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THE VERTICAL EARTH HEAT EXCHANGER — A SMALL-SCALE GEOTHERMAL ENERGY SYSTEM[1]

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The vertical earth heat exchanger (VHE) is a simple device providing a closed circuit for a fluid to take heat from the first tens/hundreds of meters of ground and to feed the cold side (evaporator) of a heat pump. Different types of VHE have evolved using coaxial tubes or U-tubes inserted into the ground in backfilled drillholes. Tube dimensions up to 10 cm diameter and probe lengths up to 100 m are the most common. Space heating and warm-water supply for a single-family dwelling with 12 KW capacity can be provided by two or three VHE's about 50 m in length. Long-term performance characteristics and the perturbations of the natural temperature field of VHE systems must be known for licensing decisions. Based on the results of field and theoretical studies, key performance parameters like fluid circulation velocity and ground thermal conductivity are identified and the necessary distance between VHE installations is discussed. It is concluded that VHE systems offer an interesting alternative energy source especially if coupled with a simple solar recharge unit.

O trocador de calor vertical (VHE) é um dispositivo simples que estabelece um circuito fechado para que um fluído retire calor nas primeiras dezenas/centenas de metros de profundidade e alimente o lado frio (evaporador) de uma bomba de calor. Tipos diferentes de VHE foram desenvolvidos utilizando tubos coaxiais ou em forma de U, que são introduzidos em perfurações no terreno as quais são novamente preenchidas. Dimensões do tubo de até 10 cm de diâmetro e comprimento das sondas de até 100 m são as mais comuns. Calefação e fornecimento de água morna, para uma residência familiar com capacidade de 12 KW, podem ser atendidas com dois ou três trocadores de calor com cerca de 50 m de comprimento. As características de funcionamento a longo prazo e as perturbações do campo natural de temperatura dos sistemas de trocadores de calor, devem ser conhecidas para efeitos de licenciamento. Com base nos resultados dos estudos experimentais e teóricos são identificados neste trabalho, alguns parâmetros importantes, tais como velocidade de circulação dos fluídos e condutividade térmica do terreno. A distância necessária entre os trocadores de calor é discutida. Conclue-se que os sistemas VHE oferecem uma interessante fonte de energia alternativa especialmente se acoplados com uma unidade de recarga solar.

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INTRODUCTION

For countries located in moderate to cold climatic zones space heating and domestic warm supply are substancial items in the energy economy. In Switzerland for example, due to its relatively high elevation, space heating must be supplied up to 8 months a year, based mostly on imported hydrocarbons (mainly oil).

In order to attain a certain degree of independence of imported fuel several domestic alternative energy sources have been considered in Switzerland. Most of the corresponding heating systems operate in combination with heat pumps (solar, ambient air, ground heat etc.) and is equipped with a warm-water storage tank and a typically low-temperature heating system like floor panels.

The heat contents of the ground can be tapped by ground water heat pumps, shallow horizontal coils or by vertical earth heat exchangers (VHE). The latter are small, decentral, closed-circuit systems, ideally suited to supply heat to smaller objects like single-family or multifamily dwellings. They can be installed in nearly all kinds of geologic media (except in materials like dry gravel with low thermal conductivity). Nearly 2000 such systems operate now in Switzerland, some of them 7-800 m deep but mainly with probe lengths of 50-100 m. In this depth range the virgin temperature field is governed by the thermal conductivity structure of the ground and by the geothermal heat flux. The latter can be influenced by the presence of flowing groundwater.

This paper will describe the VHE principle, identify and evaluate the key parameters in VHE operation with

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special emphasis on long-term performance characteristics. Since the VHE represents a heat sink in the ground, the question about the amplitude and spatial extent of temperature perturbations due to VHE system operation is addressed in particular.

THE VHE HEATING SYSTEM

The VHE probe is inserted into the ground in backfilled boreholes, normally 15 cm in diameter and up to 100 m deep. Economic optimum (drilling costs vs. useful temperature drop) is currently around 50 m depth. Bentonite-quartz sand mixture is used to backfill and thus to establish low thermal resistance between VHE and the ground. The fluid to pick up ground heat is circulated inside of a closed loop, either in a U-tube or in a coaxial arrangement (Fig. 1). The VHE tube is usually made of weldable plastic. The VHE circuit is fed into the secondary (evaporator) side of the heat pump.

