SHALLOW AND DEEP BOREHOLE HEAT EXCHANGERS-ACHIEVEMENTS AND PROSPECTS

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ABSTRACT

With almost 6'000 space heating systems based on borehole heat exchangers (BHE) using over 10'000 BHE's with a total length of nearly 1´300 km Switzerland is world leader in terms of areal density (number of BHE's per country area). The state of the art is based on field measurements of performance parameters conducted over five heating seasons as well as on validated numerical model simulations to prove the reliable long-term operation of BHE systems. New development trends include multiple BHE's for combined heat extraction/storage, foundation piles equiped with BHE's. and deep BHE's to be installed in otherwise abandoned, "dry" exploratory drillholes.

Key words : decentral space heating, design and operation, heat pumps, model simulations, single and multiple systems

1. INTRODUCTION

Switzerland undertakes, like many other countries, great efforts to reduce its dependence from foreign fossil fuels. Indigenous sources of energy like the heat content of the subsurface are especially in focus, also due to environmental concern (greenhouse effect caused by CO_2 emissions). The most popular and technologically advanced space heating system to use ground heat is the borehole heat exchanger (BHE).

Shallow, coaxial or U-shaped BHE's are installed in 30 - 150 m deep, backfilled boreholes to extract, by closed-fluid circulation, heat from the ground. They feed the cold (evaporator) side of a heat pump (HP). Attached to the "warm" HP side (compressor) is a low-temperature (e.g. floor panel) system to heat usually a single dwelling house (Fig. 1). The energy supply for the heat exchanger comes from several sources: the vertical geothermal energy flux itself, the import of energy horizontally by conduction, advective transport with groundwater if present, and the compensating effect of heat exchange between the ground surface and the atmosphere. Multiple BHE's are installed for larger units like community buildings etc. Since 1980 almost 6'000 such systems, using about 10'000 BHE's with a total length of more than 1'300'000 m have been installed in Switzerland (cf. Fig. 2). Areal density (number of BHE's per country area) is highest worldwide.

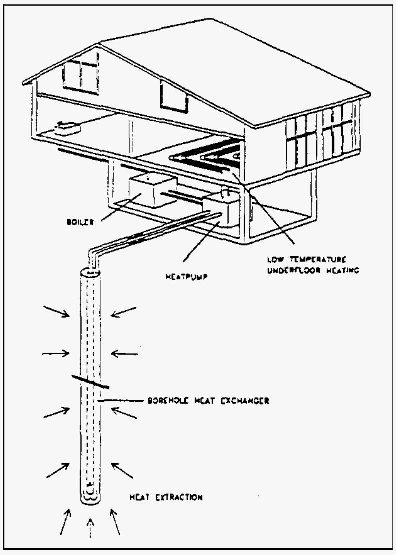

Fig. 1. Principle of a *BHE* heating system with a borehole heat exchanger (plastic tube, installed in a backfilled drillhole, typical length about *100 m),* heat pump and low-temperature underfloor heating.

The BHE can be upscaled in order to be installed in otherwise abandoned deep drillholes (e.g. in "dry" geothermal or hydrocarbon exploratory holes). Experimental as well as theoretical studies have been pursued in Switzerland in the last 10 years to establish a sound technical and energy economics base for shallow and deep BHE systems. The aim of this paper is i) to summarize the state of the art, and ii) to expose new development trends.

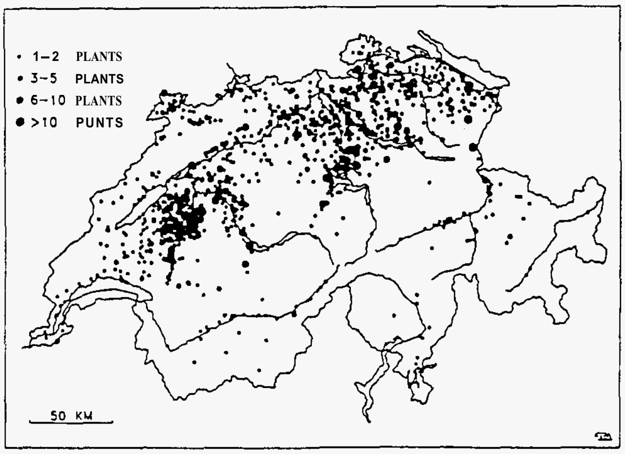

Fig. 2. Location of *BHE* systems in Switzerland with a total of nearly 6'000 heating units. Areal density (number of *BHE's* per country area) is highest worldwide, distribution corresponds roughly *to* population density.

