heat to be extracted from geothermal fluids by rejecting them at lower temperatures.

b) It can make use of geothermal fluids that occur at much lower temperatures than would be economic for flash utilizations.

c) It uses higher vapor pressures that enable a very compact self-starting turbine to be used, and avoids the occurence of sub-athmospheric pressures at any point in the cycle.

d) It confines chemical problems to the heat exchanger alone.

e) It can accept water/steam mixtures without seperation.

There are however, the following disadvantages:

a) It necessitates the use of heat exchangers which are costly, wasteful in temperature drop and can be the focus of scaling.

b) It requires costly surface condensers instead of the cheaper jet-type condenser that can usually be used when steam is the working fluid.

c) It needs a feed pump, which costs money and absorbs a substantial amount of the generated power.

d) Binary fluids are volatile, sometimes toxic and sometimes flammable; and must be very carefully contained by sealing.

e) Makers are generally inexperienced, and high development costs are likely to be reflected in high plant prices-at any rates.

f) Large quantities of cooling water are needed.

3. INDUSTRIAL APPLICATION: DRYING OF PROCESS MATERIALS

The discussions in this section are concerned with the removal of water from process materials or other substances. "The term drying is difficult to define within thermodynamic limits. From the industrial standpoint it is understood to represent the removal of a liquid usually, but not always water from solid by thermal means. It can also mean the removal of water or other volatile liquid from another liquid or gas, or the removal of water from a suspension or solution of a solid" (Gardner, 1971).

Drying methods and processes can be classified in several different ways. Drying processes can be classified as "batch", where the material is inserted into the drying equipment and drying proceeds for a given period of time, or as "continuous", where the material is continuously added to the dryer and dried material continuously removed.

Drying processes can also be categorized according to the physical conditions used to add heat or remove water vapor (Geankopolis, 1983): (1) in the first category, heat is added by direct contact with heated air at atmospheric pressure, and the water vapor formed is removed by the air; (2) in the second category, heat is added by indirect contact with air at atmospheric pressure; (3) in vacuum drying, the evaporation of water proceeds more rapidly at low pressure, and the heat is added indirectly by contact with a metal wall or by radiation (low temperatures can also be used under vacuum for certain materials that may discolor or decompose at higher temperatures); and (4) in freeze drying, water is sublimed from the frozen material.

3.1 Batch Dryers

As mentioned above in batch drying the the material to be dried is inserted into the drying equipment and drying proceeds for a given period of time, some of these type of dryers are described in this section:

3.1.1 Tray dryers

In tray dryers, which are also called shelf, cabinet or compartment dryers, the material, which may be a lumpy solid or a pasty solid, is spread uniformly on a metal tray to a depth of 10 to 100 mm. Such a typical tray dryer contains removable trays loaded in a cabinet.

Steam-heated air is recirculated by a fan over and parallel to the surface of the trays. Electrical heat is also used, especially for low heating loads. About 10 to 20% of the air passing over the trays is fresh air, the remainder being recirculated air.

After drying, the cabinet is opened and the trays are replaced with a new batch of trays. A modification of this type is the tray-truck type, where trays are loaded on trucks which are pushed into the dryer. This saves considerable time, since the trucks can be loaded and unloaded outside the dryer.

In the case of granular materials, the material can be loaded on screens which are the bottom of each tray. Then in this through-circulation dryer, heated air passes through the permeable bed, giving shorter drying times because of the greater surface area exposed to the air.

3.1.2 Vacuum-shelf indirect dryers

Vacuum-shelf dryers are indirectly heated batch dryers similar to tray dryers. Such a dryer consists of a cabinet made of cast-iron or steel plates fitted with tightly fitted doors so that it can be operated under vacuum. Hollow shelves of steel are fastened permanently inside the chamber and are connected in parallel to inlet and outlet steam headers. The trays containing the solids to be dried rest upon the hollow shelves. The heat is conducted through the metal walls and added by radiation from the shelf above. For low-temperature operation, circulating warm water is used instead of steam for furnishing the heat to vaporize the moisture. The vapors usually pass to a condenser.

These dryers are used to dry expensive, or temperature-sensitive, or easily oxidable materials. They are also useful for handling materials with toxic or valuable solvents.

3.2 Continuous Dryers

In continuous drying the material to be dried is continuously added to the dryer and dried material contiuously removed, some of these types of dryers are discussed below:

3.2.1 Continuous tunnel dryers

Continuous tunnel dryers are often batch truck or tray compartments operated in series. The solids are placed on trays, trucks or on conveyor belts which move contiuously through a tunnel with hot gases passing over the surface of each tray. The hot air flow can be countercurrent, cocurrent, or a combination.

When granular particles of solids are to be dried, perforated or screen-belt continuous conveyors are often used. The wet granular solids are conveyed as a layer 25 to about 150 mm deep on a screen or perforated apron while heated air is blown upward through the bed, or downward. The dryer consists of several sections in series each with a fan and heating coils. A portion of the air is exhausted to the atmosphere by a fan. In some cases pasty materials can be performed into cylinders and placed on the bed to be dried.

3.2.2 Rotary dryers

A rotary dryer consists of a hollow cylinder which is rotated and usually slightly inclined toward the outlet. The wet granular solids are fed at the high end and move through the shell as it rotates. The heating is by direct contact with hot gases in countercurrent flow. In some cases is by indirect contact through the heated wall of the cylinder.

The granular particles move forward slowly a short distance before they are showered downward through the hot gases. Many other variations of this rotary dryer are available, one of them being the indirect-heat-rotary-steam-tube dryer.

The indirect-heat-rotary-steam-tube dryers are used for the continuous drying or heating of granular or powdery solids which cannot be exposed to ordinary atmospheric or combustion gases. They are specially suitable for fine dusty particles because of the low gas velocities for purging of the cylinder.

The tubes through which steam flows are fastened symmetrically in one, two or three concentric rows inside the cylinder and rotate with it. Lifting flights are usually inserted behind the tubes to promote solid agitation.

Steam is admitted to the tubes through a revolving steam joint into the steam side of the manifold. Condensate is removed continuously by gravity through the steam joint to a condensate receiver and by means of lifters in the condensate side of the manifold. By employing simple tubes, non-condensable gases are continuously vented at the other end of the tubes through sacro-type vent valves mounted on an auxiliary manifold ring, also revolving with the cylinder. Vapor (from drying) is removed at the feed end of the dryer to the atmosphere through a natural draft stack and settling chamber or wet scrubber.

3.2.3 Drum dryers

A drum dryer consists of a heated metal roll, on the outside of which a thin layer of liquid or slurry is evaporated to dryness. The final dry solid is scraped off the roll, which is revolving slowly.

Drum dryers are suitable for handling slurries or pastes of solids in fine suspension and for solutions. The drum functions partly as an evaporator and also as a dryer. Other variations of the single-drum type are twin rotating drums with dip feeding or with top feeding to the two drums.

3.2.4 Spray dryers

In a spray dryer a liquid or slurry is sprayed into a hot gas stream in the form of a mist of fine droplets. The water is rapidly vaporized from the droplets, leaving particles of dry solid which are separated from the gas stream. The flow of gas and liquid in the spray chamber may be countercurrent, cocurrent, or a combination.

The fine droplets are formed from the liquid feed by spray nozzles or high-speed rotating spray disks inside a cylinder chamber. It is necessary to ensure that the droplets or wet particles of solid do not strike and stick to solid surfaces before drying has taken place. Hence, large chambers are used. The dried solids leave at the bottom of the chamber through a screw conveyor. The exhaust gases flow through a cyclone separator to remove any fines. The particles produced are usually light and quite porous.

4. COMBINED ELECTRICAL AND THERMAL PRODUCTION

The production of both electricity and thermal energy from a geothermal resource maximizes the total value of the products. This may be accomplished by making electricity from a topping cycle and using the heat from the condensing or exhaust section of the power plant to provide space and process heat. For processes that require thermal energy at a higher temperature level, a combined electrical production and process heat facility may not be possible.

A geothermal resource is more efficiently used for space and process heat than electrical production because of the low Carnot cycle efficiencies resulting from the low reservoir temperature. The greater value as a heating source also results from the lower brine temperature giving nearly reversible heat transfer to the process or heating system. On the other hand, fuel oil or conventional fuels provide heat at a much higher temperature; therefore, when used directly for space or process heat purposes without prior conversion to electricity, they have a high irrevresible loss as a result of the large temperature difference. As a result of these two factors, the use of geothermal energy for space and process heat returns a greater profit than its use for making electricity (Wahl,1977).

4.1 Production in Parallel

If a supply of steam or hot fluid can be split into two or more streams flowing in parallel with one another, each of which is used for different purposes, then the result could indeed be described as a combined production in parallel.
For example, a flow of steam or hot water could be divided in various proportions to supply, say, an electric generator, a district heating system, a group of greenhouses or some heat-intensive industry requiring low-grade heat for drying. All these applications would be operating in parallel with one another, and all would require a heat intake at more or less

the same temperature. In so far as an available supply of steam or hot fluid may exceed the demands of any one of these component applications by an adequate margin, this would certainly be conducive to the efficient use of the available heat; and if there should be a diversity in the times of incidence of the component maximum demands, the overall composite utilization factor of the heat could perhaps be better than that obtainable by any one of the component uses individually.

4.2 Production in Series

A geothermal brine processing plant that is converting thermal energy into electricity will always discharge heat. Because of the low temperature of geothermal brines, the cycle efficiency is low and the discharged heat is the major portion of the energy flowing out of the plant. Consequently, any use of this thermal energy will greatly increase the efficiency of geothermal energy utilization. This means, however, that the heat discharged from the plant must be at a higher temperature than would be desired for obtaining maximum electrical power. If this discharged heat can be utilized then we have a production in series.

Eventhough the production in series is a bit more difficult to achieve in practice, it is a group of different applications that use the same fluid over different range of temperature, and thus operate in series with one another. Since every application uses and rejects heat over a certain temperature range, a supply of steam or hot fluid could be put to the greatest possible use if the rejection temperature of one process were the same as, or very slightly higher than, the intake temperature of the next downstream process.

5. CASE STUDIES

5.1 Geothermal Utilization at the Reykjanes Peninsula

5.1.1 Fish drying

The fish drying plant at the Reykjanes peninsula dries cod heads with the use of a primary and secondary dryer. The primary dryer is a continuous one of the conveyor belt type (see Figure 7). 20 tonnes of cod heads are dryed for 24 hours from a moisture content of 80% down to 56%. The cod heads come in on the top belt and then the belt is stopped and left for about 3 hours. After that the cod heads move down to the next belt and new cod heads come in at the top, this goes on until the primary drying is over.The three lower belts move at half the speed of the other two,therefore spending a total of 24 hours inside the drying cabinet. The air used for drying is sucked through fans and heated up by geothermal steam in a heat exchanger. According to the energy balance done for the primary dryer, the heater load is 0.7 MW and the steam flow is 0.30 kg/s of saturated steam at 8 bars absolute.

The latter part of the drying takes place in a secondary dryer which is of the batch type (see Figure 8). Here the cod heads from the primary dryer are stacked into boxes, each about 2.5 m^3 large, with openings at both ends so that hot air can be blown through them. They can be stacked 2-4 in a row and also 4-6 in parallel. The drying time here is 4 days and the moisture content is reduced from 56% down to 12%. The heater load is 0.2 MW and the steam required is 0.05 kg/s at 8 bars absolute.

5.1.2 Salt and CO_2 production

Apart from the fish drying plant there is also a geo-chemicals plant whose flow diagram can be seen in Figure 9. The brine comes from the borehole at a wellhead temperature of 250°C and pressure of 44 bars in a two-phase flow of steam and brine. It enters a high pressure separator, where the pressure is reduced to 10 bars and 180°C, which is above opal saturation. The density of the down-flow brine from the separator is 1.026 g/cm^3 (Gudmundsson and Einarsson, 1988). The brine is evaporated further in a two-stage forced circulation evaporator to the brine density about 1.090 g/cm^3. The brine is acidified in the evaporators to pH 3.5 in evaporator no. 1 and to pH 2.4 in evaporator no. 2 to reduce scaling in the heat exchangers. The silica in the process stream from the evaporators used to be separated from the liquid in an open sedimentation tank by addition of caustic soda to a silica slurry recirculated into the incoming brine stream. The pH of the brine is increased htat way to about 8.2 in the tank. The overflow from the silica settling tank is evaporated further in an open evaporation pan to about saturation (density= 1.215 g/cm^3) and still further in the crystalization pans. Before the silica saturated brine goes into the crystalization pans the silica was separated further from the brine in a cyclon silica slurry circulation unit. The brine is then acidified to pH 6.5 before the liquid flows into the crystallization pans. The fishery salt, NaCl, is crystallized from the brine by further evaporation. The effluent brine from the pans has a density of 1.24 g/cm^3.

Condensate from the different heat exchangers is collected in a liquid-gas separator. The non-condensable gas containing at least 95% carbon dioxide is led to a CO_2 purification and compressing plant for production of liquid CO_2 and dry ice.

5.2 The Geothermal Power Plant at Svartsengi

The geothermal power plant at Svartsengi is a recent example of the utilization of a high-temperature geothermal resource in Iceland. The site on the Reykjanes peninsula is shown on Figure 10 among other geothermal fields in that area. The distance from the power plant to the nearest village (Grindavik) is about 5 km and to the international airport and the military base in Keflavik about 13 km.

The plant is unique in design. The geothermal fluid is a brine of 235-243°C which could not be used directly in district heating systems because of the high temperature, salinity (2/3 that of sea water) and heavy scaling.Instead it is used to produce potable hot water by heating fresh cold water, which after deaeration is pumped to the district heating systems of seven different communities as well as to the military base and international airport.

The design provides also for the generation of electrical power for own use as well as for delivering to the national grid. Currently the installed capacity is 125 MW thermal power for district heating systems and 8 MW electrical power.

There are two power houses in Svartsengi, each with different process designs to achieve similar or same results. Power house I has 4 units of 12.5 MW_t each for heating and 2 units of 1 MWe each. Power house II has 3 units of 25 MW_t each for heating and 1 unit of 6 MWe. The diagram in Figure 11 shows one of four parallel flow diagrams in power house I. Figure 12 shows one of three parallel units in power house II. Both diagrams illustrate the basic process design.

5.2.1 Power house I

The power house I at Svartsengi is designed for heating fresh water for a district heating system by using geothermal steam. The fresh water is pumped from shallow wells approximately 4 km away from the plant. The fresh water aquifer is in porous surface lavas, where a fresh water lens of only 45 m lies on top of the sea water (Ingimarsson et al.,1978). The Svartsengi geothermal site is part of a high temperature area with a base temperature of 240°C and containing a brine whose salinity is roughly 2/3 that of sea water (Kjaran et al., 1979). Scaling of equipment is an operating problem because of the high silica content (600 ppm). High fouling rates of heat exchanger surfaces dictated that only flash steam be used for the heat exchange process (Gudmundsson and Bott, 1979). A pilot plant study demonstrated, moreover, that the flash steam could be used directly (Arnorsson et al., 1975) to heat the fresh water by injection. Subsequent tests showed that because of high CO_2 content the deaeration was much easier if the H.P. (high pressure) steam was condensed in a surface heat exchanger, rather than being injected.

The decision to run the H.P. separator above the amorphous silica saturation temperature of 140°C, and to use thermal deaeration at atmospheric pressure, determines the temperatures and flow within the system. The flow is balanced to use all of the H.P. and L.P. (low pressure) steam generated based on a reservoir temperature of 240°C. Each geothermal well is designed to produce 60 kg/s, an output which is split between two units, and the power house consists of a total of four parallel units (4x12.5 MW_t). The geothermal fluid is piped in two-phase flow from the wells to a flash plant located by the power house. Two centrifugal steam separators in series produce the H.P. (5.4 bara) and the L.P. (0.39 bara) steam (see Figure 11). Water level in the H.P. separator is controlled and the spent brine discharged from the barometric leg of the L.P. separator to surface disposal at a temperature of 75°C. The H.P. steam is used for generation of electricity in a back-pressure turbine before being condensed in a plate heat exchanger. The L.P. steam is piped to a direct contact condenser where it preheats the fresh water from 5°C to 65°C and removes about 90% of the dissolved gasses from the fresh water with a steam ejector. This water is pumped to a second heat exchanger (intercooler) and on to the turbine condenser mentioned above. There the water is heated to 105°C before the atmospheric deaeration . At this point the hot water is potable and is either cooled to 85°C in the intercooler for direct use in the town of Grindavik, or heated further by H.P. steam in a plate heat exchanger to 125°C before pumping to Keflavik.

