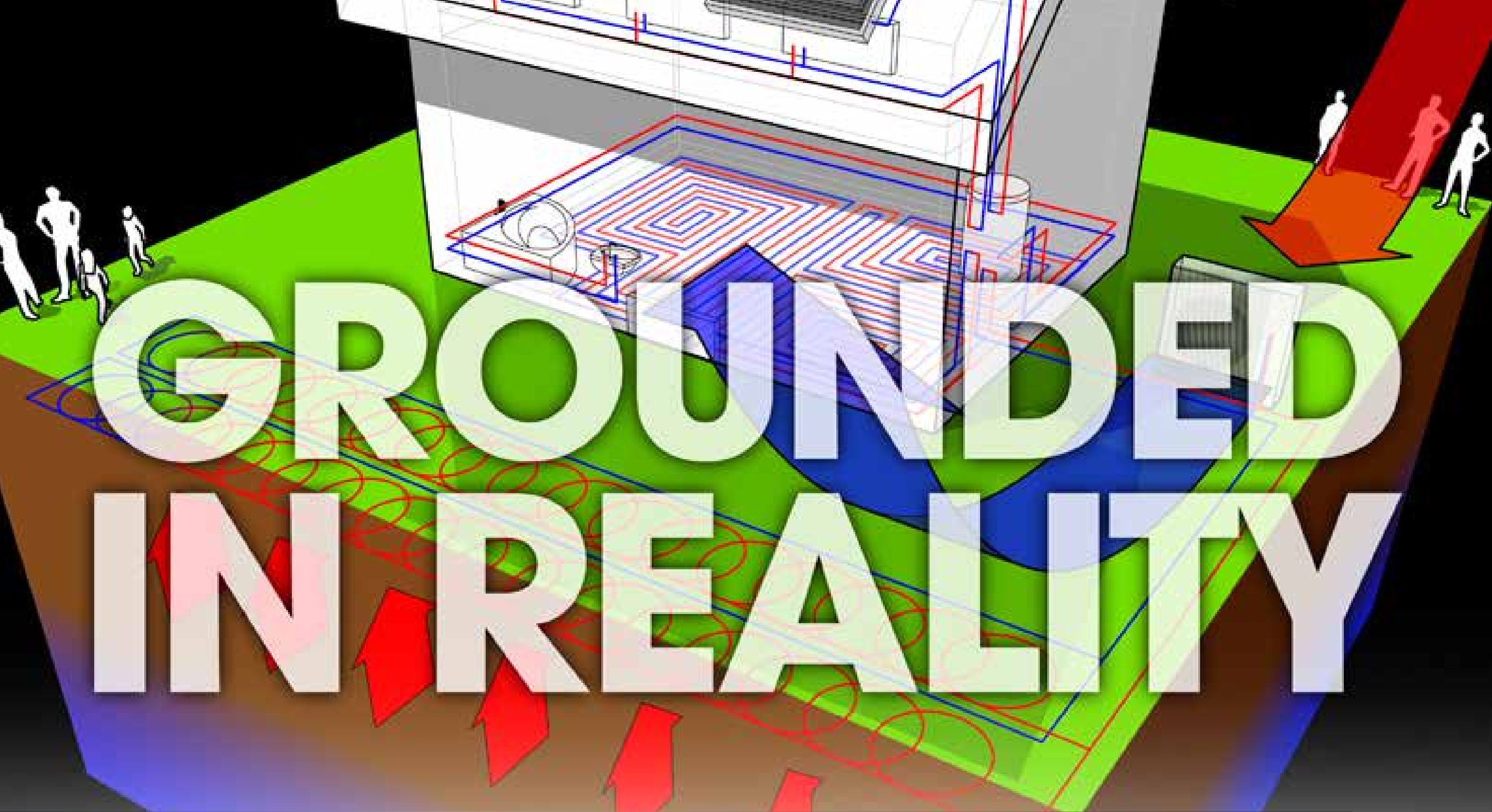
GROUNDED IN REALITY



Why do ground loops in moist soils sometimes perform better than expected? What ground loop design tactics can address building system imbalance? Engineers need to take more responsibility for their full GSHP designs, and these questions are a good place to start.

