GEOTRAINET TRAINING MANUAL FOR DESIGNERS OF SHALLOW GEOTHERMAL SYSTEMS

Geo-Education for a sustainable geothermal heating and cooling market

Project: IEE/07/581/S12.499061

www.geotrainet.eu

This manual for Designers of Ground Source Heat Pumps (GSHP) is one of the deliverables from 'GEOTRAINET: Geo-Education for a sustainable geothermal heating and cooling market'. This project is supported by Intelligent Energy – Europe and took place from September 2008 to February 2011.

Ground Source Heat Pumps already make an important contribution to energy saving and emission reduction and have the potential to make an even greater contribution in the future. Research in Europe shows that one of the barriers to a sustainable and growing geothermal market is the lack of appropriately skilled personnel. Moreover, the quality of design and application are not always satisfactory. The objective of this project is to develop a professionally-oriented European education programme (training courses and associated materials such as this manual) to support the geothermal heating and cooling market. There are a number of different groups of professionals involved in a GSHP installation. The GEOTRAINET project is focused on two target groups: Designers (those who carry out feasibility and design studies, including geology) and Drillers (who make the boreholes and insert the tubes). The project has produced an education programme comprising curricula, didactic materials, training courses and an e-leaning platform.

The present manual forms the didactic material for designers. It is based on the curricula developed in the GEOTRAINET framework. An international platform of experts on Geothermal Energy Heating and Cooling was established to provide the knowledge required for developing and delivering the teaching and supporting didactic materials for both of the target groups. This group of experts was drawn from professionals with the full range of qualifications and experience relevant to the GSHP sector. The expert platforms created provide a complete vision of the curricula necessary for designers and drillers. By working together, experts from different countries have provided a rich exchange of practice between the countries.

During the two and a half years of the GEOTRAINET project, ten courses have been delivered to a total of 380 participants. In the context of the European Directive on promotion of the use of energy from renewable sources, there is a very high demand for training courses in all EU countries. The first two GEOTRAINET courses were oriented to prepare trainers in Europe; there were also four courses for Designers and four courses for Drillers delivered by the trainers and members of the expert platform. The involvement of participants from different countries and with a range of experience and qualifications has provided an authoritative forum for the GSHP sector. The feedback of the participants in the courses has allowed refinement and improvement of the course programmes, and consequently the didactic material presented in this manual, which has been a living draft throughout the project.

The continuity of GEOTRAINET training activity will be assured through the establishment of a European Education Committee. This committee will coordinate national training activity based on the GEOTRAINET education programmes. This manual is intended to provide relevant and accessible support for the ongoing education of European GSHP Designers.

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GEOTRAINET TRAINING MANUAL FOR DESIGNERS OF SHALLOW GEOTHERMAL SYSTEMS

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Project: IEE/07/581/SI2.499061

Compiled and edited by Dr. Maureen Mc Corry with EurGeol. Gareth Ll. Jones

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DISCLAIMER

COVER

Front cover pictures clockwise from top: Vista Health Care Clinic, Naas, Co. Kildare, Ireland, 400kW open loop system; BHE insertion from a reel, Switzerland; Diagramatic representation of an open loop borehole system; Shallow geothermal borehole drilling for a domestic dwelling, Co. Cork, Ireland.

Back cover picture: The building is a marketing and dispatch centre for organic food in Upper Austria, and is heated and air-conditioned by two water-water-heat pumps on groundwater wells. © Ochsner

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CHAPTER 1

OVERVIEW OF SHALLOW GEOTHERMAL SYSTEMS *by Burkhard Sanner*

I. INTRODUCTION

Geothermal energy, in the public's perception, is often associated with volcanoes and geysers. However, beside these spectacular manifestations, there is also a more modest side of geothermal energy. The geothermal heat flow from the deeper crust to the surface normally cannot be felt by human beings, although it reaches about 40 TW of thermal output, eventually radiated into outer space. On the way down into the deeper layers of our planet, temperature rises by 3 K per 100 m of depth on average, with a doubling or tripling of this rate at geothermal anomalies.

A clear definition for geothermal energy was badly needed both for the technical as well as for the administrative and regulatory side of geothermal energy use. Based upon German practice, the European Geothermal Energy Council (EGEC) adopted a definition giving only the surface of the solid earth as a boundary for geothermal. Since July 2009, this definition is for the first time stated in the EU legislative framework; EU Directive 2009/28/EC on Promotion of Renewable Energy Sources reads:

> Art. 2:
>
> The following definitions also apply:
>
> (c) "geothermal energy" means energy stored in form of heat beneath the surface of solid earth.

The distinction between shallow and deep geothermal is not fixed. Historically a depth of ca. 400 m is used, going back to a Swiss support scheme from the 1980s. In general, shallow geothermal systems can be considered as those not pursuing the higher temperatures typically found only at greater depth, but applying technical solutions to make use of the relatively low temperatures offered in the uppermost 100 m or more of the Earth´s crust. In North America, shallow geothermal technology is also known under the term "geoexchange".

For shallow geothermal, the undisturbed ground temperature that forms the basis of heat extraction or heat injection varies between <2 °C and >20 °C, depending upon the climatic condition of the region and the depth of the borehole.

To use the constant, low temperatures of the ground, there are two options:

- Increase or decrease the temperature of geothermal heat to a usable level using heat pumps (Ground Source Heat Pumps, GSHP)
- Increase or decrease the temperature in the ground by storing heat or extracting heat (Underground Thermal Energy Storage, UTES).

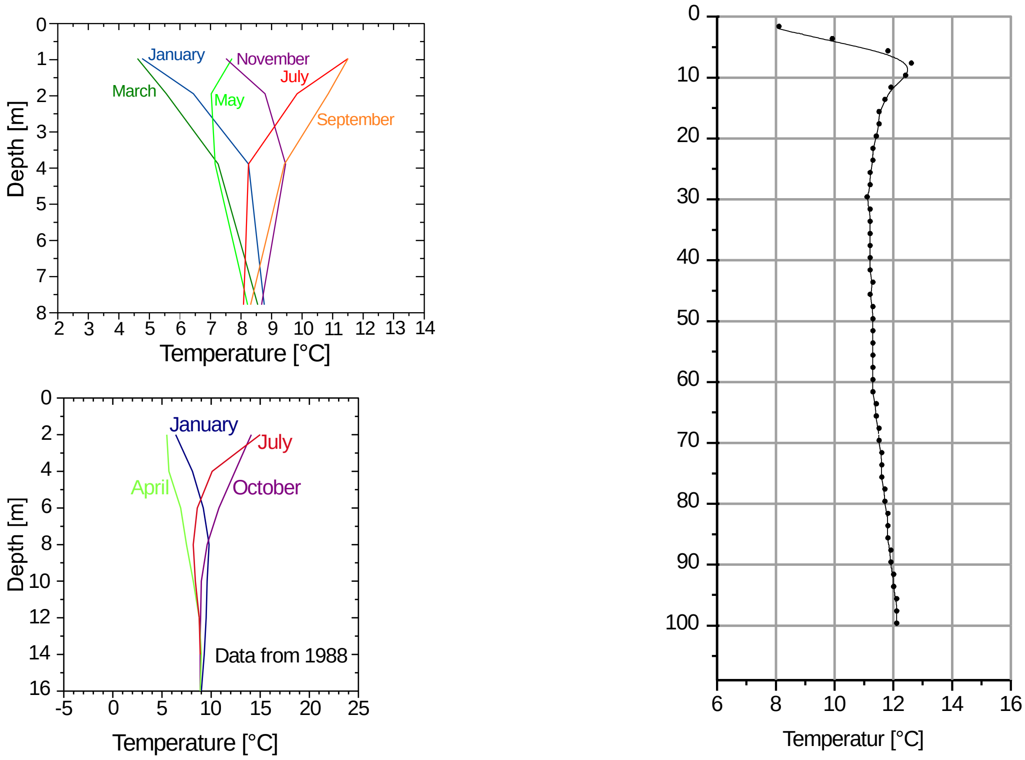

Figure 1. Constant temperature in the “Neutral Zone” at 10-20 m depth development, and temperature development down to 100 m depth (anticlockwise from top left):
measured at Royal Edinburgh Observatory, average 1838-1854 (after data from Everett, 1860);
measured at the Borehole Heat Exchanger field test station Schwalbach, Germany;
before a TRT in Germany, 2007 (courtesy of UBeG GbR)

The various shallow geothermal methods to transfer heat out of or into the ground comprise:

- Horizontal ground heat exchangers 1.2 - 2.0 m depth (horizontal loops)
- borehole heat exchangers 10 - 250 m depth (vertical loops)
- energy piles 5 - 45 m depth
- ground water wells 4 - >50 m depth
- water from mines and tunnels

Methods using a heat exchanger inside the ground are also called “closed” systems, methods producing water from the ground and having a heat exchanger (e.g. the evaporator) above ground are called “open” systems. Schematics of these methods are shown in Figure 2 and some advantages and disadvantages of closed and open systems are listed in Table 1.

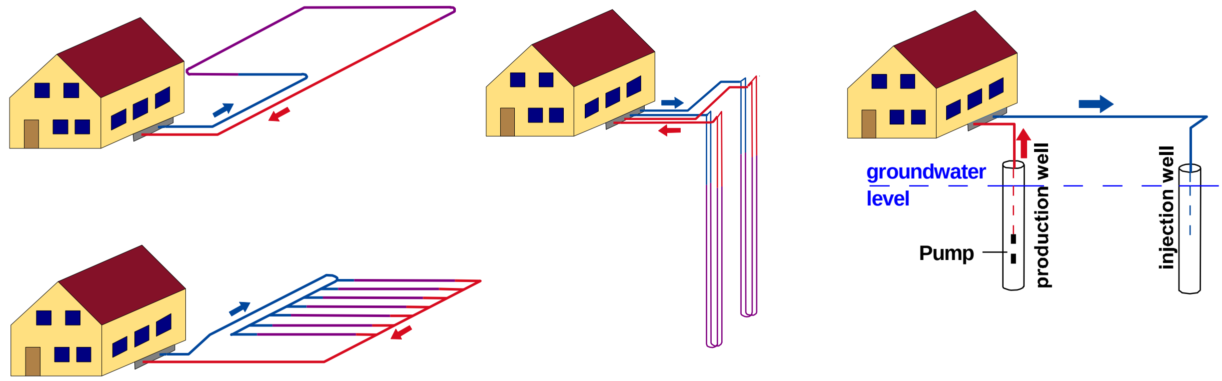

Figure 2. Schematic diagram of the most common ground-coupling methods (from left): horizontal loops, BHE (vertical loops), and groundwater wells

Groundwater wells	Borehole Heat Exchangers (BHE)
Heat transport from ground to well or vice versa by pressure difference (pumping)	Heat transport from ground to BHE or vice versa by temperature difference
Advantage: • high capacity with relatively low cost • relatively high temperature level of heat source / low level of cold source	Advantage: • no regular maintenance • safe • can be used virtually everywhere
Disadvantage: • maintenance of well(s) • requires aquifer with sufficient yield • water chemistry needs to be investigated	Disadvantage: • limited capacity per borehole • relatively low temperature level of heat source / high level of cold source

Table 1. Basic heat transport criteria and advantages/disadvantages associated with open or closed systems

While Figure 2 shows the exterior form of different ground coupling options, Figure 3 details the internal arrangements possible for closed shallow geothermal systems. They differ in the type of heat carrier medium inside the ground circuit, and in the way this circuit is coupled to the heat pump refrigeration cycle. The most common set-up is the use of a fluid as heat carrier (typically water with the addition of an antifreeze agent), which is circulated through the ground loop by pumping.

Direct expansion systems are characterized by the extension of the refrigeration cycle into the ground loop, i.e. the heat carrier is the working medium of the heat pump, and a two-phase-flow (liquid/steam) occurs inside the ground loop. In practice, direct expansion (DX) has been applied successfully to GSHP with horizontal loop, while the combination with vertical loops resulted in problems with compressor oil return, etc. The advantage of DX lies in the absence of a circulation pump and of heat exchange losses between ground circuit and refrigeration circuit; however, some of the power for circulating the refrigerant through the ground loop has to be provided by the heat pump compressor.

Heat pipes make use of a two-phase system inside a single, vertical pipe. The working medium with low boiling point is evaporated by the Earth's heat in the lower section of the pipe. The resulting steam rises to the top of the pipe due to its lower density, and transfers the heat to the refrigeration circuit via a heat exchanger. The steam thus cools down and condenses again, flowing back in liquid form on the pipe wall towards the bottom of the pipe. While both the brine systems and the DX systems can be used both for heating and cooling, the heat pipe is suitable for heating purposes only, as no heat can be transported down into the ground (the driving force is provided by gravity, which works only in one direction).

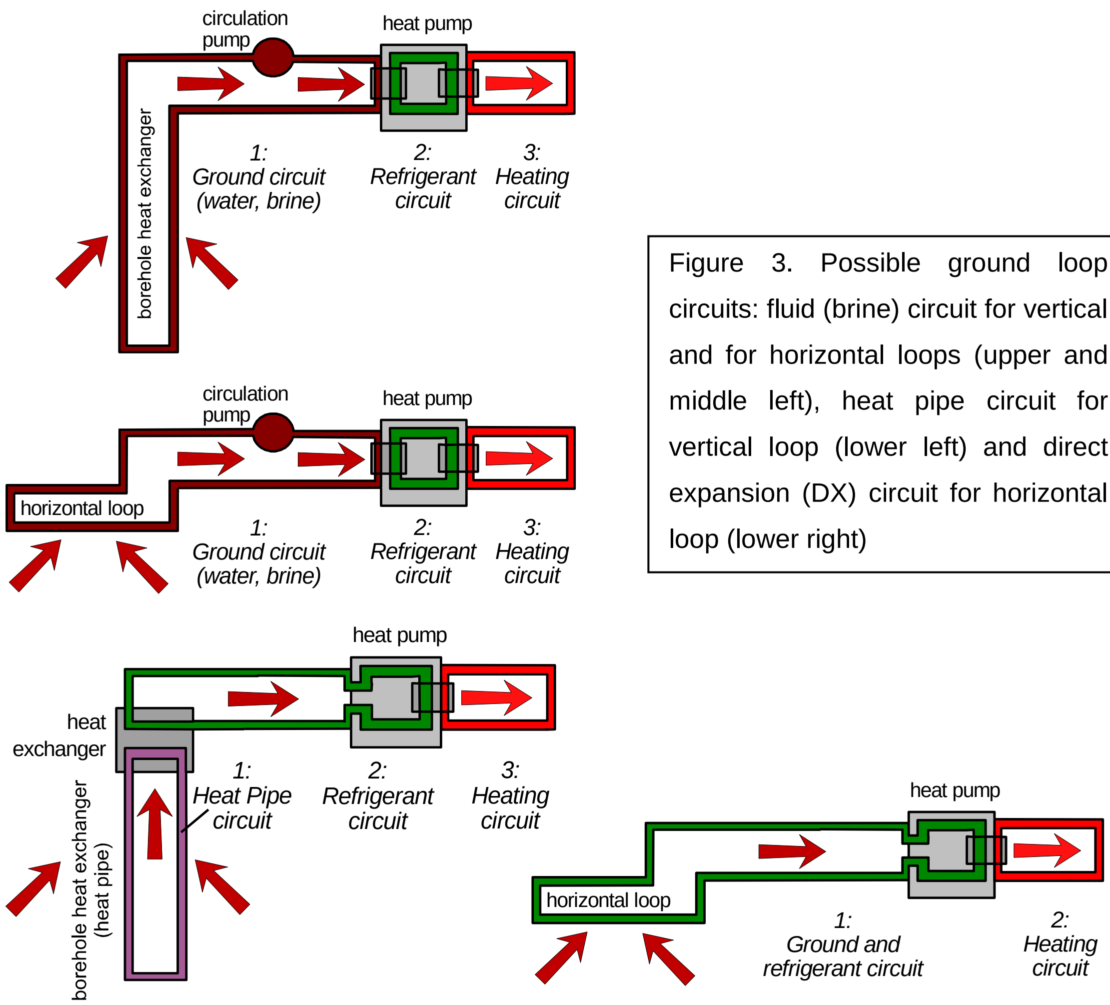

Figure 3. Possible ground loop circuits: fluid (brine) circuit for vertical and for horizontal loops (upper and middle left), heat pipe circuit for vertical loop (lower left) and direct expansion (DX) circuit for horizontal loop (lower right)

The earliest example for GSHP in literature dates from 1945 in Indianapolis, USA, and concerns a DX system with horizontal loops (Crandall, 1945). Already in 1947 an article by Kemler presented all the basic GSHP configurations we use today. In Europe (Austria, Germany, Sweden, Switzerland) the first GSHP with groundwater wells and the first horizontal loops appeared around 1970, and the first BHE before 1980.

After a short boom in these countries around 1980, associated with the second oil price crisis, the development in Europe was slow throughout the 1980s and 1990s, with the exception of

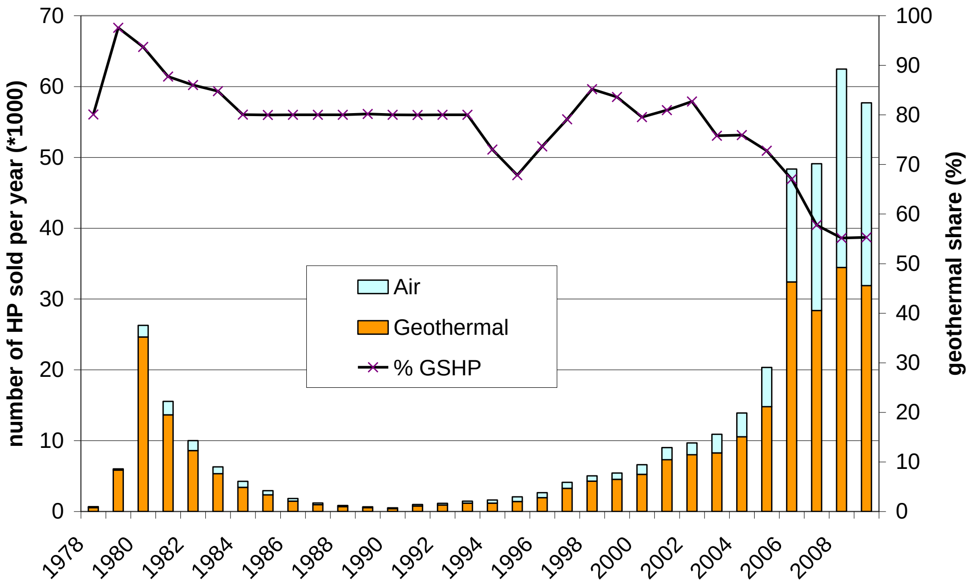

Figure 4. Development of heat pump sales in Germany (after data from BWP and GtV-BV)

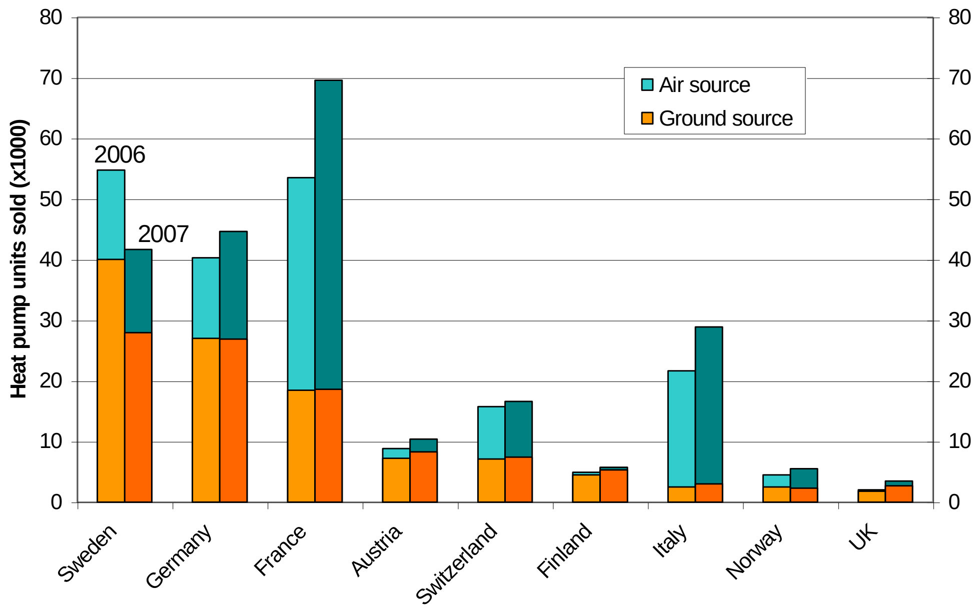

Figure 5. Heat pump sales for 2006 and 2007 in some European countries (after data from EHPA)

Sweden and Switzerland. Since about 2000 a strong market development can be seen in Germany (Fig. 4), followed by France, and now in 2010 the GSHP technology has spread to all EU countries. Figure 5 shows the heat pump units sold in some European countries in 2006 and in 2007, giving a high share for GSHP in colder regions, and a majority for air-source heat pumps in warmer lands (France, Italy).

All material for GSHP today is available from manufacturers, in proven quality: pre-fabricated BHE, grouting material, pipes, manifolds, heat pumps (Fig. 6). Methods for determining the ground parameters (thermal and hydraulic) are available (Fig. 7), design rules and calculation methods have been developed, and guidelines and standards set the frame for reliable and durable installations.

Figure 6. Examples of products for GSHP: pre-fabricated BHE, tested and delivered to the drilling site (Photos left: Haka, centre: Rehau)

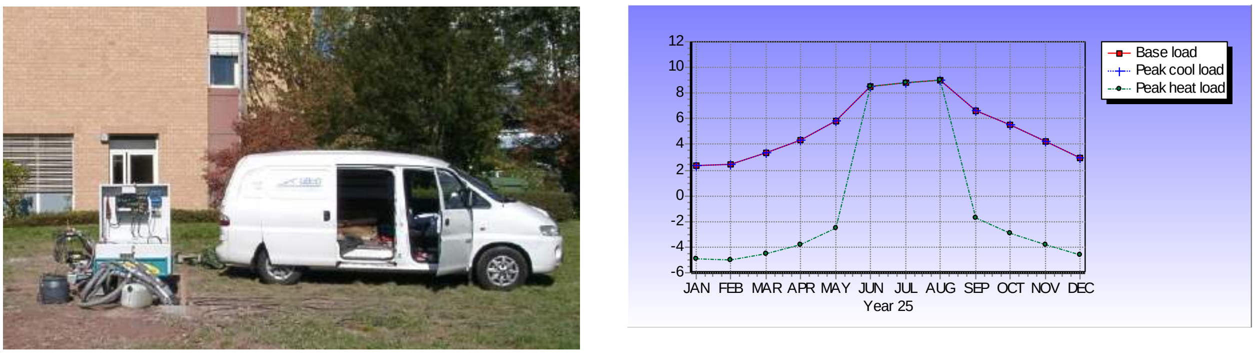

Figure 7. Example of Thermal Response Test for determining ground parameters (left) and calculation of BHE layout using EED software (right)

A useful tool for comparing different installations of BHE is the specific heat extraction rate. This is the maximum thermal capacity at the heat pump evaporator (refrigeration capacity), divided by the total length of BHE, given in Watt per Meter BHE length (W/m). In the early years of BHE in Europe around 1980, a value of 50 W/m was given as a standard value for Germany, and 55 W/m for Switzerland. These values were used for design of residential GSHP at that time – and 50 W/m is still used as a crude rule of thumb for many smaller installations today! However, the actual specific heat extraction possible in a certain project depends strongly upon ground conditions (thermal conductivity), system requirements (operating hours), system size (number and distance of BHE, interference), etc. (Sanner, 1999). So a BHE system never should be designed following a rule of 50 W/m of heat extraction, and the specific heat extraction value only used for comparison *after* a thorough design calculation has been made.

In recent times, claims by manufacturers of some new BHE types have been made for achieving specific heat extraction values of more than 100 W/m (apparently independent of any thermal properties of the underground). Using a simple consideration allows the viability of such claims to be checked.

The heat transport in a BHE system can be divided into two stages:

- the transport in the undisturbed ground around the borehole (controlled mainly by the thermal conductivity of the ground k)
- the transport from the borehole wall into the fluid inside the pipes, controlled by the type of grouting, the pipe material, the borehole and pipe geometry, etc., and given as a summary parameter r_b (borehole thermal resistance).

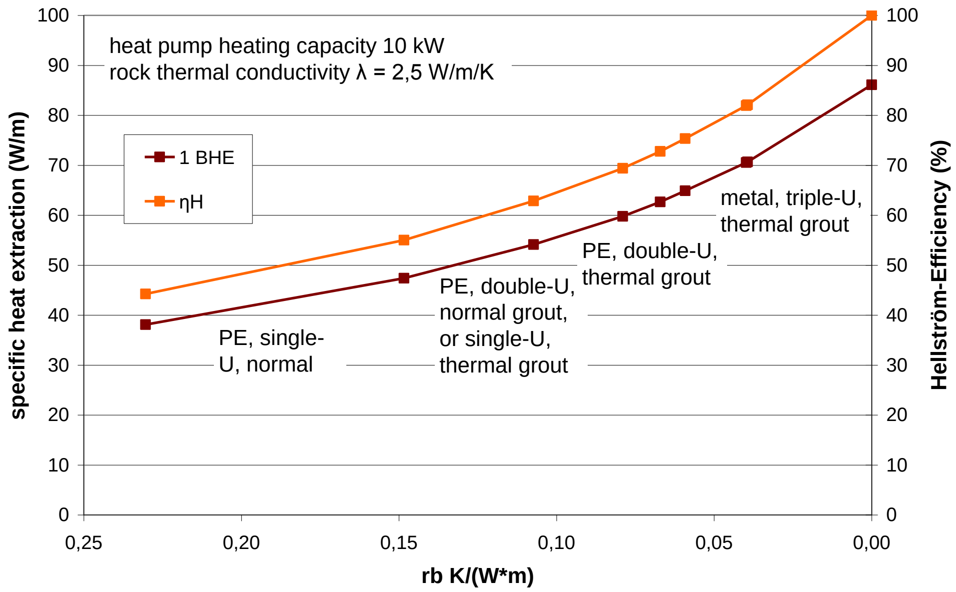

Figure 8. Specific heat extraction rates (brown curve) and Hellström-Efficiencies (orange curve) as a function of borehole resistance of different BHE types in a typical single-family house under average ground conditions; with the chosen parameters, the maximum heat extraction rate at a theoretical maximum η_H = 100 cannot exceed ca. 85 W/m

The specific heat extraction rate of a BHE can only be calculated for a certain installation, taking into account all the parameters mentioned above. A new design of BHE claiming an improvement can only influence the parameters inside the borehole, resulting in a lower value for r_b. The best BHE would be a system with r_b = 0 K(W/m), i.e. a spontaneous heat transfer between borehole wall and fluid. This can be achieved only theoretically, but can act as a benchmark for determining the efficiency of an actual BHE system. This efficiency is called Hellström-Efficiency and is given as:

η_H = sustainable heat extraction possible in a certain project/heat extraction with $r_b = 0$ where: $\eta_H = 100$ for the theoretical maximum (Fig. 8).

II. FURTHER INFORMATION

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CHAPTER 2

LIMITATIONS *by Olof Andersson*

I. INTRODUCTION

As is shown in the previous chapter, there are several different shallow geothermal systems available on the commercial market. These are, in short, ground source heat pumps (GSHP) for extraction of heat (and cold), and underground thermal energy storage (UTES) for active storage of heat and/or cold. This chapter considers the potential of these systems as well as limiting conditions when it comes to apply them in practice.

The potential is in many ways related to local or site specific conditions, not only climate and geology, but also the sector of application. The latter may be family houses, commercial and institutional buildings, district heating and cooling systems, or even industrial facilities. These all represent very different size and load characteristics in the design of a geothermal system.
The limitations can be looked upon as the outer boundary conditions that lead to a go or a no-go for project concept. They can be physical, such as climate and geological circumstances, but may also be connected to other site conditions, for example ground availability or other interests for ground use. Country specific, there are also a lot of other potential limitations. These could be of a social, cultural or political nature, but more often economical or legal. However, these limitations are flexible and may disqualify one type of system, but allow another. It is of great importance that all potential limitations are considered early (at the feasibility stage) in any project.

II. WHY SHOULD DESIGNERS AND DRILLERS CARE ABOUT A PROPER FEASIBILITY STUDY?

Properly done, any GSHP project should start up with a feasibility study. The reason for this is to create a basis for decision on how the project should be further developed. In this stage the project plan should be checked against all types of technical, economical, legal and environmental constraints that may affect the design and finalization. If a designer or a driller is not aware of the constraints and limitations, then there is a risk that a GSHP concept may turn out to be not feasible, at a late stage. This will of course lead to a dead investment for the customer and unnecessary claims on anybody involved in the realization of the plant. It may also seriously damage the reputation of and confidence for these types of systems, something that has to be avoided.

III. POTENTIAL ASPECTS

The two main renewable heat (or cold) extractions from shallow-lying geological strata are shown in Figure 1. Solar energy is the driving force of the hydrological cycle and indeed for processes that are the basis for traditional renewable energy, such as hydropower, wind and biomass.

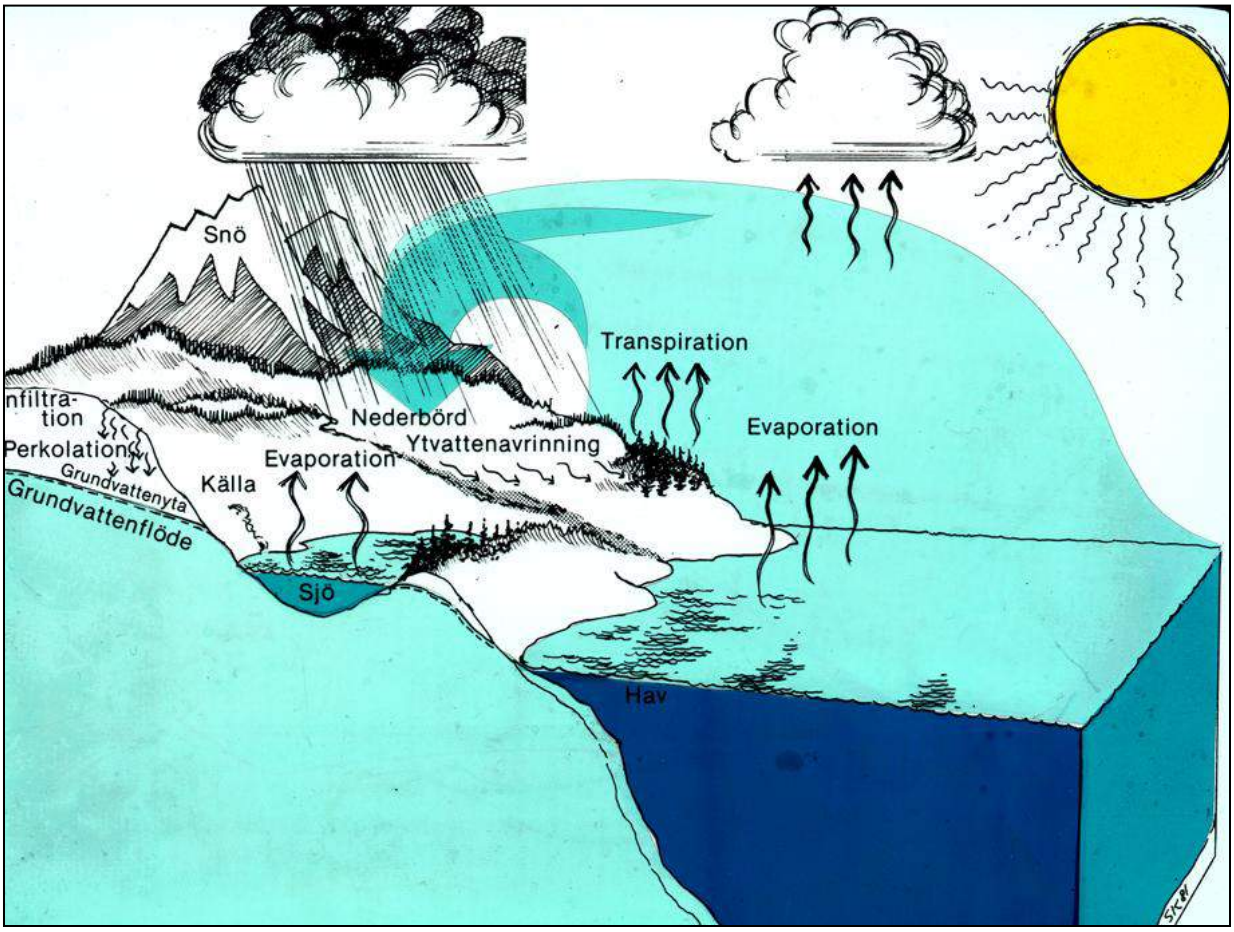

Figure 1. In the hydrological cycle all traditional renewable energy sources can be found. The geothermal heat flow is another renewable source

The average solar radiation that is adsorbed by the ground is in the order of 1500 kWh/m^2 annually, while the geothermal heat flow is restricted to some 0.6 kWh/m^2. In practice, this means that the major portion of extracted heat from the shallow underground is derived from solar energy, rather than geothermal heat from below. This basic knowledge, on how heat transfer in the underground works, suggests that shallow geothermal applications can be regarded as solar energy. For this reason the potential is huge and almost unlimited. However, putting single closed loop vertical systems too close to each other will lead to continuous chill down of the underground. Depending on geological and climate conditions and how much energy is extracted, the “safe” distance varies between 20 and 30 m.

Under normal conditions, the temperature at a depth of approximately 10 m reflects the average temperature in the air (+14.3 on average). However, at places with snow in the winter, the ground temperature will be a few degrees higher since the snow will insulate the surface. At greater depths, the ground temperature will increase due to thermal heat flow. This flow creates a geothermal gradient that on average is around 3 ^{o}C/100 m. In countries with old crystalline rocks, the gradient is often much less, while countries with clayey rocks have a higher gradient. The heat flow represents around 0.07 W/m^2. However, the variation is rather large and depends greatly on geographical position and local geological conditions.

IV. LIMITATIONS AND BOUNDARIES

IV. 1. Technical limitations

It has been shown in the preceeding section that the natural sources for GSHP systems (atmospheric and geothermal energy) are practically unlimited taking into consideration that plants are not located too close to each other. In general, the source is always there and from a technical point of view there are no limitations in using it.

For systems using the underground for seasonal (or sometimes short-term) storage of heat and cold, the source of energy for storage may be different. Such a source is for example waste heat from industrial process cooling. Another may be waste cold from heat pump evaporators. These types of sources always have technical limitations such as load, duration, temperatures, availability, etc. that are site specific. These limits should of course be established in an early stage of a given project.

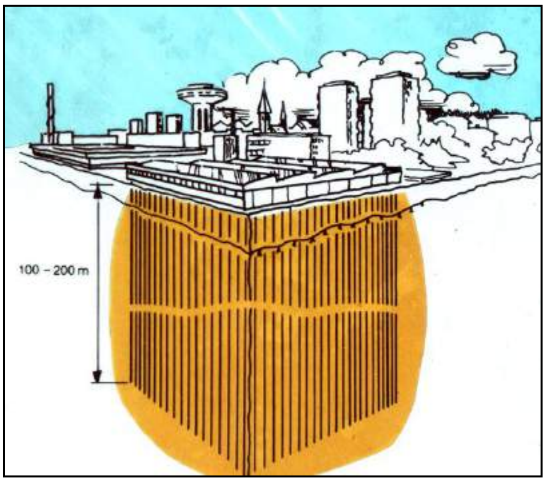

Figure 2. Technical limitations for an underground storage project may have technical limitations related to load characteristics, working temperatures, availability of energy source, etc. It is of importance to define these limitations at an early stage of the project

IV. 2. Geological limitations

In principle, one or several types of GSHP systems are technically feasible in any type of geology. It is more a matter of finding a proper construction method, related to the special geological conditions at the site for installation. Still, the geological requirements differ according to what type of system is to be installed, summarized in the following general statements.

- ***Closed loop systems*** are in general applicable in all types of geology. However, thermal properties and drilling problems may be a limiting factor

- ***Open systems*** (based on pumping ground water) require a geology containing one or several aquifers. Still, aquifer geometry, hydraulic properties and water chemistry may be limiting factors on any site.

IV. 3. Hydrogeological limitations

The hydrogeological conditions would in practice govern the design of any open loop system. Inputs, such as type of aquifer, geometry, groundwater level and gradient, textural composition, hydraulic properties and boundaries are in fact essential for the design and realization of such systems. For closed loop systems these parameters are of less importance, but can in some cases constitute limiting conditions.

- ***Closed loop systems*** may be affected by flow of ground water. For systems with heat extraction, this is normally an advantage. For systems with storage of heat and cold (BTES), it may be a disadvantage for cold extraction. Furthermore, a low groundwater level will limit the extraction of heat and cold if no backfilling is used
- ***Aquifers used for open systems*** may have a limited yield (well capacity) and/or an unfavourable chemical composition. It may also be that the size and geometry is not suitable. Furthermore, the aquifer may already be occupied by, for example, supply of drinking water. This will be a limiting factor that cannot be overcome. During such circumstances a closed loop system may or should be considered as an alternative.

IV. 4. Climate conditions

Climate plays an important role in the application of GSHP systems. There are many reasons for this, but one essential condition is that the ambient temperature of the ground is reflected by the average temperature in the air. The type of climate (tropical, arid, Mediterranean, maritime and continental) will also limit the usage of some systems (Table 1).

Climate type	**Weather conditions**	**GSHP systems**	
		GSHP	**UTES**
Tropical	Hot, no seasons	Not feasible	Not feasible
Arid	Hot, cool nights	Not feasible	Storage of cold night - day
Mediterranean	Warm Summer Mild Winter	Occasionally feasible	Seasonal storage heat and cold
Marine	Warm Summer Chilly Winter	Feasible	Seasonal storage heat and cold
Continental	Warm Summer Cold Winter	Very feasible	Seasonal storage heat and cold

Table 1. Principal feasibility for GSHP systems in different climates

Another climate factor is the humidity. In hot climates with a high humidity, there will be temperature requirement for cooling that allows condensation. In practice this means that it is not possible to directly cool a building from the ground. However, in such a case there are other technical solutions.

As indicated in Table 1, the best performance of UTES systems are linked to continental climate conditions with a seasonal swing of temperatures from summer to winter. Such conditions may also exist locally at unexpected locations, (see the example in Figure 3).

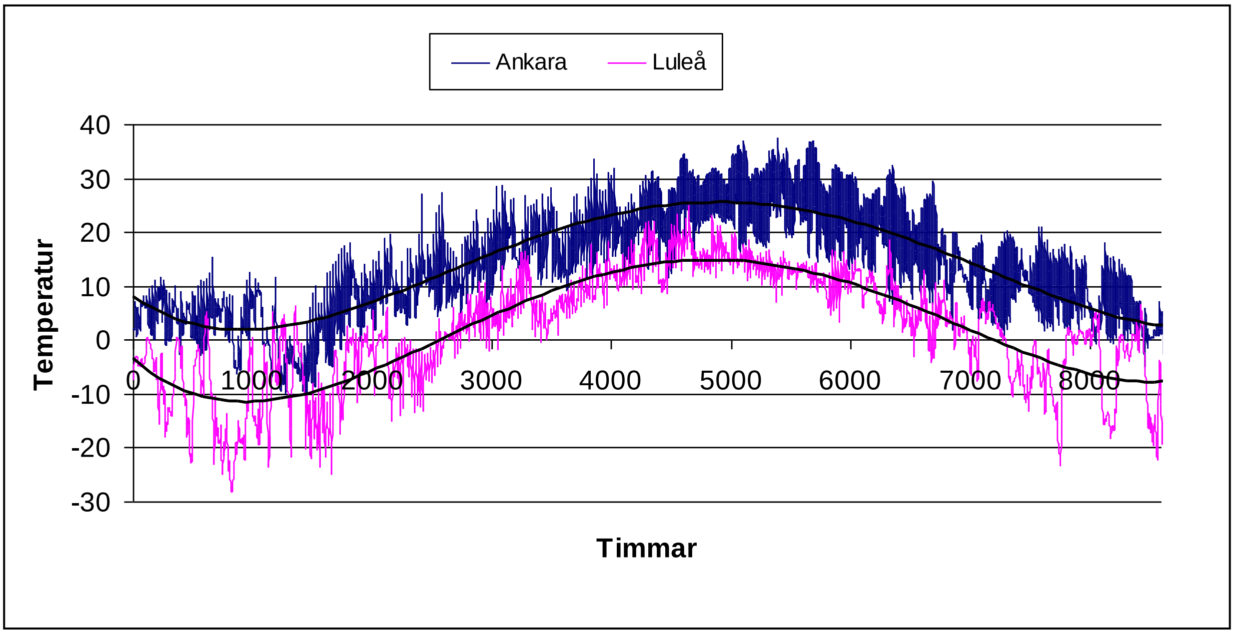

Figure 3. The climate conditions for using UTES are almost equivalent in Luleå (north Sweden) and Ankara (Turkey)

IV. 5. Environmental limitations

GSHP energy systems will in general contribute to less global emission of carbon dioxide and other harmful environmental substances. However, country specific, and maybe also locally, there may be limiting concerns such as:

- Contamination of the ground and the ground water by boreholes connecting to the surface, boreholes shortcutting different aquifers and the usage of anti-freeze
- Change of the underground temperature that may affect the chemistry and bacterial composition and growth in the underground
- Emissions, damages and local disturbances (noise, etc.) caused by drilling and construction
- Damage to buildings, fauna and flora operating the systems.

In most countries, these types of limitations are the subject for legislation. The outcome from permit applications may sometimes be that a GSHP scheme is denied by legal courts or local authorities.

In general, open loop systems are more difficult to have approved than closed loop systems. The reason is that using groundwater causes more concerns in most countries.

IV. 6. Economical limitations

In most cases, GSHP systems on the commercial market should be profitable. However, in the R&D stage, unprofitable installations can be realized as well as systems that meet environmental goals. In such cases, favourable funding will in many cases limit a less favourable economic outcome from the system. Still, from a strict commercial point of view, the cost limits can be explained as:

- The operational and maintenance costs combined must be less than for competitive systems
- The additional investment cost for the GSHP system has to be paid back by the value of saved energy and maintenance cost within the technical life time of the system
- The calculated straight pay back time varies between different sectors and different countries, but commonly 10-15 years are judged as a reasonable upper limit.

IV. 7. Legislation as a limiting factor

Legislation incorporates a complex mixture of laws, codes, standards and norms. Specifically, such regulations are more frequent in countries that already commonly use GSHP systems. In other countries there may be very limited and a type of “wild west” situation on the regulation side. This situation creates a limiting factor in itself, since the authorities do not know how to react on permit applications. Indeed, this sometimes causes good schemes to never develop further.

At this stage it seems as if the legislators do not know how to evaluate GSHP systems from a hazard point of view. Therefore, to create functional legislation in different countries, the legislator has to be more aware, informed and possibly also trained on how GSHP systems work and what they represent.

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CHAPTER 3

CONCEPT AND FEASIBILITY STUDIES *by Burkhard Sanner*

I. INTRODUCTION

For a concept study, the following questions have firstly to be answered:

- Will a Ground Source Heat Pump (GHP) with groundwater wells or Borehole Heat Exchanger (BHE) be allowed on a certain site?
- What is the underground geology in regard to thermal parameters, drilling, and environmental issues?
- What are the thermal loads to be covered?

With this data the ground-side design can be assessed in a preliminary way. For the underground data acquisition, at the concept study stage typically no investigations penetrating into the underground (drilling, geophysics) are made, in order to keep costs low.

Finally, to check the economic feasibility, we must ask:

- What are the estimated investment and operation costs?

II. POSSIBILITY FOR INSTALLATION LICENSE

This topic should be addressed first, either by consulting maps (Fig. 1) or info systems available e.g. on the internet, or by contacting the relevant authorities directly. No definite answer will be given at this stage, as authorities will not take a decision before the planning is

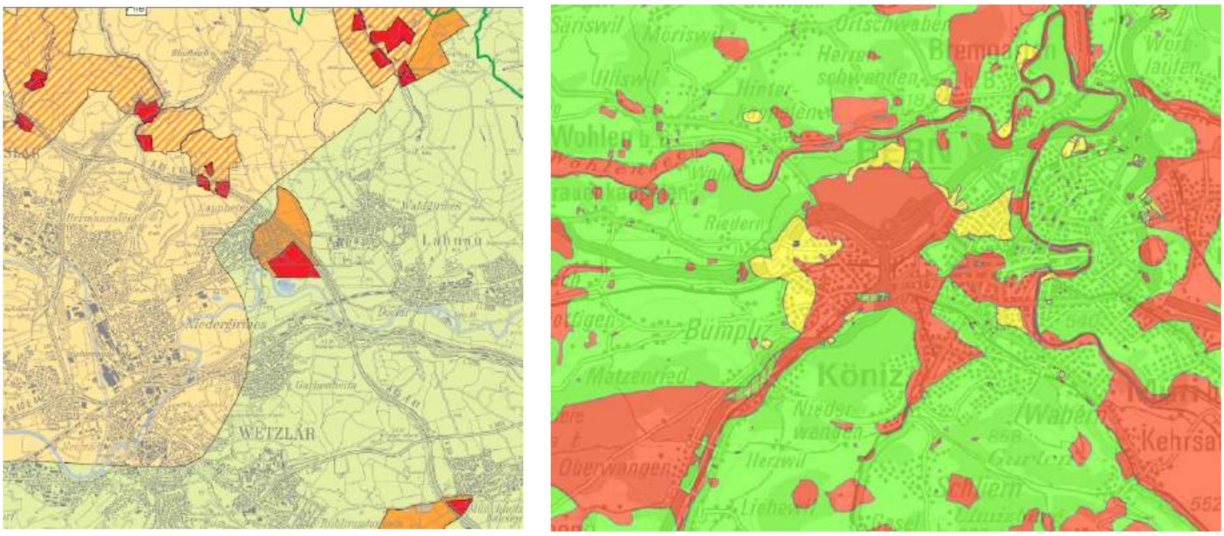

Figure 1. (left) Example of a detailed map of a small part of the German state Hessen, showing areas suitable for GHSP (green), areas requiring a case-by-case investigation and decision (light brown), and restricted areas (red); (right) a similar map for the Kanton Bern in Switzerland, from the online database: http://www.bve.be.ch/site/geo

done and submitted; however, basic obstacles like groundwater protection zones, areas with artesian aquifers, etc. can be identified quickly and a project on a site with no chance for a license can be abandoned early, before incurring too much cost. Maps or GIS databases meanwhile are available for many regions of Sweden, Germany and Switzerland; the first map was done for the Kanton Bern in Switzerland around 1990, and today the data are available as interactive GIS system (Fig. 1). In countries without sufficient published information, only the direct contact to the relevant authorities can provide the necessary information.

III. UNDERGROUND PARAMETERS

The geological situation is that part of GSHP design which cannot be changed by the planner. Hence the design needs to adapt to geology, and thus requires knowledge of geological data:

- Rock type and hardness (for GSHP drilling)
- Ground thermal characteristics (for GSHP operation)
- Groundwater situation (for GSHP drillling and operation)

For a concept study, the information can only be obtained from geological maps or neighbouring boreholes. The required data concern mainly the lithology for BHE systems and the hydrogeology for groundwater systems. From lithological information, both the preferred drilling technology and the thermal parameters can be estimated. For translating rock type into thermal parameters, a table from the German guideline VDI 4640 might help (Table 1).

	Type of rock	Thermal conductivity in W/(m·K)		Volume-related specific heat capacity in MJ/(m³·K)	Density in 10³ kg/m³
			Recommended value		
Unconsolidated	clay/silt, dry	0,4–1,0	0,5	1,5–1,6	1,8–2,0
	clay/silt, water-saturated	1,1–3,1	1,8	2,0–2,8	2,0–2,2
	sand, dry	0,3–0,9	0,4	1,3–1,6	1,8–2,2
	sand, moist	1,0–1,9	1,4	1,6–2,2	1,9–2,2
	sand, water-saturated	2,0–3,0	2,4	2,2–2,8	1,9–2,3
	gravel/stones, dry	0,4–0,9	0,4	1,3–1,6	1,8–2,2
	gravel/stones, water-saturated	1,6–2,5	1,8	2,2–2,6	1,9–2,3
	till/loam	1,1–2,9	2,4	1,5–2,5	1,8–2,3
	peat, soft lignite	0,2–0,7	0,4	0,5–3,8	0,5–1,1
Sedimentary rock	clay/silt stone	1,1–3,4	2,2	2,1–2,4	2,4–2,6
	sandstone	1,9–4,6	2,8	1,8–2,6	2,2–2,7
	conglomerate/breccia	1,3–5,1	2,3	1,8–2,6	2,2–2,7
	marlstone	1,8–2,9	2,3	2,2–2,3	2,3–2,6
	limestone	2,0–3,9	2,7	2,1–2,4	2,4–2,7
	dolomitic rock	3,0–5,0	3,5	2,1–2,4	2,4–2,7
	sulphate rock (anhydrite)	1,5–7,7	4,1	2,0	2,8–3,0
	sulphate rock (gypsum)	1,3–2,8	1,6	2,0	2,2–2,4

Table 1. Part of the table for thermal parameters as given in VDI 4640, part 1, issue 2010

In the underground, the ecological aspects are also of high importance, in respect to the protection of ground and groundwater. So possible environmental problems with GSHP on the site of the study should be investigated:

Effect on the ground and groundwater:

- leakage of antifreeze
- connecting different aquifer storeys or connecting aquifers to surface (quality of grouting / long-term tightness)
- drilling into artesian water
- thermal effects

There can also be other adverse effects due to swelling clays, anhydrite, etc.

The relevant ecological issues are further discussed in Chapter 19.

IV. BUILDING LOAD DATA

The main design criteria that should be known on the building side:

- Peak energy loads (kW) at design conditions
- Annual energy loads (MWh)
- Temperature requirements of distribution systems (heating and cooling)

A reasonable representation of the annual load variation is required. For larger projects, monthly energy loads and peak loads are minimum requirements.

The building data also comprise some information not directly linked to heat and cold demand, but to the development of the site:

- Available area for drilling
- Further limitations below or above ground

V. SYSTEM PRE-DESIGN

With the data described above, the necessary size and layout of a GSHP system can be determined. For a groundwater heat pump, 1 m^3/h of water produced from the well can provide 3.5 – 4.5 kW, as a rule of thumb. For a system with BHE, a (more conservative) estimate of the capacity of a BHE 100 m deep would be 3 - 4 kW. It is always better to make a calculation of the required borehole length e.g. with EED, but the rule of thumb can help to solve cases where not enough data are known for a reliable calculation.

Always keep in mind that such a preliminary estimation of system layout is done for a concept study only, and the proper design for the installation needs to follow and to be based upon actually measured data for ground parameters and thoroughly calculated with EED or similar programmes.

VI. ECONOMIC FEASIBILITY

For a preliminary evaluation of the economic side, a calculation of the expected investment is made:

- BHE with a unit price (e.g. 50 €/m)
- Heat Pump with a unit price (e.g. 800 €/kW)

Also the expected operation costs need to be summarized:

- Electricity consumption, electric power price (incl. special rates / off-peak)
- Maintenance and repairs

For easier comparison, calculation of the annual share of the investment and finance cost, plus the annual operation cost, is advised. Then the result is compared to the cost for investment and operation required for an alternative conventional plant.

If as a result of a concept/feasibility study there are now obstacles against drilling on a site, and if both the technical and the financial aspects of the planned GSHP system are favourable, the design can be taken a step forward to the stage of the actual filed investigations, etc.

CHAPTER 4

GROUND HEAT TRANSFER *by Burkhard Sanner*

I. INTRODUCTION

Basically there are three possible kinds of heat transfer:

- Heat Conduction
- Heat Convection
- Heat Radiation.

Inside soil and rock, heat radiation can be neglected. Hence only two transport mechanisms need to be considered. In many cases, the actual heat transfer in the underground is a mixture of both conduction and convection, in varying degrees; in solid rocks without pore space, heat transfer occurs by conduction only.

II. HEAT CONDUCTION

Heat always flows from a body with higher temperature to an area of lower temperature. The amount of heat transported is controlled mainly by two factors: the temperature difference between the areas considered, and the properties of the material in between the two areas. The ability of a material to conduct heat can be described as "thermal conductivity", given in W/m/K (or W m^{-1} K^{-1}) and is typically characterized by the letter λ. Sometimes the opposite is used, the "thermal resistance" (in particular when dealing with insulation materials); this is given in K/(W m) characterized by the letter *R*.

The parameters in heat conduction can be seen in analogy to other transport phenomena, such as electric current or hydraulics, in the following table:

Heat	Electricity	Hydraulics
Temperature difference	Voltage	Hydraulic head
Thermal conductivity	Electric conductivity	Hydraulic conductivity
Thermal resistance	Electric resistance	
Heat flow	Electric current	Fluid flow

The parameter thermal conductivity is controlled by the following components in soil and rock:

- Thermal conductivity of the solid mass (minerals or combination of minerals)
- Thermal conductivity of pore fillings
- Heat transfer at boundaries between solid mass particles, or between solid mass and pore filling.

In hard rock, only the solid mass controls the thermal behaviour of the underground. In soil, unconsolidated sediments, or rock with voids (e.g. fractures, or karst), the filling of these voids can have a substantial influence. This is also reflected in the fact that the variation of thermal conductivity in porous material is much higher than with hard rock, as the table below shows. For pores filled with air (e.g. dry gravel or dry sand), the thermal conductivity of the whole material is rather poor, while water as pore filling is much better. This is the reason why in porous materials the moisture content controls the thermal conductivity to a large extent. In hard rock, the content of quartz is a good marker for thermal conductivity, as quartz is among the frequent minerals with the highest thermal conductivity (7-14 W/m/K, dependent upon the orientation of the crystals to the direction of measurement).

	Type of rock		Thermal conductivity (W/m/K)	
				recommended
Unconsolidated rock	Clay/silt, dry		0,4 - 1,0	0,5
	Clay/silt, water saturated		0,9 – 2,3	1,7
	Sand, dry		0,3 – 0,8	0,4
	Sand, water saturated		1,5 – 4,0	2,4
	Gravel, dry		0,4 – 0,5	0,4
	Gravel, water saturated		1,6 – 2,0	1,8
	Peat, soft lignite		0,2 – 0,7	0,4
Solid Sediments	Claystone, siltstone		1,1 – 3,5	2,2
	Sandstone		1,3 - 5,1	2,3
	Conglomerates		1,3 - 5,1	2,3
	Marl		1,5 – 3,5	2,1
	Limestone		2,5 – 4,0	2,8
	Dolomite		2,8 – 4,3	3,2
	Anhydrite		1,5 – 7,7	4,1
	Gypsum		1,3 – 2,8	1,6
	Salt		5,3 – 6,4	5,4
	Hard coal		0,3 – 0,6	0,4
Magmatites	Tuff		1,1	1,1
	Vulcanite, acid to intermediate	e.g. rhyolite, trachyte	3,1 – 3,4	3,3
		e.g. latite, dacite	2,0 – 2,9	2,6
	Vulcanite, alkaline to ultra-alkaline	e.g. andesite, basalt	1,3 – 2,3	1,7
	Plutonite, acid to intermediate	Granite	2,1 – 4,1	3,4
		Syenite	1,7 – 3,5	2,6
	Plutonite, alkaline to ultra-alkaline	Diorite	2,0 – 2,9	2,6
		Gabbro	1,7 – 2,5	1,9
Metamorphic rock	Slightly metamorphic	Clay shale	1,5 – 2,6	2,1
		Chert	4,5 – 5,0	4,5
	Moderately to highly metamorphic Vulcanite, acid to intermediate	Marble	1,3 – 3,1	2,5
		Quartzite	5,0 – 6,0	5,5
		Mica schist	1,5 – 3,1	2,2
		Gneiss	1,5 – 3,1	2,2
		Amphibolite	1,9 – 4,0	2,9
		e.g. rhyolite, trachyte	2,1 - 3,6	2,9

Values for thermal conductivity can be found in several publications; a good list is given in the German guideline VDI 4640 part 1. For projects above ca. 30 kW, it is always recommended to investigate this parameter directly on site, using the Thermal Response Test (TRT, cf. chapter 8). The values in the table above are taken from VDI 4640 (issue 2010):

III. HEAT CONVECTION

Transport by convection means that heat is carried with a material of a certain temperature into areas of lower temperature. In hydrogeology, the term “convection” typically is used for the natural, vertical movement of fluids driven by density differences due to different temperatures; for the mainly horizontal fluid transport due to pressure differences in the aquifer, the term “advection” is used.