2. THE STATE OF THE ART

Field measurements of ground and system performace parameters at instrumented test facilities over five consecutive heating seasons as Well as validated numerical simulations prove the reliable operation of BHE systems. These investigations are jointly carried out by the Institute of Geophysics at the ETH Zurich and by the research and consulting company POLYDYNAMICS Ltd., Zurich.

2.1 Design parameters

The influence of design parameters like BHE length, diameter, minimum spacing, BHE tube and backfill materials, fluid circulation rate, as well as site-specific factors like topographic altitude, ground thermal conductivity structure, groundwater characteristics on BHE performance have been investigated and reported in detail (Rybach et *al.* 1990, 1992; Eugster et *al.* 1992).

BHE's can be installed in most geological materials (except in alluvial gravels with low thermal conductivity which are also problematic in the context of groundwater protection aspects of BHE's).

2.2 Typical performance Indicators

An extensive measurement campaign has been performed at a commercially delivered BHE installation in Elgg, near Zurich (Eugster 1991). Ground temperatures in 2 different radial distances and in 10 different depths (between 1 and 110 m) have been recorded at 30 minute intervals over a five year period (1986-1991). In addition, the atmospheric temperature variations and all parameters relevant to the operation of the entire system (hydraulic system flowrates, circuit temperatures, power consumption of the HP) have also been monitored.

The measurements indicate a general cooling of about 0.8 ^oC along the entire length of the BHE after the first year of operation. The growth of the temperature deficit slows down in the successive years until a new thermal equilibrium is reached. Atmospheric influences are clearly visible in the depth range 0 - 15 m; below 15 m the geothermal heat flux dominates. The BHE supplies a peak thermal power of about 45 W per m length.

2.3 Long-term behavior

The measured data were used *to* calibrate a two-dimensional, cylindrical coordinate numerical computer model. This model was selected because of the coaxial construction of the BHE. The model treats conduction in the ground formation, heat exchange and forced convection in the heat exchanger tubes and heat exchange between ground and atmosphere. A vital factor for the heat supply of the BHE is a good contact between exchanger tubes and the surrounding ground (backfilling). Once this is assured the performance is essentially determined by the thermal conductivity of the formation. The model calculations are driven by an imposed load time history which respects the variation in atmospheric temperature and the characteristics of the HP (daily runtime, evaporator temperature difference). Ground temperatures measured over the five years were fitted *to* within a few tenths of a ^oC by the numerical model. With the model so validated the ground temperatures have been calculated for a further nine years in order *to* predict the long-term performance (Rybach et al. 1992). The results prove the establishment of a new thermal equilibrium, i.e. there will be no thermal breakdown in the long term.

Measurements as well as computations indicate the development of a permanent, cusp-like distributions of residual temperature deficit around the BHE during the first two years of operation. At the centre, next *to* the BHE, this has an amplitude of about 1 ^oC. The perturbation can be detected in the numerical results out to a radius of about 10 m. The residual deficit distribution varies very little in subsequent years, although each heating season causes a supplementary transient perturbation. This exhibits a central amplitude of around 5 ^oC, varying with the severity of the winter and penetrates the formation to radius of about 3 m. Outside this radius the temperature deficit is never more than a few tenths of a ^oC and is insensitive to year to year variations in the load profile.

The numerical calculation scheme also includes a HP model *to* calculate the seasonal performance coefficient $SPC = E_d / E_{el}$ (E_d : delivered energy, E_{el} : electrical energy demand for circulation pump and HP during the entire heating season). Sensible energy economics calls for SPC > 3.0; this can be achieved with low-temperature heating systems where the delivery temperature is < 45 ^oC. By optimising BHE and HP design and using heating supply temperatures around 35 ^oC, SPC's of the order of 4.0 can be achieved.

2.4 Market Impact

The reliable operation of BHR heating systems lead in Switzerland *to* considerable popularity of this heating option, even in view of higher installation costs (30 - 40 % higher in comparison with a conventional oil-fired system, see Table 1).

As mentioned before, Switzerland has the highest BHE density worldwide (6000 BHE's with a total length of 1'300 km BHE in a country of 41'000 km^2). The number of BHE's continues *to* increase by about 800 per year; several commercial companies are offering the installation and maintenance ot such systems. They are mainly used in new single-family dwellings but the BHE option is often chosen when old oil-based heating systems are *to* be renewed/replaced. Multiple BHE's are, in comparison, rather rare although their number is also increasing. The largeset multiple system with over 40 BHE's is now operational at the Scuol spa in the Swiss Alps near St. Moritz.

