ADVANCES IN GROUND SOURCE HEAT PUMP SYSTEMS AN INTERNATIONAL OVERVIEW

James E. Bose, Ph.D., PE, Professor
Marvin D. Smith, Ph.D., PE, Professor
Mechanical Engineering Technology
Oklahoma State University
Stillwater, OK 74078 USA

Jeffrey D. Spitler, Ph.D., PE, Professor
School of Mechanical and Aerospace Engineering
Oklahoma State University
Stillwater, OK 74078 USA

In recent years, ground source heat pump system installations have grown continuously on a global basis (estimates range from 10 to 30% annually). They have broadened in application, have enjoyed the benefits of international collaboration, and are becoming recognized as a cost effective standard for energy conservation. The acceptance by the users of the ground source technology is attributable to the soundness of the technology, the development of the design and installation infrastructure, and the response of heat pump and component manufacturers. Recent research has concentrated on reducing the first costs of ground heat exchangers, determining soil thermal properties, modeling of ground source heat pump systems, development of hybrid systems and further development of design methodologies. Current research continues in these topics. This paper gives an overview of recent research and developments, primarily within the last five years.

INTRODUCTION

Ground source heat pumps (GSHP) systems exchange heat to the underground environment to provide cooling and heating for an ever-increasing number of applications. Applications include space heating and cooling, water heating, crop drying, agricultural greenhouses, government housing facilities, etc. The primary advantage of the underground source/sink when compared to the air source is that the underground environment can have a more moderate temperature swing than the ambient air temperatures and therefore a positive thermodynamic advantage. This advantage of tapping the underground thermal source sometimes comes at a higher first cost and must be offset by reduced operating costs, which give a lower life cycle cost. Secondary advantages include improved performance of heat pumps with water as the working fluid (instead of air) and lower maintenance costs.

GSHP systems were originally utilized primarily for residential buildings. Electric utilities played a strong role in supporting training programs and in some cases provided grants to homeowners in order to reduce first cost. In locations where markets were developed in the early 1980’s the residential market is viable and strong with a well-developed design and installation infrastructure. Marketing is accomplished primarily through manufacturer’s programs. Design methods, installation standards, training and annual conferencing are coordinated with the industry by the International Ground Source Heat Pump Association (IGSHPA).

Installation training for contractors and Certified Geothermal Designer (CGD) programs for engineers are offered as part of IGSHPA's activities.

MARKET GROWTH

Market growth in the U.S. has been steady and quantification comes from American Refrigeration Institute records that track water source heat pump numbers based on requested certification by manufacture's and the U.S. DOE's Energy Information Administration (EIA). There are three ARI certification standards which rate water source heat pumps. The ratings differentiate between intended application for each machine, which are rated for operation as water source [ARI 320], Groundwater Source [ARI 325], and Ground-Source Closed-Loop [ARI 330]. Depending on what percentages of these machines are selected in each standard for ground source application, the numbers of units in-service for ground source installation range from 35,000 to 50,000 units (10kW) per year. (EIA 2000) reported an increase of 28% in geothermal heat pump shipments from 1998 to 1999 of the combined totals of ARI 325 and ARI 330. The worldwide installed capacity and energy produced is estimated (Rybach 2001) to be 6,675.4 MW and 23,268.9 TJ/yr respectively. The U.S. market represents 4,800 MW (about 500,000 units) and 12,000 TJ/yr. of the total worldwide market.

More recently the non-residential market (GHPC 2000) is beginning to dominate in terms of installed capacity. In the US, schools and military housing have had significant growth. The Geothermal Heat Pump Consortium (GHPC 2000) reports over 600 schools in the U.S. use this technology. New "Super-Energy Service Provider Companies (Super-ESPCs)" implemented by the U.S. Department of Energy (DOE 1998) in 1998 allowed for procuring GSHP systems for all federal agencies nation-wide. Projects implemented by the Super-ESPCs are large in scale such as the 4003 residential units at the military base in Ft. Polk, Louisiana. Four "Super-ESPCs" were prequalified in the U. S. to do "Geothermal Heat Pump" business for the federal government.

RECENT DEVELOPMENTS

A number of recent research developments have begun to see application in the field. These include development of hybrid ground source heat pump (HGSHP) systems, improved grouting materials and borehole installation techniques, and short time-step modeling of ground loop heat exchangers (GLHE) and associated components.