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With a little guidance on ground-source heat pump design temperatures and a few rules of thumb for ground loop flow rates, most engineers are pretty comfortable designing the building side of a ground-source heat pump (GSHP) system. However, many of these same engineers are intimidated by the ground heat exchanger design and often entrust the design to others; "others" could be a mechanical contractor, the heat pump manufacturer, a pipe supplier, or even a software vendor.

A good ground heat exchanger (GHE) design will pay for itself over time and can improve overall system efficiencies with simple design and control approaches, usually beating out more traditional mechanical systems in lifecycle cost comparisons. A 2011 survey on the long-term performance of commercial building GSHPs found the cost of the ground heat exchanger to be 26% of the total system cost, with the remaining 74% attributed to inside the building costs (equipment, piping, controls, etc.). When compared to results of surveys conducted in 1995 and 2000, the ground heat exchanger cost has risen 52% since 1995 while the interior building cost has risen 177% (Kavanaugh, et. al. 2012).

As with any "new" technology, it is important to become educated in the theory behind its application. It is also good to review design information available within the industry. For GSHP system design, chapter 34 of the 2015 *ASHRAE Applications Handbook* is a good starting point. This is in addition to understanding the thermal properties of the soil or formations in which the GHE will be installed and how the GHE and surrounding soil formation interact. Among the key issues to consider are the annual GHE load balance (or more commonly imbalance) and the impact of soil moisture content.

UNDERSTANDING BUILDING SYSTEM IMBALANCE

One of the biggest debates in GSHP research and development is how to predict the imbalance in the heating and cooling loads of a building and that imbalance's impact on the long-term temperature gain of the formation surrounding the GHE. This is more easily understood graphically. Figure 1 shows the hypothetical seasonal energy usage by a balanced building. (The gold line is the heat produced or removed by the heat pumps, and the magenta line is the heat "seen" by the ground heat exchanger).

Think of the soil or formation surrounding the GHE as a giant thermal storage system. In the summer, heat from the building is deposited into the storage system, and in the winter it is withdrawn. Depending upon the geographical location of the building, it could be heating-dominated (withdrawing more heat than it deposits) or cooling-dominated (depositing

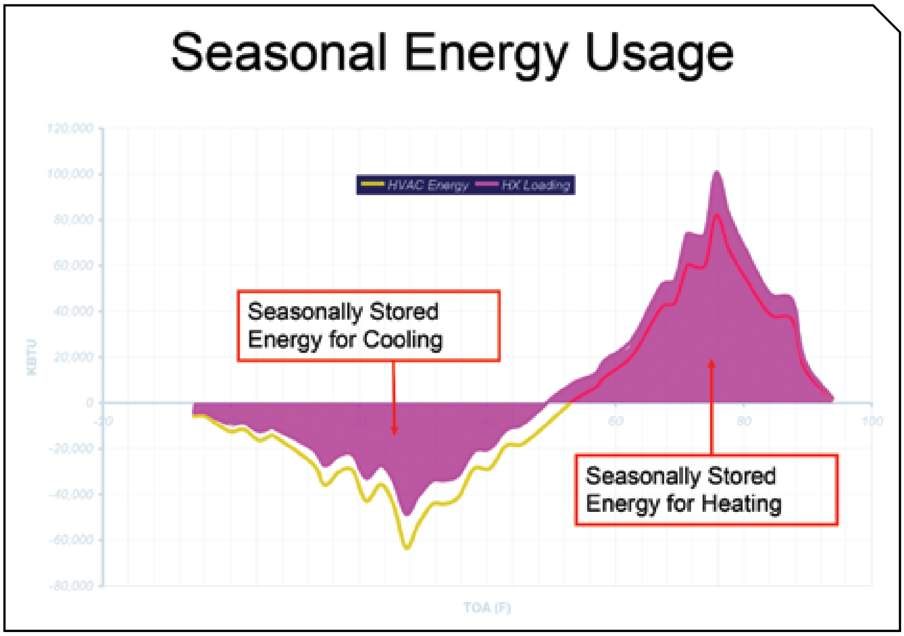

FIGURE 1. Hypothetical seasonal energy usage by a balanced building.

more heat than it withdraws). The focus of this article is specific to the latter. For heating-dominated buildings connected to a GHE, the behavior of moisture in soil is different and is not discussed here.

