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Heat of Molten Lava Used for Space Heating

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ABSTRACT

The Eldfell lava flow on Heimaey in 1973 became 130 m thick. The thickness of molten lava exceeded 100 m in many regions. Drilling showed that the intensely fractured crust was saturated with 100°C steam from surface down to the molten horizon, where the temperature escalated within a few metres up to the 1050°C of the melt. At the surface of the lava steam condensed in the tephra cover and blocked outflow of steam. The steam was therefore contained between the tephra and the molten horizon. Soon after the eruption ended interest developed to use the steam for space heating in the town of Heimaey with 4000 inhabitants. Theoretical calculations indicated that the 100 m thick molten section would not solidify through until 14 years after the end of the eruption. With controlled irrigation one might therefore be able to generate steam like on a hot pan, until the irrigation water had eaten its way through the melt and was lost through the lava bottom. Experiments also demonstrated that one could suck steam from the lava flow over long distances. This encouraged belief in using the lava heat and it was decided to construct a heating system for the whole of the town. The first phase of this system began operation near the end of year 1978, five years after the eruption ended, and it reached full capacity when the distribution system in town was completed in 1982. Selected areas with 100 m thickness of melt were subjected to controlled irrigation. The generated steam was collected into wells of wide concrete pipes and sucked to chambers of heat exchangers with the aid of chimneys. The only mechanical pumps required were those that distributed the irrigation water. The water circulating in the distribution system of the town came 35°C hot from the town to the heat exchangers where it was heated to 80°C. The cost of generating heat from the lava was about 20% to 30% of the cost of heat from oil. The generation of steam from the lava worked well until year 1988 but after that difficulties arose as the irrigation water found passages through fractures and escaped through the bottom of the flow instead of evaporating.

1. INTRODUCTION

Most volcanic eruptions occur in remote areas where there are no opportunities to use the heat of the erupted lava flows. The 1973 eruption on the island Heimaey off the south coast of Iceland was an exception. Heimaey is the largest island of the Westman Islands archipelago and the volcanic centre of the southernmost volcanic system of the Eastern Volcanic Zone of Iceland (Jakobsson (1972), Mattson and Hoskuldsson (2003)). Heimaey is the only inhabited isle in the archipelago. Before the eruption the town Vestmannaeyjar had 5,300 inhabitants and was one of the most important fishing ports of Iceland. The course of the eruption has been described by Thorarinsson et al. (1973) and Einarsson (1974). The new crater was named Eldfell (Fire mountain) but here the eruption will be referred to as the Heimaey eruption. The eruption burned, demolished and buried about one third of the homes in the town. Attempts to stop or divert the lava flow by cooling the lava have been described in a number of articles (Sigurgeirsson (1974), Jonsson and Matthiasson (1974), Williams and Moore (1983)). Some books have been published about the restoration of the town after the eruption (e.g. Gunnarsson (1973), Gunnarsson (1974), Hamar (1976)) but accounts of the utilisation of the heat in the lava for heating of houses in the town have been very limited (see though Bjornsson (1980), Bjornsson (1987)). This paper emphasizes that last aspect.

At 64°N the climate is cold and windy and the town used expensive oil to provide the 60 GWh of thermal energy needed annually for space heating. In half a year the volcano had piled up 250 million cubic metres of up to 130 m thick 1050°C hot lava containing originally some 250,000 GWh of thermal energy. Although most of that heat was doomed to be dissipitated an attempt to exploit some of it was condsidered worthwhile. It was not obvious how one could mine heat from the lava and exploit it in district heating. Secondly, there was uncertainty whether the heat source would last long enough to amortize the investment cost of installations harnessing the heat in the lava. First experiments to mine the heat began already in 1973 after the eruption ceased but it took some four years to develop the ultimate method of heat extraction and construct the district heating system to exploit it. As long as there was a molten horizon in the lava, heat could be mined efficiently by watering the lava and recovering the steam generated. That worked excellently until 1988, when the lava had solidified through and the water found passages through fractures before it evaporated. The investment in the heat mining installations on the lava and the pipeline to town had then to be written off but the investment in the distribution system throughout the town kept its value as the water could now be heated in a central electric heater. It is considered that the savings in oil during the operation of heat mining on the lava flow well exceeded the generating cost of the hot water and the construction cost of the installations on the lava and the pipeline to town. The experiment can therefore be regarded as well worthwhile.

2. COURSE OF THE ERUPTION

On January 23, 1973 a north-northeast-trending fissure rapidly opened to a length of about 2 km, traversing the island (Fig. 1), approximately 1,000 metres from the center of the town (Thorarinsson et al. (1973)). Spectacular lava fountains played in the initial phase of the eruption and within a few days homes close to the crater were completely buried by tephra. A massive blocky aa lava flow produced an expanding lava delta along the east coast and threatened to fill the harbor. The lava was alkali basalt with gradational change in chemistry from mugearitic to hawaiitic composition (Jakobsson et al., (1973)). The temperature of the lava varied from 1,030°-1,055°C during the first week of the eruption and increased later to as much as 1,080°C. Most of the lava flow went northeast out of the crater but due to the peculiar composition and cooling in the crater the lava was very viscous and formed a pile that spred to all directions. The pile crept on the sloping ground towards the sea and further on the sea bottom, replacing the sea water. At the end of the eruption the pile was up to 130 m thick, up from the sea bottom. The pile settled somewhat with time but there were extensive fields with a thickness of 100 m or more. Some of the volcanics were thrown high up from the crater and fell as ash and scoria all around the crater. The scoria piled up the walls of the crater, but some of it fell back into the crater and was carried away on top of the lava flow. The lava flow was thus covered by ash and scoria, often 10 – 20 m thick. It was not a major eruption on the Icelandic scale. The volume of erupted volcanics is estimated 250 million cubic metres (Einarsson (1974), Arnason (1975)).