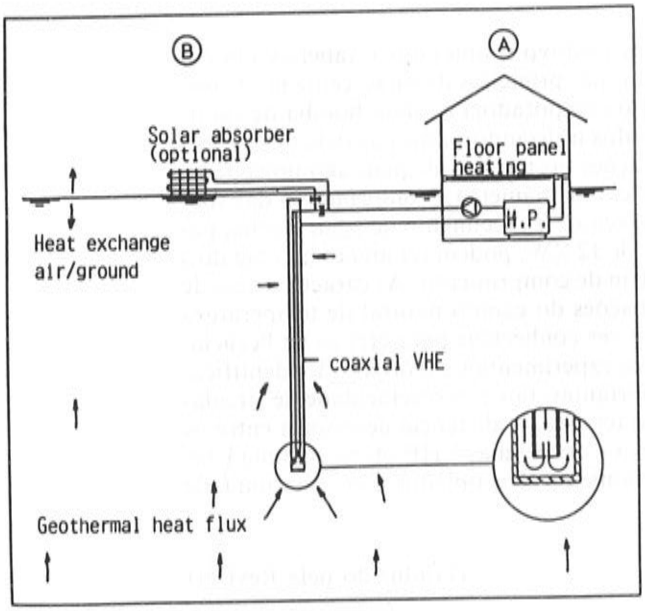

Figure 1 — Principle of a vertical earth heat exchanger (VHE) system. A: heat extraction from the ground by a coaxial-type VHE, B: optional summer recharge to convert the VHE into a small but efficient storage system. H.P.: heat pump.

VHE systems are characterized by minimum space/land requirement; their environmental impact is negligible. For a typical single-family dwelling with a demand of 12 MWh energy per year for space heating and warm water supply (conventionally supplied by an oil-fired system of 12 KW capacity) two to three VHE's are installed at a distance of a few m in the back or front yard and connected to the heat pump in the basement. The heat pump is operated during the heating season 6 to 10 hours/day with low-tariff electricity at night. The coefficient of performance (COP) of the heat pump is in the range 2.5-3.0; the amount of electric power needed to operate the heat pump approximately equals the energy which escapes unused through the chimney of an oil-based heating system.

KEY PARAMETERS IN VHE DESIGN AND PERFORMANCE

The key parameters in VHE design and performance have been identifed by field measurements as well as by theoretical studies (Schwanner et al., 1983). The theoretical studies involve numerical modeling by the integrated finite difference technique (Hopkirk et al., 1985).

The modeling was performed for a cylindrical medium of 80 m radius with a 100 m long, vertical, coaxial-type VHE in its center. The numerical code solves the heat diffusion equation in cylindrical coordinates (r, z) and also accounts for convective heat transfer in the circulating fluid as well as for the thermal contact resistance of the coaxial tube. The contact resistance h, which is an important factor in modeling, can be given (Schwanner et al., 1983) by

$$h = 0.023\, \varrho\, C_p\, V\, (C_p \mu/\lambda)^{-0.667} \mathrm{Re}^{-0.2}$$

where the Reynolds number is

$$\mathrm{Re} = (D_2 - D_1)\, \varrho\, V/\mu$$

with ϱ denoting the density (kg/m^3), C_p the specific hea capacity (J/m^3, K), V the fluid circulation velocity (m/s), λ the thermal conductivity (W/m, K) and μ the viscosity (kg/m, s); D_1 and D_2 are the inner and outer diameter (m) of the coaxial VHE. Some of the main results are summarized below.

