HEAT DISTRIBUTION

Ceramic fibres exhibit very good even heat distribution characteristics, which add to the effectiveness of the material as a thermal insulator. Probably the best example of this in practice is the use of the material as turbine insulation where temperature differentials between top and bottom casings must be kept to a minimum. A number of turbines have now been lined, the biggest being a 200 MW unit where performance of the ceramic fibre insulation has been described as excellent.

CONCLUSIONS

Ceramic fibre materials represent a major advance in high temperature, low thermal mass insulation. Individual fibre properties and fibrous mass characteristics are now well understood. Also important is the vast wealth of materials engineering and applications expertise which has been gained with respect to the wide range of product forms available.

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UTILISATION OF GEOTHERMAL ENERGY IN ICELAND

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SUMMARY

The present and future uses of geothermal energy in Iceland are reviewed. The classification of geothermal areas is mentioned and their potential estimated. High temperature areas may be able to sustain the production of 20 *MW/km*^{2} *of electricity for at least* 50 *years. The potential of the* 17 *high temperature areas is almost* 6000 *MW, which is substantially greater than that of the* 250 *low temperature areas. However, practically all the hot water used for district heating and greenhouse farming is supplied by low temperature areas. About half the population of Iceland enjoys geothermal district heating at the cost of* 35% *that of comparable fuel oil heating. Utilisation of high temperature areas is relatively recent. Saturated steam from these areas is used for industrial purposes and a* 60 *MW geothermal power plant is being constructed.*

INTRODUCTION

Iceland is probably unique in its geothermal energy potential. Modern utilisation of geothermal energy in Iceland began in the late 1920s when a few houses were heated by water from a neighbouring hot spring. District heating developed rapidly and today half the population lives in houses heated by geothermal water. Development of greenhouse farming followed and, more recently, industrial utilisation. The purpose of this paper is to review the present and future uses of geothermal energy in Iceland and to give an indication of the potential of the geothermal areas. It is felt that this study of geothermal energy development in one country will be of interest to energy resource experts in many other countries.

Applied Energy (2) (1976)—
Printed in Great Britain

GEOTHERMAL AREAS

The geothermal areas in Iceland are divided into low and high temperature areas.[7] The high temperature areas (HTAs) are in the active volcanic zone lying south-west to north-east across Iceland and the low temperature areas (LTAs) are outside it. The two main LTAs are in the south and west of Iceland at the periphery of the active volcanic zone, but other areas are widely distributed (*see* Fig. 1). A LTA is defined as an area where the temperature of the reservoir fluid in the uppermost 1000 m does not exceed 150°C. Similarly, a HTA is defined as an area where the temperature in the uppermost 1000 m exceeds 150°C. These definitions do not apply to other parts of the world. There are about 250 LTAs and 17 HTAs in Iceland.[7]

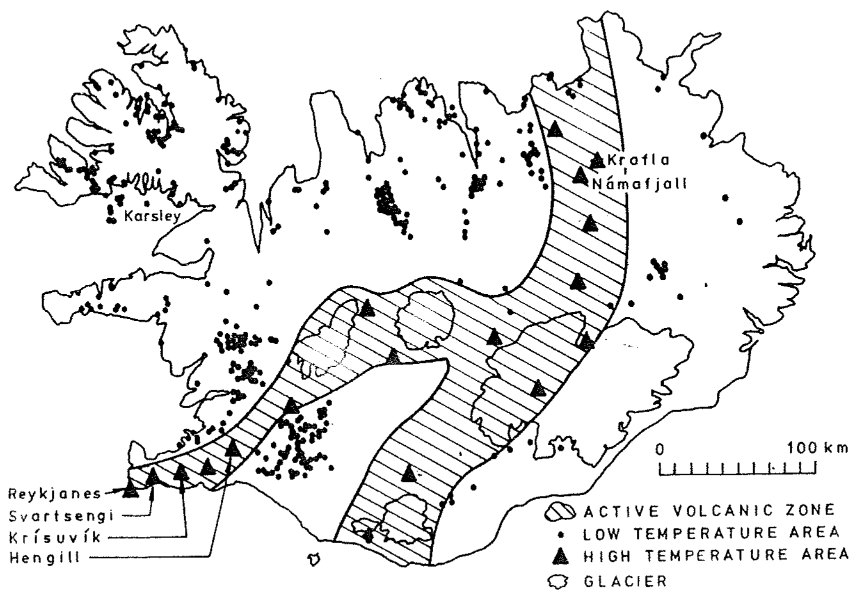

Fig. 1.

