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Geothermal Heat Pumps—Simply Efficient

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ABSTRACT

The paper provides a historical perspective of geothermal heat pump technology as it evolved in the United States. It discusses the development and impact of materials specifications, equipment specification, design tools, system performance benchmarks, codes and standards, and public outreach from a variety of entities that have combined to result in design approaches by trusted engineering professionals and building owners. This paper explores the pivotal waypoints in the development of the industry over the past 70 years. It also presents examples of simple and efficient installations, both residential and nonresidential, and the design of ground-source heat pumps, which are one of the best pathways to achieving net zero energy buildings and homes.

INTRODUCTION

Geothermal heat pump technology in the United States evolved for the most part from residential applications to larger commercial/institutional applications in the last 30 years. In addition to evolving in terms of project scale, the dominant system type also moved from groundwater systems in the early days to ground-coupled systems currently. There were growing pains over the course of this evolution, and the mature technology of today is the beneficiary of the contributions of key individuals and several organizations over the years.

HISTORY OF GEOTHERMAL HEAT PUMP DEVELOPMENT IN THE UNITED STATES

Early development of the heat pump originated in Europe during the 1800s. The first patent for an electrically driven ground-source heat pump was issued to Heinrich Zoelly by the Swiss patent office in 1912 (Zogg 2008). Three decades later, post-World War II, dozens of research projects involving laboratory investigations and field monitoring were undertaken by U.S. electric companies on ground-source heat pump system installations (Spitler 2005). During this same time period, the first commercial geothermal heat pump (GHP) installation in the United States was implemented in the Commonwealth Building in Portland, Oregon in 1946. The building is listed on the National Register of Historic Places administered by the National Park Service. It is also designated as National Historic Mechanical Engineering Landmark #46 by ASME (1948). The ASME History and Heritage Committee bestowed this landmark status for the specific feature of being the first large commercial building in the US to pioneer the use of heat pumps for heating and cooling.

Residential GHP applications began circa 1948 with the first open-loop version introduced by Professor Carl Nielsen of Ohio State University (Gannon 1978). Ohio State continued to research and publish on groundwater heat pump systems into the 1980s. Water-source heat pump technology was well established, but the challenge was how to best accommodate the ground heat exchange—with a closed-loop system or with an open water well system. Several issues arose with closed-loop heat exchanger development, which caused installations to cease and research to wane. Specific challenges included problems with the soil drying out around horizontal ground-loop heat exchangers, leakage, and under-sizing. In the 1970s came the oil crisis and with it a renewed interest in GHP technology and a focus on experimental testing. Through this effort, several of the issues identified in the 1940s were addressed. In addition, some open-loop systems, in operation

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for many years, began to experience problems associated with water quality, thus providing additional incentive for the development of closed-loop systems.

The ground heat exchanger component of a geothermal heat pump (GHP) system eliminates the need for outdoor equipment and gives architects and engineers the opportunity to provide a truly sustainable system by exchanging energy with the earth, a large body of water, or an aquifer. When correctly applied, the GHP system is the most energy-efficient HVAC system available. This has been documented by the U.S. Environmental Protection Agency (EPA) report *Space Conditioning: The Next Frontier*, which the industry regularly cites (L'Ecuyer et al. 1993). Because of this study, in 1995 the EPA established the ENERGY STAR® HVAC Equipment Labeling Program. The program is designed to identify and promote energy efficient residential HVAC technologies, including GHPs.

While the U.S. Department of Energy (DOE) and universities continue to provide research on GHP system designs and materials, several engineers within ASHRAE have worked to develop widely recognized design tools and benchmarks that engineers use today to provide efficient and cost-effective designs. These include, among others, Kavanaugh and Rafferty (2014a) and Mescher (2009). The latter discusses an approach to piping design that lends itself well to district geothermal systems and to retrofits or renovations. A more complete list of contributors is listed in Chapter 34 of *ASHRAE Handbook—HVAC Applications* (ASHRAE 2015).

ASHRAE

The current technical committee TC (6.8), Geothermal Heat Pumps and Heat Recovery Application, began in the late 1970s or early 1980s as a Special Project Committee (SPC) with the primary mission of writing a chapter in *ASHRAE Handbook*. At that time, Gene Culver from the Geo-Heat Center at Oregon Institute of Technology (OIT) and Gordon Reistad from the Mechanical Engineering Department at Oregon State University were the key players in developing the chapter, focusing on a paper they had published through ASME in 1977 about their research into the performance and operation of downhole heat exchangers. This work appeared in the 1982 *ASHRAE Handbook—Applications* as Chapter 56. The origins of the current technical committee are rooted in this work and geothermal direct use applications.