The modeling results, substantiated by the operation experience of VHE systems, revealed the following key parameters:

VHE probe — length (L), outer diameter (D), thermal contact resistance (h, see above)

circulating fluid — composition, mass flow rate (m), return temperature (T_{ret})

geologic medium — thermal conductivity (λ), ground water flow (v)

Before describing the results of parametric studies a few general remarks shall be made on VHE performance. The normal power range of a VHE (= "specific output") is, depending on rock thermal conductivity and contact resistance, within the range of 50-100 W per m probe length. For a constant fluid circulation rate, the output (in W/m) increases slightly with probe diameter. The mass flow rate of the circulated fluid amounts to a few m³/h and the fluid velocity, depending on the tube dimensions, is in the range of a few to some tens of cm/s. It is customary to use a nontoxic antifreeze brine as circulating medium to convey the heat from the ground to the heat pump; on the coldest days of the heating period the return temperature of the circulating fluid can be near or even below 0°C. The higher the thermal conductivity of the rock formation surrounding the VHE, the more efficient is the heat extraction from the ground and also the "recovery" of the thermal profile around it (see details below).

The above statements refer to "dry ground", ie. to heat transfer by conduction only. If flowing groundwater is present in the strata penetrated by the VHE probe, heat is advected to the system and thermal recovery is more efficient.

Figures 2 to 5 illustrate quantitatively the effect and interplay of the above-mentioned design and performance parameters. Fig. 2 shows that the increase of probe diameter has only a slight effect; the thermal yield is levelling off at higher flow rate/velocity (for a constant probe length of L = 100 m; thermal yield (= heat output) during the first month of operation). Fig. 3 demonstrates the significant influence of probe length on VHE performance (probe diameter constant at D = 10 cm). Fig. 2 and 3 have been calculated with a rock conductivity and heat capacity of 2.5 W/m, K and 2,5 MJ/m³, K, respectively.

High thermal conductivity of the rock formations around the VHE has a positive effect (see Fig. 4, for continuous operation over a period of 6 months). The decline of specific output, given in W per m probe length, is most pronounced in the first weeks. After about one month the output decrease is nearly linear; parametric studies can therefore be restricted to the first months of VHE operation. In calculating the curves of Fig. 4 the following parameters were kept constant: D = 0.3 m, L = 100 m, m = 1.5 m³/h.

The presence of an aquifer can also increase the efficiency of VHE heat extraction. The influencing parameters are besides aquifer thickness: aquifer porosity ϕ and groundwater velocity v. Fig. 5 demonstrates the influence of these parameters: curve A corresponds to the performance of a 50 m long VHE in dry ground, curves B and C are for a VHE of same length which penetrates a 20 m thick aquifer between 14 and 34 m depth. Curve B is calculated for $\phi = 5\%$ and $v = 8.10^{-3}$ m/s, curve C for $\phi = 30\%$ and $v = 1.3\ 10^{-3}$ m/s.

LONG-TERM VHE PERFORMANCE

During the operational lifetime of the existing VHE installations in Switzerland (i.e. for a few years only for these new systems) very few problems have been experienced and the systems are economically attractive (return of investment in 8 - 12 years). However, several questions arise, such as concerning the long-term performance and the radial extent of temperature perturbations around VHE systems; the latter in conjunction with licensing decisions by the authorities.

Due to the ongoing heat extraction the temperature profile around a VHE probe attains a funnel-like shape (see curve "end of March" in Fig. 7). The temperature depression caused by an annual heating cycle penetrates, depending on the rock thermal conductivity, to a distance of 2 to 5 m laterally into the ground surrounding the VHE. The thermal recovery of the