In the 250 LTAs there have been identified about 600 large thermal springs having enthalpies corresponding to flowrates of 1500 litres/sec of water at 75°C.[7] More recently it has been stated[4] that the temperature of the thermal springs in LTAs ranges from ambient to boiling and that individual flowrates range from 1 to 150 litres/sec. The total estimated flowrate was given as 1200 litres/sec with another 1600 litres/sec exploitable by drilling. However, recent experience at a large LTA near Reykjavík indicates that substantially greater flowrates can be

achieved than previously anticipated.[19] Assuming that the same exploration techniques can be used in other LTAs, their potential may be much greater than the above figures indicate.

Of the 17 HTAs in Iceland only six have been studied in any detail and a programme for the exploration of five other areas has been proposed.[5] So far the geothermal effort has been mainly on the Reykjanes Peninsula in south-west Iceland and in the Lake Mývatn area in the north-east.

The natural heat discharge from the active volcanic zone in Iceland has been estimated as 10,000 MW thermal[15] and that of the HTAs alone about 4000 MW thermal.[7] It is interesting to note that the natural heat flow is so much greater than total energy demand that Iceland is probably the only country in the world where geothermal energy could be regarded as a truly renewable resource! The amount of energy that could be harnessed by drilling in geothermal areas is much greater than the natural heat flow. To evaluate the potential of the HTAs, their geology and size, the enthalpy and chemistry of the reservoir fluid and the mode of utilisation, all need to be known. Assuming the explored HTAs in Iceland to be similar in character and electricity the mode of utilisation, the size of an area can be used as an indication of its potential. The six explored areas are Hengill (50 km^2), Krísuvík (10 km^2), Svartsengi (4 km^2), Reykjanes (1 km^2) in the south-west and Krafla (30 km^2) and Námafjall (3 km^2) in the north-east, in all about 100 km^2. By introducing a saturation density of electricity production based on present practice and experience in other parts of the world, the potential of the high temperature areas in Iceland can be estimated. The available data[10] indicate that HTAs may be able to sustain electricity production of 10–20 MW/km^2 of land area for at least 50 years, with the Icelandic areas close to 20 MW/km^2. This would make the potential of the six explored HTAs about 2000 MW of electrical energy. The size of the five HTAs to be explored in the next ten years probably amounts to 120 km^2. Assuming the remaining six areas are similar in size, the overall potential of the Icelandic HTAs to produce electricity may amount to 6000 MW for 50 years. However, some of the unexplored areas are so inaccessible that it is unlikely that they could be utilised in the future. For comparison, the assumed technical potential of hydroelectricity in Iceland is 4000 MW and the economic potential 3200 MW, of which only 8 per cent is presently being used. Iceland has no indigenous fossil fuels.

PRESENT USES

District heating

District heating ranks foremost in the utilisation of geothermal energy in Iceland. At the end of 1973 about 46 per cent of the population enjoyed geothermal district heating and by 1980 this figure should be about 67 per cent (*see* Table 1 and Figs.

TABLE I
DISTRICT HEATING IN ICELAND, 1973

Location	*Population**	*Percentage of total Icelandic population*	*Estimated amount of heat GWh thermal*
Reykjavík	84333	39·50	1177·6
Ólafsfjördur	1108	0·52	15·5
Selfoss	2637	1·24	36·9
Hveragerdi	990	0·46	13·7
Saudárkrókur	1750	0·82	24·4
Dalvík	1123	0·53	15·8
Húsavík	2129	1·00	29·8
Reykjahlíd	149	0·07	2·1
Hvammstangi	397	0·19	5·7
Seltjarnarnes	2460	1·15	34·3
Hrísey	297	0·14	4·2
	97373	45·62	1360·0

* The population of Iceland at 1 December, 1973 was 213,499.

2–3). The gross production of geothermal water at wellhead above 40°C in 1973 for district heating was about 1510 GWh thermal and with 90 per cent efficiency the utilised heat corresponded to 1360 GWh thermal.