There are several reasons for the BHE boom: 1) Economic considerations. At present, installation costs of a BHE system are higher than for a conventional oil-based unit. However, annual "fuel" costs (=electricity for heat pump and circulation pump) are considerably less than for an oil-heater. So the return time of the relatively high investment for a BHE is definitely shorter than the lifetime of the heating system itself. The increase of oil price is anticipated by many Swiss customers for the foreseeable future; this would also call for an oil-independent heating system like the BHE. 2) Environmental concern. The argument most frequently heard for BHE's is that home owners want *to* install an environmentally benign heating system. In particular, the emission of combustion products like CO_2 ("greenhouse effect"!) can be so avoided. In addition, there is no risk of local groundwater contamination which could happen with leaking oil heaters. The planned introduction of a CO_2 emission tax (which is under discussion on the European political scene) is a further argument to select a CO_2-free heating system. It must be mentioned here that in some Swiss cantons (="prefectures") an operating licence is needed for BHE's in or near groundwater protection zones. The Swiss Federal Office of Environment has issued guidelines *to* harmonize the differing licencing practice of the cantons. 3) Governmental subsidy. Presently the Swiss Federal Office of Energy provides a subsidy for replacing oil-heaters by heat pump systems. This applies *to* BHE-coupled heat pumps *too*. Presently the subsidy amounts *to* about 200 US$ per heat pump kW_e with an upper limit of 5'200 US$.

	BHE + HP	Oil boiler
• BHE, 135 m deep: drilling. tubing &installation, back-filling. testing	11,500	
• Heat pump (HP) incl. installation and testing	10,500	
• Compact boiler, Low NO, burner, incl. regulation	-	8,000
• Heating regulation system	2,300	incl.
• Materials and installation	4.200	
• Plastic oil tank (2x1,500 1) incl. leakage basin, all materials for installation and connection, installation	-	6,000
• Chimney with all building work, insulation and sealing	-	7,000
Total	28,500	21,000

- old research or exploration holes

- failed "dry" holes drilled in the search for hydrogeothermal, gas or oil resources

In both cases the drilling costs have usually been written off; new investment for their re-use will be restricted therefore *to* eventual cleaning out costs plus the costs of completion as a closed circuit heat exchanger. Provided that a suitable heat consumer is nearby, the viability of this undertaking will depend upon the rate and temperature level at which heat can be extracted over a long period.

3.1 Deep BHE design

As is the case around the shallow BHE's, the formation temperature around a borehole heat exchanger at greater depth will sink during heat extraction by the circulating fluid. The intensity of drawdown and hence also the source temperature of the energy delivered depends upon the rate of heat extraction from the fluid circuit and the rate of thermal replenishment of the near field. The rate of replenishment depends in its turn largely upon the thermal conductivity of the geological formations penetrated by the borehole, but also locally upon the advective replenishment by flowing groundwater. It becomes apparent that a range of choice of operational design parameters exists in any given case between:

- a higher source temperature at a lower energy extraction rate, and

- a lower source temperature at a higher energy extraction rate.

Here the nature of the heat consumer is decisive in quantifying the range of choice. For instance a modern housing development in Switzerland will accept a supply temperature of 45°C or even 35°C, whereas buildings whose heating systems date from 1970 or earlier will undoubtedly require a supply temperature of 60°C or more.

The most popular type of construction used for the shallow BHE's consists of single or double U-tubes backfilled into the borehole, see also Chapter 1 and Fig. 1. In deeper drillholes, the presence of a liner will imply that a coaxial construction, offering potentially better scope for thermal and hydraulic optimisation may be and indeed should be used. "Production" or heat delivery is via a centred coaxial pipe and the return via the annulus. According to the temperature difference between the delivery and return flows, more or less effort in insulating the two fluid streams from each other will be necessary (Morita *et al.* 1985, 1992). Furthermore, if the return temperature exceeds 20°C it can be advisable to insulate the return line from the surrounding formation down to a depth at which the temperature difference is insignificant.

3.2 Heat extraction characteristics

Interest in the potential of deep borehole heat exchangers has led to a number of studies and indeed to some more concrete design projects. The approach taken in this work has been to apply numerical simulation modelling developed in connection with the shallow BHE's and validated against field measurements. Two finite difference codes, one in cylindrical geometry for axisymmetric problems and one offering full three-dimensional capability were assembled for these tasks (Hopkirk and Rybach 1994). In the following, an example will be given to illustrate the statements made in the preceding paragraphs.

