IEA Heat Pump CENTRE
Informative Fact Sheet
HPC-IFS2, January 2002

Closed Loop Ground-Coupled Heat Pumps

Concept

As defined by the American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. (ASHRAE) the ground-coupled heat pump (GCHP) is one type of ground-source heat pump, and consists of a (reversible) vapour compression cycle heat pump unit linked to a closed loop heat exchanger buried in the ground. Most commonly GCHPs are indirect systems, with either water or a water/antifreeze solution circulating through sealed thermoplastic underground loops, and energy is transferred to or from the heat pump refrigerant circuit through a separate heat exchanger. Alternatively the refrigerant can be circulated through a copper coil ground heat exchanger, and energy is transferred in a direct expansion (DX) system. Piping for ground heat exchangers may be located in one or more vertical boreholes or laid out in horizontal trenches. In winter, since the earth remains a relatively warm source (even in cold climates) heat can be extracted by the ground heat exchanger, upgraded by the heat pump unit and transferred to the indoor distribution system for space heating purposes and possibly hot water provision. During summer the system can be reversed to provide space cooling, and the earth then acts as a “sink” to absorb the heat removed.

Benefits of GCHPs

Higher Performance

More uniform year-round earth temperatures in the ground heat exchanger ensure that the GCHP will operate with higher efficiency than conventional air-source heat pumps and fossil fuelled equipment. In heating mode GCHP installations can operate with higher heating capacities at low ambient temperatures and typically have a heating seasonal performance factor (HSPF) 20-30% higher than equivalent air-source systems. Similar performance advantages are experienced for systems operating in the cooling mode. Typical performance measurements on ground source heat pump installations that provide space heating and domestic hot water using conventional equipment indicate average SPFs of 3.0. However, more efficient systems using state-of-the-art components with optimized ground coils that provide heat to low temperature distribution systems in low energy buildings can achieve HSPFs greater than 4.0.

Lower Operating Costs

Higher efficiency levels lead to energy savings and lower operating costs for space heating and cooling. For an electrically driven GCHP operating in the heating mode typical energy costs are between 50-70% less than for electric resistance heating, depending on climatic conditions, and at least 25% less than for an air-source heat pump. As compared to other sources of heating, potential savings are dependent on local costs of natural gas and oil, corresponding furnace efficiencies, etc.

Reduced Maintenance

Since all parts of the GCHP are located either indoors or underground the system is totally sheltered from the weather and any vandalism, and little maintenance is required apart from routine servicing.

Temperatures underground are much more stable than air temperatures, enabling systems generally to operate with lower compressor pressure ratios and less thermal and mechanical stress. Relatively high ground source temperatures prevent any evaporator coil frosting problems at the heat pump, and defrost cycling is therefore avoided.

With protection from the environment and less strenuous operating conditions GCHP systems have high reliability, and life expectancies are typically 20 to 25 years.

Lower GHG Emissions

By reducing the primary energy consumption required for space heating and cooling, heat pumps have the potential to

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reduce the quantity of CO_2 produced by the combustion of fossil fuels and thus to reduce global warming. GCHPs can reduce emissions of greenhouse gases by two-thirds or more compared with conventional heating and cooling systems. However, the CO_2 emission from an electrically driven GCHP is directly related to the fuel used for power generation and the efficiency of the power plant, and the net effect is therefore region specific. For example in Montreal, Canada where electricity is generated primarily from hydroelectric sources a GCHP used for residential heating purposes would produce less than 5,000 kg of CO_2 over a 20 year period (including the direct effect from refrigerant releases), whereas a high efficiency gas furnace would emit 97,500 kg of CO_2 (plus distribution network transmission losses) over the same time frame.

Improved Aesthetics
With no outside equipment above ground level the nuisance noise from external fans is eliminated. For commercial buildings the appearance is improved by no longer needing any rooftop equipment and by fewer external penetrations of the building envelope.

Technology

Ground-source heat pumps are an established technology, with about 500,000 units currently installed worldwide and an estimated 45,000 new units being added annually. However, there are no statistics on what proportion of these are ground-coupled heat pump units. The GCHP system is comprised of the ground collector heat exchanger, the heat pump unit, and the indoor distribution network. As regards the heat pump unit itself, during the past 20 years, the same developments that have occurred in the manufacture of air-source equipment have also been applied to raising the levels of efficiency in GCHP units. Improvements have been made in component reliability and various technological advances made in equipment, including high efficiency variable speed compressors, variable speed fans, improved controls, etc. However, more significant progress has been made in other areas such as refinement of ground heat exchanger design techniques, improved collector coil configurations and cost reduction, and system integration.