Water has a rather high specific heat capacity of about 4.2 kJ/kg/K (or 4.2 MJ/m^3/K), and thus is very well suited for convective heat transport. However, there is always an interaction of the fluid with the rock mass it migrates through, and thus a heat exchange between fluid and solid mass. As a consequence, the convective heat transport is much slower than the groundwater flow itself.

For heat transport by convection, a single parameter, like thermal conductivity in the case of conduction, cannot be given. The process is much more complex and comprises fluid properties, properties of solid mass (matrix), pore size and characteristics, hydraulic properties, etc. While conductive heat transport can be reduced mathematically in a way that it can be calculated analytically, this is hardly possible for convective heat transport. And if convective heat transport occurs, there is always a conductive component involved. Hence the calculation of convective heat transfer requires numerical simulation by coupling thermal and hydraulic models.

CHAPTER 5

DESIGN CRITERIA *by Walter J. Eugster*

I. INTRODUCTION

The most important design criteria (in addition to the start-up procedures) for ground source heat pump systems are the following:

- High performance
- High reliability
- High system safety
- Cost effectiveness.

Beside these items, there is a main maxim to follow in the design procedure: simplicity. The systems should be as simple as possible. This maxim helps to minimize many of the possible system faults during operation.

A **high performance** of the GSHP installation must be achieved. The aim of high system efficiency is, on the one hand, to minimize the operational costs and, on the other hand, to compensate for the losses in the electricity generation process. The electricity generation efficiency may differ from country to country and may even be sometimes a local matter. To satisfy climate targets, the newly installed GSHP systems have to over-compensate the generation losses, both current and future.

II. FUNDAMENTALS

Planners and designers must be aware that there is an enormous difference between the lifetimes of the underground elements of the system and the installations in the plant room of the building.

The heat pump, the circulation pumps and most of the other important system parts are changed two to three times during the lifetime of the underground installations. Therefore, the borehole heat exchangers have to work with up to three new generations of heat pumps. This is the reason why another important design maxim should be followed: a borehole heat exchanger is never too long.

On the technical side, a high system performance is achieved by keeping the temperature difference between the heat source and the heat load as small as possible and by minimizing all possible losses, including energy, pressure and temperature.

GSHP systems do not need any periodical maintenance work; such systems are intended to be maintenance free. To achieve **high system reliability** over the lifetime of the whole system is no longer a sole question of proper design. Much more important are:

- the installation work
- the commissioning
- overall quality control
- installation should use only certified, tested and approved material and system parts.

To guarantee **high system safety**, both installation and the future operation have to follow exactly any manufacturers' and authorities' instructions and specifications. It is highly recommended that safety and hazard notices are placed and displayed near to the main system components.

III. COST EFFECTIVENESS

This is always important, although it can be a risky and a double-edged entity. Cost effectiveness with GSHP systems means avoiding any unnecessary costs. It does not mean lowering the overall costs by lowering the required quality of the installation or of parts of it. There are a few rules for keeping costs low and at the same retaining high overall quality:

- Install a GSHP system only in energy refurbished buildings
- Include not only the installation costs but also all maintenance and operational costs in an overall cost compilation
- Include CO_2 savings in the system benefits
- Set the inevitable GSHP implied extra costs off against "weak accounts" like environmental consciousness or green image building or against "hard accounts" like gaining in-house room for other activities or the value of specially designed wall/floor tiles, over-designed kitchens, etc.

It can be noted that, in Switzerland, 80% of the new-built small houses are equipped with a heat pump – because of the market. In greater urban areas, nobody wants to buy a house without a heat pump so that the lack of a heat pump lowers the price of a building significantly.

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CHAPTER 6

BOREHOLE HEAT EXCHANGERS *by Göran Hellström*

I. INTRODUCTION

For single-family houses and other small-scale applications the purpose of the ground-source heat pump is basically to use the natural ground temperature as a heat source during the heating mode and as a recipient of heat during the cooling mode. The ensuing change of ground temperature around the boreholes should be kept small in order to avoid reduced performance of the system. A maximum thermal interaction with the surrounding ground is desired, since the intention is to dissipate the thermal energy in the ground. The ground is also used for storage of thermal energy (Underground Thermal Energy Storage) in which case the thermal interaction with the ground surrounding the storage volume ground is undesirable.

An important issue in the design of systems using borehole heat exchangers is to identify cost-effective methods to construct the borehole heat exchanger so that heat can be injected or extracted from the ground without excessive temperature differences between the heat carrier fluid and the surrounding ground. The efficiency of a ground-source coupled device, such as a ground-source heat pump (both in heating and cooling mode), free-cooling heat exchanger or solar collector recharge is higher for smaller temperature differences. This chapter presents an overview of different designs of borehole heat exchangers (BHEs).

II. CONCEPTS

We begin with a brief description of the basic thermal processes involved when heat is transferred between the circulating heat carrier fluid in flow channels in the boreholes and the surrounding ground.

II. 1. Fluid-to-ground thermal resistance

The heat transfer between the heat carrier fluid and the surrounding ground depends on the arrangement of the flow channels, the convective heat transfer in the ducts, and the thermal properties of the materials involved in the thermal process. The thermal resistances associated with these different elements combine to form a fluid-to-ground thermal resistance. The two major parts of this resistance are the thermal resistance between the heat carrier fluid and the borehole wall, which is commonly called the borehole thermal resistance, and the thermal resistance of the surrounding ground from the borehole wall to some suitable average temperature level. The influence of the borehole thermal resistance may become relatively large in conventional designs. This is especially crucial in applications with high demands on heat injection rates and high temperatures such as solar heating systems and low temperature applications with high demands on achieving high heat transfer rates at small temperature differences.

II. 2. Ground thermal resistance

The ground thermal resistance involves the surrounding ground from the borehole wall to some suitable average temperature level. This temperature level is often chosen to be the natural undisturbed ground temperature T_0 in systems of the dissipative type, whereas the local average ground temperature T_m is more appropriate in storage applications.

II. 2. 1**. *Dissipative type applications***

For dissipative type applications, the thermal process in the ground has a genuine transient behaviour that has to be accounted for. It is convenient to consider the thermal response due to a step-change in specific heat injection rate q (W/m) given per unit length of the borehole and to associate the temperature evolution with a time-dependent ground thermal resistance R_g, so that $T_b - T_0 = q R_g$

Where T_b is the temperature in the borehole wall.

Thereby the unit of the ground thermal resistance R_g becomes K/(W/m) (Fig. 1).

II. 2. 2**. *Storage type applications***

In storage type applications a certain ground region can be assigned to each ground heat exchanger. The temperature in this ground region is called the local average temperature T_m. The thermal resistance R_g between T_b and the local average temperature T_m is defined by:

$$T_b - T_m = q R_g.$$

For relatively closed spaced boreholes, the thermal interaction between adjacent boreholes is fully developed for heat injection and extraction pulses with duration of about a week or more. Short-term variations, where the thermal interaction between adjacent boreholes typically can be neglected, are superimposed on this process. The relative importance of the borehole thermal resistance is larger for storage type applications (Fig. 2).

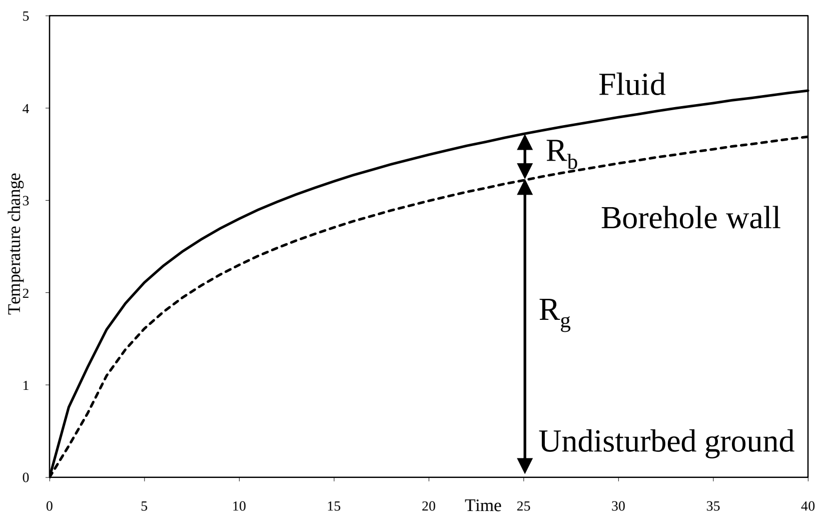

Figure 1. Dissipative system: Temperature change (° C) due to borehole thermal resistance and ground thermal resistance for a constant heat injection rate. The undisturbed ground temperature is used as a reference temperature

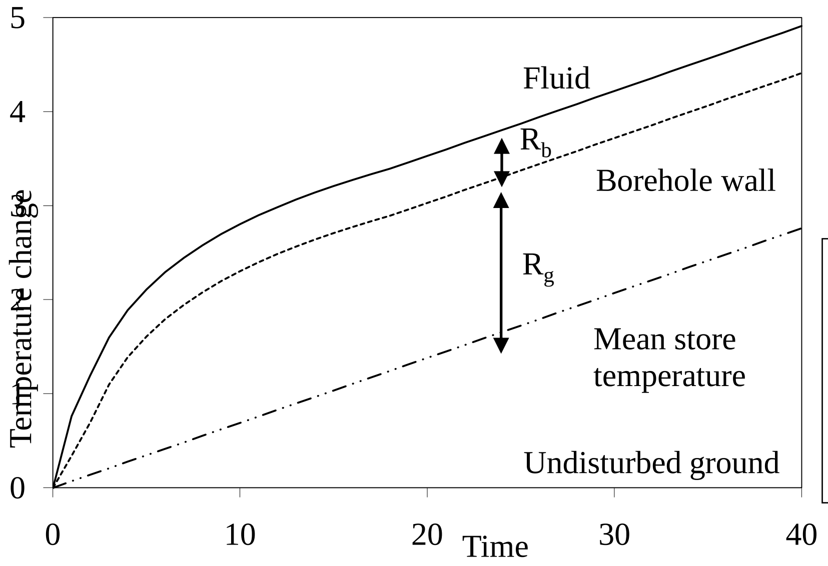

Figure 2. Storage type system: Temperature change due to borehole thermal resistance and ground thermal resistance for a constant heat injection rate. The mean storage temperature is used as the reference temperature

II. 3. Borehole thermal resistance

An important factor for the design of borehole systems is the thermal resistance between the heat carrier fluid in the borehole flow channels and the borehole wall. The fluid-to-borehole wall thermal resistance gives the temperature difference between the fluid temperature in the collector (T_f) and the temperature at the borehole wall (T_b) for a certain specific heat transfer rate q (W/m):

$$T_f - T_b = R_b \cdot q$$

This so-called borehole thermal resistance depends on the arrangement of the flow channels and the thermal properties of the materials involved. The values observed in field tests range from 0.01 K/(W/m) for the open coaxial arrangement (heat carrier fluid in direct contact with the rock) to about 0.25 K/(W/m) for single U-pipes in bentonite grout where no special precautions have been made to keep the pipes close to the borehole wall. The temperature difference between the heat carrier fluid and the borehole wall is proportional to the heat transfer rate. For a typical heat transfer rate of 50 W/m, the corresponding temperature difference becomes 0.5 ºC to 12.5 ºC. The borehole thermal resistance may have significant effect on the system performance and should be kept as small as possible. Filling materials (e.g. bentonite, concrete, etc.) in grouted boreholes usually provide better heat transfer than pure stagnant water. However, in water-filled boreholes, the heat transfer induces natural convection in the borehole water and in the surrounding permeable ground. This phenomenon, which is more pronounced at high temperatures and large heat transfer rates, leads to a reduction of the overall borehole thermal resistance. The overall thermal performance of the borehole field subject to a certain heat load variation depends not only on the borehole thermal resistance, but also on the transient thermal resistance of the surrounding ground and the thermal influence from other boreholes.

II. 4. Heat transfer between flow channels

The fluid temperatures along the flow channels will vary in accordance with the heat balance between the axial convective heat transport and the transverse heat transfer to the surrounding ground. The temperature difference that arises between the upward and the downward channels may become large at low flow rates. The ensuing heat exchange between the channels of opposing flow may lead to a reduced efficiency of the ground heat exchanger. For conventional U-pipe borehole heat exchangers, these effects are usually important when the flow is laminar, especially in combination with deep boreholes. This effect has also been observed in coaxial borehole heat exchangers with poor insulation between inner and outer flow channels.

II. 5. Heat capacity effects in the borehole

When a step change occurs in the heat transfer to a BHE, it causes a rapid increase of the temperature of the heat carrier fluid. A large fraction of the supplied heat is initially absorbed by the fluid and subsequently by other capacitive materials in the borehole such as the filling material outside the flow channels. After an initial phase, the capacitive effect of the borehole is practically negligible, and almost all of the supplied heat is transferred to the ground. Short-term pulses often require that the influence of the borehole heat capacity is accounted for.

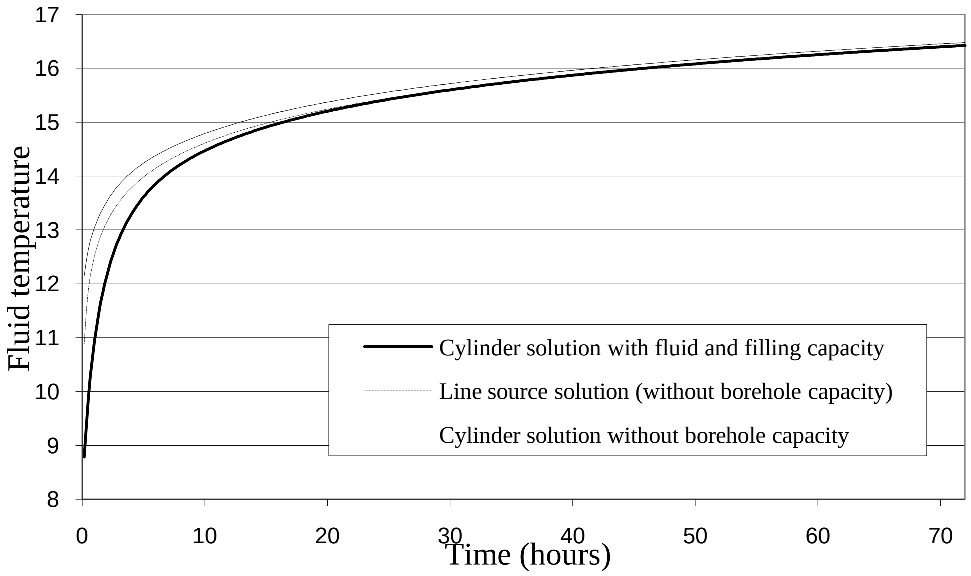

Figure 3. Fluid temperature increase as a function of time (hours) for a case based on data from a thermal response test. The initial ground temperature is 8 ºC

Otherwise, the calculated fluid temperatures will be too high (during injection of heat) or too low (during extraction of heat). This is especially important if there is a large thermal resistance between the borehole heat capacity and the borehole wall. For heat injection pulses of longer duration, the influence of the borehole heat capacity can usually be neglected.

Figure 3 shows a numerical example based on typical data from a thermal response test where a constant heat injection rate is supplied to the borehole. Such tests are commonly evaluated using a line source or cylinder source model. The example indicates that the heat capacities of the fluid and filling material have an important influence at least during the first 10 -15 hours, which is the reason why measured data from the first 15 hours are excluded during evaluation of the test results.

III. DIFFERENT DESIGNS OF BOREHOLE HEAT EXCHANGERS

Vertical ground heat exchanger piping configurations can be classified based on how the heat exchange from the flow channels takes place and to their cross-sectional geometry.

Figure 4 shows the two fundamental designs.

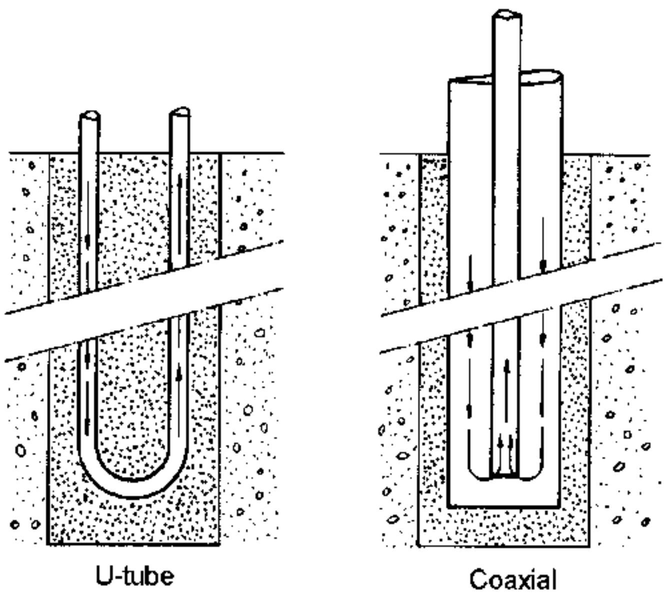

Figure 4. The two fundamental borehole heat exchanger designs

In the U-pipe type BHE, both the downward and the upward flow channels participate in the heat exchange with the surrounding ground. The characteristics of the coaxial (or tube-in-tube) type BHE is that heat exchange occurs from either the upstream or downstream flow channel (the flow direction may also be different during injection or extraction of heat). The inner return pipe is (ideally) insulated in order to avoid thermal short-circuiting between the upwards and downwards flow channels. In this section examples will be given of borehole heat exchangers intended to operate according to these two fundamental concepts. Most designs use closed circuits, which means that the heat carrier fluid is never in direct contact with the surrounding ground. A few designs permit such direct contact, thereby possibly minimizing the thermal resistance between the heat carrier fluid and the ground.

III. 1. Coaxial type BHE

Characteristics of the coaxial type BHE is that heat exchange between fluid and ground occurs from either the upwards or downwards flow channel.

III. 1. 1**. *Coaxial BHE without liner***

The simplest arrangement of the flow channels in a borehole heat exchanger is to insert a single plastic tube to the bottom of the borehole. The annular region between the plastic tube and the borehole wall provides the channel for the returning flow. This type of open borehole heat exchanger is very favourable from a heat transfer point of view because the heat transfer fluid can be in direct contact with the borehole wall. In the US, this arrangement is also called a standing column well. The surrounding rock may be permeable, in which case secondary circulation of the fluid in the formation contributes to the heat dissipation.

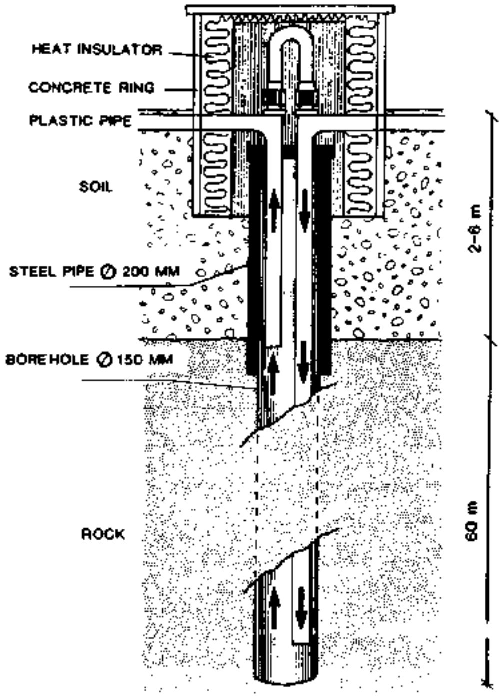

Figure 5. Coaxial BHE without liner (Luleå, Sweden)

III. 1. 2**. *Coaxial BHE with tube-in-tube***

A closed system is often required due to unstable borehole walls or because of geochemical concerns. A closed annular duct can be realized by lining the borehole with an impermeable material. Inserting and cementing PVC-tubes (or steel tubes) in boreholes is rather difficult and expensive compared to U-pipes, so this method has only been used a few times in relatively shallow boreholes in crystalline rock. Due to the considerable thermal resistance of the filling material between the outer pipe and the borehole wall, the measured borehole thermal resistance for these arrangements have been similar to those of the simpler single U-pipes. However, in deep clay formations the vertically pushed coaxial tube has been used to more advantage, since the clay around the outer pipe will in most cases eventually conform to the pipe surface (there is no “filling” material).

III. 1. 3. ***Coaxial BHE with soft liner***

There is also a possibility of using a flexible soft liner, which after insertion will be pushed against the borehole wall when the interior is filled with fluid. The advantage of this design is that there is no filling material between the liner and the borehole wall. However, several field tests have revealed problems with leakage.

III. 1. 4. ***Multichamber BHE***

The outer heat exchanging flow channel can be divided into many smaller chambers (Fig. 6). Due to the thermal resistance of the filling material between the exterior of the pipe and the borehole wall and possible thermal short-circuiting between the inner and outer flow channels, the efficiency of this design is similar to U-pipes.

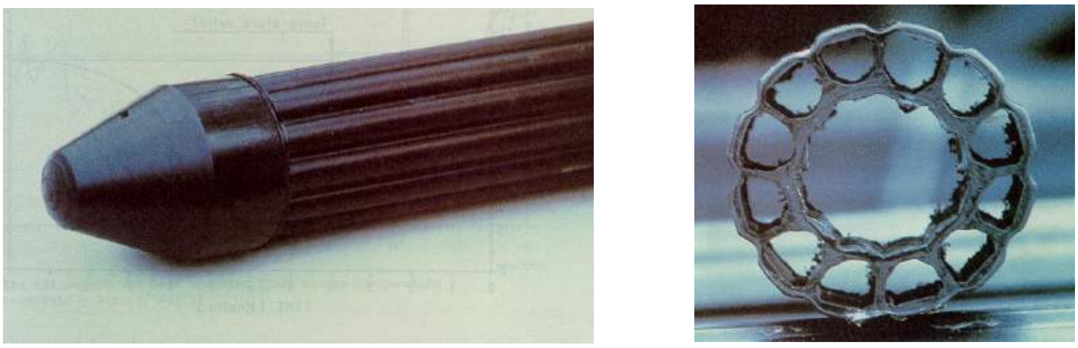

Figure 6. Multichamber BHE (Burgdorf, Switzerland)

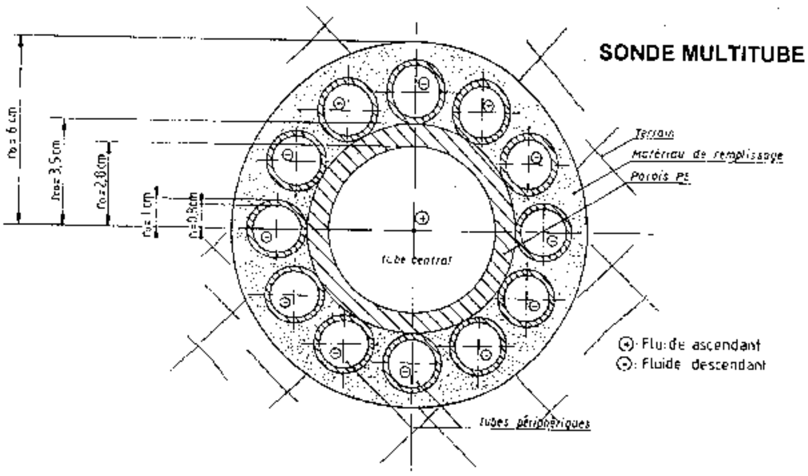

Figure 7. Multipipe BHE. Example with 12 peripheral supply polyethylene pipes (diameter 20 mm) and one central return pipe (diameter 70 mm) in an unlined borehole (diameter 120 mm) (Mathey, Switzerland)

III. 1. 5. ***Multipipe BHE***

The outer heat exchanging flow channel can also be assembled with many smaller pipes (Fig. 7). Field tests have shown that this arrangement of the flow channel can achieve high performance. The flow channels are standard polyethylene pipes of different sizes. There are currently no commercial products of this type available on the market. The challenges are the insulation of the inner pipe, the design of the bottom piece, the installation procedure and the overall costs.

III. 2. U-pipe type BHE

The usual method to achieve the heat exchange in a borehole is to insert one or more U-shaped loops of polyethylene tubing into the borehole. Single U-pipes are used in Northern Europe and North America, whereas double U-pipes are common in Central Europe. In Northern Europe, the boreholes are usually filled with groundwater to a few meters below the ground surface. In the US and in Central Europe it is common practice, and often required, to backfill the boreholes with some sealing material such as bentonite, concrete or quartz sand. Special mixtures, so-called thermally enhanced grouts, have been developed to provide for better heat transfer than pure bentonite.

III. 2. 1**. *Single U-pipe***

The single U-pipe has been the industry standard for about 30 years. The main advantages are the simplicity of the design, ease of transportation and straightforward installation compared with other alternatives. An installation based on proven best-practice procedures

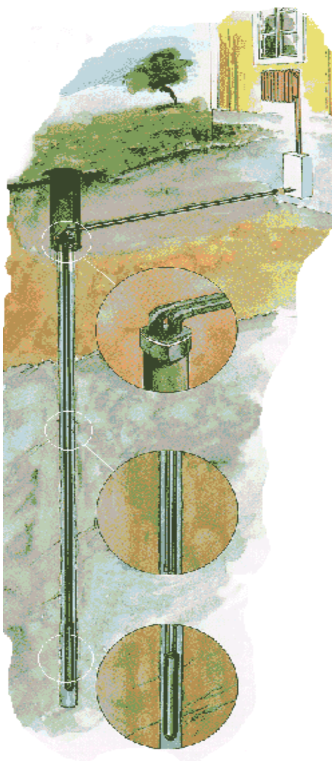

Figure 8. Single U-pipe with bottom piece including weight

has an almost unlimited lifetime. The main problems have involved leakage due to improper fusing of U-bends and weak bottom pieces. The major disadvantage of the single U-pipe is the relatively poor heat transfer capacity, especially at non-turbulent flow conditions.

III. 2. 2**. *Single U-pipe with spacers***

The thermal performance of the single U-pipe is increased if the pipes are positioned close to the borehole wall. This can be accomplished by the use of so-called spacers. Examples of such devices are shown in Figures 9 and 10.

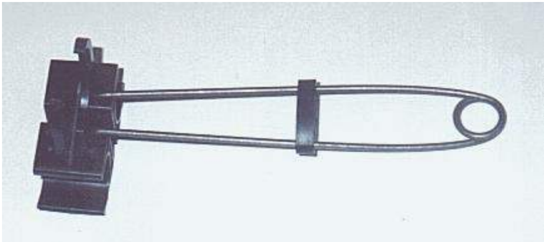

Figure 9. Single U-pipe with spacer (GeoClip, GBT Inc.): the spacer's spring-action is released as the tremie pipe (middle pipe in left figure) is pulled up

III. 2. 3**. *Multitube U-pipes***

Figure 10. Double U-pipe with spacers (Neckarsulm, Germany)

Double, triple and multitube U-pipes are simple extensions of the single U-tube concept. The main advantages of multitube arrangements compared with single U-tubes are that the effective heat transfer area increases and that the influence of the relatively large thermal resistance of the plastic tubes decreases.

The influence of the convective heat transfer coefficient also decreases, which means that the importance of non-laminar flow at design loads is somewhat less critical. This may then allow for slightly lower pressure drops across the borehole heat exchangers in order to achieve a certain heat transfer rate.

III. 2. 4**. *Three pipe arrangements***

A variation of the U-pipe borehole heat exchanger is an arrangement with two pipes in one direction and one pipe in the other direction. It was used in the early 1980s when ground-source heat pumps were being introduced in Sweden, but soon disappeared from the market due to the complexity of the design.

IV. THERMAL PERFORMANCE OF U-PIPE TYPE BHE

In this section we will take a closer look at the thermal performance of the most common type of borehole heat exchanger – the U-pipe. The most important parameters influencing the borehole thermal resistance are fluid flow rate, pipe material, number of pipes, pipe position, and thermal conductivity of filling material.

IV. 1. Pipe material

The U-pipes for normal applications use polyethylene pipes. These are flexible and durable. However, the thermal resistance of the pipes is relatively high, especially with the thicker walls of the SDR-11 and PN12 pipes (Table 1). The pressure rating refers to a temperature of 20 ^oC. The strength improves with lower temperatures, but reduces with higher temperatures. Other materials have to be considered when the pipes are exposed to higher temperatures than 30-40 ^oC. The polybutylene pipes have been used in high-temperature applications.

Type	Material	Outer diameter (mm)	Wall thickness (mm)	Thermal cond. (W/(m,K))	Thermal resistance (K/(W/m))
PE DN25 PN8	Polyethylene	25,0	2,0	0,42	0,066
PE DN32 PN8	Polyethylene	32,0	2,0	0,42	0,051
PE DN40 PN8	Polyethylene	40,0	2,3	0,42	0,046
PE DN50 PN8	Polyethylene	50,0	2,9	0,42	0,047
PE DN20 PN12	Polyethylene	20,0	2,0	0,42	0,085
PE DN25 PN12	Polyethylene	25,0	2,3	0,42	0,077
PE DN32 PN12	Polyethylene	32,0	3,0	0,42	0,079
PE DN40 PN12	Polyethylene	40,0	3,7	0,42	0,078
PE DN50 PN12	Polyethylene	50,0	4,6	0,42	0,077
SDR-11 3/4"	Polyethylene	26,7	2,5	0,42	0,079
SDR-11 1"	Polyethylene	33,4	3,0	0,42	0,075
SDR-11 1-1/4"	Polyethylene	42,2	3,9	0,42	0,077
SDR-11 1-1/2"	Polyethylene	48,3	4,4	0,42	0,076
SDR-11 2"	Polyethylene	60,3	5,5	0,42	0,076
SDR-13.5 1"	Polybutylene	28,6	2,2	0,22	0,121
SDR-13.5 1-1/4"	Polybutylene	34,9	2,6	0,22	0,117
SDR-13.5 1-1/2"	Polybutylene	41,3	3,1	0,22	0,118
SDR-13.5 2"	Polybutylene	54,0	4,0	0,22	0,116

Table 1. Properties of plastic pipes used for ground loops

IV. 2. Filling material

A vertical borehole may require that some kind of backfilling material is used to fill the space between the flow channels and the borehole wall. One reason may be to provide a good thermal contact with the surrounding ground due to low thermal conductivity of natural filling material or low ground water level. Another important issue is to seal the borehole to limit vertical water movement along the borehole that may cause environmental problems, such as migration of polluted water, drainage of soil layers near the ground surface and disturbance of the hydraulic characteristics of artesian formations.

Special grouts are used to provide a low permeability suitable for sealing the borehole. It is important that these grouts have the capability to bond against both the borehole wall and the pipes. The mixtures must be workable and pumpable during installation with little shrinkage during curing. If shrinkage occurs, there may be the potential for a fluid migration pathway. Common grouts, such as bentonite, usually have low thermal conductivity. Special thermal grouts have been developed to enhance the thermal conductivity. Use of a commercial ready-mixed product is strongly recommended. The thermal conductivity of some common filling materials are given in Table 2.

Material	Thermal conductivity (W/m,K)
Sand, gravel – dry	0,4
Water (stagnant)	0,6
Bentonite 10 %, water	0,7
Bentonite/cement/sand, 9/9/20 %, water	0,7-0,8
Sand, moist	1,0
Bentonite 10 %, frozen	1,4
Bentonite/quartzsand, 12/50 %, water	1,5
Gravel, water-saturated	1,8
Ice	2,3
Cement/sand, 27 %/58 %, water	2,4
Quartzsand, water-saturated	2,4-2,7
ThermoCem (cement/graphite)	2,0

Table 2. Thermal conductivity (W/m,K) of borehole filling materials

Grout should preferably be placed in the borehole by pressure pumping through a tremie pipe (after water or other drilling fluid has been circulated in the annular space sufficient to clear obstructions) in order to avoid bridging and voids. In the US, the recommended procedure is to lower the tremie pipe to the bottom of the zone being grouted, and then raise it slowly as the material is introduced. In Europe, the recommendation is to perform the grouting without raising the tremie pipe and then to leave it in place.

A grout with high thermal conductivity significantly reduces the borehole resistance. As the total temperature difference between the heat carrier fluid and the undisturbed ground depends on the combined borehole and ground thermal resistance, it has been found that the greatest reduction in required borehole length of the ground loop occurred with the higher ground thermal conductivity values. Where grout and ground thermal conductivities are similar, the borehole diameter is not a critical factor for the performance of the borehole heat exchanger. If the ground thermal conductivity is higher than the grout thermal conductivity, a greater borehole diameter will yield a higher combined borehole and ground thermal resistance. Smaller boreholes require less grout and have a lower total resistance, which indicates that the borehole diameter has an economic impact. Determining the optimum grout for a given project will require actual costs for grout, pipes and drilling

IV. 2. 1**. *Cementitious grouts***

- Advantages: Suitable permeability, easily pumped and mixed, suitable for most formations, properties can be altered with readily available additives
- Disadvantages: Shrinkage, long curing time, high density results in loss to formation, heat of hydration, affects water quality.

IV. 2. 2**. *Bentonite grouts***

- Advantages: Suitable permeability with high solids grouts, non-shrinking and self-healing in water-satured environment, no heat of hydration, low density, no curing time
- Disadvantages: Premature swelling, high viscosity, high density results in loss to formation, high viscosity, difficult mixing, large shrinkage in dry environment.

One serious drawback of the bentonite grout is the strong sensitivity to frost action. When the water first freezes and then thaws the bentonite loses it adsorption property and the water separates from the mixture. The previously firm bentonite becomes almost liquid during the thawing. Freezing a low-permeability bentonite mixture with high water content may lead to compression pressure on the pipes due to the volume expansion during the water-ice phase change. The compression may damage the pipes and cause leakage.

IV. 3. Pipe location

The borehole thermal resistance depends on the position of the U-pipe shanks in the borehole. The thermal resistance increases with distance between the pipes and the borehole wall. The thermal resistance in the filling material is inversely proportional to its thermal conductivity. Figure 11 shows the estimated borehole thermal resistance of a typical single U-pipe installation for three different positions of the shanks and filling thermal conductivity.

Three different pipe configurations are indicated: the pipes touching at the bore centre (Configuration A), the same distance between the pipes as between the pipes and the borehole wall (Configuration B), and each pipe touching the borehole wall at diametrically opposite points (Configuration C).

The A configuration gives the highest borehole thermal resistance and it is considered to be a very conservative design assumption. Configuration C is the optimum placement of the pipes, but it will not occur consistently along the borehole unless spacers are used to control the pipe spacing. Configuration B is assumed to be a reasonable design assumption in most situations without spacers.

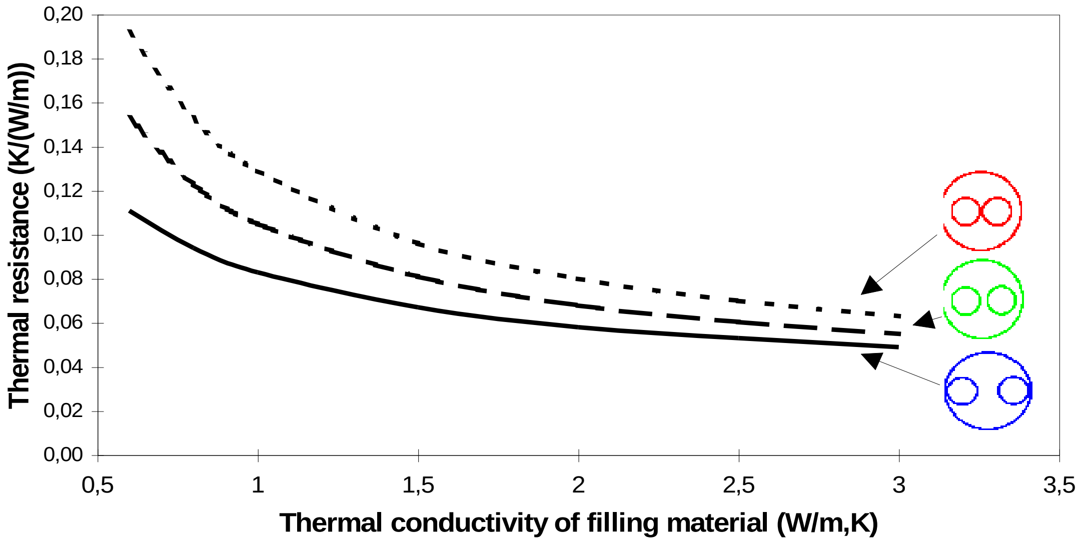

Figure 11. The borehole thermal resistance (K/(W/m) for a single U-pipe as a function of filling material thermal conductivity (W/m,K) for three different positions of the U-pipe shanks; non-laminar flow conditions (Re≈3000)

Figure 11 also illustrates the advantage of using thermal grouts (thermal conductivity 1.5 - 2.0 W/m,K) instead of standard bentonite grouts (thermal conductivity 0.7 - 0.8 W/m,K).

IV. 4. Fluid flow rate

The convective heat transfer from the bulk fluid in the pipe to the inside wall of the pipe may have a significant impact on the borehole thermal resistance. Although the equivalent thermal resistance of the convective heat transfer process is small at turbulent flow conditions, it constitutes about half of the total borehole resistance at laminar flow conditions. The influence of the internal heat transfer between the upwards and downwards flow channel, the thermal short-circuiting, can also be included in the effective borehole thermal resistance. The thermal short-circuiting increases with increasing borehole depth and decreasing flow rate. An example of the composition of the effective borehole thermal resistance as a function of the flow rate is shown in Figure 12.

The combined thermal resistance of the pipe material and the convective heat transfer inside the pipe has to be kept low. The contribution to the total borehole thermal resistance is large for single U-pipes of polyethylene, but usually decreases with number pipes in the borehole.

The borehole thermal resistance increases with decreasing flow rate due to development of laminar flow and increasing thermal short-circuiting between upward and downwards flow channels. For a given heat extraction rate, this lowers the source temperature and the Coefficient of Performance (COP) of the heat pump, which increases the amount of primary energy required to deliver a certain heating rate to the house. Higher flow rates improve the heat transfer capacity but this advantage is at some point offset by higher energy consumption by the circulation pump, which is roughly proportional to the third power of the flow rate. The pressure drop across a single U-pipe for the above example (Fig.12) is given in Figure 13.

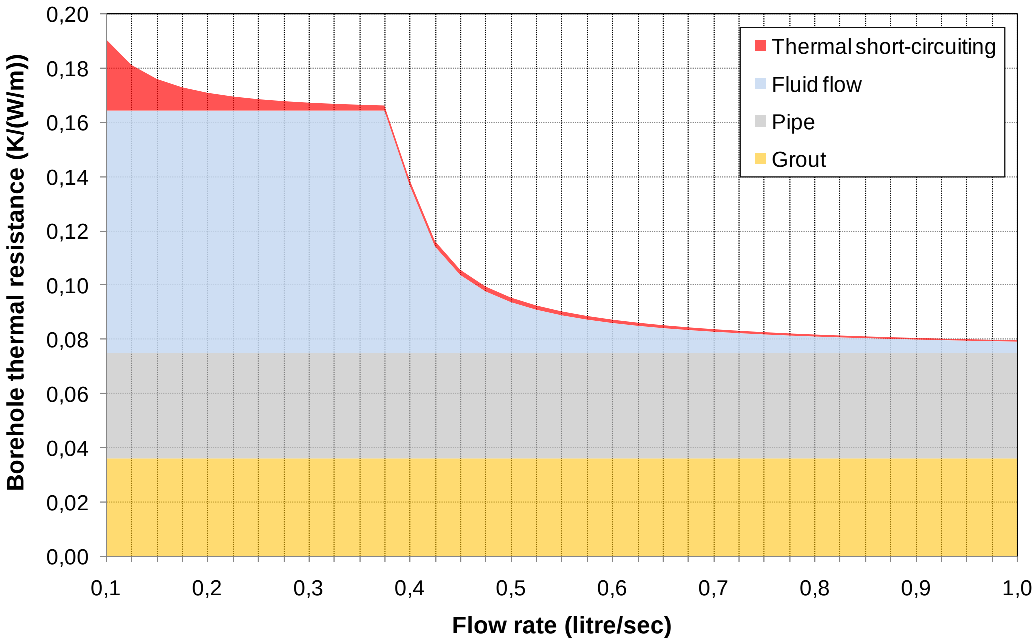

Figure 12. Components of the borehole thermal resistance (K/(W/m)) for a single U-pipe as a function of fluid flow rate (litre/sec). The example is based on a 100 m deep 14 cm borehole fitted with a single U-pipe using 40 mm polyethylene pipes (SDR11) and thermal grout (thermal conductivity 2.0 W/m,K). Fluid properties are 28% ethanol-water solution at 0 ^{o}C

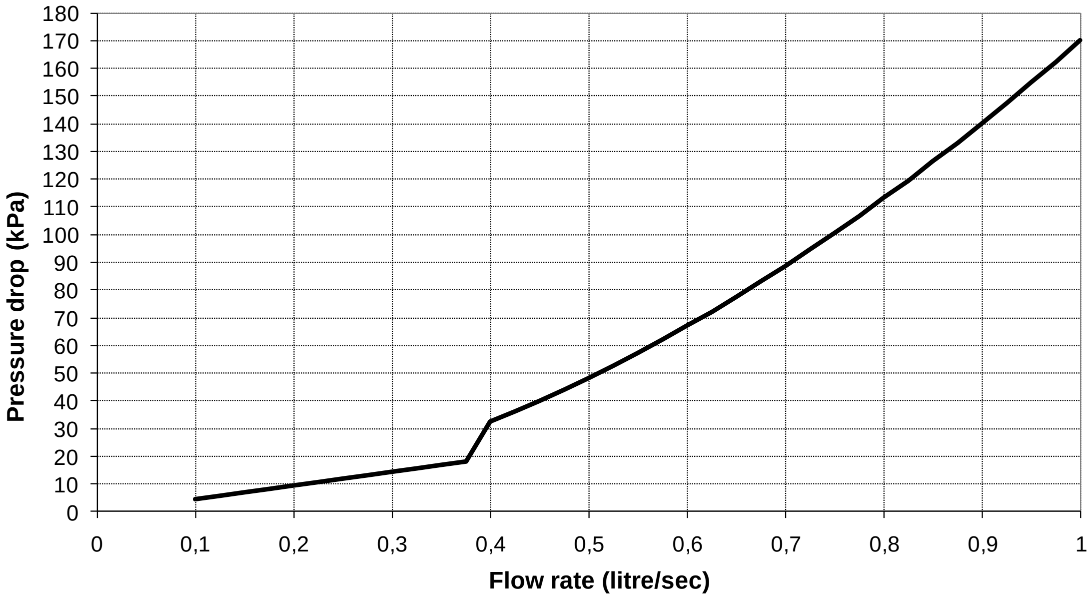

Figure 13. Pressure drop (kPa) across the borehole heat exchanger as a function of fluid flow rate (litre/sec). The example is based on a 100 m deep borehole with a single U-pipe using 40 mm polyethylene pipes (SDR11). Fluid properties are 28% ethanol-water solution at 0 ^{o}C

The recommendations of the ASHRAE design guide (Kavanaugh & Rafferty, 1997) is to strive for a Reynold's number of 2500-3000 at design energy loads (Fig. 14). This is a rule-of-thumb expressing a reasonable compromise between heat pump efficiency and energy requirement of the circulation pump.

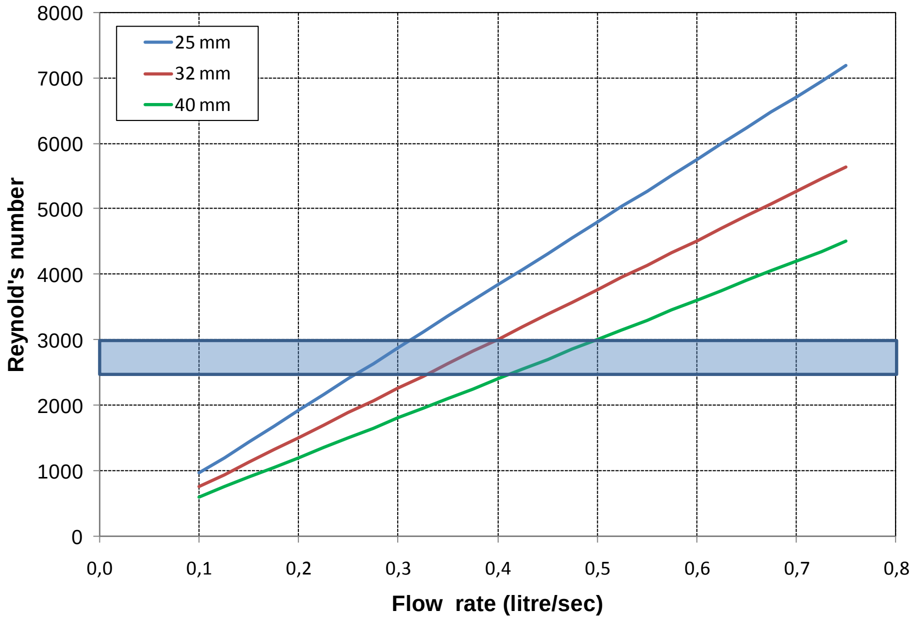

Figure 14. Reynold's number as a function of fluid flow rate (litre/sec) a 25 mm, 32 mm, or 40 mm polyethylene pipe (SDR11); fluid properties are 28% ethanol-water solution at 0 °C (the zone with a Reynold's number of 2500-3000 is indicated in blue)

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V. GENERAL COMMENTS

The thermal performance of different designs of borehole heat exchangers can be quantified according to the borehole thermal resistance evaluated from tests in the field or laboratory. Although most of these values are in reasonable agreement with theoretical estimates, they should be used with caution.

V. 1. 1. *Thermal response tests*

Many values originate from thermal response tests where ideally heat is injected at a constant rate and the resulting fluid temperature evolution is measured. The evaluation of these tests typically uses an effective ground thermal conductivity and the borehole thermal resistance as free parameters to obtain the best fit between measured and simulated values. The simulation models assume that the heat transport outside the flow channels takes place by heat conduction only. However, there may be deviations from this assumption. In a permeable water-saturated material there is convective heat transport by moving groundwater. Evaporation and condensation occur in unsaturated conditions. Freezing may take place if the thermal response test uses heat extraction. These other modes of heat transport may disturb the evaluation with a conductive model, so that the fitted parameters do not reflect the "true" borehole thermal resistance.

V. 1. 2**. *Internal heat transfer***

The temperature difference between the downwards and upwards flow channel causes an internal heat transfer, a so-called thermal short-circuiting, that reduces the efficiency of the borehole heat exchanger. This effect may be included in an effective borehole thermal resistance for the whole borehole. It can be demonstrated theoretically that this value is composed of local borehole thermal resistance between the flow channels and the borehole wall and an additional short-circuiting part, which depends on the thermal resistance between the upwards and downwards flow channels, the borehole length and the flow rate. The thermal response test measures this effective borehole thermal resistance. The same borehole heat exchanger design may then give a slightly different effective borehole thermal resistance because of differences in borehole length and flow rate. The flow rate (and type of heat carrier fluid) will of course also influence the heat transfer coefficients between the fluid and the walls of the flow channels.

V. 1. 3**. *Groundwater movement***

In grouted boreholes, groundwater movement can only occur outside the borehole. There may be a regional groundwater flow, but also a large-scale natural convection induced by temperature gradients around the borehole. The magnitude of the natural convection depends on the heat transfer rate and the temperature level. The driving force is the difference in density of the groundwater and the flow resistance depends on the permeability of the ground and the viscosity of the groundwater. The driving force tends to be higher and the flow resistance markedly lower at higher temperatures. The evaluated effective thermal conductivity and borehole resistance from a thermal response test may then depend on whether heat was injected or extracted during the test.

The situation becomes more complicated when water-filled boreholes are used. If the borehole is drilled in impermeable ground, there is still the possibility of local natural convection between the exterior surface of the flow channels and the borehole wall. This natural convection enhances the heat transfer through the groundwater in the borehole. The enhancement depends on temperature, specific heat transfer rate and geometry of groundwater filled area of the borehole (Littlefield & Desai, 1986).

In permeable ground, such as porous media and fractured rocks, the water-filled borehole serves as a conduit for vertical water movement. The pressure differences causing the vertical movement can be due to artesian conditions or induced by temperature changes in the borehole water.

V. 1. 4**. *Short-term variations***

The borehole thermal resistance as commonly used is defined based on a quasi-steady-state temperature difference between the heat carrier fluid and the borehole wall during a constant specific heat transfer rate. This steady-state condition takes some time to be established. The duration of the initial transient period depends on the heat capacity of the material in the borehole. A large heat capacity is favourable since it reduces the temperature increase for short-term variations. This aspect of different borehole heat exchanger designs is not included in the ”steady-state” borehole thermal resistance.

V. 1. 5. *Borehole diameter*

It should be noted that the borehole thermal resistance values reported here relate to boreholes that may have different diameters. The thermal response of a borehole heat exchanger depends on both the borehole thermal resistance and a transient thermal resistance of the surrounding ground. A larger borehole diameter results in a lower ground thermal resistance. However, if the filling material has lower thermal conductivity than the ground, a larger borehole may lead to a larger increase in borehole thermal resistance! The combined thermal resistance of borehole and ground then increases. With proper design, a larger borehole diameter could be used to reduce total thermal resistance, reduce internal heat transfer for U-pipe type BHE by increased shank spacing, and increasing the heat capacity for favourable short-term behavior.

V. 1. 6. *Serial or parallel coupling*

Another aspect of interest when considering applications of multiple boreholes is the pros and cons of parallel and serial hydraulic coupling of the different BHE. Although not a property of the BHE per se, the hydraulic coupling influences the flow conditions and thus the heat transfer in the BHE.

V. 2. Coaxial type BHEs

The borehole thermal resistances of coaxial type BHEs determined in some experiments are listed in Table 3.

Site	Type, filling material	Borehole Therm.res. K/(W/m)
Luleå	open, turbulent	0,01
Schwalbach	tube-in-tube (steel), sand	0,09-0,13
Sigtuna	tube-in-tube (corrugated),concrete	0,09
Grafenberg	tube-in-tube	0,09
Djursholm	tube-in-tube, ice	0,09
Djursholm	tube-in-tube, quartz sand	0,09
Djursholm	tube-in-tube, water, heat extr.	0,11
Stocksundstorp	soft liner	0,02
Muskö	soft liner	0,03
Cormontreuil	soft liner	0,03
Lund (laboratory)	multipipe (C-pipe)	0,01-0,03
Zurich	multipipe	(0,03)*

* Estimated value.

Table 3. Borehole thermal resistance (K/(W/m)) of coaxial type BHE

The thermal performance of coaxial type BHEs depends on:

- shape of flow channels (annular, multichamber, multipipe, spiral)
- material (soft liner, tube-in-tube)
- borehole filling material.

The open borehole with a concentric inner tube has the lowest borehole thermal resistance of all borehole heat exchangers investigated. The advantage of this design is that the heat carrier fluid is in direct contact with the ground, which during turbulent flow results in very favourable heat transfer capacity. This BHE is also very simple to manufacture and to install. There are, unfortunately, several disadvantages. It requires that: the borehole wall is stable; water is used as heat carrier fluid; the geochemical composition of the water does not result in corrosion or precipitation of minerals in heat exchangers; precautions are taken to avoid water losses in the store.

The borehole heat exchangers with a tube-in-tube design have a rather high borehole thermal resistance. In order to insert the relatively stiff tube-in-tube arrangements, there has to be a certain clearance between the outer tube and the borehole wall. The ratios between the tube and the borehole diameter for the designs vary from 0.5 - 0.8. The space between the tube and borehole wall has to be filled with either groundwater or a solid filling material. Situations such as water-filled boreholes at low temperatures (heat extraction) or boreholes grouted with standard bentonite will give especially high thermal resistances. Plastic outer tubes, which are relatively easy to handle, have large thermal resistances. Conventional polyethylene pipes (SDR11; PN12, PN18) have values of about 0.075 K/(W/m). Assuming a tube-to-borehole ratio of 0.8 combined with a thermal grout filling of high conductivity (2.4 W/(m,K)) gives a borehole thermal resistance of 0.055 K/(W/m) (not accounting for internal heat transfer). The tube-in-tube designs do not seem to offer any distinct advantage compared to common U-pipe designs, except the possibility to limit internal heat transfer, which may be necessary in very deep boreholes and low flow rates.

Another alternative aiming at combining the advantages of the open borehole with concentric inner tube and the tube-in-tube BHE is to use a soft liner (rubber, reinforced polyurethane, etc.) and an inner plastic tube. These designs have relatively low resistances, but there have been many problems with leakage and installation of the soft liners.

Coaxial type BHE designs using multiple pipes are still in the development phase. There seem to be possibilities to achieve low, or even very low, borehole thermal resistances. The main challenge is currently to find an arrangement (bottom piece, multiple pipes and top piece) that can be installed without too much difficulty and still ensure that the pipes are very close to the borehole wall.

V. 3. U-pipe type BHE

V. 3. 1. ***Single U-pipes***

Single U-pipes are the most common type BHE used in the world. In the USA and in Central Europe they are usually placed in grouted boreholes. During recent years there has been considerable interest in using thermal grouts. There are now several brands of ready-mixed thermal grouts available commercially. Spacers to keep the shanks separated and close to the borehole are also used. In Scandinavia and Canada it is common to leave the boreholes filled with ground water. The borehole water may freeze during peak heat extraction periods. The borehole thermal resistances of single U-pipes are listed in Table 4.

Site	Filling material	Borehole Therm.res. K/(W/m)
USA, several	bentonite	0,13-0,15
USA, several	thermal grout	0,09-0,10
Luleå	water, heating	0,05-0,06
Norway	water, heating	0,05-0,07
Lund (laboratory)	water, heating	0,05-0,07
Lund (laboratory)	(copper),water, heating	0,03-0,05
Studsvik	ice	0,09

Table 4. Borehole thermal resistance (K/(W/m)) of single U-pipes

The borehole thermal resistance of single U-pipes depends on:

- pipes: diameter, thickness, thermal conductivity
- position of pipes: shank spacing
- borehole filling material.

In grouted boreholes it is common to use a polyethylene pipe with diameter of about 40 mm (SDR 11 1" or PEM DN40 PN10). These pipes have a thermal resistance of 0.075 - 0.078 K/(W/m). A single U-pipe with such pipes inserted with spacers and combined with a thermal grout filling of high conductivity (2.4 W/(m,K)) should give a borehole thermal resistance of about 0.08 K/(W/m) (without spacers about 0.09 K/(W/m). Polyethylene pipes with half the thermal resistance lowers the resistance to 0.06 K/(W/m).

In water-filled boreholes, there will be an enhanced heat transfer between the pipes and the borehole wall due to convection of the borehole water. This enhancement increases with higher temperatures, heat transfer rates and magnitude of artesian type water flows. The values obtained during thermal response tests with heat injection lie in the range 0.05 - 0.07 K/(W/m) with 40 mm pipes (PEM DN40 PN6,3). If these values are adjusted to account for the much lower fluid pumping rates during actual operation, then the range should be about 0.06 - 0.08 K/(W/m). During heat extraction, when the influence of the natural convection becomes lower, the values should be about 0.08 - 0.10 K/(W/m). The performance of the water-filled borehole is better (heat injection) or similar (heat extraction) than for single U-pipes with spacers in high conductivity grout.