Hybrid Ground Source Heat Pump Systems

On an annual basis, many commercial buildings reject significantly more heat to the ground than they extract. This imbalance requires either a very large ground loop heat exchanger (GLHE) or some mechanism for rejecting excess heat must be found. Because the costs of installing a very large GLHE may be excessive, a number of alternative ways of rejecting heat have been evaluated. These include cooling towers and fluid coolers (Yavuzturk and Spitler 2000), ponds (Chiasson et al. 2000a), water heating for gas station car washes (GHPC n.d.), near surface heat exchangers (Smith 2000), parking lot and sidewalk heating (Chiasson et al. 2000b).

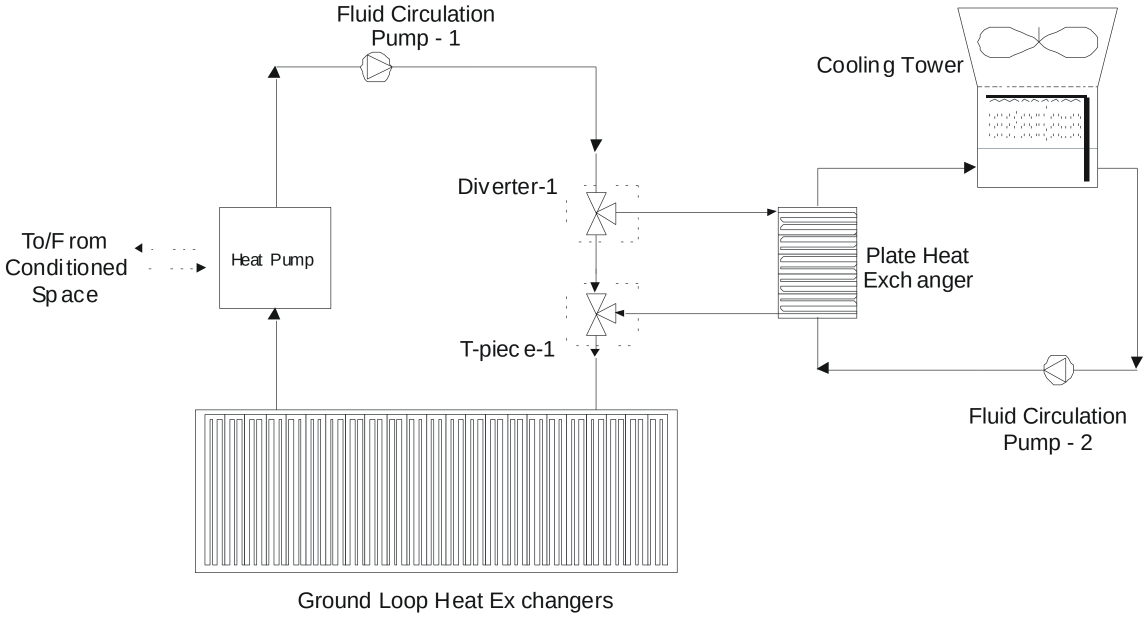

Figure 1 Hybrid Ground Source Heat Pump System with Cooling Tower

In some applications, the imbalance is in the other direction – additional heat must be injected into the GLHE. This might be addressed in a number of different ways, including glazed solar collectors, an idea tried in the 1970's. Two recently described methods involve what might be thought of as low-cost, unglazed solar collectors: concrete heat absorbers integrated with a roof in the Netherlands (van de Ven 1997) and a concrete bridge deck which is heated with hydronic tubing in the winter, but which absorbs heat in the summer (Chiasson and Spitler 2001, Polydynamics Engineering 2000).

Systems that incorporate both a ground heat exchanger and an above ground heat rejecter are commonly referred to as hybrid ground source heat pump (HGSHP) system. Initial implementations of hybrid GSHP systems have used the simplest possible control strategy--switching the cooling tower on when the loop temperature exceeded a set point. However, further study (Yavuzturk and Spitler 2000) has shown that it is possible to reduce both the first cost and the operating cost by operating the supplemental heat rejection in a more optimal manner. As it turns out, a substantial amount of the annual heat rejection may be done in the winter at a lower cost than during hot summer afternoons. This may still be accomplished with relatively simple control systems, say rejecting heat when the difference between the wet bulb temperature and loop temperature exceeds some value for a cooling tower. An initial study for a small commercial building in Tulsa, OK, U.S. resulted in a 20% decrease in ground heat exchanger length. The same building located in Houston, TX had a larger decrease in heat exchanger length because of the greater cooling requirement at that location.