5.2.2 Power house II

The second power house has a different arrangement of L.P. separator , pre-heater and deaerator. Successful tests were carried out in a unit where these pieces of equipment were combined in one column. The L.P. steam goes to a heater/ deaerator which is operated under vacuum, and after that the water heated further in a plate heat exchanger using back-pressure steam from the turbine and H.P. steam.

The design of the three identical parallel units in power house II is to achieve similar or same results as in power house I as mentioned above, the main difference in the design of power house II was that the before mentioned three pieces of equipment were now contained in one column. The main reason for this change was that a considerable cost reduction could be achieved. Pipes and pumps between the direct contact heater and the deaerator made of corrosion resistant material could now be eliminated. The total cost reduction of the pieces of equipment and pipes involved was calculated to 20-25% (Björnsson and Albertsson, 1984).

The power house II is constructed with appropriate space for one unit of 25 MW_t in addition to the three units already installed. The house is also designed to be lenghtened at a latter date to house two additional units. There is also a 6 MW_e turbo-generator unit, which generates electricity for delivery to the national grid in the Western Reykjanes area, mainly during winter time.

5.3 Drying of Diatomite at Namafjall

A minute single-cell plant called diatomaceous (silicic) algae lives in Lake Myvatn. It constitutes an important link in the life chain as an animal fodder. The algae forms a shell of many compartments. The shells are of many sizes and shapes. The main substance of the shell is silicic acid which the algae absorbs from the lake. When the algae die the shells fall to the bottom. Over a long period of time an immeasurable quantity of shell has accumulated to the bottom of Lake Myvatn, forming a bottom layer of up to 15 meters. This bottom material constitutes the raw material and offers all the most favorable conditions for the formation of diatomaceous earth, such as an abundance of dissolved silicic acid, shallows, an extensive supply of nutrients, and rapid renewal of water. Each year the lake supplies additional raw material,but opinions differ about the quantity. It is noteworthy that water flowing into Myvatn is saturated with silicic acid, but the outflow is free of it.

5.3.1 Mining operation

A slurry with 3% concentration of diatomaceous earth is dredged from Lake Myvatn boosted and sent to a pumping station. Inside the pumping station this slurry is coarsely cleansed and then pumped over a distance of about 3 km to the main plant area. Here ash and dirt are largely separated from the slurry through a hydrocycloning process. The separated part of the slurry is then pumped over a distance of about a kilometer to a raw material holding pond. Dredging of raw material proceeds during summertime only (May to October) when it continues throughout the 24 hour day, this is due to the fact that the lake will freeze because of cold weather during the latter part of the year.

5.3.2 Wet end operation

Slurry is pumped from the raw materials pond to the slurry tanks within the main plant area. From these tanks the slurry is taken to the vacuum filters (see Figure 13). Before reaching the vacuum filters the slurry is heated up to 80-90°C, this is done by the direct injection of geothermal steam into the pipe carrying the slurry. Apart from the steam sulphuric acid with a pH of around 4.2 is also injected with the purpose of maintaining the pH of the final product.

The vacuum filters have a capacity of 6 tonnes per hour of dry material and use 5.6 metric tonnes of steam per tonne of slurry over filter, the recovery is 60.9% (Nilsson, 1988). A mud cake with 25% dry material having a temperature of 60°C is formed after the vacuum filtering process.

The indirect-heat-rotary-steam-tube dryers are the ones which have the highest consumption of geothermal steam, 30 tonnes per hour, and the most important regarding the drying process. There are a total of four of these dryers within the plant. Inside the dryers the mud coming from the vacuum filters is dried to about 90% dry material with a temperature of 90-95°C. The left over wet material from the dryers is taken to a heater and heated up to 110-115°C, this is done to avoid plugging occuring in the dryer cyclone where it is dried to a certain limit and then goes onto a screw conveyor and is again fed into the dryers and cycles the above mentioned process.

5.3.3 Dry end operation

The dried material from the steam dryers is stored in an ore bin before being taken into a separator. This separator is of a centrifugal type using air for its purpose. Within the separator crude materials are separated and the particle size of the ash being formed is kept within limits. After leaving the separator the diatomite is fed with sodium carbonate and aglomeration takes place with the objective of whitening and increasing the particle size. Hereafter the diatomite goes into an oil-fired rotary kiln where it is fully dryed to around 97%, organic materials are burnt and separated, calcining also takes place at temperatures between 1110-1200°C. Having finished this process the diatomite is ready for packing. The plant has a capacity of producing 24000 tonnes of diatomite per year as finished product.

6. DESCRIPTION OF WORK

In this part of the work a ficticious geothermal reservoir with similar or same characteristics of other known geothermal reservoirs in Iceland is taken into consideration. It is then tried to use the available energy on a maximum basis. In order to do so a production in series, generating electricity and using the exit steam for drying; and a production in parallel with a condensing turbine (condensing temperature of 40°C), generating electricity in the same amount as above and using the remaining part of the steam for drying will be taken into consideration and be compared. At the same time a comparison between air heated dryers and indirect steam heated dryers for both types of production will be made. The electric generating capacity will be based on the maximum output of the back-pressure turbine (production in series) from one well. The maximum drying capacity will also be compared for both cases and for both type of dryers.

6.1 Geothermal Resource

The reservoir taken into account is of the liquid dominated type with a temperature of 250°C. A well with a total depth of 1600 m is to be drilled in order to exploit the resource. The well is designed with a 13-3/8" casing down to 800 m and a 9-5/8" slotted liner down to the bottom. The flow output characteristics are shown in Figure 14. The flow decline of the well considering a decline rate of 1-5% per year is shown in Figure 15. The enthalpy within the well and the well-head pressure under operating conditions will be assumed to be constant.

6.2 Available Work From Well

Gudmundsson and Thráinsson (1985) propose a method which consists of estimating the maximum available work from each well.They indicate that the exergy, E, which can be extracted from a unit mass of steam passing through a turbine, is given by the relationship

$$E = h_{g1} - h_{g2} - (T_2 + 273.15)(s_{g1} - s_{g2}) \qquad ....(1)$$

where h_{g1} and s_{g1} are the enthalpy and entropy at inlet conditions, h_{g2} and s_{g2} are the enthalpy and entropy, and T_2 is the temperature in centigrades, at the outlet condition.

The electrical power production for isoentropic expansion through the turbine depends on the amount of steam mass flow rate, and enthalpy difference between the inlet and exit of the turbine. The amount of steam produced, depends on the separation pressure; the lower the pressure, the more the steam and hence more power production. On the other hand the lower the inlet pressure to the turbine, the lower the inlet enthalpy and hence lower power output. It follows that there must exist an optimum condition where available energy shall be at maximum. Figure 16 shows such a typical maximum available energy for borehole temperatures from 200 - 280°C. This characteristic of geothermal power generation was first demonstrated by Jónsson (1976).

The mass fraction of steam, X_1, obtained in steam/water separation, is given by the mass and energy balance relationship

$$X_1 = (h_o - h_{f1})/(h_{g1} - h_{f1}) \qquad ....(2)$$

where h_o is the enthalpy of the steam/water mixture entering a separator, and h_{g1} and h_{f1} the steam vapor and liquid water enthalpy at the pressure of separation. In geothermal developments the steam/water mixture enthalpy at the wellhead is usually assumed the same as that of the fluid entering the well downhole (reservoir enthalpy); the wellbore flow is isoenthalpic; there is negligible heat loss up the well from the feedzone to the wellhead.

Taking into consideration the mass fraction of steam obtained from a unit mass of wellbore flow, X_1, and taking into consideration the exergy, E, available from a unit mass of steam, the following relationship gives the available work, W, per unit mass of wellbore fluid which can be extracted in geothermal developments

$$W = X_1 E \qquad \ldots.(3)$$

The available work that can be extracted from liquid water at 250°C, assuming steam/water separation at different pressures (inlet condition), and two outlet conditions (atmospheric exhaust at 1.2 bar for the case in serie and 40°C condenser temperature for the case in parallel) are shown respectively in Figures 17 and 18. The figures show that a maximum exists at 9 bara separator pressure (175.38°C) for the atmospheric exhaust at 1.2 bara and 4 bara separator pressure (143.63°C) for a 40°C condenser temperature.

6.3 Power Potential of Well

The electric power generation potential, P, of the well was calculated for different separator pressures using the relationship

$$P = m_s W \qquad \ldots.(4)$$

where the available work, W, is multiplied by the individual steam mass flowrate, m_s, at the corresponding pressure. Figures 19 and 20 are based on the electric power potential calculated respectively for the well for the atmospheric exhaust at 1.2 bara and for the condenser temperature of

40°C. From these Figures we see that the maximum electrical output can be achieved at pressures of 7 bara for back-pressure units of 1.2 bara and at a pressure of 4 bara for the condensing unit.

The selection of separator pressures should also be in accordance with the solubility of amorphous silica. Gudmundsson and Bott (1977) discuss that quartz is the most stable and amorphous silica the least stable among the several forms of silica that exist in equilibrium with water. Quartz is therfore the least soluble and amorphous silica the most soluble . In high temperature areas the amount of silica dissolved in the reservoir fluid depends on the solubility of quartz. It has, however, been demonstrated that amorphous silica is the form which precipitates from geothermal and other aqueous solutions on concentration and cooling. The solubility of amorphous silica in water is shown in Figure 21. The composition of geothermal waters involving say the concentration of dissolved silica, depends to a large extent on mineral equilibria with water. 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 at which the geothermal waters may be used without deposition being a problem. For the case of reservoir temperature of 250°C the lowest temperature is 140°C (3.6 bara), therefore, in order to avoid the problem of deposition and to be on the safe side a separator pressure of 5 bara is selected.

The maximum electrical output for the back-pressure unit at 7 bara is 6 MW_e, assuming a total turbine efficiency of 0.75 the net output will be 4.5 MW_e.

From the flow output characteristics curve in Figure 13 we see that we have a steam flow rate of 20 kg/s and 22.78 kg/s for 7 and 5 bara respectively.

Since we base our electrical production on that generated by the back-pressure unit (connection in series) which has a net output of 4.5 MW_e we need to find out the amount of steam required by the condensing unit (connection in parallel) to produce this same amount of electricity, by using the relationship

$$X_1 = (s_{g1} - s_f)/(s_g - s_f) \qquad \ldots.(5)$$
$$X_1 = 0.813$$

$$h_{g2} = h_f + (h_g - h_f)\ X_1 \qquad \ldots.(6)$$
$$h_{g2} = 2124.24\ kJ/kg$$

$$m_s = P\ /(h_{g1} - h_{g2})\ \eta_t \qquad \ldots.(7)$$
$$m_s = 10.01\ kg/s$$

Therefore the remainder part of the steam which will be 12.77 kg/s will be available for drying.

For the back-pressure unit the exit steam will be separated and be available for drying. To know the amount we follow a similar procedure like for the above case. Using equations 5 and 6 we get X=0.9 and h_2=2459.1 kJ/kg. Assuming an isoentropic efficiency of 0.8 and using the following relationships

$$\eta_{is} = (h_{g1} - h_2{}')/(h_{g1} - h_2\ ) \qquad \ldots.(8)$$
$$h_2{}' = 2519.98\ kJ/kg$$

$$X_2 = (h_2{}' - h_f)/(h_g - h_f) \qquad \ldots.(9)$$
$$X_2 = 0.927$$
$$m_s = m_s\ \ X_2 \qquad \ldots.(10)$$
$$m_s = 20\ x\ 0.934$$
$$m_s = 18.54\ kg/s$$

6.4 Air Heated Rotary Dryer

The dryer taken into account will be a countercurrent rotary dryer as the flow diagram shows in Figure 22. The dryer will be used to dry a material from a moisture content of 0.75 to 0.1 kg water moisture per kg of dry material with an annual production rate of 11500 tonnes of dry material per year (S=0.403 kg/s). The selected dryer is 3.3 m in diameter and 12.1 m long. Air at 20°C and 55% humidity is heated over steam-coils to 100°C before being admitted to the dryer and is exhausted from the dryer at 70°C. The solids are raised in temperature from 60°C to 90°C at discharge. The power required to drive the dryer will be assumed to be $8D^2$ (in kW), where D is the diameter of the shell; one third of the energy dissipated being transmitted to the shell through the girth gear ring (Keey, 1978). The following mass and energy balance is done to estimate the air and steam requirements.

i) Inlet air humidity, Y_1

$$Y_1 = (M_W / M_G) \times ((\psi \times P_W) / (P_o - \psi \times P_W) \quad \ldots.(11)$$

$$Y_1 = 0.00811 \text{ kg/kg}$$

ii) Inlet air enthalpy, I_1

$$I_1 = C_{PG} \times T_{a1} + ((C_{PW} \times T_{a1}) + \Delta H_{vo})\ Y_1 \quad \ldots.(12)$$

$$I_1 = 122.427 \text{ kJ/Kg}$$

iii) Outlet air enthalpy, I_2

$$I_2 = C_{PG} \times T_{a2} + ((C_{PW} \times T_{a2}) + \Delta H_{vo})\ Y_2 \quad \ldots.(13)$$

$$I_2 = 70.35 + 2631.2\ Y_2$$

iv) Inlet solids enthalpy, I_{s1}

$$I_{s1} = (C_s + (C_{LW} \times X_{s1}))\ T_{s1} \quad \ldots.(14)$$

$$I_{s1} = 807.42 \text{ kJ/kg}$$

v) Outlet solids enthalpy, I_{s2}

$$I_{s2} = (C_s + (C_{LW} \times X_{s2}))\ T_{s2} \quad \ldots.(15)$$

$$I_{s2} = 124.9 \text{ kJ/kg}$$

vi) Heat loss, Q_L

The surface area of the shell is $\pi DL = 125.44\ m^2$.

For an emmisivity of 0.7 the wall loss due to convection and radiation from the outside shell is 581 W/m^2.

$$Q_L = 0.581 \times 125.44 \qquad ....(16)$$

$$Q_L = 72.88\ kW$$

vii) Frictional heat loss, Q_F

$$Q_F = 8D^2 / 3 \qquad ....(17)$$

$$Q_F = 29.04\ kW$$

viii) Moisture balance

$$(Y_1 - Y_2)\ G + (X_{s1} - X_{s2})\ S = 0$$

$$(0.00811 - Y_2)\ G + 1.164 = 0 \qquad ....(18)$$

ix) Enthalpy balance

$$(I_1 - I_2)\ G + (I_{s1} - I_{s2})\ S = Q_L - Q_F$$

$$(52.007 - 2631.2\ Y_2) + 275.05 = 0 \qquad ....(19)$$

solving equations 18 and 19 simultaneously:

$$Y_2 = 0.02094\ kg/kg$$

$$G = 90.72\ kg/s$$

x) Ambient air enthalpy

$$I_A = (C_{PG} \times T_A) + ((C_{PW} \times T_A) + \Delta H_{vo}) \qquad ....(20)$$

$$I_A = 40.65\ kJ/kg$$

xi) Heater load

$$Q_H = (I_1 - I_A)\ G \qquad ....(21)$$

$$Q_H = 7418.81\ kW$$

xii) Steam consumption

$$S.C = Q_H / (h_g - h_f) \qquad ....(22)$$

S.C = 3.3 kg/s for production in serie

S.C = 3.1 kg/s for production in parallel

xiii) Moisture evaporated in the dryer

$$G_v = (X_{s1} - X_{s2})\ S \qquad ....(23)$$

$$G_v = 1.164\ kg/s$$

xiv) Specific steam demand

$$S.S.D. = m_s / G_v \quad \ldots.(24)$$

S.S.D. = 2.8 and 2.6 kg steam per kg evaporated for the production in serie and in parallel respectively.

xv) Air heater size

$$Q = U \times A \times LMTD \quad \ldots.(25)$$

Cosidering that the dryers in the serie and parallel connection have approximately the same Q and U, then

$$A_1 / A_2 = LMTD_2 / LMTD_1$$

$$A_1 / A_2 = 3$$

This means that the air heater in the serie connection is three times much larger in area than the one connected in parallel if air is to be heated in both cases to 100°C.