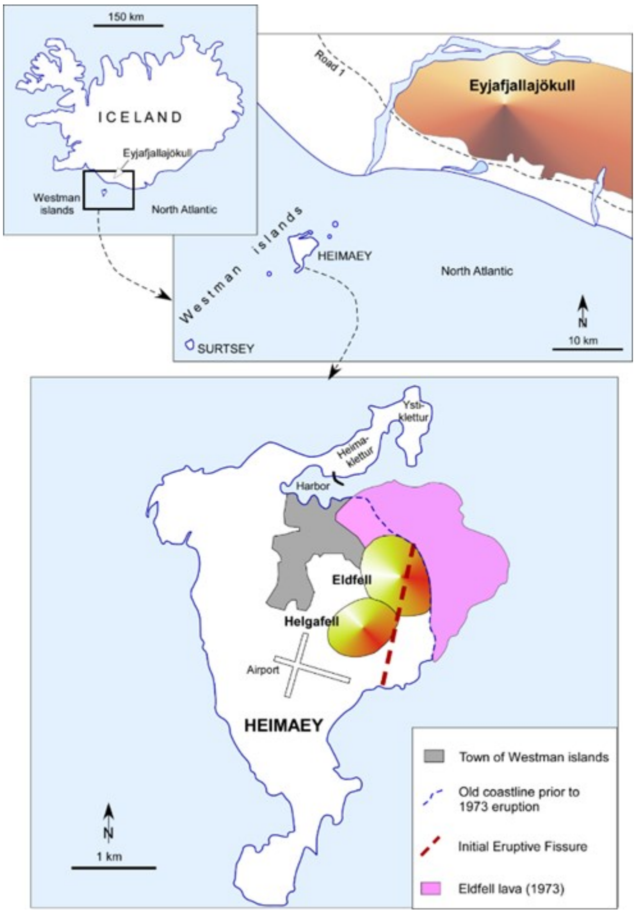

Figure 1. The island Heimaey off the south coast of Iceland.

3. COOLING OF THE LAVA FLOW

The lava is cooled both from above and below. Heat is conducted up to the surface and rain water percolates through fractures, cooling the rock down to 100°C when it boils on the fracture walls. Conditions at the bottom were uncertain but it was considered likely that the flow was initially molten at the bottom but kept cold by groundwater and tidal currents. Another possibility was that solidified lava piled up under the flow as it advanced along the sea bottom. In that case the volume of molten lava would be less than assumed and the lava would solidify through much earlier.

Most lava flows cool down to environmental temperatures in a few months or years. The Heimaey lava was different because of the unusual thickness. Drilling into the lava 5 years after the eruption verified the expectations of cooling from above. The depth to the molten horizon was found to be 30 m in two exploratory wells and it was estimated that 25 million cubic metres of the 110 m thick lava were still molten and would take further 9 years to solidify through. Each cubic metre of molten lava that solidifies and cools down to environmental temperatures releases nearly one megawatthour of thermal energy. The remaining molten lava thus contained about 25 million megawatthours or 400 times the annual energy required to heat the whole town of Heimaey.

3.1 Heat in lava and evaporation of water

Molten lava is a mixture of compounds that solidify and crystallize at different temperatures. The solidification of lava therefore does not occur at a definite temperature but in a temperature range. The upper limit, liquidus, is the temperature when the first crystals form, the lower limit, solidus, where the last crystals are developed. The liquidus can be around 1,300°C but the solidus near 1,000°C. At temperatures in between the lava is partially molten. The Heimaey lava had a temperature of 1,030 – 1,080°C and about half of the mass was crystallized (Jakobsson et al. (1973)). When the lava crystallizes fully it releases the remaining latent heat of crystallization and cools further from the solidus to environmental temperatures. The thermal energy released from a cubic metre of lava that is cooled down to 100°C is

$q = (L' + C_b(T_1 - T_3))\rho_b$ J/m^3

where L' is the latent heat of crystallization, C_b the specific heat of the lava, ρ_b the specific mass, T_1 the temperature of the molten lava, and T_3 =100°C. For the half crystallized Heimaey lava L'=2.09*10^5 J/kg, C_b= 1.046*10^3 J/kg°C, ρ_b = 2,700 kg/m^3, T_1 = 1,050°C and T_3 = 100°C one obtains q=3.25*10^9 J/m^3 or q= 0.9 MWh/m^3. This is the heat that must be removed by cooling to solidify a cubic metre of the Heimaey lava and cool it down to 100°C.

If the cooling occurs by pouring 5°C water on the hot lava, where the water evaporates, each kg of water would mine

$q_1 = C_p(T_3 - T_2) + L_w$ J/kg

where C_p is the specific heat of the water, L_w the latent vaporization heat of the water, T_3 = 100°C, and T_2=5°C. For C_p=4.187*10^3 J/kg°C and L_w= 2.26*10^6 J/kg we obtain q_1=2.66*10^6 J/kg or q_1=0.74 MWh/m^3 for each cubic metre of the cooling water.
Each cubic metre of water would thus cool 0.82 m^3 of lava to 100°C. The precipitation in the Westman Islands averages 1.4 m/year or 1.4 m^3/m^2 per year. That would solidify and cool down to 100°C a 1.15 m thickness of lava each year. When sea water was sprayed on the lava the cooling was hundred times faster or about one metre in 4 days. The total amount of sea water used for cooling was 6.2 million cubic metres which with evaporation would have cooled 5 million cubic metres of lava to 100°C.

3.2 Cooling of the lava by conduction

In the first hours after a flow has occurred most of the thermal dissipation is through radiation, but as soon as a crust has formed the heat is primarily lost by thermal conduction. Convecting air carries the heat away and keeps the surface at environmental temperature. The molten lava looses heat by conduction and the crust thickens with time. According to the equation of thermal conduction (Carslaw and Jaeger (1959), Eliasson (1978)) the depth to the molten horizon will be $d = 2\alpha\sqrt{kt}$ where k is the thermal diffusion coefficient of the lava, t is the time and the coefficient α is determined by the equation $\alpha\ \mathrm{erf}(\alpha)\ e^{a^2} = (C_b(T_1 - T_2))/(L'\sqrt{\pi})$ where erf is the Gaussian error function. When T_1= 1,050°C, T_2=5°C, k=19.0 m^2/year and L' and C_b as before the equation simplifies to $d=9.35\sqrt{t}$ where d is in metres and t in years. Here the 1,050°C isothermal surface is taken as the surface of solidification. The equation

$$\frac{T-T_2}{1200} = \mathrm{erf}\left(\frac{x}{2\sqrt{kt}}\right)$$

yields the depth x to an isothermal surface T lying between the surface and the surface of solidification. For a definite isothermal surface T_n the depth is $x_n = a_n\sqrt{t}$. The results of these calculations are shown in the upper half of Fig. 2.

The lava also looses heat by conduction to the rock at the bottom. If the bottom is dry its temperature will be the average of 1,050°C and 5°C or 527.5°C. Regarding the permeable ground this is, however, less likely than a bottom kept cold by ground water and tidal currents. If cold water flowing at the bottom does carry the heat away the bottom will stay at 5°C and the cooling by conduction will be the same as in the upper half of the flow. The isothermal surfaces are then symmetrical about the medium surface as shown in Fig. 2, calculated for a flow of 100 m thickness. The surfaces of solidification from the surface and the bottom meet at 50 m depth after 29 years. At that time the lava would be solidified through according to these calculations.