In April, 1975 the cost of geothermal water in Reykjavík was 39·36 kr/m^3 or 0·80 kr/kWh thermal. This corresponds to about 0·12 £/m^3 or 0·72 £/GJ. (August,

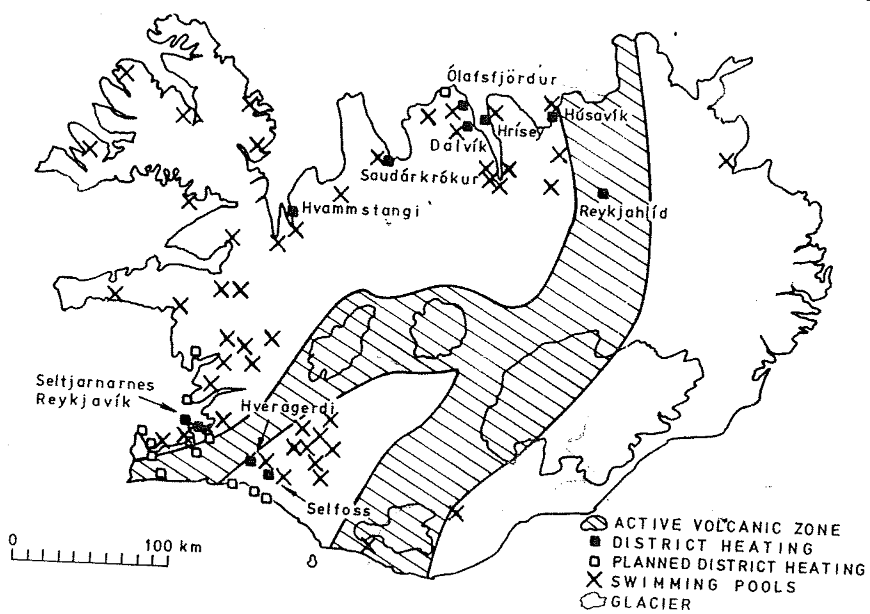

Fig. 2.

1975 1£ = 340 kr.) At the same time the heating cost of comparable installations using fuel oil heating was 2·18 kr/kWh thermal. Under these conditions geothermal district heating in Reykjavík costs about 35 per cent of fuel oil heating.[22] In new district heating systems this percentage is usually not as favourable initially and could be as high as 80 per cent, reflecting the high capital investment required. It is customary to assume that hot water enters a house at 80°C and spent water leaves at 40°C. (*Editor's note*. The rejection of heat at 40°C probably reflects the use of standard central heating equipment. The use of the latest forms of air-blown radiators could reduce the drain temperature and bring overall cost savings.)

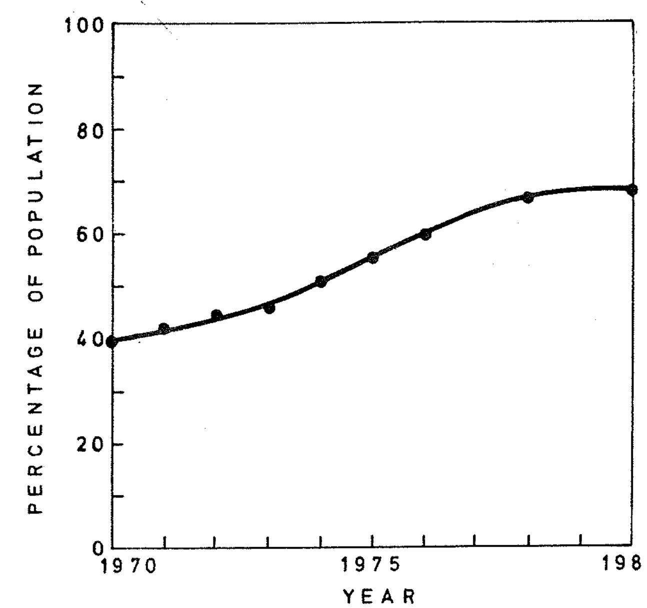

Fig. 3. Population enjoying district heating.

With few exceptions, the thermal waters used for district heating are from LTAs. The water from these areas is usually close to boiling and relatively free from dissolved constituents causing operational problems such as corrosion and fouling of equipment. Because the LTAs are mostly located on low ground in valleys and lowlands by the coast, they tend to be close to communities and thus ideally placed for exploitation. In rural areas farms, schools, swimming pools and even whole villages have been built in thermal areas to take advantage of the natural heat.

The district heating system in the town of Selfoss (2600 inhabitants) is typical of the many similar systems in towns and villages outside the Reykjavík region. It is owned by the township and uses water from a LTA 1·5 km outside the town. The area is capable of producing 80 litres/sec of water at 80°C from 12 shallow drill-holes, the deepest being about 500 m.[8,14] The water is piped to the town and used directly in radiators and, when cold, returned to the town drains.