6.5 Steam Heated Rotary Dryer

This dryer will be of the indirect-heat-rotary-steam-tube type. The same conditions as in the case of the air heated dryer will be taken into consideration. Thus, the moisture and enthalpy balance will be carried out and a comparison of these dryers connected in series and in parallel will be made.

The dryer will have an evaporating capacity of 4200 kg/h for a drying material flow rate of 0.403 kg/s. The flow within the dryer is cocurrent as can be seen in the flow diagram of Figure 23.

i) Heat delivered by the steam

$$Q_S = m_s (h_g - h_f) \quad \ldots.(26)$$

Q_S = 2642.2 kW for dryer in serie

Q_S = 2718.2 kW for dryer in parallel

ii) Moisture balance

The moisture balance for the dryer connected in serie will be the same as for the air heated dryer. See equation 18.

iii) Enthalpy balance

$$(I_1 - I_2)\ G + (I_{s1} - I_{s2})\ S = Q_L - Q_F - Q_S$$

$$(52.077 - 2631.2\ Y_2)\ G + 2873.41 = 0 \qquad \ldots.(27)$$

solving equations 18 and 27 simultaneously:

$Y_2 = 0.19709$ kg/kg

$G = 6.16$ kg/s

iv) Moisture and enthalpy balance for dryer connected in parallel

For the dryer connected in parallel we will have the same amount of air flow (G) and calculate the amount of dry material that can be produced.

$$(0.00811 - Y_2)\ 6.16 + 2.889\ S = 0 \qquad \ldots.(28)$$

$$(52.007 - 2631.2\ Y_2)\ 6.16 + 682.52\ S = -2674.36 \qquad \ldots.(29)$$

solving equations 28 and 29 simultaneously:

$S = 0.414$ kg/s or 11800 tonnes per year

$Y_2 = 0.20227$ kg/kg

v) Number of dryer units required for each case

No.= total amount of steam/steam consumption

a) Production in series
- 5 air heated dryers
- 14 steam dryers

b) Production in parallel
- 4 air heated dryers
- 10 steam dryers

7. RESULTS

Summarizing calculations in Chapter 6, the following results were obtained (see Table 1):

I) In the case with production in series (using the back-pressure turbine) after having produced 4.5 MW_e with 20 kg/s of steam would have 18.54 kg/s of steam available for drying.

If the use of an air heated rotary dryer is considered then the specific steam consumption per dryer is 3.3 kg/s and we would have sufficient amount of steam to run 5 dryers enabling us to have 57500 tonnes of dried material per year as finished product.

If on the other hand an indirect-heat-rotary-steam-tube dryer is used, then the specific steam consumption per dryer will be 1.166 kg/s and we would have enough steam to run 14 dryers. Thus, the total production capacity of dried material will be 161000 tonnes per year.

II) In the case of production in parallel the condensing turbine with a condensing temperature of 40°C will need 10.01 kg/s of steam to generate 4.5 MW_e. The remaining part of the steam that is 12.77 kg/s is available for drying.

If an air heated rotary dryer is used then the specific steam cosumption per dryer is 3.1 kg/s and the amount of steam available would be sufficient to run 4 dryers producing 46000 tonnes of dried material per year.

If on the other hand an indirect-heat-rotary-steam-tube dryer is used, having the same specific steam consumption per dryer as the air heated one, then there will be sufficient available to run 10 dryers with a production capacity of 118000 tonnes of dried material per year.

8. DISCUSSION

There are major difficulties that one encounters when trying to decide what would be the best options for utilizing geothermal energy. The site-specific nature of the resource complicates the exploitation. Other difficulties are lower temperatures (than the ones produced by conventional hydrocarbons) and the chemistry of the geo-fluids which can at times limit the form of utilization.

Experience in Iceland shows that instead of indirect use (electric generation) or direct use (industrial or drying purposes) a combined use of indirect and direct use is more advantageous both from the technical and economical point view.

The combined use of geothermal energy can be a result of a production in series or in parallel. Both cases have advantages and disadvantages as follows:

a) Production in series
   i) advantages
      - higher total thermal efficiency
      - exhaust steam from turbine can be utilized
      - back-pressure units are cheaper compared to condensing units

   ii) disadvantages
      - limitation on electricity generation (usually about 5 MW_e)
      - Exhaust steam from turbine at atmospheric pressure or slightly higher (temperature about 100°C), this gives a limit on the use according to the Lindal diagram (see Figure 1)

b) Production in Parallel
   i) advantages
      - higher thermal efficiency of electrical production

- amount of steam can be regulated either for generation of electricity or direct use giving more flexibility
- higher temperature of process steam

ii) disadvantages
- lower thermal efficiency due to large amount of heat being thrown away by condenser
- condensing units are relatively complex and expensive especially for small power plants

A study was made of utilizing geothermal energy for a dual-purpose (generation of electricity and drying) both in series and in parallel. For both cases two types of dryers, one which is air heated and the other steam heated were considered and compared.

The combined use of geothermal energy in series with the use of the steam dryer has the advantage of harnessing more heat and thus results in higher total thermal efficiency, moreover it has a higher output yield of dried material, for the particular case studied.

In practice it is very difficult to judge which of these methods of combined production is more advantageous. One has to know for example; where the geothermal resource is located; its yield in energy terms; the chemistry of the geo-fluids and the existance of a secondary resource (material to be dried or industrial process) within a certain boundary. Because of the many uncertainities in the decision making for utilizing a new geothermal field it is emphasized that one must be very careful in interpreting experience from one geothermal field to another.

There is no formula as such for deciding which method is appropriate and all the above mentioned factors influence in deciding which method is best.

9. CONCLUSIONS

1) The capacity of the air heated rotary dryer is approximately 1/3 of the capacity of the indirect-heat-rotary-steam-tube dryer.

2) The air heated dryer in parallel produces only 75% of the production in series, however the air heater in series is 3 times much larger than the one in parallel. This has, however, very small effect on the total cost when compared with a 20% difference in production.

3) The use of the indirect-heat-rotary-steam-tube dryer seems to be the best option for the case considered, both from the the thermodynamic as well as economic view point. This dryer is more advantageous when used in series although the relative difference in production is not as high as for the air heated dryers.

4) The combined use of electrical generation and drying processes give higher thermal efficiencies when used in series than in parallel, i.e. electricity is produced from a back-pressure turbine and the exit steam used for drying purposes.

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NOMENCLATURE

C_{LW} - Mean heat capacity of moisture liquid (kJ/kg°K)
C_{PG} - Mean heat capacity of dry air (kJ/kg°K)
C_{PW} - Mean heat capacity of moisture vapor (kJ/kg°K)
C_S - Mean heat capacity of solid (kJ/kg°K)
E - Exergy (kJ/kg)
G - Mass flow rate of air (kg/s)
G_V - Moisture evaporated in dryer (kg/s)
h_f - Enthalpy of liquid (kJ/kg)
h_{f1} - Enthalpy of liquid water at separation pressure (kJ/kg)
h_g - Enthalpy of steam (kJ/kg)
h_{g1} - Enthalpy of steam at separation pressure (kJ/kg)
h_{g2} - Enthalpy of saturated steam at outlet of turbine (kJ/kg)
h_o - Reservoir enthalpy (kJ/kg)
h_2 - Enthalpy of steam at outlet of turbine (kJ/kg)
h_2' - Enthalpy at outlet of turbine after isoentropic expansion (kJ/kg)
ΔH_{VO} - Latent heat of vaporization at 0°C (kJ/kg)
I_1 - Inlet air enthalpy (kJ/kg)
I_2 - Outlet air enthalpy (kJ/kg)
I_{s1} - Inlet solids enthalpy (kJ/kg)
I_{s2} - Outlet solids enthalpy (kJ/kg)
LMTD - Log mean temperature difference (°C)
M_W/M_G - Molar mass ratio of water/air = 0.6228
m_s - Mass flow rate of steam (kg/s)
P - Electric power potential of well (kW)
P_o - Total pressure (Pa)
P_W - Saturated vapor pressure (Pa)
Q - Heat load (kW)
Q_F - Frictional heat loss (kW)
Q_H - Heat load in exchanger (kW)
Q_L - Heat loss through wall of dryer (kW)
Q_S - Heat delivered by steam (kw)
S - Mass flow rate of dry matter (kg/s)
s_f - Entropy of saturated liquid (kJ/kg°K)

s_g - Entropy of saturated steam (kJ/kg°K)

s_{g1} - Entropy of steam at inlet of turbine (kJ/kg°K)

s_{g2} - Entropy of saturated steam at outlet of turbine (kJ/kg°K)

S.C - Steam consumption by dryer (kg/s)

S.S.D - Specific steam demand per dryer (kg/s)

T_2 - Temperature of steam at outlet of turbine (°C)

T_A - Ambient air temperature (°C)

T_{a1} - Inlet air temperature (°C)

T_{a2} - Outlet air temperature (°C)

T_{s1} - Temperature of solid at dryer inlet (°C)

T_{s2} - Temperature of solid at dryer outlet (°C)

U - Overall thermal conductance ($W/m^2 \cdot C$)

W - Available work from well (kJ/kg)

X_1 - Mass fraction of steam at separator (kg steam/kg total)

X_2 - Mass fraction of steam at outlet of back-pressure turbine (kg steam/kg total)

X_{s1} - Moisture content of solid at dryer inlet (kg H_2O/kg dry material)

X_{s2} - Moisture content of solid at dryer outlet (kg H_2O/kg dry material)

Y_1 - Inlet air humidity (kg air/kg H_2O)

Y_2 - Outlet air humidity (kg air/kg H_2O)

η_{is} - Isoentropic efficiency (%)

η_t - Total efficiency of turbine (%)

ψ - Relative humidity of air (%)

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Table 1 - Table of results

		Drying capacity and number of dryers	
		annual production (tonnes)	No. of dryers
Air dryer	series	57500	5
	parallel	46000	4
Steam dryer	series	161000	14
	parallel	118000	10

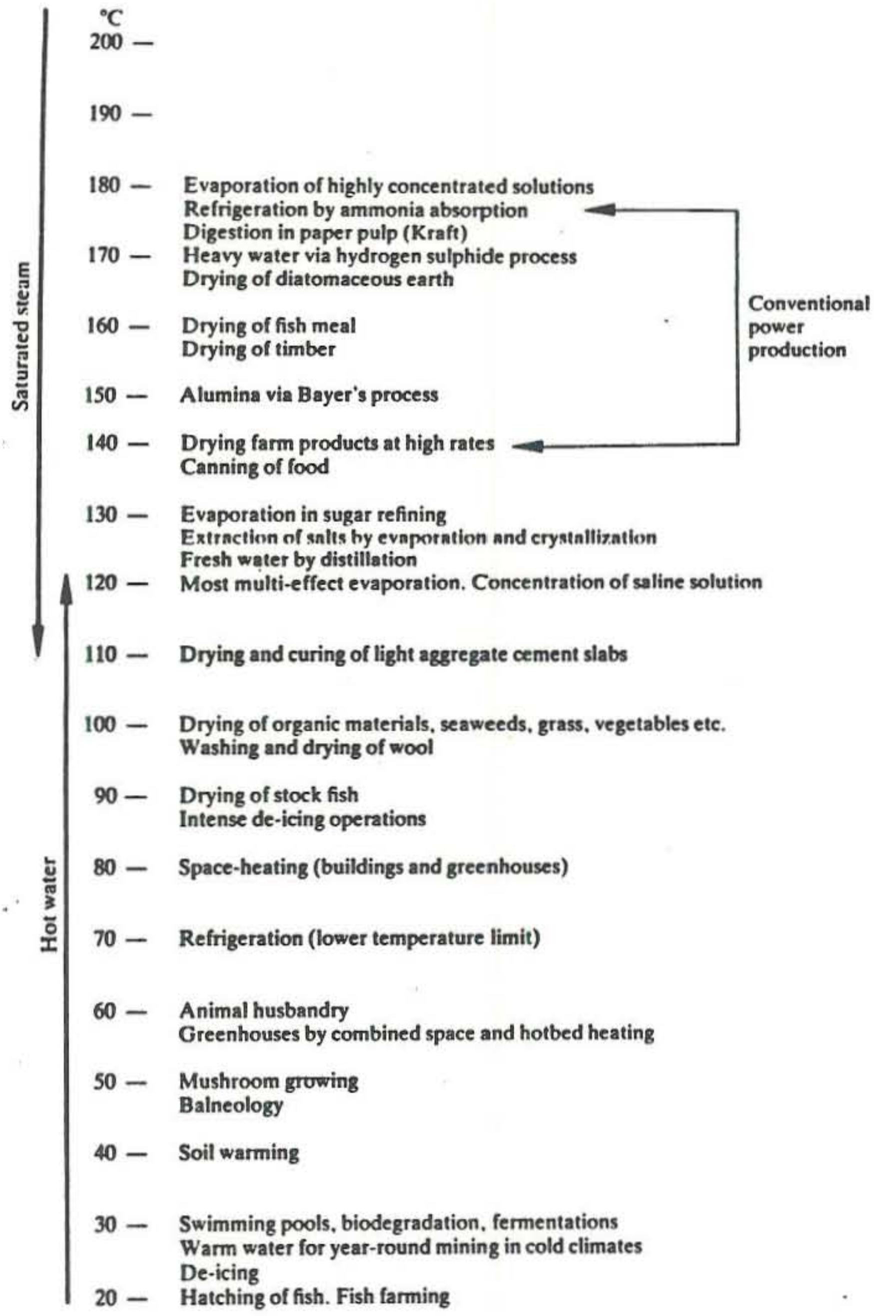


Figure 1 - The Lindal diagram (Lindal, 1973)