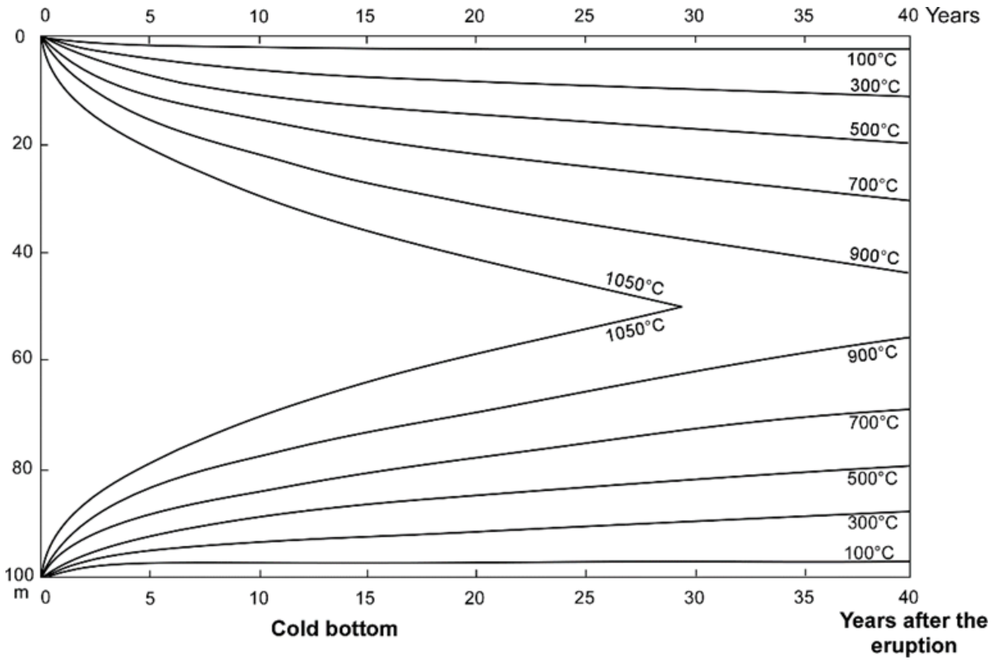

Figure 2. Temperature in a 100 m thick lava flow cooled by conduction only. The temperature at the surface and the bottom is fixed as 5°C. The lava is assumed to 50% crystallized and at a temperature of 1,050°C.

3.3 Cooling by precipitation in the upper section of the lava

The upper section of the lava flow is open for precipitation. Rain water percolates down fractures and gets heated until it boils and evaporates. The steam ascends and heats the water percolating downwards. Near the surface the steam is partly condensed in the scoria and saturates the pores. The water saturated scoria keeps the steam underground, unless the current of steam is strong enough to dry out the pores. Then areas of steaming ground are formed. Such steam fields were common in the first years after the eruption but they became fewer with time. Outflow of steam was mostly found on hills and in the crater wall itself. Between the surface of solidification and the lava surface steam dominates and maintains a temperature near 100°C. Several metres above the solidification surface the temperature increased rapidly as shown in Fig. 3. In that section the heat is conducted but further up convecting steam dominates in the heat transport.

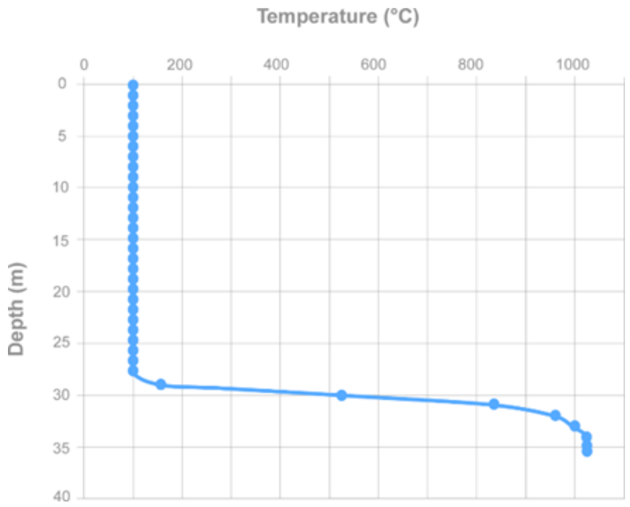

Figure 3. Temperature log of an exploratory well drilled in March 1978 into the Heimaey lava to find the depth to the molten horizon.

Accurate calculations of the rate of cooling under these circumstances are difficult (see e.g. Eliasson (1976)), but a good approximation is obtained by adding the cooling effect of the precipitation to that predicted thermal conduction alone. This is done in Fig. 4. The precipitation, 1.4 m/year, then increases the depth to the surface of solidification by 1.15 m/year beyond the depth predicted by thermal conduction alone. According to this a lava flow of 80 m thickness would have solidified through in 12 years, 90 m in 15 years and 100 m in 18 years, if the bottom is kept cold. Because of increased cooling from above the surfaces of solidification now meet below the central thickness of the flow. The upper half of the flow is mostly at 100°C, where water and steam fracture the rock to small cubes and wash out most of the heat.

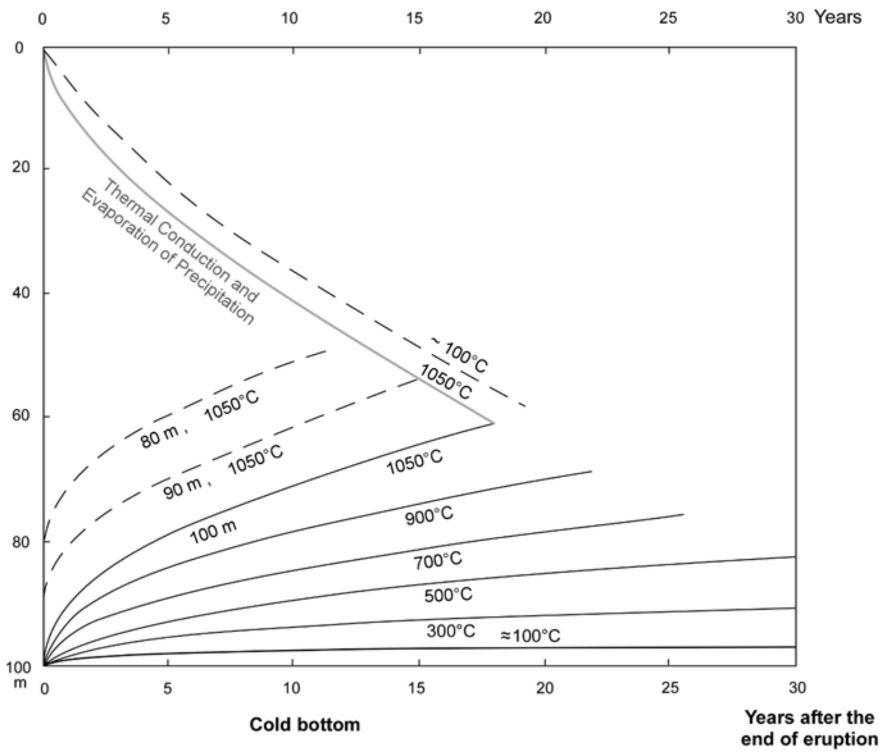

Figure 4. Temperature in lava flows cooled by thermal conduction to a 5°C surface and bottom and evaporation of precipitation. The lava is assumed to be 80, 90 or 100 m thick, 50% crystallized and at a temperature of 1,050°C.