In the early 1990s, individuals interested in GSHPs joined TC 9.4, Applied Heat Pump Systems. Increased participation by heat pump practioners was created when Lew Pratsch at the US DOE Geothermal Office took an interest in the technology (and provided funding for research). At this time "geothermal heat pump" terminology came into wide use, and it was around this time that the technical content relative to ground-source heat pumps (GSHP) began to be included in the ASHRAE Handbook chapter on Geothermal Utilization. In the 1995 edition of the chapter, the TC focused for the first time on categorizing the different types of GSHPs, including ground-coupled, groundwater, and surface water applications. It is important to note here that the industry uses several different names (e.g., geothermal heat pumps, ground-source heat pumps, ground-coupled heat pumps) to reference the same technology and it often causes confusion to building owners, thus led to the creation of a section on terminology for inclusion in the ASHRAE Handbook chapter (ASHRAE 2015). During this period there was also a lot of discussion about who would own the ground-source technical content: TC 6.8 or TC 9.4. To resolve this, the decision was made that TC 6.8 would handle everything outside the building and TC 9.4 would cover everything inside the building (Rafferty 2018). This was the tipping point for the committee to become what it is today with most of the content focused on ground-source applications and very little on direct use.

In 2010, with dwindling membership in TC 9.4, it was proposed that the two TCs recombine, which has produced the current structure of the TC covering both the handbook chapters on Geothermal and on Heat Pump and Heat Recovery Applications.

Oklahoma State University (OSU) and International Ground-Source Heat Pump Association (IGSHPA)

The primary focus of the 1970s development of closed-loop GSHPs at Oklahoma State University (OSU) was for residential buildings. The school is located 25 miles from a major trenching machine factory and 100 miles from where high density polyethylene (HDPE) was discovered (for more information, see http://www.cpchem.com/en-us/company/loc/Pages/Bartlesville.aspx). The area is largely rural with many homes located on large lots. Thus, the natural evolution of the technology was toward unitary equipment and horizontal ground heat exchangers. Some early loops were made of PVC pipe, polybutylene, and a few with copper. The durability, ease of installation, cost, availability, and local expertise of thermally fused HDPE soon won the day. The National Rural Electric Cooperative Association was a major supporter of this early work, providing funding for research and the first design manuals.

In 1978 OSU received a DOE grant for a project entitled "DOE Solar Assist." Key industry developments that ensued from the ongoing research include the use of in place, or *in situ*, formation thermal properties testing, the development of manuals for design and installation of GSHP systems, improvement of thermal grouts, the use of polyethylene pipe and heat fusion joining, the development of slinky heat exchangers, and software design programs for both commercial and residential applications (Bose 2018). From OSU, the International Ground-Source Heat Pump Association (IGSHPA) was formed in 1987. IGSHPA is an association for companies, professionals, and users dedicated to promoting the science, benefits, and use of geothermal (ground source) heating and cooling technology.

In 2009, the IGSHPA *Ground Source Heat Pump Residential and Light Commercial Design and Installation Guide*

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was updated, incorporating more than 20 years of research and development to the substantial revision (Remund 2009). The Electric Power Research Institute and the Department of Energy also made major contributions to the geothermal research efforts of IGSHPA and OSU.

Geothermal Exchange Organization (GEO)

The Geothermal Exchange Organization (GEO) is the reincarnation of the former Geothermal Heat Pump Consortium (GHPC), a Department of Energy/Utility and GSHP industry partnership started in 1994 (GEO 2011). During the first six years of operation, the GHPC enjoyed significant funding from the DOE Geothermal Technologies Program, electrical utilities, and geothermal heat pump industry members. The funding provided many things, including five regional training centers, a design assistance program for building owners, informational workshops, video productions, and a newsletter called *Outside the Loop*. The GHPC also partnered with IGSHPA and the Association of Energy Engineers (AEE) to create a Certified GeoExchange Designer Program. When utility restructuring took place and funding from the DOE ended in 1999–2000, the GHPC repurposed itself to focus on advocacy and outreach. The current organization remains in operation as a nonprofit whose objective is "to advance the geothermal heat pump industry through public policy advocacy, public relations, communications, branding, consumer acceptance, coordination with utilities and renewable and alternative energy advocates, and related efforts, with the primary goals of removing market barriers and promoting industry standards, training, certification and accreditation programs" (GEO 2011).