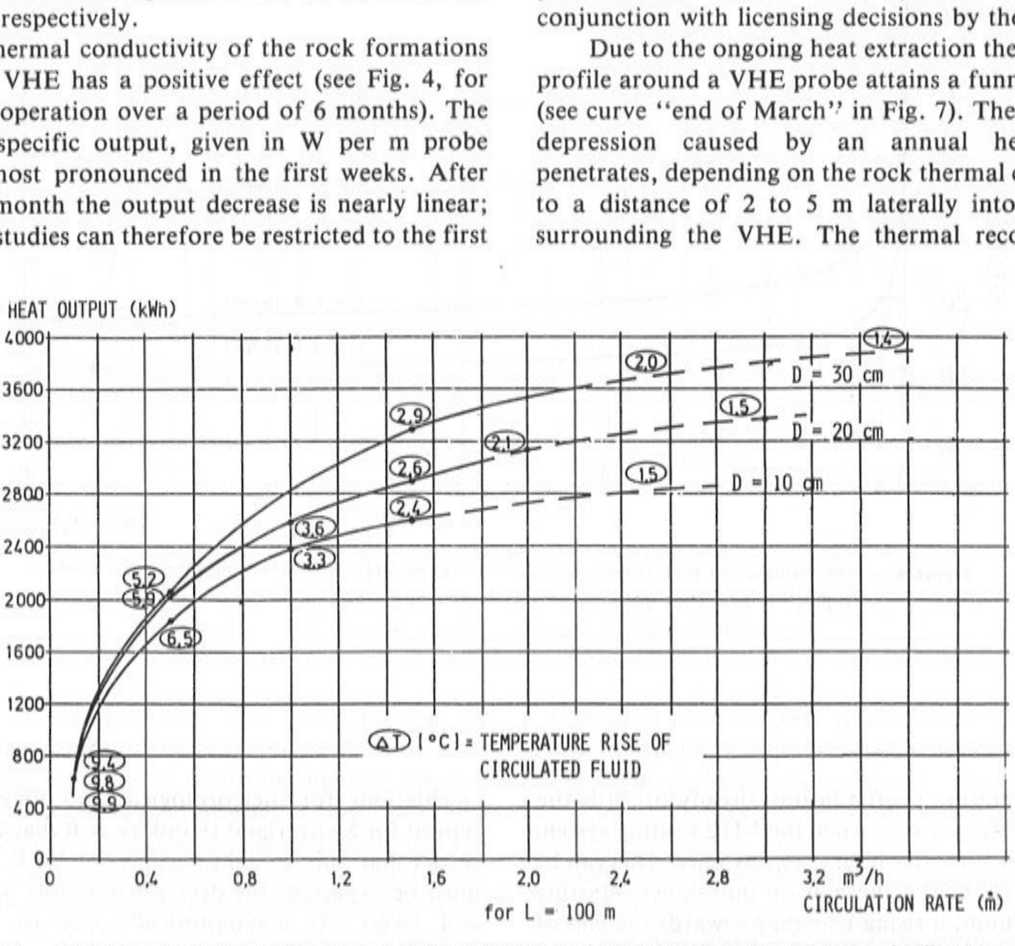

Figure 2 — Influence of probe diameter (D) and fluid circulation rate (m) on VHE performance (for details see text).