3.4 Cooling of the lower part of the lava

As already explained the rate of cooling from below depends on the conditions at the bottom of the lava. If ground water percolates under the bottom and keeps it cold, the cooling will proceed as shown in Fig. 4. The molten middle section is impermeable for water. Therefore the rain water does not affect the lower half of the lava. Groundwater and seawater could, however, enter below the molten section through fractures. The elevated rock temperatures do though maintain steam pressure in the fractures that delays the inflow of the water. The experience obtained by watering the lava flow indicates that the lower half solidifies dry with fractures and columns more coarse than the upper half. After the lava is solidified sea water gradually enters through fractures. Steam fields at the coast indicated how far the sea water front had come. In the first years this front backed about 20 m per year from the coast. When the fractures are filled with seawater, the water boils due to heat conducted from the hot surrounding rock. When the lava is solidified through rain water sickers through fractures down to the lower part of the lava and floats as a fresh water layer at sea level.

4. USE OF THE HEAT IN THE LAVA FLOW

Nobody knew at first what would be the best approach to harness the heat of the lava. Experiments were carried out step by step as shown in Fig. 5. Considering all the steam that accompanied the Heimaey eruption and the attempts to cool of the lava it is no wonder that ideas to use the heat for the heating of houses came up. Steam flowed through the sewage system in the eastern part of the town, filled houses that were buried in volcanic ash and boiled them internally.

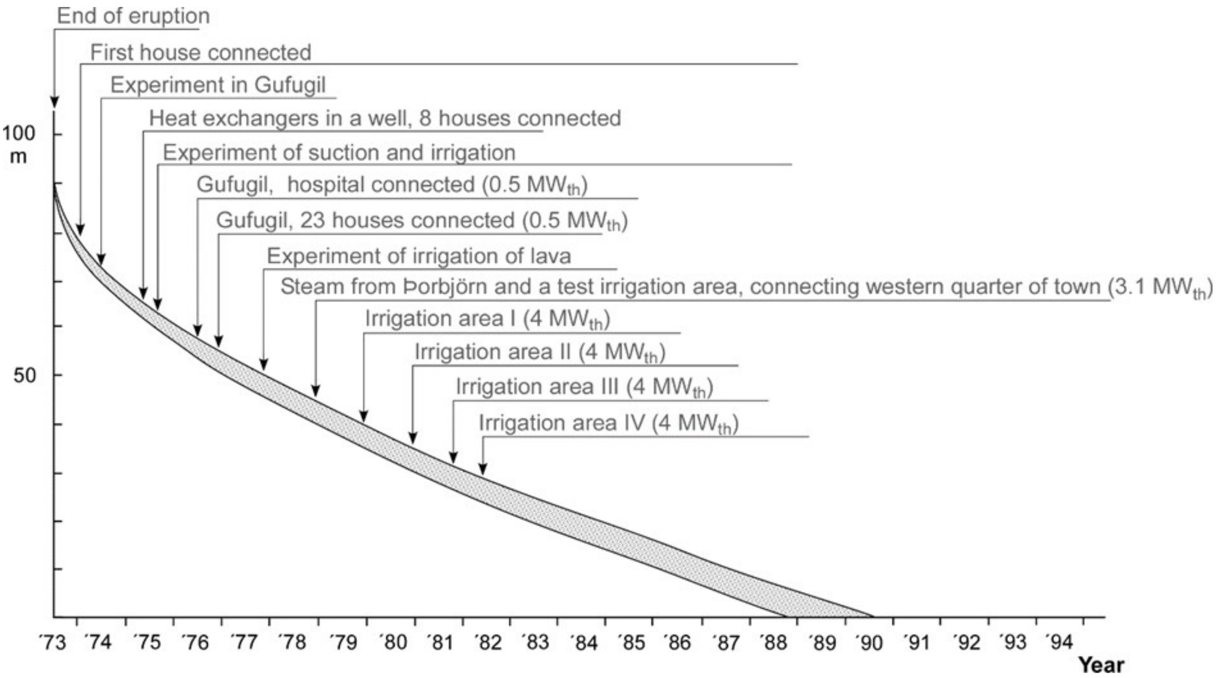

Figure 5. Estimated thickness of molten lava and steps towards harnessing the heat. The curve of thickness is explained in Fig. 10.

4.1 Heat exchangers

In an account on the steam in the Westman Islands and how to control it Sigurgeirsson (1973) mentioned positive aspects of uses, such as heating of houses, swimming pools and greenhouses. About that time attempts were made to bury heat exchangers in wells where there was ample steam in the volcanic ash. Water from the first heat exchanger was piped to a house on January 20, 1974, less than a year after the eruption broke out on Heimaey. The experiments continued, now in the Steam Gorge between the Baejarhraun lava tongue and the main lava flow. There plumes of steam were associated with high temperatures at shallow depth. Water was led through the pipes of the heat exchanger and from there down to town where it was offered to heat the new hospital. The mananging directors hesitated though as they did not consider the heat supply reliable. The steam was rich of sulphur and corroded the heat exchanger pipes on the outside. In the next experiment plate radiators of stainless steel were buried in the volcanic ash. The heating worked fine, if not too well, as the water boiled in the radiators if care was not taken. Steam that condensed on the outside of the radiators appeared though to corrode the steel, where it had been stretched in the construction and after a while the corrosion developed small leakages. The corrosion was most extensive near the surface of the ash and it was anticipated that atmospheric oxygen in the steam accelerated the corrosion.

The next experiments aimed at finding optimal procedures to gather steam and endurable heat exchangers. It was obvious that it would be most economical to use the steam in the steamfields as long as it was there, but a suitable material for heat exchangers that could withstand the corrosive steam had to be found.

Pipe heat exchangers of various materials, stainless steel, black iron and iron coated with various protecting substances were now tested in a wide well in a rock pile in the Steam Gorge. The heat exchanger was hanging in the well surrounded by 95°C hot steam. As it was anticipated that contact with the volcanic ash could accelerate corrosion care was taken not to let the heat exchanger come into contact with the ash and the well was firmly closed on the top to prevent atmospheric oxygen from entering the well. Water was circulated from the heat exchanger to heat 8 houses in town and returned to the well for further heating. This experiment was initiated in the spring of 1975 and continued for nearly 3 years. In the beginning some corrosion was noted on the heat exchanger pipes but it did not increase after the first year. Experiments in collecting steam showed that the most economic procedure was to dig wells and build a pile with several levels of concrete sewage pipes. These wells are described in section 4.7 and Fig. 8.