The possibility has been investigated of completing a "dry" 1700 m geothermal drillhole in northern Switzerland as a BHE in order to provide space heating energy to all or part of a new residential development. The application to a brand new development opens the scope for heating system conceived from the start with a low supply temperature (35°C). Nevertheless, initial numerical simulations showed that a useful heating energy supply (peaking at over 200 kW) would only be possible in combination with a heat pump. The moderate source temperature, on the other hand, means that neither an expensive, thermally insulated production pipe, nor insulation from the formation of the return flow in the annulus over the upper part of the drillhole are necessary.

Figure 3 shows temperature and heat flux profiles along the BHE at various times during the operating lifetime for two different types of coaxial production pipe. The upper frames concern an insulated, double-walled construction with a total wall thickness of 22 mm and an effective thermal conductivity of 0.027 W/mK. The lower frames present the same information for a simple MDPE (medium density Polyethylene) pipe, having a wall thickness of 8 mm and a thermal conductivity of 0.44 W/mK. These plots were developed from numerical simulation runs using a steady, uninterrupted heat extraction rate of 110 kW.

comparison of the heat flux plots reveals that for the case with the highly insulated pipe an energy loss to the formation takes place over the upper 200 m and that thereafter energy flows into the annulus. A very small loss is experienced from the production pipe. The effect of the poorer insulation offered by the plastic pipe is seen not only in the negative heat flux to the production pipe, but also as a net energy gain by the return flow in the annulus over the whole depth range, more than compensating for the losses to the cooler upper ground layers.

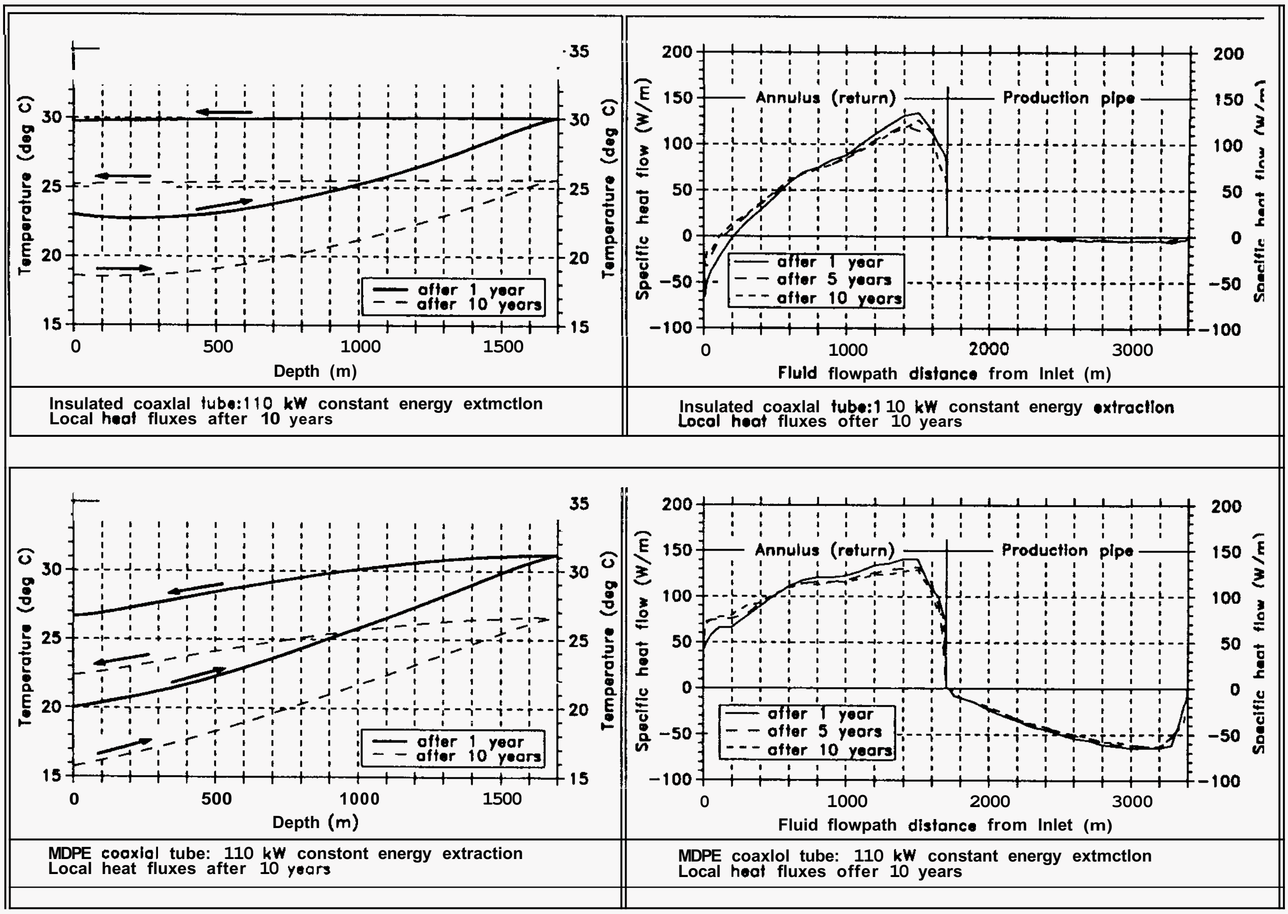

Fig. 3. Profiles of temperature and specific heat exchange flux along the return and delivery flowpaths of the 1700 m long BHE at various times and under steady load.