Heat Pump Types
The most common type of heat pump used in such systems is the water-to-air unit in North America and water-to-water in western and northern Europe. Generally a single unit is sufficient for residential applications, but in the commercial sector modular systems are often used with separate independent units serving individual zones. The water-to-refrigerant coil is linked to the in-ground water (or water/antifreeze) loop, and serves as the condenser in cooling mode and the evaporator in heating. In North America the refrigerant-to-air coil is usually linked to a forced air circulation system (ductwork). There is also increasing use of water-to-water heat pumps for applications in hydronic heating/cooling, dedicated hot water heating, underfloor heating, etc.

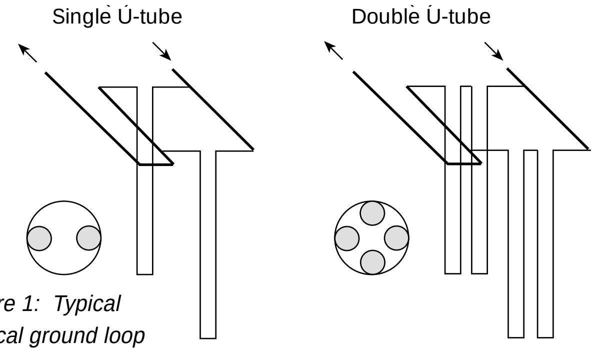

Figure 1: Typical vertical ground loop configurations.

Ground Heat Exchanger
Heat transfer to or from the ground coil is driven by the temperature difference between the ground and the circulating fluid. Ground temperatures near the surface vary considerably with the time of year, but at lower depths (typically below 2 m) these temperature swings are reduced and at a depth of 10 m the ground remains at its mean temperature throughout the year. Other factors affecting the heat transfer are ground thermal properties, primarily the thermal conductivity and the thermal capacity of the soil. As well as variation with types of rock and soil these properties are strongly influenced by moisture content of the ground. Thermal conductivity of soil remains relatively constant above a specific threshold called the critical moisture content (CMC). However, below the CMC the conductivity drops rapidly and may lead to serious degradation in performance of the ground heat exchanger. Such problems are usually avoided in applications where the water table remains relatively high and cooling loads are moderate. Underground movement of water also has a significant impact on heat transfer, since heat is also transferred by convection to the moving water channels.

Ground heat exchanger coils may be installed in either vertical or horizontal configurations, with the choice depending on availability of land area at the site, local soil conditions, and excavation costs. Some rules of thumb are available for estimating typical earth heat extraction rates. One source suggests a range between 38-91 W/m for vertical heat exchangers and 38-59 W/m for horizontal circuits. However, the wide variations depend on many variables, and are suitable only to assist in preliminary feasibility explorations.

Vertical Collectors
A vertical closed-loop arrangement is an appropriate choice where land area may be limited, for example in residential suburban homes where land space is often restricted. The most common types of vertical borehole heat exchangers are shown in Fig. 1. Typically in North America single U-tubes are inserted into bored holes, but double U-tube configurations have also been used in some European countries. Boreholes are generally 100 mm to 150 mm diameter, with a depth of 15 m to 150 m depending on soil conditions and size of the system. Performance degradation may occur if adjacent boreholes are not spaced far enough apart, and a separation distance of 5 m is usually considered adequate to avoid