V. 3. 2**. *Multiple U-pipes***

Double U-pipes are common in Central Europe, where they are used in grouted boreholes. In Sweden, double U-pipes in water-filled boreholes have been used in cooling applications with large, short-term variations of the heat load. Designs with more than two U-pipes have only been tried in a few experimental setups. The borehole thermal resistances of multiple U-pipes are listed in Table 5.

Site	Type, filling material	Borehole Therm.res. K/(W/m)
Luleå	U2, water, heating	0,03
Lund (laboratory)	U2, water, heating	0,035-0,055
Burgdorf	U2, water, cooling	0,04
Montezillon	U2, bentonite	0,13
Montezillon	U2, bentonite, spacer	0,12
Montezillon	U2, bent./sand, spacer	0,11
Montezillon	U2, quartz sand, spacer	0,08
Grafenberg	U2, bentonite, spacer	0,10-0,11
Germany, several	U2, bentonite	0,10-0,13
Germany, several	U2, thermal grout	0,06-0,08

Table 5. Borehole thermal resistance (K/(W/m)) of multiple U-pipes

The borehole thermal resistance of multiple U-pipes depends on:

- pipes: number of pipes, diameter, thickness, thermal conductivity
- position of pipes: shank spacing
- borehole filling material.

Double U-pipes are typically made of 32 mm polyethylene pipes (PEM DN32 PN12 or PN18). The pipes are arranged around a central tremie pipe used for injecting grout into the borehole. The tremie is often left in the borehole. A double U-pipe with spacers and a high conductivity thermal grout filling should give a borehole thermal resistance of about 0.05 K/(W/m). Polyethylene pipes with half the thermal resistance through the pipe wall lower the resistance to 0.035 K/(W/m).

Response tests performed on double U-pipes in water-filled boreholes give resistances of 0.03 - 0.04 K/(W/m). If these values are adjusted to account for the much lower fluid pumping rates during actual operation, then the range should be about 0.03 - 0.05 K/(W/m during heat injection and 0.05 - 0.07 K/(W/m) during extraction. The performance of the water-filled borehole is better than (heat injection) or similar to (heat extraction) double U-pipes with spacers in high conductivity grout. In Sweden, double pipes installed at depths below 200 m have used 40 mm polyethylene pipes (PN8).

V. 4. Optimal performance of borehole heat exchangers

A summary of the discussion of optimal performance and possible improvement in sections IV - V is given in Table 6. The thermal grout is assumed to be have a thermal conductivity of 2.4 W/(m,K), the spacers put the U-pipe shanks at an assumed distance of about 2 mm from the borehole wall, and the low-resistance pipe has half the thermal resistance of a regular polyethylene pipe.

Type	Filling material	Borehole Therm.res. K/(W/m)
Single U-pipe (40 mm)	water, heat injection	0,06-0,08
Single U-pipe (40 mm)	water, heat extraction	0,08-0,10
Single U-pipe (40 mm)	thermal grout	0,09
Single U-pipe (40 mm)	thermal grout, spacers.	0,08
Single U-pipe (40 mm)	thermal grout, spacers, low-resistance pipe	0,06
Double U-pipe (32 mm)	water, heat injection	0,03-0,05
Double U-pipe (32 mm)	water, heat extraction	0,05-0,07
Double U-pipe (32 mm)	thermal grout	0,055
Double U-pipe (32 mm)	thermal grout, spacers.	0,05
Double U-pipe (40 mm)	thermal grout, spacers, low-resistance pipe	0.035
Triple U-pipe (25 mm)	thermal grout, spacers.	0,035
Triple U-pipe (25 mm)	thermal grout, spacers, low-resistance pipe	0,025
Open borehole		<0,01
Tube-in-tube	thermal grout, water	0,055
Soft liner		0,02-0,03
Multiple pipe	thermal grout, water	0,01-0,03

Table 6. Estimated "optimal" borehole thermal resistance (K/(W/m)) for different kinds of borehole heat exchangers

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CHAPTER 7

GEOLOGY *by Iñigo Arrizabalaga*

I. INTRODUCTION

The geological framework is a mandatory issue in every shallow geothermal system design procedure. In comparison to conventional heating and cooling installations, the ground is the additional element in a GSHP. While designing a GSHP installation, an accurate knowledge of the geological conditions where the GSHP is located and the way of integrating this data while sizing the heat pump are key parameters in the success of the project.

The differences between rocks and soil, the basic classification of different families of rocks, understanding its disposition in the ground, knowing the fundamentals of ground mechanical, thermal and hydrogeological behaviour are necessary matters in the design of medium and large GSHP systems.

In small systems, a basic geotechnical and hydrogeological knowledge can be useful in order to avoid safety and environmental risks. A great number of designers come from the building side of the geothermal system. Very often, loop design, even of large installations, is provided by the manufacturer of the heat pump several hundred kilometres away from the work site. They do not have a broad enough knowledge of the ground conditions and the site investigation methodology to employ in the project design. This investigation, especially in new drilling sites, will determine the cost and the viability of the geothermal system and the environmental issues.

The most usual problem is to underestimate the importance of geological issues in the design process. At best, it will cause over pricing of the project. In other cases, the system will not run properly.

Common questions are:

- How to choose between an open and a closed loop?
- How can we calculate the length of the closed loop?
- How can we calculate the yield flow from a well to match the building thermal load?
- How does geology determine the drilling method, borehole completion and costs?

A geological approach is necessary from the starting phase of the project. To collect any kind of geological, geotechnical, hydrogeological and thermogeological information for the project area will be useful and can save lots of money.

This chapter aims to refresh, clarify and improve the geological knowledge of GSHP designers coming from the building side of the technology. They will improve the understanding of how the ground works and make communication between members of the interdisciplinary project teams easier.

II. GEOTHERMAL ENERGY CONCEPTS

This chapter will try to clarify some concepts about geothermal energy:

a) Where does it come from?
b) What are the main parameters?
c) Geology
d) What is the relationship between thermal energy and water in the ground?
e) Why a pilot borehole?

a). Geothermal energy is the energy stored in the form of heat below the earth surface.

Low Enthalpy Geothermal Energy or Shallow Geothermal Energy is the energy stored at a very low potential, usually below 25 ºC.

The Ground Source Heat Pump is the most common technology developed to use Shallow or Low Enthalpy Geothermal Energy, usually, but not always, by means of a heat pump.

Low Enthalpy Geothermal energy has several origins. In many sites employed energy may be a mixture of:

- Geothermal deep flow. The Earth core reactor provides, on a human scale, an endless heat flow towards the surface of the planet. As a result, the Geothermal Gradient averages 3 ºC/100 m depth, and a heat flow rate on the surface of the Earth between 30 and 100 mW/m^2
- Solar absorbed radiation. Heat transfer at the surface. Several factors have to be taken into account, such as the fraction of solar radiation diffused into the ground, water percolation and heat transfer with the air by convection and thermal radiation. However, the assumption is often made that the temperature of the ground (for the first 10 m) is a function of the temperature of the surface. Under 10 m, the ground temperature is no longer sensitive to yearly air temperature variation.
- Ground water advection. Ground water flow is able to transfer large amounts of energy along the ground. This process, known as advective flow, is a main agent in many shallow geothermal systems
- Thermal storage capacity of rock. Rock, with its ability to store heat energy, average ≈ 0,65 kWh/m^3/ºC, provides a large amount of energy, especially in vertical closed loop systems where a borehole can involve thousands of cubic metres of rock
- Artificial recharge (regeneration). The storage capacity of the rock may provide an excellent low-cost seasonal scale thermal store able to manage waste heat from cooling processes, refrigeration, solar surplus, etc.

b). The main parameters defining thermal properties of the ground are:

- Thermal conductivity of the ground
- Volumetric thermal capacity
- Undisturbed ground temperature.

The ability of the ground to transfer and store heat depends on a number of factors, principally:

- *Rock mineralogy*. Generally, the higher the quartz content, the higher the thermal conductivity
- *Density*. High density of the material usually means a closed texture and absence of voids. The higher the density, the higher the thermal conductivity and diffusivity
- *Water content*. Water presence improves the heat transmission even in the absence of flow. It fills the voids, increasing the thermal conductivity of the rock or soil.

c). Geology is also the main agent shaping the landscape. Tectonic forces fold and fault rocks. Weathering, transport and deposition agents are key issues in the tireless transformation of all geological environments. Landscape conditions will determine the project site conditions that fit the drilling equipment.

In addition, geology provides good information about mechanical and geotechnical properties of the rock, which are key influences on the cost of the drilling works (Fig. 1). The main parameters, according to their cost influence are:

- Rate of penetration (ROP). ROP will depend on various properties of the rock, mainly:

- Fracture degree
- Texture
- Planes of weakness: exfoliation, stylolites
- Specific gravity and density
- Porosity
- Permeability
- Hardness
- Compressive strength
- Abrasivity
- Elasticity
- Plasticity

- Stability. The ability of the drilled ground to maintain stable borehole walls determines three very important parameters with a very high impact on the project's final cost:

- Diameter of the borehole
- Auxiliary casing needs
- Mud use needs.

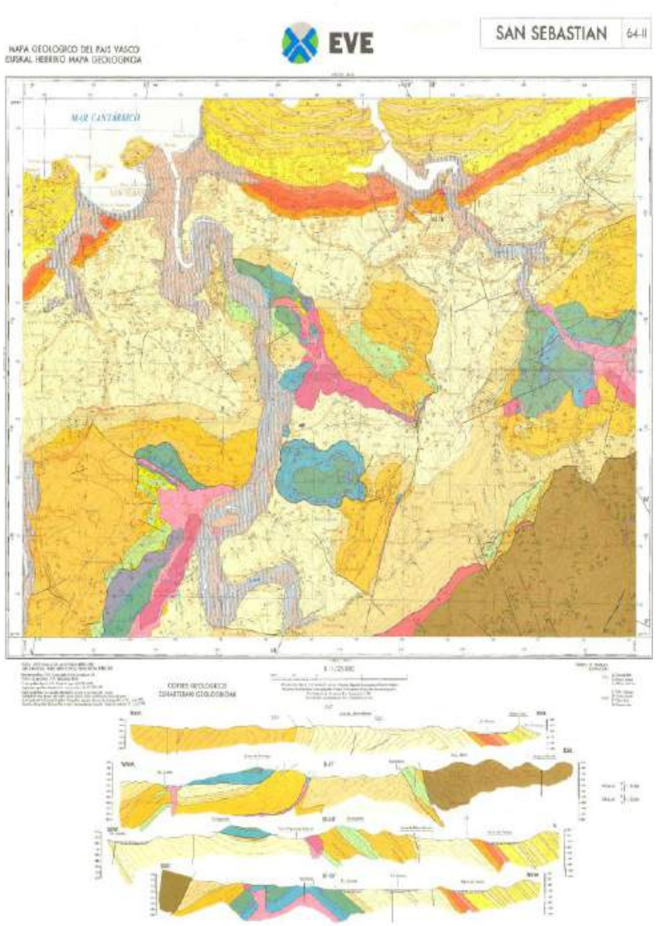
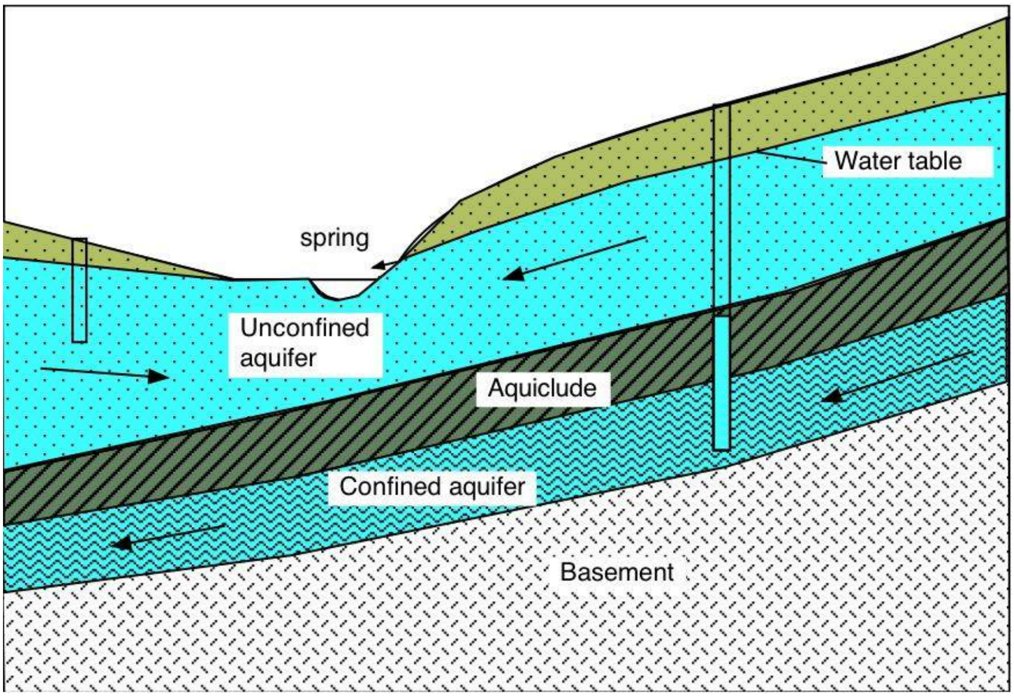


Figure 1. Example of a solid geology map



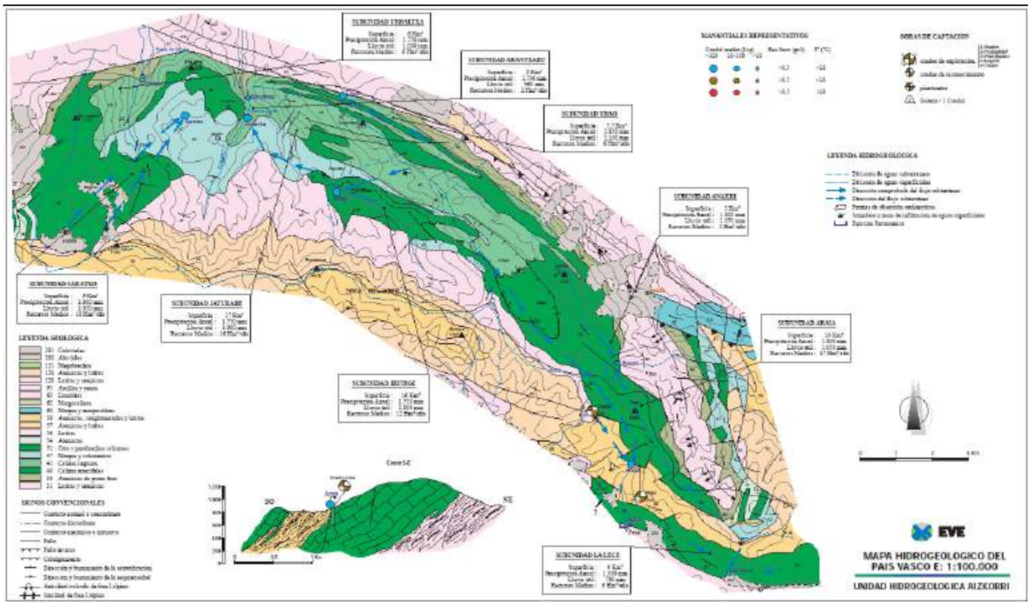


Figure 2. (top) Hydrogeology, aquifer diagram

Figure 3. Hydrogeological map

d). Hydrogeology is another field to take into account for preliminary analyses (Figs 2 and 3). Ground water presence is of prime importance in GSHP system design procedures, as illustrated by the following five points:

- It determines the typology of the geothermal system. In yielding enough aquifers, the typology of the loop could be directed toward an open loop or Standing Column Well system, sometimes even as a result of an unexpected water yield of the pilot borehole. Otherwise, a closed loop system may be the ultimate solution
- The water table position determines the thermal conductivity of the ground

- Advective flow may transfer a huge amount of energy, increasing the apparent thermal conductivity of the ground and providing higher extraction and rejection ratios
- On the other hand, advection may preclude seasonal thermal storage in the ground
- Ground water pollution is the main environmental risk of GSHP technology. An adequate knowledge of the hydrogeology of the geothermal site is compulsory to evaluate pollution risk and to design the sealing sketch for the borehole when necessary.

e). The pilot borehole

A good example of a geological investigation tool for vertical closed loop shallow geothermal systems is the pilot borehole. Drilling a pilot borehole with an adequate geological control provides full value information about:

- Lithology log
- Ground fracture degree
- Hydrogeology
  - Water table position
  - Aquifers
  - Productivity, specific flow rate, drawdown
  - Hydrochemistry
  - Filling/grouting selection
- Drilling parameters
  - Formation stability, voids and holes
  - Drill ability
  - Diameters
  - Auxiliary casing need
  - Drilling speed
- Drilling Cost
- A borehole for installation of a PE exchanger for Thermal Response Test (TRT)
- An additional pipe for borehole logging, undisturbed ground temperature, temperature log before, during and after TRT, other kinds of geophysical logs, etc.

III. TECHNICAL AND PROFESSIONAL RESOURCES

The technical resources needed for this phase will differ according to the scale of the project. In small size installations, below 30 kW, basic geological knowledge, training and experience may be enough. Many countries and several autonomous regions have geological services using comprehensive documentation about the work site, geological and hydrogeological maps, groundwater databases, groundwater pollution risk, soil and slope maps, etc.

In addition, many drilling companies may provide information about lithology, the geological column, groundwater prognosis, etc. This helps us to supply the geological information requested for mining, water and local authorities about the proposed work site.

Larger size installations, over 30 kW, require deeper and more specific geological knowledge. Integrating a hydrogeologist into the project team could be compulsory, especially in groundwater-based open loop systems.

The profiles of professionals working in the geothermal, as in the hydrogeological, field vary.

The professional background of people working in this field should be a ground-based qualification: geology, mining or civil engineering, with a good knowledge of hydrogeology. The Designer must be able to understand a geological map. He must know, at least, basic rock classification and be able to identify the main rock types in his work area. He should also have some basis in structural geology and an understanding of geological relations between different ground materials, their orientation and deformation processes.

In many medium and large scale projects, it may be compulsory to have a relevant geothermal qualification in order to get appropriate risk insurance or to integrate the geothermal item into the building project.

III. 1. Using the resources

Geological knowledge must be integrated into GSHP from the first stage and will be present throughout the design process. Geology determines directly or indirectly:

- Loop typology: Open, Closed, Standing Column Well
- Thermal properties of ground/groundwater
- Loop viability: digging/drilling system, well/borehole completion
- Environmental issues.

The scope is very complex according to the chosen typology. It could vary from geological/geotechnical cartography to a pumping test of a groundwater abstraction or re-injection well.

Chapter 16 provides comprehensive information about site investigation in GSHP design.

IV. ENERGY EFFICIENCY AND ECONOMIC COST BENEFIT

The energy efficiency of a geothermal system is fully related to the typology of the circuit. Efficiency in a geothermal system ranges from a Seasonal Performance Factor (SPF) of <3 in many horizontal dug closed loop geothermal systems up to >5 in several groundwater source open loop systems. For the same typology, e.g. vertical closed loop system, building thermal load and exchange length performances could range from <3.5 to >4.5 depending on ground thermal conductivity and groundwater Darcy velocity.

Ground properties, building thermal loads and energy cost will determinate the viability of the geothermal alternative. Loop typology will define the cost range of the geothermal system. Vertical closed loop systems can usually supply a few hundred thermal kW. It may easily cost >1200 € per installed power kW, with a payback time over 12 years.

In contrast, an open loop ground water system can provide several MW of thermal power and its cost may be cheaper than 100 €/kW with a payback period of a few months.

IV. 1. Regulations

The main specific regulation regarding this domain is about filling and grouting materials and procedures. Several central Europe countries, such as France, Germany, Austria and Switzerland require the borehole to be grouted with a sealing compound, usually cement and bentonite mixtures, in order to avoid aquifer pollution. But usually, after grout placement and casing removal, no further tests are carried out to verify the grouting position. These regulations can be useful in some geological conditions, e.g. in karstic terrains, low water table positions, gypsum terrains, boulder unconsolidated terrains, but not in others.

In other countries, such as the Scandinavian area, the borehole is filled with water. The wellhead casing annulus is grouted and the inner space between U-pipe and casing is sealed with expansive rubber packing. This completion is considered safe enough to ensure that no pollution of aquifers occurs from the surface through the borehole.

Many countries are unregulated. As in many things, the sealing procedure must be conditioned by geology and hydrogeology. Often, prevention of cross pollution between different potential aquifers is not possible with grouting alone. This needs specific treatment, for example, the placement of a grouted casing isolating the upper aquifer before the lower aquifer is drilled. A very similar situation may take place in case of strong artesian conditions. On the other hand, a requirement to seal a low permeability formation without aquifers along the entire borehole is unnecessary and only increases the bore field cost and decreases the thermal transmission through the borehole annulus.

The same prescription is not always the best one for different illnesses. Qualified staff must study and design the safe solutions for each hydrogeological situation.

V. CONCLUSIONS

Geology defines the ground behaviour of thermal energy. A fitted design of a medium or large size shallow geothermal system cannot be done without an analysis of geological issues.

Designers need to understand heat transfer basic concepts in the ground, the different factors affecting the energy budget, heat recharge and discharge and the role of ground water. They must also know some basic geology and hydrogeology, the main rock formations and lithologies, the position of the aquifers and the vulnerability, at least of the specific work area, in order to choose the best circuit typology in each place. They must be aware of consequences and risks of a bad geological evaluation.

The most common consequence of misuse is increased cost and the misfunction of the designated geothermal system. In the case of inappropriate circuit typology selection, a more expensive alternative may be chosen, increasing the cost of the geothermal system. Sometimes, the economical limit may be exceeded and the geothermal alternative will be rejected. A poor knowledge of the thermal properties of the ground can also lead to the wrong decisions. An even worst option can be in the case of underdesign. The system will never work properly or troubles will appear after a few years of operation. Moreover, an incorrect geological evaluation can produce geotechnical and environmental hazards, some even with penal consequences.

V. 1. The future

Future evolution of this matter will involve a stronger influence of professionals with ground-related backgrounds in geothermal design. In medium- and large-scale projects, their knowledge will be compulsory inside a multidisciplinary work team. Determining ground properties, ground water behaviour, thermal storage ability of the project site or choosing the best and safest environmental heat transfer completion sketch of the borehole will be a specialist task. Hydrogeological and geophysical tools will be widely employed and adapted to improve bore field design and work quality control.

VI. FURTHER INFORMATION

Bibliography

Many geothermal design handbooks dedicate at least a chapter to explain some basic geological concepts.

Websites

European Union countries have a wide net of geological surveys, many with web services offering useful information, geological and hydrogeological information, water spot data bases, ground thermal conductivity inventory, groundwater temperatures, hydrochemistry, etc.

See: http://www.uni-mainz.de/FB/Geo/Geologie/GeoSurv.html

Other associations of interest are:

International Association of Hydrogeologists (IAH): www.iah.org

National geologist, mining and civil work engineering associations have plenty of information on their websites about these topics.

See: http://geology.about.com/ where you will find a lot of geological information to retrofit your secondary school geological lessons.

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CHAPTER 8

DRILLING *by Iñigo Arrizabalaga*

I. INTRODUCTION

Shallow geothermal systems are mainly based on boreholes and wells. These are fundamental elements that define closed loop vertical systems, energy foundations and open circuits based on ground water.

Knowledge about the different drilling methods and tools, the field of application, their limitations, costs and risks are principal issues. In the same way the designer should know about casing systems, piping alternatives, filling and sealing materials, as well as methods of execution.

The designer should be capable of choosing the appropriate drilling method for the current system, be familiar with the tools, be capable of determining diameters and the necessity for auxiliary casing and forecast the costs in order to evaluate the technical and economical feasibility of different alternatives.

The most important questions for a designer are related to the most appropriate drilling method, optimum diameters, piping and sealing material and methods, necessary auxiliary casing, estimated costs and the risks of this kind of work.

The designer must know that the costs of closed loop vertical system drillings can range from 50 - 70% of a geo-exchange circuit's extra charges, in comparison to a conventional air conditioning system. Getting maximum definition from the initial feasibility study stage is therefore of the utmost importance. The first step in the process of dimensioning a ground source heat pump is to define the demand of the system. This process should include an analysis of the different possible alternatives, ranging from most to least economical, based on the geological and hydrogeological conditions of a work site, and excluding the non-feasible ones.

The objective of this chapter is to give a brief overview of the drilling. The complexity of this theme is important, but the aim is to illustrate the principal drilling methods applicable to the construction of geothermal exchange circuits.

II. CONCEPTS

This sub-section aims to describe the principal drilling systems used in the vast majority of geothermal system constructions, especially for installations <30 kW. The fundamental part of a geothermal system is of course the geothermal exchange circuit. There are geothermal installations of low temperature without pumps, but none without a geothermal exchange circuit.

II. 1. Drilling methods

Boreholes and drillings have a long history. There is evidence of boreholes over 2000 years old, hundreds of metres deep and drilled with a primitive rig, using bamboo canes as drill pipes.

Traditionally, there has been a distinction between two common drilling methods: percussion and rotation methods. Nevertheless, other methods exist as well, which either contain elements from the previous two, like the roto-percussion method, or are relatively recent technological developments that, despite evolving from previous ones, present important peculiarities: sonic drilling, horizontal directional drilling, etc.

Percussion	Rotation	
Digging Direct Push (Rc<50 Mpa)	Augering (Rc<60 Mpa)	
Cable tool	Rotary	Tricone (Rc<150 Mpa) Bit (Rc<60 Mpa) Coring Bit Polycrystaline Diamond Compact (PDC)
Roto-percussion: Down The Hole Hammer (DTH), Head Hammer (HH) Hydraulic Hammer Drilling (HHD) (Consolidated formations)		
New Technologies: Sonic, Horizontal Directional Drilling (HDD), Coil Tubing,…		

Figure 1. Drilling methods

- Percussion

In this section, some authors would include two well construction types: digging and direct push. Because of its scarce use, further elaboration is not pursued here. Two interesting aspects are worth mentioning:

– Currently there are pre-manufactured piles for thrusting (deep foundation structures that are being placed in the earth with repetitive impact, until no further penetration is possible) that either incorporate an exchange circuit or have a hollow core for a circuit placement at its disposal

– Direct push systems are improving their performance in an important way. These systems could be the economical option for installing coaxial exchangers in non-consolidated formations.

The main percussion method is cable tool percussion. According to Calver "*This drilling method uses a heavy bit that is repeatedly lifted and dropped that crushes and breaks the formation. With a cable tool rig, an experienced driller can drill through any formation,* *including large crevices and caverns that can cause problems with other drilling methods ……..Drilling is accomplished with a tight drill line. The pitman arm and spudder beam impart an up-and-down motion to the cable and drill bit. The length of cable is adjusted so that on the down stroke the tools stretch the line as the bit hits the bottom of the hole, striking with a sharp blow and immediately retracting. The twist, or lay, of the cable imparts a slight turning motion to the tools so the bit hits a new face with each stroke. Left lay cable is used so that the twisting action tightens the tools screwed connections on each upstroke. If the borehole is dry, water is added to form a slurry that is bailed out. Usually about 1.5 m of well hole is drilled between bailing*"

The slow rate of penetration (ROP) of this method, usually <10 m per day, raises the costs well above the closed loop systems' feasibility limit. Its use in practice is consequently restricted to:

– Open loop, construction of deep wells, with high yield ratio in unconsolidated aquifers or karst areas

– Energy foundation; drilling in boulder zones for in situ pile construction.

- Rotary

Rotary drilling is the best known drilling method for oil, mining and hydrogeological exploration. The basic proceedings consist of transmitting a torque, with a rotation table or a rotation head, to a train of threaded drill pipes supplied with drill bits at the tip. This drill bit can be a tricone for crunch drilling or a core drill for drilling with continuous sample recuperation. In the last few years, a new bit type has been incorporated from the world of hydrocarbon: the PDC (Polycrystaline Diamond Compact). Furthermore, in superficial drillings, <50 m, in unconsolidated materials and normally in foundations, the augering system is the common one. Here the excavated material is extracted with an Archimedes bolt, keeping the hole opened.

The majority of the rotary methods, however, use mud as wellbore fluid and are classified as direct or inverse rotations, depending on the function of the drilling mud's flow:

– *Direct circulation*: mud is pumped into the drill pipe, cleaning the bottom of the hole using the nozzles at the end of the bit. The mud returns to the surface through the annulus between borehole and drill pipe. The mud carries cuttings and detritus from the bottom of the hole. Direct circulation methods fit well for narrow diameter boreholes, <300 mm, and in consolidated formations with compressive strength of up to 150 Mpa

– *Reverse circulation*: mud is pumped down the annulus and back up through the drill pipe. The pressure inside the drill pipe sinks, which permits the mud and the detritus to evacuate towards the surface where it is deposited in the decantation vessel. These systems are used in wide diameter boreholes, >300 mm, and in unconsolidated formations.

- Roto-percussion (Rotary hammer)

Roto-percussion methods are currently the most common drilling methods for geothermal borehole drilling, integrating elements of both rotary and percussion methods. The drilling tool is ether a jackhammer or a hydraulic hammer that breaks the formation with alternate striking at frequencies between 500 and 2000 strikes per minute. The hammer is activated through the drill pipe and put down by a torque. It constantly changes the point of impact, thus avoiding wedging the tool and facilitating the rock disintegration and the borehole's verticality. Cuttings are evacuated by means of water or compressed air.

Roto-percussion systems are classified according to the point of impact:

– T*op hammer*. The striking occurs at the head of the drill pipe and is transmitted to the hammer at the base of the chain. This is a frequent method in shallow blasting boreholes, <50m. It's the standard drilling method for drilling in quarry blast pits and public work as well as in tunnels and gallery drilling

– *Down the hole hammer*. A piston within the hammer at the bottom of the drillstring strikes the rockface. High-pressure air is injected through the drill pipe, normally 12-30 Bar, causing an alternative movement at the hammer's trigger. The trigger strikes the drill bit, pushing out the compressed air through the drill bit's nozzle, thus completing the sweep, and transports the rock cuttings to the surface. Depending on the direction of the drilling fluid there are two main types:

- *Direct circulation*: fluid is injected through the drill pipe and returns through the annulus. This system is appropriate for strongly or very strongly consolidated formations and great depths, with diameters comparatively smaller, <300 mm, as well as with small occurrence of water or with deep water table
- *Reverse circulation*: double drill pipes are used. Fluid is injected through the annulus between both pipes. An inverter, connecting the wall of the drill pipe to the hammer, is placed directly above the hammer. Once struck and swept, the striding surface brings the fluid with the filling to the inside of the inner drill pipe, as it returns to the surface. This method is appropriate for use in formations, alternating between consolidated and unconsolidated, for wide diameter drilling, >300 mm, and for boreholes with high water occurrence and high water table level.

Drilling in strongly consolidated formations with deep overburden, or unconsolidated levels, is a major challenge for any drilling system. From the classical solution, different solution methods have emerged, such as oversized and auxiliary casing and telescoping, for overcoming these areas without diameter loss. These are systems that enable drilling and piping in one single manoeuvre, thus securing the formation's stability, the absence of collapses and cuttings recovery – even in caves found frequently in karstic areas – and preventing interruptions in the flow back. The most common systems are double rotary head and double piping: the Odex type and the Symmetrix type.

II. 2. Drilling fluids

A fundamental part of drilling is a correct selection of drilling fluids. Normally it is water or mud based on a mixture of water and bentonite clay. Nevertheless, based on the mineralogy of the terrain, the composition of the ground water or the formation pressure and the blow out risk, a great variety of compounds can be added.

Air based	Air Air / Water Air / polymer
Water based	Water Water / polymer Water / bentonite (mud) Special mud: High density Saturated Hydrocarboned Lost circulating materials

Figure 2. Types of drilling fluids

High-pressure air is also a very common fluid. The air can be mixed with water, in order to reduce the dust, and eventually with foaming products to facilitate the cuttings and water lifting as well as the cleanliness. Drilling fluids serve multiple purposes, mainly these:

- Basic functions: Cooling of the drill bit
- Removal of cuttings as they are produced
- Transporting cuttings up the hole

Also, they are often used to:

- Stabilize the hole to prevent cave-ins
- Minimize formation fluid migration into the hole
- Minimize fluid losses to the formation
- Lubricate mud pump, bit and the annulus between the drill string and the hole
- Reduce drill string corrosion
- Suspend cuttings during periods of non-circulation
- Assist in collection and interpretation of samples and diagraphies
- Release cuttings in the mud pit.

II. 3. Cost assessment

The drilling cost in a geo-exchange circuit project could be more than 50% higher than for conventional technology. The drilling costs vary in a very important way. A borehole, 60 m deep and with a 90 mm diameter, drilled in cohesive unconsolidated materials, could cost 30 €/m. On the other hand, a 1500 m deep borehole for geothermal or hydrocarbon exploration could surpass 1000 €/m. Concerning closed vertical circuits and formations with a good rate of penetration (>100 m/d), the drilling costs lie somewhere between 20 and 40 €/m. Major changes can occur, depending on the country and the conditions of the market: equipment disposability, demand, etc.

The main determining factors of drilling costs, concerning the terrain, are these:

- depth and diameter
- kind of formation/auxiliary casing need
  - consolidated: limestone, sandstones, shale
  - non-consolidated: sand, gravel, mud, boulders
- hardness of formation/abrasivity
- fracture degree
- groundwater: water head and flow rate.

Moreover, there are a number of factors when studying the construction of a geothermal borehole area. Those with the greatest impact are:

- available surface
- foundation configuration, drain grid, earth grid,..
- time scheduling structure works: digging, piles, walling….
- interferences between subcontractors
- rig site preparation
- cuttings and/or mud management
- waste disposal
- other parties services affect, electric grid, telephone, gas, water, tunnel,..
- ground water evacuation

II. 4. Risk evaluation

Another drilling-related aspect of major importance is the assessment of risks related to this kind of work. These are principally broken down into five risk-related categories:

- Safety and health at the well site
- Environmental risk: affect on water supplies, springs, crossed pollution, undesirable mixtures between different aquifers
- Energy risk: mis-design, poor execution, under/over calculation, low performance, low comfort
- Economic risk: bad cost/benefit balance, under yielding flow rate, bad quality water supply
- Geotechnical risk: structural damages, foundations, railroads, roads.

All of these aspects should be considered and evaluated, based on the field conditions.

Drilling requires costly equipment and specialized personnel. When designing a drilling programme, a further distinction has to be made between domestic geothermal projects, < 30 kW, and institutional and commercial installations. For the former, contacting companies with experience in the project area could be enough. They will be familiar with drilling conditions, risks and required permits for the area, and can thus keep the designers informed on the proceedings.

For large projects, >30 kW, it is recommended that a pilot borehole is drilled with an adequate hydrogeological control, as the first step of the project. This borehole will be piped for the TRT as well and will make it possible to determine the lithology, rate of penetration, aquifers, water table position, ground water yield ratio, need for auxiliary casing and other information so that the best drilling programme is chosen and also for cost assessment.

III. TECHNICAL AND PROFESSIONAL RESOURCES

The designer should know about the main drilling systems, their requirements, influence of the geological conditions of the task, size, manoeuverability and drilling equipment mobility, as well as auxiliary means required. One should also know about the limitations and costs of every system.

In some countries and regions, the drilling project planner should have accredited knowledge in geology, mining or civil engineering, with a thorough education in ground materials.

The designer should choose the drilling method using the smallest possible diameter in order to guarantee a correct installation of the selected piping and filling, and should do this at minimum cost and impact. The most common option for consolidated formations and hard terrain is *down the hole hammer*. Down the hole hammer very often gets ROP higher than 25 m/h, usually with diameters between 127 and 140 mm and depths exceeding 150 m.

Drilling fluid	Usually water-based drilling mud
Telescoping casing	Several drilling diameters
OD Systems	ODEX TUBEX Up to 25 m depth
Rota-OD	Rota-ODEX Up to 40 m depth
Double Rotary Head	Up to 150 m depth

Figure 3. Unconsolidated formations

In unconsolidated formations, *direct circulation* may not be feasible due to the collapses it causes in the formation. The solution is often to install a temporary casing and decrease the borehole diameter (telescopic boring). This technique can double the cost per cased metre.

Reverse circulation can solve this problem but requires a much larger drilling diameter, and usually mud must be prepared. The diameter, the volume of filling stuff and cuttings and the cost of the borehole increases.

Drilling performance and cost vary widely, based on the driller and the rig crew. The experience, training, dexterity and responsibility of the crew are the most difficult variables to estimate when planning drilling operations. Their influence on the costs of the drilling operation is very often crucial. We frequently find several rigs of the same model working in the same place with very different yields.

IV. ENERGY EFFICIENCY

From an energy efficiency point of view, the influence of the drilling method used for closed loops is limited. The selected method determines the drilling diameter. For example, the boreholes made by *reverse circulation* require a minimum diameter of 300 mm. In practice, this causes an important increase in the borehole's thermal resistivity in every situation where the borehole filling's thermal conductivity is lower than that of the ground. As a consequence, a superior temperature gradient is needed in order to transmit the same heat flow as minor diameter drilling, thus providing lower performance.

In open systems with groundwater pumping and re-injection, a poor decision on drilling method could, among other consequences, cause damage to the formation, reduction of the specific flow rate and decrease the dynamic level. This would increase the pumping pressure and the energy consumption.

	Loose sand Gravel	Alluvial fans Glacial drift with loose Boulders	Clay, Silt, Shale	Sandstone Cemented Conglomerates	Limestone	Limestone Cavernous	Basalt Layers	Basalt-HighlyFractured-Lost Circulation Zones	Granite&Other Non_Fractured Metamorphics
Cable tool	Slow	Slow-difficult	Slow-medium in brittle shale	Slow	Slow	Medium	Slow to medium	Slow, sometimes difficult	Slow
Direct rotary (air)	NOT RECOMMENDED			Fast	Fast	Slow	Fast	Medium	Medium to fast
Direct rotary (fluid)	Fast	Impossible to very slow	Fast	Med. to fast	Med. to fast	Slow to impossible	Slow to medium	Slow to impossible	Slow to medium
Air hammer	NOT RECOMMENDED			Harder types Fast	Very fast	Fast	Fast	Medium to fast	Fast
Reverse rotary	Fast	medium	Fast	Med. to fast	Medium	Slow to impossible	Slow to medium	Slow to impossible	Slow to medium
Drill thru-casing driver	Very fast	Medium to difficult	Fast	NOT APPLICABLE					
Dual wall	Very fast	Medium	Fast	Med. to fast	Med. to fast	Fast	Fast	Med. to fast	Slow to medium

Figure 4. Drilling rates (after: Gene Culver 1998, chapter 6, Drilling and Well Construction. In Linieu, P. (ed). Geothermal Direct Use Engineering and Design Guidebook (3rd edition))

Drilling is the most sensitive variable in feasibility analysis of low temperature geothermal systems. In big projects – vertical circuits of more than 3000 m – cost differences of ± 10% in borehole constructions cause greater annual pay-back variations. Choosing an adequate method for obtaining maximum yields at minimum cost is therefore of the utmost importance. At the same time, the method should be compatible with the other simultaneous duties in the task. In open circuits, a poor choice of method or a defective work design can cause unacceptable levels of turbulence, silt and sand in the pump and the thermal exchanger, thus ruining the entire operation and the previous investment.

V. CONCLUSIONS

The designer should have knowledge about the main borehole drilling methods, the advantages and disadvantages and the area of application for each technology. Furthermore, the designer should know about the costs associated with each system and the possible risks associated with a bad design or malpractice. The risks of a bad design or malpractice can prove important. Five possible risk fields can be discerned:

- Safety and health at the borehole field/well site
- Environmental risk: affects water supplies, springs, crossed pollution, undesired mixtures between different aquifers …
- Energy risk: mis-design, bad execution, under/over calculation, low performance, low comfort
- Economic risk: bad cost/benefit balance, under yielding flow rate, bad quality water supply
- Geotechnical risk: structural damages, foundations, railroads, roads.

In the majority of geothermal exchange circuits, drilling is a principal variable in execution costs. Hence, reducing the costs through possible advancements in drilling technology would have a multiplying effect on the geothermal energy installations.

In a few years, new drilling systems will be developed that are adapted to low temperature geothermics, smaller and more manoeuverable rigs, smaller drilling diameters, bigger ROP, etc.

VI. FURTHER INFORMATION

Bibliography

There are good drilling manuals published in almost every language, though the majority of them are oriented towards deep borehole drilling. In Spanish, the following books are of interest:

Pozos y sondeos

Carlos López Jimeno *et al.* 2006. Manual de sondeos (2 volúmenes) UPM. ETSI Minas de Madrid.

Drilling: The manual of methods, applications, and management. 1997. Australian Drilling Industry Training Committee Limited.

Websites

There are also many useful web sites. Some of these are:

http://www.geoheat.oit.edu/**pdf/tp65**.**pdf**

http://www.welldrillingschool.com/courses/pdf/DrillingMethods.pdf

http://www.atlascopco.com

http://www.bauer.de

http://www.americawestdrillingsupply.com/

http://www.hfdrilling.co.uk/products/overburden_drilling_systems

CHAPTER 9

SITE INVESTIGATION (GROUND CONDITIONS / LICENCES AND PERMITS)

by David Banks

I. INTRODUCTION

This chapter considers the importance of pre-investigation before finalizing a ground source heating and cooling (GSHP) design and commissioning a system. It will argue that there are at least three phases to pre-investigation:

- *Desk Study*. What is already known about the ground conditions and subsurface hazards at the site in question? Can you predict what hazards and risks you are likely to encounter when excavating or drilling?
- *Legal and Regulatory Issues.* What permits do you require before (a) commencing drilling or (b) commencing operating a scheme? What information is a regulatory body likely to require before granting permission?
- *Site Investigation.* Under what circumstances will you need to use geophysics, trial drilling / excavation, test pumping or thermal response testing to characterize ground conditions? How do you perform and interpret these tests?

Note that there is a degree of interaction and overlap between these three categories. The quantity and quality of pre-existing knowledge about ground conditions will determine how much additional site investigation is necessary. A regulatory body may require a formal risk assessment (desk study) or the results of a pumping test (site investigation) before permitting a GSHP scheme.

II. WHY SHOULD A DESIGNER CARE ABOUT PRE-INVESTIGATION?

If a designer (or, indeed, a driller or installer) does not invest time and effort in pre-investigation, then there is a risk that a borehole will be drilled “blind” and unexpected hazards will be encountered.

For example:

- Contaminated ground – with health and safety risks to personnel, risks of contaminating deeper aquifers
- Buried services – telecommunications cables, high pressure gas pipelines, mine workings, underground railways. You’d better make sure your insurance is up to date!!
- Multiple aquifers, artesian groundwater conditions.

Moreover, you also need to be able to apply sensible hydrogeological parameters (hydraulic conductivity, porosity, storage, transmissivity, groundwater head) and thermogeological parameters (thermal conductivity, ground temperature, volumetric heat capacity) when designing your GSHP scheme. Having some knowledge of geological and hydrogeological conditions at the site will enable you to make sensible choices for these parameters and thus to select efficient and sustainable designs. Better still, if you can obtain empirical, site-specific determinations of these parameters, rather than just using generic values from literature, you will have far more confidence in your design and will be able to refine it with far smaller margins of uncertainty.

III. DESK STUDY AND IMPACT / RISK ASSESSMENT

Before commencing any penetrative investigation works for a ground source heating or cooling (GSHP) scheme, and even before applying for licences and permissions, it will be necessary to carry out:

- A desk study, to give as good an indication as possible of the ground conditions you are likely to encounter
- Some form of impact assessment or risk assessment, to identify the possible geological or geotechnical risks that you may encounter when drilling or excavating. This will enable you to develop plans and working methodologies to minimize these risks to an acceptable level.

In considering a "desk study" here, we are not talking about the design of a borehole or trench array or of the surficial portions of a GSHP scheme. We will restrict our consideration simply to an assessment whose main concern is to answer the question:

"Do we know what ground conditions and geological sequence we are likely to encounter when we start drilling or excavating?"

As part of this assessment, we will most likely perform the following evaluations:

- Develop a risk-based Health and Safety plan for the drilling / excavation work
- Identify any buried services that we may encounter during our drilling or excavation work. These may include (but may not be limited to):
  - water mains and sewerage pipes
  - culverted streams
  - gas mains
  - electricity cables
  - telecommunications / fibre optic cables
  - strategic gas mains or fuel transport pipelines
  - underground storage tanks
  - transport tunnels, underground railways
  - underground rooms (secret bunkers!)
  - mines and known caves (especially if used for recreational purposes)
  - archaeological remains

  Before commencing drilling or excavating, we will normally also use a cable avoidance tool (CAT), firstly at the surface and then in the base of a shallow hand-dug inspection pit, to confirm the absence of buried structures. Note that a CAT is not a toy and must only be used by a skilled, trained operative. Note also, that it will only detect certain types of buried conduits and will *not detect all services.*

Finally, you also need to make a note of any above-ground services - for example, suspended electricity cables or telephone lines - and establish the safe working distance for a drilling rig or excavator from these cables (this may be governed by legislation)

- Geological and hydrological prognosis

  Can we predict what geological strata / succession we will encounter when drilling? - and thus select appropriate drilling methods?

  - Is there a risk of encountering artesian groundwater conditions? If we unexpectedly encounter strong artesian flows of water it can be very difficult to bring them under control. Uncontrolled artesian wastage of groundwater will be contrary to water resources legislation in many countries and could lead to prosecution or enforcement. If artesian conditions can be predicted, they can be managed by an experienced driller using responsible casing and grouting techniques
  - Is there a risk of encountering multiple aquifer horizons? The uncontrolled hydraulic interconnection of independent aquifer horizons will be contrary to water resources legislation in many countries. Such horizons can be kept separate by an experienced driller using responsible casing and grouting techniques
  - Is a thick evaporite sequence likely to be encountered? Evaporite minerals (e.g. halite, anhydrite, gypsum) carry a significant risk of being dissolved or hydrated by leakage of groundwater along a borehole unless rigorous drilling and grouting techniques are employed. Major geotechnical damage has been allegedly caused at Staufen, Germany, by groundwater migrating along the axes of closed loop GSHP boreholes and hydrating anhydrite to gypsum, in turn resulting in mineral swelling and ground heave (Goldscheider & Bechtel, 2009).

- Is there any risk of encountering contaminated land or groundwater beneath the site (a historical land-use survey will be of value here)? If so, there will be additional Health and Safety concerns for site personnel. It will usually also be necessary to make contact with the relevant Environmental Regulator or local authority to develop drilling / excavation methods that are (a) safe and (b) which do not risk further spreading the contamination in the groundwater, surface or airborne environment. Furthermore, any cuttings / spoil from the borehole or excavation may have to be treated as hazardous waste - it will need to be handled and disposed of appropriately
- Is there any risk that our drilling / excavation work, or indeed the eventual operation of a GSHP scheme, will adversely affect any external:
  - water body or resources

  - environmental habitat (nature reserve, site of special scientific interest etc.)
  - infrastructure
  - groundwater abstraction (neighbouring well or spring). Are you within the source protection zone of any public water supply well? Be aware that your drilling activity could release turbidity or mobilize chemicals that could find their way into a water supply
  - neighbouring ground source heating / cooling scheme?
- Will the operation of our scheme carry a risk of ground movement or subsidence (see "evaporites" under Point 3 above)? In particular:
  - will a ground source heating scheme result in significant amounts of frozen ground? This may carry a risk of "frost heave". Is this acceptable?
  - will our GSHP scheme be operating at high temperatures for prolonged periods? If so, there may be some risk of thermal expansion of the ground. Probably not a major risk for GSHP schemes in a normal operational range. Order of magnitude?? Maybe a few mm to > 10 mm in the worst cases
  - will thermal expansion of pore waters due to warming cause a temporary increase in pore pressures that may reduce the stability of a sediment sequence?
  - will repeated freeze / thaw cycles lead to the settlement of thick sedimentary sequences?
  - will repeated freeze / thaw cycles lead to damage of grout backfill and loss of grout integrity (may be an issue with bentonite-rich grouts - VDI 2001)?
  - will pumping groundwater from an open-loop well lead to significant declines in groundwater head and thus to risk of settlement or compaction of clay-rich or organic-rich soils?
  - does the pumped groundwater from an open-loop borehole contain significant amounts of suspended sediment? (It shouldn't do, if the well has been properly cased, grouted and screened). If so, there is a possibility that you are simply pumping away the ground beneath your feet and risking settlement in the future.

For more advice on these issues, refer to Chapter 13 of Banks (2008).

IV. PERMITS AND LICENCES

The EU's Water Framework Directive (2000/60/EC or **WFD**), and its daughter Groundwater Directive (2006/118/EC), are the primary pieces of European legislation that regulate our use of groundwater and subsurface heat.

They clearly set a framework for the management of (a) the water resources (*quantity*) and (b) the water *quality* of water bodies such as groundwater aquifers. Nevertheless, the WFD's pronouncements on heat are open to considerable scope for interpretation. Paragraph 33 states that:

“Pollution” means the direct or indirect introduction, as a result of human activity, of substances or ***heat*** *into the air, water or land which may be harmful to human health or the quality of aquatic ecosystems or terrestrial ecosystems directly depending on aquatic ecosystems, which result in damage to material property, or which impair or interfere with amenities and other legitimate uses of the environment.*

This does seem to imply that:

- The introduction of heat to the ground or groundwater *can* cause pollution, but only if a relevant risk scenario can be identified. The introduction of heat to the ground or groundwater *can* also be viewed as a positive action if it creates or enhances a resource
- The extraction of heat (introduction of “coolth”) is not classed as pollution.

Furthermore, paragraph 31 of the WFD defines a “*Pollutant*” as “*any substance liable to cause pollution”*. This causes British environmental regulators great problems because “heat” (e.g. from a closed loop GSHP scheme) is not a substance and cannot therefore necessarily be controlled as a pollutant. Hot water (from an open loop scheme) is, however, a substance and can be controlled. No doubt different EU nations have found different ways of interpreting these statements and this may partly be reflected in the variety of different regulatory approaches.

IV. 1. General permissions

Consider whether any of the following permits are required before commencing drilling or excavating:

- Permission from land-owners - not only to drill on their land, but to gain access across it for an excavator or a drilling rig
- Permission from a utilities company: to drill or excavate in the protection zone around a high pressure gas or strategic fuel pipeline, or other services
- Permission from a water utilities company to drill or excavate within the Source Protection Zone of a public (or other protected) water supply
- Permission may also be required from a Planning Authority. In the UK, however, there is a general consensus that Planning Permission is not usually required for a borehole, provided that there are no permanent head-works above ground level.

In some, but not all, EU nations, permission may be required from a Water Resources Regulator, a Mining Regulator or a National Geological Survey before a borehole is commenced.

In England / Wales for example, the situation is unclear. Permission is required from the Environment Agency to drill a borehole for water (e.g. open loop system), and there is also a requirement to notify the British Geological Survey of any borehole drilled for water or minerals. But no permission is currently (early 2009) required in England or Wales (from anyone!) to drill a closed loop GSHP borehole for heat and there is no requirement to notify anyone.

Be aware that in areas of active or historic underground mining, there may be a requirement to obtain a permit from a mining authority before commencing drilling. In the UK, a permit from the Coal Authority is required before drilling in any coal-bearing strata or penetrating any active or abandoned workings. The process of obtaining such a permit should serve to focus the driller’s mind on the potential risks resulting from contaminated mine water and mine gas (asphyxiating

CO_2 or explosive methane) and on the risks of loss of drilling fluid or grout into open abandoned mine cavities.

When a borehole is completed, it is good practice to submit construction details, a location map and a drilling log to the national repository of geological information (often, the national Geological Survey). This may be a legal requirement in many nations.

IV. 2. Closed loop schemes

In most countries, it is fair to say that closed loop GSHP schemes are more loosely regulated than open loop schemes. In some countries, no permission may be required from any authority (e.g. England & Wales, at present - see above), because the borehole is not extracting any physical substance from the ground. The Environmental Authorities merely do what they can to encourage installers to follow a code of good practice (e.g. Section 10 of EA 2008).

In other countries, closed loop boreholes may fall under specific Geothermal, Mining, Water or Environmental legislation.

In Switzerland, for example, closed loop boreholes are regulated by Water / Environmental legislation and there are even “exclusion zones” where no such boreholes are permitted, in order to protect groundwater resources and abstractions from indiscriminate drilling (Rybach, 2003). In Germany (VDI 2000), closed loop GSHP schemes may fall under Water Resource legislation (i.e. defined as “water usage”, even though groundwater is not physically abstracted) and also under Mining Legislation (although this is typically applied only to borehole installations >100 m).

IV. 3. Open loop schemes

Open loop GSHP schemes involve the abstraction and discharge of water - usually groundwater - and thus fall squarely under the Water Framework Directive and the national transpositions thereof.

Normally, national legislation will require some form of license for the abstraction of groundwater from a well, borehole or spring, at least above a certain threshold. In England/Wales, any abstraction over 20 m^3 per day requires an abstraction licence, regardless of whether the water is re-injected back to the aquifer. A prerequisite for the licence will be some form of impact assessment of the hydraulic effects of the abstraction on nearby wells and groundwater-supported habitats. The regulator will often require a pumping test to be carried out. In some cases, where the available water resources of a groundwater body (an aquifer) are fully utilized, a licence may not be granted unless 100% of the water is reinjected to the aquifer from whence it came.

A separate permit may be required to discharge the water back to the aquifer or to a surface water body (river, lake, etc.). In the UK this is termed a discharge consent. A risk assessment of the likely impacts (e.g. heat pollution) resulting from the discharge may be required. The regulator may set limits on:

- the maximum permitted temperature of the discharge
- the permitted water quality of the discharge
- the flow rate of the discharge
- and, maybe, the maximum net heat rejection (MWh/a). This approach may become more common with the increasing density of open loop cooling schemes in urban

areas, where the thermal capacity of aquifers may be approaching a critical point (Ferguson & Woodbury, 2006; Fry, 2009).

If the thermally “spent” water from an open loop scheme is discharged to sewer, permission will usually be required from (and a fee payable to) the relevant utilities undertaker or local municipality.

In some EU nations, the operation of GSHP open loop schemes *may* fall under specific Geothermal legislation or even Mining legislation, rather than solely Water Resources legislation. VDI (2000) details how open loop GSHP systems are licensed in Germany.

V. SITE INVESTIGATION

In many European nations, where the shallow geology is very well mapped and the hydrogeological conditions are well understood, it could be argued that there is little need for a pilot / investigation borehole merely to confirm the geology.

In areas where the geology and hydrogeology are poorly known, there will be value in sinking a pilot borehole before full-scale GSHP scheme construction. Indeed, VDI (2001) recommends a pilot boring, which should be geophysically logged, for all GSHP schemes exceeding 30 kW peak capacity.

The other function of a pilot borehole is to be able to undertake two types of testing, that will have a significant impact on the subsequent design and dimensioning of a ground source heating and cooling scheme. These are:

- hydraulic testing (“test pumping”) - to determine transmissivity (and thence hydraulic conductivity), storage and well efficiency. These are particularly important for designing an open loop GSHP scheme
- thermal response testing (TRT) - to determine thermal transmissivity (and thence average thermal conductivity) and borehole thermal resistance. These are particularly important for designing a closed loop GSHP scheme.

Don’t forget, a pilot or test borehole is seldom wasted money. It can usually be converted to a functioning closed loop GSHP borehole or open loop water well that can be commissioned as part of your final scheme.