In addition to the base loads for heating and cooling of the building, the efficiency of the ground source heat pump factors into the seasonal energy usage. For example, a nominal 1-ton heat pump provides 12,000 Btuh of heating to a building. At specific design conditions, and a coefficient of performance (COP) of 4.0, this example heat pump withdraws 9,000 Btuh from the ground and the remaining 3,000 Btuh is contributed by the heat from the heat pump compressor. During heating, 75% of the heat required by the building is coming from the ground. A 1-ton heat pump provides 12,000 btuh of cooling capacity with an energy efficiency ratio (EER) of 13.6. In this case, the ground receives 15,000 Btuh total; 12,000 Btuh from the building and 3,000 Btuh from the heat pump compressor. During cooling, an additional 25% of heat is deposited into the ground or our giant thermal storage system.

Even for the ideal building (Figure 1), which has equal numbers of equivalent full load hours in both heating (AEFLHh) and cooling (AEFLHc) annually, there is an imbalance in what the ground "sees" due to the compressor heat of the ground-source heat pump as well as other likely performance differences between heating and cooling due to the temperatures involved. This becomes heat stored that must be addressed by good design.

So what to do? Experienced engineers know that this situation can be handled with reasonable pipe sizing, spacing, length, and right-size pump selections for the ground loop water distribution system. Ground loop size can be adjusted for the anticipated temperature creep or penalty. As mentioned previously, the debate in the industry is HOW MUCH is the creep and when does the ground heat exchanger become ineffective? With good design, the answer to this question is "never." Inexperienced engineers don't take the time to understand how the ground heat exchanger functions and may tell their clients that, "the ground loop may get too hot and will have to be abandoned after 20 years." Yikes! For the investment any building owner makes in an energy-efficient ground-source heat pump system, this is NOT the right answer.

GROUND LOOP SIZING TOOLS

Depending upon the type of building planned for connection to a GSHP system, there are a variety of tools available to assist the engineer in designing the GHE. For residential and light commercial buildings there are equations in the International Ground Source Heat Pump (IGSHPA) *Ground Source Heat Pump Residential and Light Commercial Design and Installation Guide* (Remund, 2009).

Some heat pump manufacturers and third-party software providers use these equations in their software. For commercial buildings more rigorous calculations are required. Two different approaches (G-factor and G-function) to these heat exchanger calculations are presented in the *ASHRAE Handbook* (ASHRAE, 2015). Depending upon the approach and tools used by the engineer, the analysis may provide very different results. It is important that the engineer understand the basis of their calculations and evaluate their results based on empirical data. This is very challenging for an inexperienced engineer because there is very little empirical data available on this topic. Why is that?

AN 80-YEAR-OLD PROBLEM

As early as 1932, researchers were trying to understand the impact of moisture in soils. Chapter 4 of the *CRREL Monograph 81-1, Thermal Properties of Soils* is an excellent resource for gaining a better understanding of the complexities of this phenomenon because it reviews and categorizes much of the research in 1981 on the topic into a format more usable to practitioners.

Because of the complexity of how moisture in soil behaves, heat transfer is difficult to predict. Due to this challenge, many of the current software tools available to design engineers do not consider the additional potential cooling effect of moist soil resulting from phase change from liquid to vapor (thus taking a very conservative approach). This occurs when soil moisture levels are reduced as a result of heat input when heat is rejected from the building into the GHE. This is not a new problem. In fact, researchers have been struggling to understand how moisture levels in soil affects soil strength and thermal properties for highway construction and electric power distribution systems for almost a century.

FIGURE 2. Thermal properties tester (photo courtesy of GRTI).