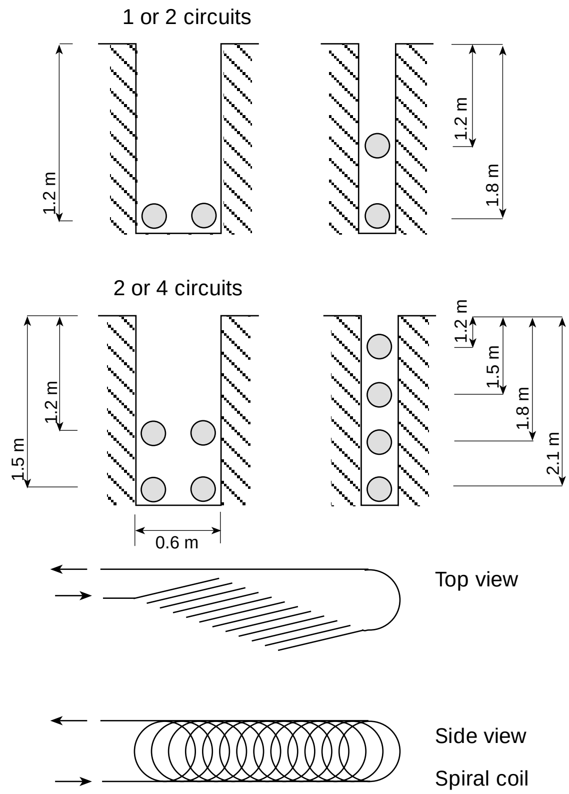

Figure 2: Typical horizontal heat exchanger circuit configurations.

thermal interference between them. Sizing of the vertical ground heat exchanger, including the number of boreholes required and circuit layout design, etc., is usually determined by using an hour-by-hour energy analysis program to calculate the building heating and cooling loads (especially in the case of commercial buildings).

Horizontal Collectors

Horizontal loop installations require a relatively large area, and are therefore more common in rural areas where properties are larger. They are most appropriate for residential applications, particularly for new construction. The most common piping configurations are shown in Fig. 2. Multiple pipes (up to six) are laid in trenches with pipes placed either side-by-side or in an over-under configuration. In North America the trenches are normally 1.2 m to 2.1 m deep, depending on the number of pipes in a trench. For installations in westerm Europe and Scandinavia a depth of 1.0 m or less is considered adequate. Trenches may be anywhere from 150 mm to 600 mm wide, and at least 2 m apart in order to minimize any thermal interference. Similarly within each trench a minimum spacing between pipes of 0.3 m is recommended, horizontally or vertically. The spiral coil heat exchanger is produced by stretching a tight coil of small-diameter polyethylene tubing out to form an extended coil (about 600 mm diameter). The spiral is then placed vertically in a narrow trench or laid horizontally at the bottom of a wider trench. The heat exchange surface is effectively a cylinder with the diameter of the spiral coil, and required trench lengths are reported to be only 20% to 30% of those for a single pipe configuration.

Circuiting

The piping loops used in both horizontal and vertical configurations can be connected either in series or parallel. Most systems use flow loops in parallel, with connections to supply and return headers. This arrangement leads to reduced pumping power, and material costs are also lower since pipe diameters are usually less for most of the piping runs. The length of piping in each circuit must be designed to ensure the same flow in each loop. Alternatively some systems use manifolds with valves to control loop flows.

Materials

The piping material selected for the ground heat exchanger affects the service life, maintenance costs, pumping power, capital cost, and heat pump performance. It is important therefore that the size, strength, and material be well suited to the application. High density polyethylene or polybutylene piping are the industry standards, and typical pipe sizes used are between 20 mm and 40 mm in diameter. These materials are flexible,and pipe joints can be easily made by thermal fusion to provide reliable leak-resistant loops that require no maintenance. For DX systems copper piping (12 mm dia.) is normally used for the ground collector coil. Depending on soil conditions, plastic coating may be necessary to prevent corrosion. Better heat transfer with copper reduces the length of coil required, and this may help to offset the higher material cost.

Installation

Careful installation of the ground coil is necessary for efficient operation of the system, and the most important consideration is to ensure that continuous and reliable heat transfer is maintained between the earth and the coil. For installation of horizontal ground collectors, standard construction equipment such as backhoes, bulldozers, and chain trenchers are usually sufficient to excavate the trenches required. It is recommended that the pipes are laid on a bed of sand in the trench, then covered with a 15 cm layer of sand before backfilling with the removed soil. The installation should then be watered and compacted to minimize settlement. In the case of heat exchanger piping laid at multiple depths the same technique is required when installing each layer of pipe.

For most vertical ground heat exchanger installations the boreholes must be drilled, and a variety of drilling methods and equipment are used depending on the geological conditions encountered and depth required. After the plastic U-tube heat exchangers are inserted into the boreholes a careful backfilling operation is again necessary. In the case of shallow installations backfilling from the surface may be possible using excavated earth from the drilling operation. However, for deeper boreholes (>50 m) the backfill material must be pumped to the bottom of the hole (tremie grouting) to form a grout that fills the void between the borehole surface and the U-tube heat exchanger section. Pumpable grouting materials are either cement-based or bentonite-based, and the choice of grout depends on factors such as the subsurface conditions, anticipated operating temperatures, and grouting material properties. Thermally enhanced grouts are also available to provide improved heat transfer of these materials if necessary.