VI. HYDRAULIC TESTING - PUMPING TESTS

The process of test pumping a water well is familiar to all hydrogeologists and we will not spend a lot of time here describing the procedure. A good introduction is provided by Misstear *et al*. (2006) and the definitive collection of pumping test interpretation techniques has been written by Kruseman *et al*. (1990). In brief, in a hydraulic pumping test:

- we measure the “static” rest groundwater level (h_0) in an aquifer (strictly speaking, we should talk about groundwater “head”. Head is a measure of hydraulic potential energy.
- we then start to pump a drilled well in the aquifer at a constant rate (Q). In other words, we *stress* the aquifer

- we measure the aquifer's response to stress by measuring the groundwater level (h) at given times (t), either in the pumped well (of radius r_w) or in an observation well at a distance r from the pumped well (Fig. 1)
- for each data point at time t, we calculate the *drawdown* in water level $s = h_0 - h$.

For most conventional groundwater wells, there are normally two types of test that we perform:

- Short term step-testing. This normally comprises a sequence of four or five short 100 - 120 minute tests at increasing pumping rates $Q_1 \ldots Q_5$ (Fig. 2)
- Constant rate testing. A longer pumping test, at a constant rate, representative of operational conditions, for a duration typically of 24 to 72 hours (although it can be longer).

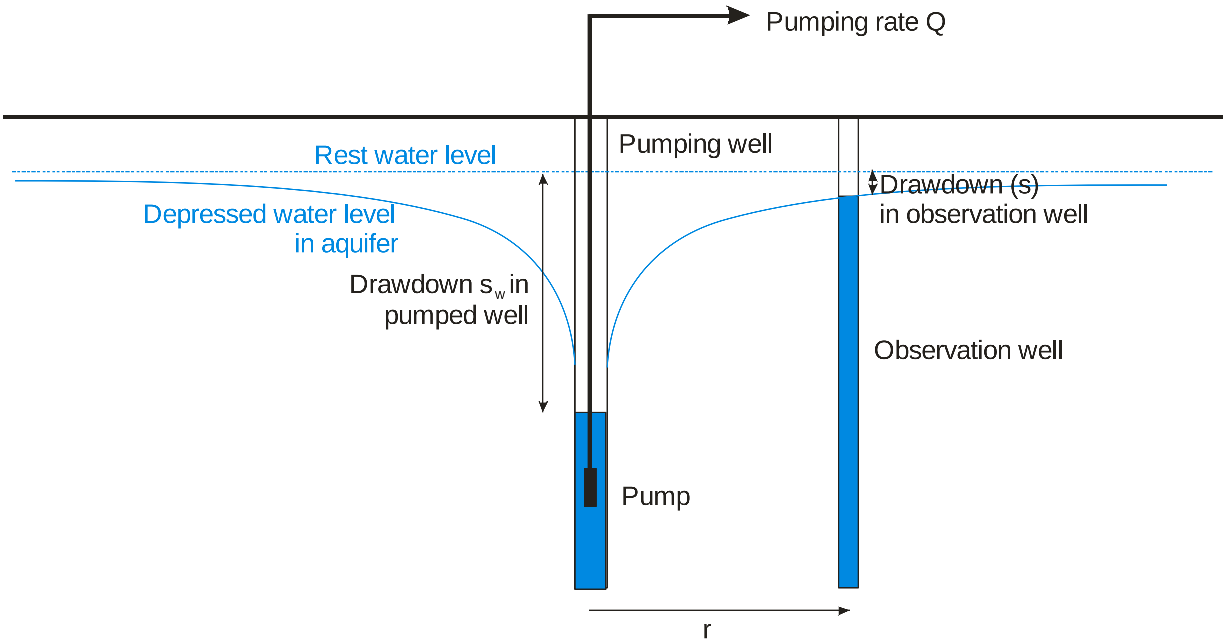

Figure 1. Schematic set-up for a hydraulic pumping test

VI. 1. Step testing

This normally comprises a sequence of four or five short 100 - 120 minute tests at increasing pumping rates $Q_1 \ldots Q_5$ (Fig. 2). Its objective is to provide a measure of the well's hydraulic efficiency and to indicate the maximum yield of the well.

At the end of the test, we will have four or five data points - i.e. four or five values of pumping rate Q and the corresponding value of drawdown in the pumping well (s_w). We can plot these on a diagram of Q versus s_w (Fig. 3). This type of diagram allows us, at one glance, to relate a given yield to a given drawdown, and thus to a given pumping head and energetic efficiency.

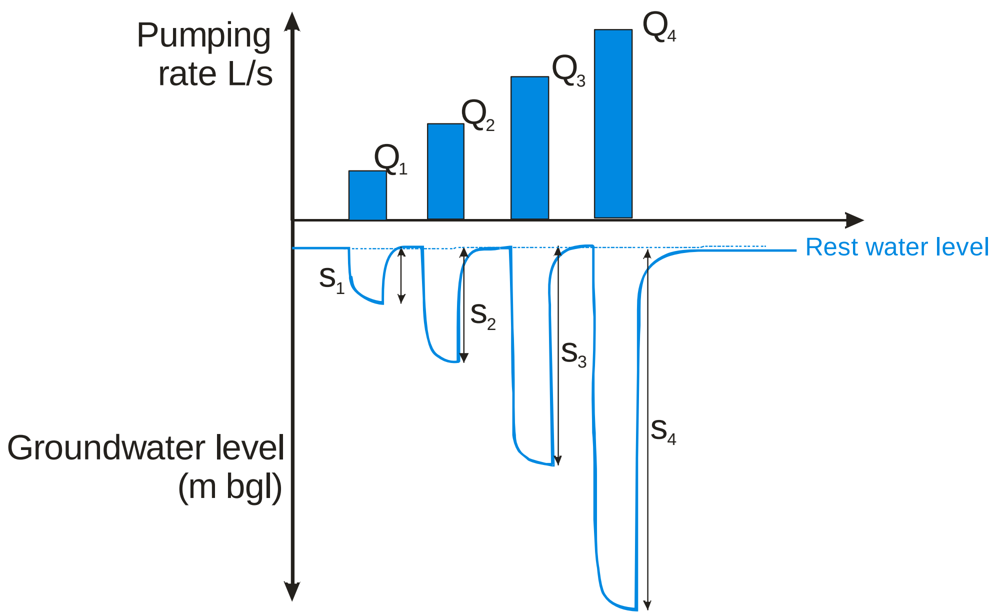

Figure 2. A schematic diagram showing the process of step-testing. The duration of each "step" of the test is typically 100 to 120 minutes. Drawdown is measured in the pumping well

Q (L/s)	s_w (m)
14.7	1.43
31.5	3.46
44.4	5.41
57.6	8.90

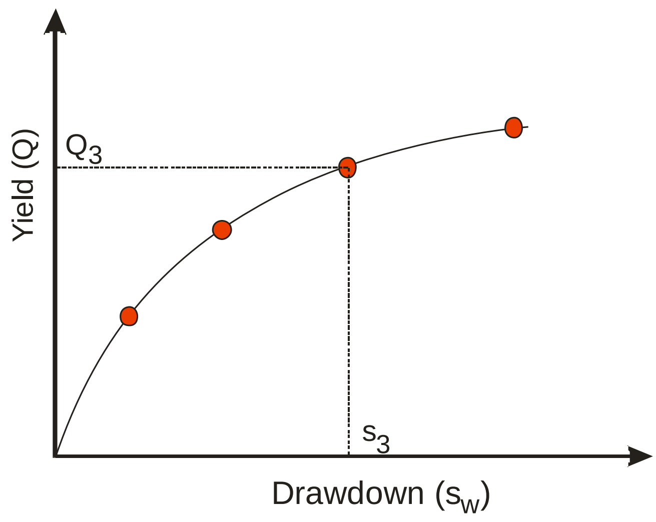

Figure 3. Plotting the yield and drawdown coordinates on a Yield/Drawdown diagram (note that s_w refers to drawdown in the pumped well)

Rather simplified well performance theory states that:

(1) $s_w = BQ + CQ^2$

where: *B* and *C* are constants, corresponding to the aquifer's hydraulic resistance (*B*) and the well's hydraulic resistance (*C*), respectively. For an ideal well, $s_w = BQ$ and we should see a straight line relating s_w and *Q* on Figure 3. Real wells always give a somewhat upwardly convex curve and from this convexity, we can estimate how efficiently the well is performing.

VI. 2. Constant rate testing

Here, we tend to plot the drawdown (*s*) against the elapsed time (*t*) since the start of the test. The drawdown evolves quickly at first and then ever slower with increasing time. If we plot *s* against *t* on log:log paper, we obtain a curve similar to that shown in Figure 4.

The curve in Figure 4 should fit an idealized equation, called the Theis equation:

(2) $$s = \frac{Q}{4\pi T} W\left(\frac{r^2 S}{4Tt}\right)$$

where: *T* = transmissivity, *S* = groundwater storage and W(u) is a complex polynomial expansion, called the well-function.

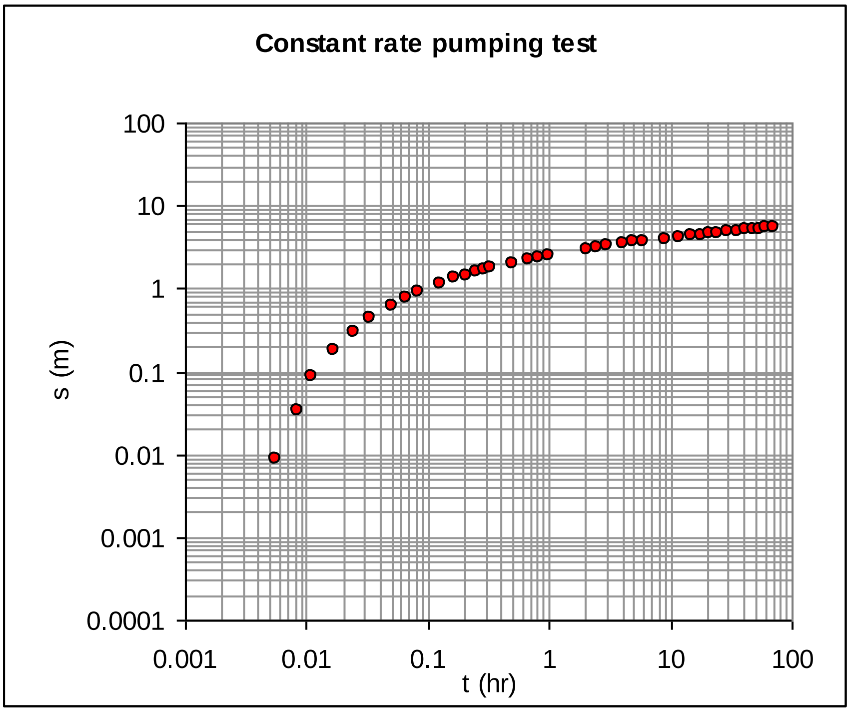

Figure 4. Typical curve from a constant rate pumping test, plotted on log:log paper. Modified after Misstear *et al*. (2006)

By comparing the shape of the curve in Figure 4 to the idealized Theis curve, we can derive a value of transmissivity. Transmissivity is simply the hydraulic conductivity integrated over a finite aquifer thickness. Thus, if an aquifer consists of *n* layers, each of hydraulic conductivity K_n and thickness D_n, the transmissivity is:

(3) $$T = \sum_{1}^{n} K_n D_n$$

Alternatively, if we just consider data at large *t* and/or relatively small *r*, we can use the so-called Cooper-Jacob equation, which is an approximation to the Theis equation:

(4) $$s \approx \frac{Q}{4\pi T}\left[\ln\left(\frac{4Tt}{r^2 S}\right) - 0.5772\right]$$

This predicts that drawdown (*s*) is approximately proportional to ln(*t*). Thus, on a plot of *s* versus log(*t*), the slope of the data trend will be inversely related to *T* (Fig. 5). The intercept of the line will give us a value of *S*.

If we measure the drawdown in the pumping well (i.e. s_w), we can normally derive a reasonable value of *T*. However, if we wish to have a reliable value of groundwater storage *S*, we normally need to measure drawdown (*s*) in an observation borehole (Fig. 1).

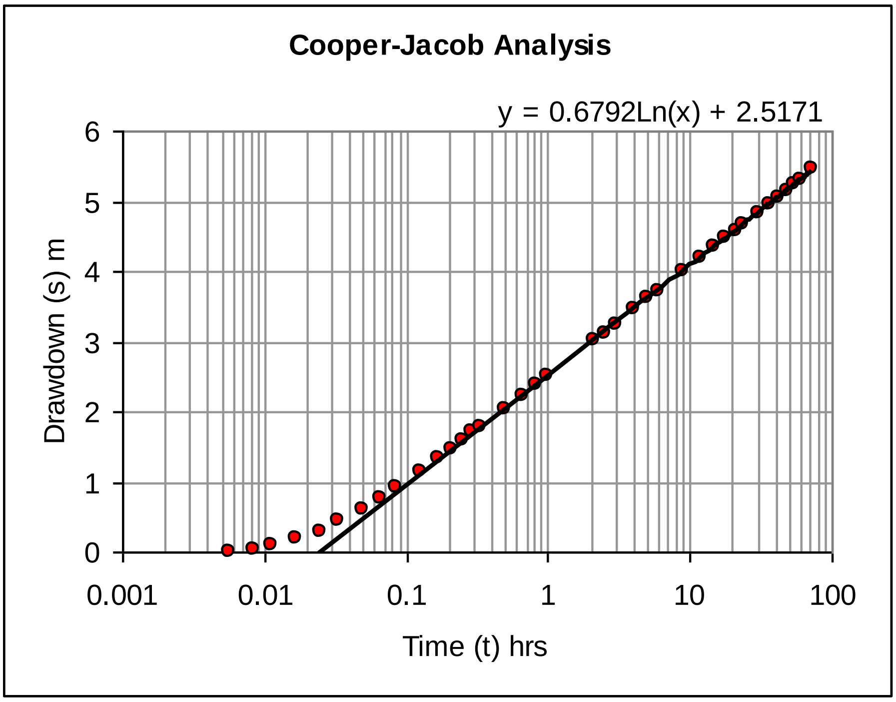

Figure 5. Typical curve from a constant rate pumping test, plotted on log:linear paper. Modified after Misstear *et al.* (2006)

VII. THERMAL RESPONSE TESTING

In a thermal response test:

- we measure the "far-field" initial average ground temperature (T_0) in an aestifer (temperature is a measure of thermal potential energy. Aestifer - a geological unit that stores and transports heat in economically exploitable quantities. From the Latin aestus = summer / heat, ferre = to bear / carry)
- we then start to inject (or extract) heat from a closed loop GSHP borehole in the aestifer at a constant rate (*q*) per drilled metre. In other words, we *stress* the aestifer
- we measure the aestifer's response to stress by measuring the average circulating carrier fluid temperature (*T*) at given times (*t*)
- for each data point at time *t*, we calculate the *thermal displacement* in carrier fluid temperature $\Delta T = T_b - T_0$.

In most thermal response test rigs, the source of heat is one or more electric resistance heaters, whose output is known (power = current x voltage), although gas burners are used as an alternative in some rigs to avoid dependence on an electricity supply. (If we carry out a heat *extraction* test, we would typically use a heat pump). The set-up of most test rigs is as shown in Figure 6.

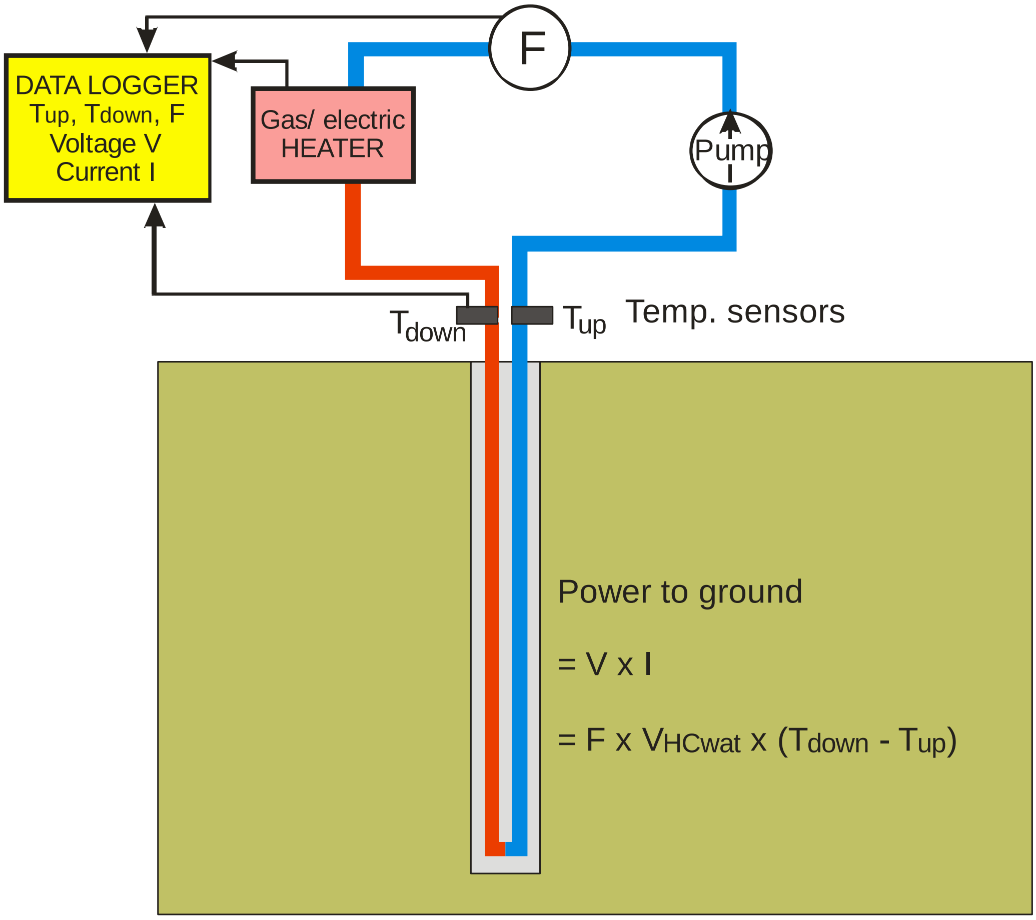

Figure 6. Schematic thermal response test set-up

The temperature of the circulating carrier fluid (usually water) is logged as it enters (T_{down}) and exits (T_{up}) the subsurface closed loop. The flow of carrier fluid (F) is logged, usually via an in-line flowmeter. The heat power transmitted to the ground can be calculated either from the applied voltage x current to the heaters (plus an additional small amount of heat released by the circulation pump) or by:

(5) $Power = (T_{down} - T_{up}) \times V_{HCwat} \times F$

where: V_{HCwat} is the volumetric heat capacity of the carrier fluid = c. 4.19 kJ/L/K - if it is water. The average carrier fluid temperature (T_b) is calculated by:

(6) $T_b = (T_{down} + T_{up})/2$

VII. 1. International guidelines

There is a broad international consensus regarding standard procedure. IGSHPA (2007) has published a set of standards, which broadly reflect the recommendations of The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE 2002, 2007). The main points of these are summarized below (but the reader is referred to the original documents for the full versions):

- *Test durations of 36 to 48 hours are recommended*
- *Standard deviation in applied power should be <1.5% of average power and spikes should be <10% of average power*
- *Heat rates of 50 to 80 W per drilled metre should be applied*
- *A minimum of 5 days shall elapse between loop completion / grouting and test start-up*
- *An initial measurement of undisturbed ground temperature measurement should be made at the end of the equilibration period either by:*
  - *direct insertion of a probe inside the closed loop heat exchanger at various depths, or*
  - *measurement of fluid return temperature from loop on commencement of test*
- *Carrier fluid flow rates that result in a 3 to 7° C differential between flow and return temperatures are recommended*
- *The rig heater and above ground portions of the loop should be well insulated to limit heat loss to less than 2% of total heat input at the minimum outdoor temperature possible during testing*
- *Borehole diameter should be <6 inches (150 mm) according to IGSHPA (2007)*
- *If a test needs to be restarted, the loop temperature should be allowed to naturally return to within 0.5° C of the original undisturbed temperature before restarting. ASHRAE note that, following a 48 hour test, a re-equilibration period of 10-12 days is likely to be necessary in higher conductivity formations and 14 days in lower conductivity formations.*

Draft Guidelines (Sanner *et al*., 2005) have also been developed by the working group of Annex 13 “wells and boreholes” of the Implementing Agreement on Energy Conservation through Energy Storage of the International Energy Agency (IEA). The salient points of these are summarized as follows:

- *The test should run with a constant thermal load for at least 50 hours*
- *The rig should be placed as close to the borehole head as possible and all connecting pipes thermally insulated*
- *The initial ground temperature should be determined by one of two methods:*
  - *measuring the temperature profile inside the heat exchanger pipes (without circulation)*
  - *after the circulation pump is started, record the first 10-20 minutes of pumping through the pipe without applied heat load*
- *Typical values of applied thermal load during a heat injection test should be between 30 W/m (low conductivity formation) and 80 W/m (high conductivity*

formation). (In the case of a heat extraction test, Prof. Javier Urchueguía suggests 20-50 W per drilled metre)

- *Carrier fluid flow rate should be turbulent throughout the test and never laminar. Carrying out a test with laminar flow will tend to overestimate borehole thermal resistivity.*

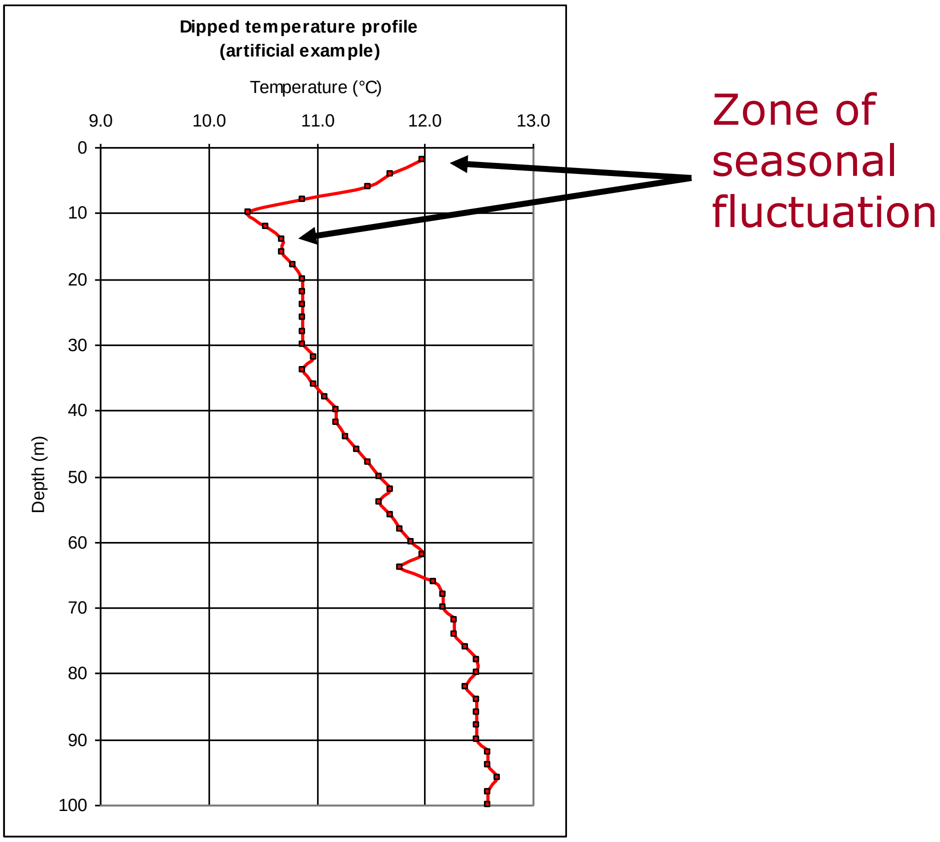

Figure 7. Example of "dipped" temperatures in a closed loop GSHP borehole. Note the "seasonal fluctuation" in the top, say, 10 m of borehole. The average temperature T_0 is calculated at 11.7° C

VII. 2. Measurement of initial temperature

As will be seen from the above, it is important to measure the initial average temperature of the ground (T_0) along the length of the closed loop borehole. This can be achieved either by "dipping" the borehole with a thermocouple on a graduated tape, and taking an average of the readings at every, say, 2 m (Fig. 7).

Alternatively, carrier fluid can be circulated throughout the loop (without any heat input). The temperature of the return fluid can be observed over the duration of one fluid cycle through the loop (Fig. 8). The average return fluid temperature over this duration will approximate to T_0.

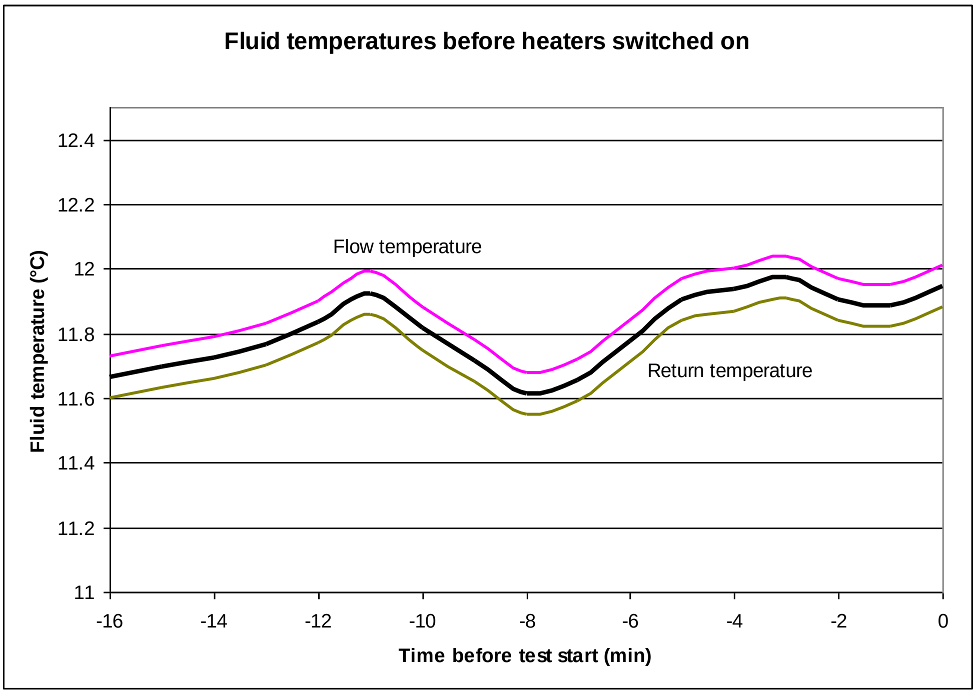

Figure 8. Example of fluid temperatures in pre-test phase where carrier fluid is circulating before heater switch-on; the average return fluid temperature in the initial 8 minutes is 11.7°C (Note that the flow temperature is slightly warmer than the return temperature, due to a small heat input from the circulation pump itself)

VII. 3. The heating test

After the heaters are switched on at time $t = 0$, the mean fluid temperature evolves quickly at first and then ever slower with increasing time. If we plot average fluid temperature (T_b) against t, we obtain a curve similar to that shown in Figure 9. Clearly the thermal response test can be conceived as being analogous to a constant rate aquifer test; temperature (T_b) is analogous to drawdown (s) and heat injection rate (q) is analogous to groundwater pumping rate (Q).

The average fluid temperature in the borehole after heater switch-on (T_b) evolves analogously to drawdown (s) in a constant rate aquifer test. A simple assumption regarding heat transfer within the borehole heat exchanger itself (borehole thermal resistance R_b) leads to a theoretical equation describing how T_b evolves following heater switch-on:

(7) $$T_b - T_0 = \frac{q}{4\pi\lambda} E\left(\frac{r_b{}^2 S_{VC}}{4\lambda t}\right) + qR_b$$

where:

q = heat input per installed metre of loop (W/m)

λ = thermal conductivity of rock (W/m/K)

S_{VC} = volumetric heat capacity of rock

r_b = borehole radius

$E(u)$ = complex polynomial function, which looks suspiciously like the Theis well function (equation (2))!

R_b = borehole thermal resistance (Km/W)

At large values of *t* (typically *t* > 10 hours), this equation can be simplified to a logarithmic expression (which looks suspiciously like the Cooper-Jacob approximation (equation (4))

(8) $$T_b - T_0 = \frac{q}{4\pi\lambda}\left[\ln\left(\frac{4\lambda t}{S_{VC} r_b^{\ 2}}\right) - 0.5772\right] + qR_b$$

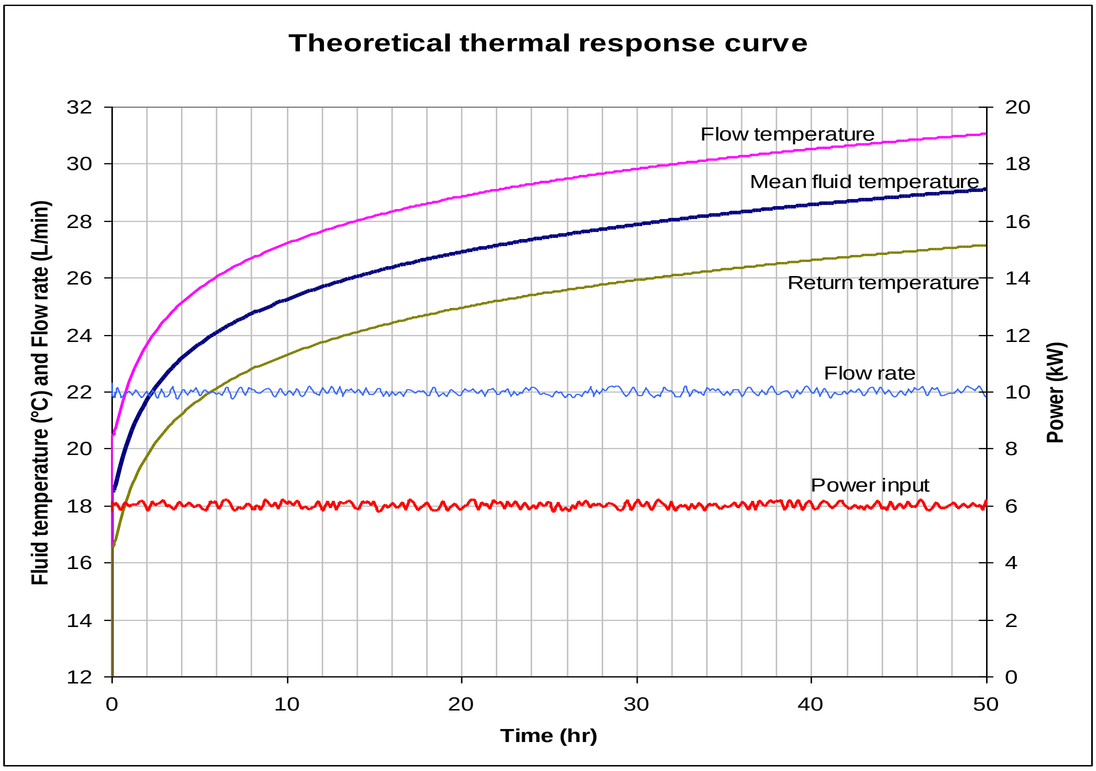

Figure 9. Typical evolution of fluid temperatures in a thermal response test (idealized curve)

Thus, if we plot the temperature displacement

9) $\Delta T = T_b - T_0$

against the natural logarithm of time (t), we should get a straight line whose slope is $\frac{q}{4\pi\lambda}$ (Fig. 10). Thus, in Figure 10, the slope of the $\log_e$ plot is 2.3957 (the slope of the $\log_{10}$ plot is nearer 5.52). If the heating power is 6 kW and the borehole depth is 100m, then *q* = 60 W/m and the thermal conductivity is given by:

(10) λ = 60 W/m / (4 x 3.1415 x 2.3957 K) = 1.99 W/m/K

If we assume a value for the *volumetric heat capacity* of the ground (S_{VC}), which does not normally vary greatly for saturated strata (typically 2 to 2.5 MJ m^{-3} K^{-1}), then we can also use the intercept of the graph on the y-axis to calculate a value of the borehole thermal resistance (R_b) in Km/W (Banks 2008). Sanner et al. (2000) and Mands & Sanner (2001) cite values of borehole thermal resistance between 0.06 and 0.50 Km/W for thermal response tests in

Germany. All except two of the German tests yield values below 0.12 Km/W, however, while boreholes filled with thermally enhanced grout yield values of 0.06 – 0.08 Km/W.

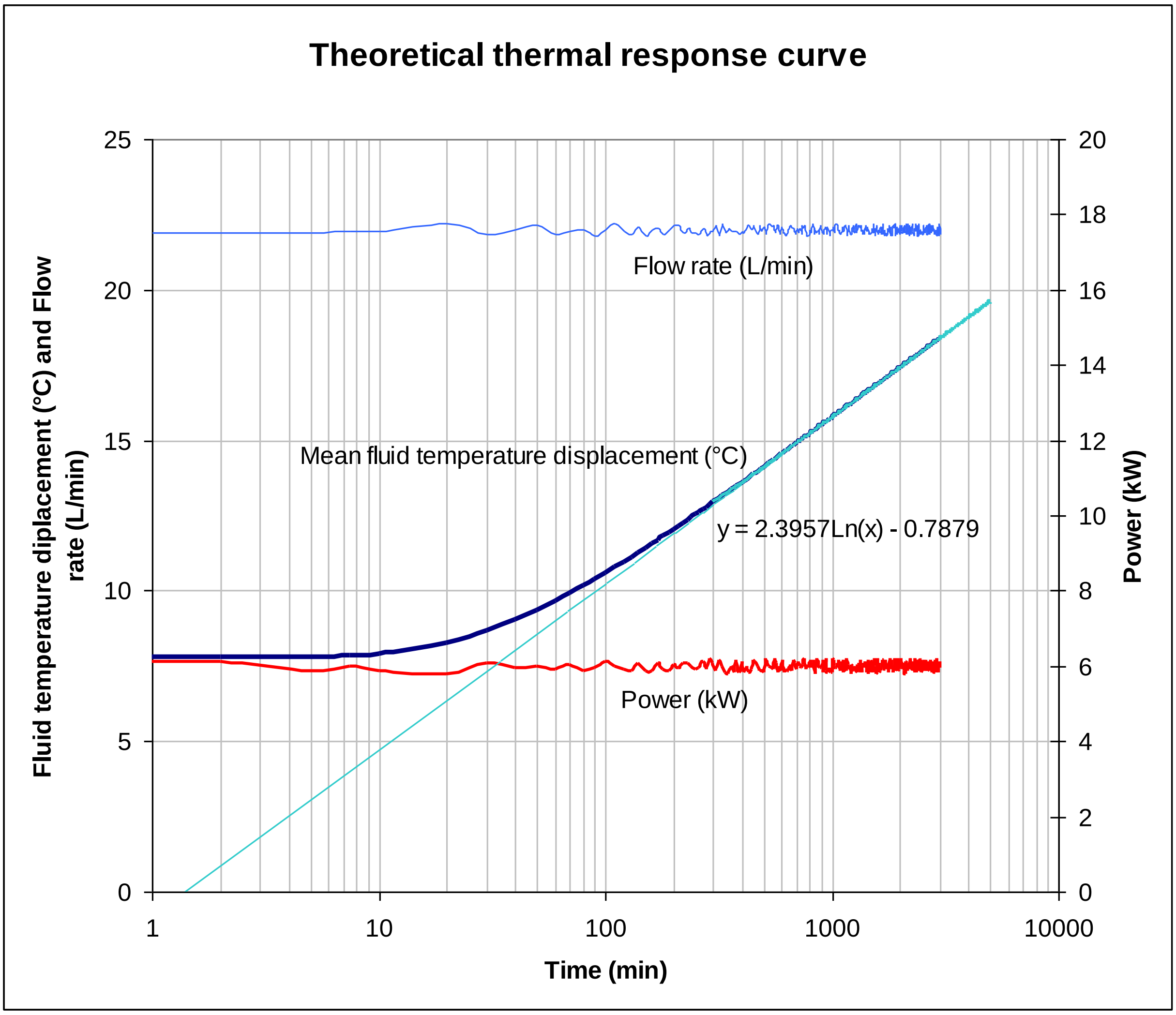

Figure 10. Typical evolution of fluid temperatures in a thermal response test, plotted as temperature displacement on a log:linear plot (idealized curve)

VII. 4. Alternative methods of analysis

The method of analysis described in VII.3. is termed the “line source method”. It does not really simulate very realistically the temperature evolution within the backfill of the borehole itself - it merely treats the borehole as a steady-state thermal resistance. For this reason, we need long tests to “see” into the rock beyond the borehole wall.

Other methods of analysis are available, of increasing complexity, which treat the borehole in a more sophisticated manner. The cylinder source method, for example, treats the borehole as a finite cylinder rather than a “line” of negligible radius. If we have time and money to burn, or if we wish to assess other parameters (such as volumetric heat capacity) in a more detailed way, we can use numerical models to simulate the thermal response test.

The method described above requires that the heat input to the borehole is constant. This can, occasionally, be a little tricky to maintain - perhaps due to unforeseen wobbles in a generator's output or due to loss of heat to (or gain from) the atmosphere through header pipes between the rig and the borehole top (although these header pipes should be insulated with reflective insulation to minimize this effect). If we have a set of test data which does not have a constant power input, there are ways around this. We can simulate the varying heat input by superimposed step functions, each step obeying an equation of the form of (*7*) or (*8*). Or we can use some form of parameter-fitting model of the type developed by Shonder & Beck (2000) and applied in their freely available GPM (*Geothermal Properties Measurements*) code. Other dynamic simulation models that can be used for parameter-fitting include TRNSYS, EPlus and 3D-CFD.

VII. 5. Recovery test

At the end of our heating test, the heaters will be switched off and fluid temperatures will return back towards the initial ground temperature in a shape which almost exactly mirrors the heating curve (Fig. 11). It only "almost exactly" mirrors the heating curve because, in the recovery phase, there will still be a small input of heat (maybe 100-300 W) from the circulation pump / frictional fluid losses in the pipe. Thus, the curve never quite returns to its starting point. However, the recovery curve can be analysed, if the input from the circulation pumps is approximately known to yield a "backup" set of values of λ and R_b.

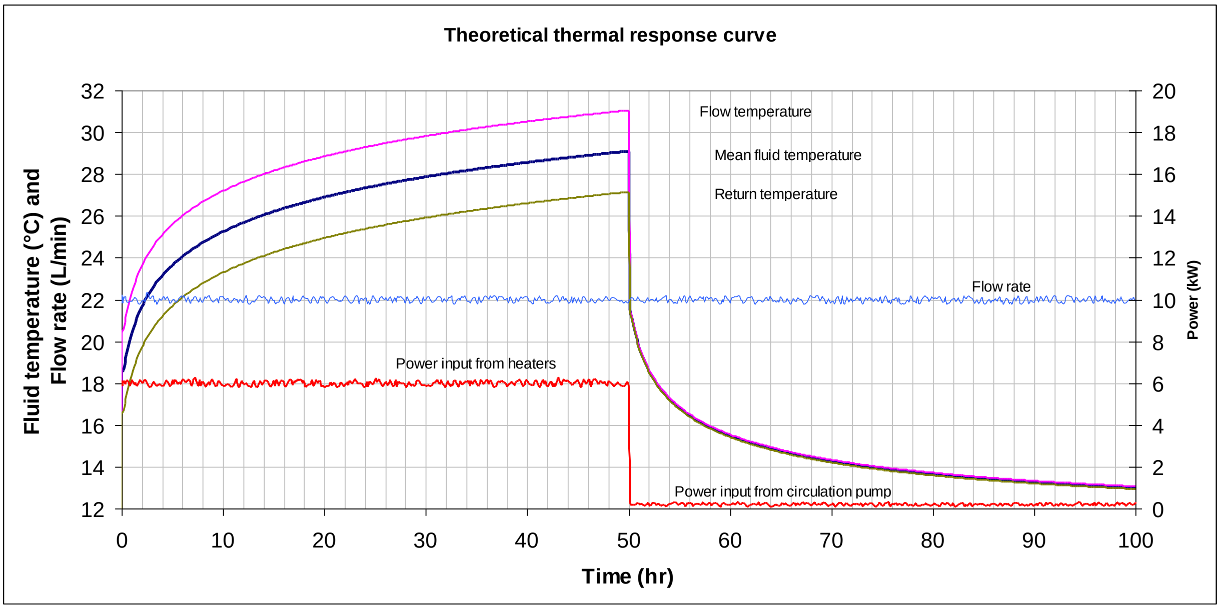

Figure 11. Theoretical curves for fluid temperature evolution during a thermal response test and subsequent thermal recovery test

VII. 6. Uncertainty in results from a thermal response test

The results from a thermal response test *must* be cited with an associated indication of uncertainty (or, as consultants like to call it, confidence !). Thus, we might say that:

λ = 2.0 ± 0.2 W/m/K

Note that the level of confidence cited in the results of line-source analysis of thermal response tests typically reaches around 10% (Gehlin, 2002; Signorelli *et al*., 2007). Zervantonakis & Reuss (2006) cite typical levels of confidence of 9% in λ, and 14% in R_b.

Finally, note that the output from a thermal response test is, strictly speaking, the thermal transmissivity of the geological sequence penetrated. Thermal transmissivity is simply the thermal conductivity integrated over a finite aestifer thickness. Thus, if GSHP closed loop borehole penetrates a rock sequence comprising of n layers, each of thermal conductivity λ_n and thickness D_n, the thermal transmissivity is:

(11) $$T_{th} = \sum_{1}^{n} \lambda_n D_n$$

Strictly speaking, the slope of a log-linear thermal response test plot of the type in Figure 9 is equal to:

(12) $$Gradient = \frac{q}{4\pi\lambda} = \frac{Q}{4\pi\lambda H} = \frac{Q}{4\pi T_{th}}$$

where: Q = total heat power input and H = borehole depth. The value of thermal conductivity (λ) we derive from the test is really only the average thermal conductivity of the geological sequence - in other words, T_{th}/H. This may be important if the geological sequence comprises a number of layers of differing thermal conductivity.

VIII. COST VERSUS BENEFIT FOR SITE INVESTIGATION

A desk study should always be performed before installing a GSHP system. The cost of such a desk study in time and effort is usually low (probably only several hundred € for domestic schemes), but the potential risks involved if you neglect the desk study are huge.

For example, you may find yourself in a situation where you do not know what geological and hydrogeological conditions to expect when drilling a borehole. Drilling through 60 m of boulder clay before reaching granite can add thousands of € to your drillers' invoice, if you were only expecting 6 m of clay before reaching bedrock. Likewise, penetrating unexpected flooded mine workings at 50 m depth may require costly strings of permanent casing. Encountering a strongly artesian (overflowing) aquifer can take a large amount of time and effort to bring under control, and may lead to prosecution by regulatory bodies.

More seriously, drilling through anthrax-contaminated ground leads to serious health risks for drillers. A coal mine filled with methane or a high pressure gas pipeline could lead to an exciting explosion sufficient to destroy several houses. Drilling through a fibre optic cable could land you with a repair bill in excess of € 1 million. A desk study is well worth the effort.

Likewise, early liaison with regulatory authorities should lead to a cooperative approach to problem-solving, permitting and licensing, rather than a confrontational one. Don't forget that most environmental regulators should, in principle, be eager to see a carbon-saving GSHP scheme up-and-running: they should not want to hinder you at every turn. Remember that a good relationship with an environmental regulator can be worth its weight in gold – they often have valuable geological information and can even be a source of free advice and consultancy.

Money invested in penetrative site investigation can be a little more difficult to justify, especially if the GSHP scheme is small and/or the geology and ground conditions at the site are well constrained by a desk study. But let us take an example: let us imagine that we are designing a ground source heating scheme in a limestone area. Scientific literature tells us that the thermal conductivity is around 2.9 ± 0.5 W/m/K. In the worst case, therefore, the thermal conductivity could be 2.4 W/m/K (and in the best case 3.4 W/m/K). If we design our scheme on the basis of the 2.9 W/m/K figure we may find that we require 8 boreholes to 100 m. If we are responsible designers, however, we may choose to incorporate a factor of safety and use the worst conceivable value of 2.4 W/m/K, leading to a recommendation for 10 boreholes to 100 m (1000 m total).

Now let's say that we perform a thermal response test and the result comes out as 3.1 ± 0.3 W/m/K. We have received a payback from our investment in the test: our margin of uncertainty is much reduced. Our worst case thermal conductivity is now 2.8 W/m/K and we might be able to recommend an array of 8 boreholes to 105 m (total 840 m). We have saved 160 m drilling – a potential cost saving of maybe € 6400, set against the cost of the TRT, which was maybe € 5000.

The point at which a thermal response test becomes worthwhile is thus governed by the relative costs of drilling additional borehole metres and of the test itself. As a general rule of thumb, it often becomes worthwhile doing a thermal response test when we are dealing with around 800-1000 m of drilling (8-10 bores to 100 m).

Remember, of course, that our thermal response test may have given a value of 2.2 ± 0.2 W/m/K ! If we had used our original "worst" guess of 2.4 W/m/K we may have ended up with an under-dimensioned array. Our thermal response test has saved us from that ignominious fate !

VIII. CONCLUSIONS

Time and effort expended in carrying out a through desk study of ground conditions (buried services, contamination risk, mining history, geology, hydrogeology and thermogeology) prior to commencing the design and installation phase of a GSHP scheme is always well-invested.

Likewise, a clear understanding of the regulatory framework and the necessary licenses and permits will enable an early approach to be made to the regulator, with a view to solving potentially contentious issues at an early stage and licensing the scheme in a timely manner.

With increasingly large GSHP schemes, the investment in penetrative site investigation becomes increasingly attractive, in order to more tightly constrain the subsurface hydrogeological and thermogeological conditions.

IX. FURTHER INFORMATION

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CHAPTER 10

HEAT PUMP TECHNOLOGY *by Javier Urchueguía and Paul Sikora*

I. INTRODUCTION

Among the final consumers of energy, the residential sector occupies one of the main positions. In recent years, the European Union has shown growing interest in making the energy consumption of buildings more efficient and better for the environment. Heat pumping technologies are widely used for upgrading natural low-temperature energy from renewable sources, such as air, water, ground and waste heat, to useful temperatures. They are used for residential and commercial space and water heating, cooling, refrigeration and in industrial processes.

The heat pump is a very efficient system. This advantage is enhanced when integrating the use of renewable energies (solar, thermal) in the processes that use heat pumps applied to buildings. In Figure 1 we can see the evolution in sales of renewable energy in Europe from 2005 to 2008. From 2007 to 2008 sales have increased by nearly 50%

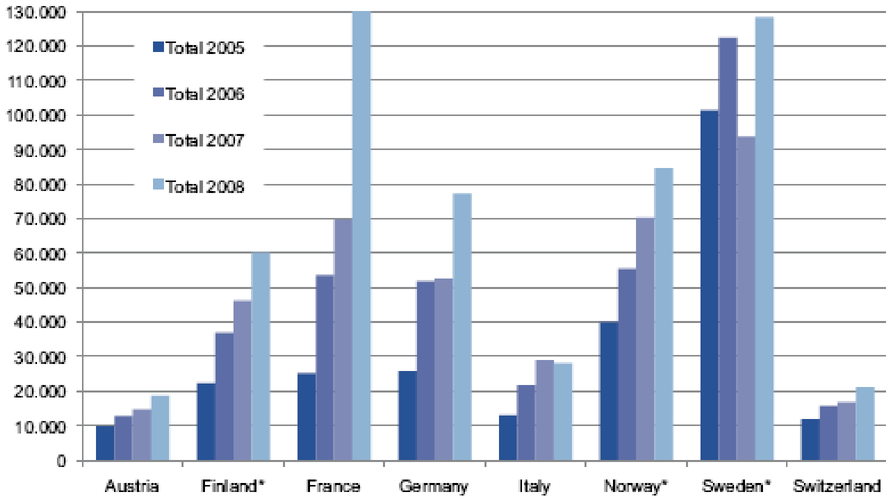


Figure 1. Sales of renewable energy In Europe, 2005 – 2008

The aim of this chapter is to inform designers about the technology of the heat pump so that they are able to make a correct choice in the design of a GSHP. The selection phase of a heat pump must be carried out subsequent to the thermal load analysis phase and after the internal distribution system is defined.

The designer must understand the differences between a GSHP and a conventional system of heat pump.

It is very important to be rigorous in choosing the heat pump because that conditions the design of the geothermal heat exchanger.

II. THEORY

II. 1. Definition

It seems natural that heat energy will flow from a hot object to a cold object. Heat Pumps use work to reverse the "natural" direction of heat energy flow.

A heat pump is a machine or device that moves heat from one location (the 'source') to another location (the 'sink' or 'heat sink') using mechanical work. A heat pump is subject to the same limitations from the second law of thermodynamics as any other heat engine and therefore a maximum efficiency can be calculated from the Carnot cycle.

A European standard for testing and rating heat pump performance, EN 14511 – Part 1, defines a heat pump as follows:

"[a] heat pump [is an] encased assembly or assemblies designed as a unit to provide delivery of heat. It includes an electrically operated refrigeration system for heating. It can have means for cooling, circulating, cleaning, and dehumidifying the air. The cooling is by means of reversing the refrigeration cycle".

The advantage of pumping heat is that it takes less electrical energy than it does to convert electrical energy into heat (as in electric furnaces, baseboards and radiant heaters). In fact, in mild winter temperatures you can get three times as much heat out of each watt of electricity as you get from an electric furnace.

II. 2. How a heat pump works

The working fluid, in its gaseous state, is pressurized and circulated through the system by a compressor (Fig. 2). On the discharge side of the compressor, the now hot and highly pressurized gas is cooled in a heat exchanger, called a condenser, until it condenses into a high pressure, moderate temperature liquid.

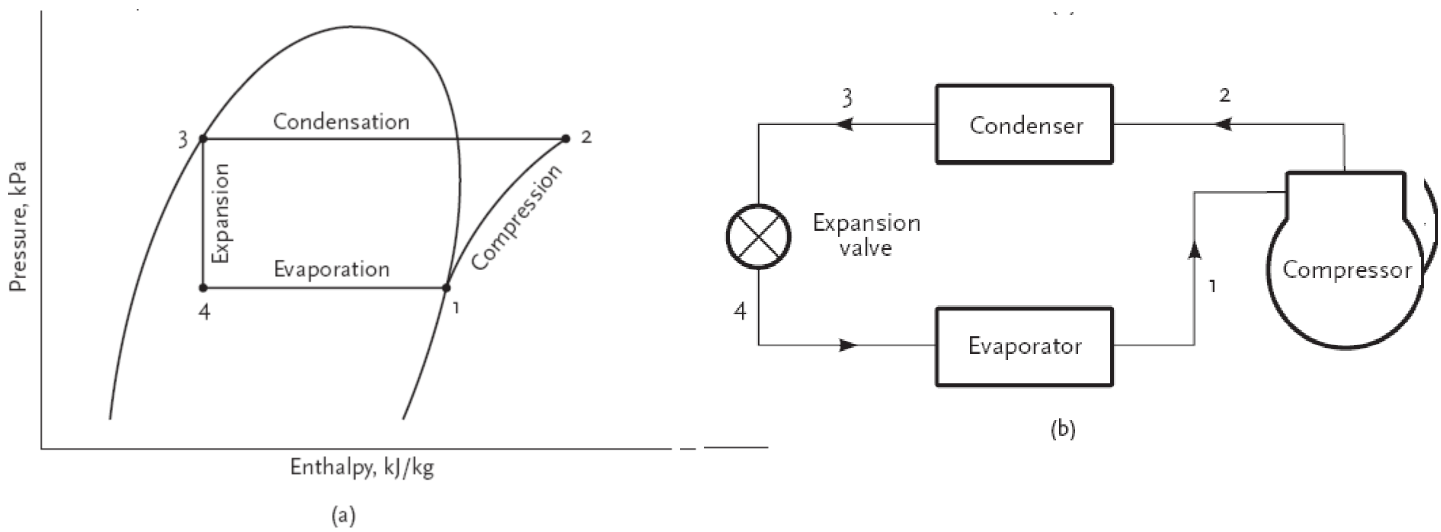
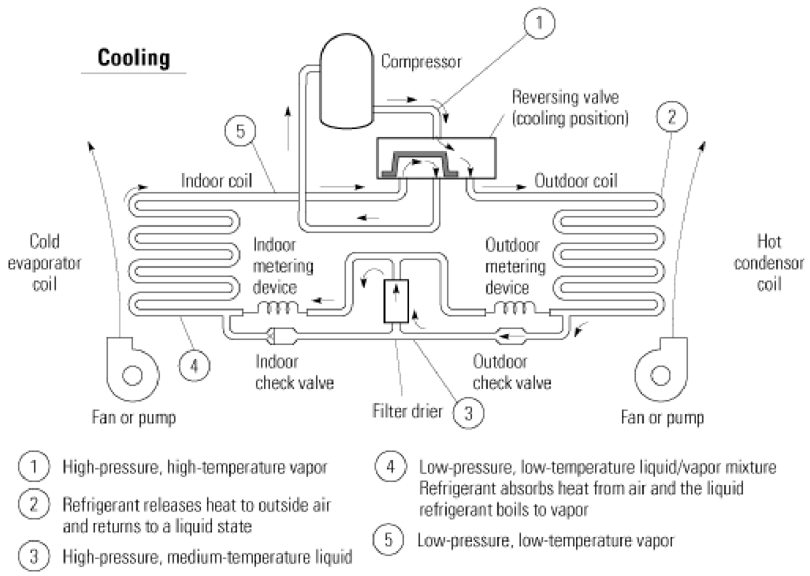


Figure 2. (a) Carnot and (b) Heat pump scheme

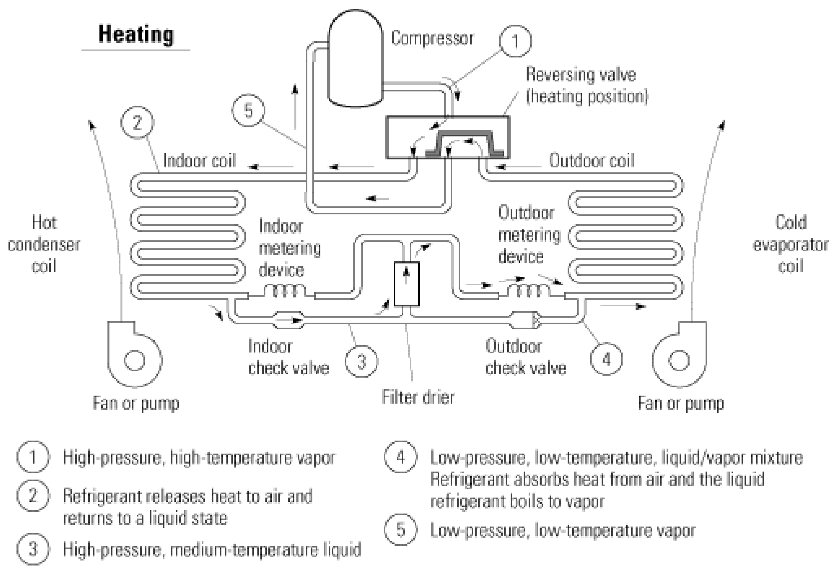
The condensed refrigerant then passes through a pressure-lowering device like an expansion valve or capillary tube. This device then passes the low pressure, (almost) liquid refrigerant to another heat exchanger, the evaporator, where the refrigerant evaporates into a gas via heat absorption. The refrigerant then returns to the compressor and the cycle is repeated.

II. 3. Heating and cooling mode

Heating and cooling modes of heat pumps do exactly the same thing. They "pump" the heat from one location to another (Fig. 3). In cooling mode, it functions just like an air conditioner, moving heat from the inside of a building to the outside; in heating mode, the refrigerant flow is reversed so it takes low-temperature heat from the source and mechanically concentrates it to produce high-temperature heat, which is then delivered to a building.