Texas Roots

In 1982, a small pilot program to install geothermal heat pumps at Manchacha Elementary in Austin, Texas was partially funded by a major heat pump manufacturer . At that time there was little research available, so rule-of-thumb recommendations for the ground loop were employed with guidance from the GHP manufacturer: 240 ft/ton (40.6 m/kW) per installed heat pump capacity for the boreholes, 10 ft (3 m) spacing in a single row, and cuttings used for borehole backfilling. The Austin Independent School District (AISD) facility director, Bob Lawson, was pleased with the results of the pilot project and began implementing the technology in several school additions and HVAC renovations within the district. Several engineering firms in the Austin area were hired by AISD to do this work. With the experience of the pilot project behind them, engineers began specifying that the boreholes be filled with pea gravel and sand, and shortly thereafter switched to grouting from the bottom up. Many of the early pea gravel and sand backfilled projects east of Interstate 35 (I-35) are still in operation due to the high water table. Pea gravel and sand in a borehole with water has much better heat transfer capability than (dry) pea gravel and sand alone. This is because the presence of water increases the conductivity of the U-bend assembly through the borehole to the surrounding earth. This high water table east of I-35 resulted in numerous ground-loop pipes being pushed up out of the boreholes when not immediately backfilled. Concrete caps to seal the boreholes often disappeared overnight due to the pea gravel and sand backfill settling and poor backfill procedures causing bridging. Experience during this pioneering time in Austin resulted in several improvements to the ground loop portion of the systems.

Over a few years, the boreholes placed at 10 ft (3 m) centers and 240 ft/ton (40.6m/kW) started to overheat, particularly on projects where the connected heat pump was more than 5 tons (17.6 kW) and bores were arranged in a grid pattern rather than a single row. Subsequent boreholes were placed at 15 ft (4.6 m) centers and eventually developed to the current practice of 20 ft (6.1 m). Loop depths were also increased to 300 ft per ton (50.8 m/kW).

Unfortunately, drillers often would use cuttings as backfill rather than bentonite and would shorten the loops when drilling became difficult. Because the U-bend at the bottom of each loop was field fabricated and was believed to the main cause of loop leakage, this led to manufacturers incorporating a factory fused U-bend and prefabricated standard loops lengths of 240 and 300 ft (73.2 and 91.4 m). Printing loop lengths on the pipe was also included, thus facilitating loop length confirmation by installers and engineers.

It was also discovered during this period that many of the schools had begun to implement this technology for kitchens, libraries, gymnasiums, cafeterias, offices, etc., and the runtimes in these occupancies were much higher than the classrooms due to a dramatic increase in after-hours programs and community use. Additionally, large heat pumps of the period had much lower cooling efficiencies and were connected to vertical bores arranged in grid patterns. This resulted in the overheating of the ground loop and the setting the vertical grid spacings to be at least 20 ft (6.1 m).

In 1999, Mike Green with MEP Engineering was interviewed for industry newsletter *Outside the Loop*, which was at that time sponsored by the Geothermal Heat Pump Consortium. In the interview he was asked about his experience with the technology. It was during this interview that the key features and benefits of the technology were praised, and those same features and benefits hold true today: the systems had almost no callbacks or problems because they were so simple. "Rarely was there a time I had to go back and solve a problem with a geo system, which was totally unlike all the other complex systems we had been designing" (Kavanaugh 1999).

For this reason, one school district, Leander Independent School District (LISD), committed to the technology early and have been enthusiastic proponents ever since. This ever-expanding school district has 6 high schools, 7 middle schools, and 27 elementary schools with GHP systems. In 2009, LISD started participating in the ENERGY STAR program. In 2010, they entered all their facilities that had been operational for a minimum of a year into ENERGY STAR. Their average

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GSHP school score was a 97. Four of their elementary schools scored 100. After extensive research into the ENERGY STAR Certified Building and Plant locator site, it was discovered that there were only a handful of school districts that had more than four schools having a score of 100 for that year, and they were all in California. LISD has a philosophy of continued improvement, verification of results, and keeping it simple, which has enabled the engineers to make design and performance improvements for each successive school.