The Reykjavík Municipal District Heating Service is by far the largest in Iceland, if not the world. It has been highly successful, both technically and economically. Figure 4 shows how the production of geothermal water used in Reykjavík has increased in the last 20 years. Presently the District Heating Service utilises water from LTAs both within and outside the city. In the Laugarnes area 11 deep drill-holes are being used, producing 300 litres/sec of water at 128°C. In the Ellidaár

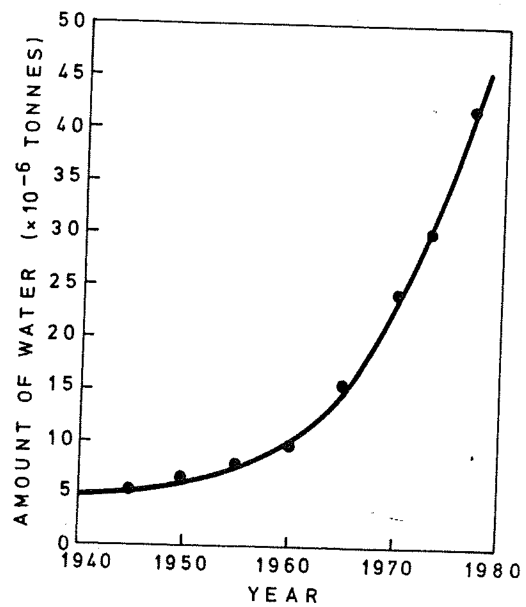

Fig. 4. Utilisation of geothermal water in Reykjavík.

area five of 12 deep drillholes are being used to produce 180 litres/sec of water at 103°C.[1] The Reykir area is 15 km east of the city and by the end of 1975 it should be capable of producing over 1200 litres/sec. In 1966, 72 shallow holes had been drilled, producing 340 litres/sec of water at 86°C of which Reykjavík received 290 litres/sec.[1] In 1973 21 deep holes (1400–2000 m) had been drilled since 1966, capable of producing 950 litres/sec of water at 65–99°C.[18] By 1976 the total addition of holes from 1966 is expected to be 35–40.[21]

The water from the boreholes in the Reykir area flows by gravity into collecting tanks from which it is pumped 15 km to the city and stored in six tanks with a capacity of 26,000 m^3 (*see* Fig. 5). From the storage tanks the water is pumped to