An alternative that will likely have lower maintenance costs is a heat rejection pond. Chiasson, et al. (2000a) showed that the heat rejection pond should have first costs that are lower or similar to a cooling tower, if the cost of the real estate does not represent an extra cost. In a follow-up study, Ramamoorthy, et al. (2001) showed both lower first costs and lower electricity costs compared to the HGSHP systems with cooling towers studied by Yavuzturk and Spitler (2000). Nevertheless, the pond heat rejection system will only be feasible in some situations. Furthermore, both studies only looked at one office building in two locations, with a limited range of control strategies – further work looking at a wider range of buildings, locations and control strategies is needed.

Looked at from another perspective, these systems store “cold” (or, more accurately, availability) in the winter and use it in the summer. Going even farther, there is the possibility of earth energy storage systems that do this, or the converse, and utilize the energy directly, either without the benefit of a heat pump, or using the heat pump only for heating. At the Terrastock 2000 conference (Benner and Hahne 2000), held in Stuttgart, Germany, several such applications were presented, including cooling of telecommunications stations and district heating. Another recent application is used to prevent preferential icing on a bridge deck (Polydynamics Engineering 2000) in the Swiss Alps. A similar project (Chiasson and Spitler 2001) is underway in the U.S. See Figure 2.

Short Time Step Modeling

To the extent that some advances have been made in understanding hybrid GSHP systems, they have only been possible due to the application of system simulation. While many heating and cooling systems may be adequately designed without the aid of system simulation, it is difficult or impossible to adequately design a hybrid GSHP system without some form of system simulation. Whereas building heating loads are generally calculated considering only a peak hour, and building cooling loads are generally calculated considering only a peak day, the hybrid GSHP system requires consideration of a whole year, at a minimum. At the least, the ground loop heat exchanger requires an annual simulation, and ideally, all of the components are simulated together. This puts a premium on automating the heat transfer analysis in the form of component models.

In the last several years, component models have been developed for ground loop heat exchangers (Yavuzturk and Spitler 1999), ponds (Chiasson, et al. 2000a), pavement heat rejecters (Chiasson, et al. 2000b), and water-to-water heat pumps (Jin and Spitler 2002). When coupled with existing models of pumps, piping, cooling towers, etc. in environments such as TRNSYS (SEL 1997) and HVACSIM+(Park, et al. 1985), the entire system may be simulated for a number of years to investigate long term performance.

Grouting and Borehole Design

For a number of years, the most commonly used borehole design in North America has been the single high-density polyethylene U-tube grouted with bentonite grout. This design protects aquifers from contamination and is very reliable. However, it leaves much to be desired from a heat transfer performance standpoint, as the grout is a significant thermal resistance. Some work has been done to investigate higher conductivity grouts (Remund 1999), (Kavanaugh and Allan 1999), and (Smith and Perry 1999) and several varieties are commercially available in North America.

Figure 2 Geothermally Heated Bridge Deck at Oklahoma State University.
Above: Before concrete has been poured with hydronic tubing visible.
Below: Near the end of a 200 mm snow fall in December of 2000,
with heated portion in foreground

Primarily in Europe, some work has been done to optimize the piping configuration (Hellström and Kjellson 2000), such as using two U-tubes and co-axial tubes. Experimental investigations have been done at OSU on pipe spacing clips (Nash 1998) which force the two legs of the U-tube out against the borehole wall. Thermal response tests for five boreholes, with different combinations of grout and clip spacing are shown in Figure 3. Each test had the same heat input and significantly enhanced performance (i.e. significantly lower temperature rise) can be seen with the use of thermally-enhanced grout and spacer clips. The impact of this change in resistance on a ground loop heat exchanger design is variable—in one design where the annual heat rejection and extraction are relatively balanced, and peak loads are high, the use of thermally enhanced grout and spacer clips can allow a 30% reduction in the total borehole length, compared to the standard installation.