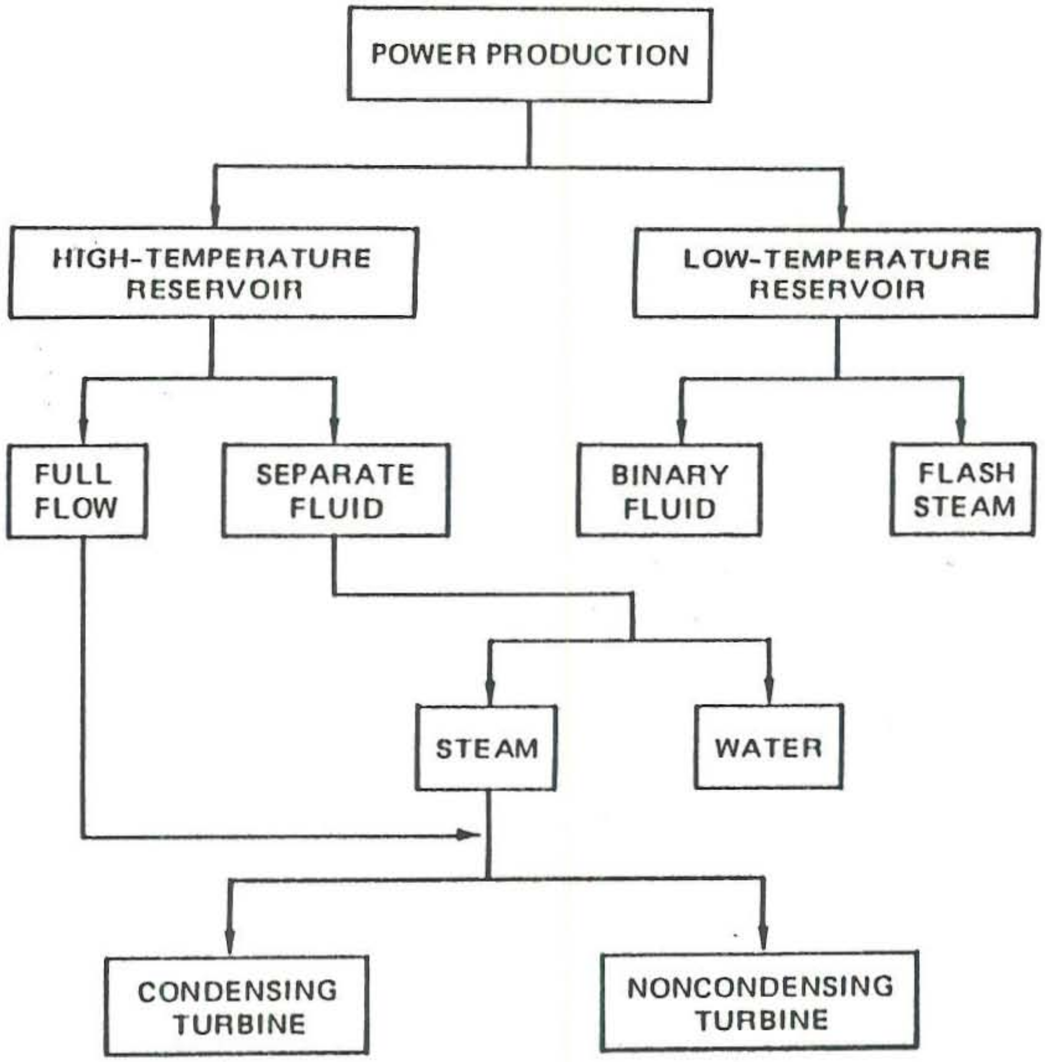


Figure 2 - Possible means of power production using geothermal fields (Jónsson, 1976)

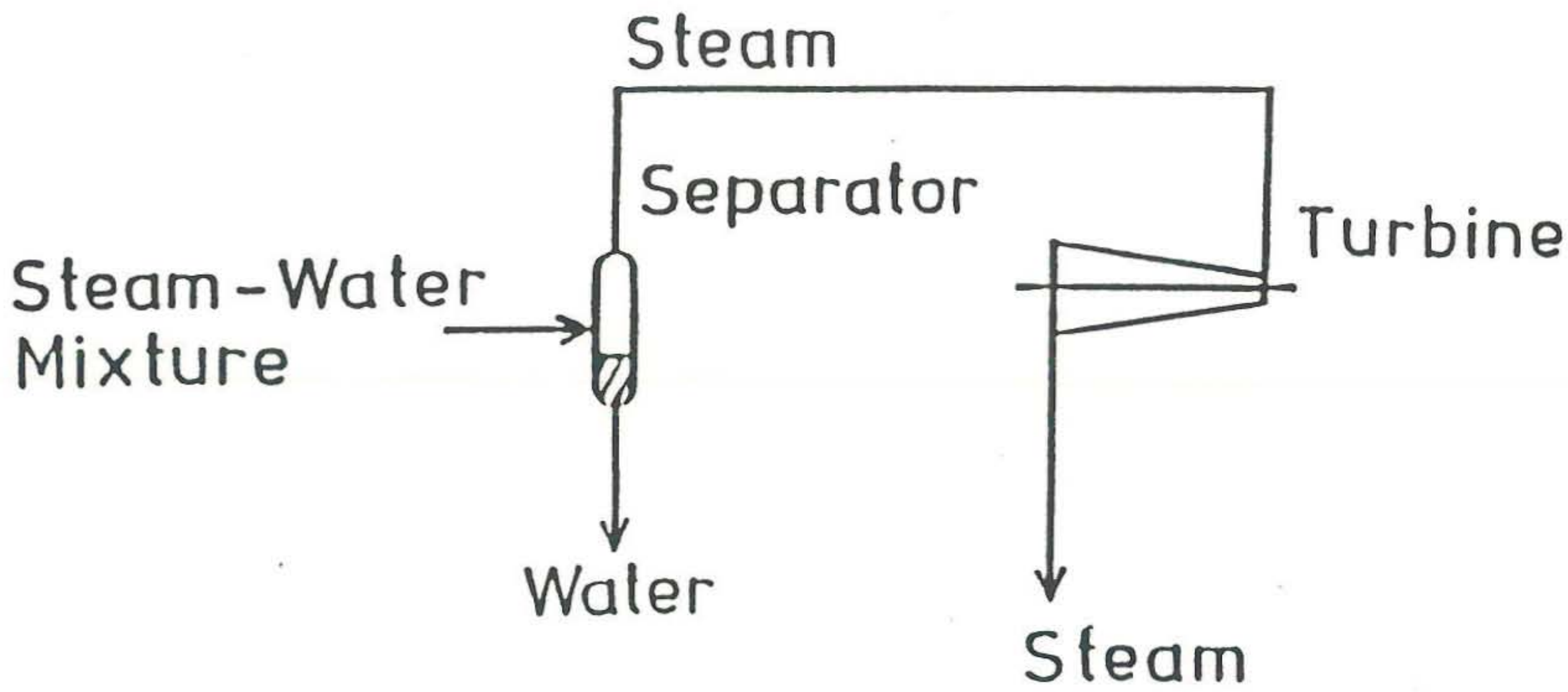


Figure 3 - Back-pressure unit

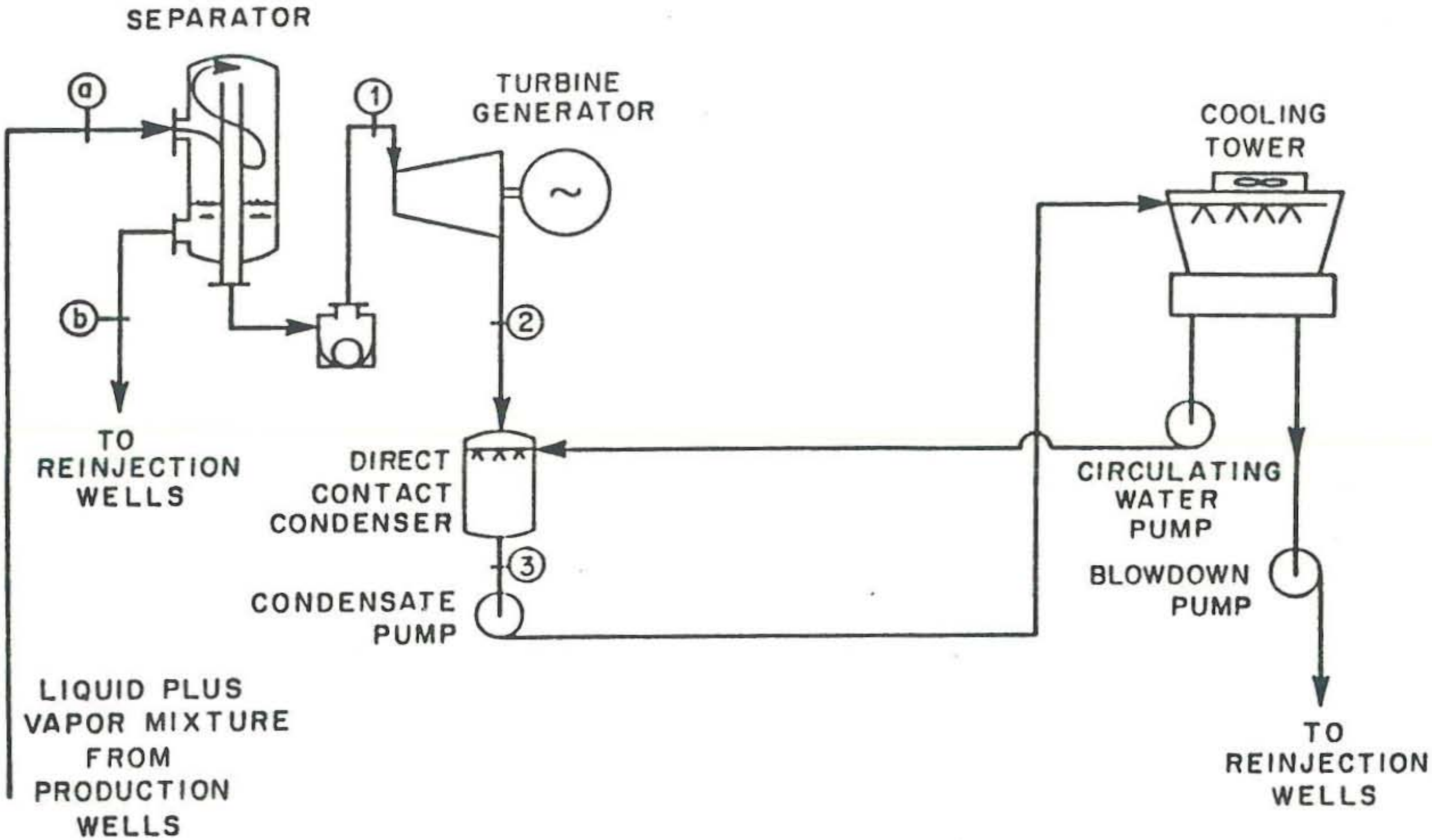


Figure 4 - Single-flash cycle (Dipippo, 1980)

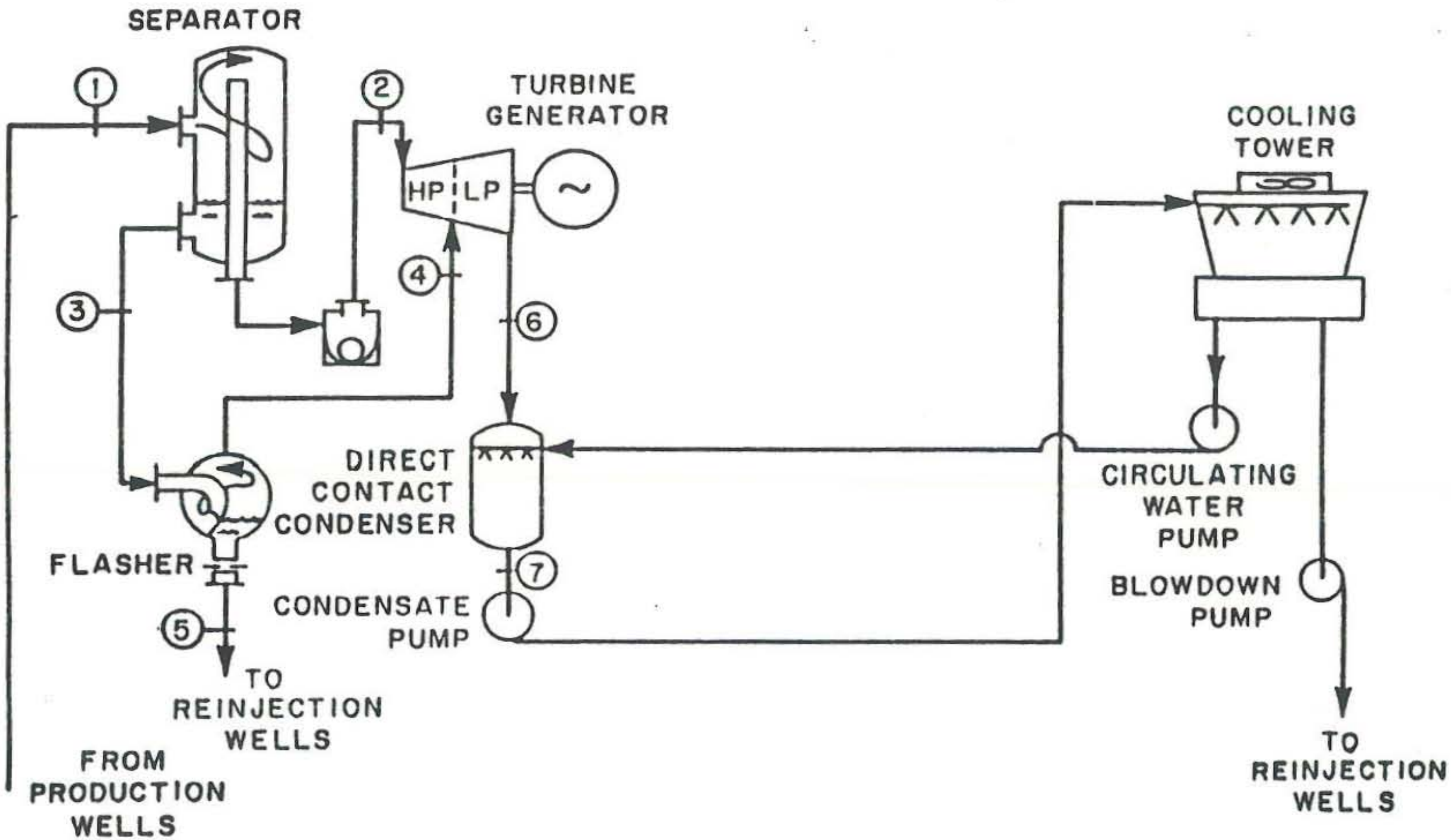


Figure 5 - Double-flash cycle (Dipippo, 1980)