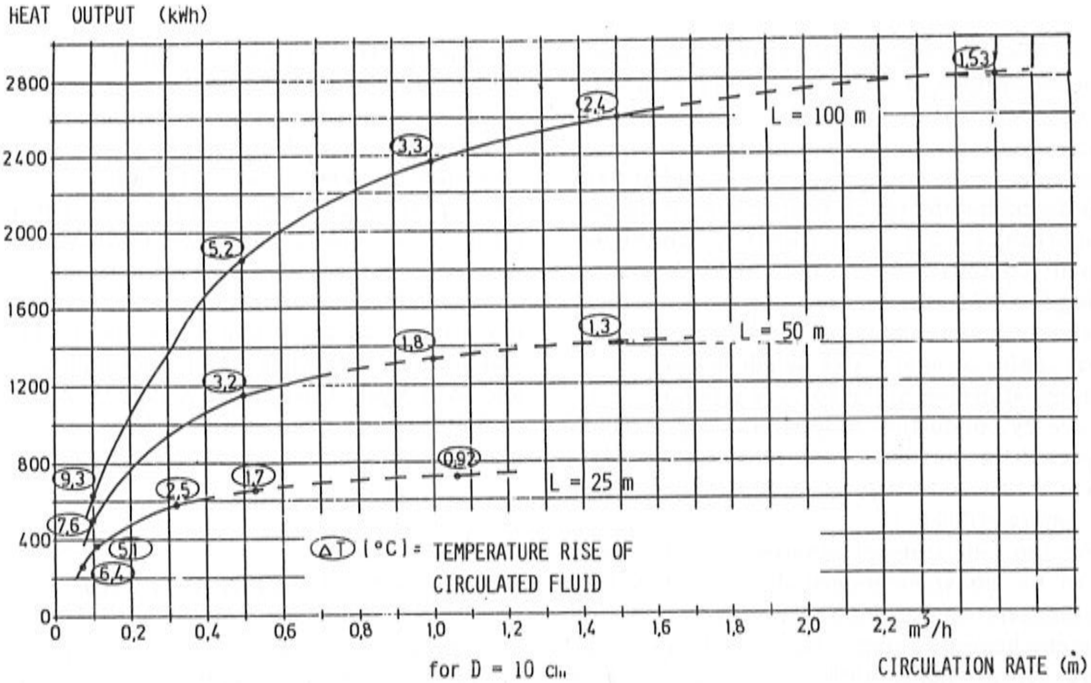

Figure 3 — Influence of probe length (L) and circulation rate (m) on VHE performance (details see text).

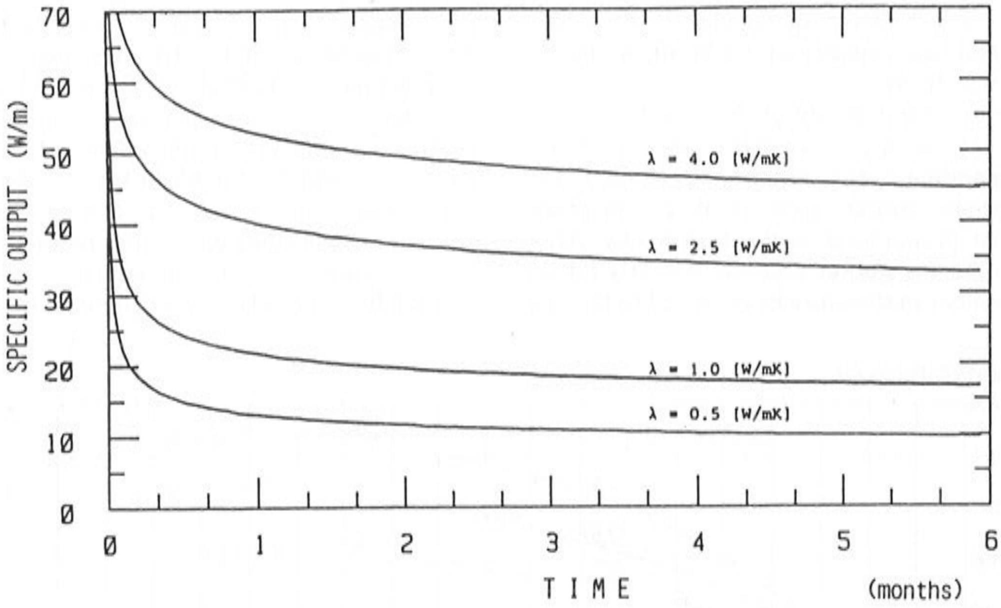

Figure 4 — The influence of rock thermal conductivity (λ) on VHE specific output (Watts per probe length; for details see text).

ground temperature profile begins already towards the end of the heating season when the VHE heating system is switched on for a few hours per day only. This can be seen from Fig. 6: the thermal output shows, starting from a minimum, a rising tendency towards the end of each heating cycle. Fig. 6, which is the result of model calculations for meteorological and rock parameters typical for Switzerland (Hopkirk & Ryback, 1986), also shows that only a slight decrease of VHE performance must be expected; the decrease amounts to about 10% and levels off assymptotically due to a long-term dynamic equilibrium.