Two software packages, GshpCalc and Loop Link Pro, do consider this effect by bounding the results between formations with high and low porosity. All software packages recognize that to calculate the results with high precision is impossible given the inability to determine the soil and moisture characteristics at great depths coupled with the uncertainty of rainfall.

"It is the primary aim of science to reduce the areas in which only the specially gifted can achieve success to place them more in the realm of scientific organization and reproducibility. Unfortunately, the very complexity of most soil systems renders them unattractive to the pure scientist and makes significant experimental study quite expensive (Winterkorn, 1962)."

To understand the combined moisture and heat transfer in soils caused by temperature gradients, the conductivity of the soil must first be determined. In reviewing the aforementioned CRREL document (Farouki, 1981), it becomes clear that this task (at that time) had a +/-25% accuracy. It is also assumed that that the soil in question has been tested or has nearly identical makeup to one which has been tested and in situ density and moisture content are accurately known. Today, to eliminate some of the inaccuracies from not knowing the soil properties on GSHP projects requiring 20 tons or larger vertical GHE, a formation thermal properties (TP) test can be performed (Figure 2).

The TP test provides information on the formation (drill log) and the deep earth temperature, average conductivity, and diffusivity. This is information required by all software programs to perform the required ground heat exchanger calculations. For TP test run at the higher end of the recommended test duration (48 hours), the short-term cooling effect due to the moisture in the soil within 6 in of the bore is somewhat accounted for.

"In addition to the upward geothermal heat flow, the soil near the earth's surface is subject to continuously varying temperature gradients, particularly due to the diurnal and seasonal cycles. The daily reversal of the temperature gradients in the soil furnishes an unceasing source of energy that causes heat and moisture transfer (Farouki, 1981)."

Temperature fluctuations induced at the surface of the ground heat exchanger pipe influence the phase and condition of water in the surrounding soil. "Variations in temperature therefore disturb the equilibrium, or accentuate the disequilibrium, and give rise to water movement," (Farouki, 1981). This movement can occur by a variety of mechanisms, some or even most of which may take place simultaneously. These mechanisms include latent heat transfer; vapor convection; and combined-series, vapor-liquid water transfer which is an evaporation-condensation mechanism (Philip and De Vries 1957).

In a nutshell, moisture in soil may be present in the soil in liquid, vapor, or solid form. The amount of energy available in water in moist soils is not accounted for in the current approach to ground heat exchanger design. It is energy that may be used on an annual basis (assuming replenishment by annual rainfall) to improve ground heat exchanger performance beyond the current theoretical computer models used to predict ground heat exchanger performance. This is why ground loop systems that have been designed for a temperature range of, say, 45-90°F never reach the outer limits of their design range, and on the flip side, this explains why some computer models predict that a ground loop system will overheat in 20 years!

SAMPLES & EXAMPLES

Case in point, several schools in Austin, TX have been operating for over 15 years with formation temperatures at 71°F. The successful operation of these GHEs comes from the engineer's knowledge of the local formations (limestone), and understanding of the cooling-dominated buildings' operation and energy trends (Green, 2015).