4.2 Watering of the lava and suction of steam

One of the local promoters of these experiments, Sigmund Johannsson, had ideas that one could suck hot air and steam from the lava, even outside the steam fields in the lava flow. In the autumn of 1975 he chose an area where there was high temperature at shallow depth but no indication of steam in the lava. He evened an area in the volcanic ash and placed there two parallel air conditioning stocks. A number of pipes with open holes was laid from the stocks to all sides. The stocks and pipes were buried in volcanic ash and covered with a double plastic sheet which extended out to all edges of the construction. Sigmund intended to collect hot air or steam with these stocks, either by sucking from both stocks, or by blowing air into one of the stocks and sucking from the other. The outfit worked well. Surprisingly, one could suck hot, humid air for several days from the lava without any significant drop in temperature. Water poured into the sucked area was returned as steam within short time. This experiment demonstrated that there was considerable steam in the lava although in did not come to the surface. One could suck this steam over long distances to a central heat exchanger. The watersaturated volcanic ash covering the surface of the lava was less permeable than the ash and rock below and therefore steam could be sucked from long distances far outside the plastic covered central area without significant contamination of air. The experiment of watering also showed that the water evaporated quickly and was sucked to the central area but did not escape as steam all around as one might have expected. This meant that production of steam by watering would be no problem as long as there was sufficient heat in the lava below the place of watering. It would thus be possible to generate steam to supplement the natural steamfields when they gradually declined.

Water in the lava is confined between the molten surface and the watersaturated cover of volcanic ash, stored as water or steam. The steam is overall in the lava and can easily be drawn into wells by advective flow in chimneys. The flow could be increased by suction and additional steam generated by watering in selected locations. This was clearly the method of heat extraction that had been looked for and it opened the possibility of utilising the heat whereever it was found in the lava flow. This method of heat extraction is closely related to the method of sea water cooling that was used to hinder the advance of the lava flow. The only difference is that now the watering is more tempered, using steam from rainwater and adding water to the lava where required.

4.3 An appraisal heating system in the Steam Gorge.

At this stage one may say that a suitable method for extracting the heat had been found and secondly the outlook for duration of heat in the rock was rather favourable. People became optimistic and decided to build an appraisal system in the Steam Gorge to test the method of heat extraction on full scale and collect experience for the optimal construction of heat exchangers, avoiding corrosion and other difficulties in operation. It was decided to distribute the hot water to the new hospital and 23 houses in its neighborhood. Engineering consultants designed the distribution system and the main pipelines from the Steam Gorge, but employees of the town built the wells and the heat exchangers. Two wells were dug into the Steam Gorge. The wells had three levels of crossed sewage pipes, as described earlier and the steam from both wells was conducted to a container filled with heating radiators that were used as heat exchangers. The hot water of the distribution system was circulated between the houses in town and the heat exchangers. It gained heat in the radiators as steam condensed on the outside of the radiators. The thermal power of this appraisal system was about 1 MW or 1/20 of the total power required for the whole of the town. The hospital was connected early in the spring of 1976 and the heating was excellent. The distribution system for the other houses was built in the summer of 1976 and the houses connected.

4.4 Heat exchangers for a mixture of steam and air

There were several technical problems in utilising the steam. The engineering consultants worked on the design of heat exchangers that would make best use of the steam. The main problem was that the steam was mixed with air and did not condense until the mixture had been cooled down to the condensing point that corresponded to the partial pressure of steam in the mixture. Pure steam has a partial pressure of one atmosphere and condenses at 100°C. If, on the other hand, one third of the mixture is air, the partial pressure of the steam is only two thirds of an atmosphere and the steam does not condense until it has been cooled down to 70°C. As most of the thermal energy is coming from the latent heat of condensing, the water of the district heating system does not attain a temperature higher than the condensing temperature of the steam-air mixture where it enters the container of the heat exchangers.

The heat exchangers were made of bent steel pipes coated with epoxy to prevent corrosion. The epoxy coat, however, tended to swell up and hinder the heat exchange. Copper pipes on the other hand gave good results and were not corroded. Each exchanger unit was designed to recover 0,8 MW of heat from a mixture of 70% steam and 30% air. They fully withstood those demands.

4.5 Experiments of watering

In the autumn of 1976 it had become clear that the hot lava could be the main heat source for the district heating system of the town, if sufficient steam could be obtained and the source could last for a period that would justify the investment costs of the installations. There was still considerable power in the natural steam fields but it was uncertain how long they would last. Experiments in producing steam by watering were needed to confirm that sufficient power for the whole of the town could be obtained with acceptable cost. Experiments in that direction began in 1977. About 1 l/s of water was let out on the ash where there was no visible steam. After a week a steaming field with a diameter of 40 m had developed around the watering spot. Five wells were dug to collect the steam and they delivered 70% of the downflowing water in the form of nearly pure steam. This result showed that there should not be lack of steam as long as there was a layer of molten rock in the lava. The water boils on the glowing rock and returns as steam. The durance of extractable heat for the district heating service would thus depend on how long it takes for the lava to solidify through. After the lava is completely solidified production of steam will be difficult as the water will be lost through fractures to the bottom before it evaporates.

4.6 Beginning of the Vestmannaeyjar District Heating

As already mentioned the eruption destroyed one third of homes in the town. When restoration began one of the first tasks was to build a new quarter of appartment houses on the western border of the town. Streets were planned and the ground levelled with pumice that was excavated from roads and lots in the eastern half of the town in the summer and autumn of 1973. As this project was undertaken before one realised that heat from the lava could be used the plans were to heat the water in a central electric heating plant, and have oil heating as a reserve. The first part of this system, named Vestmannaeyjar District Heating, was taken into use in the spring 1975 with a provisional oil heating plant. Heating with electricity was, however, never realised as it was replaced with the heat from the lava.

When it became clear that it would be possible to heat the whole town with heat from the lava the first step of development was to build four heat exchangers exploiting natural steam field at the mound Thorbjarnarfell in the eastern part of the lava flow and one to use the steam generated by watering in the first testing area. These heat exchangers were taken into use in December 1978, serving the new quarter and some streets next to it. The projected thermal potential was 3.1 MW and 0.8 MW were added early in 1979. The distribution system now reached to one fourth of the town but the main construction of a distribution system for other parts of the town stood over from the spring of 1979 until the spring of 1981 when all the houses that were to be connected had got heat. Parallel to that a new field for watering to produce steam was prepared as the natural steam fields were not expected to last long. A pipeline circulated water from the heat exchangers on the lava flow to the pumping plant near the center of the town.
Fig. 6 shows the percentage of houses that were connected to the district heating system each year and how heat from the lava replaced oil as a heat source. About 15% of the total volume of houses in the town were already heated by electricity. The volume of those houses is not included.