Comparison of Borehole Heat Transfer for Five Grout and Pipe Configurations
Oklahoma State University T&F Building Loop Field

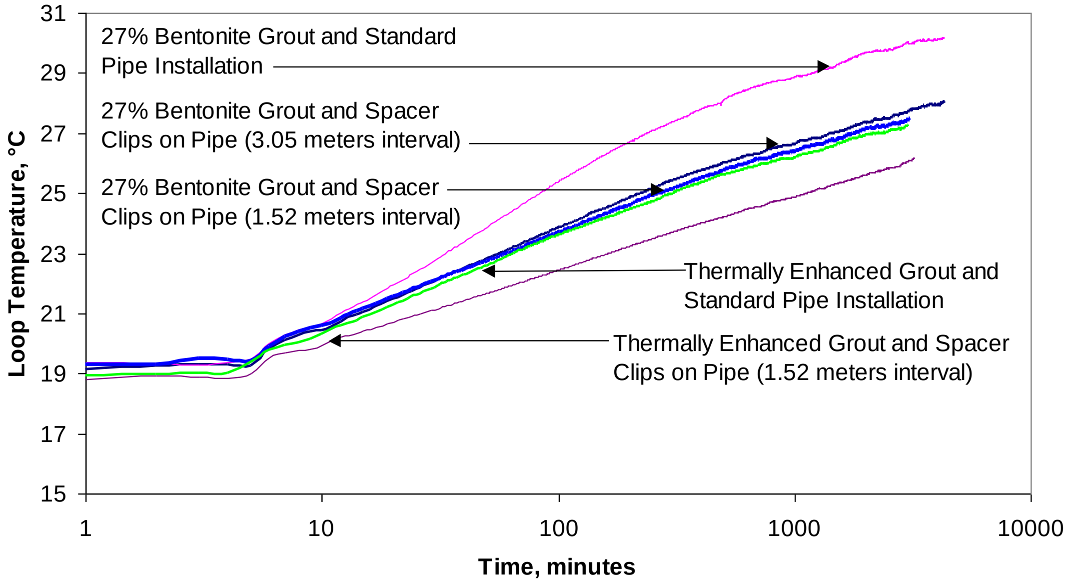

Figure 3. Ground Heat Exchanger Loop Performance Comparisons

In Situ Measurement of Ground Thermal Properties

For design and simulation of ground loop heat exchangers used in ground source heat pump systems, the ground thermal properties are important input parameters. Both ground loop heat exchanger design tools and the simulation models rely on some estimate of the ground thermal conductivity and volumetric specific heat. This estimate is critical to the design, yet it is very difficult to make. The required borehole depth or length is highly dependent on the thermal properties of the ground.

The traditional approach to estimating the ground thermal properties has been to first ascertain the type (or types) of soil or rock that surrounds the borehole. Once the type of soil or rock is determined, its thermal conductivity can be estimated from tabulated data, such as that contained in the Soil and Rock Classification for the Design of Ground-Coupled Heat Pump Systems Field Manual (EPRI, 1989). Since thermal conductivity values for ground formation types are reported in the literature within a rather broad range of values, a method for more accurately estimating the ground thermal conductivity is highly desirable.

Such a method, referred to as an in situ thermal conductivity test or a thermal response test, infers the ground thermal conductivity from the temperature response caused by imposing a constant heat pulse on a test borehole. Since a test borehole is required, this method is commonly used only for larger commercial systems, where the potential savings justifies the cost of the test borehole and experimental measurement. Mogensen (1983) described the concept of using such a measurement to estimate the ground thermal conductivity. Subsequently, development of an experimental apparatus began in 1995 at Oklahoma State University and was described by Austin (1998). The experimental apparatus is shown in Figure 4, at a test site in Lincoln, Nebraska. Simultaneously and independently, a similar apparatus was developed by Eklof and Gehlin (1996).

Figure 4. In Situ Test Apparatus on Site in Lincoln, Nebraska

A range of analysis procedures, all of which inversely estimate the ground thermal conductivity from the temperature response to a heat pulse have been developed. These include methods based on the line source model (Mogensen 1983; Gehlin 1998; Witte, et al. 2002), cylindrical heat source model (Kavanaugh and Rafferty 1997), or a numerical algorithm (Shonder and Beck 1999; Spitler, et al. 1999; Austin, et al. 2000).

General recommendations for performing the test can be found in Austin (1998) and Martin and Kavanaugh (2002). One contentious issue has been the required length of the test for sufficient accuracy. Commercial contractors generally prefer shorter tests, typically less than 18 hours. Researchers have generally recommended longer tests, from 36-72 hours in duration.

Design Software

A number of software tools for design ground heat exchangers have been developed and are currently in use around the world. These tools are able to size the ground heat exchanger to meet user-specified minimum and maximum heat pump entering fluid temperatures for a given set of building loads, ground thermal properties, borehole configuration, etc. These include EED (Hellström and Sanner 2000), GchpCalc (Kavanaugh n.d.), GLDesign (Peterson 2000), GLHEPRO (Spitler 2000), and GS 2000 (Morrison 1997).