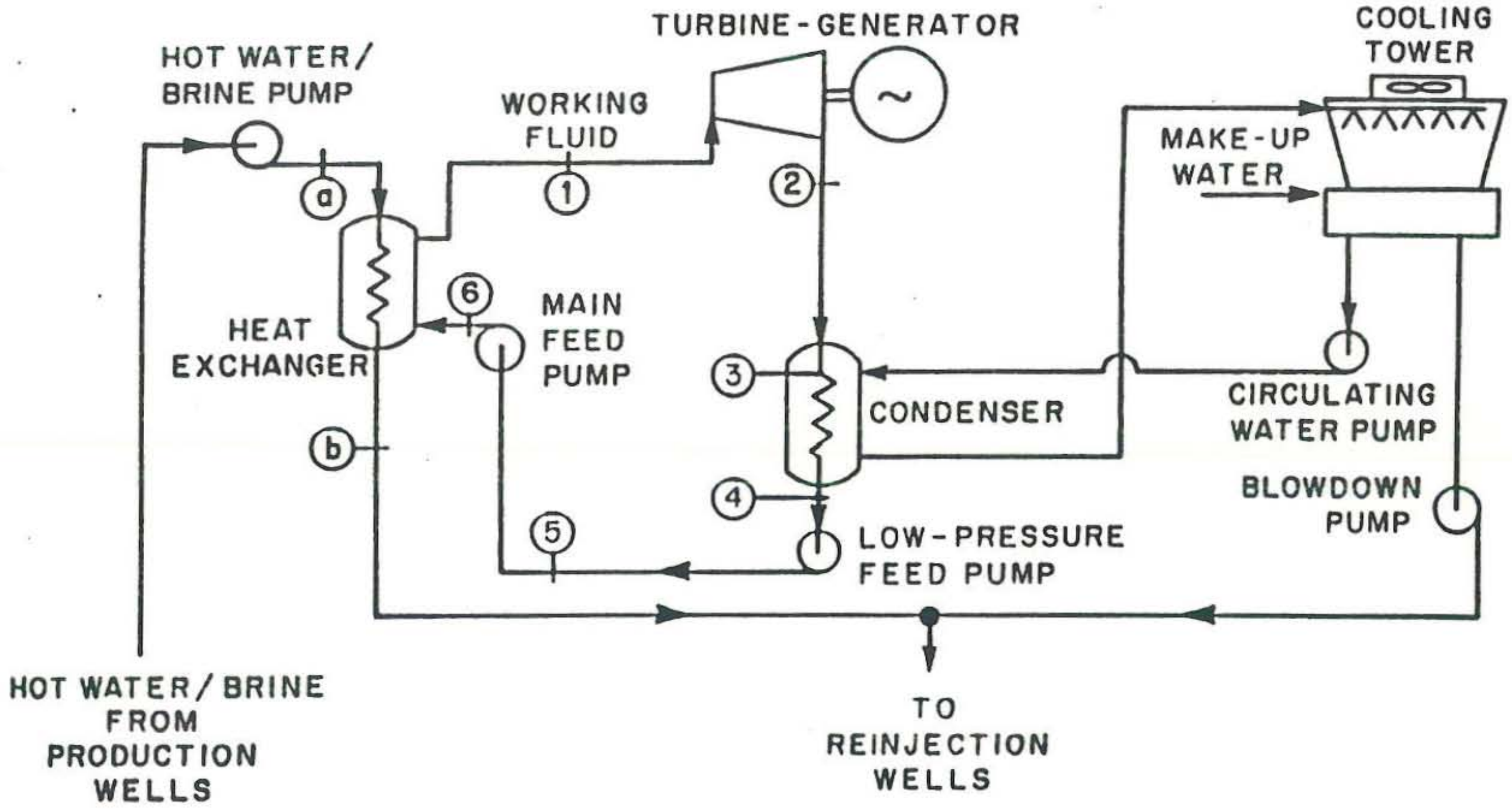
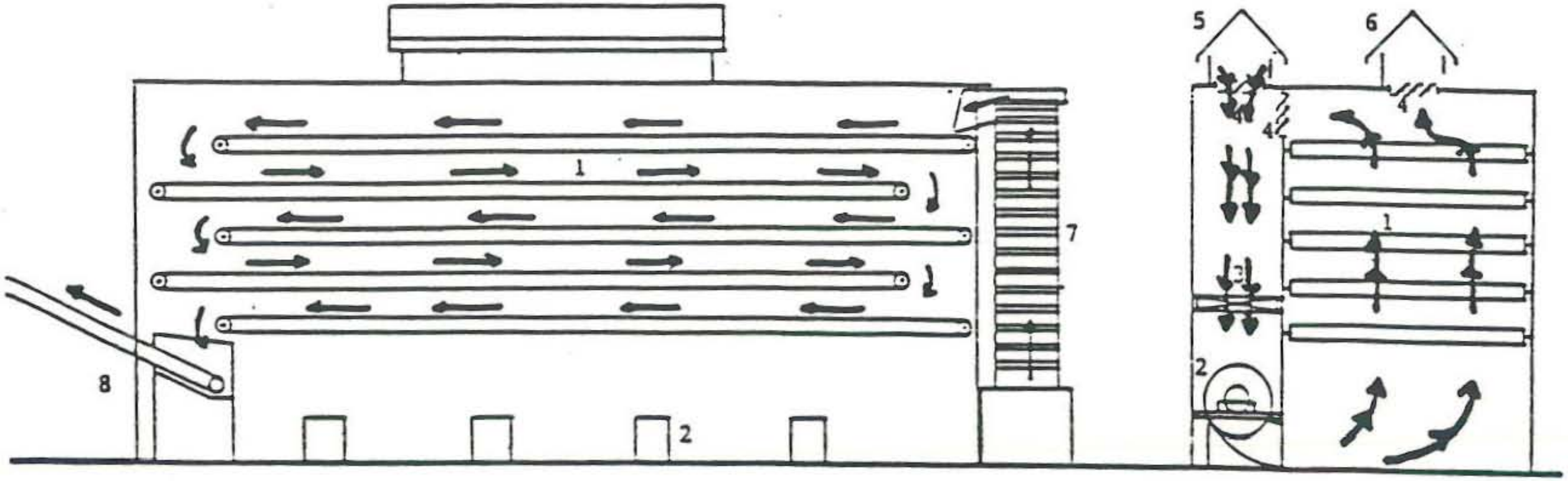


Figure 6 - Binary cycle (Dipippo, 1980)



1. Conveyor.
2. Fan.
3. Heater.
4. Valves.
5. Inlet of air.
6. Outlet of air.
7. Feeding conveyor.
8. Product.

air.
fish.

Figure 7 - Conveyor belt dryer

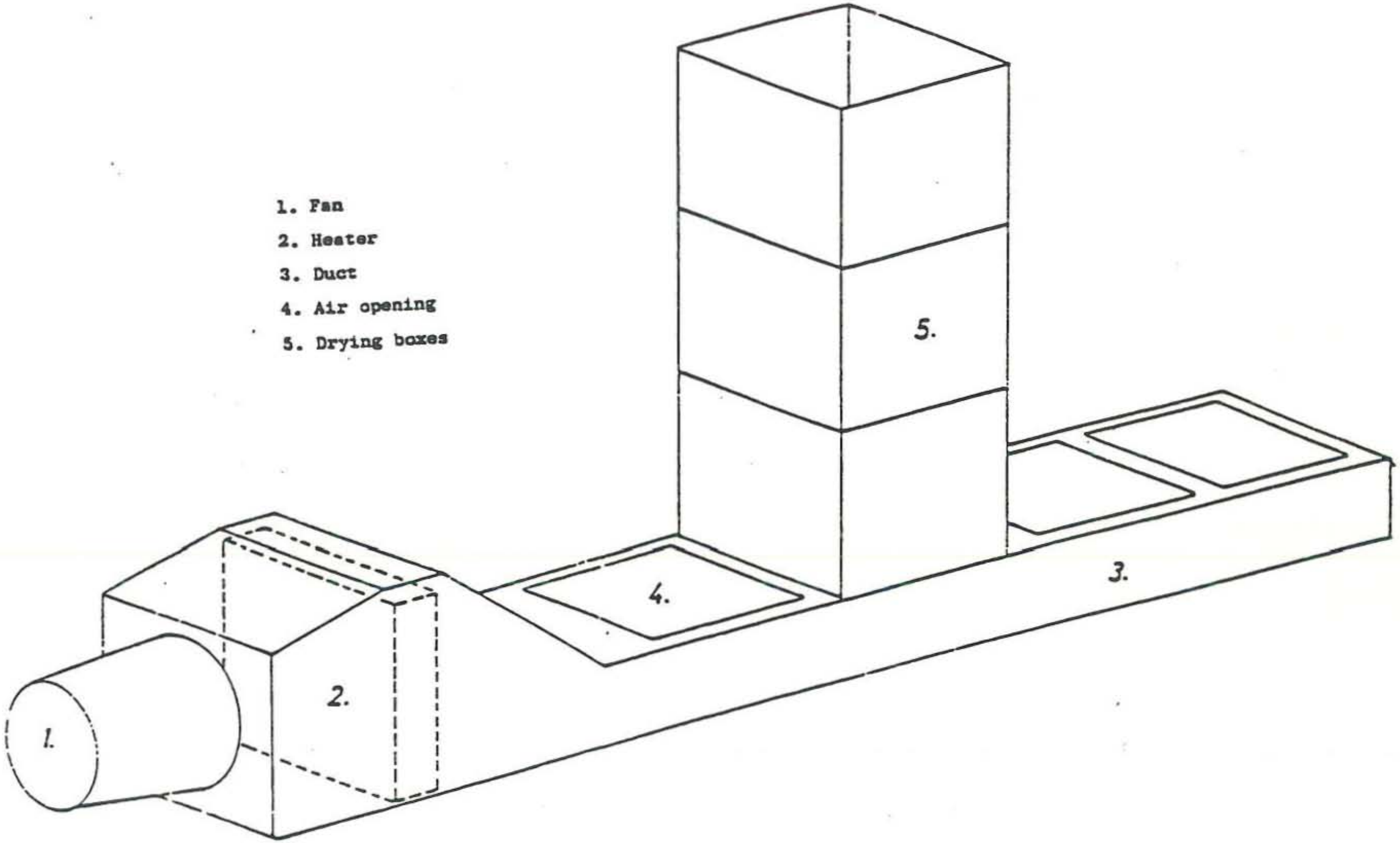


Figure 8 - Secondary drying device

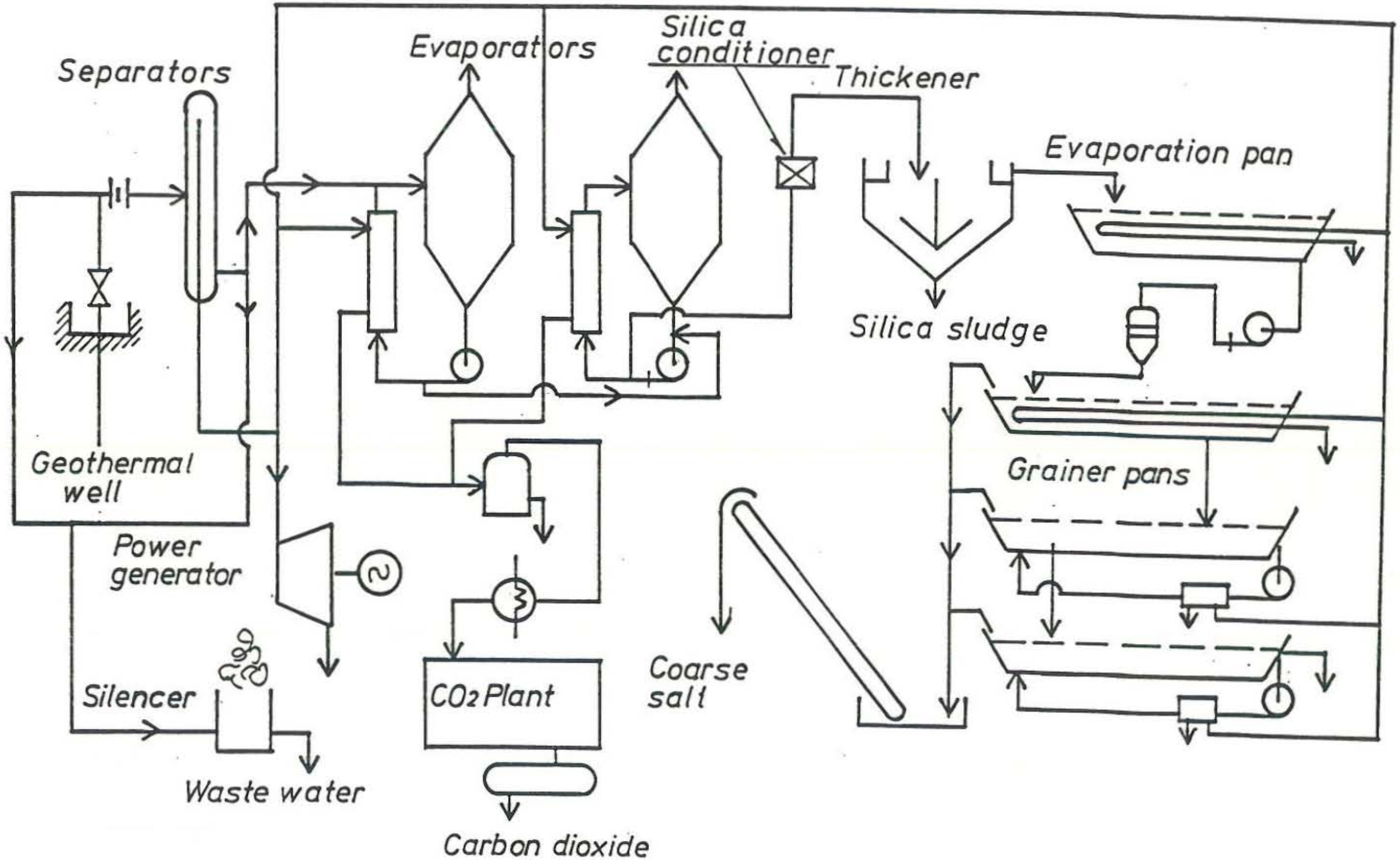


Figure 9 - Flow diagram of Geo-chemicals plant at the Reykjanes peninsula (Lindal, 1988)