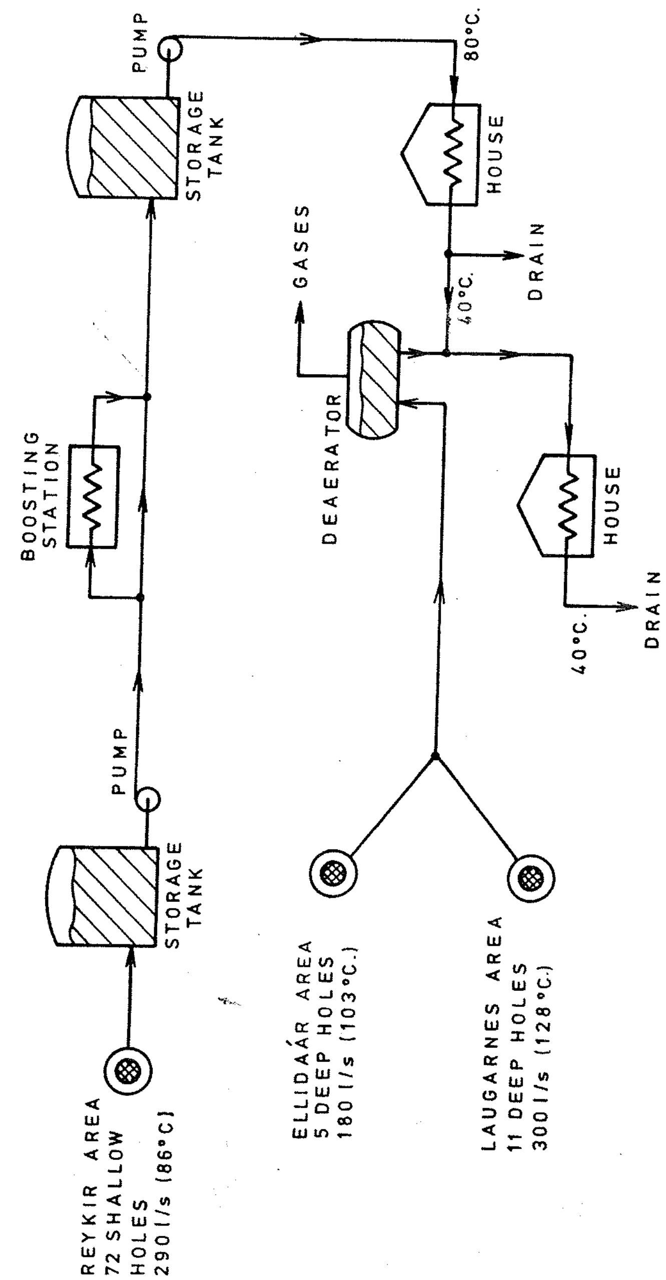

Fig. 5. Reykjavík municipal district heating service.

the various pumping stations in the city from where it is delivered directly to the customers at about 80°C. In most parts of the city the spent water goes down the drain but in some places it is blended with the higher temperature water from the Laugarnes and Ellidaár areas. The boreholes in these two Reykjavík areas are equipped with pumps placed at 110–120 m depth. The water is pumped to the nearest pumping station where it passes through deaerators to remove dissolved gases and is then blended to 80°C with the colder return water.[8]

The Reykjavík system is designed to meet the heat load of the city when the air temperature is −10°C. In colder periods there are provisions for boosting the temperature of the geothermal water. This is done in oil-fired and off-peak electricity power plants. In 1968 the boosting stations provided about 8 per cent of the total thermal energy used in Reykjavík.[8] All the system pipework is underground. It consists of welded black mild steel pipe, laid in concrete channels when the diameter is larger than 75 mm, and insulated with rock wool or aerated concrete. Street mains of small diameter, as well as house connections, are black mild steel pipe insulated with polyurethane foam in the annular space between the steel pipe and an outside protective jacket of high density polyethylene pipe.

Presently the Reykjavík Municipal District Heating Service is extending its system to the neighbouring towns. By 1976 it should provide district heating for over 50 per cent of the total population of Iceland.

There are only two district heating systems in Iceland that receive water from HTAs. These are Reykjahlíd in the Námafjall area and Hveragerdi in the Hengill area. Both of these systems are recent, built in 1971 and 1973 (connected to an already existing distribution system), respectively, and both use residual water when 260–280°C water has flashed to 100°C. Because of the high silica content of the residual water (300–700 ppm) the Reykjahlíd and Hveragerdi district heating systems have experienced great difficulties with silica scaling. However, in late 1974, dilution of the borehole fluid with fresh water was started at Hveragerdi, apparently solving the scaling problem. This system involves degassing.

Agriculture

There are about 120 greenhouse farms in Iceland, mostly in the south and south-west of the country. Hveragerdi is the largest centre of greenhouse farming, with almost 40 farms having over 40,000 m² under glass. Figure 6 shows the increase in area under glass since 1930, including the estimated 135,000 m² in 1973.[9] About 70 per cent of this area is used for vegetables, mostly tomatoes and cucumbers, and about 30 per cent for flowers, such as roses, carnations, chrysanthemums and various potted plants.[12] In 1972 geothermal energy utilisation in greenhouse farming was 80 GWh thermal. Greenhouses in Iceland are generally heated by means of radiator pipes which are placed along the walls on the long side of the house. A water temperature of 80–95°C is common.

If fossil fuels were used to heat greenhouses in Iceland, the heating cost could amount to 35–40 per cent of the production cost.[13] No information is available on the cost of using geothermal energy, but the cost of district heating may be used to arrive at an approximate figure. As shown above, the cost of geothermal district heating in Reykjavík amounted to about 35 per cent of fuel oil heating, but could be as high as 80 per cent for new installations. It is possible that heating costs of greenhouses in Iceland using geothermal water could represent 12–14 per cent of the production cost and might even be as high as 28 per cent in some locations.