OTHER DEVELOPMENTS

Despite the importance of the above-described research in lowering life cycle costs and broadening applicability of ground source heat pump systems, a number of developments have come from outside the academy. These include:

- Faster, lower cost pipe-joining methods: stab, socket fittings, and electro-fusion
- New pumping configurations: variable-speed, multiple pumps in parallel, and zoned on-off circulator pumps sharing a common ground heat exchanger

NEEDED RESEARCH

In order to continue lowering the life cycle cost and broadening the applicability of ground source heat pump systems, additional research is needed in the following areas:

- Develop computationally efficient methods for simulating ground loop heat exchangers. Although some work has been done on vertical borehole heat exchangers, little or no work has been done to model short time-step behavior of horizontal systems, where interaction with the aboveground environment is important.
- Continue development of more cost-effective borehole heat exchangers.
- Develop lower cost methods for estimating ground thermal properties. Currently available methods take longer and are more expensive to perform than would be ideal for widespread commercial utilization.
- Development of design methodology that incorporates system simulation, allowing the simultaneous interactions between the building systems, supplemental heat rejecters, and ground loop heat exchanger to be resolved.
- Develop optimized fluid pumping systems configurations and controls to reduce installation and operating costs. Central station pumping, while convenient from a maintenance standpoint may not be optimal for distributed individual heat pump installations.

To summarize, there are a wide variety of potential applications of earth energy storage. Many of the applications are economically feasible today, and many more may be feasible in the near future, with refinements in system design made possible by the thoughtful application of heat transfer engineering.

TECHNOLOGY TRANSFER ACTIVITIES

Although the research developments described above are important, a number of other activities are important in transferring the technology to the field. These include:

- Installation workshops for contractors who specialize in residential programs. These are offered by IGSHPA and others certified by

IGSHPA to offer training in its "Train the Trainer" program. There are currently over 45 certified trainers.

- Certified Geothermal Designers training is offered by IGSHPA and the Association of Energy Engineers (AEE 2002) for engineers and other designers of commercial applications.
- Marketing conferences for presentation on new technology and applications. IGSHPA is conducting one marketing-oriented conference per year.
- Technical conferences to present research and application improvements and promote installation standards. IGSHPA is also conducting one three-day technical conference per year.
- The Annual World Energy Engineering Conference, sponsored by the Association of Energy Engineers, has included a significant number of presentations at recent meetings on ground source heat pump systems.
- The American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE) is offering professional development seminars and short courses on ground source heat pump system design.
- ASHRAE has also recently published several relevant books: "Operating Experiences with Commercial Ground-Source Heat Pump Systems" (1998), "Ground-Source Heat Pumps - Design of Geothermal Systems for Commercial and Institutional Buildings" (1997), and has a forthcoming book entitled "Geology and Drilling Methods for GSHPs: An Introduction for Engineers".

CONCLUSIONS

"The three important constraints for increased use of heat pumps are initial cost, lack of awareness and knowledge among architects and installers, and the relative low temperatures that can be achieved using heat pumps. – Ms. Hanneke van de Ven, IEA Heat Pump Centre." While the last constraint is primarily a problem for retrofit of hydronic heating systems, the first two constraints seem to be universal. In addition to high initial costs caused by overdesign, cost over-runs on loop installations can also be a problem. (Barakat and Chamberlin 1997)

The research and development efforts described in this paper have primarily addressed reduction of first cost, either through improved performance (e.g. thermally-enhanced grouts, hybrid systems, etc. which allow smaller, less costly ground exchangers) or through more accurate design analyses done with design software and supported by in situ measurements.

The technology transfer efforts have significantly improved awareness of architects and engineers. Arguably, a great deal of additional work needs to be done before ground-source heat pump systems are regularly utilized in all applications and parts of the world where they make economic and environmental sense.

ACKNOWLEDGEMENTS

Research funding sources at Oklahoma State University that have supported much of the work described above include the following:

- American Society of Heating Refrigerating and Air-conditioning Engineers
- Electric Power Research Institute

- National Rural Electric Cooperative Association
- State of Oklahoma, Department of Commerce
- US Department of Energy
- U.S. Department of Transportation

REFERENCES

Austin,W. A. 1998. Development of an In-Situ System for Measuring Ground Thermal Properties. Master's thesis. Oklahoma State University. Stillwater, Oklahoma. (Also available at http://www.mae.okstate.edu/Faculty/spitler/Austin_thesis.pdf.)