The temperature profiles show that, while after one year of operation the source (production) temperatures differ by almost 7 K, the difference diminishes with time (5K after 10 years). This implies that the cheaper solution with poorer insulation offers a lower but more constant source temperature over the operating lifetime of the plant. Moreover, the heat pump has been considered to use R22 refrigerant and can operate therefore at a maximum evaporation temperature of approximately 13°C. The cheaper solution offers more than enough temperature differential across the evaporator for the heat pump to be able to run always close to this temperature and thus at its maximum efficiency. This result forms the basis of the construction and choice of materials for the BHE.

At this stage it becomes possible to determine the true potential size of the heating load, which can be carried by this BHE. Simulations using the same model but with application of a typical seasonal heating demand profile for the site region and a detailed model of a heat pump have been made. Suitable supply temperatures were obtained when the peak extraction rate was fixed at 170 kW. The seasonal performance factor of the optimised heat pump, delivering energy for low temperature heating systems, including system losses was over 4.9 over a simulation for 30 years operation. Figure 4 shows temperature/time histories of the relevant system temperatures over the first ten years of operation. The slow and diminishing rate of cooling of the surrrounding rock mass is reflected in the plots of Figure 4. Figure 5 shows for the same period the change in vertical ground temperature profile at a distance of 1.75 m from the BHE. The cooling in the lower part of the region is clearly to be seen, as is a certain warming effect due to the heat loss to the formation (discussed with Figure 3) in the upper part. This trend is similar, although slower at the greater depths below the essentially isothermal ground surface, to the cooling around shallow vertical borehole heat exchangers reported by Rybach *et al.* (1992).

In this particular case the use of the failed geothermal hole (at Reinach, near Basle) as a borehole heat exchanger can be shown to be economically attractive when compared with a modern oil-fired heating system, even more so when a local distribution network at wellhead temperature in combination with decentralised heat pumps is considered.

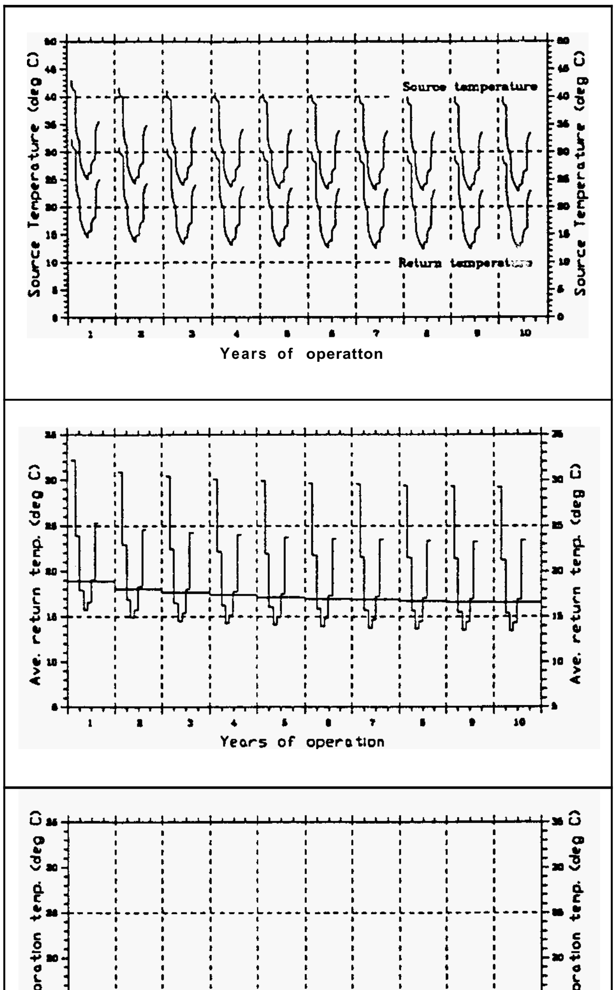

Figure 4: Temperature- time histories over 10years for wellhead delivery and return temperatures with monthly averages for return and heat pump refrigerant evaporation temperature.