Secondary Fluids

For an indirect system the circulating fluid is either water or a water/antifreeze solution. In northern Europe and colder climate areas of North America an antifreeze solution is normally required. It is recommended that the freezing point of the antifreeze solution be at least 5 K below the mean of the heat exchanger design inlet and outlet temperatures. Other factors affecting selection of the secondary fluid include materials compatibility, heat transfer/pressure drop characteristics, environmental impact, cost and availability. No single antifreeze solution fulfills all of these requirements. Those most commonly used are either salts such as calcium chloride and sodium chloride, or organics such as glycols and alcohols.

The salt solutions are generally non-toxic, low cost, and have good heat transfer characteristics. However, they are very corrosive to most metals in the presence of air, and corrosion inhibitors must be added to reduce the oxidation of heat pump materials. Glycol solutions are non-corrosive, have fair heat transfer characteristics, but are relatively expensive. Also at low temperatures (below -10ºC) their viscosity levels increase, requiring greater pumping power and therefore reducing heat pump system efficiency. Ethylene glycol is moderately toxic whereas propylene glycol is practically non-toxic. Glycols are commonly used in Europe.

Alcohols such as methanol are relatively non-corrosive, reasonably low cost, and have good heat transfer and pressure drop characteristics. The major disadvantage is that they are flammable and highly toxic.

In North America solutions of potassium acetate are being used in some applications, as it appears to offer a reasonable compromise of the necessary criteria.

Design Guidelines and Software

Accurate sizing of the ground coil is critical for systems where the capital cost is dominated by the cost of the in-ground heat exchanger. Oversizing leads to higher cost and equipment short cycling problems. Undersizing causes lack of capaciity and reduced performance. Some design manuals and computer models have been developed to assist in overcoming such problems. In North America ASHRAE has published an engineering manual and a design guide for commercial applications (see References). For residential installations the NRECA/OSU design manual is widely used, supplemented by information on specific issues contained in separate publications of the International Ground Source Heat Pump Association (IGSHPA). For actual sizing of the in-ground heat exchanger various models are available, and a comprehensive review and analysis of these design tools was has been carried out for the Geothermal Heat Pump Consortium (see DynCorp reference).

Applications

As is the case for air-source heat pumps, the main applications for GCHPs are for space heating and cooling and hot water heating in both the residential and commercial sectors.

Residential

So far the main market in this sector for GCHPs has been for space heating in new low-energy housing where high insulation levels result in lower heating demand. This enables air distribution temperatures in forced air systems to be reduced to 30ºC-50ºC, and low temperature hydronic systems can operate with delivery temperatures of 45ºC to 55ºC. Underfloor water heating systems with distribution temperatures of 30ºC to 45ºC can also be used in such applications. Although the retrofit market is potentially much larger the penetration into this area has been limited due to the higher distribution temperatures required in conventional central heating systems that make it less economic to replace those systems with heat pumps in general. However, in North America GCHPs have been installed for retrofit in parallel with existing heating systems, where the heat pump provides a large proportion of the annual heating load at reduced operating temperatures and reduces the energy peak demand requirements for the conventional system. As well as providing central heating, GCHPs can also be used in single room applications, and a highly efficient system using a pre-charged DX horizontal ground collector has been developed for this purpose in Sweden, as well as a propane based unit in Austria.

As it has for air-source heat pumps, the need for space cooling has driven the market for ground-source heat pumps in North America. Most systems there are reversible and often sized to meet the peak cooling load since this is frequently higher than heating, even though the total annual energy consumption for cooling may be less than for heating. In western and northern Europe air-conditioning is not considered to be a high priority in residential homes, although the market has been growing in recent years.

In addition to space heating and cooling GCHPs can also be used to heat domestic hot water, and since this is a year-round load it can serve to improve the overall load factor for the heat pump. Water heating is usually accomplished by using a desuperheater which extracts heat from the refrigerant hot gas in the compressor discharge line and uses it to heat water that is pumped from the hot water storage tank. The desuperheater heating capacity is about 20% of the condenser capacity at typical operating conditions, and this provides partial water heating during heat pump operation in either heating or cooling mode.