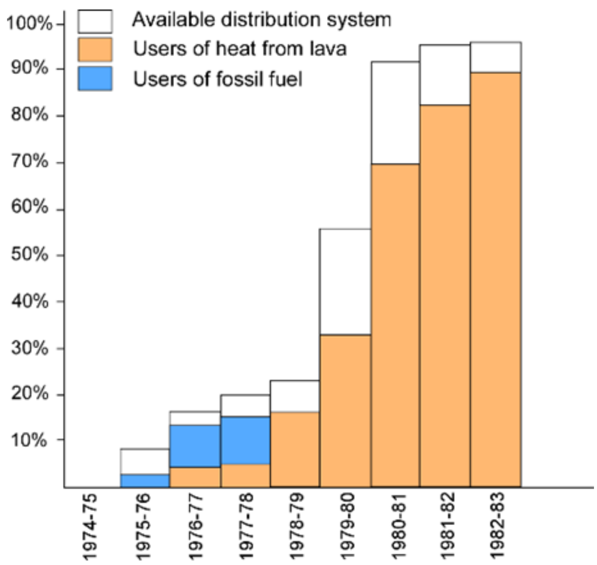

Figure 6. Construction phases of the district heating system in town. The brown columns show the percentage of inhabitants who used heat from the lava. Not connected are houses heated with electricity, about 15% of the total volume in town (Adapted from Karlsson (1984)).

4.7 Generation of steam by watering the lava

To generate steam by watering for the whole town an area was chosen, where the lava was thought to be 100 m thick and had not been cooled previously by watering (see Fig. 7). Full recovery of the steam generated by watering was expected as long as there was a molten section in the lava. Then the watering would have to be shifted to another area with a molten section. The watering area was planned as four quadrangles, 120 x 120 m each. The heat exchanger units were located in the center of each quadrangle but only one fourth of the quadrangle was subjected to watering at each time, planned to work its way through the molten section in 2-3 years. When diminishing recovery of steam indicated that the lava had solidified through the watering was shifted to another one fourth of the quadrangle. In this way watering could be carried out for 10 – 12 years without moving the cluster of heat exchangers in each qudrangle.

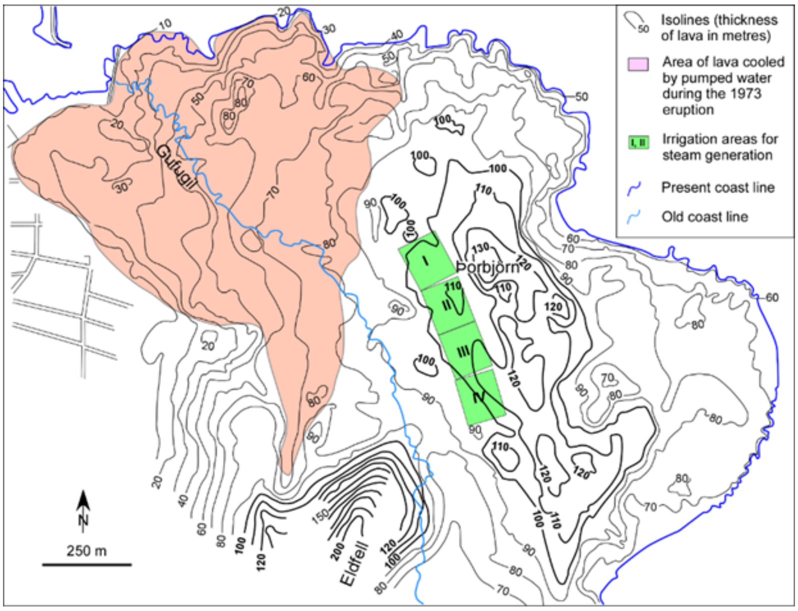

Figure 7. Extent of the Heimaey lava flow and its thickness in metres. The thickness is calculated as the difference between land elevation on April 30, 1973 and land elevation and sea depth before the lava flow ran. The former shoreline is drawn on the map. It lies just east of the new crater Eldfell and bends northwest to the mouth of the harbour. Since the eruption, land near the crater has subsided some 10 m but risen near the coast. The brown area nearest to the town was cooled with sea water while the lava was running. The green qudrangles I – IV are the areas which were used to generate steam by controlled watering. Before that natural steam fields were used in the Steam Gorge (Gufugil) and south of the Thorbjorn mound.

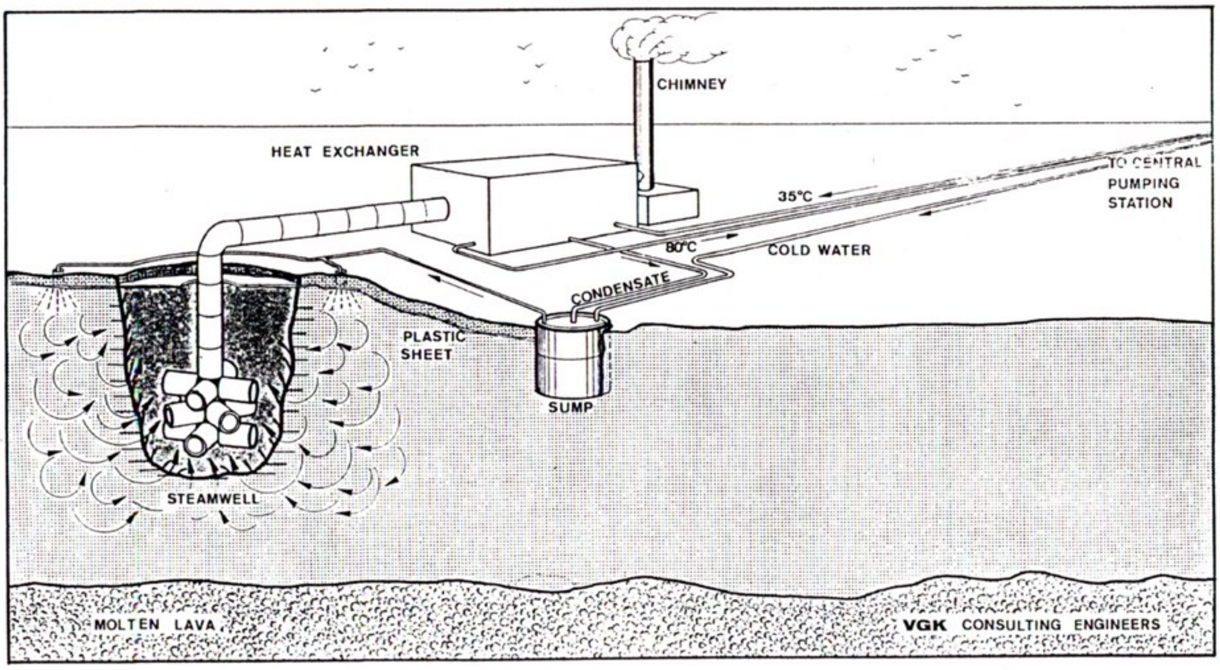

Figure 8. Schematic diagram of the wells collecting steam in the watering areas and conveying it to the heat exchangers (Adapted from VGK Consulting Engineers).