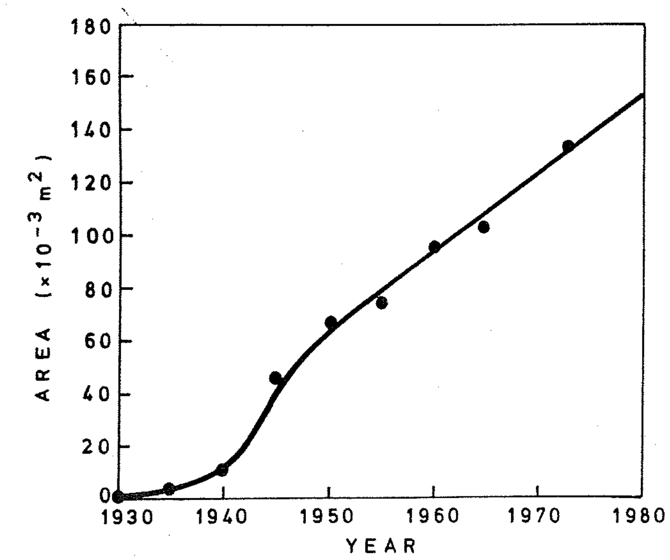

Fig. 6. Area of greenhouses.

Several fish-breeding stations in Iceland use geothermal energy for tempering the water fed to the ponds. In most of these salmon and trout are hatched for release in lakes and rivers. Recently a station was built where it is hoped to raise 50 tonnes annually of 200 g trout ready for market. The station has an area of 7000 m² under water and regulates the temperature of the inside and outside ponds to 12–14°C.[2]

Industry

Large-scale industrial utilisation of geothermal energy in Iceland is relatively recent. It began in 1967 when a diatomite plant started operation in the Námafjall geothermal area, using diatomaceous earth dredged from the bottom of Lake

Mývatn, 3 km away. The plant, which is jointly owned by the Icelandic State and an American company, produces over 24,000 tonnes annually of diatomite filter aids which are exported mainly to Europe. Forty tonnes per hour of saturated steam at 10–11 bar are used, the plant drawing this from boreholes 600 m away at Námafjall.[12,16] In 1974 the price of steam at Námafjall was about 52 kr/t (0·15 £/t). The price of geothermal steam was recently estimated to be less than 0·25 £/t and the price of steam generated using fossil fuels 0·5–1·0 £/t, depending on location and the availability of fuel.[20]

At Karlsey in the west of Iceland a plant has been built for the drying of seaweed collected in the area. The conveyor-dryer used will require 45 litres/sec of geothermal water at 95°C. The water is being obtained from two boreholes, 3 km away. The 4000 tonnes per year production will mainly be exported to Scotland and used in the production of alginates.

For some years now light aggregate cement building slabs have been cured by applying geothermal steam directly.

Electricity

Seven boreholes have been drilled in the Námafjall area with a maximum depth of 1200 m and temperatures as high as 280°C have been recorded.[16] The six drill-holes presently used produce 40 t/h of steam at 10–11 bar and 60 t/h of steam at 8–9 bar. In addition to the saturated steam, much hot water is produced. At Námafjall the cyclone steam–water separators operate at 8–12 bar, producing the required steam and 400 t/h of water. When this water flashes at 100°C it produces about 80 t/h of steam and 320 t/h of water. About 90 t/h of the water is used for the Reykjahlíd district heating system, the excess steam and water being rejected.

In 1969 a 3·2 MW non-condensing turbine was installed at Námafjall using about 60 t/h of saturated steam at 8–9 bar. The specific steam consumption is therefore 18·75 kg/kWh. The plant was mainly built to gain experience in producing geothermal electricity and the turbine used is a reconditioned machine, not designed for the operating conditions at Námafjall. Assuming the price of steam to be the same as supplied to the diatomite plant, the cost of electricity in 1974 would have been about 0·28 p/kWh. However, the thermodynamic efficiency of non-condensing turbines is only 3 per cent compared with 7 per cent for direct condensing turbines.[17] The cost of electricity from a direct condensing turbine, as commonly used in geothermal areas, would therefore be about 0·12 p/kWh, with a specific steam consumption of 8 kg/kWh.

Prior to the Námafjall power plant being built plans had been made to construct a 15 MW station at Hveragerdi. At least eight boreholes had been drilled when the scheme was abandoned after it was decided to build a large hydroelectric power plant at Búrfell. Recently, however, proposals have been put forward to use these eight boreholes and build greenhouses on a large scale (0·335 km^2) and produce flowers and vegetables for export.[13] Because light becomes a limiting factor during the winter in Iceland, artificial lighting is being considered. The steam fraction from the eight boreholes would be used to produce electricity for lighting and the water fraction for heating of the greenhouses.