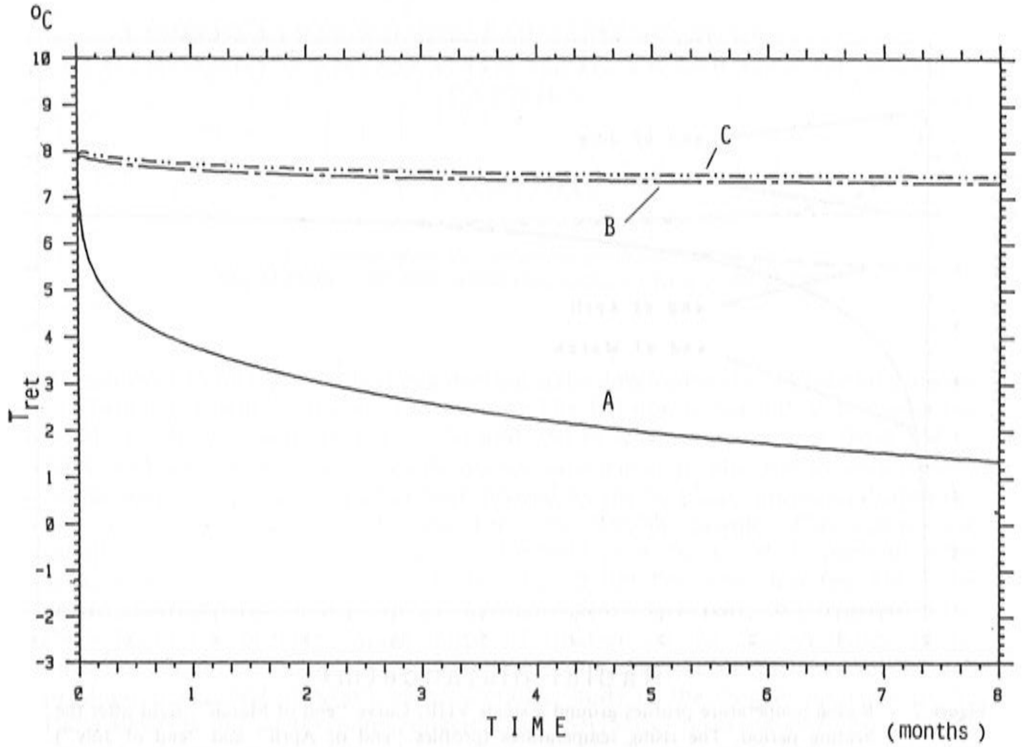

Figure 5 — The effect of an aquifer on VHE performance.Curve A: dry ground, curves B and C with aquifer. T_{ret}: daily average VHE return temperature (details see text).

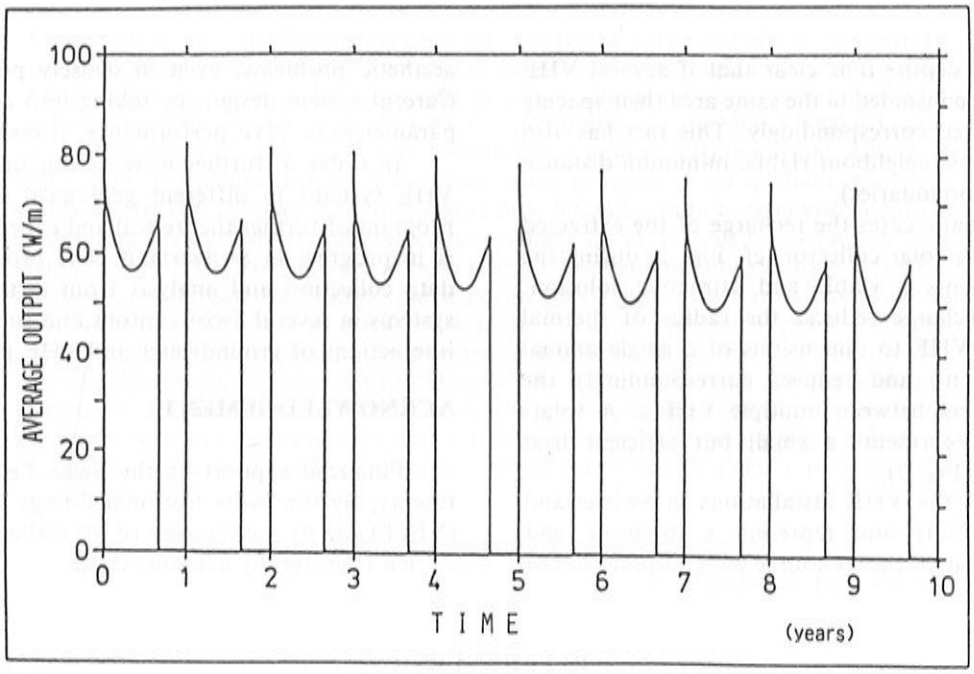

Figure 6 — Long-term VHE performance: the sharp peaks mark the begin of heating period but is incomplete which results in a slight, asymptotic decrease of VHE output.