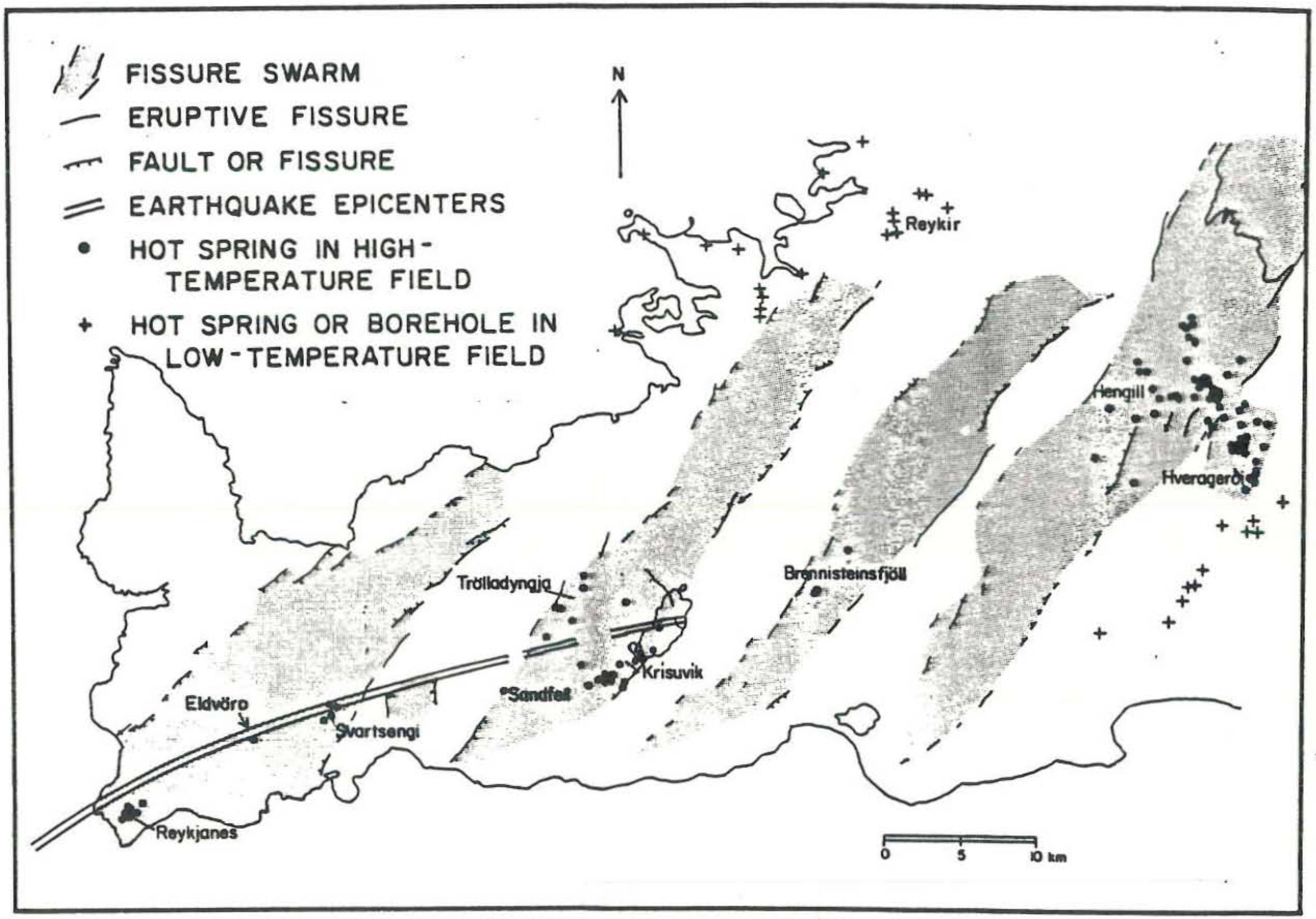


Figure 10 - The western Reykjanes peninsula

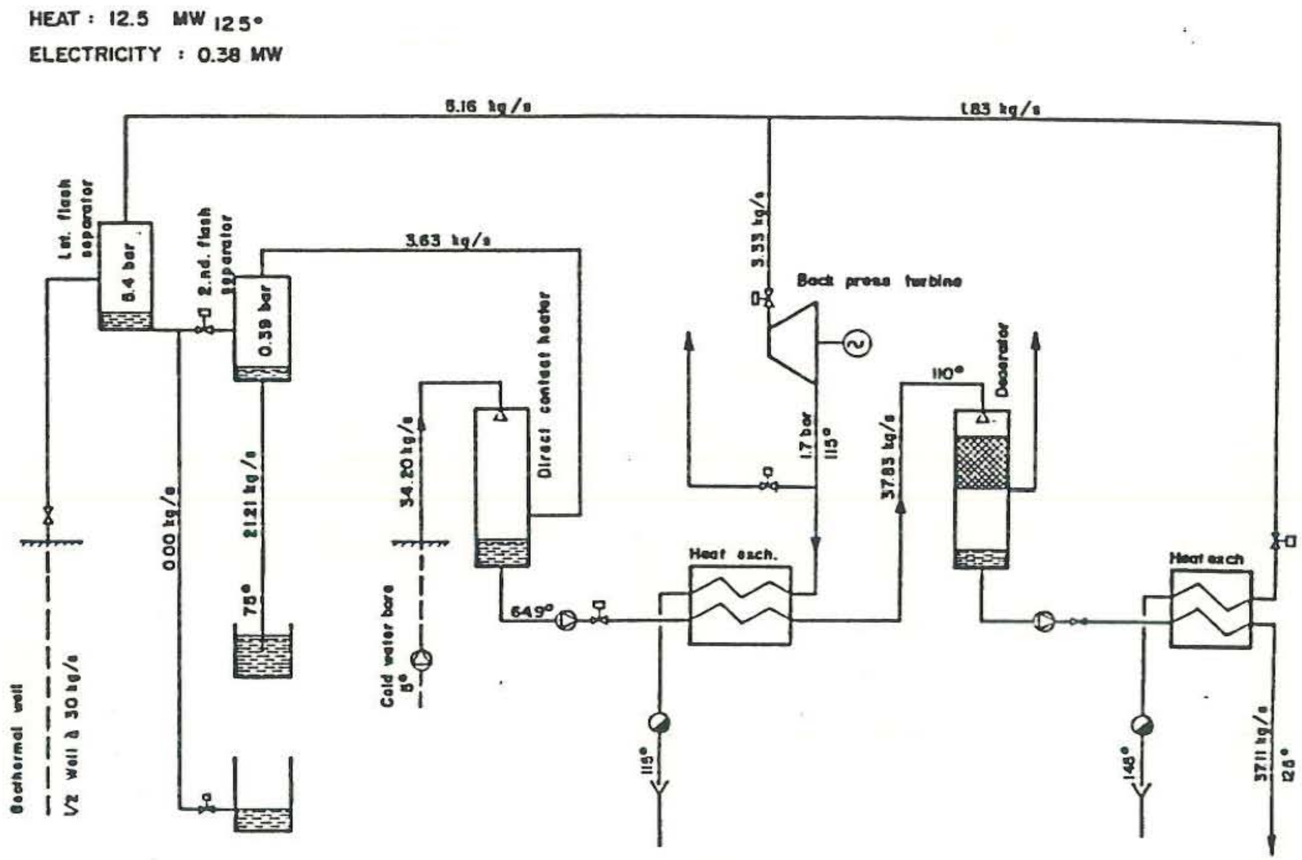


Figure 11 - Flow diagram of one unit in power house I
(Björnsson and Albertsson, 1985)

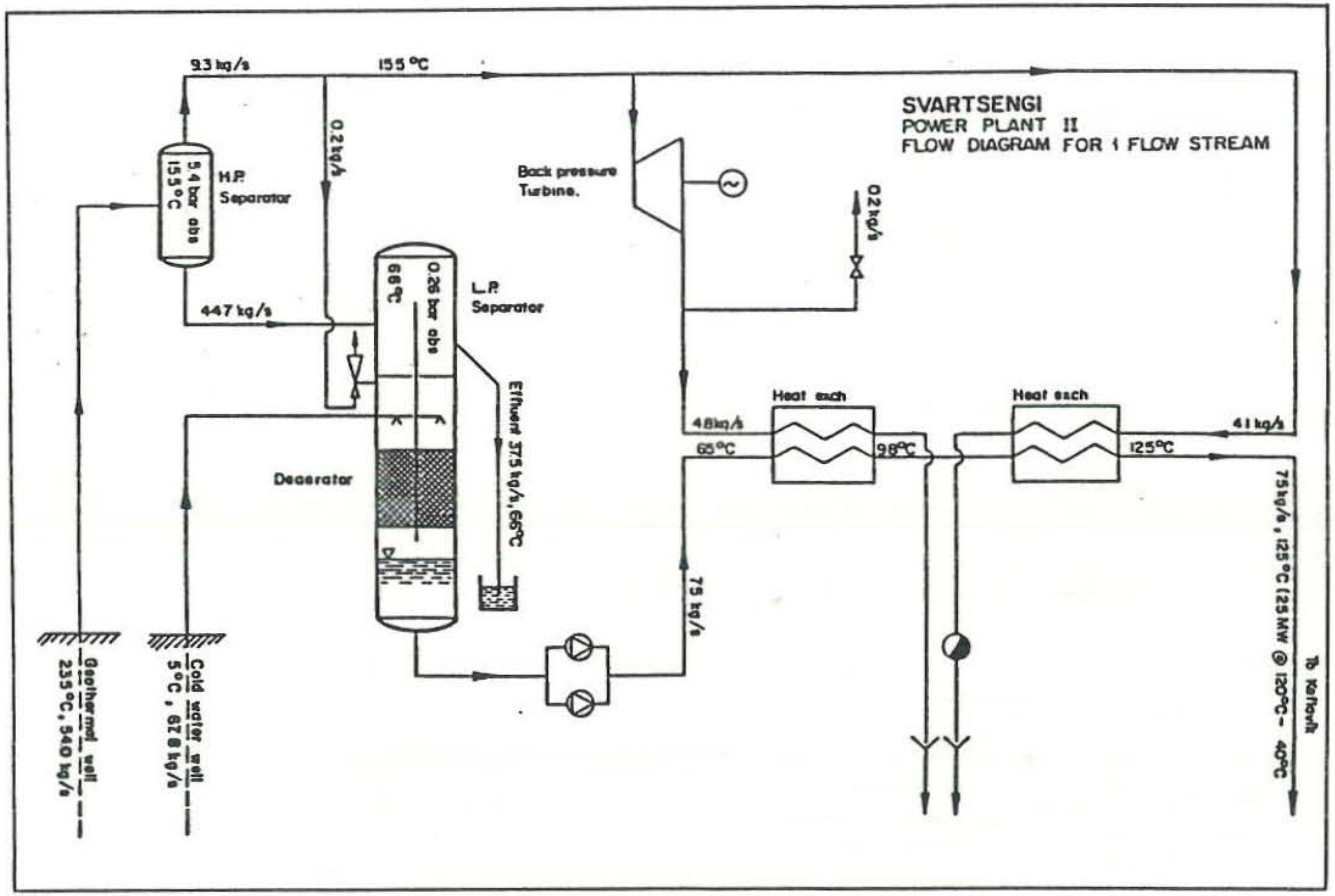


Figure 12 - Flow diagram of one unit in power house II
(Björnsson and Albertsson, 1985)

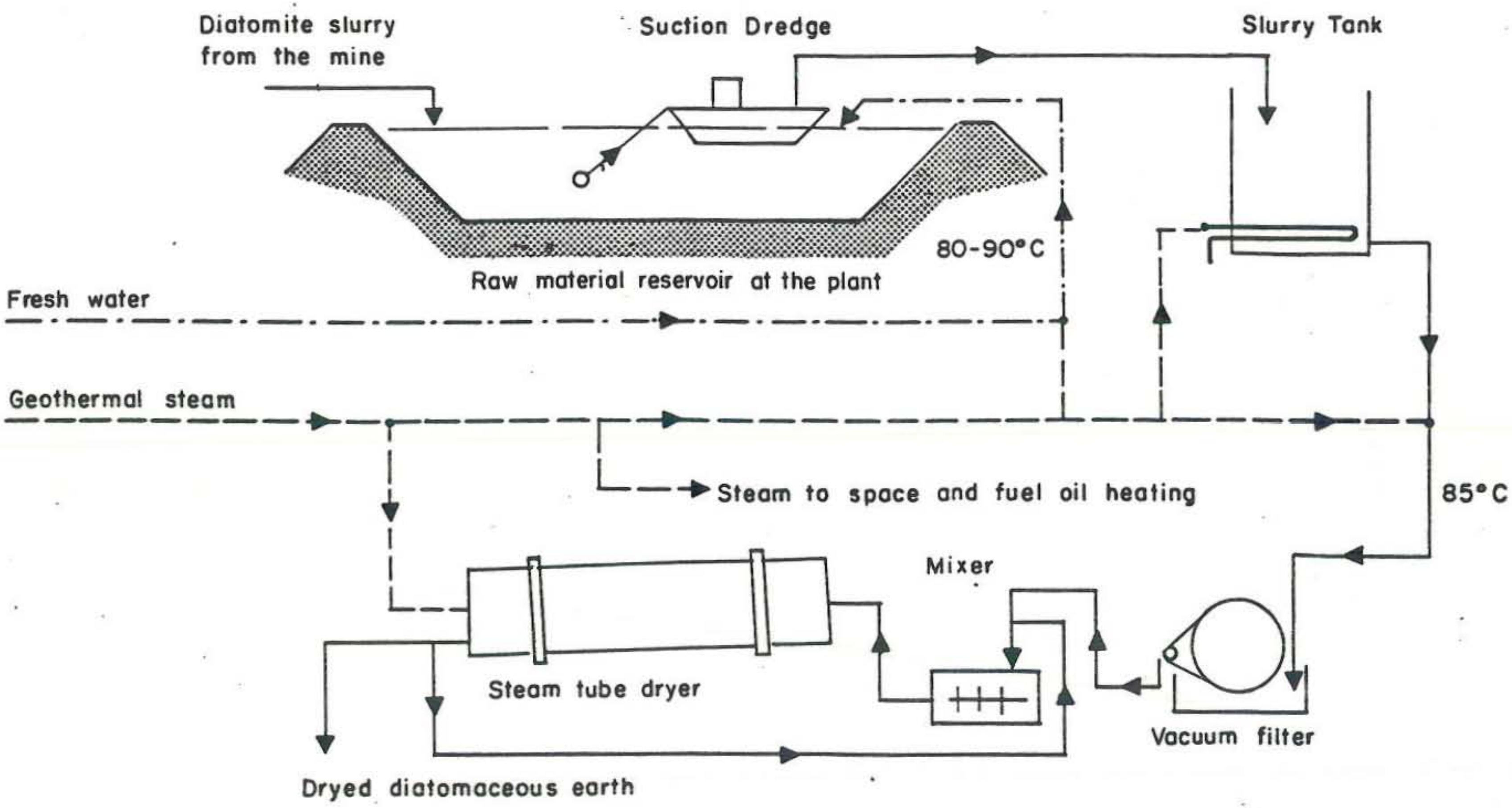


Figure 13 - Flow diagram of diatomite plant at Namafjall (Lindal, 1973)