Austin, W.A., C. Yavuzturk, J.D. Spitler. 2000. *Development of an In-Situ System for Measuring Ground Thermal Properties.* ASHRAE Transactions Vol. 106(1):365-379.

Barakat & Chamberlin. 1997. "Geothermal Heat Pump Profitability in Energy Services" Prepared for U.S. Department of Energy, Idaho Operations Office by Barakat & Chamberlin, Inc. Dallas, TX. DOE/ID10878 November 1997

Benner, M. and E.W.P. Hahne, Editors. Proceedings of Terrastock 2000, The 8th International Conference on Thermal Energy Storage. August 28-September 1, 2000. Stuttgart, Germany. See http://www.itw.uni-stuttgart.de/terrastock/.

Chiasson, A.D., J.D. Spitler, S.J. Rees, M.D. Smith. 2000a. *A Model for Simulating the Performance of a Shallow Pond as a Supplemental Heat Rejecter With Closed-Loop Ground-Source Heat Pump Systems.* ASHRAE Transactions. 106(2):107-121.

Chiasson, A.D., J.D. Spitler, S.J. Rees, M.D. Smith. 2000b. *A Model for Simulating the Performance of a Pavement Heating System as a Supplemental Heat Rejecter With Closed-Loop Ground-Source Heat Pump Systems.* ASME Journal of Solar Energy Engineering. November 2000. 122(4):183-191.

Chiasson, A. and J.D. Spitler. 2001. *Modeling Approach to Design of a Ground-Source Heat Pump Bridge Deck Heating System*. Transportation Research Record 1741:207-215.

EIA (USDOE Energy Information Administration) 2000. Survey of Geothermal Heat Pump Shipments, Renewable Energy Annual 2000, http://www.eia.doe.gov

Eklof, C. and S. Gehlin. 1996. TED – A Mobile Equipment for Thermal Response Test. Master's Thesis 1996:198E. Lulea University of Technology, Sweden.

EPRI. 1989. (Bose, J.E., Editor) Soil and Rock Classification for the Design of Ground-Coupled Heat Pump Systems—Field Manual. Electric Power Research Institute Special Report, EPRI CU-6600.

(GHPC 2000), Numerous case studies of GSHP systems applied to commercial buildings may be found at the website of the Geothermal Heat Pump Consortium: http://www.ghpc.org/

Gehlin, S. 1998. Thermal Response Test, In-Situ Measurements of Thermal Properties in Hard Rock. Licentiate Thesis, Luleå University of Technology, Department of Environmental Engineering, Division of Water Resources Engineering. 1998:37.

GHPC. n.d. *Case Study: Conoco's "Skunk Creek" Service Station, Sandstone, Minnesota.* Available online at: http://www.ghpc.org/commercial/com_conoco.htm

Hellström, G. and E. Kjellson. 2000. Laboratory Measurements of Heat Transfer Properties for Different Types of Borehole Heat Exchangers. Proceedings of Terrastock 2000, Stuttgart, Germany, August 28-September 1. Vol. 1, pp. 183-188.

Hellström, G. and B. Sanner. 2000. Earth Energy Designer User Manual, Version 2.0. More information about EED may be found at: http://www.buildingphysics.com/earth1.htm.

Jin, H. And J.D. Spitler. 2002. *A Parameter Estimation Based Model of Water-To-Water Heat Pumps for use in Energy Calculation Programs*. ASHRAE Transactions. 108(1). In Press.

Kavanaugh, S. P. and K. Rafferty, 1997, Ground-Source Heat Pumps, Design of Geothermal Systems for Commercial and Institutional Buildings, Atlanta: ASHRAE

Kavanaugh, S.P. and M.L. Allan. 1999. Testing of Thermally Enhanced Cement Ground Heat Exchanger Grouts. ASHRAE Transactions. 105(1):446-450.

Kavanaugh, S.P. n.d. Designing Vertical Ground-Coupled Heat Pumps with GchpCalc Version 4.0. Available on-line at: http://www.geokiss.com/software/Ver40_Instructions.PDF. Additional information on GchpCalc may be found at http://www.geokiss.com/software.htm.