FUTURE USES

District heating

Svartsengi is one of the HTAs on the Reykjanes Peninsula. In 1971 two shallow boreholes were drilled. These holes are 240 and 400 m deep and capable of discharging 60 to 70 kg/sec respectively of a steam–water mixture with an enthalpy corresponding to water at about 200°C. In 1974 two deep boreholes were drilled. They are 1500 and 1700 m deep, both capable of discharging about 90 kg/sec of a steam–water mixture with an enthalpy corresponding to water at about 240°C.

At Svartsengi the geothermal fluid is not of rain water origin, as is general in Iceland, but originates from sea water. This geothermal brine differs, however, from ordinary sea water in that its chloride content is about two-thirds that of sea water. The geothermal brine has more calcium and potassium, but less magnesium and sulphate, than ordinary sea water. The difference in composition of the two results from flashing of the hot water and its interactions with the surrounding rock.[6] Because of its high temperature, the brine contains large amounts of silica (500–600 ppm), which precipitates out to form hard scale on equipment, resulting in operating difficulties.

Presently, plans are under way to construct a district heating system for the communities (11,000 people) on the Reykjanes Peninsula using steam and brine in the Svartsengi area. The problems involved in heating fresh water with silica-laden brine led to the development of a system not requiring any heat transfer surfaces (*see* Fig. 7). After issuing from the borehole the steam–brine mixture is separated in a cyclone separator. The hot brine goes to a secondary separator operating under vacuum. More steam is formed and the now concentrated brine is rejected. The newly-formed steam is condensed in a barometric condenser by fresh water. Steam from the primary separator is injected into the fresh water condensate stream, which goes to a degassing unit to remove oxygen, carbon dioxide and hydrogen sulphide.

Electricity

Whereas utilisation of LTAs for district heating purposes is well established in Iceland, the exploitation of HTAs is still in its infancy. HTAs are ideally suited for process heating and the production of electricity, depending on the location.

A 60 MW geothermal power plant is being built at the Krafla HTA in north-east Iceland. Two exploration boreholes were drilled in 1974 to 1138 and 1204 m. The maximum temperature found was 298°C (the highest in Iceland so far). Production drillings started in 1975 and the first 30 MW unit should be operational at the end

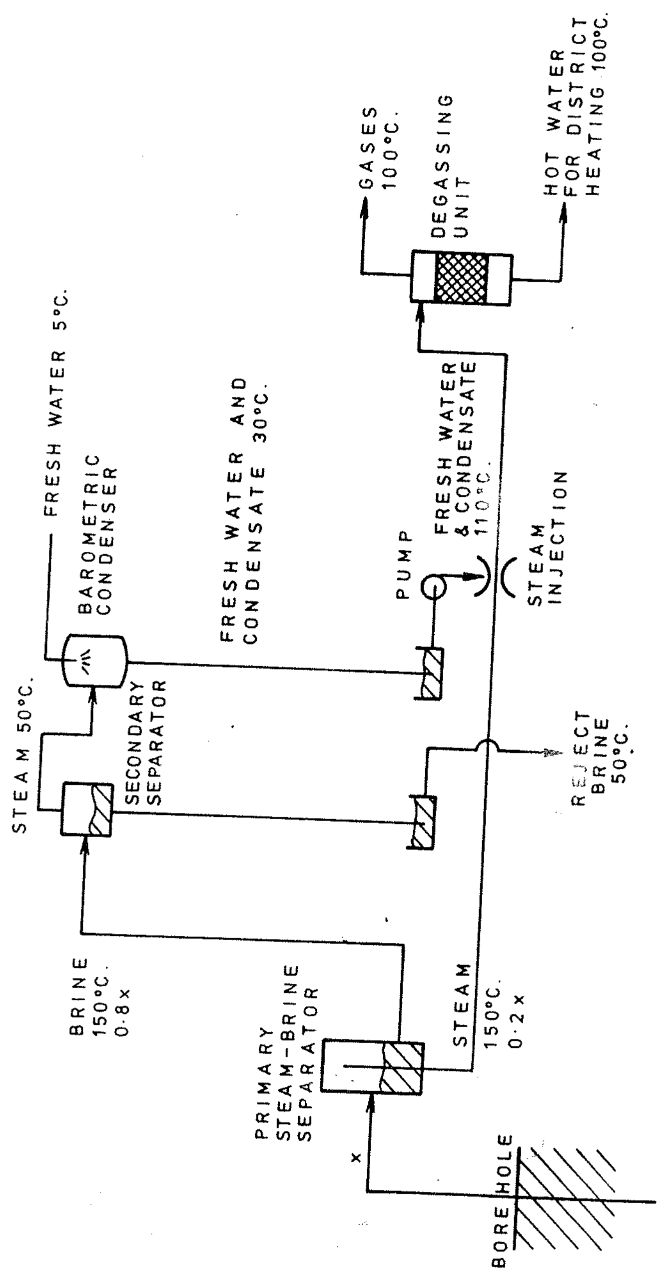

Fig. 7. District heating station at Svartsengi.