3a. Heat pump cooling mode



3b. Heat pump heating mode

Figure 3. Schematic diagram of an air-to-air heat pump operation (adapted from ASHRAE)

II. 4. Components of a heat pump

The components of a heat pump are:

- The refrigerant - the substance which circulates through the heat pump, alternately absorbing, transporting, and releasing heat
- The reversing valve - controls the direction of flow of the refrigerant in the heat pump
- The evaporator - a coil (heat exchanger) in which the refrigerant absorbs heat from its surroundings and boils to become a low-temperature vapour
- The compressor - squeezes the molecules of the refrigerant gas together, increasing the temperature of the refrigerant
- The condenser - a coil (heat exchanger) in which the refrigerant gives off heat to its surroundings and becomes a liquid
- The expansion device - releases the pressure created by the compressor.

There are different types of heat exchanger (condenser or evaporator) in a heat pump, the most common are:

  - Shell-and-tube heat exchangers (Fig. 4) are fabricated with round tubes mounted in cylindrical shells with their axes coaxial with the shell axis. There are various design considerations to be taken into account such as routing of fluids (shell or tube), pressure drop, etc.

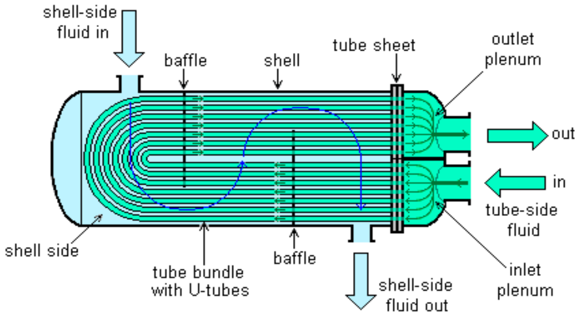


Figure 4. Tube heat exchanger scheme

  - Plate and frame heat exchangers (Fig. 5) are usually built of thin plates. The plates are either smooth or have some form of corrugation, and they are either flat or wound in an exchanger. Generally, these exchangers cannot accommodate very high pressures and temperatures.

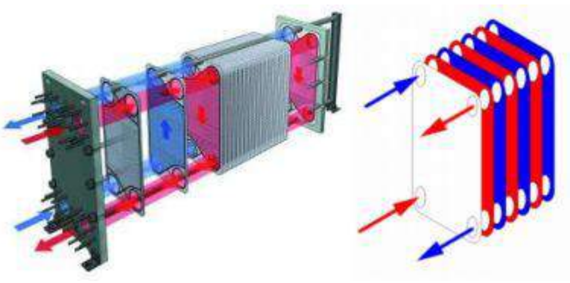


Figure 5. Plate and frame heat exchanger

Typical shell and tube heat exchangers use a “bundle” of tubes encased in a shell, in which heat energy is transferred from hot liquids or gases flowing in through the tubes to liquid or coolant which flows over and around the tubes within the shell, capturing heat energy and flowing back out. Plate and flat plate heat exchangers work similarly with hot and cold liquid chambers separated by metal plates.

Among the compressors, we can distinguish three different types used in a heat pump:

- Piston compressors - a positive-displacement compressor (Fig. 6) that uses pistons driven by a crankshaft to deliver gases at high pressure. The intake gas enters the suction manifold, then flows into the compression cylinder where it is compressed by a piston driven in a reciprocating motion via a crankshaft, and is then discharged
- Screw compressor - a type of gas compressor (Fig. 7) which uses a rotary type positive displacement mechanism. The rotary-screw compressor uses two meshed rotating helical rotors within a casing to force the gas into a smaller space
- Compressor scroll - a compressor (Fig. 8) that has two spiral walls or rotary components that intermesh with each other and are used to compress a refrigerant. One of the spiral-shaped components is generally fixed, or stationary, and the other is driven in an orbiting pattern to perform its function. Scroll compressors are simpler and more efficient than piston units.

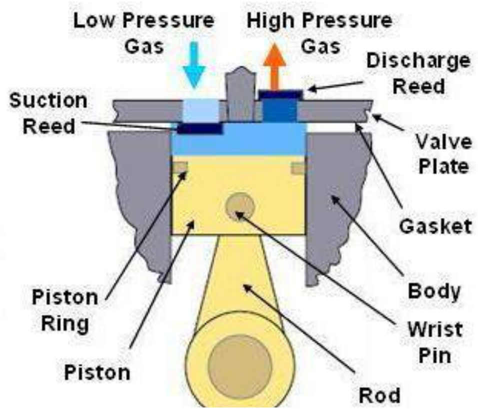


Figure 6. Piston compressor scheme

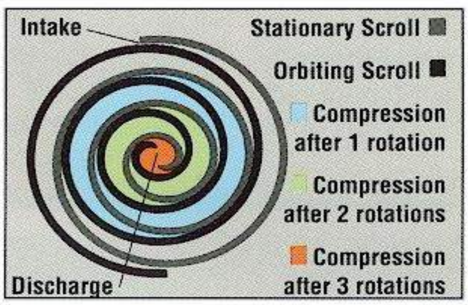


Figure 8. Scroll compressor scheme

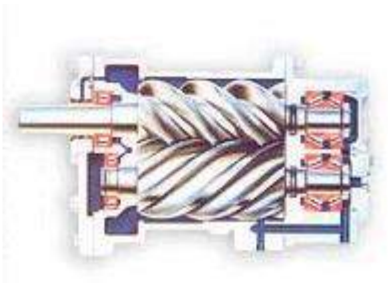


Figure 7. Screw compressor scheme

III. REFRIGERANTS

A refrigerant is a compound used in a heat cycle that undergoes a phase change from a gas to a liquid and back. The two main uses of refrigerants are refrigerators/freezers and air conditioners.

The ideal refrigerant has good thermodynamic properties, is non-corrosive, and safe. The desired thermodynamic properties are a boiling point somewhat below the target temperature, a high heat of vaporization, a moderate density in liquid form, a relatively high density in gaseous form, and a high critical temperature. Since boiling point and gas density are affected by pressure, refrigerants may be made more suitable for a particular application by choice of operating pressure. Corrosion properties are a matter of materials compatibility with the components used for the compressor, piping, evaporator, and condenser. Safety considerations include toxicity and flammability.

The main refrigerants can be classified into three different groups:

- CFCs - have been used as refrigerants in air conditioners and refrigerators, in aerosol spray cans, in manufacturing foams as industrial solvents, and as cleaning agents in the manufacture of electronics. One U.S. chemical industry gave them the trade name of "Freons," and the term has since become a household word. Chemically, CFCs are a subset of the more general class of compounds known as halocarbons (carbon- and halogen-containing compounds). CFCs are halocarbons that contain only the elements carbon, chlorine, and fluorine. The most common CFCs are small molecules containing only one or two carbon atoms. CFCs, have the highest Ozone Depletion Potential (ODP)
- HCFC - refers to the chemical composition of the refrigerant. Hydrochloric-Fluoro-Carbon indicates that the refrigerant is comprised of Hydrogen, Chlorine, Fluorine, and Carbon. HCFCs are man-made chemicals used as refrigerants and in producing foam materials. They are non-flammable gases. Along with other substances, they act in the upper atmosphere to destroy the ozone layer above the Earth which helps to protect the Earth's surface from harmful ultraviolet radiation. They also contribute to global warming. The major releases of HCFCs are as leakage from refrigeration and air conditioning equipment. There are no natural sources of HCFCs
- Hydrofluorocarbons (HFCs) - a group of compounds containing carbon, fluorine and hydrogen (unlike HCFCs, which also contain chlorine). They are generally colourless and odourless gases at environmental temperatures and for the most part chemically unreactive. HFCs are mainly used as substitutes for CFCs and HCFCs (ozone depleting substances) that are being phased out under the 1987 Montreal Protocol. Major usage is as refrigerants in refrigeration and air conditioning equipment and as propellants in industrial aerosols and newer MDIs (Metered Dose Inhalers, e.g. for asthma). Minor uses include foam-blowing (e.g. making plastic foams for food packaging), solvent cleaning and in some fire extinguishing systems.

III. 1. Montreal Protocol

Since it was discovered in the 1980s that the most widely used refrigerants (CFCs) were major causes of ozone depletion, a worldwide phase-out of ozone-depleting refrigerants has been undertaken. These were being replaced with "ozone-friendly" refrigerants (HCFCs, HFCs). In 1987, the Montreal Protocol, an international environmental agreement, established requirements that began the worldwide phase-out of ozone-depleting CFCs (chlorofluorocarbons).

Phase-out schedule for HCFCs and CFCs for developed countries	
Date	Control Measure
1 January 1996	CFCs phased out (1) HCFCs frozen at 1989 levels of HCFC + 2.8% of 1989 consumption of CFCs (base level)
1 January 2004	HCFCs reduced by 35% below base levels
1 January 2010	HCFCs reduced by 65%
1 January 2015	HCFCs reduced by 90%
1 January 2020	HCFCs phased out allowing for a service tail of up to 0.5% until 2030 for existing refrigeration and air-conditioning equipment

IV. EFFICIENCY

There are various terms that define the efficiency of a heat pump.

All of these terms depend on:

- The efficiency of the heat pump (determined mainly by the quality of its components)
- The temperature of the heated or cooled water/air produced by the heat pump
- The temperature of the incoming brine (water/antifreeze mix) from the ground loop (in the case of a ground source heat pump) or the outdoor air (in the case of an air source heat pump).

IV. 1. Classification of terms

The coefficient of performance (COP) is a measure of a heat pump's efficiency. It is determined by dividing the energy output of the heat pump by the electrical energy needed to run the heat pump, at a specific temperature. The higher the COP, the more efficient the heat pump. This number is comparable to the steady-state efficiency of oil- and gas-fired furnaces. The COP for a heat pump in a heating or cooling application, with steady-state operation, is:

$$COP_{\text{heating}} = \frac{\Delta Q_{\text{hot}}}{\Delta A} \leq \frac{T_{\text{hot}}}{T_{\text{hot}} - T_{\text{cool}}}$$

$$COP_{\text{cooling}} = \frac{\Delta Q_{\text{cool}}}{\Delta A} \leq \frac{T_{\text{cool}}}{T_{\text{hot}} - T_{\text{cool}}}$$

where:

-ΔQcool is the amount of heat extracted from a cold reservoir at temperature Tcool

-ΔQhot is the amount of heat delivered to a hot reservoir at temperature Thot

-ΔA is the compressor's dissipated work.

All temperatures are in absolute units.

Seasonal performance factor (SPF). The SPF refers to the performance over an entire season. The power input and output is cumulated for the season; then the total power output is divided by the total power input, to give the SPF.

Total power output (KWH)/Total power input (KWH) = SPF.

The SPF is a better method of comparing heat pump performance as this figure will give a more accurate estimate of running cost over an entire season.

The energy efficiency ratio (EER) measures the steady-state cooling efficiency of a heat pump. It is determined by dividing the cooling capacity of the heat pump in Btu/h by the electrical energy input in watts at a specific temperature. The higher the EER, the more efficient the unit.

EER= COP*3.412

Heat pumps are more effective for heating than for cooling if the temperature difference is held equal. This is because the compressor's input energy is largely converted to useful heat when in heating mode, and is discharged along with the moved heat via the condenser. But for cooling, the condenser is normally outdoors, and the compressor's dissipated work is rejected rather than put to a useful purpose.

V. TYPES OF HEAT PUMPS

Heat Pump systems are available in an array of types and combinations that can suit almost any application.

For heating purposes, they can be divided into basic types, determined by the source and the destination of the heat and the medium that the heat pump uses to either absorb or reject the heat in each of these locations.

At either of the heat exchangers, the heat transfer media can be either liquid (water, or often a glycol mixture) or Air; sometimes it is a combination of the two. In describing the type of heat pump, generally the heat source is provided first, followed by the destination or heat sink.
The main variants in common use are:

- Air to Air
- Water to Water
- Water to Air
- Air to Water
- Ground to Water
- Ground to Air

V. 1. Air to air

Air to Air systems use the heat energy contained in the outside air and its vapour as a source of free heat. This heat is then delivered directly by fan-assisted units to the air in the indoor space.

These heat pumps are good choices for areas with milder climates. They do not work adequately in extreme temperatures. In cases when the temperature is extremely cold the heat pump has an auxiliary heat strip that will power on. This strip will produce much more heat than the heat pump alone, but also costs significantly more to operate.

Another type of air source system is the exhaust air heat pump. This unit uses as its thermal source the stream of air being vented (exhausted) from the building. Because the source air is generally at the temperature of the house interior, it will not suffer the same performance reduction as an external air source heat pump. It is essential to point out that the exhaust air heat pump is normally only a supplement to another heating system since its source heat has had to come from elsewhere. If the house is unheated the exhaust air heat pump must use essentially ambient temperature air. Moreover the volume flux of source air is limited to the air change rate of the dwelling it serves.

Single-split systems comprise two pieces of equipment located indoors and outdoors respectively, joined by pipe-work and electrical connections. Multi-split systems have a similar configuration of one main outdoor unit but with two or more indoor units serving different locations in the building. In many cases these are capable of independent control of their own space.

V. 2. Water to water

Water to Water systems operate in the same way as Air to Air systems except that the heat source is water, generally ground water, river or pond water, or even waste heat from factory processes. The heat is then delivered to either radiators or fan-coil units within the indoor space. In the case of river or lake water, the source liquid is seldom circulated, due to fouling of pipes, etc. Approvals are needed for this type of installation and restrictions exist on the type of anti-freeze solution used. Water to Water systems can be configured as heating only or they are available as Heating/Cooling reversible systems.

V. 3. Water to air

The heat source is as described in the Water to Water system; the heat is rejected to the air in the indoor space. Systems are available in a similar range of sizes.

Similar load flexibility, giving simultaneous heating/cooling, can be obtained using a warm water loop arrangement, known as a water source energy transfer system. The building is equipped with a ring main water flow and return pipe to each room through which warm water is circulated by a central pump.

Each room in turn is equipped with a small self-contained reversible heat pump unit. The two heat exchangers in the heat pump are a combination of water and air source. Room air is passed through one, water from the ring main through the other, while the heat pump compressor circulates refrigerant through the internal pipes in the heat exchangers.

A room requiring heat draws its heat source from the warm water. If cooling is required, the heat absorbed is rejected into the water circuit.

To operate efficiently, the system requires the building's heating/cooling load to remain in equilibrium for much of the time in operation. Where the water loop temperature exceeds the operating limits during a heavy cooling demand, excess heat can be rejected to the outside air through a cooling tower or dry cooler. Conversely, if extra heat is needed, a small boiler is attached to the loop to raise its temperature. In optimum working conditions, the building demand is at equilibrium and it is self-sufficient in heat and both the cooling tower and the boiler remain at standby.

V. 4. Air to water

Heat is absorbed from the outside air and delivered to a water based indoor system of radiators or fan coils. Heat can also be absorbed from exhaust air by this type of heat pump.

This can be a means of recovering some of the heat otherwise lost from the dwelling. Blending exhaust air with ambient air will increase the source air temperature. Care must be taken to ensure that the more humid exhaust air does not aggravate the tendency for the evaporator to build frost.

V. 5. Ground source systems

Heat energy is extracted from the ground using closed pipe loops buried horizontally in trenches or in vertical boreholes that are connected back to the GSHP. The fluid circulating in the closed loop will normally be a water/propylene glycol or acceptable equivalent antifreeze mixture. However, some direct-acting GSHPs will use refrigerant in the closed loops. Open loops may also be used to collect water from an aquifer and discharge via a separate aquifer downstream of the water table flow. However, permits are normally required from the Environment Agency.

Heat may also be extracted from surface water bodies: streams, ponds, lakes or the sea. Such systems are normally referred to as hydrothermal. Designs of any such systems must take careful account of water quality and water temperature and will often require permits from the appropriate Environment Agency.

Heat is introduced to the dwelling and distributed either to a water heating system (ground to water HPs) or to an air distribution system (ground to air HPs).

VI. COP VARIATIONS

The COP increases as the temperature difference decreases between heat source and destination. The COP can be maximized at design depending on the system chosen. In heating mode, by selecting a system requiring low temperature and a heat source with a high temperature we can increase the COP. In cooling mode, selecting a system requiring high temperature and a heat source with a low temperature we can increase the COP.

The COP drops as the temperature difference increases between the source and destination. In winter, air heat pump COP obtained is low, due to low outside air temperature (-5 ºC) which increases the thermal difference with the destination.

The COP can increase too if we have requirement for heating and cooling at the same time. A system that can perform cooling in one part and reject the heat absorbed in the process into another part. In these cases the COP for the heat pump is:

$$COP = \frac{\Delta Q_{heat} + \Delta Q_{cool}}{\Delta A}$$

where:

- ΔQcool is the amount of heat extracted from a cold reservoir at temperature Tcool
- ΔQhot is the amount of heat delivered to a hot reservoir at temperature Thot
- ΔA is the compressor's dissipated work.

In order to make it possible to compare the performance of different heat pumps, manufacturers normally publish COP figures at standard temperatures for the heated water and the brine/air. For ground source heat pumps, the COP figures are normally given at evaporator temperature (brine temperature) of 0 ºC and at heated water temperatures of 35 ºC (a typical temperature for a well-designed underfloor heating system), 45 ºC (a typical temperature for heating with radiators) and 60 ºC (a typical temperature for hot tap water production). For air source heat pumps, the COP ratings are normally produced at the same temperatures for the heated water and at 7 ºC outdoor temperature.

The COP of heat pumps should be established under a well-defined norm. The current European norm is called EN1461. This norm will supercede the old norm EN255. Many manufacturers still give their COP ratings under the old norm which sometimes leads to confusion. The new norm is more conservative since it takes into account not only the electricity consumption of the compressor but also that consumed by the circulation pumps. Due to the more conservative definitions, the COP of the same heat pump can be up to one unit lower under the new norm, compared to the rating under the old norm. The design of the

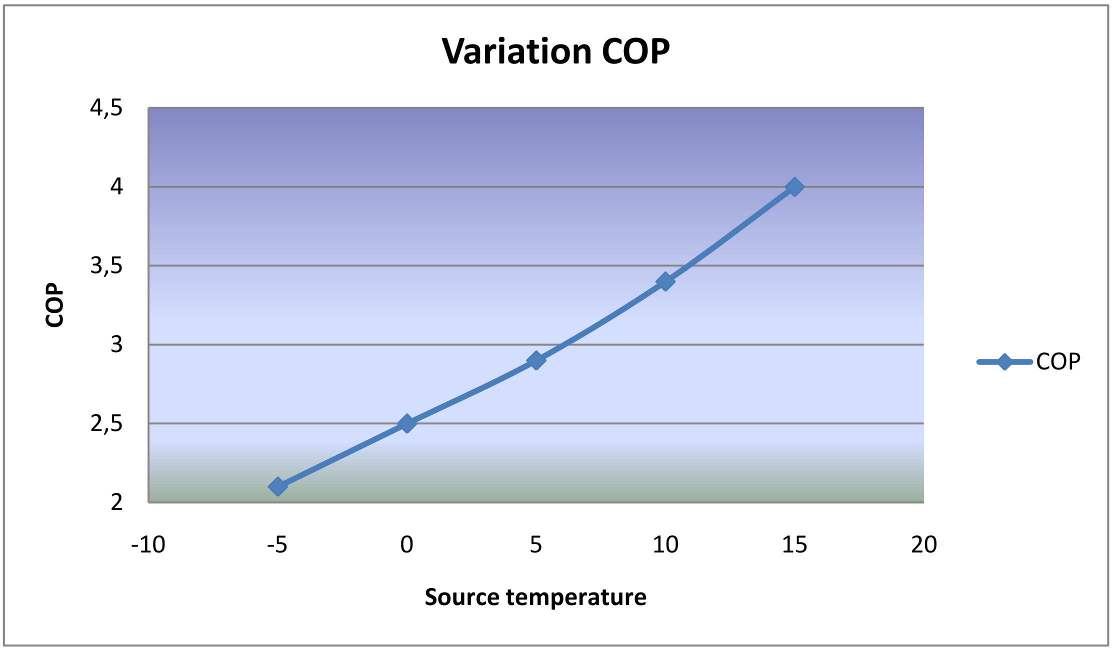


Figure 9. Variation COP

central heating system has a strong impact on the COP; the lower the flow temperature, the higher the COP. The highest COPs for heating are therefore obtained in well-insulated properties with carefully designed underfloor heating.

For ground source heat pumps, the design of the collector system also impacts on the COP. A more generous size of collector will result in higher average temperatures of the incoming brine and therefore a higher COP.

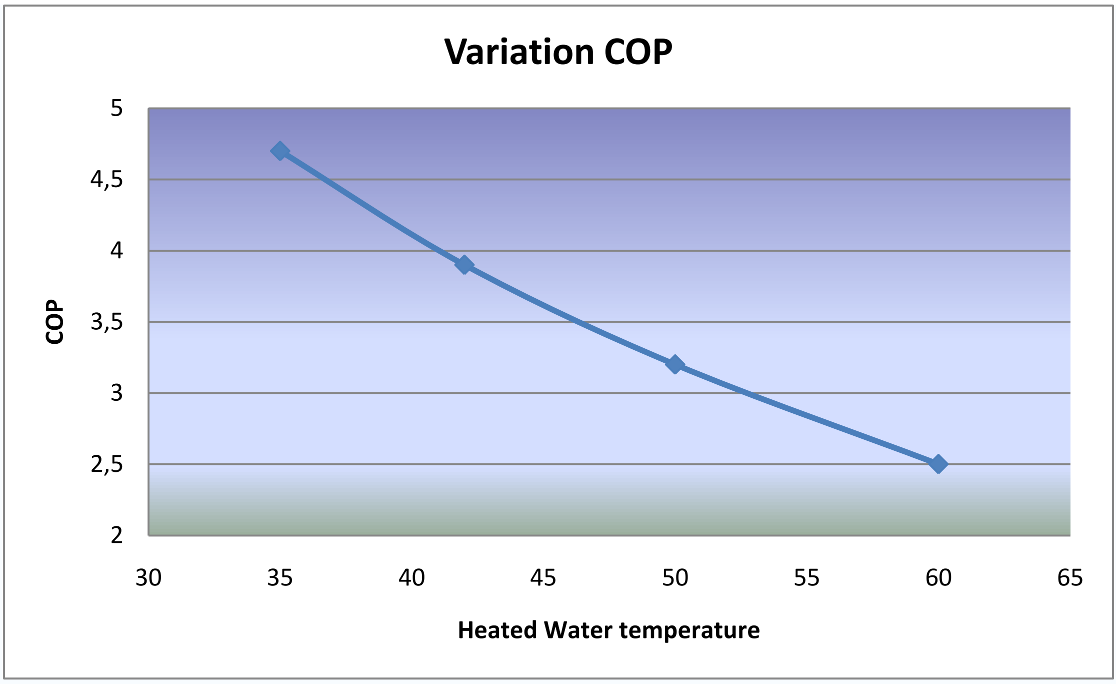


Figure 10. Variation COP

The graph (Fig. 9) shows the variation of the COP versus the heat source temperature producing a heat water temperature of 45 ºC (fancoils units). To get a COP of 4, it is necessary to get a source temperature of 15 ºC (ground source). We can see if the source temperature decreases to 0 ºC the COP is 2.5 ºC (air temperature in winter).

The graph (Fig. 10) shows the variation of the COP versus the heat water temperature produced with an evaporator temperature of 0º C. To get a COP of 4, it is necessary to keep the heated water down to 35° C. This is only possible with a good underfloor heating system. If radiators are used, then they must be oversized to keep the temperature down as far as possible. If you want to produce heated water at 60º C the COP decreases to 2.5.

VII. RENEWABLE HEAT PUMPS

The “DIRECTIVE 2009/28/EC defines minimum efficiency standards and measurement of renewable output for heat pumps.

The amount of aerothermal, geothermal or hydrothermal energy captured by heat pumps to be considered energy from renewable source for the purposes of this Directive, E_{res}, shall be calculated in accordance with the following formula:

$$E_{res}=Q_{usable}*(1-1/SPF)$$

where:

- Q_{usable} = the estimated total usable heat delivered by heat pumps fulfilling the criteria referred to in Article 5(4), implemented as follows: Only heat pumps for with SPF > 1.15*1/η shall be taken into account
- SPF = the estimated average seasonal performance factor for those heat pumps
- η is the ratio between total gross production of electricity and the primary energy consumption for electricity production and shall be calculated as an EU average based on Eurostat data.

By 1 January 2013, the Commission will establish guidelines on how Member States are to estimate the values of Q_{usable} and SPF for the different heat pump technologies and applications, taking into account differences in climatic conditions, especially very cold climates.

VIII. CONCLUSIONS

The heat pump is the heart of a GSHP. The main ideas that a designer must know to make a good choice of a heat pump are:

- To know the thermodynamic processes in which are based the heat pump and the different components (condenser, evaporator, refrigerants, reversing valve)
- To know how a heat pump works, specially the variation of the COP versus the temperature condenser and evaporator condenser

- The designer must learn the difference between a conventional heat pump and a ground source heat pump and its advantages.

The designer must perform the implementation of this phase carefully because it affects the rest of the design of GSHP.

IX. FURTHER INFORMATION

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CHAPTER 11

ENERGY LOAD *by Javier Urchueguía and Paul Sikora*

I. INTRODUCTION

There are several parameters that are of importance in the design and development of an optimized ground coupled heat exchanger (GCHE):

- The climatic conditions
- The building type and its energy demand profile
- Geological conditions and the thermal parameters of the subsurface
- Borehole/trench construction, borehole/trench backfilling
- Hydraulic properties, heat-exchanger type and dimensions (resistance to heat transfer, pressure loss and pumping power) and medium properties
- Geo-hydrology, influence on vertical and horizontal systems (seasonally changing underground water levels, partial saturation zones, etc.).

In this paper we focus on the analysis of the building energy demand profile and on the detailed thermal load calculations of cooling and heating, which will be necessary in future tasks within the project and for the general ground coupled heat exchanger (GCHE) design. Both represent basic aspects in the conception and final dimensioning of a system based on GCHE, as they affect the basic energy balance between the soil surrounding the GCHE and the installation.

When designing a GCHE installation we must take into account both the peak power and the energy demand, because it is only when the heat pump is in operation that the ground heat exchanger will transfer or absorb heat. Because the heat pump is dimensioned for the worst operating conditions, when the thermal load of the building is less than the power of the heat pump, this will work intermittently. This issue affects the soil thermal resistance, since for its calculation we have to know the total amount of heat that is injected or extracted during a whole season.

As a general idea, the design of all thermal installations should be based on the knowledge of various factors, such as: the indoor conditions to be obtained, the influence of the outdoor conditions, and the criteria and rules which allow achieving the welfare, security and rational use of the energy within the building.

Every building has different comfort levels, end uses, design characteristics, etc. Therefore, by following regulations and indications given by the responsible authorities, a pattern of comfort and specification design can be pursued. Besides, outdoor conditions, such as dry bulb/wet bulb temperature, relative humidity, solar radiation, etc., are necessary to establish the maximum instantaneous thermal energy demand, in order to scale up all the equipment and the systems of the building.

Once the design conditions are fixed (i.e. indoor and outdoor conditions, thermal insulation of the building, etc.) in order to determine all thermal loads on every heating and cooling system, the following design factors will also be taken into account:

- Facade construction and orientation characteristics
- Solar factor and glazed surface protection
- Influence of surrounding building
- Hourly working of subsystems
- Heating thermal gains
- Ventilation and removal index

All calculations will be performed individually for each local part of the building, so the maximum and minimum load can be obtained. Hence, the heating and cooling power to be supplied by the heat pump system should be fixed to the sum of all thermal loads obtained before, taking into account the heat losses through the distribution network. On the other hand, dynamic simulations are needed in order to calculate the energy demand profile of the building.

II. THEORETICAL FUNDAMENTALS

Knowledge of this area is essential for designers. Depending on their basic training (engineer, geologist, etc.), the development issues can be more or less complex.

II. 1. Gains and loads

The thermal load is defined as the amount of heat to be drawn out or supplied to the building in order to maintain the temperature and humidity constant and equal to a preset value.

The thermal load calculation process has two stages:

- Heat gains calculation. The heat gains represent the instantaneous heat flow (positive or negative) from the outside (ambient or adjacent rooms) to the inside
- Thermal load calculation.

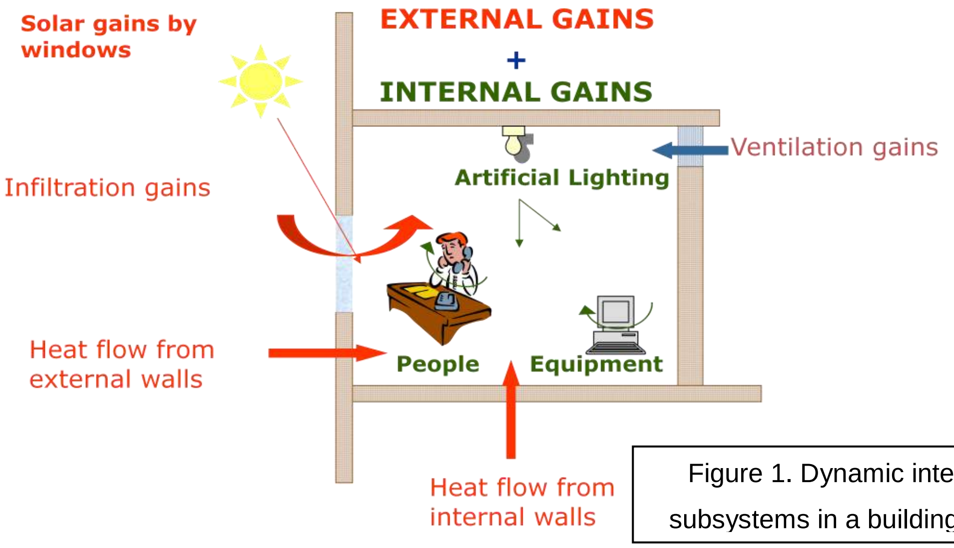

Figure 1. Dynamic interacting subsystems in a building context

We can divide the heat flow into two groups (Fig. 1):

- External gains
  - Heat gain from the incoming radiation from windows and skylights
  - Heat gain by conduction through walls, ceilings, windows in contact with the outside
  - Heat gain by conduction through walls, ceilings, etc,, in contact with a different temperature environment
  - Heat gain by conduction through walls, floors in contact with the ground
    Infiltration gains (air flow from outside only).
- Internal gains
  - Heat gain due to people
  - Heat gain due to artificial lighting
  - Heat gain due to equipment.

As well as these, we must consider the ventilation gains (air flow from a user-defined source like a HVAC system).

Each heat gain has two fractions: a convective fraction and a radiation fraction (Figs 2 & 3). The first directly affects the internal space as long as the second is absorbed and stored by the perimeter walls, and is delivered later to the internal space by air convection. Thus, the convective fraction of the heat gain turns to thermal load instantaneously and the radiation fraction of the heat gain is damped and lagged before being considered as thermal load. In order to obtain the thermal load from the radiation fraction of the heat gain, the method of transfer function or response factors is used.

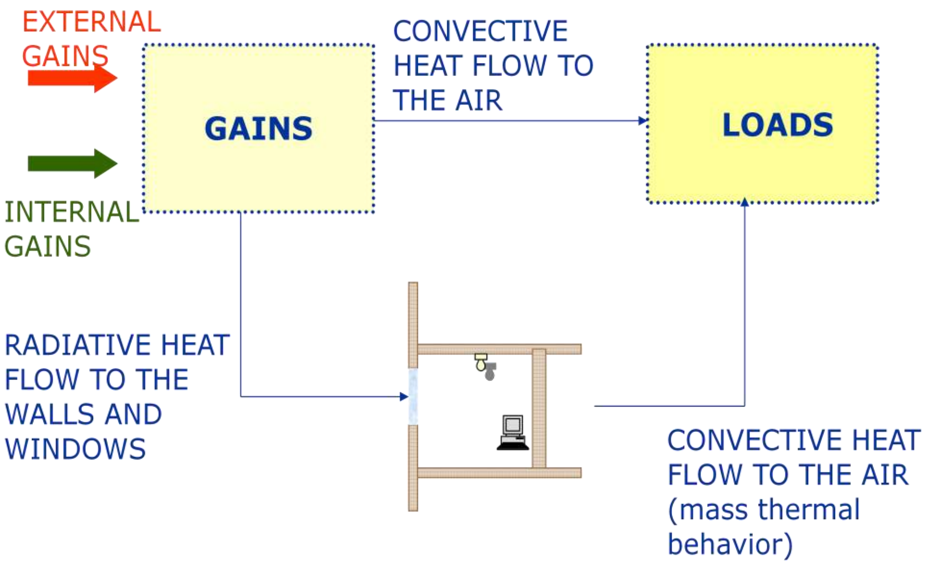

Figure 2. Relationship between heat gains and loads

The method of the transfer function or response factors can be described as the method of the thermal history of the wall. The wall is considered as a black box and depending on its components (layers, materials, etc.) it has a different thermal behaviour. Basically, we may consider heavy or light walls with low or high thermal mass. A heavy wall is formed by high density materials with considerable thickness, while the wall thermal mass is characterized by the materials' thermal conductivity and thermal capacity.

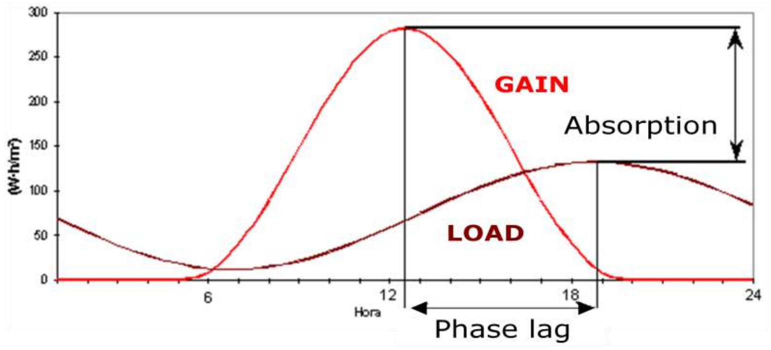

Figure 3. Graphic example of load and gain

II. 2. Heat gains calculation

This sub-section describes the mathematical models for calculating the heat gains. The purpose is a basic understanding of these models that are implemented in different numerical codes available on the market for calculating heat loads and for simulating the building energy profile.

II. 2. 1. ***External walls***

Usually the external walls are modelled according to the transfer function relationships of Mitalas (1971) defined from surface to surface. For any wall, the heat conduction at the inside surface at a current time n is described as follows:

(1) $$\dot{Q}(n) = \sum_{i=0} a_i E(n-i) - \sum_{i=1} b_i Q(n-i)$$

where:

- a and b are z-transfer function coefficients
- E represents the outside surface temperature.

The number of time steps (n) needed for the calculations shows whether the wall is a heavy or a light wall with a high or a low thermal mass. If only a few time steps have to be considered to describe the thermal behaviour of the wall, the expression (1) can be replaced by a thermal resistance definition neglecting the thermal mass.

II. 2. 2. ***Internal walls***

For the calculation of the heat gains for internal walls (Fig. 4), the hypothesis of low thermal mass and constant boundary conditions (wall surface temperature) is as follows:

(2) $$\dot{Q} = \frac{\Delta T}{\frac{1}{h_1} + \sum_n \frac{\Delta x_i}{K_i} + \frac{1}{h_2}}$$

where:

- h is the convective heat transfer coefficient at surface (W/m^{2}K)
- ΔT is the temperature gradient through the wall (K)
- x is the thickness of the layer i (m)
- K is the thermal conductivity of the layer I (W/mK).

The above expression can also be written as (3), where U is the global transfer coefficient:

$$\dot{Q} = U \cdot \Delta T \qquad (3)$$

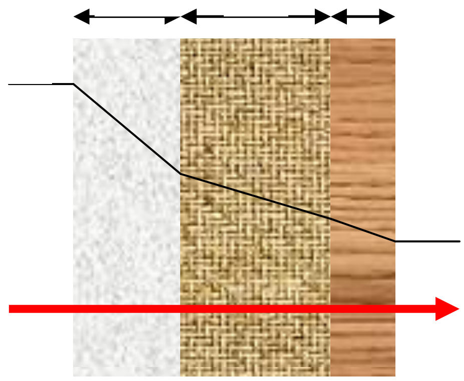

Figure 4. Heat transfer in internal walls

For example, in Spain, maximum U values recommended for exterior walls vary according to the climate of the area (1.2 (warm area) and 0.74 (cold zone)). For internal walls, these values vary from 1.22 (hot zone) to 1.00 (cold zone)).

II. 2. 3. ***Heat gains through windows***

The heat transmission through glass surfaces is, on the one hand, due to the temperature gradient between the two glass surfaces that determines a conduction heat transfer, and on the other hand, due to the incident solar radiation, causing what is known as radiant transmission (Fig. 5).

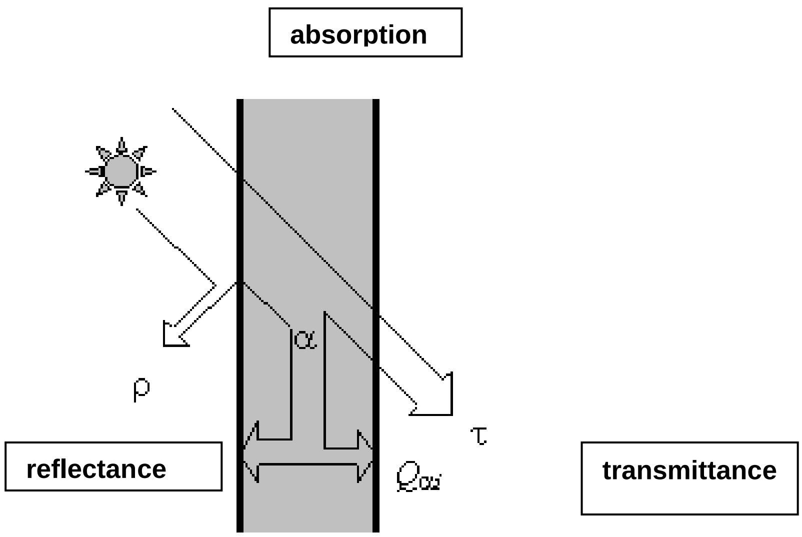

Figure 5. Effects of solar radiation through windows

To calculate the heat transfer by conduction we can use the expression (3) due to the low heat capacity of glass sheets.

To consider the effect of solar radiation, we define a glass solar factor (SF) as the ratio between the total energy that enters through the glazing and the solar energy that strikes the surface outside of the glass.

This energy is the sum of the direct heat transmission and of the absorbed solar energy fraction transmitted through the window due to convection:

(4) $$SF = \tau_D I_D + \tau_d I_d + h_i \frac{\alpha_D I_D + \alpha_d I_d}{h_e + h_i}$$

where:

- τ, α and ρ are the transmittance, absorption and reflectance coefficients with values between 0 and 1 according to the properties of the glass
- h is the convective heat transfer coefficient at internal or external window surface (W/m^2K)
- I_D is the direct solar radiation (W/m^2)
- I_d is the diffuse solar radiation (W/m^2).

II. 2. 4. ***Infiltration and ventilation gains***

All incoming energy due to infiltration and/or ventilation can be considered purely convective, so that any heat gain becomes a thermal load immediately. The heat gain (or loss) is obtained through an energy balance performed on the outside air volume:

(5) $$\dot{Q}_{\inf} = \dot{m}_{\inf}\, \rho\, Cp\, (T_{outside} - T_{inside})$$

(6) $$\dot{Q}_{vent} = \dot{m}_{vent}\, \rho\, Cp\, (T_{vent} - T_{inside})$$

where:

ρ (Kg/m^3) and Cp (J/KgK) are the air density and the air specific heat capacity.

For calculating the infiltration heat load, the mass flow rate (m_{inf}) (m^3/s) is estimated by empirical methods, while the ventilation parameters (mass flow rate, m_{vent} (m^3/s) and temperature T_{vent}) (K) are fixed by national legislation.

II. 2. 5. ***Internal heat gains***

Internal heat gains are those factors whose common feature is that the heat source is inside the conditioned space: people, artificial lighting and equipment. The instantaneous heat gain from these sources can be expressed as follows:

(7) $$\dot{Q} = n\, \dot{Q}_0\, f$$

where:

- For people, Q depends on n (number), Q_0 (degree of activity, clothing factors, etc.), f (schedule)

- For artificial lighting, Q depends on n (number), Q_0 (type of lamp), f (control strategy, schedule)
- For equipment, Q depends on n (number), Q_0 (installed power), f (schedule)

In the calculation of internal gains, one should take into account both the sensible heat and the latent heat, due to the fact that the moisture balance effect is very important for cooling.

III. PRACTICAL FUNDAMENTALS

III. 1. Methods for thermal loads calculation

III. 1. 1. ***European standards*** (Dick van Dijk and Marleen Spiekman)

EN ISO 13790 Thermal performance of buildings - Calculation of energy use for space heating and cooling. In Europe, the publication from December 2002 of the Energy Performance of Buildings Directive (EPBD, EPBD 2002) was followed by a Mandate to CEN to develop a set of standards on energy performance in buildings (M343 2004), in order to support the EU Member States for the national implementation of the EPBD. More information on the set of CEN standards is given in the so-called CEN "Umbrella Document" (CEN/TR 15615 2007).

In 1995, the European standard EN 832 (EN 832 1995) was developed, containing a simplified calculation method of the energy use for heating of residential buildings. Its follow up was the above quoted EN ISO 13790:2003, including also non-residential buildings. As part of the Mandate 343 to CEN to support the EPBD, the 2004 version of this international standard has been expanded with the calculation of the energy use for space cooling and additional features (EN ISO 13790 2007).

In short, the new EN ISO 13790:2008 gives calculation methods for assessment of the annual energy use for space heating and cooling of a residential or a non-residential building, or a part of it, referred to as “the building”.

This method includes the calculation of:

- the heat transfer by transmission and ventilation of the building zone when heated or cooled to constant internal temperature
- the contribution of internal and solar heat gains to the building heat balance
- the annual energy needs for heating and cooling, to maintain the specified set-point temperatures in the building – latent heat not included
- the annual energy use for heating and cooling of the building, using input from the relevant system standards referred to in ISO 13790:2008 and specified in Annex A.

ISO 13790:2008 also gives an alternative simple hourly method, using hourly user schedules (such as temperature set-points, ventilation modes or operation schedules of movable solar shading).

The procedures are given for the use of more detailed simulation methods, in order to ensure compatibility and consistency between the application and results of the different types of method. ISO 13790:2008 provides, for instance, common rules for the boundary conditions and physical input data irrespective of the calculation approach chosen.

ISO 13790:2008 has been developed for buildings that are, or are assumed to be, heated and/or cooled for the thermal comfort of people, but can be used for other types of building or other types of use (e.g. industrial, agricultural, swimming pool), as long as appropriate input data are chosen and the impact of special physical conditions on the accuracy is taken into consideration.

The calculation procedures in ISO 13790:2008 are restricted to sensible heating and cooling. The energy use due to humidification is calculated in the relevant standard on the energy performance of ventilation systems, as specified in Annex A; similarly, the energy use due to dehumidification is calculated in the relevant standard on the energy performance of space cooling systems, as specified in Annex A.

ISO 13790:2008 is applicable to buildings at the design stage and to existing buildings. The input data directly or indirectly called for by ISO 13790:2008 should be available from the building files or the building itself. If this is not the case, it is explicitly stated at relevant places in ISO 13790:2008 that it may be decided at national level to allow for other sources of information. In this case, the user reports on which input data have been used and from which source. Normally, for the assessment of the energy performance for an energy performance certificate, a protocol is defined at national or regional level to specify the type of sources of information and the conditions when they may be applied instead of the full required input.

III. 1. 2. ***ASHRAE standards***

The transfer function method (TFM) is a well known standard recommended by ASHRAE (American Society of Heating, Refrigerating and Air Conditioning Engineers). It can be considered the most used tool currently available for the thermal analysis of a building. (ASHRAE Handbook of Fundamentals, 2005. Chapter 32, Energy Estimating and Modelling Methods; ASHRAE Handbook of Fundamentals, 2009. Chapter 18, Non-residential Cooling and Heating Load Calculation).

III. 1. 3. ***Degree-day method***

Cooling or Heating degree day (CDD, HDD) are quantitative indices designed to reflect the demand for energy needed to cool or heat a building. These indices are derived from daily temperature observations, and the heating or cooling requirements for a given structure at a specific location are considered to be directly proportional to the number of HDD/CDD at that location.

For instance, the HDD are defined relative to a base temperature - the outside temperature above which a building needs no heating. The most appropriate base temperature for any particular building depends on the temperature that the building is heated to, and the nature of the building (including the heat-generating occupants and equipment within it). For calculations relating to any particular building, HDD should be selected with the most appropriate base temperature for that building.

There are a number of ways in which the HDD can be calculated: the more detailed a record of temperature data, the more accurate the HDD that can be calculated. However, most HDD are calculated using simple approximation methods that use daily temperature readings instead of more detailed temperature records such as half-hourly readings. One popular approximation method is to take the average temperature at any given day, and subtract it from the base temperature. If the value is less than or equal to zero, that day has zero HDD. But if the value is positive, that number represents the number of HDD on that day.

III. 2. Programs for the simulation of the building energy performance

Despite the large number of building energy modelling programs on the market, most are unknown to the professional designer or their use is restricted to the calculation of thermal loads for sizing the air conditioning systems. According to a study of the Czech Technical University (Fig. 6) the most used modelling programs used by architects and engineers are: eQuest, Energy10, DOE-2, TRNSYS, VISUALDOE, ECOTECT, ESP-r, EnergyPlus.

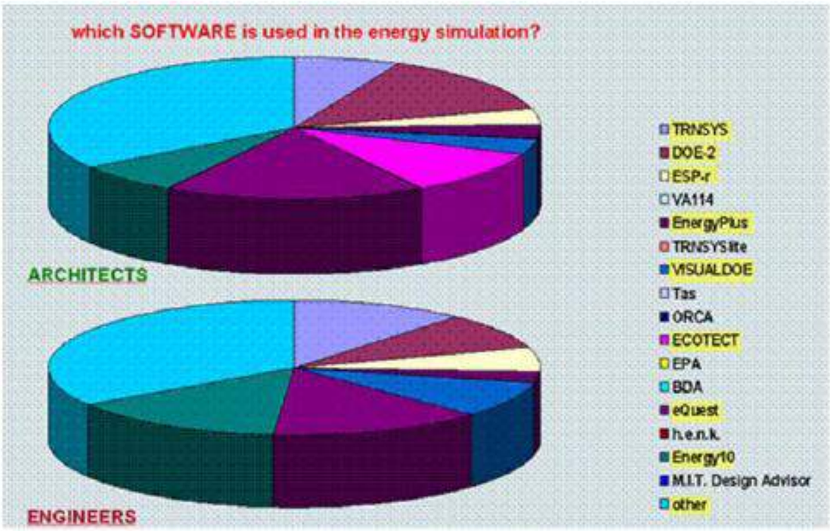

Figure 6. Software used in the energy simulation (Altavilla *et. al*, 2004)

The new Directive 2010/31/EU (Energy Performance Buildings Directive recast), approved on 19 May 2010, foresees the development of a European programme for building energy simulation.

III. 3. Example

As an example we will show a load profile study for an existing residential area in the city of Valencia (Spain). The software used for the evaluation of the heating and cooling load profile is CALENER (2001), a package made to characterize the building energy efficiency in Spain.

III. 3. 1. ***General description of residential block***

The residential block consists of 10 housing blocks; each block has a ground floor with parking spaces and commercial areas, and three floors of apartments. Each floor counts with two dwellings having an identical distribution around an internal patio to which three out of four bedrooms are orientated. A window in the staircase also faces this inner patio.

Each dwelling has a surface area of 65.33 m^2: a kitchen, a living room, a toilet, a bathroom, a storage place, four bedrooms and a corridor. Moreover, each floor has a corridor of the stair room and an inner patio. The two building facades are oriented to the North and to the South; on each side there are balconies. The main access to the building is situated on the southern facade.

Since they have identical functions and orientations, the toilet and bathroom have been modelled as a single space. The same occurs with bedrooms 3 and 4.

The living room and the four bedrooms are considered as conditioned zones, while the rest of the rooms and the garage are considered as non-conditioned.

Total (m^2)	conditioned (m^2)	Non-conditioned (m^2)
56.300	25.404	30.896

III. 1. 2. ***Heating and cooling load profiles***

Table 1 shows the heating and cooling demands for each month of the year, distinguished in the following way:

- For heating: Conduction Walls, Conduction Roofs, Conduction Ground, Infiltrations, Conduction Windows, Solar Heating through windows, Persons present, Lighting and Equipment
- For Cooling: Conduction Walls, Conduction Roofs, Conduction Ground, Infiltrations sensible, Infiltrations Latent, Conduction Windows, Solar Heating through windows, Persons present sensible, Persons present latent, Lighting and Equipment sensible and Equipment latent.

For a better understanding of the results shown in the table, the following considerations need to be made:

First of all, the interior temperature and relative humidity levels established to evaluate the energy demand are different in heating and in cooling mode. That is why for the same time, different demands can be found for different temperature and humidity levels. Therefore 20 ºC can be established as a temperature for heating demand and 24 ºC to evaluate the cooling demand.

It also needs to be taken into account that during a simulation period (e.g. one month) the various load fractions might have opposite signs, while it is the sum of these fractions, the total or net value, which determines the heating demand (in case of a negative value) or the cooling demand (positive net value). While analysing the heating load during the month of January, for instance, some fractions with negative values can be found (normally conduction through walls, roofs, windows and ground, as well as infiltrations) and other fractions with positive values (usually energy spent in lighting, electrical equipment, energy generated by people in the building and solar radiation that enters through the windows).

Finally, it is not easy to know in advance whether a building will be in heating or in cooling regime during a certain time period (except in obvious situations). Therefore the energy demand for each regime and each time period must be evaluated (although CALENER evaluates each hour, the results shown only give information on a monthly basis). Afterwards, the total values (sum of load fractions) of heating and cooling can be compared for each month in order to predict the regime that will exist.

HEATING REGIME (kWh) – RESIDENTIAL BLOCK IN VALENCIA

Component	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Conduction Walls	-18490	-12460	-9590	-2400	-870	0	0	0	10	-370	-9720	-18340	-72230
Conduction Roofs	-10020	-6490	-3810	-380	-360	0	0	0	0	-330	-5580	-10220	-37190
Conduction Ground	-1950	-1750	-1860	-1550	-780	-20	0	0	-10	-620	-1690	-1950	-12180
Conduction Windows	-11230	-8390	-7180	-3550	-1390	-10	0	0	-10	-1220	-6930	-10880	-50790
Solar Radiation Windows	7750	6870	6350	3270	1120	0	0	0	10	820	5050	7120	38360
Lighting	6060	5040	4720	2830	1270	10	0	0	10	1040	4690	6050	31720
Infiltration	-33590	-26600	-24420	-13620	-5560	-50	0	0	-50	-4380	-20790	-32140	-161200
Persons	7330	6240	6080	4150	2010	40	0	0	30	1780	6010	7320	40990
Equipment	6060	5050	4720	2830	1270	10	0	0	10	1040	4690	6050	31730
Total	-48080	-32490	-24990	-8420	-3290	-20	0	0	0	-2240	-24270	-46990	-190790

COOLING REGIME (kWh) – RESIDENTIAL BLOCK IN VALENCIA

Component	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Conduction Walls	-790	-1270	-1410	-1040	4680	13160	21690	22800	16420	4030	-730	-810	76730
Conduction Roofs	-180	-470	-640	640	5180	9020	13010	12230	7670	870	-570	-160	46600
Conduction Ground	0	-10	-90	-340	-1170	-1870	-1950	-1950	-1880	-1330	-190	0	-10780
Conduction Windows	-280	-440	-680	-1290	0	3100	6800	7080	3980	-190	-420	-290	17370
Solar Radiation Windows	3120	5500	10880	15500	19810	21640	23370	22280	19430	15360	6150	2770	165810
Lighting	440	830	1780	3460	5230	6270	6500	6500	6280	5450	1600	450	44790
Infiltration	-1370	-2400	-4420	-7410	-6680	80	9410	10760	3620	-4890	-2610	-1270	-7180
Persons	380	730	1630	3300	5700	7420	7710	7710	7430	5930	1450	380	49770
Equipment	440	830	1780	3470	5240	6280	6500	6500	6280	5460	1600	450	44830
Total	1760	3300	8830	16290	37990	65100	93040	93910	69230	30690	6280	1520	427940

Table 1. Heating and cooling demands for each month

Note: It must be emphasized that when cooling loads are found in months of clear winter conditions the user must be extremely careful interpreting these data for different reasons:

- Firstly, the appearance of net positive values in winter months only means that during some hours of the month the net balance was positive, hence there was a heat gain
- Secondly, the ratio between hours of heat gain (refrigeration) and hours of heat loss (heating) determines whether during a certain month the building is in heating regime, cooling regime or is subject to thermal inversion
- In certain zones of a building, such as interior spaces, refrigeration might be needed during the whole year since the heat losses are very low and always smaller than the internal heat gains.

Negative values represent heat losses, positive values represent heat gain. For cooling, the heat losses are a positive effect since it reduces the quantity of energy that needs to be dissipated by the cooling systems.

Analysis of the data shown in the tables above shows that the fraction that causes the highest refrigeration load is solar radiation through windows, with a total value of 165.810 kWh per year. In order to reduce the solar heat gain, a reflecting glass can be installed (which will have a negative impact on the heating load) or we can use other kinds of protection. The results also show that the main factors that have an influence on the heating load are infiltration (-161.200 kWh/year), followed by conduction losses through walls (-72.230 kWh/year) and to a minor extent through windows and roofs. It is important to remember that this is an example of heating and cooling load calculations of a real residential block in Valencia (Spain). The

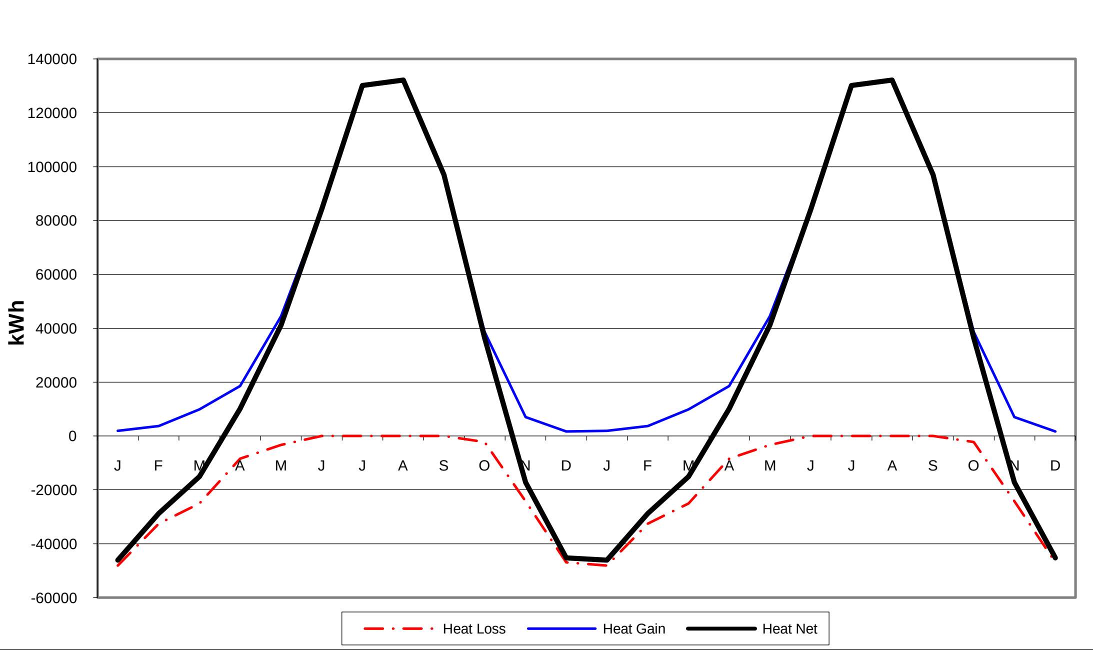

Figure 7. Total values per month for both cooling and heating in a residential block in Valencia

load profile can vary considerable depending on several factors such as: the building's orientation, the climate, shadows caused by adjacent buildings, materials used in walls, roofs, doors, windows and floors, occupation, artificial and natural lighting, equipment, variability in air humidity, infiltrations, ventilation, lighting control, etc.