From the wells the steam was conveyed in concrete pipes of 60 cm diameter, and 100 cm wide pipelines to six heat exchangers which were housed in concrete containers at the center of the field. Behind them were chimneys that sucked the steam from the collecting conduits into the heat exchangers. No mechanical pump was required. The layout of the heat extraction system is shown on Fig. 9. The heat exchangers were made of narrow pipes of copper. The retour water coming from the distribution system in town was led through the pipes of the heat exchangers and heated from 35°C to 70 - 80°C by the steam condensing on the outside of the pipes. The condensate was returned to the watering hoses for renewed production of steam. Some of the steam generated was not recovered and therefore water had to be added to the watering hoses from the fresh water supply of the town.

The heat exchanger units yielded 0.8 MW_{th} each. In this way a capacity of about 4.8 MW_{th} was obtained from each of the four 14,400 m^2 quadrangles. Together the heat exchanger units had a capacity of 19.2 MW_{th}. The steam production continued in this manner from the end of 1979 until 1990.

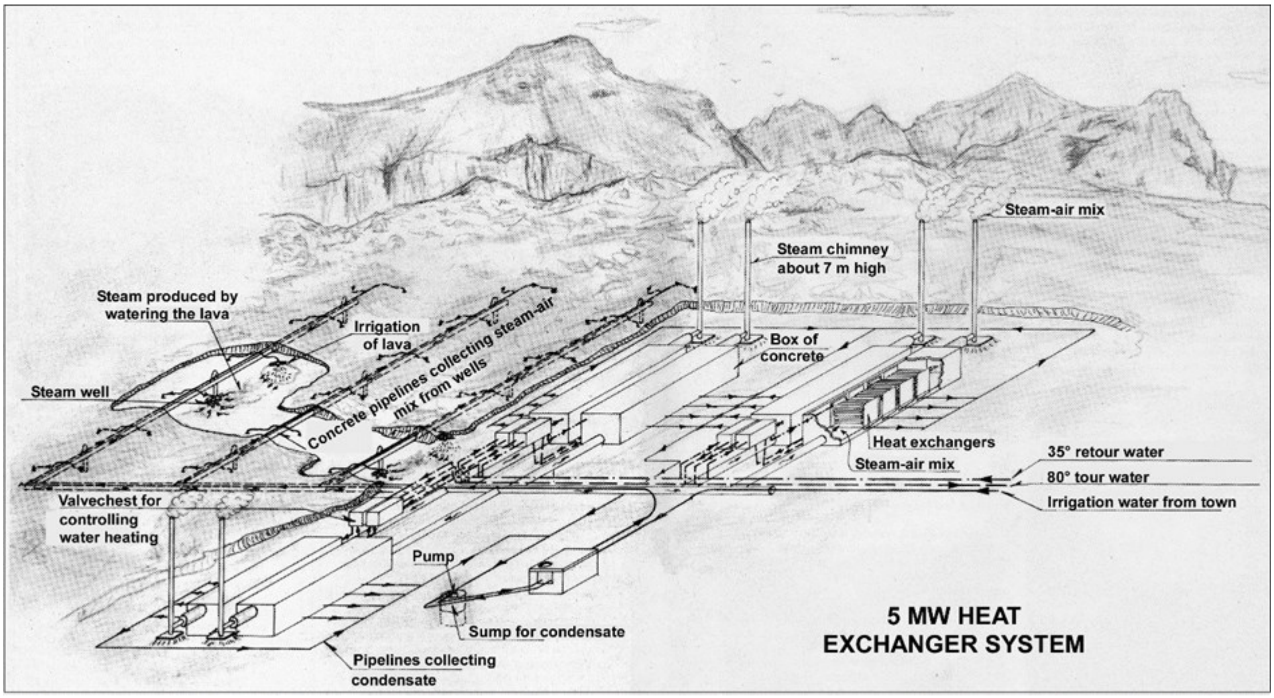

Figure 9. Isometric diagram of layout of a 4.8 MW_{th} heat extraction system on the lava. Steam is generated by controlled and distributed watering of the lava. The chimneys suck the steam through steamwells into the heat exchanger units. Retour water from the distribution system in town arrives at the heat exchangers with a temperature of 35°C. It gets heated in the pipes of the heat exchangers as steam condenses on the outside of the pipes. The water leaves the heat exchangers at a temperature of 70 - 80°C and is returned to town. The condensate of the steam and additional water from the fresh water supply of the town are used for the watering. The only pumps in this installation are the small pumps used to distribute the watering over the field. This drawing was made by Sigurdur Olafsson, VGK Consulting Engineers.

Fig. 10 shows the estimated thickness of molten lava according to the calculations described in section 3.4. Dots in the figure show which thickness of molten lava was experienced by watering each quarter of a quadrangle. It is known how much water was used.