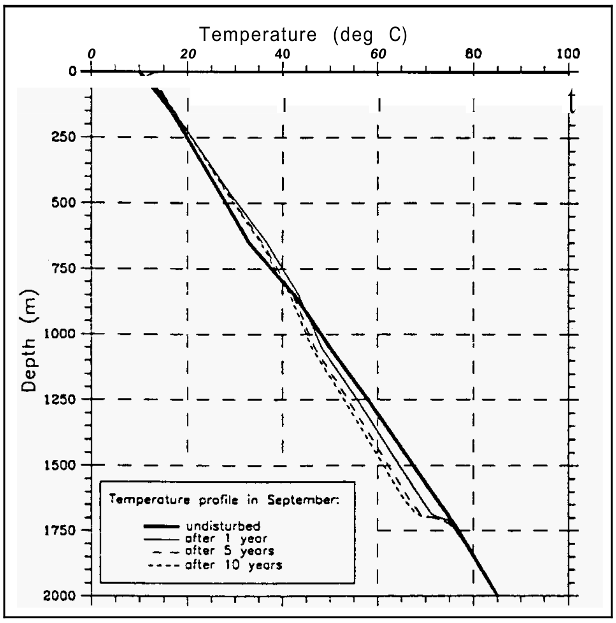

Figure 5: Evolution of the vertical temperature profile along the 1700 m long BHE, shown each time in September after a full year's operation (winter loading and summer recovery).

3.3 An operational example

In the center of the community Weggis, on the shore of Lake Lucerne, *a* private investor commissioned a 2.3 km deep geothermal borehole. Since the productivity of the envisaged formation (Miocene Lower Freshwater Molasse) was uncertain, the installation of a deep BHE was planned from the beginning. The water yield of the well was indeed negligible. So it was completed with the following BHE construction: a 7" casing (0 - 1902m), inside of it a double, vacuum-isolated production tube (0 -1780m), followed by an unisolated pipe (1780 - 2281m), in a 5 1/2" hanger-liner (1781 - 2295m) with a prefabricated bottom seal.The corrected bottom hole temperature (BHT) was 78 °C.

The drillsite is well-situated amidst the potential energy users. In order to assess the heating potential of the deep BHE over at least 30 years a two-stage program was performed: 1) a series of short test runs to determine the BHE behavior under different load conditions, and 2) model calculations considering all relevant heat transfer processes, formation and BHE design characteristics.

During the test runs (at different circulation rates and heat loads) the injection and return fluid temperatures as well as the circulation rates were recorded. The test runs were performed with open circulation, by injecting fresh water into the annulus. This phase was preceded by a 20-week operation test during winter 1993/94 at low thermal load (max. 50 kW). Fig. 6 shows a time window from these records.

The measurement results reveal the dynamic thermal response of the deep BHE to the operating condition and load history. In addition, the thermal conductivity of the drilled formations was measured in the laboratory on cuttings. These data, together with the BHE designs geometry, are accomodated by the numerical model.