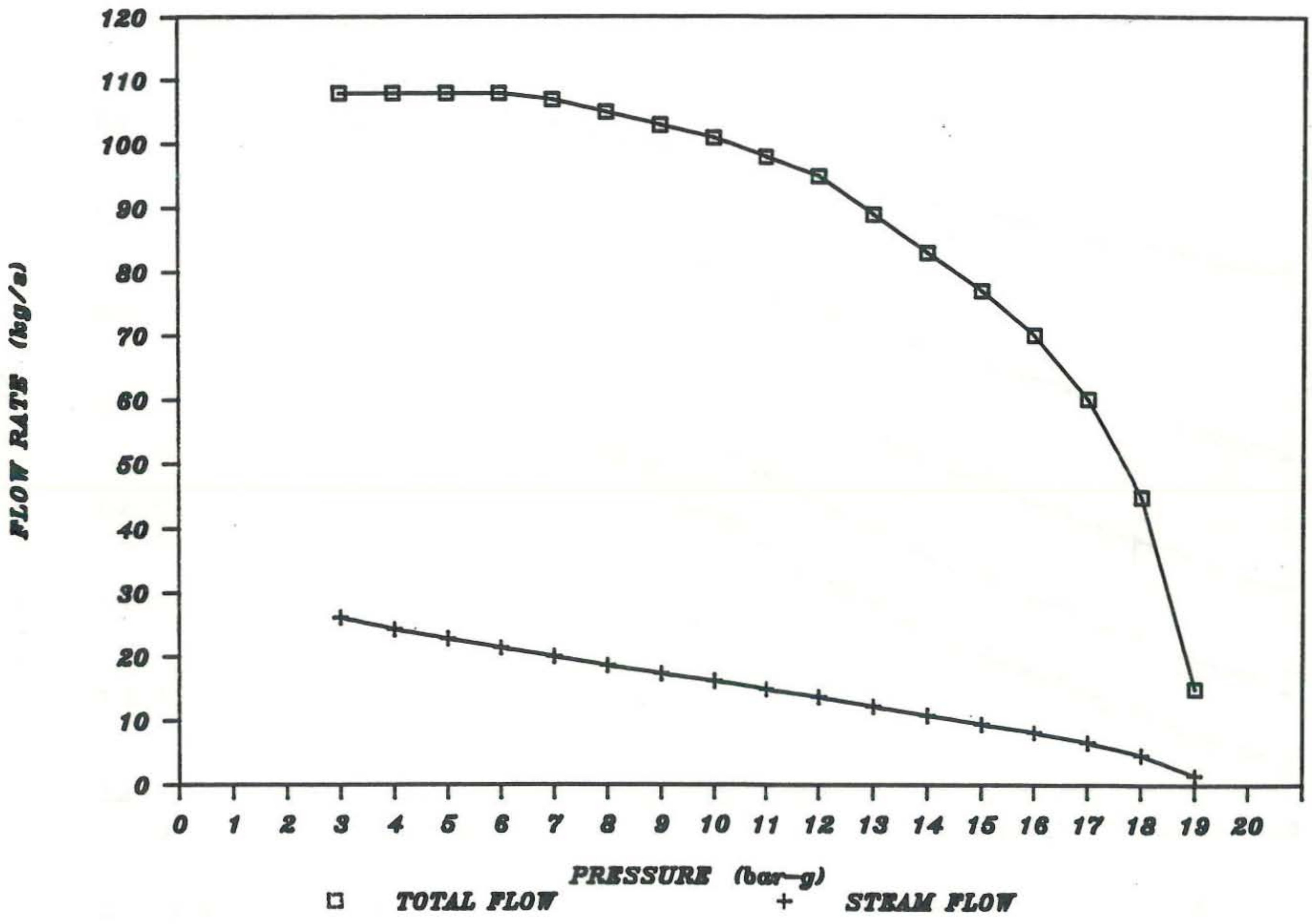


Figure 14 - Flow output characteristics of well

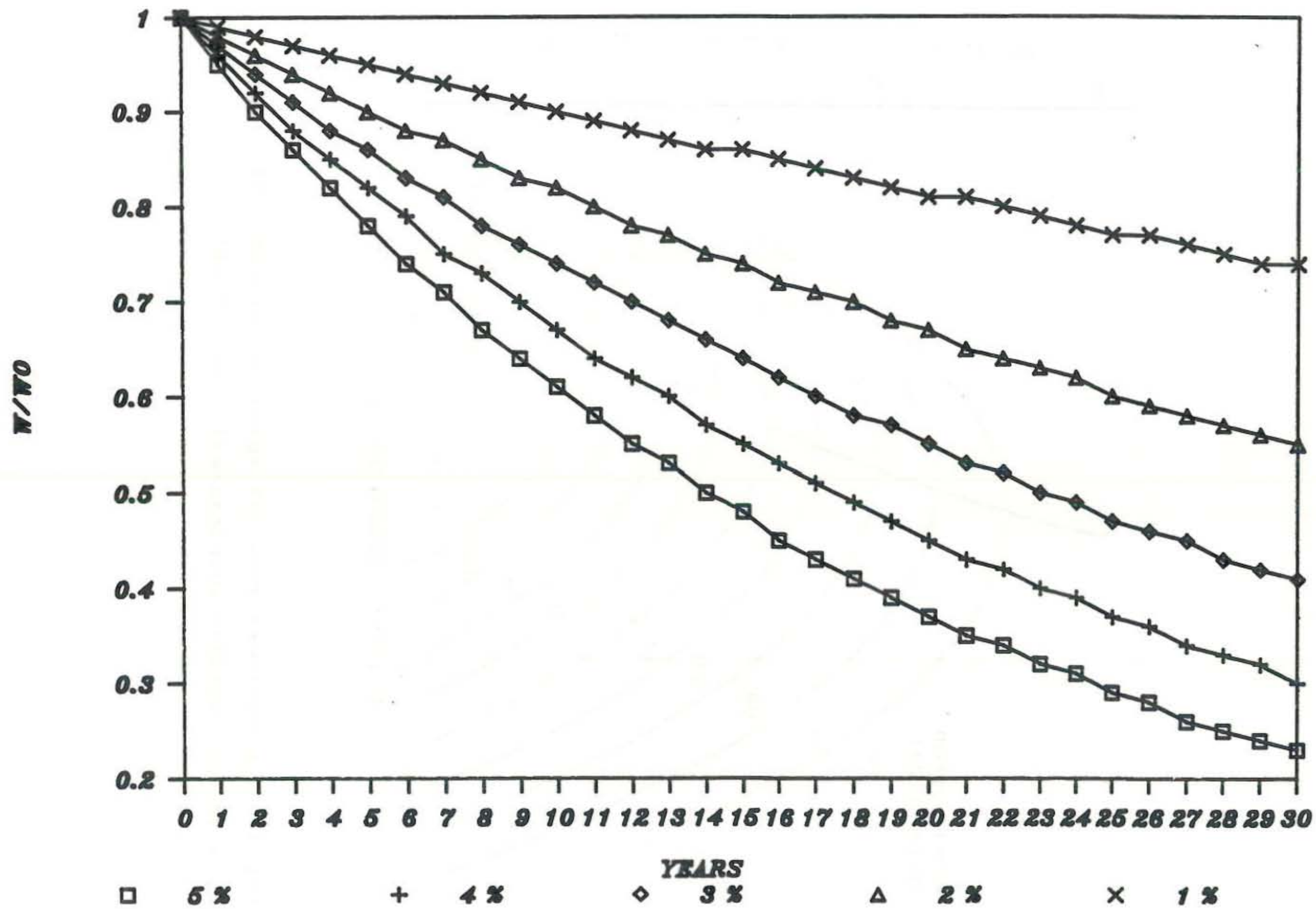


Figure 15 - Flow decline characteristics of well

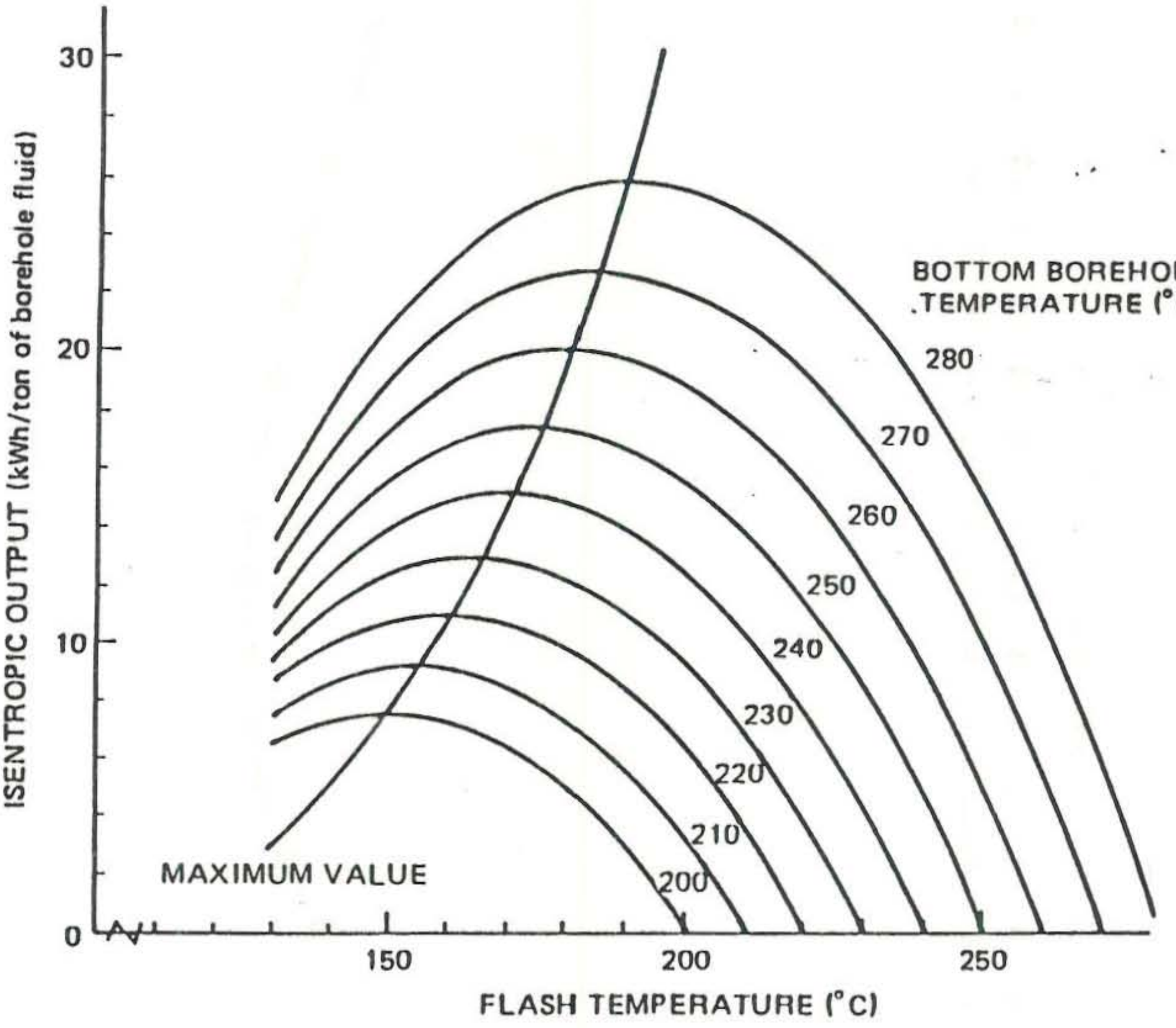


Figure 16 - Available energy for back-pressure unit (t=100°C) for borehole temperatures between 200-280°C

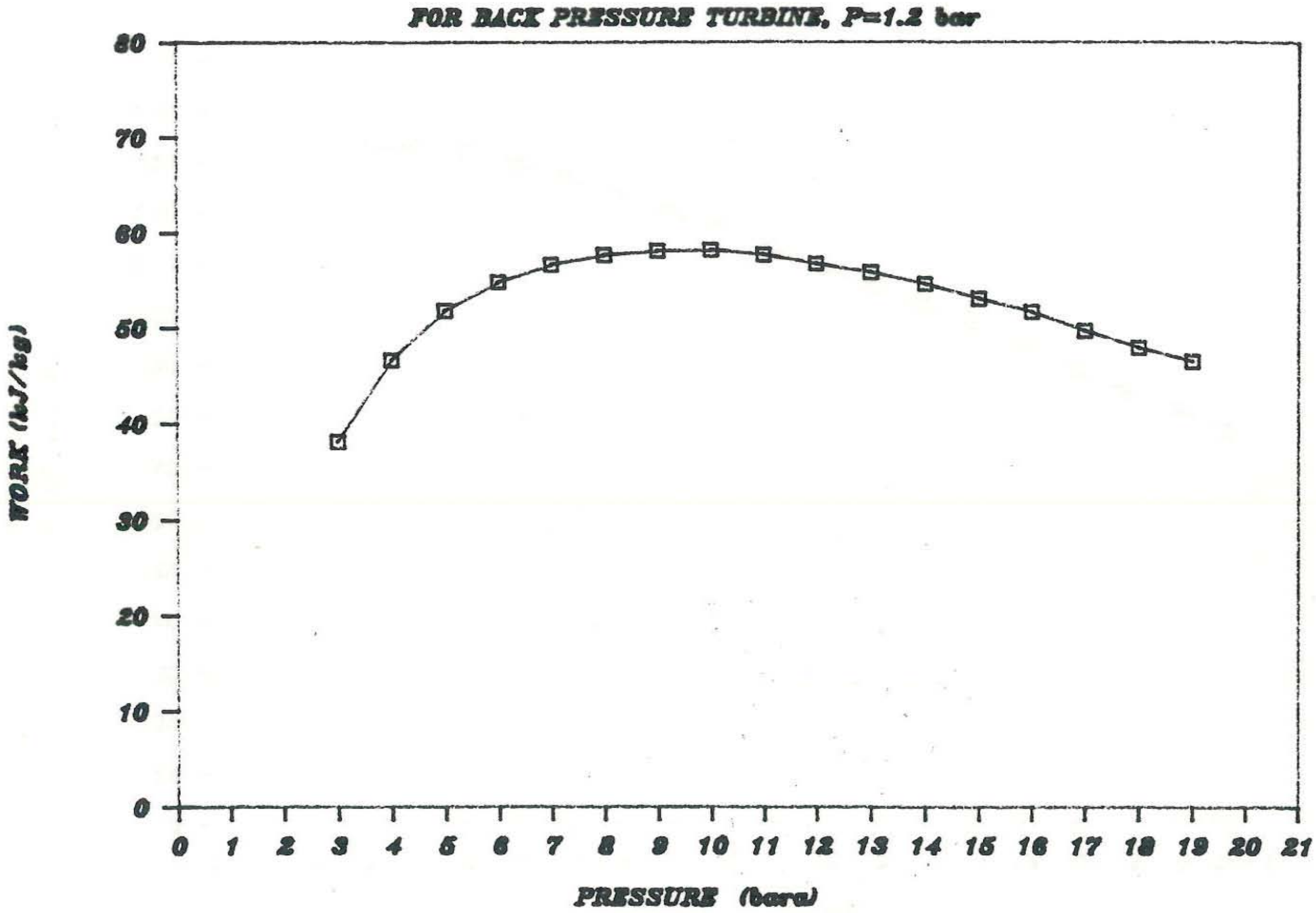


Figure 17 - Available work per unit mass for back-pressure turbine

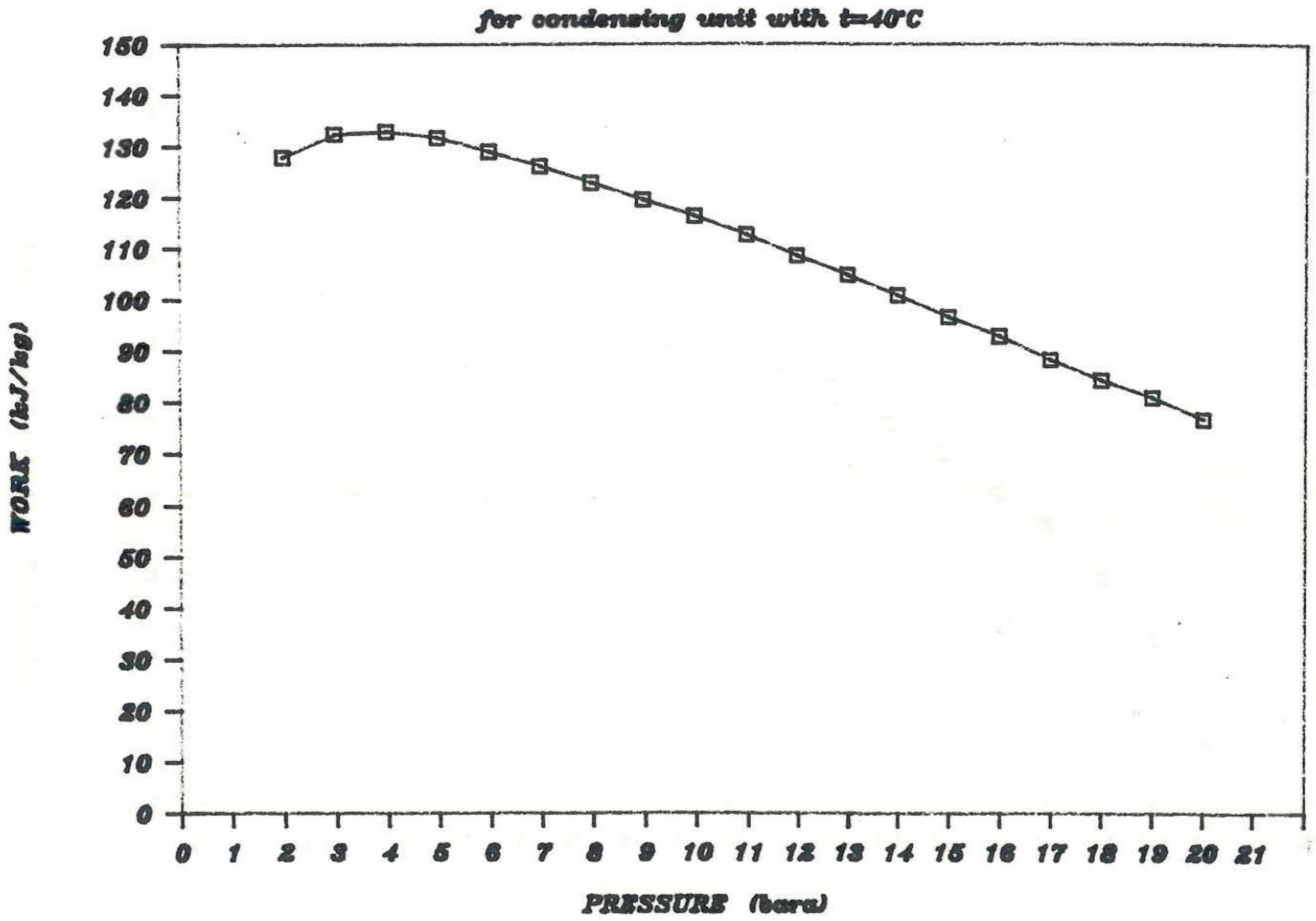


Figure 18 - Available work per unit mass for condensing turbine (t=40°C)