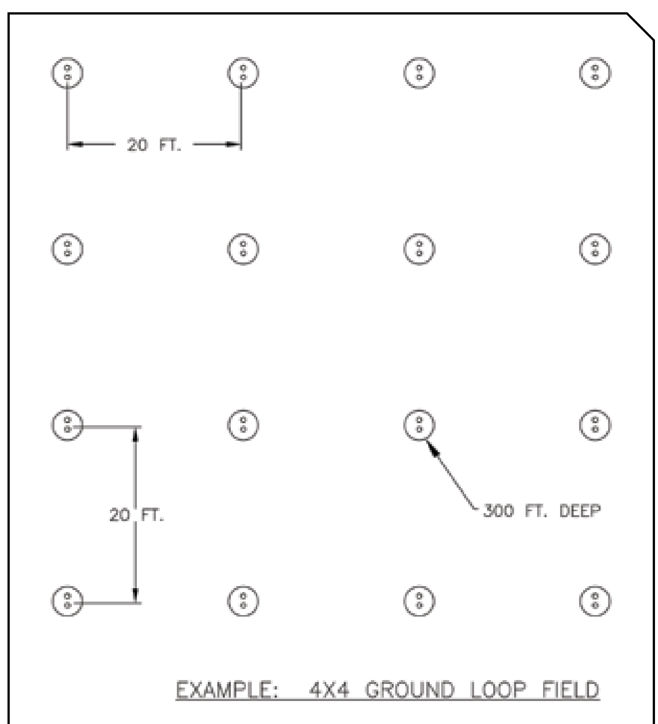

FIGURE 3. Ground loop field layout for example.

While the moist soil behavior above really pertain more to near surface soil and not the majority of the soil in contact with a vertical GHE, an example of how this may be extended to the deep soil in contact with a vertical GHE follows.

Example: A 4x4 ground heat exchanger at 20 ft centers supports a small office building with a nominal 16-ton load. Assume 1 borehole = 1 ton of load for this project located in Sacramento, CA. The soil is silty clay with gravel and a soil moisture content by weight at 5%.

- Density of the soil, ρ_s= 115-151 lb/ft^3 (use average of 133 lb/ft^3)
- Deep earth temperature, T^g = 68°F
- Specific heat, c^p= 0.26-0.27 Btu/lbm°F (clay)
- Density of water, ρw= 62.3 lb/ft^3 (70°F)

How much heat is required to increase the average ground loop field by 1°F?

ρg= 133 lb/ft^3 x 0.95 + 62.3 lb/ft^3 x 0.05 = 136.1 lb/ft^3 (Note that moisture fills voids, no new added volume)

c_{pg} = 0.26 Btu/lbm°F x 0.95 + 1.0 Btu/lbm°F x 0.05 = 0.297 Btu/lbm°F

Volume of the ground loop field = 80 ft x 80 ft x 300 ft = 1.92 x 10^6 ft^3

Q = V x ρg x cpg x (Ti – To) = 1.92 x 10^6 ft^3 x 136.1 lb/ft^3 x 0.297 Btu/lbm°F x 1° F = 7.76 x 10^7 Btus

Now, how much heat is required to reduce the total moisture content in the ground loop field by 0.5%?

mg = 1.92 x 10^6 ft^3 x 136.1 lb/ft^3 =2.61x10^8 lbm

mw= 2.61x10^8 lbm x 0.005 = 1.31 x 10^7 lbm

Q= mw x hfg (@68°F) = 1.31 x 10^7 lbm x 1055.12 Btu/lbm = 1.38X10^9 Btus.

Note: 1.38X10^9 Btus/ 7.76 x 10^7 Btus = 17.8

(Where hfg is the enthalpy during moisture vaporization.)

Long-term change occurs in the larger GHE as is shown in the previous example. Vapor migration occurs much more forcefully than liquid movement. In this case, the heat required to the soil by 0.5% moisture content is over 17 times as much heat to raise the temperature of the formation by 1°F.

Another way to look at this is that if this example assumes each borehole represents 1 ton of annual cooling (1,000 AEFLHc and 300 AEFLHh), the amount of annual heat rejection to the formation is as follows.

16 bores x 12,000 btush-bore x 1,000 hrs of cooling x 1.25 (adjusted for EER and heat rejection) = 1.92x10^8

1.38x10^9/1.92x10^8 = 7 times the amount of energy rejected from the building each year!

With reasonable rainfall, this source of cooling may be replaced if portions of the formation are porous. The evaporative cooling effect is significant compared to the thermal capacity of the ground although the amount of impact has not been thoroughly studied (Kavanaugh and Rafferty, 2014).

As noted previously, the change within 6 in of the bore is more a short-term phenomenon, which to some degree is accounted by the TP test if it is allowed to operate for at least 48 hours. Vapor migration occurs much more forcefully than liquid movement. There is, however, a tipping point where the increase in temperature near the borehole results in the moisture content dropping to a point where the formation thermal conductivity takes a nosedive. This is a major reason for designing for larger bore separation, to prevent this from happening before the heating season begins and moisture is drawn or flows back into the formation. This caution is echoed by Salomone, where it is noted that excessive moisture migration will drive down the thermal conductivity of granular soils and porous formations (Salomone and Marlow, 1989).