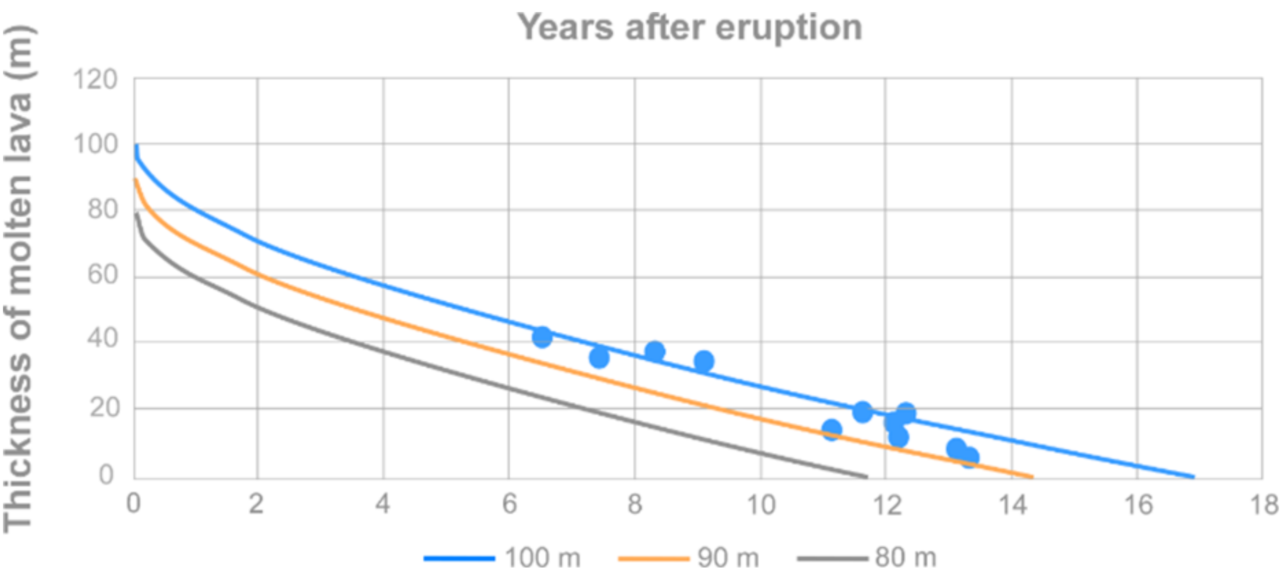

Figure 10. Decreasing thickness of the molten section in the lava since the eruption ended in July 1973. The lava solidifies from above and from below but the central part stays molten for some time. The calculations assume a 5°C cold surface and bottom and a precipitation of 1.4 m/year. They are made for a total thickness of the lava flow as 80, 90 or 100 m. The blue dots show the thickness of the molten section which was experienced by watering each quarter until reduced return of steam indicated that the watering had broken through the molten horizon. The dots fit best with a total thickness of 95 – 100 m.

The first watering quarter of 3,600 m^2 received 165,000 m^3 of water before signs of loss due to leakage through the lava flow were noted. Besides that the area received precipitation over the three years of watering. To evaporate this water and the precipitation one requires the heat released by solidification and cooling to 100°C of a 41 m thickness of molten lava. These figures therefore point to that the molten lava was 41 m thick under this area when the watering was begun there in early 1980. Other dots show what was experienced in other watering quarters. The position of the dots fits well with the estimated thickness of the molten lava, if the thickness of the lava flow was 95 - 100 m. The elevation of the field is about 70 m above sea level and before the eruption the bottom under the area was at 20-30 m below sea level. A total thickness of the lava of 95 m is therefore very likely. The figure shows also that in the beginning of 1987 there were hardly more than 5 – 10 m left of the molten lava. This procedure in exploiting the heat of the lava was therefore likely to come to its end that year. When the molten layer has been perforated, the water will be lost through fractures and only a small amount will be returned as steam. The power of generated steam will then fall below 1 MW within a few months. Under those conditions a power plant on the lava cannot supply the total heat required by the town but it could supply some base of power needed for additional years, as long as the operating costs are not too high.

5. THE DISTRICT HEATING SYSTEM

5.1 Transmission pipes

The transmission pipes from the heat exchangers on the lava to the pumping station of the distribution system were 2.5 km long. In year 1977 a double pipeline of asbestos, 200 mm and partly 250 mm in diameter, was laid. The transport capacity was increased in 1981 with a 300 mm asbestos pipeline and partly with 250 mm insulated steel pipes. This wider pipeline transported the retour water to the heat exchangers but the two older pipelines carried the heated water to the pumping station. The pipelines were mostly buried in pumice and covered with earth to prevent erosion by wind and shelter against rain. The asbestos pipelines had no other insulation. The water lost 2°C on the way to the pumping station but heat in the soil maintained the temperature of the retour water which arrived at the heat exchangers at a temperature not lower than leaving the pumping station.

5.2 Pumping station

The pumping station was located near the center of the town. The water was circulated to the heat plant and after that circulated through the central heating system in the town. It had to be pumped up to the higher standing part of the town. The retour water coming from the houses was pumped back to the heat exchangers on the lava to become heated and returned to the pumping station. In this way all water went twice through the pumping station and could be given additional heat with an oilheated kettle in the pumping station if required.

5.3 The distribution system

The distribution system was built in the conventional manner for geothermal systems in the country, steel pipes insulated with polyurethan within a coat of plastic pipe, buried in ditches and generally covered with pumice. A short section laid in a concrete conduit. The main connections and provisions for expansion of pipelines are in wells, precast as baskets in concrete and covered with a lid after the connections have been completed.

The distribution system is a closed loop, i.e. the water which is sent to the user is returned to the pumping station. No tap water is taken out of the system but cold water from the fresh water supply system is heated up by the hot water in heat exchangers. The same water was circulating from the heat exchangers to the user and back to the heat exchangers. The losses in the system were insignificant. Therefore it was optional to use any other heat source to heat the circulating water when the heat from the lava could no longer hold up the capacity needed.

5.4 Cost

The generation of hot water on the lava saved the inhabitants of Vestmannaeyjar burning of oil that would have costed them 1,200 million IKR or 26 million USD on the price level of year 1988 (Central Bank of Iceland, 1990). The price they paid for the hot water amounted on average to about 57% of the heating cost with oil or a total of 14.9 million USD on the price level of 1988. The generation of the hot water on the lava and the piping of the water to the central pumping station in town costed some 20% of the heating cost with oil in the first years and increased to about 30% in the final years of operation, 1988 - 1990. The remaining net income of the district heating company, about 10.5 million USD on the price level of 1988, was used to pay other operating costs and contribute to pay down the investment cost of the whole heating system. The investment in the heating installations on the lava and the pipeline to town amounted to about 32% of the total heating system. This investment had to be written off when the generation of hot water on the lava ceased in 1990 but the pumping station and the distribution system in town, about 68% of the investment, kept full value as hot water for the town was from then produced in a central electric heater at the pumping station.

6. CONCLUDING REMARKS

The circumstances for utilisation of the lava heat in Heimaey were unusually favorable. The eruptive fissure broke out on the border of a town with 5,000 inhabitants and in a cold climate where houses must be heated all the year around. The thick and viscous lava developed into a pile that exceeded 100 m thickness and took more than 15 years to solidify. During the eruption extensive watering of the lava front demonstrated how it was possible to extract heat from the lava through evaporation of the water. Escalating prices of heating oil in the seventies also made an effort to utilise steam from the lava tempting. It took some 5 years after the eruption to develop the best procedures for the heat extraction. After that the town could be supplied for 10 years with sufficient heat that costed the inhabitants 57% of the heating cost with oil. It also gave the heating service net income that paid the heating installations on the lava and contributed substantially to the construction cost of the distribution system in the town which kept its full value when other heat resources took over.

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