As the operating lifetime progresses, the thermal perturbation penetrates radially outward a distance which is larger by an order of magnitude than the one caused by a single annual heating cycle. In purely conductive cases (= no groundwater present) the VHE draws from the ground heat deposited by the geothermal heat flux. In the densely populated areas of Switzerland the terrestrial heat flow amounts to 0.08 Wm^{-2}; therefore a VHE system which delivers about $4.5*10^{10}$ J heat per year to a modern, thermally well-isolated single-family dwelling, requires a surface area which corresponds to a circle with a radius of 75 m.

CONCLUSIONS, PROSPECTS

The heat which flows radially towards a VHE from the near field originates from the geothermal heat flux

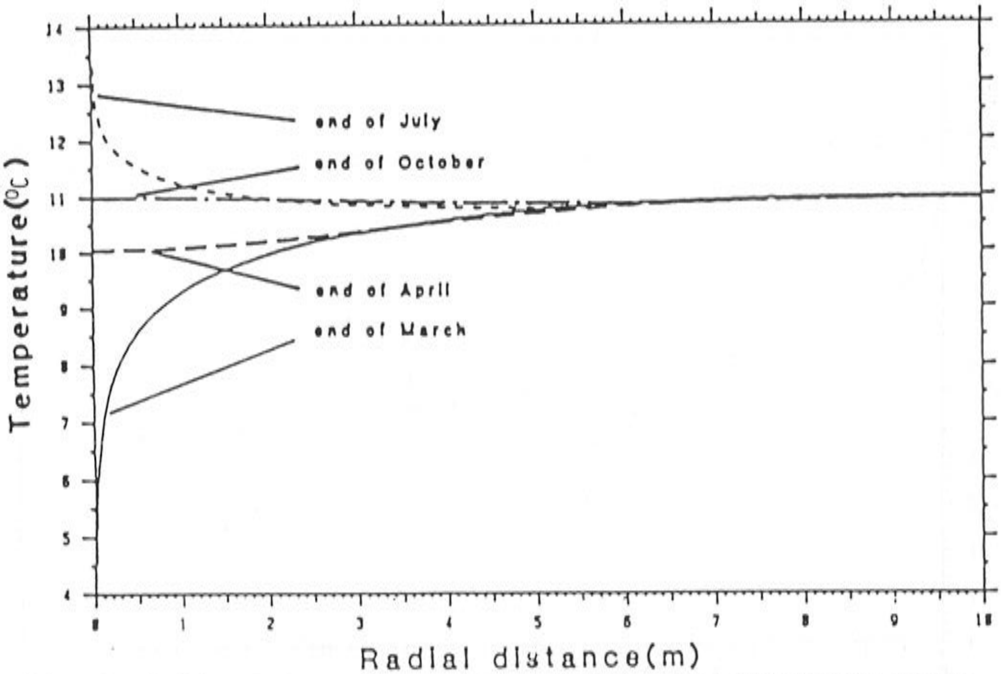

Figure 7 — Radial temperature profiles around a single VHE. Curve "end of March": right after the heating period. The rising temperatures (profiles "end of April" and "end of July") demonstrate the effect of summer recharge by a solar energy absorber.

and thus from depth. It is clear that if several VHE systems are to be installed in the same area their spacing must be increased correspondingly. This fact has also legal implications (neighbour rights, minimum distance from property boundaries).

In problematic cases the recharge of the extracted heat by a simple solar collector (cf. Fig. 1) during the summer represents a viable and attractive solution. Yearly solar recharge reduces the radius of thermal influence of a VHE to dimensions of a single annual cycle (max. 5 m) and reduces correspondingly the minimum spacing between multiple VHE's. A solar-coupled VHE represents a small but efficient heat storage system (Fig. 7).

At present, the VHE installations in Switzerland operate successfully and represent a domestic and economic alternative energy source with no pollution or aesthetic problems, even in densely populated areas. Careful system design, by taking into account the key parameters in VHE performance, is essential.

In order to further increase our understanding of VHE systems in different geological environments a program of further theoretical and experimental studies is in progress in Switzerland. The program embraces data collection and analysis from instrumented VHE systems in several Swiss cantons and further studies on interactions of groundwater and VHE probes.

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