The graph in Figure 7 shows the predominance of cooling on a yearly basis: during seven months cooling is required, while only during five months must the heating be switched on. Moreover, the maximum cooling load is two times higher than the maximum heating load.

III. 4. European areas and aplications

Regional differences in climate, building tradition and user behaviour in Europe will have an impact on the calculation procedures, the input data and consequently on the energy performance.

Several standards allow choices between different options to be made at national level. Some of the standards contain a reference method (often detailed) and allow national annexes with (often simplified) national methods. Most standards allow the input data and boundary conditions to be specified at national level. This is also the case for EN ISO 13790.

IV. ENERGY EFFICIENCY AND ECONOMIC COSTS-BENEFIT ASSESSMENT

The calculation of the building energy demand influences the design of the ground heat exchanger in the following ways:

- long-term evolution of the soil thermal conditions under the requirements based on the thermal energy demand (base load), i.e. increased or decreased ground temperature
- ground behaviour at the peak power required by the installation (peak load), i.e. analysis of the degradation that can occur in buried pipes due to work at extreme temperature in the heat pump.

For this reason a correct estimate of the building energy profile is important to a good sized ground heat exchanger in order to obtain an adequate system performance and this also affects the investment in building it. Besides the building energy demand, it represents the principal data needed for the calculation of the installation payback.

V. CONCLUSIONS

As a general conclusion, the two steps necessary for setting up heating and cooling systems are:

- Thermal load calculations
- Analysis of the energy demand.

Both are a basic aspect in the conception and final dimensioning of a system based on ground coupled heat exchangers (GCHE), because they affect the ground behaviour and the system efficiency.

Therefore, in order to determine the thermal load, it is necessary:

- to identify the characteristics of the construction (materials, dimensions, shape and outside colour), the environmental information (climate data, selecting design conditions)
- to select the indoor design conditions (temperature, humidity and ventilation),
- to select the site characteristics (illumination requirements, occupant activities, equipment and process involved)
- to select the day and time for which the load is determined, preferable for the maximum and minimum requirements.

A good tool for these calculations is the EN ISO 13790:2008 that gives a method for the assessment of the annual energy use for space heating and cooling of a residential or a non-residential building. More complicated tools to calculate the building energy demand profile are the dynamic simulations programmes.

VI. FURTHER INFORMATION

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CHAPTER 12

DESIGN OF BOREHOLE HEAT EXCHANGERS *by Burkhard Sanner*

I. INTRODUCTION

A borehole heat exchanger (BHE) is meant to carry a fluid inside the underground and allow for exchange of heat from the underground into the fluid (heat extraction, heating mode of the system) or for exchange from the fluid into the underground (heat injection, cooling mode of the system). The BHE consists of pipes containing the fluid; because it needs to be installed down to a certain depth, it is typically long and slim. The BHE must include a design for the return of the fluid from the deepest point in the borehole back to the surface.

The different methods of coupling the fluid circuit inside the BHE to the heat pump are shown in Chapter 1, Figure 3. Because of the need to circulate a fluid down into the earth and up again, there are only a few basic options for BHEs:

- Coaxial (or concentric) pipes, also known as pipe in pipe
- U-pipes (two or more simple pipes connected at the bottom)
- Only for heat pipes (see Chapter 1, Figure 3). A single pipe is sufficient, as the vapour can rise upwards in the centre of the pipe while the condensate flows down along the pipe walls.

Over the course of >60 years of BHE development, various design alternatives have been developed and tested. Due to cost effectiveness, only a few rather simple designs prevail (Fig. 1). These BHE are inserted in boreholes, and the remaining annulus between the pipes and the borehole wall is either filled with a special grouting material (see Chapter 15), or with water if the borehole is stable (limited to Scandinavia).

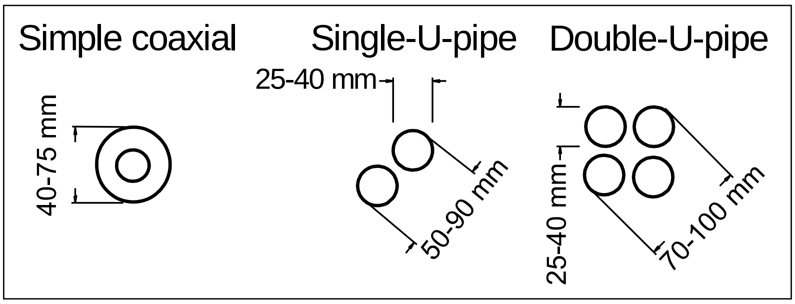
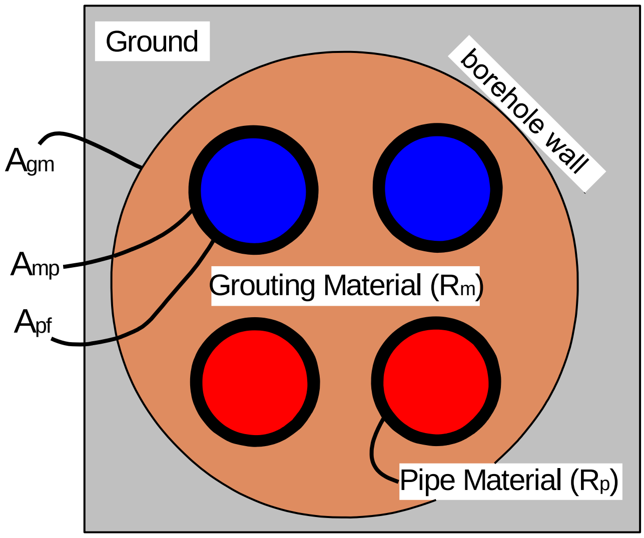


Figure 1. Cross sections of three most frequent BHE types

The effectiveness of BHEs can be described using a summary parameter, the borehole thermal resistance R_b. This parameter includes all the heat transfer phenomena from the ground outside the borehole right into the fluid inside the pipes (Fig. 2). For BHE design, only these parameters can be influenced by engineering, as the ground outside the borehole cannot be changed.

The maximum efficiency of a BHE under given load circumstances (i.e. permissible temperature difference ground-fluid and planned operation time) can be calculated and plotted against R_b (see Chapter 1, Figure 8). So the quality of a BHE type can be benchmarked using R_b and the Hellström-efficiency η_H. It depends mainly on pipe material, pipe size, pipe configuration, and filling of the annulus.



A: Transfer resistances
B: Material resistances

Rb = Agm + Rm + Amp + Rp + Apf

Figure 2. The components of R_b shown in the cross sections of a double-U-BHE

For sizing of BHEs to a given heating and/or cooling load, different methods are available both for smaller and larger projects. For smaller systems such as in single-family-houses, design is done using tables or nomograms (e.g. VDI 4640 or SIA 384/6), or calculations with easy-to-use software. For larger systems, design calculations with simple software like EED or even with numerical simulation is required. The boundary between small and large typically is set at about 30 kW thermal capacity. The procedures are described in Chapter 13.

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CHAPTER 13

BHE DESIGN EXAMPLES

(a) SMALL SYSTEMS *by Burkhard Sanner*

I. INTRODUCTION

For small buildings, the design is normally done by using a specific extraction rate in W/m. For using this simple design method, certain limits need to be observed (list according to VDI 4640, 2001):

- Valid only for heating (incl. Domestic Hot Water (DHW)), no cooling
- Length of individual BHE not less than 40 m and not exceeding 100 m
- Smallest distance between BHEs 5 m for depth down to 50 m;
  6 m for depths exceeding 50 m
- Double-U-pipes or coaxial pipes
- Not applicable to a larger number of small plants in a limited area.

The values given in VDI 4640 can only give a rough estimate and will prevent the design to be completely out of any meaningful sizing. Compared to calculated values for specific cases, this rudimentary resolution becomes obvious (Fig. 1). In any case, the VDI values can give an idea of the range of BHE heat supply possible under Central European conditions. Some rules of thumb used in the past were much more arbitrary; statistics from BHEs in some German states show that the vast majority of BHEs for smaller projects are sized for ca. 50 W/m extraction rate!

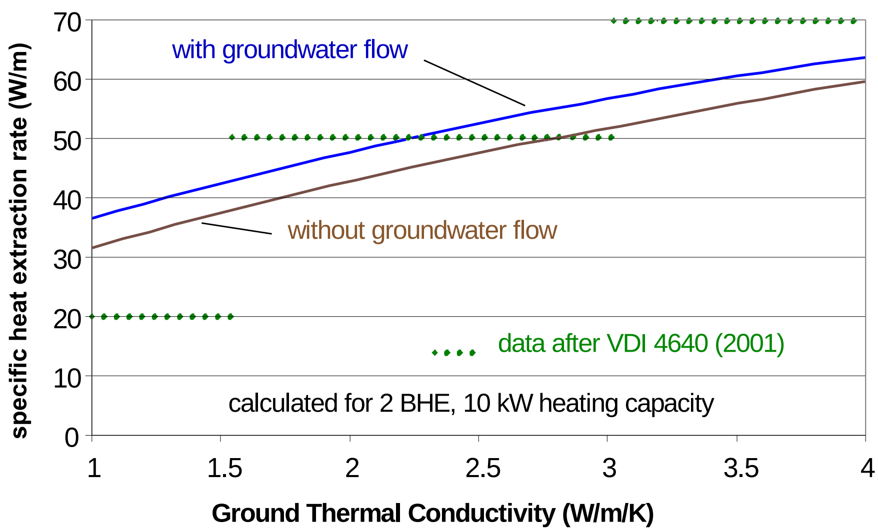


Figure 1. Comparison of specific heat extraction rate after VDI 4640 (2001) and EED software

A comparison of the various methods is provided for a single family house and a heat pump for heating only. The basic assumptions are:

• Maximum building heat load	12 kW
• Average full-load hours of heat pump	1800 h/a (typical for systems without domestic hot water (DHW))
• Heat distribution system	floor heating (slab heating)
• Heat supply temperature	max. 35 °C
• Expected average SPF	3,8
• Underground geology	Sandstone
• Mean ground surface temperature	9,5 °C

Using the following formulae, the evaporator capacity (which in heating mode is equal to the heat to be supplied from the ground) can be calculated from heating capacity and SPF:

$$P_{ground} = \frac{P_{heating}}{SPF} \cdot (SPF - 1)$$

$$P_{ground} = \frac{12}{3{,}8} \cdot (3{,}8 - 1) = 3{,}16 \cdot 2{,}8 = 8{,}8$$

where: P_{ground} = heat pump evaporator capacity in W or kW

$P_{heating}$ = heat pump heating capacity in W or kW

SPF = Seasonal Performance Factor (COP over heating season).

The resulting ground heat supply (evaporator capacity) is 8.8 kW or 8800 W.
As the plant is inside the constraints given in VDI 4640, the specific heat extraction rate can be used for BHE design ("loop sizing"). The basic formulae are:

$$P_{ground} = n_{BHE} \cdot l_{BHE} \cdot P_{BHE}$$

respectively:

$$l_{BHE} = \frac{p_{ground}}{n_{BHE} \cdot P_{BHE}}$$

where: P_{ground} = heat pump evaporator capacity in W

P_{BHE} = specific heat extraction rate in W/m

l_{BHE} = (average) length of one BHE in m

n_{BHE} = number of BHE.

II. VDI 4640

A value for the thermal conductivity of the sandstone on site has to be estimated; the recommended value for sandstone as to VDI 4640 is used (see table in Chapter 4), which is λ = 2,3 W/m/K. Then the relevant value for the specific heat extraction rate can be taken from the table in VDI 4640 (column for 1800 h/a):

Method	Range	Specific heat extraction rate P_{BHE}
General Values	1,5-3,0 W/m/K	60 W/m
Values for specific rock types	Sandstone	65-80 W/m

Now the required borehole length can be calculated with the formula given above (the heat pump evaporator capacity has to be converted from kW to W):

From general values

$$l_{BHE} = \frac{8800}{2 \cdot 60} = 73{,}4\ m$$

From specific rock values

$$l_{BHE} = \frac{8800}{2 \cdot 65} = 67{,}7\ m \quad \text{to} \quad l_{BHE} = \frac{8800}{2 \cdot 80} = 55{,}0\ m$$

As a result, 2 BHEs of 55.0 m – 73.4 m length would be required – quite a range! The designer now has to judge from experience to size the design closer to the lower or to the upper limit of the range, according to the rock type (fractures, weathering) and the presumed accuracy of the heat load data.

III. SIA 384/6

In SIA 384/6, the design for smaller projects is given in annex D3. Here some curves are provided for a standard BHE and for various correction factures. The process is shown using the same example as above.

First, the specific heat extraction rate of a standard 100 m BHE according to SIA 384/6, D3, figure 7 (pipe diameter 32 mm) is read as: 37 W/m

The same formula as above can be used for calculating required standard BHE length:

$$l_{BHE} = \frac{8800}{2 \cdot 37} = 119\ m$$

The resulting value of 2 BHEs each 119 m deep (more than twice the smallest sizing according to VDI 4640!) now has to be adjusted with different correction factors.

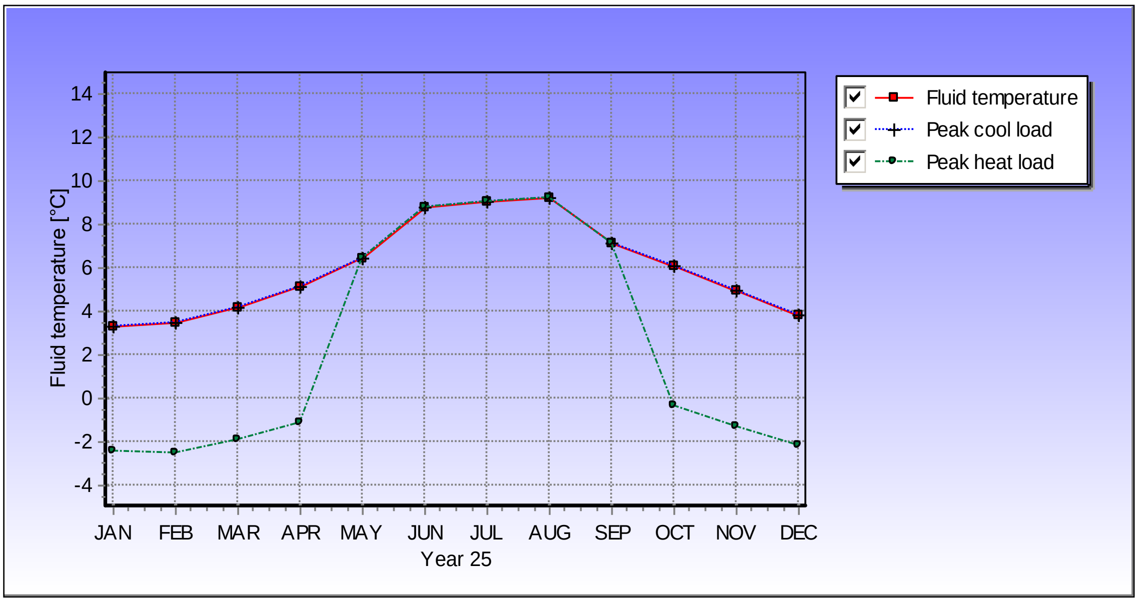
As for the standard BHE, an operation time (full-load hours) of 1850 h/a is assumed, a correction for differing values is required. Figures 11-19 of annex D3 SIA 384/6 provide graphs showing curves for different full-load hours, BHE patterns and BHE distances. The correction factors can be obtained from these curves. As an example, no correction for the operation time is required, but the fact that 2 BHEs are used would lead to a required increase in BHE length of 3% if the BHE distance is not below 7.5 m (the value for 5 m distance would be 5%; however, this distance is too short according to VDI 4640). The interim design for 7.5 m distance would be 2 BHEs each 122.5 m deep.

In the last step, the correction for temperatures in the ground and desired extraction temperatures has to be made, using formulas (19) and (20) given in annex D3 of SIA 384/6. For the current example, the result of this correction is negligible, so a depth of 123 m for each BHE is selected.

IV. CALCULATION WITH EED

With EED, small projects can also be calculated in a speedy way. The annual heating work is calculated (12 kW x 1800 h = 21,6 MWh), and the default monthly distribution used for base load. For peak load, the heat pump heating capacity of 12 kW is given, and a reasonable number of hours per day (e.g. 18 h in January).

The temperatures shown in Figure 2 were found where a calculation is made for a period of 25 years, and for 2 BHEs each 110 m deep at 7.5 m distance. These are quite suitable (albeit slightly lower than the 0/-3 °C limits of SIA 384/6, which would be -1.5 °C in EED).



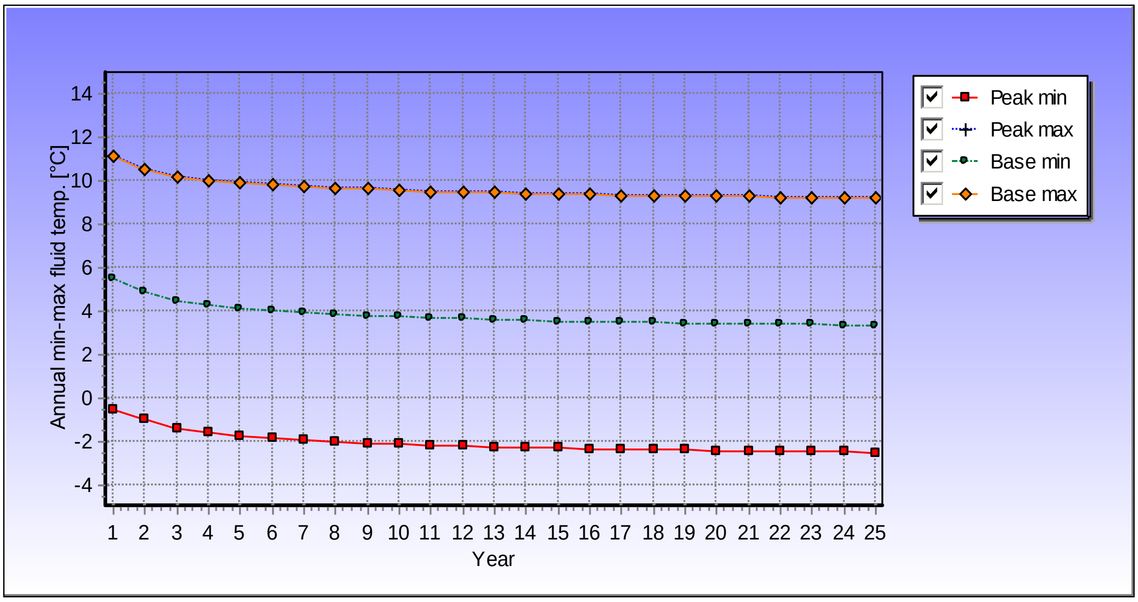


Figure 2. EED-calculation with BHE 2 x 110 m, temperature variation over the 25th year of operation and minima and maxima over 25 years

Table 1 summarizes the various design methods. There are large variances from the smallest VDI 4640 sizing to the largest SIA 384/6 sizing; boundary conditions and methods differ, and for VDI 4640 a new version with revised calculation is due in the near future

Method	Number BHE	Length BHE	Total length
VDI 4640, general	2	73,4 m	147 m
VDI 4640, specific	2	55-68 m	110-136 m
SIA 384/6	2	123 m	246 m
EED	2	110 m	220 m

Table 1. Comparison of results for a small project with 12 kW heating capacity

CHAPTER 13

BHE DESIGN EXAMPLES

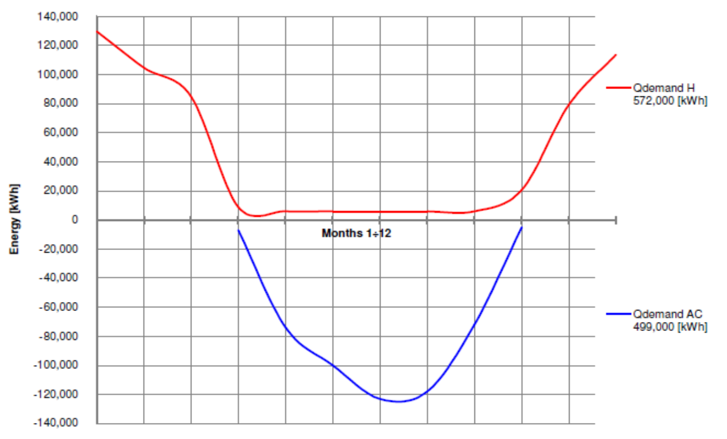
(b) A CASE STUDY OF GOOD PRACTICE IN GROUND SOURCE HEATING / COOLING: AUTO SHOWROOM, OFFICES AND WORKSHOP VW BUCHAREST – ROMANIA *by Radu Polizu and Radu Hanganu-Cucu*

I. INTRODUCTION

Bucharest Midocar is a long-standing client of the company ASA GEOEXCHANGE. Over time, it has been "converted" to the concept of geothermal HVAC systems, using open and closed loop systems for its buildings located in the north of Bucharest. On the basis of good operational technical and economical results, Bucharest Midocar decided to install a closed-loop, borehole-based geothermal HVAC system at a new facility in the eastern part of Bucharest.

II. PROJECT AREA AND OBJECTIVE

Figure 1. Variation of Thermal Demand for the building



The plans for Midocar East objective included a showroom, offices and repair workshop located on the left bank of the Dambovita River. The development was constructed with large south- and west-facing glass surfaces, its other exterior walls and construction elements were specified with an appropriate thermal resistance for the Bucharest climate. The total thermal energy demand of the building was calculated to be 1071 MWh/year, with winter peak heating loads of 390 kW and summer peak cooling loads of 421 kW (Fig. 1).

The solution chosen for the ground heat exchanger was a closed loop array comprising equally-spaced vertical boreholes (Fig. 2). Data on the building energy demand and the soil properties was entered into the loop simulation programme Ground Loop Design. It was concluded that a 16 x 7 array comprising a total of 112 boreholes of 140 mm diameter with 72 m thermally active depth would be required to support the loads. The borehole spacing

Figure 2. Equally-spaced boreholes

was 5 m. The boreholes were installed with single U 33.4 mm OD PE pipe (1 inch SDR11), with shank spacers placed at

3 m intervals. The boreholes were sealed with a thermally enhanced bentonite / silica sand grout with a minimum conductivity 1.7W/m/K.

A thermal response test was conducted on the first borehole, which indicated an average ground temperature of 13 °C and an average thermal conductivity of 2.01 W/m/K.

The building energy performance is controlled by Direct Digital Control (DDC). The ground loop is designed such that fluid entry temperature to the heat pumps (EWT) should not fall below +5 °C in winter mode, while the ΔT (temperature differential) across the heat pumps should not exceed 3.5 ˚C. For this reason, clean water (with no anti-freeze) was selected as the carrier fluid. The use of anti-freeze is detrimental to system performance as it reduces heat transfer efficiency and increases circulation pumping costs. (Of course, to maintain a high enough fluid temperature to avoid anti-freeze requires capital expenditure on a large borehole array!).

The project uses a total of a 10 water-to-water heat pumps located in 2 geothermal plant rooms: one with the showroom and offices, and the other in the workshop. Of these, 7 heat pumps provide secondary thermal fluid to fan coil units and radiant floors, 2 heat pumps are dedicated to domestic hot water production, while the remaining heat pump operates in cooling mode all year round, supporting the 4-way fan coil units. In addition, the building uses a total of 8 water-to-air heat pumps, which work in tandem with air-to-air heat recovery units.

The DDC system implemented in the building allows precise control of each unit of the HVAC system. It also permits remote processing and transmission of certain control parameters.

III. RESULTS OF BUILDING MONITORING THROUGHOUT ONE CALENDAR YEAR

The monitoring results are shown in Figures 3a-e, 4 and 5.

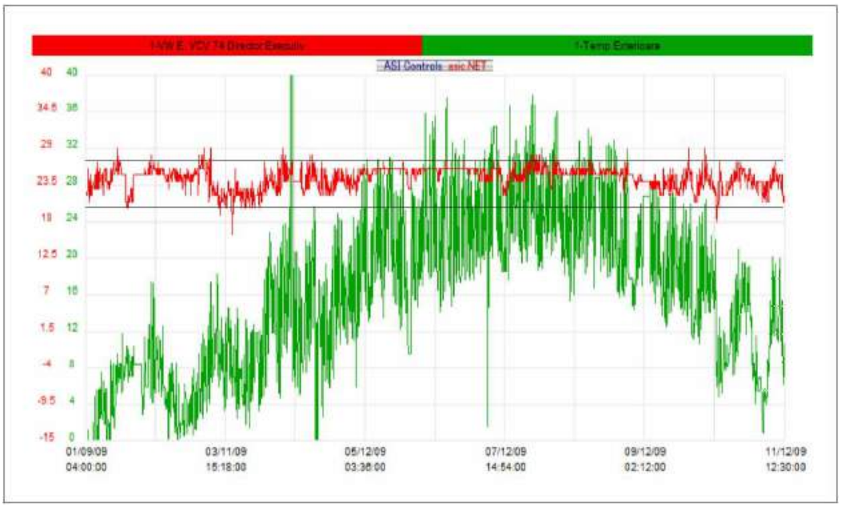


Figure 3a. DDC Showroom – The control of internal air temperature (red) vs. outside air temperature (green)

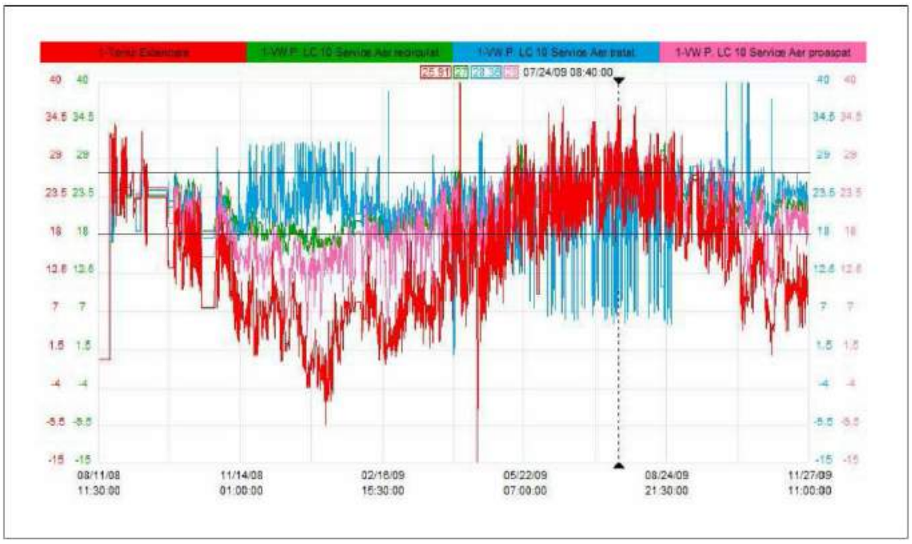
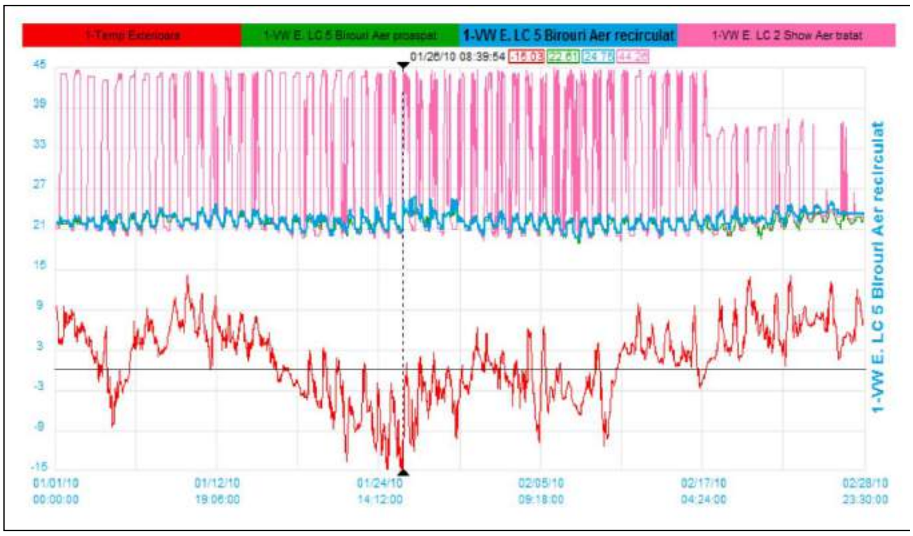


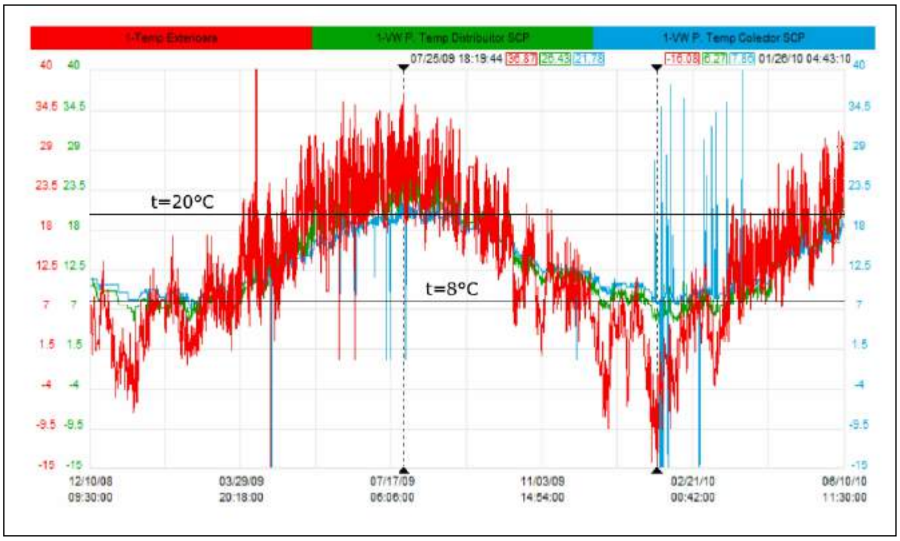
Figure 3b.
DDC Service – The control of internal air temperature vs. outside air temperature (red)

Figure 3c.



DDC Showroom – Heat Recovery System during January/February 2010. The red curve shows outdoor air temperature. Blue = recirculated air temperature from offices; Green = fresh air temperature after heat recovery unit; Pink = treated air temperature.

Figure 3d.



DDC – Temperature variation of borehole heat exchanger carrier fluid. Red = exterior air temperature Green = fluid entering ground heat exchanger. Blue = fluid entering heat pump from borehole heat exchanger

Figure 3e. DDC – Electricity consumption (green) [kWh] vs. outside air temperature (red) [°C]

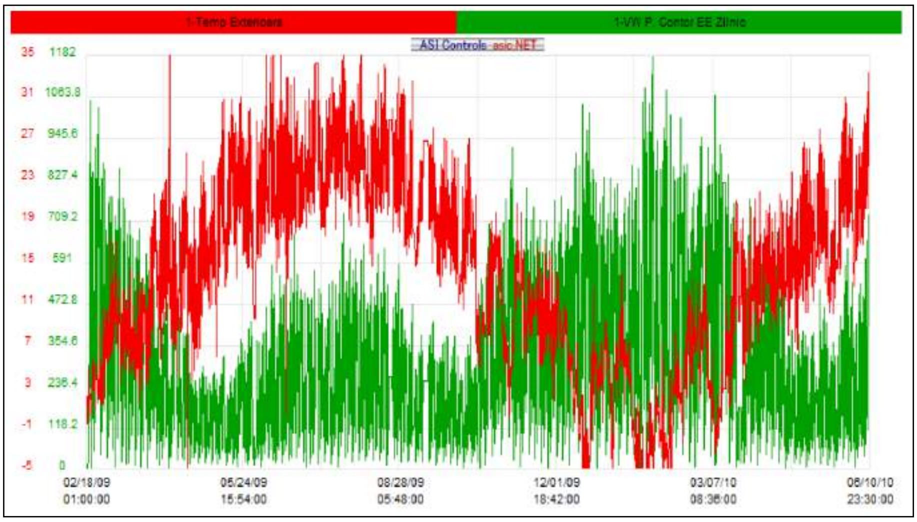
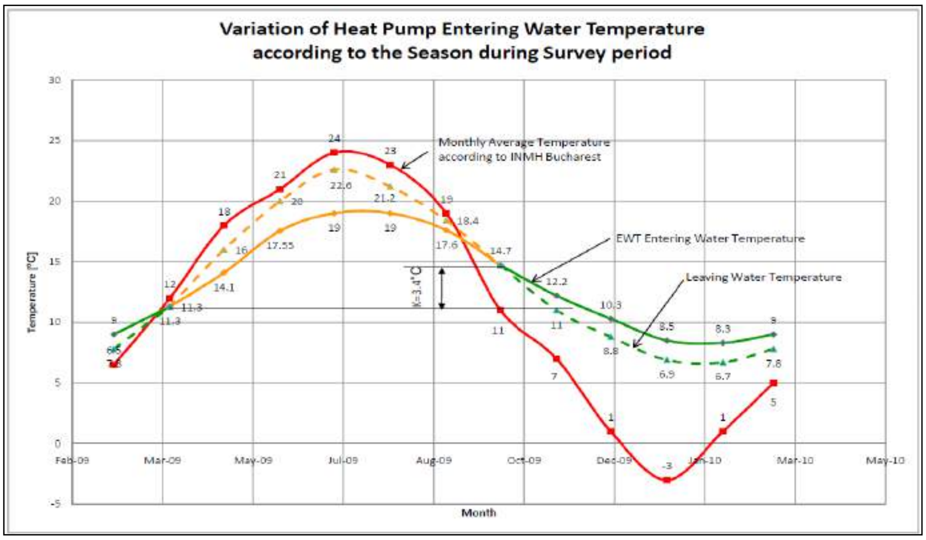


Figure 4. Monitoring results of geothermal HVAC system (carrier fluid temperatures)



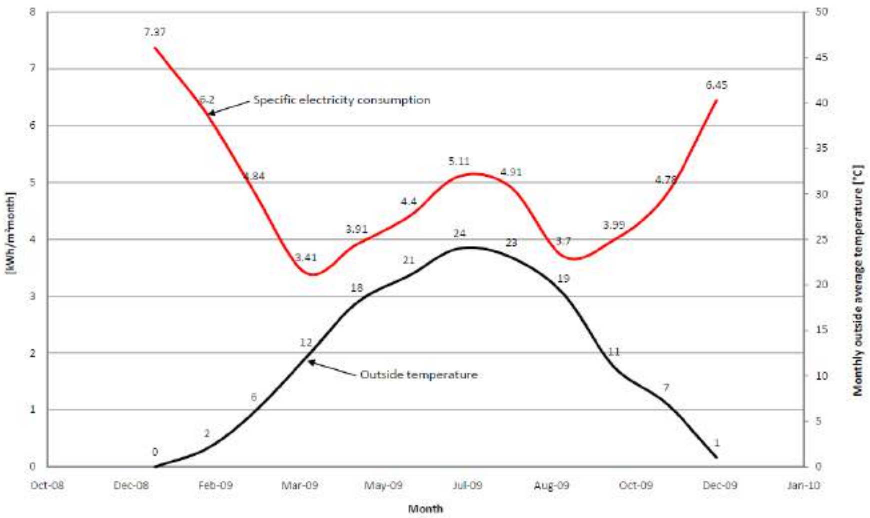


Figure 5. Variation of monthly energy consumption

Annual specific electricity consumption: $\Sigma e_{driving}$ = 59.07 kWh/m².yr.

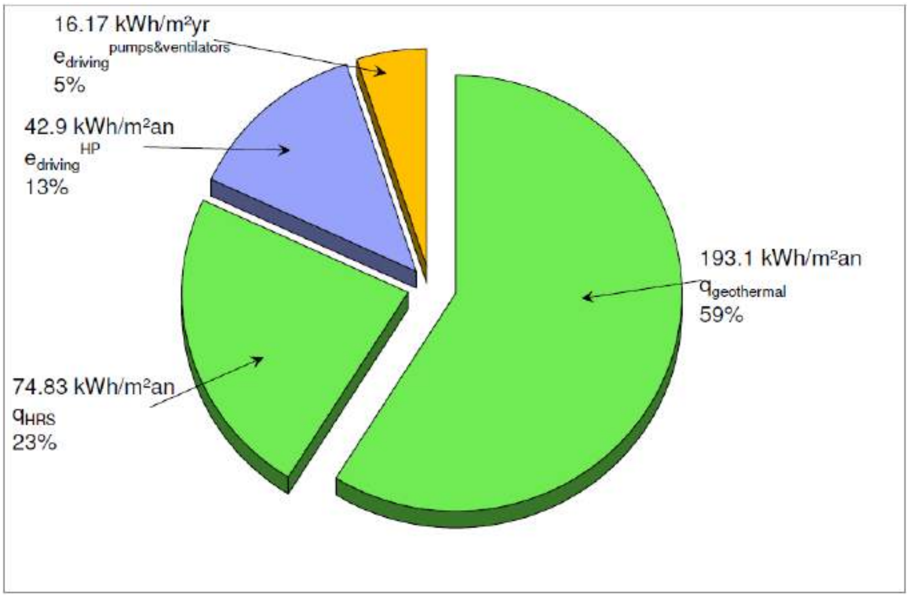


Figure 6. Graphic representation of the energy of the system

$$q_{usable} = q_{geotermal} + e_{driving}^{HP} + e_{driving}^{pumps\&ventilators} + q_{HRS} = 327\ kWh/m^2.yr$$

(see the above chart)

$$SPF_{yr} = \frac{327\ kWh/m^2.yr}{59.07\ kWh/m^2.yr} = 5.5$$

$$e_{RES} = q_{usable}\ (1\text{-}1/SPF_{yr}) = 327\ (1\text{-}1/5.5) = 268\ kWh/m^2.yr$$

IV. CONCLUSIONS

The HVAC system, using ground-coupled water-to-water and water-to-air heat pumps, not only utilizes the geothermal heat resource, but recovers significant secondary energies from the building. The renewable energy produced on location significantly exceeds the electrical input power. For an electricity conversion factor f_{EE} = 2.5 $kWh_{primary\_energy}/kWh_{electricity}$, the energy ratio according to Directive 2010/31/EC is calculated as:

$$\frac{e_{RES}}{\Sigma e_{driving}} = \frac{268}{2.5 \times 59.07} = 2.2$$

Because $e_{res} >> \Sigma e_{driving}$, this application can be regarded as a "Nearly-Zero Energy Building" with zero carbon on location.

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CHAPTER 14

DESIGN OF HORIZONTAL COLLECTORS

by Paul Sikora and Javier Urchueguía

I. INTRODUCTION

The horizontal array is the most demanding of all geothermal collector types in terms of the ground area required to produce a specified geothermal energy yield. For this reason it is very seldom used in urban or even suburban installations. Nonetheless, in rural settings or in regions of low density development, the horizontal array can have advantages over borehole geothermal collectors. The purpose of this section is to identify and discuss the factors which must be considered in the evaluation of a site for a possible horizontal collector.

Applications for horizontal arrays are for the most part domestic or small commercial projects. In such cases it is not normally economical to carry out the comprehensive thermal analysis needed to produce a closely calculated collector design. In addition, horizontal arrays are influenced to a significant degree by seasonal variations which limit the usefulness of any short term thermal measurements. Hence, the geothermal designer must be able to work with limited information to decide whether the available area at a given site will support an adequate horizontal collector. Software packages and small-scale measuring equipment are available to the designer for applications where their use can help to refine the design.

II. THEORETICAL FUNDAMENTALS

The shallow horizontal array (SHA) can be compared in one sense to an unglazed solar collector with a large thermal mass. The thermal capacity of the soil mass is sufficient to damp out the daily and short term climatic fluctuations, but the collector parcel still shows significant temperature swings over a year. In addition, the SHA responds both to precipitation and to wind. In this section, the major influences which determine the performance of SHA collectors are enumerated and discussed briefly.

II. 1. Climate

The first factor is the solar flux incident on the parcel. This exerts a direct influence on the temperature of the collector parcel. Its effect will be influenced by the site particulars: shaded or open; sloping or flat; the compass orientation of the slope, particularly in high latitudes and the type of surface cover. A snow cover is beneficial since it reduces the heat losses from the ground surface. Precipitation, particularly rainfall, has a major influence on SHA performance. Moisture content has a large bearing on the effective heat capacity of the soil. In addition, it influences the thermal conductivity of most moisture-permeable soil types. Thirdly, water percolating through the collector parcel introduces the transport of heat by mass movement in addition to the mechanism of conduction. For the last-mentioned heat transfer mechanism to be effective, the soil must be permeable and the parcel must have effective drainage so that it does not become waterlogged. Moisture migration by repeated evaporation and condensation may lead to drying out of the soil around the pipe when the SHA is used for cooling applications. This results in considerably poorer heat transfer properties.

Wind exposure also provides a thermal contact mechanism, but one whose overall effect is not easy to assess.

II. 2. Soil

The mineral composition of a soil is a factor influencing SHA performance by virtue of its principal thermal attributes, namely its thermal capacity and thermal conductivity. In the case of soils, as opposed to the rock underlying them, these factors are secondary indicators rather than primary determinants of geothermal collector performance.This is because soils are heterogeneous agglomerates of rock particles and organic matter and water.

The suitability of a soil for use as a geothermal collector depends on the size distribution of the mineral grains as much, if not more than, on the mineral type itself. The grain size distribution has a major influence on the dry soil properties, but it has an equally important influence on the ability of the soil to hold water and to permit its movement through the soil. Organic matter in the soil plays an important role through its affinity for water, although when dry it has extremely poor thermal properties. Hence, a good candidate soil for use as a geothermal SHA will generally be a deep soil, suitable for arable crop production. Clays are usually poor performers due to their small or negligible water permeability. Silty, sandy and gravelly soils can be usable but may need special preparation to improve their water permeability or their moisture holding properties (Boyer & Grondzic, 1987). Saturated sands and gravels can offer excellent prospects for collectors, due to their high thermal conductivity and volumetric heat capacity.

II. 3. Topography

If available, a sloping site is generally preferable to one on the level. A sloping site encourages movement of soil moisture and is less likely to suffer from waterlogging. A site positioned on a longer slope will be able to take advantage of the downhill migration of soil moisture. Indeed, if the choice is available, the preferred parcel shape would be a long narrow ribbon running along a contour in order to intercept the maximum amount of soil water movement.

The compass aspect or facing of a candidate ground parcel also affects its likely performance as host for a SHA collector. Especially in higher northern latitudes, a south-facing ground parcel will intercept more solar flux than one on the flat, and still more than a north-facing one. The difference is not as significant as for solar panels since the ground parcel is fully receptive to diffuse solar radiation; but, other things being equal, a south-facing site is preferable.

Using the same line of reasoning, a site in a hollow is to be avoided if other alternatives are available. On this type of topography it will also be difficult to lay out the pipework in a way that does not have a propensity to airlocking.

II. 4. Surface cover

The intended or possible uses envisioned for a ground parcel will have a major bearing on its suitability for use as a geothermal SHA. Although it is commonly thought that a matt black surface would be the most desirable type of cover, the fact is that most natural ground coverings have high solar absorption. The most important single attribute for the surface cover of a SHA is that it be permeable to moisture. Moisture percolating into the ground carries heat with it. Moisture maintained in the ground contributes substantially, both to the thermal storage capacity of the soil and to the ability of heat to move toward or away from the buried pipes as desired.

Hence, any surface cover which is impermeable to water is likely to degrade the thermal performance of the collector substantially. This is particularly true for collectors designed to provide useful cooling. The effect of using water-permeable pavements such as cobble block or even permeable asphalt has not been fully documented, although some investigations of this are underway (Greene *et al.*, 2008). The preferred type of cover is typically grass or other low vegetation. There is also anecdotal experience that vegetables and bush fruits are not measurably affected by the presence of a properly dimensioned SHA beneath the ground parcel.

III. PRACTICAL FUNDAMENTALS

The process of evaluating a site for the possible use of a shallow horizontal array collector consists of finding answers to a few basic questions:

- What is the yearly import and export of thermal energy required by the load at the site?
- What are the averages of temperature, global solar radiation, rainfall and snow in the area?
- What are the characteristics of the soil in the area?
- What is the estimated thermal productivity of the soil in the area?
- Can the soil thermal productivity be improved?
- Is the available area sufficient to provide acceptable performance of the GSHP?

The starting point for information about site thermal loads (kW heating and/or cooling) is the Building Energy Rating or similar document carried out by a qualified professional for the site in question. This may need to be adjusted by any particular requirements of the client not covered by the rating exercise. For temperate and northerly latitudes, the requirement is usually dominated by heating. At lower latitudes, there will often be cooling as well as heating requirements. The basic result sought is the net annual energy (kWh/yr) to be supplied by or rejected into the geothermal collector.

These energy import and export amounts must be set against the capability of a potential SHA at the site. Each square metre of horizontal surface in Europe receives an annual input of solar radiation ranging from more than 2000 kWh/m^2/year in the sunniest regions, down to about 600 kWh/m^2/year in the most northerly parts of Europe (European Solar Radiation Atlas, 1984, 1986). Temperate zones receive about 1200 kWh/m^2/year. The net thermal energy import or export by geothermal collection must remain small in comparison with the solar input if the average ground temperature is to remain sensibly undisturbed. For temperate zones where heating is the dominant if not the only demand of the load, a nominal guideline figure of 50 kWh/m^2/year is often used to arrive at a collector size estimate. VDI Blatt 2 suggests a range of 50 to 70 kWh/m^2/year. If the energy rating of the building is, for example, 60 kWh/m^2/year and the building heated area is 150 m^2, the collector parcel size should be adequate to supply 60x150 or 9000 kWh/year to the building. Of this amount, only the fraction (1-1/COP) is supplied by the collector.

For a heat pump having a seasonal performance factor of 4, the guideline SHA parcel area is:

$$(1-1/4) \times 9000/50=135 \text{ m}^2.$$

This procedure results in a ratio of almost one square metre SHA area per square metre of heated building area. This correspondence has given rise to a rough rule, often used as a feasibility yardstick, but it is important to carry through the exercise for each case since particular site conditions may easily change the result.

If an area of 135 m^2 is available for use as a SHA emplacement zone (free of pipes, cables or other buried services; not intended for a future building area; not to be paved for car parks or other use requiring water to be drained from it), then it needs to be examined for geothermal productivity. This productivity is the ability of the parcel to yield or absorb thermal power fluxes without developing unacceptably high temperature gradients.

Specific guidance in making this assessment is available from numerous sources. Descriptions and terminology vary considerably and local experience will also be valuable. The principles outlined earlier in the section should be kept in mind when assessing a site:

- Visual inspection of an excavation down to the intended emplacement depth will show the soil morphology and can be used to establish drainage characteristics. Time of the year must also be noted. Test pits dug for geotechnical evaluation or for percolation tests can be very useful for this purpose
- Heavy clay layers, shale or other types of broken rock present difficulties which may make the parcel expensive or unfeasible to develop
- Sands or gravels can be very favourable provided they contain adequate moisture during the heat pump working season.

Promising soil types can yield up to 40 W/m^2, while very poor types may yield down to 10 W/m^2. These figures are based on a typical temperate European heating season of approximately 1800 hours (VDI Blatt 2). Much of this difference in collector yield can result from degrees of moisture saturation, so that rainfall patterns and the yearly use of the system must enter into the evaluation process.

For the example discussed above, the collector parcel of 135 m^2 could support a heat pump of about 1.8 kW heating capacity (or 1.35 kW of cooling capacity) with the least productive soil type. These figures would increase to 7.2 kW and 5.4 kW respectively for a high productivity collector parcel. These results show that collector parcel size alone does not guarantee that a workable SHA will result.

Semi-quantitative evaluation of potential collector performance requires measurement of soil thermal properties. Equipment capable of producing this type of information for SHA collectors is now available in the form of a needle probe device capable of measuring apparent soil thermal conductivity (Soil Heat/Carbon Zero Consulting, Ltd.). Some software packages, including Ground Loop Design (GLD) allow the semi-quantitative simulation of different SHA collectors using soil thermal parameters, loop layout, pipe diameter, etc. as input parameters.

IV. ENERGY EFFICIENCY AND ECONOMIC COST EFFECTIVENESS

There are number of ways in which the GSHP designer can improve the effectiveness of a SHA collector. It is clear that this collector type can result in considerable reduction in the overall cost of the system, but its successful implementation will require that the installer is conversant with techniques for maximizing the performance of a SHA collector.

The following is a list of several measures which have been used to improve such collectors. The list is by no means exhaustive, but it may suggest other possibilities which a site may present:

- Reduce the net yearly thermal draw on the parcel. This allows the parcel size to be reduced. This can be done by a large number of measures, including the channelling of surface runoff water into the collector; placing the SHA parcel beneath a graywater percolation area; using the SHA as a source of free cooling during summer; and other options
- Improve the thermal productivity of the SHA parcel. Free-draining soils can be improved by incorporating a layer of organic material in the vicinity of the collector tubing. Low-cost options for such materials include waste silage, spent compost used for mushroom growing, wood chippings, grass cuttings and others available in the locality
- Improve the thermal productivity of the SHA parcel. Waterlogging soil parcels can be improved by adding drainage - via gravel layers, drain pipes or other permeable elements as convenient
- Choose the most suitable pipe layout and emplacement depth. Many options exist for the pipe layout and considerable savings in installation work may be realised by careful selection. In temperate Europe, it is common to bury collectors at depths of 1.2 to 1.5 m. However, in moist temperate zones, collectors may be placed at depths as shallow as 80 cm where frost is not a problem and where soil conditions permit and moisture recharge rates are adequate. In any event, a prudent selection must take account of extreme weather conditions as well as collector installation costs.

V. FURTHER INFORMATION

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CHAPTER 15

INSTALLATION AND GROUTING *by Walter J. Eugster*

I. INTRODUCTION

Installing the Borehole Heat Exchanger (BHE) and grouting the borehole have the same importance for the completion and the future operation of the system as the drilling itself or as connecting the BHE to the Heat Pump (HP).

The following key points ensure a good job:

- The borehole must be kept open until grouting has finished. Thus any auxiliary casing is removed after grouting
- The BHE tubes need very careful handling during transport, on-site storage and installation
- Grouting needs special attention and care. These are the three main functions of the grout:
    - Sealing the borehole to inhibit any vertical water flows along the BHE (groundwater protection function)
    - Ensuring a good thermal contact between the BHE walls and the surrounding underground (thermal function)
    - Protecting the embedded BHE tubes from mechanical damage (technical function)
- The installing and grouting work is done by the driller. But the designer should know what to expect from this working phase.

II. INSTALLATION PROCEDURE

II. 1. Preliminary work

It is strongly recommended that some preparatory work is done before inserting the BHE into the borehole. The drilling staff may do this step during the drilling phase.

The BHE has to be mounted on and fixed to a decoiler (Fig. 1), if the BHE length is longer than 50 m. This avoids unreeling the BHE on the ground of the construction site, which is a high risk for any mechanical damage to the BHE. If the BHE is longer than 150 m the decoiler is preferably equipped with a brake to ensure a slow and careful insertion into the borehole.

The BHE tubes need a visual check to detect damage. For PE100/PN16/SDR11-tubes, notches and damage of max. 10% of the tube wall thickness are acceptable.

It is also recommended that a first tube tightness check is performed using air at about 6 bar to detect damage, especially when the transportation of the BHEs to the construction site and/or the storing of the BHEs on site were not made under the supervision of the drillers.

Then additional weights are normally fixed at the BHE foot and the injection tube is fixed to the BHE near to the foot.

Remember: use, preferably, factory welded BHEs. If the foot is welded to the BHE on the drilling site, the driller needs a valid welding certificate.

Figure 1. BHE on a decoiler during the first density test using air (picture: Polydynamics Engineering Zurich)

Figure 2. Ready-to-insert BHE with an additional weight, protected foot and a fifth injection tube (picture: Polydynamics Engineering Zurich)

II. 2. Insertion of the BHE

The BHE is inserted as vertically as possible (Figs 2 and 4) into the borehole. Some drillers use guide rollers to ensure this. The sharp casing endings should be protected to avoid BHE damage through abrasion (Fig. 3). The BHE is moved carefully, slowly and with speed control into the borehole.

The pressure conditions inside/outside the BHE tubes need special attention during insertion:

- BHE must be filled with water if there is water in the borehole

- Be aware of the following limits for PE100/PN16/SDR11 tubes:
    - Δp (inner → outer): max. 21 bar
    - Δp (outer → inner): max. 8 bar !!

      If this value is exceeded the BHE starts to collapse!!

After complete insertion, the BHE is cut to the required length (often BHEs are only available at certain specified lengths).

In preparation for the grouting, the BHE is then completely filled with water (Fig. 5), a primary pressure is applied and the BHE is hermetically sealed (valve). The pressure limits for the tubes must be taken into account.

Figure 3. Two different casing ending protectors (picture: Polydynamics Engineering Zurich)

Figure 4. Guide rollers to ensure vertical insertion (picture: Polydynamics Engineering Zurich)

Figure 5. Cut the tubes to required length, fill them with water, apply a first pressure and seal them (picture: Polydynamics Engineering Zurich)

III. GROUTING

The grouting material itself has to fulfil a number of specifications, given by the local authorities or by professional associations.

The following material characteristics may be regulated:

- Minimal Density of the grouting suspension
- Minimal stability of the suspension
- Minimal compression strength of the hardened backfill material
- Maximal hydraulic permeability of the hardened backfill material
- Optionally a minimal thermal conductivity
- Optionally a minimal resistance against structural damage after several freeze-thaw cycles.

Figure 7. During grouting the auxiliary casing still prevents the borehole from collapsing. The BHE is under pressure (picture: Polydynamics Engineering Zurich)

Figure 6. Various types of grouting equipment (pictures: Polydynamics Engineering Zurich)

Industrially fabricated and bagged backfilling material with a constant blending and controlled quality is the preferred solution. Self-made mixtures on the drilling site never have the same constant quality as industrially blended materials.

Grouting material is either mixed in tanks of a given volume and then pumped tank by tank through the injection pipe into the borehole, or it is continuously mixed using a proportioning pump (Fig. 6). The quality of the grout suspension must be constant over the whole grouting procedure and has to be checked by density measurements.

To guarantee the groundwater protection features of the grout material, the driller has to follow exactly the manufacturer's mixing recipe.

The Borehole is grouted either using the previously fixed injection pipe or sometimes using metallic BHE mounting rods which then are removed rod by rod during grouting (Fig. 7). Basically and essentially, grouting must be done from the bottom to the top of the borehole following the so-called contractor process. The injection pipe is left in the borehole and the deepest rod must be kept below the grout material level over the whole grouting process. Grouting from the top using any buckets or pumping the suspension from the surface is not permitted.

The grouting process is finished, when the out-flowing grout suspension at the wellhead has the required quality. Now the auxiliary casing is removed and the BHE is prepared for final testing.

Note: To avoid uncontrolled gas or water outflow from the borehole, the grouting process has to take place immediately after inserting the BHE!!

Due to the limits regarding the pressure difference inside/outside the BHE, the following system limits and recommendations are given for PE100/PN16/SDR11 BHEs (Table 1).