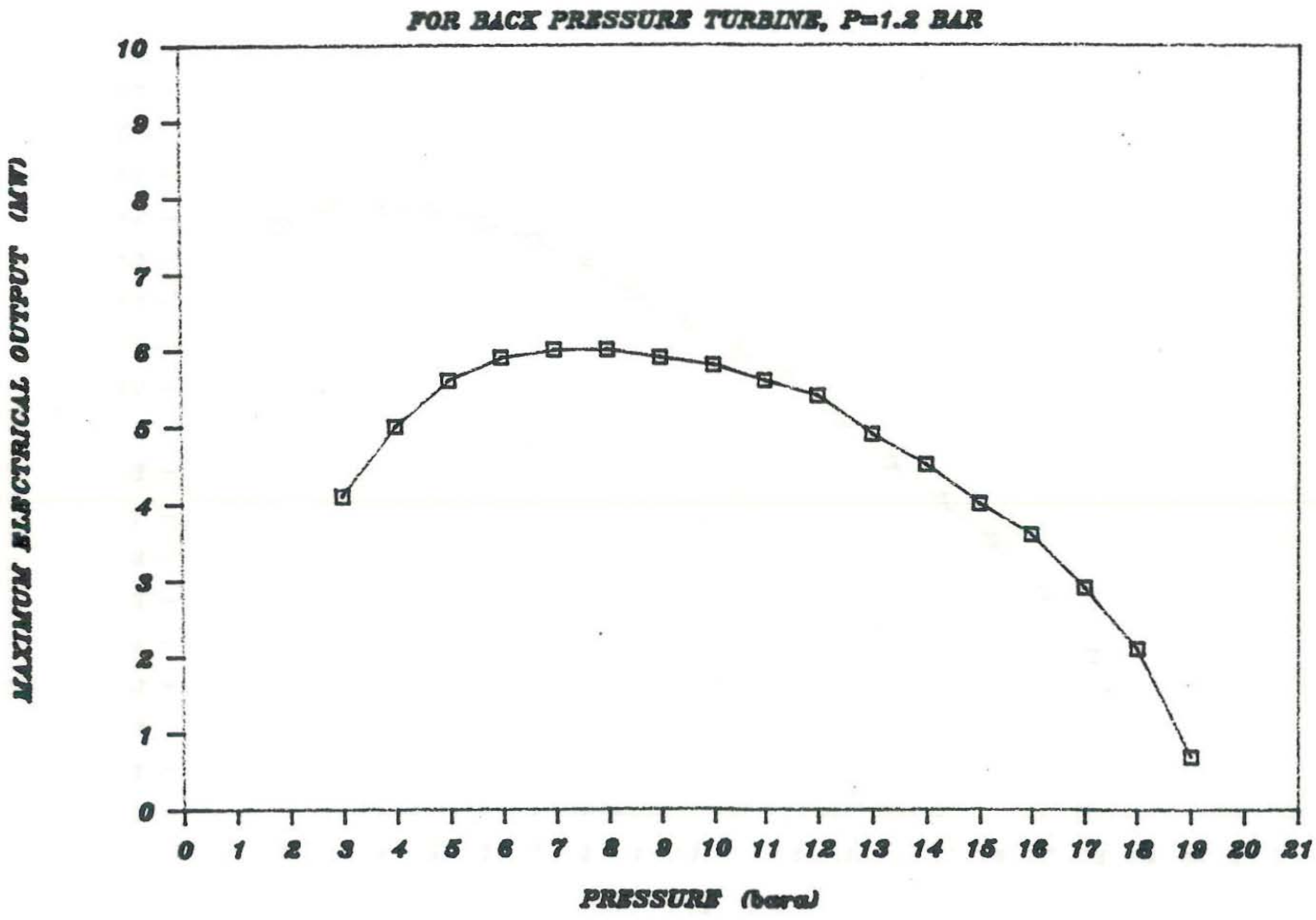


Figure 19 - Electrical output for back-pressure turbine

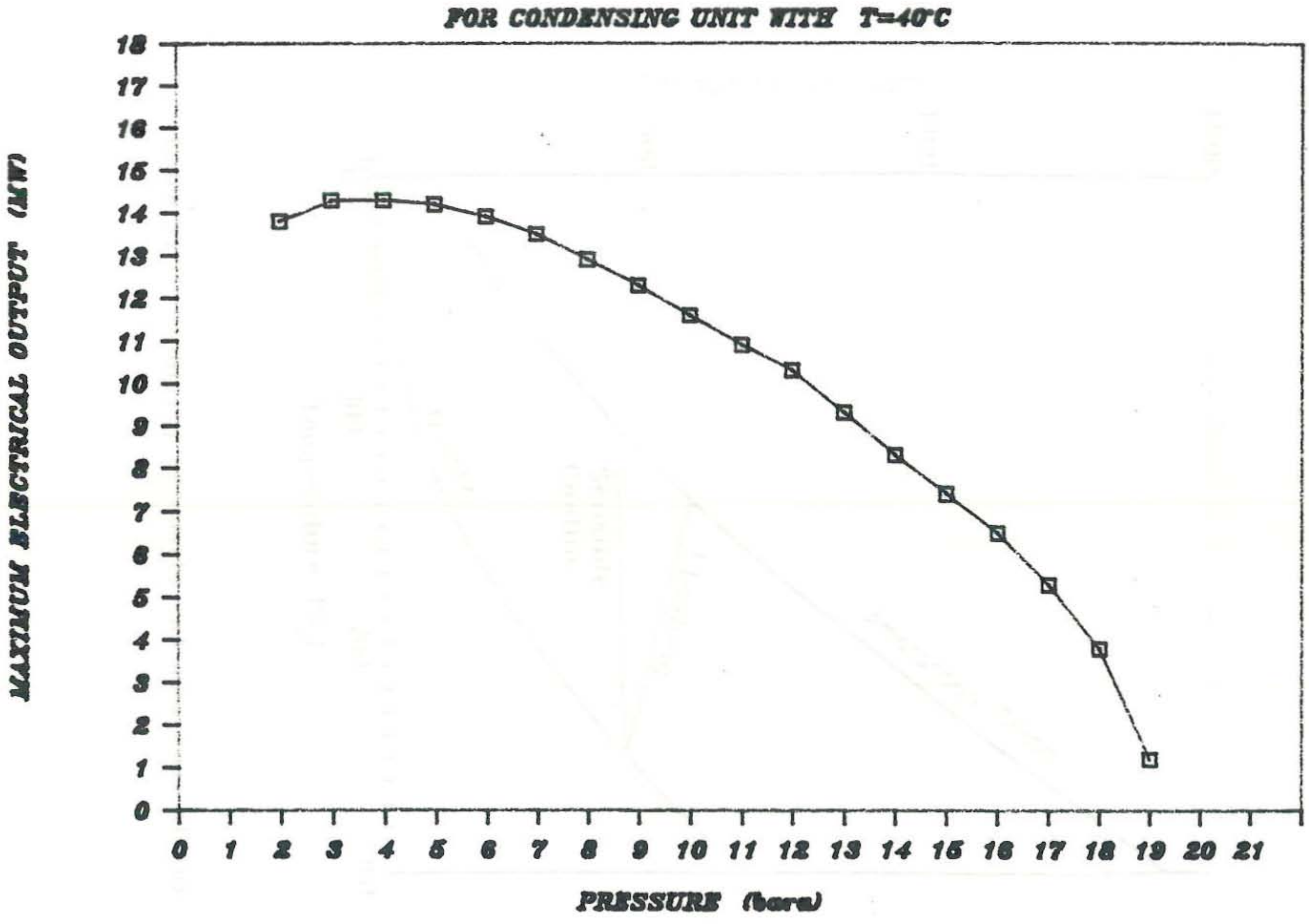


Figure 20 - Electrical output for condensing turbine (t=40°C)

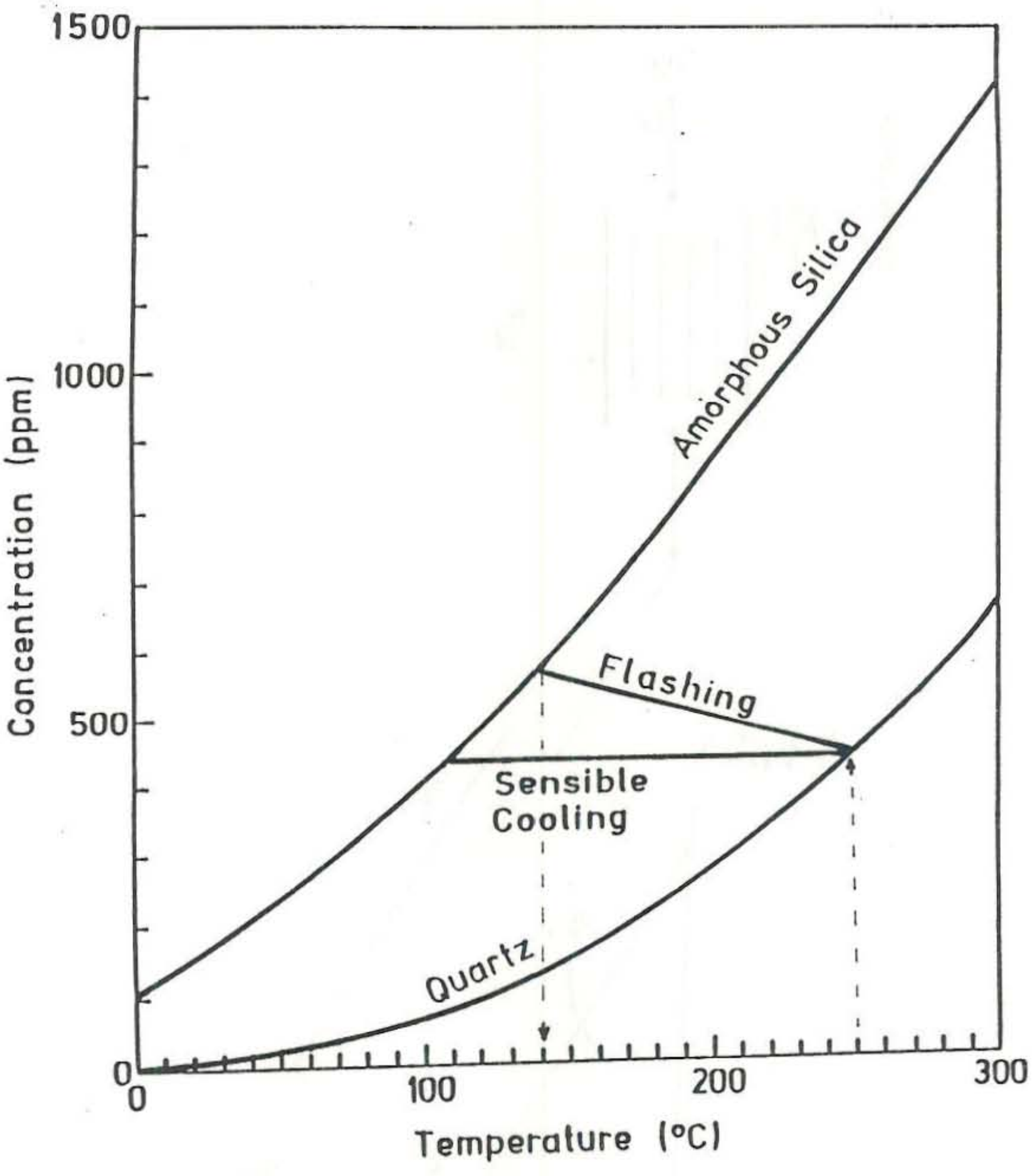


Figure 21 - Solubility of quartz and amorphous silica

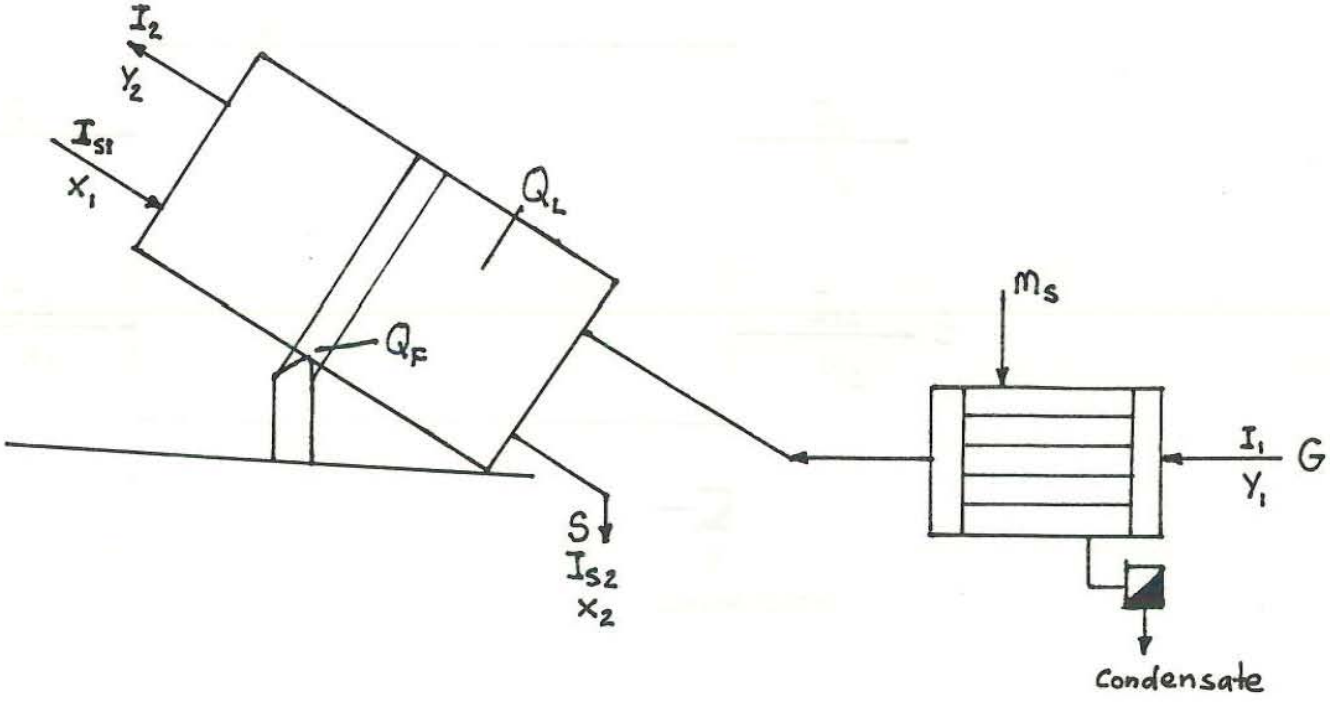


Figure 22 - Flow diagram of countercurrent air heated dryer

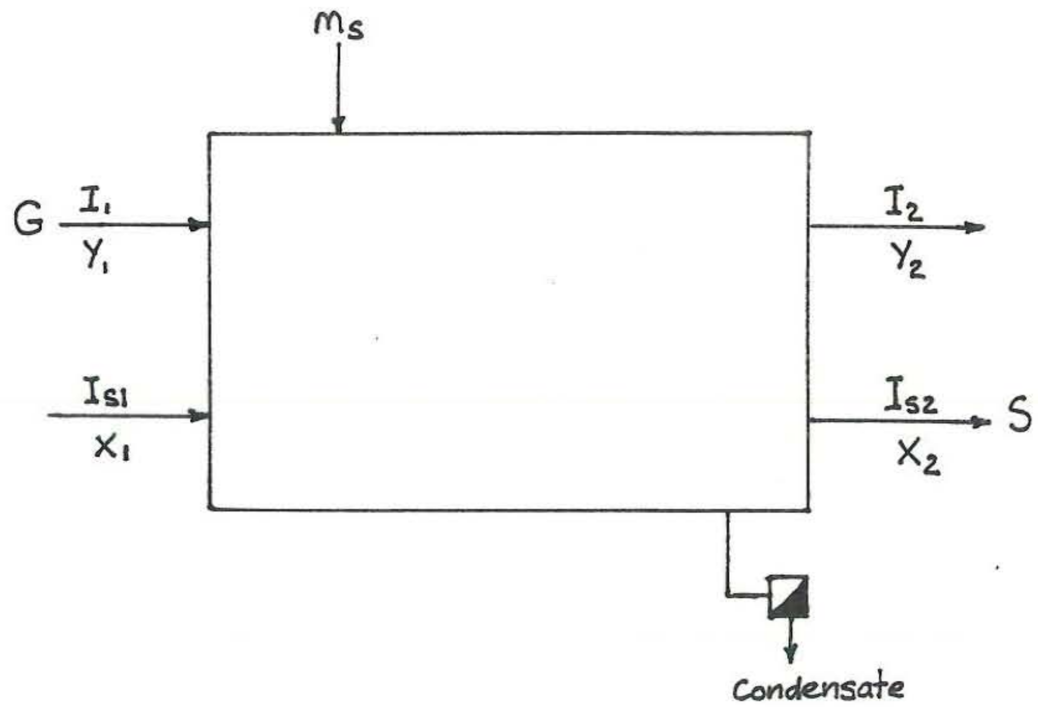


Figure 23 - Flow diagram of steam heated dryer