Commercial

The commercial sector is much more diverse than the residential sector and GCHPs have been used for heating and cooling in a wide range of applications including offices, schools, shops, hotels, sports complexes, institutional buildings, etc. This market sector has been growing in recent years, especially in the US where the Geothermal Heat Pump Consortium is involved in the promotion and uptake of ground-source heat pump technology for both commercial and residential heating and cooling. A coalition organization with similar objectives has also been established in Canada, with the focus there clearly directed at the commercial/institutional market sector. Even in northern and western Europe the market for GCHPs is growing in this sector, largely due to increased levels of building occupation density

Table 1: Typical costs for residential GCHP systems.

Country	Costs (USD)	Cost (USD/kW) installed cap.	Comments
Austria	21,000 (inc. underfloor heating) 13,000 (excl. distribution system)	1,500 930	horizontal DX
Canada	9,500 - 13,000 (inc. ≈2900 for air distribution system + DHW)	700 - 1,000	lowest - horizontal DX highest vertical
Norway	7,500 - 10,000 (excl. distribution system)	1,500 - 2,000	vertical, underfloor heating ≈5 kW (sized to meet 50% of design load)
Sweden	6,300 (excl. distribution system) 7,100 (inc. distribution)	1,250 - 1,420	as above
Switzerland	20,000 (excl. distribution system) 27,000 - 36,500 (inc. distribution system)	1,900 2,800 - 3,800	vertical, underfloor heating
USA	7,500 - 10,000	700 - 1,000	vertical, air distribution

and radical changes in office equipment leading to increased demand for space cooling.

Due to the larger capacity of commercial and industrial systems, horizontal ground collectors are generally not suitable and multiple vertical boreholes are required. The network of in-ground heat exchangers can be used with a range of building heating and cooling distribution systems. These may include central systems with all heat pumps in a central plant room, modular systems with dedicated heat pumps and ground loops in individual zones, or distributed systems where the GCHP is used to replace the boiler and cooling tower in a building water loop heat pump (WLHP) system. Building hot water can also be provided by the GCHP as described in the residential sector.

Standards and Regulations

In recent years there has been a steady movement towards greater international harmonization of performance standards for all types of heat pumps and air-conditioning equipment. As regards GCHPs harmonization is continuing in the area of standards for performance rating and testing methods as well as electrical safety standards. Harmonization of minimum efficiency regulations is less likely as these are often used as instruments of national policy.

The International Organization for Standardization (ISO) published recommended testing and rating standards for performance of water-source heat pumps in 1998. ISO Standard 13256-1 covers water-to-air and brine-to-air heat pumps, and the scope includes ground loop heat pump applications up to 40 kW. This standard was adopted in the US by the Air-Conditioning and Refrigeration Institute (ARI) in 1998, replacing ARI Standard 330 for this specific application. In 2000 ARI incorporated ISO 13256-1 as a basis for its corresponding product certification programme, and also made recommendations that data be used for increasing the minimum efficiency requirements under ASHRAE Standard 90.1 for water source heat pumps. ISO 13256-2 covers water-to-water and brine-to-water heat pumps, and this standard was also adopted by ARI in 1998, but is not yet incorporated into its certification programme. In Canada the corresponding rating standard CSA C446-M90 Performance of Ground and Water Source Heat Pumps is compatible with the US regulation, but also includes efficiency ratings for DX systems.

In Europe the European Committee for Standardisation (CEN) works to establish sets of standards for products, consistent with the harmonized trading policies within the EU and EFTA. The standards are arrived at by consensus and when adopted they are considered to be binding on all CEN member countries. In 1997 standards EN 255-2 and EN 814-2 were issued covering the testing and rating of heat pumps with electrically driven compressors in heating and cooling modes. These standards include test conditions for ground-source heat pumps.

Responsibility for setting international standards for electrical safety comes under the International Electrical Commission (IEC). In the case of heat pumps electrical safety requirements are specifically treated under IEC Standard 355-2-40. This standard has also been adopted by the European body responsible for electrical safety standards, and designated EN 60355-2-40. Mechanical and refrigerant safety aspects are covered at the international level by ISO Standard 5149 and in European countries under EN 378.