Density of grout suspension	Allowed BHE length without reservation	Grouting only when BHEs are hermetically sealed	BHE length exceeds pressure limitations
1200 kg/m^3	up to 400 m	no limitation	no limitation
1400 kg/m^3	200 m	> 200 m	no limitation
1600 kg/m^3	120 m	120 – 340 m	> 340 m
1800 kg/m^3	100 m	100 – 260 m	> 260 m
2000 kg/m^3	80 m	80 – 200 m	> 200 m

Table 1. Technical limits for PE100/PN16/SDR11 BHEs

There are many different grouting materials on the market. Some of those have a higher thermal conductivity, others show a higher resistance against freeze-thaw cycles and others need only a short time until a rather high compression and/or shear strength is provided.

Therefore, there is a wide range of different products with different physical properties. It is up to the drillers or the designers to choose the optimal material for their purposes. In addition, of course, the price of the grout is an important criterion for the clients in an open market.

A higher thermal conductivity, for example, lowers the borehole resistance and increases the thermal capacity of the BHE. This is a big advantage especially in the cooling case. In the heating case, the total BHE length could be reduced under certain circumstances.

Both a higher thermal conductivity or a higher resistance against freeze-thaw cycles induce higher density of the grout suspension. This could lead to reaching the technical limits of the BHEs more quickly. It is moreover a question of the total system design.

IV. TIPS AND REMARKS FOR DESIGNERS

Licensing authorities may impose special conditions regarding BHE quality, length, position, grouting, etc. – always follow these!

To avoid delays due to non-professional work, it is advised to contract only experienced, certified BHE drillers with nationally or internationally accepted well-known labels or certificates who will ensure:

- Skilled drilling staff to carry out the scoped work
- Suitable drilling expertise to deal with specific site geology and hydrogeology
- The use of drill rigs equipped with adequate safety equipment to detect, e.g., gas and artesian water outflows as well as drilling staff trained to face such incidents.

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CHAPTER 16

FUNCTIONAL AND QUALITY CONTROL *by Walter J. Eugster*

I. SYSTEM CONTROL

Leakage, pressure, temperature (Fig. 1)

The Borehole Heat Exchanger (BHE) circuit must at the least be equipped with:

- Filling and flushing fittings
- A de-aeration device
- A pressure-relief valve
- A manometer
- A pressure control device
- An expansion vessel

and preferably;

- An anti-icing control device (if no anti-freeze is added)
- Temperature devices.

Each individual BHE circuit must be equipped with a flow control and shut-off valve to allow for adjustment of flow and pressure drop of each individual circuit.
Note: the natural expansion of deeper BHE tubes (forced by the weight of the fluid column at lengths >ca. 250-300 m) could exceed the calculated ordinary expansion vessel volume. This effect depends on the grout material.

II. TESTING, COMMISSIONING AND DOCUMENTATION

II.1. Final testing

The final testing of a BHE consists of two stages:

a) a flow test
b) a leak tightness test (pressure test).

Before performing the tests, it is necessary to flush the BHE tubes (Fig. 2), preferably from both sides, to clean the BHE and flush out dirt or any other remains in the tubes.

a). Flushing the BHE

Fresh water is pumped through each BHE circuit to flush out any dirt particles, preferably from both sides, until each circuit is completely flushed once.

b). Flow test

The aim of the flow test is to prove that the tested BHE circuit does not have an increased pressure drop, i.e. an increased hydraulic resistance (Figs 3, 4).

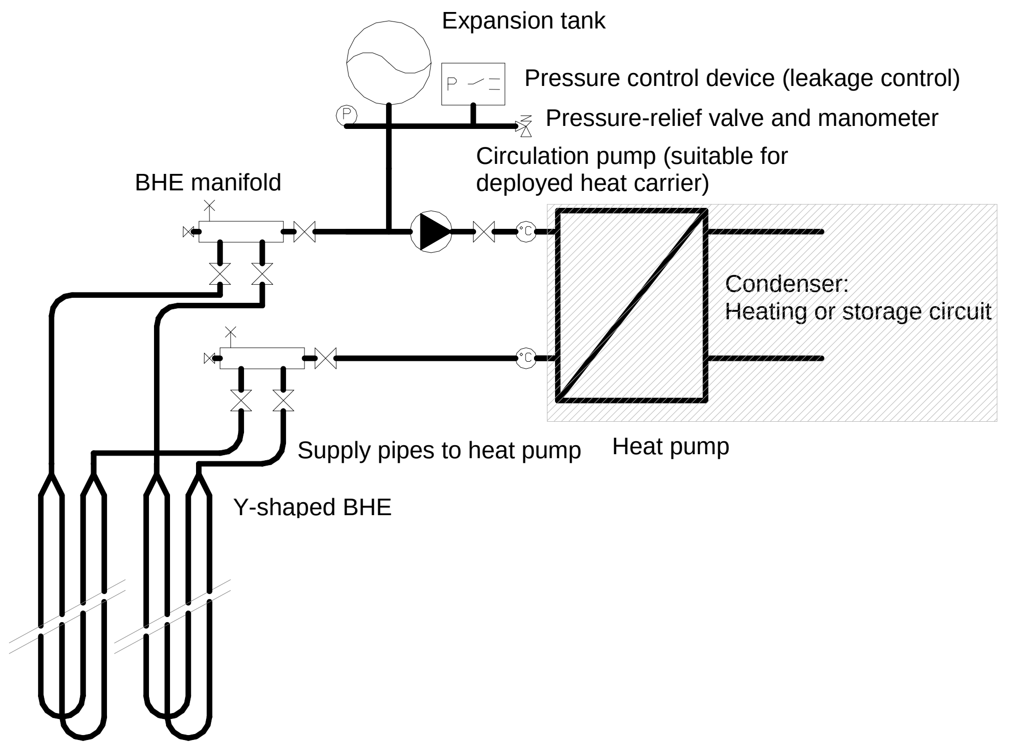

Figure 1. Example of a minimal equipment of primary circuits featuring 2 BHEs (drawing from SIA 384/6 (SN 546 384/6))

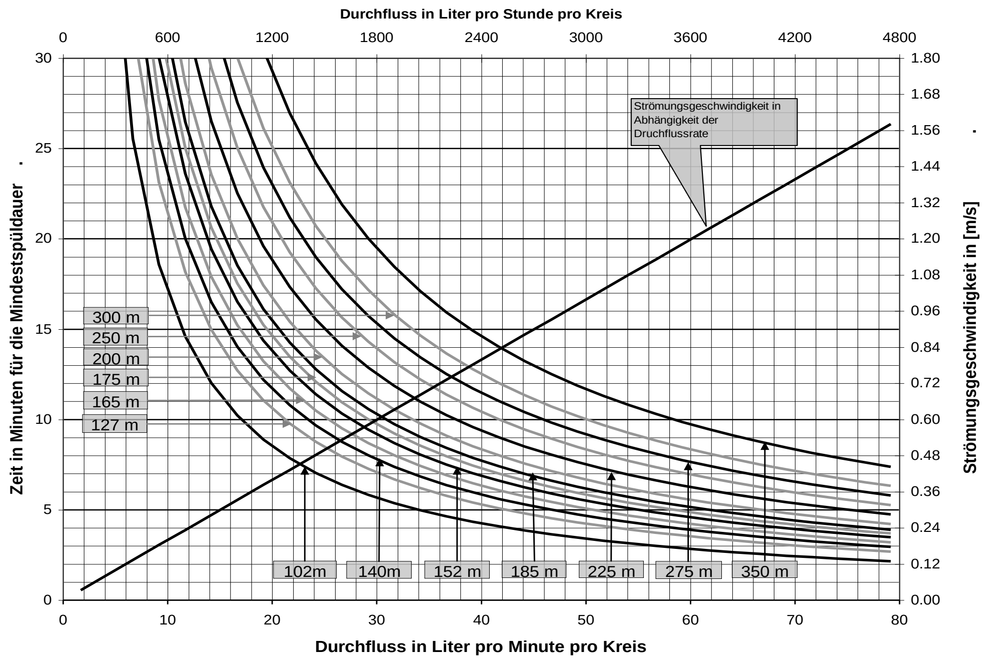

Figure 2. Example for the minimal flushing duration per circuit for a BHE tube Ø 40x32.6 mm as a function of the flow rate and the BHE length (graph from SIA 384/6 (SN 546 384/6))

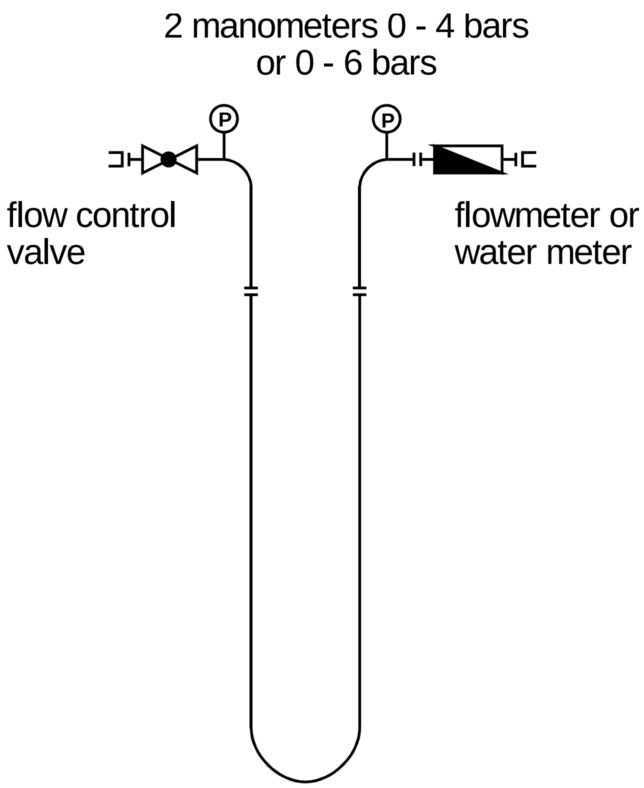

Figure 3. Flow test configuration (graph: Polydynamics Engineering Zurich)

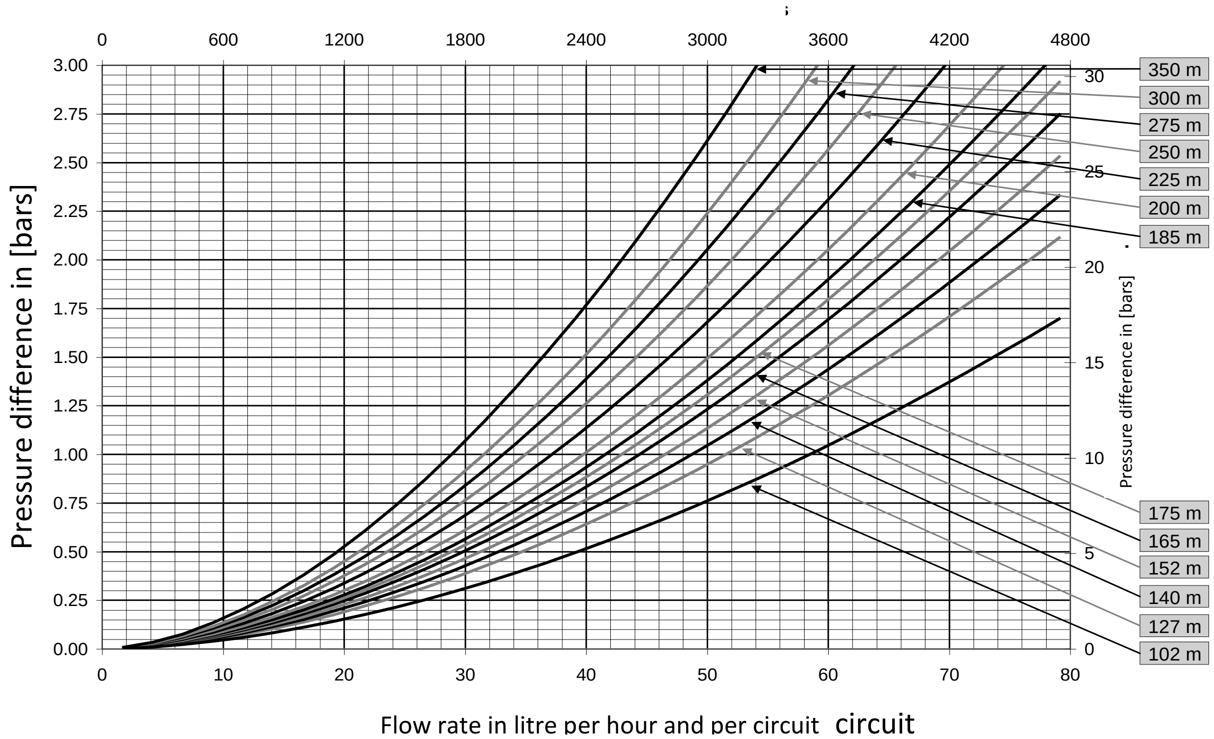

Figure 4. Theoretical maximal allowed pressure drop per circuit of a BHE, tube Ø 40x32.6 mm (graph from SIA 384/6 (SN 546 384/6))

A slight overpressure (outside → inside) during installation may deform the BHE tubes to an oval shape with a smaller sectional area. This effect increases the pressure drop. Possibly a larger circulation is then needed to ensure the projected flow rate.

The pressure difference (inflow – outflow) at constant flow rate must not exceed a certain theoretical value. The flow test may be combined with the tube flushing.

The equipment needed to perform the flow test is as follows:

- 2 manometers (0 - 4 or 0 - 6 bar)
- 1 flow control valve
- 1 flow meter (an impeller water meter is sufficient).

c). Leak tightness test (pressure test)

Leak tightness (pressure) testing has to follow the EN 805 prescriptions. For polyethylene (PE) tubes, the pressure testing has to be carried out as a 'compression test'. An overpressure (inside → outside) is applied to the pipe over the whole length. This step inflates slightly the PE pipe over its whole length. Then a sudden pressure drop of around 10% of the testing pressure is applied (Fig. 5). This pressure drop allows the pipe to compress again. If the pipe is tight, a pressure increase is measured.

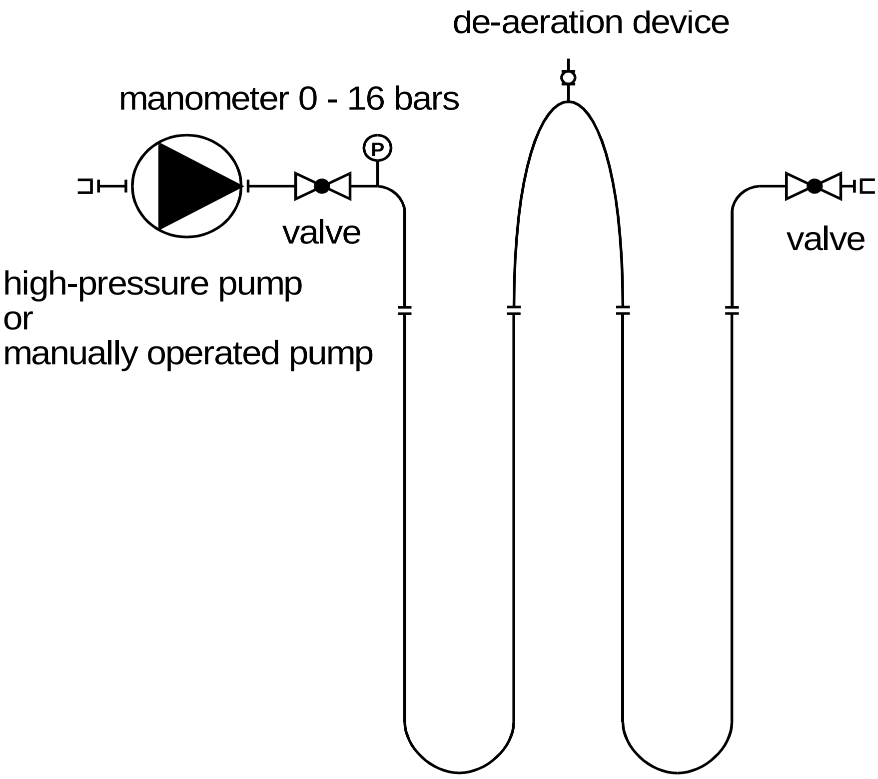

Figure 5. Leak tightness test configuration (graph: Polydynamics Engineering Zurich)

To perform such a test, the following equipment is needed:

- A high-pressure pump or a manually operated pump
- 2 stop valves

- 1 manometer 0 -16 bar
- A de-aeration device, if both circuits are tested at once

  This pressure test must be carried out immediately after having finished the grouting and when the grout material has still not hardened.

Test pressure for PE100/PN16/SDR11 tubes is recommended as follows after SIA 384/6 (SN 546 384/6):

- Overpressure at BHE foot: > 0.5 bar during testing
- Pressure at BHE heat: > 7.5 bar.

Test procedure in detail (Fig. 6):

- 1 h Idle period. No overpressure is applied to the tube ①
- Apply the test pressure. For PE100/PN16/SDR11 BHEs see Table 1. For other materials follow the manufacturer's specification ②
- 10 min Keep up pressure test ③
- 1 h Idle period. The tube is going to expand over the whole length
- Pressure measurement. The pressure drop may not exceed the manufacturer's specifications ④
- Sudden pressure drop of at least 10% of the test pressure ⑤
- 10 mins. First pressure measurement ⑥ A
- 20 mins. Second pressure measurement ⑥ B
- 30 mins. Third and final pressure measurement ⑥ C

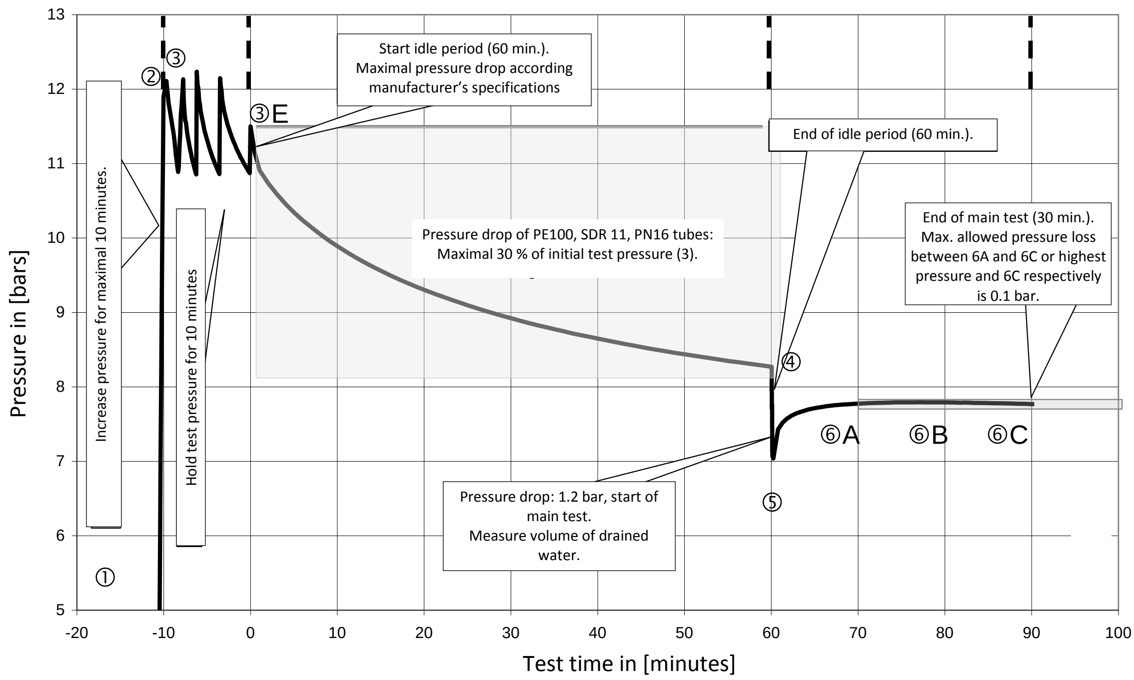

Figure 6. Graphical test procedure (graph from SIA 384/6 (SN 546 384/6)).

The BHE has passed the test if the pressure difference (pressure drop) between ⑥ C and ⑥ A does not exceed 0.1 bars.

The upper part should not be filled up with water in cold weather, when there is a risk of freezing.

BHE length	Density of grout suspension				
	1200 kg/m^3	1400 kg/m^3	1600 kg/m^3	1800 kg/m^3	2000 kg/m^3
60 m	8.0 bar	8.0 bar	9.0 bar	10.0 bar	11.0 bar
80 m	8.0 bar	9.0 bar	10.0 bar	12.0 bar	14.0 bar
100 m	8.0 bar	9.0 bar	11.0 bar	14.0 bar	17.0 bar
120 m	8.0 bar	10.0 bar	13.0 bar	17.0 bar	21.0 bar
140 m	8.0 bar	11.0 bar	15.0 bar	19.0 bar	24.0 bar
160 m	9.0 bar	12.0 bar	17.0 bar	22.0 bar	27.0 bar
180 m	9.0 bar	13.0 bar	19.0 bar	25.0 bar	31.0 bar
200 m	9.0 bar	14.0 bar	21.0 bar	27.0 bar	34.0 bar
220 m	10.0 bar	15.0 bar	23.0 bar	30.0 bar	no BHE

Test pressure for different BHE lengths and grout suspension densities.

No ordinary leak tightness testing. Testing only according to manufacturer's specifications.

Table 1. Test pressure determination for PE100/PN16/SDR11 BHEs (after SIA 384/6 (SN 546384/6))

After the final testing, the BHEs commonly are commissioned to the client (owner or installer respectively).

Figure 7. Protection of the BHE endings (picture: Polydynamics Engineering Zurich)

Figure 8. Example for sealing the BHE after final testing (picture: Polydynamics Engineering Zurich)

The final connection to the complete heat pump system could take place later – from a few days up to several months. Therefore, the BHEs have to be protected from any occasional damage during further construction work. The BHE endings are closed soundly and the BHE endings are marked and protected (Figs 7, 8).

III. COMMISSIONING

The final testing of the BHEs represents the commissioning of the BHE drilling work. The client should receive an invitation to attend the final testing. All driller logs and test records are handed over to the client.

This is the moment, the driller hands his responsibility for the BHEs to the customer and the legal warranty starts to run.

A final commissioning takes place when the complete heat pump (HP) system is finished. This includes at least the following points:

- Leak tightness test of the complete hydraulic system
- Check system temperatures, pressures and flow rates
- Check the function of each device
- Run the heat pump system
- Hand out a complete documentation to the customer
- Instruction of the future system operator in using and maintaining the system and what to do in case of a disruption.

IV. DOCUMENTATION

If there are no relevant national regulations, at the least the following data have to be attached on site (heat pump) and documented in the project papers:

- Year of construction
- Drilling company
- Number, length and distance of the BHEs
- Length and diameters and supply/return pipes between heat pump and BHEs
- Brand, exact product description and mixture of heat carrier
- Volume of BHE circuits
- Flow rate and delivery height of the circulation pump(s)
- Brand and exact product name of the HP
- Heat and refrigeration capacity of the HP at design temperature.

The following additional data should complete the project papers:

- Drilling log and profile and – if applicable – the geological expertise
- Site map with exact (measured) location of the BHEs and the supply/return pipes
- Calculated capacity of the BHEs (dimensioning)
- Final test logs and records of delivery (commissioning).

V. MAINTENANCE

In principle, a BHE installation is maintenance-free! Nevertheless, a few points should be checked:

- Measure or look up the system pressure (yearly by the operator). Note the value in a log file
- Record each addition of liquids (water or antifreeze, added volume, pressure before and after adding)
- Check the antifreeze protection of the heat carrier every 10 years.

VI. MONITORING

System monitoring delivers the base of any future system optimization. The system control should record and preferably store the following system parameters:

- Total time of operation
- Minimal supply and return temperature of the BHE circuit
- Supply and return temperature of the heat/user circuit
- Optionally: electric power consumption.

If there is no automatic data logger, recall these values from the system control and note them in a log file.

For smaller installations, record or recall these parameters in the beginning on a daily or weekly basis; later on, a monthly or yearly recording/recalling is sufficient.

For larger installations, a more detailed and automatic monitoring is recommended.

CHAPTER 17

EUROPEAN LEGAL SITUATION AND STANDARDS

by David Norbury with Burkhard Sanner

I. INTRODUCTION

Geothermal heating and cooling is an immature market in Europe as a whole so that there is little in the way of European level standardization or normalization of the design or installation of ground source heat pump systems. In some countries, the market has been in existence for longer and has developed to the point that there is a substantial market which has prompted development of the national standards for various aspects of the design and installation.

This chapter sets out the situation on normative standards across Europe and considering national situations, and summarizes the key aspects of the most important available standards. The way forward in the development of further normalization is identified for discussion.

For Geothermal energy and heat pumps, three different areas have to be distinguished in the installation process, and they are typically covered by different workforces:

a) Installation on the geothermal side (drilling, pipe laying, well construction, etc.). No standards at EU level exist

b) Heat pumps (work with refrigerating/thermodynamic systems, systems under pressure, electrical safety, etc.). A number of standards exist at European or international level

c) Classical heating and air conditioning installation (plumbing, radiators, air ductwork, etc.).

For the electrical side, IEC has developed a number of standards in the IEC 60335 series about safety of household and similar electrical appliances that are ratified on a European level. Item c) rules are identical for any conventional heating and cooling installation.

The overall status of implementation of Standards across Europe is:

- Heat Pumps – there are comprehensive and harmonized technical standards for the equipment
- EU member states (plus Switzerland and Norway) have adopted the EN standards for testing, rating and safety of heat pumps
- EN Standards exist only for safety of drill rigs (shallow wells), and from the petroleum industry (which may have some relevance for any deep well drilling that might be carried out)

- For shallow geothermal systems, technical standards exist in the countries where the market is already well developed. This includes Germany, Sweden, Austria and Switzerland
- Certification of installers and drillers exists only in those countries where the market has matured.

In the Geothermal and heat pump sector, standards and codes can be classified in various ways:

  - Technical standards for efficiency, safety, longevity etc apply mainly for the heat pump sector
  - Technical standards for environmental protection, as for drilling, borehole heat exchangers, etc. apply mainly for the ground side (geothermal)
  - Regulations and guidelines for licensing of geothermal systems (typically concerning groundwater protection), include legal regulations for the access to and ownership of the geothermal resources
  - Certification of skill and work quality for installers and drillers.

II. EUROPEAN STANDARDS

For heat pump equipment there is a comprehensive and well harmonized set of technical standards. For shallow geothermal systems in general, technical standards exist in those countries where the market has already developed. The main administrative and licensing barriers applying to geothermal works are well covered by the overall EN standards.

Heat pump equipment is covered by a comprehensive and well harmonized set of technical standards. Member states have adopted the basic EN standards for testing and rating, safety, etc. into national standardization; Switzerland, Norway and Iceland have joined into the same set of standards. While not all relevant EN standards are yet implemented in all member states, the process is well under way.

In the same process, most pre-existing national standards have been withdrawn and replaced by EN standards. National standards existed in particular in the traditional heat pump countries like Austria, Germany, Sweden and Switzerland. In several cases, pre-existing national standards are kept valid for specific areas not covered by the EN standards.

For geothermal energy, EN standards exist only for the safety of drill rigs (shallow geothermal), and for the sector of the petroleum industry (which has some relevance for deep geothermal, together with US API standards). The standards from the petroleum industry are listed only in the common EN form, and their national adaptation is only apparent in Germany and France.

For shallow geothermal systems in general, technical standards exist in those countries where the market has already developed. This includes Germany, Sweden, Austria, and the non-member-state Switzerland. A similar situation also pertains for the certification/licensing of installers and drillers. Guidelines concerning the legal regulations for geothermal installations exist only in some countries, with the most developed requirements being in some German states, and in some Swiss cantons.

Existing European Standards are listed below for information (Table 1), for those involved in the design of geothermal systems. The status of National Specifications (e.g. DIN, VDI) varies between countries.

EN 378-1:2008	*Refrigerating systems and heat pumps – Safety and environmental requirements – Part 1: Basic requirements, definitions, classification and selection criteria* The 2008 revision included harmonization with the European Pressure Equipment Directive (PED). (EN 378 is widely used as a basic Standard across much of the European Union as well as in many adjoining countries)
EN 255-3	*Air conditioners, liquid chilling packages and heat pumps with electrically driven compressors - Heating mode - Testing and requirements for marking for domestic hot water units*
EN 14511-1:2004	*Air conditioners, liquid chilling packages and heat pumps with electrically driven compressors for space heating and cooling – Parts 1-4*
ISO 13256-1:1998	*Water-source heat pumps -- Testing and rating for performance - Part 1: Water-to-air and brine-to-air heat pumps*
ISO 13256-2:1998	*Water-source heat pumps -- Testing and rating for performance - Part 2: Water-to-water and brine-to-water heat pumps*
EN 12171:2002	*Heating systems in buildings. Procedure for the preparation of documents for operation, maintenance and use. Heating systems not requiring a trained operator*
EN 12170:2002	*Heating systems in buildings. Procedure for the preparation of documents for operation, maintenance and use. Heating systems requiring a trained operator*
EN 12828:2003	*Heating systems in buildings – Design for water based heating systems*
EN 12831:2003	*Heating systems in buildings - Method for calculation of the design heat load*
EN 1 5316/4/2:2008	*Heating systems in buildings - Method for calculation of system energy requirements and system efficiencies - Part 4-2: Space heating generation systems, heat pump systems*
EN 15450:2007	*Heating systems in buildings. Design of heat pump heating systems*

Table 1. European Standards

The content of these national Standards provide useful reference of local best practice and should be included as references for technical purposes.

There are also a number of Standards on drilling (Table 2) which may be relevant to shallow geothermal systems.

EN 791:1996	*Drill Rigs Safety*
ISO 3551:1992	*Rotary core drilling equipment System A*
ISO 3552:1992	*Rotary core drilling equipment System B*
ISO 10097:1999	*Wireline diamond core drilling equipment System A*
ISO 10098:1992	*Wireline diamond core drilling equipment System CSSK*
EN 12717:2001	*Safety of machine tools, drilling machines*
EN ISO 22475/1:2006	*Geotechnical investigation and testing – Sampling methods and groundwater measurements - Part 1: Technical principles for execution*

Table 2. Standards on drilling

The Normative Standard **"Heating systems in buildings – Design of heat pump heating systems"**, **EN 15450** October 2007, concerns the design of heat pump systems not only for water and ground-source but for air-source as well. It is the first EN standard for the heat pump system in general.

EN 15450 elucidates the basic problem for a geothermal standard on a European level:

- Climatic conditions throughout Europe vary widely giving large differences in heating/ cooling demand
- Geological conditions vary widely from unconsolidated soils to hard, crystalline rock
- Traditions in heating and cooling vary significantly (e.g. hydraulic versus air-based systems, closed loop versus open loop).

As a result, it is recognised that EN 15450 can only give a general minimum framework for design and installation, with many items to be filled in locally or regionally.

This standard contains the following sections:

- System requirements
- Installation requirements
- Commissioning of the system
- Maintenance requirements.

According to this European Norm, the first appropriate parameter to be defined for the system design is the heat source which can be air, water or ground. Moreover, the electrical supply must be ensured as well as the positioning of the installation and its noise level. If an additional back-up heater is needed, its power has to be reduced to a minimum since it is not a renewable energy technology. Furthermore, domestic hot water tank and other attached systems such as buffer storage must be specified. The control of the system, safety arrangements and operational requirements are of the utmost importance and must be defined according to the standards.

In the commissioning of the system the following must be fulfilled:

- Checking of the system in satisfactory and safe operation
- Checking all components of the system in operation according to the design conditions
- Tuning of control parameters in order to meet the operation conditions according to the design
- Balancing the heat distribution system.

Concerning maintenance requirements for the system, there is reference to the EN 12170 and EN 12171. Moreover, it is mentioned that the staff involved in maintenance of the system must be qualified and certified according to EN 13313.

Finally, there are four annexes which contain the following:

- Annex A (informative) – Guidelines for determining design parameters
- Annex B (normative) – Guideline for designing heat pump systems
- Annex C (normative) – Recommended minimum and target values for the SPF
- Annex D (normative) – Average daily tapping patterns for domestic hot water production.

Differences can be seen between different countries in terms of implementation of European Standards:

- Denmark and Sweden have adopted all relevant EN standards into national standards, and have a wide range of national standards, legal regulations, and licensing/certification of companies and persons
- France has adopted the relevant EN standards into national standards, and has some national standards, too. Certification of drillers and installers has started
- Romania has already adopted most relevant EN standards into national standards, and does not have much more in national standards. For licensing and legal matters, only deep Geothermal is yet covered.

III. NATIONAL STANDARDS

Technical standards for heating and heat pumps exist at a national level in countries where the market is well developed such as Austria, Germany, Sweden and Switzerland.

These national standards are listed below (Table 3) and are generally in the local language except VDI 4640 which is available in both German and English.

The most advanced and comprehensive national Standard is the **German document VDI 4640.** This German standard focuses especially on the GSHP system as a whole (mainly in part 2), in contrast to the others that focus more on discrete elements of the system. The contents of this document are as follows:

• Part 1: General / Licenses / Environment, status 2001-06

• Part 2: Ground Source Heat Pumps, status Dec. 2001-09, under revision

• Part 3: UTES, status 2001-06

• Part 4: Direct uses (cooling, ground-air heat exchanger), status 2004-09.

Country	Document Number	Document Title	Date
AT	ÖNORM M 7753	Heat pumps with electrically driven compressors for direct expansion, ground coupled	1995
AT	ÖNORM M 7755-2+3	Electrically driven heat pumps	2000
AT	ÖWAV Regelblatt 207	Thermal use of the groundwater and the underground, heating and cooling	2009
CH	AWP T1	Heating system with borehole heat exchangers	2007
CH	AWP T2	Heating system with horizontal ground collector, energy piles or energy cages	2007
CH	AWP T3	Groundwater as heat source	2007
CH	AWP T5	Filling of borehole heat exchanger systems	2007
CH	SIA D 0190	Use of earth heat through foundation piles and other building parts in contact with the ground	2005
CH	SIA 384/6 (SN 565)	Borehole heat exchangers for 2009 heating and cooling	2009
DE	DIN8901	Refrigerating systems and heat pumps – Protection of soil, ground and surface water	2002
DE	VDI 4640 Blatt 1	Thermal use of the underground – part 1: Fundamentals, approvals, environmental aspects	2009
DE	VDI 4640 Blatt 2	Thermal use of the underground – part 2: Ground source heat pumps	2001
DE	VDI 4640 Blatt 3	Thermal use of the underground – part 3: Underground thermal energy storage	2002
DE	VDI 4640 Blatt 4	Thermal use of the underground – part 4: Direct uses	2004
DE	DE DIN 8901	Refrigerating systems and heat pumps - Protection of soil, ground and surface water	2002
SE	Normbrunn-07	Drilling for water wells and energy	2008
* Note that Switzerland: AWP T1 is the first Standard to call for grouting to be carried out from bottom to top of the borehole installation.			

Table 3. National standards

The first part of **VDI 4640** refers to the following general information for GSHP systems:

- Fundamentals concerning the definition of geothermal energy and the principles for the design of a GSHP system
- Approvals concerning water rights as well as mining law
- Safety aspects of the heat pumps
- Location assessment concerning small systems up to 30kW depending on assumptions and estimates
- Environmental aspects concerning the material selection for installations in the underground such as pipes, water mixture, etc.

The second part of **VDI 4640** refers to design and installation of a complete GSHP system:

- Groundwater well systems (design and installation)

- Closed-loop systems
  - horizontal loops – horizontal ground heat exchangers (design and installation)
  - vertical loops - borehole heat exchangers (design and installation)
- Special features of systems with direct evaporation (design and installation)
- Characteristics of other heat sources such as “energy piles”, compact horizontal ground heat exchangers etc
- Incorporating the system (manifolds & collectors, fittings & pumps, connections pipes between manifolds and heat pumps, dimensioning the pipes and pumps)
- Heat usage systems
- Dismantling GSHP systems.

The third part of **VDI 4640** refers to thermal energy storage, more specifically:

- General information of thermal energy storage (definitions, special environmental aspects, choice of materials for higher temperatures)
- Incorporation into an energy supply system (energy balance, temperature levels, utilization ratio of the storage system, uses: storage of cold and/or of low-temperature heat with or without a heat pump, solar energy and heat storage, heat and power cogeneration plant coupled with heat storage, complex energy supply systems utilizing and storing waste heat, further system variants of underground thermal energy storage)
- Aquifer storage (system description, natural site requirements, site exploration, design of the wells, special aspects relating to the licensing of aquifer storage, possible operating problems arising from the chemical composition of the groundwater)
- BHEs (geometry of the storage system, layout, construction)
- Other underground thermal storage (cavern storage, abandoned mines, near-natural underground thermal energy storage systems).

The fourth part of **VDI 4640** refers to thermal source systems without using a heat pump, more specifically:

- Direct thermal use of ground water (system description, environmental influence and special aspects relating to water management and water legislation, design)
- Direct thermal use of the underground with borehole heat exchangers, energy piles, etc. (system description, environmental aspects and questions relating to water legislation, construction and installation including dismantling)
- Air heating and cooling in the underground (system description, environmental aspects, air hygiene, design, installation, selection of materials, dismantling, control strategies, economic efficiency).

The drilling and ground testing standard **EN ISO 22475/1** requires that at least the following information shall be available prior to work being allowed to start in the field:

- objective of the measurements
- location of the planned boreholes or groundwater measurements

- orientation, inclination and acceptable deviations in boreholes
- surveying requirements, and expected geological and hydrogeological conditions
- frequency of measurements
- environmental and safety risks
- possible risks, e.g. services, traffic, ordnance, contamination)
- planned depths of boreholes and/or excavations
- in situ tests intended
- hole completion method and reinstatement
- environmental care
- emergency arrangements
- backfilling and restoration of work areas to ensure that no hazards are left to harm the public, the environment or animals in accordance with regulations.

Testing of conditions at a site in order to determine the suitability for and design of the GSPH is included within a number of other standards such as:

ISO 14686:2003. *Hydrometric determinations. Pumping tests for water wells. Considerations and guidelines for design, performance and use.*

IV. COMMISSIONING, MAINTENANCE, COMPETENCE, CERTIFICATION, PERMITTING

Commissioning of a constructed system must include checks that the:

- system is operating satisfactory and safely
- all components of the system are operating according to the design conditions
- tuning of control parameters
- balancing of the heat distribution system.

The assessment of competence of operators and audit of their continued competence is considered by many to be a prerequisite for a healthy GSHP market. The certification of drillers, installers etc and generally of all specialists that contribute to the design, installation and maintenance of GSHP systems is a very important issue in order to guarantee the proper operation of the system.

One of the commonest barriers to increased use of geothermal energy is the permitting process where permits may be required for the use of groundwater as heat source and for drilling.

IV. 1. Commissioning and maintenance

Testing of heat pumps is included within a number of standards (Table 4). For the maintenance requirements, there is reference to EN12170 and EN12171. Personnel involved in maintenance of the system must be qualified and certified according to EN13313.

ISO 14686:2003	*Hydrometric determinations. Pumping tests for water wells. Considerations and guidelines for design, performance and use*
ISO 13256-1:1998	*Water-source heat pumps - Testing and rating for performance - Part 1: Water-to-air and brine-to-air heat pumps*
ISO 13256-2:1998	*Water-source heat pumps - Testing and rating for performance - Part 2: Water-to-water and brine-to-water heat pumps*
EN 14336:2004	*Heating systems in buildings – Installation and commissioning of water based heating systems*

Table 4. Heat pumps testing standards

IV. 2. Competence and audit

The assessment of competence of operators and audit of their continued competence is considered by many to be a prerequisite for a healthy GSHP market. This is also one of the main concerns of the European Commission in that without such measures, the public will be left open to poor service by less scrupulous operators. The main recent European Standard which is relevant in this area comes from the geotechnical field but can be taken to be relevant in the GSHP field. The requirements are not so high that this should pose a problem to any reputable operator involved in construction and installation of GSHP.

EN ISO 22475/ *Geotechnical investigation and testing -- Sampling methods and groundwater measurements -- Part 2: Qualification criteria for enterprises and personnel* defines the required competencies of the:

- Responsible Expert
- Qualified Driller
- Enterprise (or company).

The responsible expert shall have proven knowledge concerning:

- laws, health and safety regulations, rules and standards
- geology, hydrogeology, soil and rock mechanics
- knowledge of EN ISO 22475-1
- the quality assurance system.

The responsible expert shall be able to understand the aim of the work programme, supervise the work of the qualified driller and to call for additional expertise if required.

The qualified driller shall have documented competence regarding:

- basic knowledge of the purpose of ground investigation
- mechanical and hydrogeological principles
- excavation methods and groundwater measurements including borehole backfilling
- completion of records according to EN ISO 22475-1
- relevant health, safety and environmental regulations
- functioning, safe operation and maintenance of the equipment
- the quality assurance system.

The enterprise carrying out investigation or works according to EN ISO 22475-1 shall be able to provide:

- experienced personnel and appropriate facilities
- a health and safety system
- a quality assurance system
- that all equipment in use shall comply with the appropriate technical specifications, be correctly maintained, calibrated and used
- a qualified driller who shall be continuously present and responsible for the performance of sampling, measurements and recording at each drill rig
- compliance with bylaws, health and safety regulations and technical rules
- cover for public liability.

EN ISO 22475/3:2007 *Geotechnical investigation and testing -- Sampling methods and groundwater measurements -- Part 3: Conformity assessment of enterprises and personnel by third party* requires that a conformity assessment of the applicant enterprise shall demonstrate the ability to meet all the qualification criteria according to EN ISO/TS 22475-2. When full assessment is judged satisfactory, the conformity assessment body will issue a certificate to the enterprise which is to be valid for 3 years.

There are also standards on certification in connection with refrigeration systems:

EN ISO 17024:2003. *Conformity assessment - General requirements for bodies operating certification of persons*

EN 13313:2001. *Refrigerating systems and heat pumps. Competence of personnel.*

IV. 3. Certification

The certification of drillers, installers, etc. and generally of all specialists that contribute to the design, installation and maintenance of GSHP systems is a very important issue in order to guarantee the proper operation of the system. Certified designers, manufacturers and installers (including drillers) are necessary to ensure high efficiency and longevity of a GSHP system. Also for the certification of drilling companies, joint basic rules should be developed in order to facilitate cross-border service.

For all parties involved in GSHP drilling and installation, only a few countries have existing schemes for licenses and certification for heat pumps or geothermal energy. Normally only the general rules for work and trade apply; these may in some instances act as trade barriers. It must be ensured that existing and upcoming special regulations will not prevent the exchange of work and services in the common market.

For the heat pump installation, the EU-CERT.HP programme may prove very helpful, and has the potential for a common application throughout EU-27. National quality certificates such as in France are voluntary and may be included in a common scheme or may continue in co-existence without problems. No common activity exists yet for the ground side. For setting up such schemes, the cooperation of the relevant professional bodies and industrial associations will be necessary, in order to ensure acceptance of the resulting programmes in the Geothermal sector.

Well drilling for water or shallow Geothermal used to be a regional business and so EU-wide rules have not been important. Some national certifications for drilling companies can develop into a barrier, if they are made mandatory by regional authorities. Relevant certifications from other member states need to be made acceptable to the authorities in other parts of Europe. Hence a common EN standard based on the national approaches should be initiated.

At present, certification for drillers exists only in Germany, Sweden and Switzerland and in Austria this matter is under development (Table 5).

DVGW W 120	Qualifikationsanforderungen für die Bereiche Bohrtechnik, Brunnenbau und Brunnenregenerierung	Certification of professional drilling companies	2005-12 (DE)
DACH-Gütesiegel EWS	Gütesiegel für Erdwärmesonden-Bohrfirmen	Certification of professional drilling companies	2001/2006 (CH/DE)
RAL/ZDB	RAL-Gütezeichen „Erdwärme“, Gütegemeinschaft Geothermische Anlagen	Certification of professional drilling companies	2007 (DE)
C-Borrare	Certifiering av brunnsborrningsföretag	Certification of well drilling companies	2006 (SE)

Table 5. Certification for drillers

It is critically important that all site operations are carried out in a safe manner, without damage to the operators, the public or the environment. Safety requirements can be summarized by stating that respective national Standards, specifications or statutory requirements shall be applied wherever respective international Standards are not available (EN ISO 22475/1).

For quality testing and certification of heat pumps, the basic requirements are given by EN 14511 and, for the domestic hot water side, by EN 255-3. Other relevant heat pump standards like EN 378 or EN 60335- 2-40 (on electrical safety) are also common throughout Europe. Quality labels like P-mark in SE or the Gütesiegel Wärmepumpe in AT, DE and CH are based upon testing according to the common EN standards mentioned above. The European Heat Pump Association is working to establish a harmonized quality label (EHPA quality label), or at least to harmonize the existing ones.

IV. 5. Legal permits

One of the commonest barriers to increased use of geothermal energy is the permitting process. Permits may be required for the use of groundwater as heat source, but also for BHE and for drilling as such.

Of course, regulations for permits are necessary in order to protect the groundwater and ground against pollution. A problem is more that the procedures and rationale for decision making vary greatly not just between member states, but also within countries at provincial level. In some cases, even the relevant permitting authority is unclear, as the example of water authorities and mining authorities for larger GSHP-plants in Germany shows. On the other hand, guidelines for permitting procedures and simplified procedures for small (residential) GSHP in non-critical areas have facilitated the market growth in some German states and in CH.

The procedure of licensing of GSHP systems varies among European countries. In the field of permits for geothermal drilling and exploitation, European harmonization could provide an outline framework with details to be completed at national or even regional level to accord with local provisions.

For example, German law governs shallow geothermal systems by water law but there are exceptions where shallow geothermal is governed by mining law. Moreover, the Federal Mining Act is applied at a federal level and the Federal Water Household Act at a state level and so it is not obvious which is the relevant authority to address for each application.

Most German states have published own guidelines on how the application and licensing process should be handled. These publications actually guide the applicant to understand the procedure and point out the requirements for water protection. Good guidelines provide also an easy path for GSHP projects below a certain capacity, and in hydrogeologically unproblematic conditions.

In Austria, the permit for open- and closed-loop GSHP systems is focused on water rights. A first guideline for application, like those of the German states, has been published in Upper Austria.

In Greece, given that there is a separate regulation for “systems for heating and cooling by the exploitation of the heat of underground and groundwater that are not considered as geothermal potential (temperature below 250 ^{o}C)”, there is no confusion with the Mining Law. Moreover, there is no further reference to water rights and environmental issues.

According to these indicative cases, it is obvious that the main references to legal permits are water rights and the exploitation of underground potential.

V. CONCLUSIONS

The introduction of EN standards for heat pumps has been crucial as these products are manufactured and traded throughout Europe. Barriers for the trade of machinery and components hardly exist any more within the common market for heat pump systems. Efficiency or quality labels based on these standards are transparent and comparable among member states.

Some technical differences for ground-side installations (in particular BHE) and drilling between Scandinavian countries and Central Europe have their main reason in different geological situations, and thus cannot easily be harmonized. The Geothermal technology always has to respect the regional geological situation, which varies widely throughout Europe and cannot be influenced at all by policy.

Barriers for work and services do exist to some extent, but not more than in the construction sector in general. Specific certifications are voluntary, and new certifications for heat pump installers have the chance to become adopted in most of the countries.

The biggest problem is in the legal regulations, concerning both the environmental permits and the ownership / license for the resource. Without a clear title on the use of the resource, no investment is possible. However, this cannot be regulated by standards, but must be dealt with by the legislative bodies.

Because the drilling and installation for Geothermal systems in the shallow Geothermal realm typically is a service rendered by contractors more locally, the need for harmonized standards is not so urgent as the need for suitable standards at all, as in many countries no guidelines and standards exist and thus consumer protection is not guaranteed. Here a negative impact on the market can be expected if demand increases and poor workmanship is delivered in countries without specific standards.

Common Standards are therefore desirable for the Geothermal side. The first real standard is under development in Germany and will deal with material, construction and installation of borehole heat exchangers.

Items to be covered in new European standards for shallow geothermal applications could include:

- Layout (sizing) of the geothermal system (groundwater wells, borehole heat exchangers, horizontal loops, etc.), in accordance with the different climatic and geological conditions within Europe
- Materials for wells, borehole heat exchangers, other pipe loops, manifolds, etc.
- Geothermal groundwater wells: Drilling, well construction and well completion
- Borehole heat exchangers: Drilling, installation and completion (grouting, or open completion)
- Pipe laying for horizontal loops
- Other types of ground heat exchangers
- Connection to heat pump or other systems, system integration, interfaces.
- Considering the large differences in climate and geology, standards with a generic framework for Europe and appendices specific to countries (or regions) might be an option.

Generally, certification of specialists and GSHP system components will guarantee the quality and proper operation of GSHP systems and it will help the European market to have a rapid growth.

VI. FURTHER INFORMATION

Standards

Most standards can be obtained from National Standards organizations that generally have on-line search and ordering facilities. Free inspection of these Standards is generally not available and acquisition needs to be made through individual purchase or a subscription system.

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CHAPTER 18

ENERGY EFFICIENCY BUILDING CODES *by Radu Polizu*

I. INTRODUCTION

The implementation of a project with an efficient HVAC GSHP system is impossible without knowledge of the technical details of the project and, at the same time, the legal aspects of the development. During the engineering activities of such a project (study, design, implementation, testing commissioning and hand over), the specialists must consider all the regulatory elements required by the efficiency standards.

Usually, not only among those familiar with the RES domain, but even with specialists, there is a commonly-held view that an HVAC system with GSHP solution is efficient just because it extracts from the ground a part of the thermal energy useful for a building.

Two recent EU Directives (**EPBD** – Energy Performance of Buildings Directive and **RESD** – Renewable Energy Sources Directive) have clarified many efficiency aspects in buildings with HVAC GSHP systems. These directives state that only those applications that have a seasonal performance factor better than a certain value are efficient. In this chapter, we will try to clarify what the minimum level of performance is and how we calculate the added energy from Renewable Energy Sources (RES). We will also define EPBD and RESD in relation to energy efficiency projects with GSHP HVAC and explain the use of the primary energy concept as a unifying element between input and output energies.

The information presented here is required from the start of the feasibility study phase for a GSHP application, and is extremely useful at the stage of monitoring the application, so all engineering phases involved in a project with GSHP require the concepts and guidelines presented here to be available.

Across Europe and around the world, the approach to GSHP HVAC systems is in a stage of maturing. Programming documents adopted by the EU in the last two years are no longer limited to setting targets/objectives in the field of RES and development of efficient buildings, but have switched to quantifying the energy produced from RES and to establishing minimum performance requirements in this domain. As a matter of fact, this new approach has resulted in the focus coming towards quality and no longer on quantity aspects.

The emergence of the concept **"Net Zero Energy Building"** in the European regulatory system, and also in the U.S., required clarification of algorithms that determine whether a building falls into the category Net Zero Energy or not.

In order to correctly address the requirements of RESD and EPBD provisions, a specialist needs: thorough understanding of the essence of the two documents; a correct understanding of energy efficiency of the GSHP HVAC application issues, of the coefficient of performance, the specific requirements of the geographical area in which the project is implemented and the system requirements in terms of heating and/or cooling. This knowledge allows any certified specialist in GSHP HVAC to realize sound and efficient projects.

Specialists involved in this activity must be engineers who have a deep understanding of the concepts of energy, who have taken a training course authorized by a specialized authority and who were tested by an authorized professional certification structure.

The need for consistent and congruent data provided by a project in the performance monitoring stage, after the commissioning phase, requires mandatory certification of specialists involved in this activity.

II. THE DIRECTIVES

To correctly appreciate the quality of a geothermal heat pump project, the two EPBD and RESD directives that establish the impact of using a low enthalpy geothermal source to the project building and the calculation methods used for energy economy and CO_2 emission reduction, need to be examined.

The geothermal demand can be quantified only by a detailed analysis of the building and its thermal installations, whose main energy source is geothermal energy.

To better understand this mechanism we use the scheme from Figure 1, which shows the following:

- There is a continuous energy exchange between the building and the exterior environment, made through the building's envelope. The exterior temperature in the cold season of the year plays the most important role. Direct and diffuse solar radiation influences significantly the interior air temperature in summer and winter. The need for fresh air in the building is achieved by ventilation. None of these aspects can be neglected by the annual energy balance of the building
- The building's HVAC system is that system of interior installations that assure the indoor comfort for the building's occupants. The HVAC system contains:
  - The heating subsystem
  - The domestic hot water subsystem
  - The ventilation subsystem
  - The cooling subsystem (air conditioning).

The HVAC system, through its subsystems, satisfies the thermal energy demand of the building, the "Building's energy demand".

Between "building's HVAC system out" and "building's HVAC system in" there is a value difference represented by the energy loss of the building's HVAC system.

- The building's geothermal heat pumps are a part of its HVAC system. Today, most are electrically driven and so need electrical energy to sustain the ground heat exchange. In temperate and mainly hot European countries, geothermal heat pumps are reversible and so have the heating as well as the cooling function. In European countries with mainly cold climate, the heat pumps are used only for heating, achieving the heating of the building without using the cooling cycle of the thermal machine.

- Geothermal low enthalpy energy is obtained from the ground by turning the thermal machine with water evaporator from a closed circuit to an open circuit used for heat exchange with the ground. In Figure 1, the ground heat exchanger of the building's HVAC system is a closed vertical circuit.

III. DEFINITION OF TERMS IN EPBD AND RESD DIRECTIVES

III. 1. Energy performance of the building

The quality parameter of the building given by the energy effectively consumed or estimated to be needed to respond to the normal use of the building.

III. 2. The performance need

The minimum level of the building's energy performance that needs to be fulfilled so that the building's owner can obtain certain advantages which might include the building's construction authorization, the quality label of the building and the right to rent or the right to sell the building.

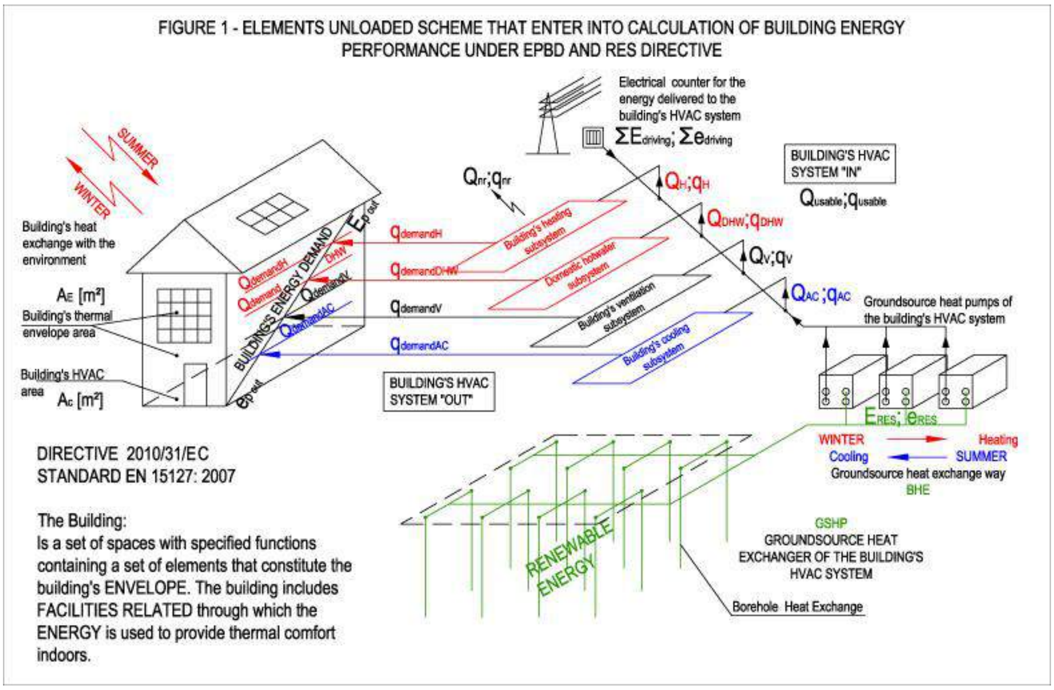

Figure 1. Calculation of building energy performance under the EPBD and RES directives

III. 3. Energy performance Indicator of the building EP

This is a global indicator that represents the algebraic weighted sum of the energy supplied to the building from the exterior for all types of energy (for example: the building in Figure 1 uses two energy types: electrical and geothermal).