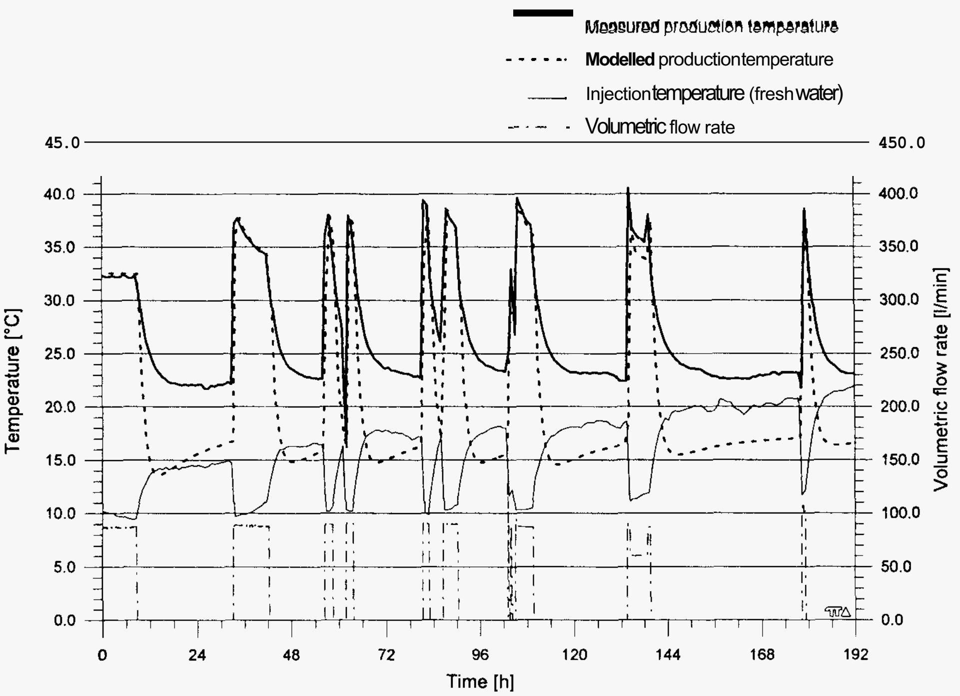

Fig. 6. Short-term test run at the 2.3 km deep BHE in Weggis: a time section with measured and modelled flow temperatures. For comments see text.

The model calculations, performed with the finite difference code COSOND to simulate coaxial BHE's, consider different load types. Therefore surface connections to users and to the heat utilisation system are also incorporated (Hopkirk *et al.* 1995). The model has been calibrated by the short-term results. The complex BHE design needs special attention: the thermal couplings steel pipe/cement/formation, the turbulent heat exchange between fluid and pipe, and the combined heat exchange mechanisms (radiation-free convection, conduction) in the double production pipe must all be considered.

The double pipe (with an underpressure of 0.2 bar inbetween) shows special characteristics: in certain depth sections the radiative heat exchange between the pipes becomes evident. Unfortunately the thermal contacts at the casing collars of the inner pipe have an even more pronounced effect: the latter serve also as centering inserts, thus forming efficient thermal bridges between the two pipes.

Fig. 6 also shows the comparison of measured and modelled temperatures: first the end of a 5-day in-phase, and subsequent in/out phases. During operation/circulation the agreement between model and measurement is within 0.1 K. During the out phase the modelled temperatures (at the borehole head) are significantly lower than the measurements (performed in the warm heating facility).

For long-term system behavior the modelling assumes heat extraction over 30 years. Two load scenarios have been investigated: houses with a peak load of 100 or 250 kW. For each additional year the corresponding load profile was inserted. Fig. 7 shows the calculated injection and source temperatures. The 31th year is shown in detail. The load of 250 kW marks the upper limit of loadability of this deep BHE.

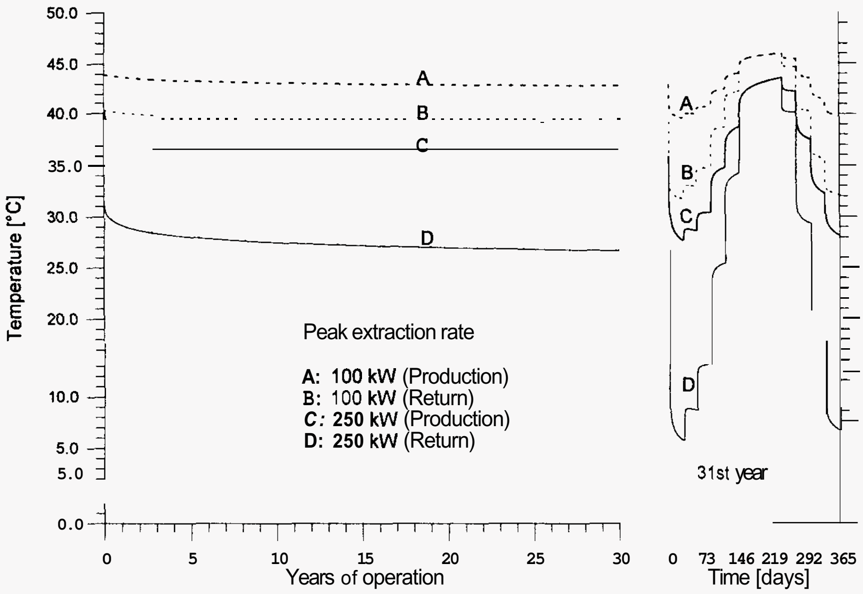

*Fig. 7. Modelled injection and return flow temperatures over **31** years of operation for two load scenarios **(100** kW, 250 kW) of the Weggis deep BHE.*

3.4 Remarks on deep BHE economics

The above examples have showed how existing deep boreholes can be converted to create heat exchangers to provide an environmentally attractive energy source and to revive an otherwise forcibly written off investment. At the same time the bounding considerations leading to an unavoidable compromise between energy supply temperature and rate associated with the essentially diffusive heat flow in the ground have been highlighted.