Cost impact

The capital costs for a GCHP system are made up of the equipment costs for the heat pump unit, the ground coil piping, the distribution system, and the corresponding installation costs. Of these the costs for the ground heat exchanger and the drilling or trenching required for its installation typically range between 20% and 50% of the total capital cost. Drilling or trenching generally costs more than the material costs for the piping used, so it is important to maximize the heat extraction per unit length of borehole/trench. The spiral coil clearly offers an advantage in this respect. In North America GCHP systems are usually sized to meet 75%-80% of the design heat loss, so the loop size can be reduced, lowering the installed cost considerably. (There may be less scope for this in Scandinavia where GCHPs are typically designed to meet 40%-70% of design heat loss.) Actual costs of drilling or trenching are obviously dependent on the ground conditions and the type of equipment and methods used. For example in the US the total cost for an installed vertical ground collector (including materials, drilling, backfilling, etc.) is typically between 45 and 70 USD per metre. Total capital costs for some residential installations in various countries are shown in Table 1, indicating a wide spread in the cost per kW of installed capacity.

International Energy Agency

The International Energy Agency (IEA) was founded in 1974 as an autonomous body within the Organisation for Economic Co-operation and Development (OECD) to implement an international energy program. Activities are directed towards the IEA Member countries' collective energy policy objectives of energy security, economic and social development, and environmental protection.

IEA Heat Pump Programme

Set up by the IEA in 1978, the IEA Heat Pump Programme carries out a strategy to accelerate the development and use of heat pumps, in all applications where they can reduce energy consumption for the benefit of the environment. Within the framework of the programme, participants from different countries collaborate in specific heat pump projects known as Annexes.

Vision

The Programme is the foremost world-wide source of independent information and expertise on heat pump, refrigeration and air–conditioning systems for buildings, commerce and industry.

Mission

The Programme serves the needs of policy makers, national and international energy & environmental agencies, utilities, manufacturers, designers & researchers. It also works through national agencies to influence installers and end-users.

The Programme develops and disseminates factual, balanced information to achieve environmental and energy efficiency benefit through deployment of appropriate high quality heat pump, refrigeration and air-conditioning technologies.

IEA Heat Pump Centre

A central role within the Programme is played by the IEA Heat Pump Centre (HPC). The HPC contributes to the general aim of the IEA Heat Pump Programme, through information services and knowledge transfer.

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As indicated above the GCHP benefits from relatively low operating and maintenance costs. In the case of maintenance, for example in the US the cost for a commercial GCHP system is reported to be on average about one third of that for a conventional heating and cooling system.

Payback times for GCHP systems when compared with alternative systems depend on the relative energy costs for other systems. For residential systems in the US, payback periods ranging from 2 to 7 years are reported for replacement of direct electric heating, but paybacks can be longer, if a substantially cheaper fuel is available. On the other hand in Austria systems using horizontal DX collectors are reported to be fully cost competitive with conventional fossil fuel systems in new dwellings.

For systems used in commercial/institutional buildings the economics are generally more favourable. These are larger systems designed to provide heating and cooling, and there are some economies of scale. In Canada a detailed life cycle cost analysis was completed in 1999 to assess the cost competitiveness of ground-source heat pump applications for new construction in the non-residential market. Results indicated an average payback period for all building types and geographical regions of approximately six years, with the lowest being for office buildings, followed by sports complexes and high schools.

References

- Ground-Source Heat Pump Systems, IEA Heat Pump Centre Newsletter, Vol. 17 No. 1, 1999
- Ground Source Heat Pumps - A Technology Review, BSRIA Technical Note TN 18/99
- Commercial/Institutional Ground-Source Heat Pump Engineering Manual, Caneta Research Inc., ASHRAE 1995
- Ground-Source Heat Pumps - Design of Geothermal Systems for Commercial and Institutional Buildings, Kavanaugh S P., Rafferty K., ASHRAE 1997
- ISO Standard 13256:1998 Water-Source Heat Pumps: Testing and Rating for Performance – Parts 1&2
- Closed-Loop Ground Source Heat Pump Systems Installation Guide, NRECA/OSU 1988
- International Ground Source Heat Pump Association Web site http://www.igshpa.okstate.edu
- Geothermal Heat Pump Consortium Web site http://www.ghpc.org
- Natural Resources Canada - The Canadian Renewable Energy Network (CanREN) Earth Energy Program Web site http://www.canren.gc.ca
- Design Tools Benchmarking Study, DynCorp, Geothermal Heat Pump Consortium 1996
- Ground Source Heat Pump Market Development Strategy - Marbek Resource Consultants, Ottawa, Canada, March 1999