III. 4. Ways to express the performance indicator

- By the annual primary energy specific use value for the building [kWh/m^2 yr]
- By the green house specific emissions value produced by the building's HVAC system sources [kg CO_2/m^2 yr].

III. 5. Primary energy

Is that energy that has not been subjected to any conversion or transforming process and comes from energy sources as:

- Nonrenewable: fossil fuels, nuclear energy
- Renewable: defined in RES Directive.

III. 6. Electrical energy conversion factor to primary energy in the community space

For electrical heat pumps, according to the November 9, 2007 Decision published in The European Union Official Journal - L301/14 November 20, 2007, the electrical energy conversion factor to primary energy has a value of:

(1) $\mathbf{f_{EE} = 2.5}$

this means that:

(2) **1 kWh electrical energy = 2.5 kWh primary energy**

This Decision is based on a European median production yield for electrical energy, including the loss from the distribution network, having a value of:

(3) $\mathbf{\eta_{tot}}$ **= 0.4 average yield for the production of electricity in the European Community (Annex II Directive 2006/32/EC)**

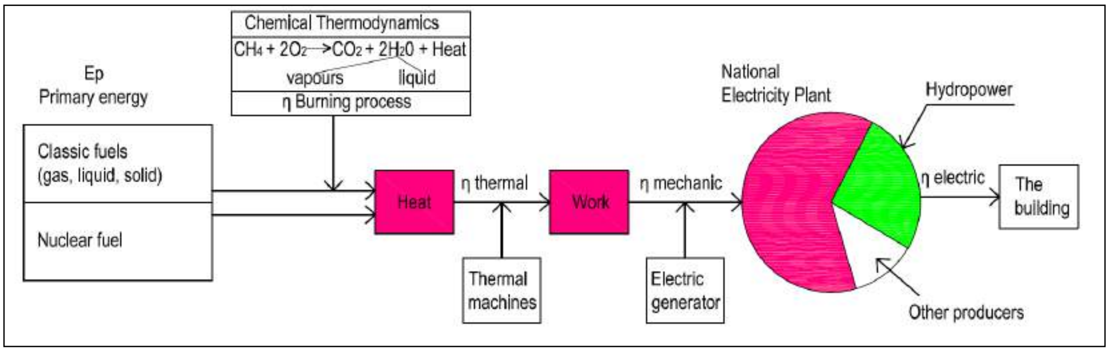

Figure 2. Flowchart of the energy chain to provide electricity to the final consumer

By the same Commission's Decision, the European median yield for natural gas used as a thermal energy producing source, has a value of:

(4) $\mathbf{\eta_{gas}}$ **= 0.91 average yield for natural gas energy conversion in final consumer energy**

This value concerns the natural gas distribution system loss and allows the calculation of the conversion factor of the natural gas energy to primary energy:

(5) **f_{gas} = 1.1 = 1/ η_{gas}= 1.1 conversion factor of the natural gas energy to primary energy (Official Journal of the European Union L114/76: 27.4.2006)**

To determine the conversion factor values mentioned above, the 2006/32/CE Directive of the European Parliament and of the Europe Council from April 5 2006, regarding the energy efficiency to the final consumers and the energy services, was taken into consideration.

III. 7. Energy Performance of Buildings Indicator as primary energy

This expresses the annual specific use of primary energy of the building **ep_{in}** reported in conditioned area and is calculated using the formula:

(6) $$ep_{in}\ [kWh/m^2\ yr] = Ep_{in}\ [kWh/yr]\ /\ A_c\ [m_2]$$

where:

- Ep_{in} [kWh/yr] is the annual energy use of the building expressed as primary energy

- A_c [m^2] is the conditioned surface of the building established according to the standard and represents the sum of the surfaces of the rooms' floors that use the HVAC system. Not included here is the uninhabited space, such as unheated rooms - basements, attics and storage rooms.

III. 8. Energy Performance of Buildings Indicator as greenhouse gas emissions

This expresses the specific pollutant greenhouse gas emission **GES** reported in conditioned area of the building and is calculated using the formula:

(7) $$GES\ [kg\ CO_2/m^2\ yr] = m\ CO_2\ [kg\ CO_2/yr]\ /\ A_c\ [m^2]$$

where:

- **m CO_2** [kg CO_2/yr] is the green house gas emissions sum calculated in equivalent kg CO_2/yr.

The GES emission factor specific to electrical energy production at a community level, resulting from the weighted calculation of the national emission factors for European Community countries has a value of:

(8) $$f_{EE} = 0.486\ kg\ CO_2/kWh$$

The GES emission factor, specific to natural gas burning in boilers for producing hot water has a value of:

(9) $$f_{NG} = 0.29\ kg\ CO_2/kWh$$

III. 9. Energy from renewable sources

The energy from renewable sources is known as E_{RES} [kWh/yr] and is the non fossil energy used by the building's HVAC system to satisfy its energy demands. The energy that comes from renewable sources includes wind energy, solar, aero-thermal, geothermal, hydrothermal, ocean energy, hydropower or the energy of falling water, biomass gases and biogases coming from organic and fermentable city waste treatment plants.

The group of geothermal, aero-thermal and hydrothermal energy represents the energy stored as heat under the Earth's surface, in the air and in the surface water of the Earth (lakes, seas, oceans, etc.).

III. 10. Building's energy demand

The building's energy demand is known as Q_{demand} or Ep_{out} [kWh/yr] and represents the weighted sum of the HVAC building's subsystems energy demand.

(10) $$\mathbf{Q_{demand} = Q_{demandH} + Q_{demandDHW} + Q_{demandV} + Q_{demandAC}\ [kWh/yr]}$$

where:

- $Q_{demandH}$ [kWh/yr] = heating subsystem's energy demand
- $Q_{demandDHW}$ [kWh/yr] =domestic hot water producing subsystem's energy demand
- $Q_{demandV}$ [kWh/yr] = ventilating subsystem's energy demand
- $Q_{demandAC}$ [kWh/yr] = cooling subsystem's energy demand.

III. 11. Energy demand for the building's HVAC system

The energy available to satisfy the building demand is known as Q_{usable} [kWh/yr] or Ep_{in} [kWh/yr] and to calculate it we need to appreciate the energy loss of the building's HVAC subsystems, noted as Q_{nr} [kWh/yr].

The calculation formula for Q_{usable} is:

(11) $$\mathbf{Q_{usable} = Q_{demandH} + Q_{demandDHW} + Q_{demandV} + Q_{demandAC} + Q_{nr}\ [kWh/yr]}$$

or:

(12) $$\mathbf{Q_{usable} = Q_{demand} + Q_{nr}}$$

Each term of equation (11) is determined by a specific technology. For example, for $Q_{demandH}$ the EN 15316-1:2007 Standard was established, based on various software packages (Energy Plus; TRNSYS; TRACE 700 Load Design, etc.) officially agreed by each community, software that can be amalgamated to a single software for all community countries.

When a building's HVAC system is reduced only to heating and hot water production, equation (11) becomes:

(13) $$\mathbf{Q_{usable} = Q_{demandH} + Q_{demandDHW} + Q_{nr}\ [kWh/yr]}$$

where Q_{nr} [kWh/yr] represents the annual energy loss of the heating and domestic hot water subsystems.

III. 12. Electrical energy use for the building's HVAC system

Called $\Sigma E_{driving}$ [kWh/yr].

In a HVAC heat pumps system, the electrical energy use" $\Sigma E_{driving}$" has two components:

- The annual energy required to run the heat pumps and when using 1÷n heat pumps, the size of the first component is:

(14) $$\mathbf{\Sigma^{n}_{i=1} E_{driving\ i}^{HP}\ [kWh/yr]}$$

- The annual energy use for running all the other components of the building's HVAC system, excepting the heat pumps. This component represents the sum of energy use for the circulating pumps, fans and fan-coil units for heating and cooling:

  (15) $\Sigma^{n}_{i=1} E_{driving}^{pumps}$, $\Sigma^{n}_{i=1} E_{driving}^{fancoils}$

So, we can write:

(16) $\Sigma E_{driving} = \Sigma^{n}_{i=1} E_{driving\ i}^{HP} + (\Sigma^{n}_{i=1} E_{driving}^{pumps} + \ldots\ldots)$

Equation (15) helps us assess the annual electrical energy use by the HVAC system for those two components:

- The first term of equation (16) represents a "positive" use of electrical energy because without electrical energy, we cannot extract primary energy from a renewable source. Moreover, the calorific equivalent for the annual active energy for the heat pumps can be found a useful component of heat in the building's HVAC system
- The second term of equation (16) represents a loss within the HVAC system, and it is best that, in HVAC heat pump-based systems, all the terms in brackets be as small as possible and not bigger or equal to 10% of the $\Sigma E_{driving}$ value.

Having made this assessment, we can re-write equation (16) as:

(17) $\Sigma E_{driving} = \Sigma^{n}_{i=1} E_{driving\ i}^{HP} + Q_{nr}^{driving}$ **[kWh/yr]**

where $Q_{nr}^{driving}$ represents the energy loss resulting from using energy in running the electrical equipments of the HVAC subsystems. Meaning:

(18) $Q_{nr}^{driving} = \Sigma^{n}_{i=1} E_{driving}^{pumps} + (\Sigma^{n}_{i=1} E_{driving}^{fancoil} + \ldots\ldots)$

In the case of using GSHP and respecting a loss limit of 10%, we can write:

(19) $Q_{nr}^{driving} = 0.1\ \Sigma E_{driving}$ **[kWh/yr]**

or:

(20) $\Sigma E_{driving} = 1.1\ \Sigma^{n}_{i=1} E_{driving\ i}^{HP}$ **[kWh/yr]**

In other applications with aero-thermal or hydrothermal heat pumps, the source temperature depends on the variable exterior air temperature for covering the energy needs of the building and is possible only by using additional sources of energy (see reference [1] in section V!) from fossil sources such as electrical energy, natural gas and liquefied fuel.

Additional sources of energy quantum raise the value ΣEdriving by increasing the value of Q_{nr} when the heating energy supplement is electrical:

(21) $Q_{nr} = Q_{nr}^{driving} + Q_{nr}^{resistor}$ **[kWh/yr]**

or:

(22) $\mathbf{Q_{nr} = Q_{nr}^{driving} + Q_{nr}^{resistor} + Q_{fuel}}$ **[kWh/yr]**

when the heating energy supplement is both electrical and from additional fuel.

III. 13. The renewable energy contribution delivered to the building

For the renewable energy group, using heat pumps, geothermal, aero-thermal and hydrothermal energy, the RES Directive established in VII Annex the following relation:

(23) $\mathbf{E_{RES} = Q_{usable}\,(1-1/SPF)}$ **[kWh/yr]**

where:

- E_{RES} is the annual renewable energy obtained by using heat pumps
- Q_{usable} is the energy demand of the building's HVAC system, calculated according to equation (11).

SPF is the seasonal performance factor of the building's HVAC system, defined as:

(24) $\mathbf{SPF = Q_{usable} / \Sigma\, E_{driving}}$ **[-]**

where:

- $\Sigma\, E_{driving}$ represents, when using geothermal heat pumps, the annual total electrical energy used by the HVAC system to cover the heating, domestic hot water, ventilating and air conditioning.

Equation (24) is relatively easy to use because Q_{usable} can be obtained using specialized software that simulates the energy use of the building for a year and $\Sigma\, E_{driving}$ is the sum of monthly electrical energy meter readings for the building's HVAC system. The responsibility for determining Q_{usable} is given to an authorized person, called the Energy Auditor established by EPBD provisions and who functions independently. The responsibility for determining the theoretical variations of the energy required by the HVAC subsystems lies with the designer of the building's HVAC system.

An analysis for the annual thermal behaviour of a building from Romania is shown in Figure 3. The building is located in an urban area, which has a re-designed HVAC system using reversible heat pumps with a thermal ground source, after the model shown in Figure 1. Figure 3 shows that SPF is a dynamic performance factor that synthesizes precisely the building's energy performance. It is observed that SPF has a maximum value in summer, when the heat pumps are used as chillers and a minimum value in the transition period between the cold and hot seasons of the year.

Using the seasonal factor (determined monthly and on both cold [Oct-Dec and Jan-Apr] and hot [Apr-Oct] periods of the year in the analyzed case) an average value is established, termed:

$\mathbf{APF=SPF_{yr}}$ **annual performance factor**

APF is determined by integrating the monthly current values.

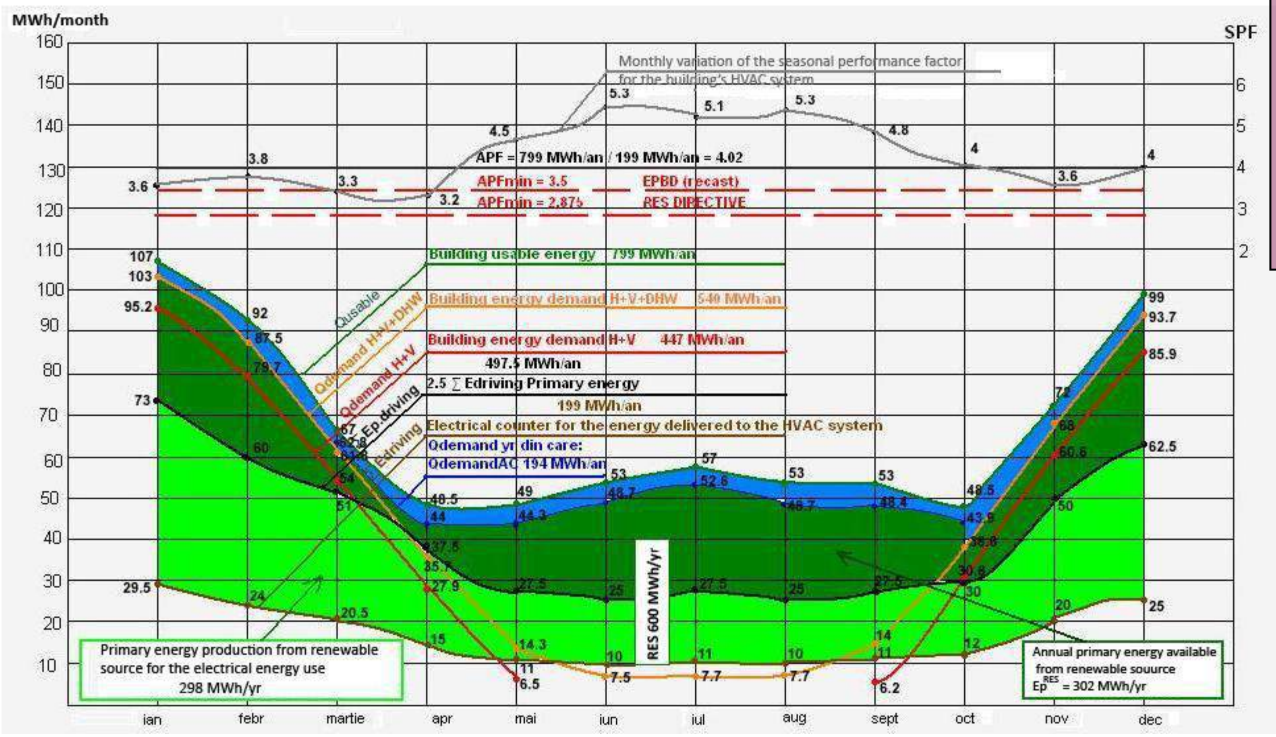

Figure 3. Graphic representation of the monthly energy variations used to calculate the energy performance of the building and the seasonal performance factor

IV. SPF AND APF MINIMUM VALUES USED BY THE HVAC-GSHP DESIGNERS

For the GSHP designer, the Borehole Heat Exchanger (BHE) required for calculation are:

- Monthly variation of the power and energy from the HVAC system
- Heat pump performance.

Both are linked by the energy variation given by $\Sigma\ E_{driving}$. This variable appears in the equations:

(25) $\mathbf{Q_{usable} = E_{RES} + \Sigma\ E_{driving}\ [kWh/yr]}$

(26) $\mathbf{\Sigma\ E_{driving} = Q_{usable} / SPF\ [kWh/yr]}$

If we eliminate the variable $\Sigma\ E_{driving}$ from equation (25), using equation (26), we obtain:

(27) $\mathbf{Q_{usable} = E_{RES} + Q_{usable} / SPF\ [kWh/yr]}$

or:

(28) $\mathbf{E_{RES} = Q_{usable}\ (1\text{-}1/SPF)\ [kWh/yr]}$

Equation (28) tells us that the annual renewable energy variation that BHE needs to provide to the building's HVAC-GSHP system depends on the HVAC system energy demand and the seasonal performance factor variation.

So, the GSHP Designer must know and integrate into this assessment the lower limits of the seasonal performance factor as called for by the EC Legislation.

Those two EU directives that make up the "Energy-Efficiency Building Codes" are extremely severe and not every heat pump application of GSHP type is successful by these criteria. So, according to VII Annex – RES Directive: “*only those natural environment heat pump applications that satisfy the condition (29) will be acceptable*”:

(29) $\mathbf{SPF_{HP} > 1.15 \times 1/\eta_{tot}}$

If η_{tot} is given by formula formula (3), then

(30) $\mathbf{SPF_{HP} > 2.875}$

The annual average SPF_{HP}, called APF by the RES Directive, can be seen in Figure 3 where the application analyzed respects equation (30) as in the Community Legislation and the SPF values are above the minimum limit of 2.875.

Further, the EPB Directive, (see [2] in Section VI) defines the “NET-ZERO” ENERGY BUILDING which is a building that, as a result of a very high level of energy efficiency, has an annual total use equal to or smaller than the energy production from renewable sources. This condition means:

(31) $\mathbf{E_{RES} \geq 2.5\ \Sigma E_{driving}}$

If we consider that by definition $SPF = Q_{usable} / \Sigma E_{driving}$, we obtain:

(32) $\mathbf{E_{RES} \geq 2.5\ Q_{usable} / SPF}$

If we combine equations (32) and (28), we obtain $\mathbf{Q_{usable}\ (1\text{-}1/SPF) \geq 2.5\ Q_{usable} / SPF}$**:**

(33) **$\mathbf{SPF_{min}}$ EPB Directive (Recast) ≥ 3.5 for geothermal heat pumps with ground water or surface water source and ≥ 3.75 for ground source (htpp://www.wp-effizienz.ise.fraunhofer.de/german/index)**

In Figure 3, we can see that even if APF in the analyzed application has a value of over 3.5, we still have values of the SPF in the cold season of the year below the limit set by (33). However, the building can still be placed in the category NET-ZERO ENERGY BUILDING, because the average of the SPF values in the cold season (Oct-Dec and Jan-Apr) is greater than 3.5.

If we continue our analysis with E_P^{RES} $_{as}$ the part of the primary energy remaining from E_{RES} after we subtract the used electrical energy value ($\Sigma E_{driving}$ in primary energy units) we have the expressions:

(34) $\mathbf{E_P^{RES} = Q_{usable}\ (1\text{-}1/SPF)[1\text{-}1.5/(SPF\text{-}1)]\ [kWh/yr]}$

(35) $\mathbf{E_P^{RES} = E_{RES}\ [1\text{-}1.5/(SPF\text{-}1)]\ [kWh/an]}$

Both (34) and (35) help us analyze more widely the settings presented above. So:

- If SPF = 1, then $E_{RES} = 0$. This outcome makes no sense
- If SPF = 2.5, then $E_{RES} = 0.6\ Q_{usable}$ and $E_P^{RES} = 0$. This variant has no primary energy available after allowing for the used electrical energy value in the building’s HVAC system. This application of natural environment heat pumps is not acceptable in Europe
- If SPF ≥ 2.875, then $E_{RES} \geq 0.65\ Q_{usable}$ and $E_P^{RES} \geq 0.2\ E_{RES}$. This is the minimal condition set by the RES Directive by VII Annex. The primary energy available from

renewable sources, after allowing for electrical energy use, must be a minimum of 20% of the renewable energy value. In the SPF range 2.5-2.875, the building equipped with natural environment heat pumps uses less primary energy than it produces, but is not acceptable by RES

- If SPF ≥ 3.5, then $E_{RES} \geq 0.71\ Q_{usable}$ and $E_P^{RES} \geq 0.4\ E_{RES}$. European buildings built this way, using renewable energy sources can be called "NET-ZERO" ENERGY BUILDINGS that produce over 40% more primary energy than they consume from fossil sources.

Figure 4 shows graphically the E_P^{RES} function represented in equation (32). The figure includes SPF and APF values which show projects of a level of construction and exploitation, by hydrothermal and geothermal heat pumps, in three categories. These are:

- UNACCEPTABLE – where SPF, APF <2.875
- ACCEPTABLE – where 2.875 ≤ SPF, APF <3.5
- GOOD and NEARLY-ZERO – where SPF, APF ≥3.5 for hydrothermal heat pumps and >3.75 for geothermal heat pumps.

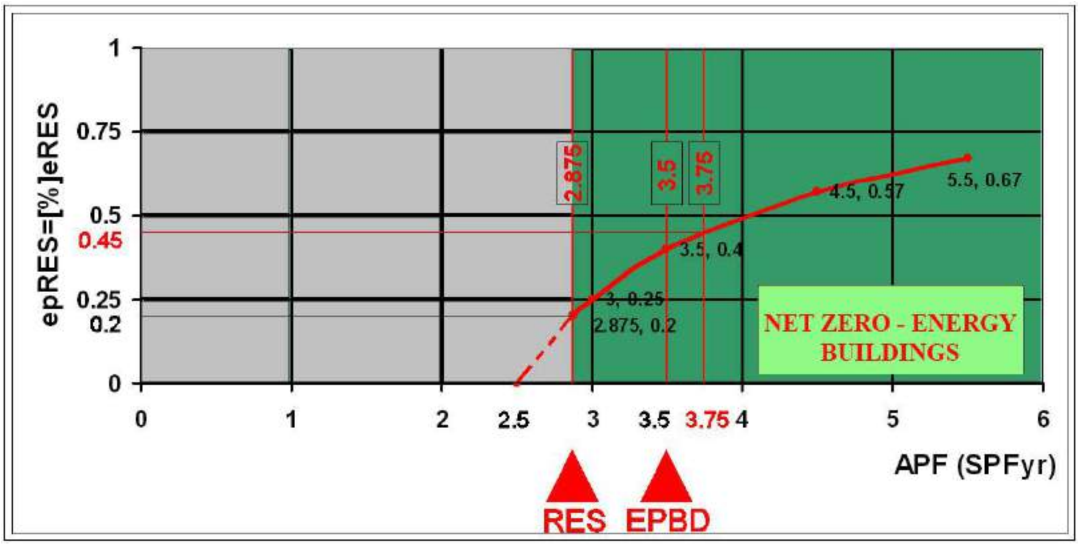

Figure 4. Minimal performances of the technical building's systems that use natural environment heat pumps, according to RES Directive 2009 and EPB Directive Recast 2009

So, it is not enough that APF is within the limits set by a certain category, but it is necessary that the seasonal values, established by the average of the monthly values, are above these limits.

V. THE COP AND REE PERFORMANCES SET FOR THE AMBIENT ENVIRONMENT SOURCE HEAT PUMPS

"SPF" is a dynamic performance factor varying by month, season and year to year, which depends on the "fixed point" performance for the building's HVAC system heat pumps.

The "fixed point performance" of a heat pump means the response of a heat pump when tested under factory conditions. Heat pump performance certification is based on EUROVENT.

The Commission Decision from November 9, 2007, regarding the establishment of ecological criteria to support ecological labelling for electrical heat pumps is limited to a heating capacity of maximum 100 kW. This capacity effectively covers the maximum thermal power of heat pumps sold in Europe. This group of products does not include:

- Heat pumps for producing exclusively domestic hot water
- Heat pumps used exclusively for extracting heat from a building and evacuating it into the air, soil or water, for cooling the building.

The performance of a heat pump is established by determining:

- The coefficient of performance (COP) that represents the relationship between the heating power and electrical energy use for a given source and a certain obtained temperature
- The efficiency rate (REE) that represents the relationship between the refrigeration power and electrical energy use for a given source and a certain given temperature.

To establish which of the natural environment heat pumps can be considered in designing HVAC heat pumps systems to be included in the RES Directive provisions (SPF_{min} = 2.875) we use Table 1 (COP) and Table 2 (EER) from the Commission Decision Annex and we select either a high efficiency or a low efficiency thermal pump.

VI. PRIMARY ENERGY REPORTING OBTAINED IN GEOTHERMAL HEAT PUMP APPLICATIONS

The purpose of measurements foreseen in the EPB Directive (Recast) is to obtain primary energy over the energy use from fossil sources in all natural environment heat pump applications destined for new buildings but also when modernizing a major part of an existing building. In the case of new buildings, the use of renewable energy is compulsory.

Germany, in anticipating the provisions of the European Parliament and Council, introduced, on January 1 2009, a Law proposing renewable sources in the heating sector (section IX [3]) and from April 30, 2009 the second part of the Law regarding the building's energy efficiency [4]. In January 2007, the European Commission proposed a package ENERGY-CLIMATE aiming to reduce energy consumption and greenhouse gas emissions by 20% and to increase the amount of renewable energy by 20% by 2020.

The complete implementation deadline by the Public Authorities of the measures foreseen in EPB Directive (Recast) is December 31, 2010 (for all buildings with a surface >250 m^2).

The documents quoted above give the obligation for each EU member state to ensure an independent control mechanism to guarantee the Energy Performance of the Building Certificates. These Certificates are required to clearly state the annual specific consumption of renewable energy and the primary energy economy.

As an example of the primary energy obtained when using geothermal heat pumps, we will analyze the case of a building design whose energy results were presented in Figure 3.

The building in our example [2] has a monthly energy need for heating, ventilating and air conditioning as shown in Figure 5.

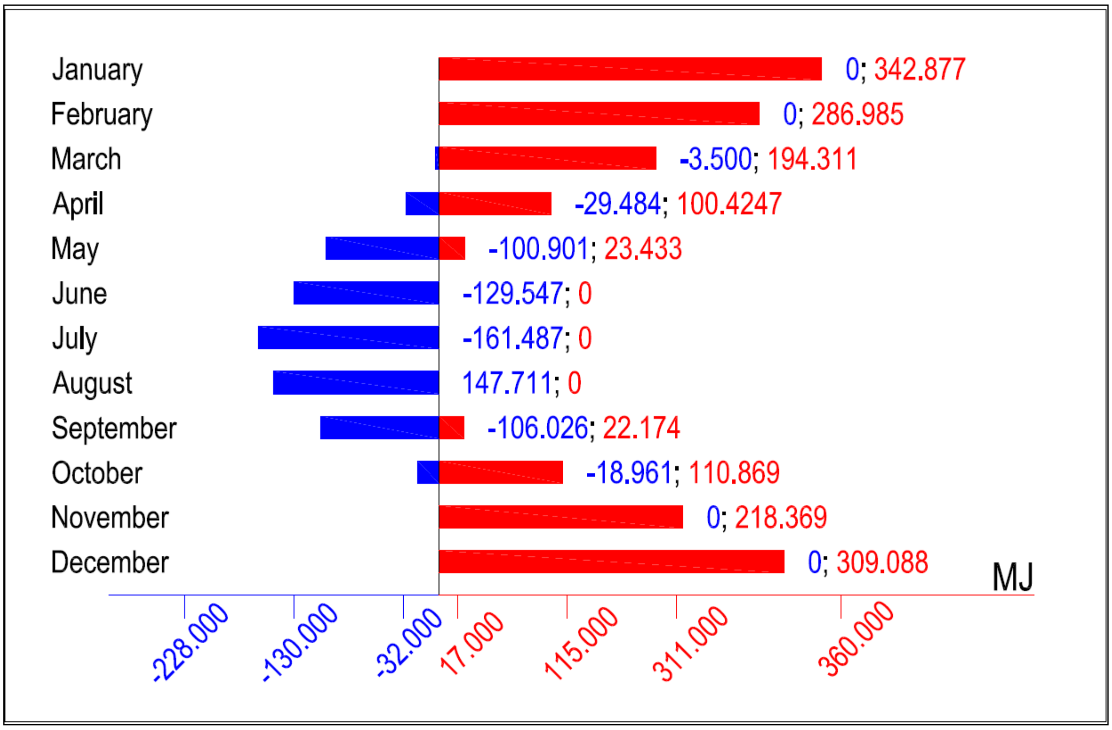

Figure 5. Monthly energy demand of the heating, ventilating and air conditioning subsystems of a residential building of P+ 4 floors, Ac = 5363 m^2, located in Bucharest Romania

By using the conversion 1Wh = 3600 J, we obtain:

36 $\mathbf{Q_{demand\ H+V} = 447\ MWh/yr}$

$\mathbf{Q_{demand\ AC} = 194\ MWh/yr}$

For the number of inhabitants, it was determined that:

37 $\mathbf{Q_{demand\ DHW} = 93\ MWh/yr}$

In the project feasibility study, it was determined that for the building in our example, there are two solutions for the building's HVAC system as follows:

- The typical HVAC system, based on fossil energy sources, which has the demand for heating, ventilating and domestic hot water which are assured by burning natural gas in a thermal power plant with a useful thermal capacity of 250 kW. The cold needs of the building are achieved by installing a chiller on the building's roof, with an air-cooled condenser. The thermal balance of this system can be seen in Figure 6. The HVAC system has an annual energy demand Q_{usable} of 820 MWh/yr, 668 MWh/yr from natural gas (approximately 82%) and 152 MWh/yr from electrical energy. Thermal loss of the building's HVAC system Q_{nr} is 280 MWh/yr (approximately 34%)
- A geothermal HVAC system based on installing a BHE (Borehole Heat Exchange = Ground Source Heat Exchange) having a renewable thermal capacity of 600 MWh/yr, made up of 360 MWh/yr for heating and 232 MWh/yr for cooling. The 70 boreholes of 70 m depth are installed at a depth of 2 m under the green space of the building. The

thermal balance of the system is presented in Figure 7. The HVAC system has an annual energy need Q_{usable} of 799 MWh/yr of which E_{RES} represents 600 MWh/yr and electrical energy 199 MWh/yr. Thermal loss of the building's HVAC system Q_{nr} is 65 MWh/yr (approximately 8%).

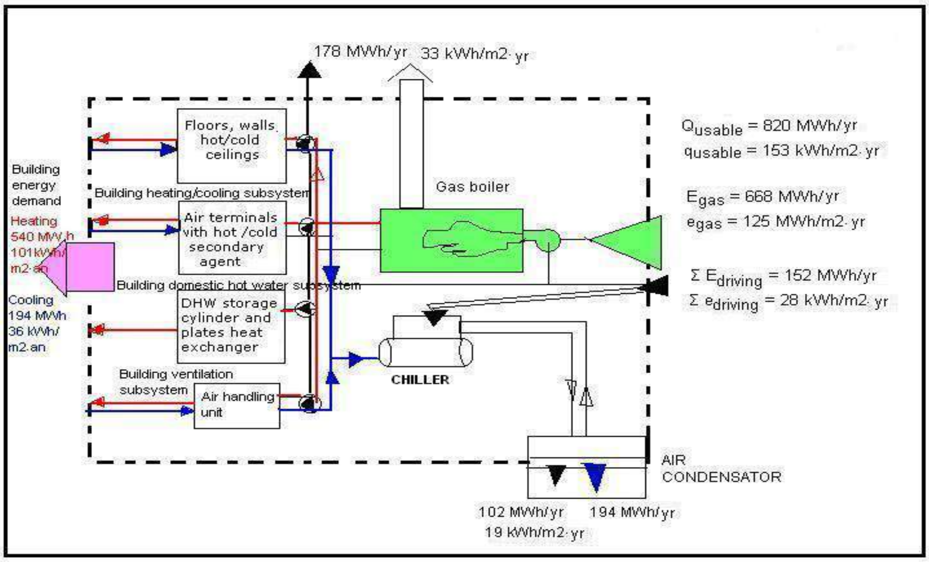

Figure. 6. Thermal balance of a typical HVAC system

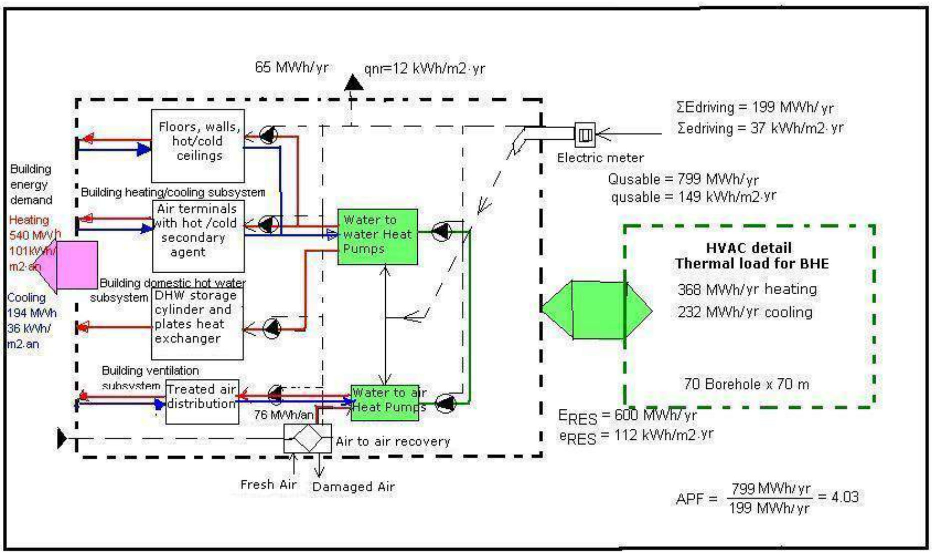

Figure 7. Thermal balance of a geothermal HVAC system

These two options are summarized in Table 1.

Analyzing the data from Table 1, we can see that:

- The geothermal source produces a total of 600 MWh/yr primary energy, out of which 199 x 2.5 -199 = 298 MWh/yr must be deducted as the electrical energy used by the building's HVAC system. A primary energy surplus of 302 MWh/yr (56 kWh/m^2 yr) remains which is entered into the calculation of the annual specific energy use of the building, whose value is 149 kWh/m^2 yr

- By replacing the HVAC classic system with a geothermal one, the energy performance of the same building is increased by 30% and the building is moved from “B” class to a superior energy class “A”, and the specific greenhouse gas emission drops by a factor of 2.8.

Energy performance indicator of the building	**The building using a classic HVAC system**	**The building using a geothermal HVAC system**
The specific annual primary energy consumption for normal use of the building [kWh/m^2 yr]	The natural gas specific use in primary energy units: ep_{gas}= 137 kWh/m^2 yr The specific energy use in primary energy units: $\Sigma ep_{driving}$= 71 kWh/m^2 yr The energy performance of the building in primary energy units. The annual specific energy use: $ep_{gas}+\Sigma ep_{driving}$=**208 kWh/m^2 yr**	The specific energy use from renewable source using (35) for an SPF=799/199=4.02 ep^{RES}=56 kWh/m^2 yr The specific energy use in primary energy units: $\Sigma ep_{driving}$= 93 kWh/m^2 yr The energy performance of the building in primary energy units. The annual specific energy use: ep^{RES}+ $\Sigma ep_{driving}$=**149 kWh/m^2 yr**
The specific greenhouse gas emissions produced by the building’s HVAC system sources [kg CO_2/ m^2 yr]	The specific emission for the natural gas: GES_{CO2}=36 kg CO_2/m^2 yr The specific emission of the electrical energy use: GES_{EE}=(152,000 kWh/yr) / (5363 m^2) x 0.486 GES_{EE}=14 kg CO_2/m^2 yr The energy performance of the building: GES=GES_{CO2}+GES_{EE} = **50 kg CO_2/m^2 yr**	* The specific emission of the electrical energy use: GES_{EE}=18 kg CO_2/m^2 yr The energy performance of the building: GES= GES_{EE} = **18 kg CO_2/m^2 yr**

Table 1.

The primary energy saving and emission reduction is calculated as:

- The primary energy saving = (the annual specific primary energy use from the HVAC classic system plus the annual specific primary energy use, equivalent to the annual electrical energy use covered the provision of the HVAC geothermal system) x 5363 m^2 = 1,614,263 kWh/yr = **1,614 MWh/yr.**

If we want to express the saving of primary energy in equivalent petroleum tons, we use the conversion factor:

1Mtoe = 11.63 MWh. This way, the primary energy economy in the analyzed case is: **139 Mtoe/yr** or **26 Ktoe/m^2 yr,** the equivalent of 300 kWh/$m^{2\cdot}$yr primary energy

- The reduction of the greenhouse gas emissions = (GES in the case of a building with classic HVAC system minus GES in the case of a building with a geothermal HVAC system) x Ac [m^2] = (50 kg CO_2/ m^2 yr - 18 CO_2/ m^2 yr) x 5363 m^2 = **171,616 CO_2/yr = 172 t CO_2/yr** or **32 kg CO_2/ m^2 yr.**

The saving of 172 t CO_2/yr represents the equivalent of an urban bus in a European capital, driving more than 1 million km.

VII. ENERGY EFFICIENCY AND ECONOMIC COST BENEFITS

The content of this chapter presents the algorithm for the evaluation of the energy efficiency of a project with GSHP HVAC, based on the framework defined by EPBD and RESD.
Proper application of the algorithm described in this chapter gives the entrepreneur/investor the capacity to adopt an efficient GSHP HVAC solution, so that the produced RES energy which exceeds the input energy from conventional sources will represent the contribution/savings/real intake of GSHP applications.
EPBD and RESD clarify this issue at European level. German law in this matter correctly anticipated the described European legislation, presenting the correct methods and algorithm which should be followed.

VIII. CONCLUSIONS

The designer needs to be aquainted with the following issues:

- EPBD - the energy performance criteria of the building
- The HVAC with GSHP system is a subsystem of the building
- The building and its HVAC GSHP system are classified as a single entity
- The energy classification is based on the annual specific consumption of primary energy [kWh/yr]
- The GSHP system produces primary energy
- RESD requires that the primary energy from renewable sources should replace energy used by the building's HVAC system using fossil source
- A HVAC with GSHP system efficiency control is made by the calculation of SPF
- The RES Directive requires that SPF ≥ 2.875
- EPBD Recast introduces the NET-ZERO ENERGY BUILDING (NZEB) concept that represents the next decade's target for Europe and the USA

- In the next decade, all new buildings, residential and non-residential, should use renewable energy sources
- A building will be placed in the NZEB Category if its seasonal performance coefficients are greater than the 3.5 value that assures >70% of the total annual thermal energy use of the building is renewable energy.

The main consequences of incorrect or incomplete use of these concepts are:

- **In the short term** – The design / implementation of an energy-inefficient GSHP solution
- **In the medium and long term** – Higher operation costs for the entire building lifecycle, not only compared to a high quality RES solution, but also compared to a classic HVAC solution.

The next step is for the presented EPBD and RESD provisions to be included into national regulation frameworks, rules and procedures. The fulfilment of this step is the guarantee that, in the future, the HVAC GSHP projects will increase efficiency in heating / cooling systems, producing energy savings and positive environmental impacts.

IX. FURTHER INFORMATION

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[2] Eng. Radu POLIZU, Ph. D – “NET-ZERO” Energy Buildings – Uppsala, Sweden, 10-12 June 2009

[3] Act on the Promotion of Renewable Energies in the Heat Sector (Erneuerbare-Energien-Wärmegesetz EEWärmeG), Bundesgesetzblatt Jahrgang 2008 Teil I Nr.36 vom 18. August 2008, S. 1658.

[4] Bundesgesetzblatt Jahrgang 2009 Teil Nr. 23, ausgegeben zu Bonn am 30 April 2009. Verordnung zur Änderung der Energie-Einsparverordnung.

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CHAPTER 19

ENVIRONMENTAL ISSUES *by Burkhard Sanner*

I. INTRODUCTION

Environmental aspects in respect to the protection of ground and groundwater are of paramount importance in any shallow geothermal project. The main environmental problems associated with GSHP can be categorized as follows:

Impact on ground and groundwater:

- leakage of antifreeze or refrigerant
- connecting different aquifers or connecting aquifers to surface (quality of grouting / long-term tightness)
- drilling into artesian aquifers
- thermal effects.

Other impacts:

- There can also be other adverse effects due to swelling clays, anhydrite, etc.
- Pollution by a rig from a polluted drilling site, not properly cleaned.

II. LEAKAGE

Figure 1. Installation of a BHE from a reel hanging above the borehole

Leakage of closed systems (horizontal or vertical loops) has to be avoided at all costs. It will render the relevant loop unusable and might cause environmental problems in cases where the fluid escapes from inside the pipes and is then hazardous to groundwater. Two precautions must be taken:

- All steps in the production and installation of a ground loop must be designed for optimum tightness and longevity of the loop; installation procedures must be set up in such a way that the danger of damage of the pipe during installation is minimized (for instance using a reel hanging from the drill rig above the borehole to install a BHE into that hole, (Fig. 1).

- Heat carrier fluids must be selected in such a way that the possible impact to the groundwater after leakage is minimized, i.e. the fluids should be non-toxic and easily biodegradable. The ideal heat carrier from both the environmental and thermodynamic perspective is pure water. Alas, in most of central and northern Europe water can hardly be used for closed loops, as the design temperatures in winter typically are below 0 °C. So, an antifreeze has to be added to achieve a lower freezing temperature; Table 1 gives details on some antifreeze agents.

Name	Percentage	Freezing point
Monoethylenglycol	25 %	-14 °C
Monoethylenglycol	33 %	-21 °C
Monopropylenglycol	25 %	-10 °C
Monopropylenglycol	33 %	-17 °C
Ethanol	25 %	-15 °C
Salt (brines):		
Potassium carbonate	25 %	-13 °C
Potassium carbonate	33 %	-20 °C
Calcium chloride	20 %	-18 °C

Table 1. List of some suitable antifreeze agents; water-antifreeze mixtures with the amount of antifreeze given in column “percentage”

III. CONNECTING AQUIFERS

For a shallow geothermal drilling it is esential that aquifers are not connected to the surface, nor should aquifers at different depths be connected with each other. Connection to the surface can be prevented by grouting the BHE, or by cementation of the annulus in the case of a well. In Scandinavia, keeping the hole open and just sealing it to the ground surface is a widely accepted practice explained e.g. in the Swedish guideline “Normbrunn 07”. However, even in Sweden for difficult situations, like saltwater intrusion into the soil from the sea, grouting meanwhile is recommended.

To prevent the connection of aquifers to each other (Fig. 2), again a good grouting is required. In difficult cases, even a “BHE packer” can be used to seal the borehole, as patented recently in Switzerland (Fig. 3). For wells, the well screen must not extend through the boundary of different groundwater aquifers.

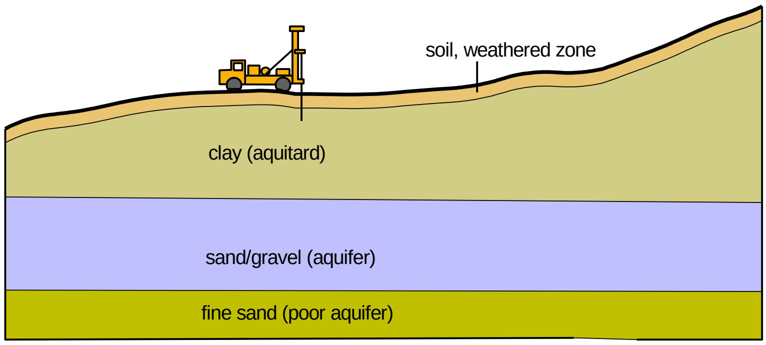
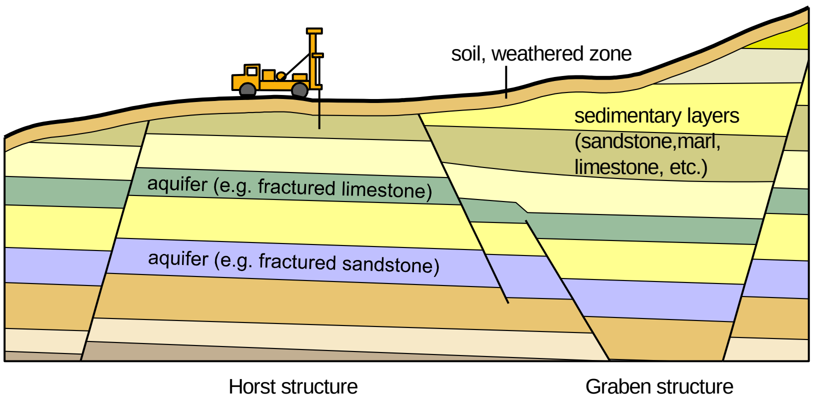


Figure 2. Geological situations with possible problems in respect to connection to the surface (above) or problems with connecting different aquifers (right)



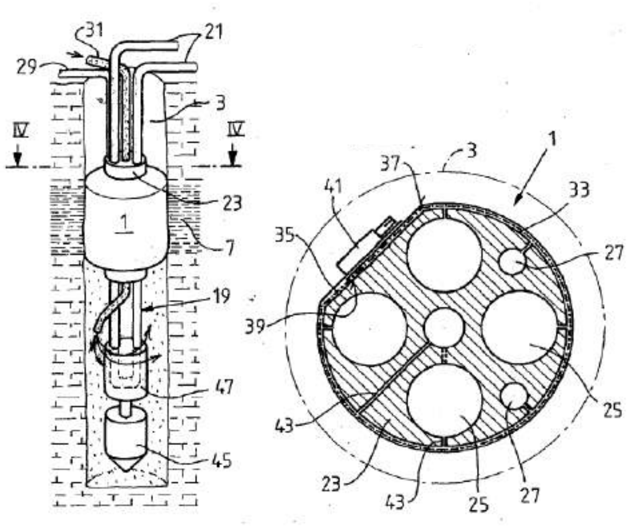


Figure 3. Schematic diagram of the "BHE packer" as supplied by Haka Gerodur, Switzerland (from the relevant EU patent application EP 1 865 146 A1)

IV. ARTESIAN GROUNDWATER

An artesian well or spring produces water at the surface without the need for pumping. The principle schematic diagram is shown in Figure 4. The reason for the free outflow is that the catchment area (where water infiltrates the ground) is higher than the ground surface at the site considered, and that impermeable layers prevent the water from rising towards the surface.

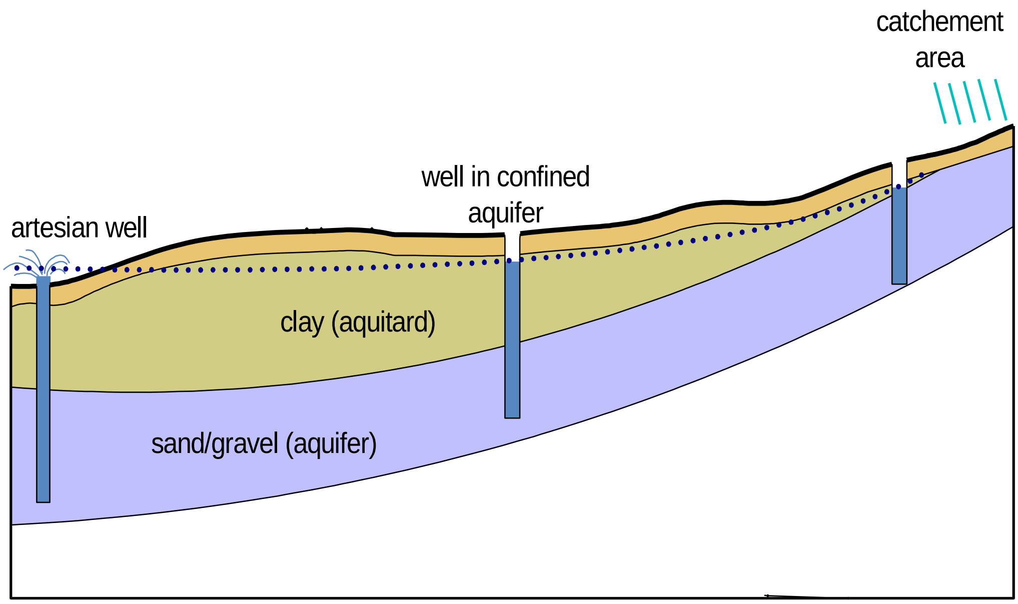


Figure 4. Schematic diagram of a confined and of an artesian well

For some regions, GIS data provided via the internet allow an assessment for the risk of artesian groundwater (Fig. 5). In the maps, both the known artesian wells or springs as well as the area with possible hazard are shown. As a clear rule it can be said: never try to install a BHE in an artesian aquifer! Grouting will not be enough to keep the water from migrating (this would be possible just for small overpressure). Artesian wells can be quite a spectacle (Fig. 6).

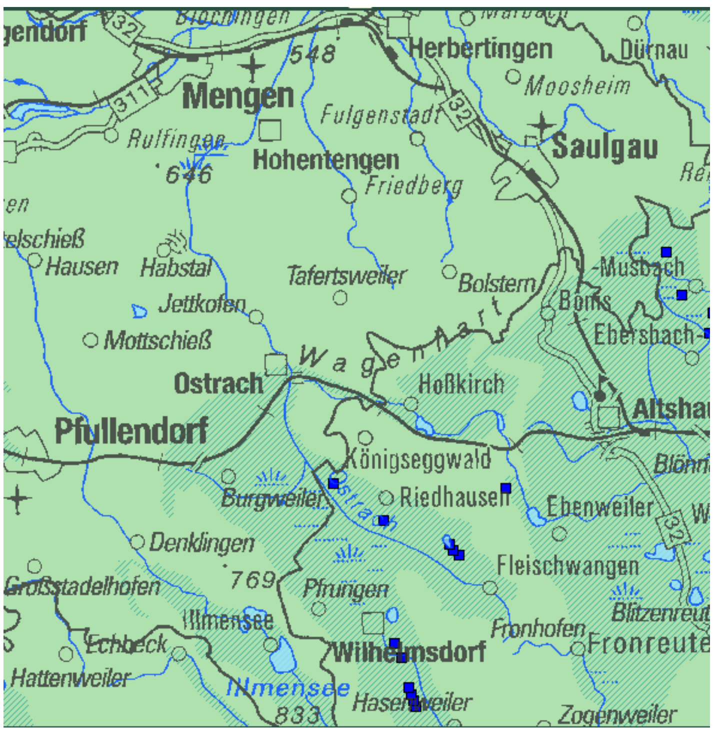


Figure 5. Map from GIS for shallow geothermal in the German state Baden-Wuerttemberg, showing known artesian wells/springs (blue squares) and areas with potential hazard of artesian water (blue shading);
(from: http://www1.lgrb.uni-freiburg.de/isong/)

Figure 6. Artesian aquifer perforated in Hoechst (near Frankfurt); large amount of water pressing through the drill pipe

It is not necessary for the groundwater level to be fully artesian (i.e. the pressure head would be above ground level) to cause trouble. Also confined aquifers with a pressure head slightly below ground surface can flood a construction pit, underground parking, or similar, if the drilling was done from the bottom of the excavation. Examples exist in many places; in Frankfurt (Germany) both a construction pit and underground parking have been flooded from geothermal drilling during the last 10 years, in different projects.
Artificial groundwater drawdown might also fool the driller. Often the water table near a construction site is lowered by pumping to enable work in a pit. Drilling wells or BHE in such a pit and not sealing the perforation will result in flooding of the pit (or the basement or underground parking, respectively, that might have been constructed in the pit after drilling) once the pumping to lower the water table has been stopped after all work is finished.

V. SWELLING ROCKS

Severe damage might be caused by rocks which swell under the presence of water. This damage starts very slowly, but cannot be stopped once it has been started. Rocks susceptible to swelling include:

- Clay and marl with 3-layer-clay minerals
- Anhydrite

In southwestern Germany a small city is endangered by ground movements due to anhydrite in contact with groundwater after geothermal drilling (Fig. 7). Anhydrite ($CaSO_4$) is slowly transformed into gypsum ($CaSO_4$ * 10 H_2O), which is accompanied by a considerable growth in size of the mineral.

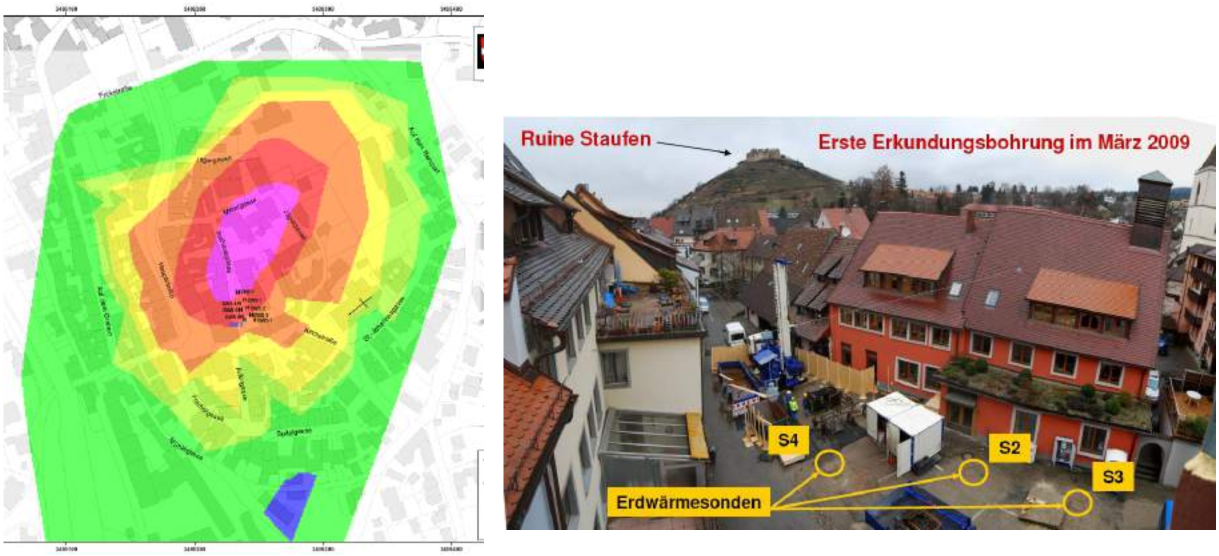


Figure 7. Rate of upheaval in the Suebian city Staufen, started after geothermal drilling accessed a layer of anhydrite (Map RP Freiburg); (right) view of the old city with the damaged area (photos: I. Sass)

European Federation of Geologists		www.eurogeologists.eu
European Geothermal Energy Council		www.egec.org
Arsenal Research, Austria		www.arsenal.ac.at
Bureau de Recherches Géologiques et Minières, France		www.brgm.fr
GT Skills, Ireland		conodate@mac.com
Romanian Geoexchange Society		www.geoexchange.ro
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The GEOTRAINET Training Manual

The GEOTRAINET project: Geo-Education for a sustainable geothermal heating and cooling market, supported by Intelligent Energy – Europe, has delivered this Training Manual for Designers of Shallow Geothermal Systems. It was overseen by the European representative organizations for geologists and for geothermal energy.

This manual has been developed for European designers of shallow geothermal systems and it is intended to provide relevant and accessible support for their ongoing education. It is based on the curriculum developed by an international platform of experts from this sector over the period of the project.

Training courses and meetings were held by partners drawn from universities, research organizations and commercial organizations from across Europe in Belgium, Austria, France, Germany, Ireland, Romania, Spain, Sweden and the UK. The course covers all matters from concept and feasibility, through design and integration to installation and regulation.

The manual is designed as the course text for a formal training programme in the design of shallow geothermal systems, including practical demonstrations and real case studies based on experience. Successful completion of the GEOTRAINET training will lead to the award of a European certificate, for which a system of European accreditation has been proposed as part of the project.

For ongoing support and information see the GEOTRAINET website:

www.geotrainet.eu