So where does this leave us? While the intention of this article is not to give the design engineer free license to design for higher GHE temperatures or the impetus to run away from GSHP system design, it is meant to explain why there are differences in computer software model results and explore why certain design practices such as good borehole spacing are beneficial. It is also intended to provide recommendations and support for continued research and development, including increasing the pool of empirical data available to practitioners. While one might assume that the upper end of the borehole may have local water replenished in the soil near the top of the borehole, it is unclear what happens at depths of 200 ft or 500 ft. Further research into the presence of moisture in the soil, and how it impacts heat transfer generally and vertically through the soil, will be of particular interest.

CONCLUSIONS

While GSHP systems are not a "new" technology, its more frequent application on net zero and LEED buildings may be new to many engineers and building owners. In summary:

- Engineers need to know their subject, including the best application for any technology employed. There are some applications in which vertical GHEs may not be the best option (locations with high ground temperatures and/or low moisture content, cooling-only applications, etc). This might be indicated by software computer models where project design data is reasonably accounted.
- Engineers need to take single-point responsibility for their designs and not leave portions of it to others. The GSHP equipment inside the buildings needs to be designed in collaboration with the GHE (outside of the building) for the system to operate efficiently and as sold to the building owner.
- Engineers need to understand the theory behind the tools they use for design. Garbage in is garbage out. Results of computer analysis need to be scrutinized and checked for accuracy.
- Engineers of GSHP systems need to recognize that from a heat transfer perspective for a GHE the ground cannot be assumed to be infinite and act as an infinite heat sink/source. An understanding of how the building's imbalance in cooling impacts the engineer's choice of borehole spacing, pipe size, depth, design flow rate, and grout selection are all very important variables in good GHE design.

In addition to the conclusions above, it is recognized by many in the HVAC industry, and reaffirmed here, that the GSHP industry still has a lot of work to do. There is a strong need to collect field data on the long-term temperature effect on ground heat exchanger performance. **ES**

REFERENCES

1. 2015 *ASHRAE HVAC Applications Handbook*, ASHRAE, Atlanta, GA.
2. Kavanaugh, S.P., M. Green, and K.T. Mescher. 2012. "Long-Term Commercial GSHP Performance, Part 4: Installation Costs", ASHRAE Journal, Atlanta, Vol. 54, No. 10.
3. Remund, C. *Ground Source Heat Pump Residential and Light Commercial Design and Installation Guide*, International Ground Source Heat Pump Association, Oklahoma State University, 2009.
4. Farouki, O. CRREL Monogram 81-1 "Thermal Properties of Soils," United States Army Corp of Engineers Col Regions Research and Engineering Laboratory, Hanover, NH, 1981.
5. Phillip J.R. and D.A. DeVries. 1957. "Moisture Movement in Porous Material under Temperature Gradients," Transactions of the American Geophysical Union, vol. 38., p. 222-232.
6. Winterkorn, H.F. 1962. "Behavior of Moist Soils in a Thermal Energy Field" Ninth National Conference on Clays and Clay Minerals, Purdue University, Lafayette, Indiana. Pergamon Press.
7. Green, M. 2015. Telephone interview, January 15.
8. Kavanaugh, S.K, and K. Rafferty. 2014. "Geothermal Heating and Cooling – Design of Ground-Source Heat Pump Systems," ASHRAE, Atlanta.
9. Salomone, L.A. and J. I. Marlowe, Soil and Rock Classification for the Design of Ground-Coupled Heat Pumps, EPRI CU-6600, Electric Power Research Institute, Palo Alto, CA, 1989.

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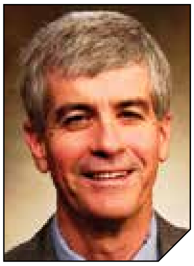

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