Martin, C.A. and S.P. Kavanaugh. 2002. Ground Thermal Conductivity Testing—Controlled Site Analysis ASHRAE Transactions. 108(1). In press.

Mogensen, P. 1983. Fluid to Duct Wall Heat Transfer in Duct System Heat Storages. Proceedings of the International Conference on Subsurface Heat Storage in Theory and Practice. Swedish Council for Building Research. June 6-8.

Morrison, A. 1997. GS2000 Software. Proceedings of the Third International Heat Pumps in Cold Climates Conference, Wolfville, Nova Scotia. August 11-12, 1997. pp. 67-76. Additional information about GS2000 may be found at: http://greenbuilding.ca/gs2k-1.htm.

Nash, R. 1998. U.S. Patent No. 6,000,459.

Park, C., Clark D. E., Kelly G. E. 1985. An Overview of HVACSIM+, a Dynamic Building/HVAC/Control Systems Simulation Program. Building Energy Simulation Conference, Seattle, Washington. August 21-22, 1985.

Peterson, B. 2000. http://www.geocities.com/tagusaku/physics/GLDesign/gldesignindex.html

Polydynamics Engineering. 2000. http://www.polydynamics.ch/e/r_d/page_e_serso.htm

Ramamoorthy, M. H. Jin, A. Chiasson, J.D. Spitler. 2001. Optimal Sizing of Hybrid Ground-Source Heat Pump Systems that use a Cooling Pond as a Supplemental Heat Rejecter – A System Simulation Approach. ASHRAE Transactions. 107(1): 26-38.

Remund, C. 1999. Borehole Thermal Resistance: Laboratory and Field Studies. ASHRAE Transactions. 105(1):439:445

Rybach, L. 2000. Status and Prospects of Geothermal Heat Pumps (GHP) in Europe and Worldwide; Sustainability Aspects of GHPs, Institute of Geophysics ETH, Zurich, Switzerland: 85-100.

Shonder, J.A. and J.V. Beck. 1999. Determining Effective Soil Formation Thermal Properties from Field Data Using a Parameter Estimation Technique. ASHRAE Transactions. 105(1):458-466.

Smith, M.D., R.L.Perry. 1999 *Borehole Grouting:Field Studies and Thermal Performance Testing*. ASHRAE Transactions. 105(1):451-457.

Smith, M. Real-World Trial of Shallow Heat Exchanger Technology. Proceedings of the World Energy Engineering Congress. October 25-27, 2000. Atlanta. pp. 173-180.

Spitler, J.D., S.J. Rees, C. Yavuzturk. 1999. More Comments on In-situ Borehole Thermal Conductivity Testing. The Source. 12(2):4-6. March/April 1999.

Spitler, J.D. 2000. GLHEPRO -- A Design Tool For Commercial Building Ground Loop Heat Exchangers. Proceedings of the Fourth International Heat Pumps in Cold Climates Conference, Aylmer, Québec. August 17-18, 2000. Available on-line at: http://www.hvac.okstate.edu/pdfs/HPCC_GLHEPRO.pdf Additional information about GLHEPRO can be found at: http://www.mae.okstate.edu/glhepro.

Solar Energy Laboratory (SEL), University of Wisconsin-Madison. 1997. TRNSYS, A Transient Systems Simulation Program, User's Manual, Version 14.2.

Van de Ven, H. 1997. International Energy Agency Newsletter, Volume 15, No. 2/1997, P 29

Witte, H., G. van Gelder, J. Spitler 2002. In-Situ Thermal Conductivity Testing: A Dutch Perspective. ASHRAE Transactions. 108(1). In press.

Yavuzturk, C., J.D. Spitler. 1999. *A Short Time Step Response Factor Model for Vertical Ground Loop Heat Exchangers*. ASHRAE Transactions. 105(2):475-485.

Yavuzturk, C., J.D. Spitler. 2000. *Comparative Study to Investigate Operating and Control Strategies for Hybrid Ground Source Heat Pump Systems Using a Short Time-Step Simulation Model.* ASHRAE Transactions. 106(2):192-209.

.

Additional Information

Air-Conditioning & Refrigeration Institute (ARI), 4301 N. Fairfax Drive, Suite 425, Arlington, VA 22203, USA, phone: (+1) 703-524-8800, fax: (+1) 703-528-3816, e-mail: ari@ari.org

GSHP Installation Specifications can be downloaded from the following website: http://www.eren.doe.gov/femp/financing/specs.html