of 1976. Direct condensing turbines will be used requiring about 500 t/h of steam drawn from about 15 boreholes. This corresponds to a specific steam consumption of 8·33 kg/kWh. Recent estimates[3] of capital costs at Krafla are 1706 Mkr (~30%) for boreholes and steam supply system and 4132 Mkr (~70%) for the power plant itself, in total 5838 Mkr or 286 £/kW.

Industry

Proposals are being studied for the extraction of sea chemicals from geothermal brine at the Reykjanes HTA. Since 1968, when exploration of the area started, eight boreholes have been drilled. The deepest hole is over 1700 m with temperatures greater than 250°C.[6] Like the Svartsengi area, the Reykjanes area produces a mixture of geothermal brine and steam. The plan is to evaporate the brine in multiple effect evaporators using the geothermal steam. The plant would produce 250,000 tonnes annually of sodium chloride, calcium chloride, potassium and minor amounts of bromine. A new process has been proposed for the production of magnesium chloride and soda ash at the Reykjanes sea chemicals complex. It has been estimated that seven deep drillholes will be required to produce the 350 litres/sec of steam–brine mixture for the Reykjanes plant.[6]

CONCLUSION

The potential of the geothermal areas in Iceland has been shown to be so substantial as to make the country unique. By 1980 the total utilisation of geothermal energy should be about 2500 GWh per annum, an increase of 1000 GWh over 1972. When these figures are compared with the 1973 production of hydroelectricity of 2200 GWh, the relative importance of geothermal resources to the 214,000 people in Iceland will be appreciated.

After 1980, most communities having access to geothermal energy will have district heating systems, serving about 70 per cent of the total population. For the remaining 30 per cent, electrical heating will be more economic. HTAs will increasingly be utilised and multi-purpose geothermal installations will be used for the generation of electricity and processing purposes with the low grade energy being exploited for space heating and agricultural uses.

ACKNOWLEDGEMENT

The author is grateful to the National Energy Authority (Orkustofnun) in Iceland for use of reports and other material to prepare this paper.

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AN INTERFEROMETRIC STUDY OF A COLD AIR JET WITH BY-PASS STREAMS ISSUING INTO STILL AMBIENT AIR

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SUMMARY

A two-dimensional air jet with identical by-pass streams (all at $\sim 0°C$) issuing vertically upwards, with exit velocities $<20\ m\ s^{-1}$, into virtually still, ambient air (at $\sim 19°C$) has been studied. The temperature fields in and around the jets were mapped interferometrically for a distance of 30 cm downstream of the nozzle. Studies were also made of a single-stream two-dimensional jet of equivalent nozzle width.

The centre-line temperature decay of the jet with by-pass streams was less rapid for jets with ratios of by-pass to central jet stream velocities greater than 2·12 than that for the single stream jet of equivalent nozzle width. Thus the use of a by-pass configuration system for the forced convective cooling of constrained personnel, such as aircraft pilots, would result in lower impingement temperatures, and hence require less energy to achieve a given degree of cooling.

NOMENCLATURE

a	Empirical constant
A_1, A_2	Parameters relating the initial flow of momentum and energy respectively to the conditions at the centre of the nozzle
A_q, A_τ	Turbulent exchange coefficients for heat and momentum respectively
b_o	Nozzle aperture half-width, m
c_p	Specific heat of air at a point, kJ kg^{-1} K^{-1}
h	Overall nozzle aperture width, m
L	Length of nozzle, m
r	Least squares fit correlation coefficient
Re	Nozzle exit Reynolds number ($= 2b_o U_{om}/\nu_o$)
S, S_o	Distances of the considered cross-section and nozzle exit respectively from the hypothetical line source of the jet, m

Applied Energy **(2)** (1976)—
Printed in Great Britain