The economic viability of a given conversion, or indeed of a new project depends therefore, not only as for all geothermal heating applications on the size and proximity of the energy user, but also on the temperature at which heat is to be delivered.

The conversion of failed geothermal or hydrocarbon exploration boreholes offers an truly economical alternative to oil heating. If drilling costs were to be included in the capital investment plan, a hole of the depth available at that site would not have been economic without outside financial support. For a fairly broad size range of users however, the shallow BHE's with heat pumps are fairly expensive but nevertheless attractive. It is suggested here, that there exists also a corresponding user size range of the order of 100 kW to 1 MW at which the deep BHE in a purpose-drilled hole now or in the near future can be equally attractive.

4. NEW DEVELOPMENT TRENDS

Interesting new areas for further BHE development are given by i) multiple BHE's, ii) "energy piles" .

Multiple BHE's can be used to access a ground storage volume for seasonal storage of waste heat from large buildings or with solar energy (solar collectors, flat roofs of buildings, surfaces of streets or parking areas). In this respect, a well-balanced management of the subsurface stock, taking into account local factors, is essential. The stock can be installed directly beneath the buildings; its use for heating in winter and cooling in summer is technically feasible. This double usage can reduce investment in cooling capacity and renders the BHE costs more attractive. Applications of this type promise to broaden the market substantially for BHE usage.

New developments are also emerging with so-called energy piles. Piles up to tens of m length are driven into problematic ground to increase foundation stability. The idea is to equip these piles with heat exchangers. The influence on load bearing capacity of the temperature reduction around the piles and the effects of cyclic heat extraction over the years need to be carefully investigated.

5. CONCLUSIONS

With state-of-the-art design the BHE can be installed in practically all geologic media and operate reliably over decades, since the heat supplying factors (vertical geothermal heat flux, horizontal conductive heat supply, advective groundwater heat transport, atmospheric heat exchange) produce collectively a state of modified thermal equilibrium around the BHE which is already reached after the first years of operation.

The BHE system becomes more and more popular in Switzerland despite the fact that installation costs (to heat a typical single dwelling house with a capacity demand of about 10 kWth) is 30 - 40 % higher in comparison with a conventional oil-fired system. Environmental awareness, enforced by a Governmental subsidy, is the main incentive for new installations. With over 5'000 operating installations Switzerland has at present the highest areal BHE density world wide.

Encouraging new developments are clearly visible: efficient, combined heat extraction/storage can be achieved by multiple BHE's, carefully managed and operated to yield optimal heat delivery. Foundation piles can be equiped with heat exchangers, although here some open questions remain to be solved. Finally, deep BHE's can be installed in "dry" (failure) holes to heat larger objects, Thus the BHE is a powerful option on the space heating scene.

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6. REFERENCES

Eugster, W.J. (1991): Erdwarmesonden - Funktionsweise und Wechselwirkung mit dem geologischen Untergrund. Feldmessungen und Modellsimulation. Ph.D. Thesis ETH Zurich no. 9524.

Eugster, W.J., Seifert, P.K., Hopkirk, R.J. and Rybach, L. (1992): Einfluss von Klima und Standort auf das Betriebsverhalten von Erdwarmesonden-Anlagen. Proceedings "Geothermal Energy Symposium" Erding/Munich FRG, pp. 335-344.

Hopkirk, R.J. and Rybach, L. (1994): Deep borehole heat exchangers. Proc ."GEOTHERMICS 94 IN EUROPE - From research to development", Orleans F , Document B.R.G.M. no. 230, pp. 323-330.

Hopkirk, R.J., Rybach, I. and Stadler, Th. (1995): Tiefe Erdwarmesonden. In: Proceedings, 2. Symposium "Erdgekoppelte Warmepumpen", Rauischholzhausen/D (in press).

Morita , K., Matsubayashi, O. and Kusunoki, K. (1985): Down-hole coaxial heat exchanger using insulated inner pipe for maximum heat extraction. GRC Transactions Vol. 9 (I), pp. 17-23.

Morita, K., Bollmeier, W.S. and Mizogami, H. (1992): An experiment to prove the concept of the downhole coaxial heat exchanger (DCHE) in Hawaii. GRC Transactions Vol. 16, pp.9-16.

Rybach, L., Hopkirk, R.J., Eugster, W.J. and Burkart, R. (1990): Design and long-term performance characteristics of vertical earth heat exchangers. GRC Transactions 14, Part I, pp. 343-349.

Rybach, L., Eugster, W.J., Hopkirk, R.J. and Kaelin, B. (1992): Borehole heat exchangers: Long-term operational characteristics of a decentral geothermal heating system. Geothermics 21, pp. 861-867.