BEST PRACTICES FOR GEOTHERMAL HEAT PUMP SYSTEMS DESIGN

The Evolution of GSHP Best Practices for Larger Buildings

The transition from residential to the commercial/institutional building segment was slow. Many applications lacked enough acreage to accommodate adequate horizontal ground heat exchanger lengths. Early on, the vertical heat exchangers developed for small residential lots were influenced by water well technology that incorporated large diameter (4 to 6 in. [100 to 150 mm]) a closed PVC casing with a smaller inner pipe to supply fluid ot the bottom of the heat exchanger. Unfortunately, leaks were common, so the transition was made to smaller diameter HDPE U-bend assemblies.

The transition was also slowed due to the absence of design guides for larger buildings and, for this reason, many engineers often avoided the technology. However, many early adopters of successful residential GSHP applications were passionate and pushed for the implementation in larger buildings. Some engineers acquiesced to clients' wishes or demands, and a few of the early designs resulted in success. However, many of the designs were not successful, and the energy and maintenance savings were often insufficient to justify the added cost.

There is no guarantee that connecting heating and cooling equipment to a ground, groundwater, or surface water heat exchanger will result in an efficient and low-maintenance system. While the attention of failed nonresidential GSHPs often focused on the exterior portion of the system, frequently the heating, cooling, and auxiliary equipment inside the building was inappropriate. To remedy this rather than just concentrating on the reasons for failures, best practices evolved from studying GSHPs that performed well by reducing energy and maintenance costs but had modest installation cost premiums.

Nonresidential GSHP design approaches can be grouped into two main paths:

1. Apply conventional central HVAC technology but replace the cooling tower, boiler, or outdoor heat exchanger with a ground loop, groundwater heat exchanger, or surface water coil.
2. Apply successful residential-like practices to each zone of larger buildings. Examples of this would be unitary or subcentral ground-loop configurations.

While neither approach is universally superior, many of the most successful applications have followed the latter path with continuing modifications to accommodate requirements of larger buildings. The energy savings associated with this approach are related to the elimination of auxiliary fan and pump operations that are absent in unitary system designs. The energy savings with the first approach is limited since the cooling performance of systems with an affordable GSHP heat exchanger compared to one with a cooling tower or fluid cooler will be modest. Maintenance savings can be realized with a well installed closed-loop GSHP system. The installation cost premium should be the difference between the GSHP heat exchanger and cooling tower/ boiler cost.

The potential of the second path can be seen in the results of the 2012 Commercial Building Energy Consumption Survey (www.eia.gov/consumption/commercial/data/2012/c&e/cfm/c4.php). Buildings with all types of heat pumps consumed less site energy (75.9 kBtu/ft^2 [239 kWh/m^2]) than buildings with central chillers (108.7 kBtu/ft^2 [343 kWh/m^2]), economizers (102.2 kBtu/ft^2 [322 kWh/m^2]), building automation systems (100.1 kBtu/ft^2 [316 kWh/m^2]), and district chilled water and heating networks (140.0 kBtu/ft^2 [442 kWh/m^2]). Since the surveyed heat pump equipment was primarily air source, the advantage of GSHP equipment should be significant. Maintenance savings should also be realized due to the absence of exposed outdoor equipment and single packaged factory-charged units.

Note the use of the phrases "can be" and "should be" in the preceding paragraphs. Much like computer-based simulation results, these opinions are conjecture, not fact. The mantra of the National Comfort Institute expresses the approach well: "If You Don't Measure, You're Just Guessing™" (https://www.nationalcomfortinstitute.com/).

GSHP Performance Measured

A project to measure the long-term performance of commercial GSHP was cosponsored by the Electric Power Research Institute (EPRI), the Southern Company (SoCo), and the Tennessee Valley Authority (TVA). In the project energy use, electrical demand, equipment specifications, heat exchanger design, ground-loop temperatures, occupant satisfaction ratings, ENERGY STAR ratings, and installation costs were assembled for 40 sites. A summary of the results appeared in a series of seven *ASHRAE Journal* articles between July 2012 and February 2013 (Kavanaugh and Kavanaugh 2012; Kavanaugh and Meline 2013).

Sufficient information was available for 25 of the buildings to determine the ENERGY STAR rating. Figure 1 shows the results for the twelve buildings that attained a rating above 90 (Kavanaugh and Kavanaugh 2012). The buildings under the heading One-Pipe Loop are 1950s vintage elementary schools in central Illinois retrofitted with GSHPs that incorporate on-off circulator pumps activated with the compressors of water-to-air heat pumps. These pumps extract liquid from a central distribution pipe and return it downstream. A central

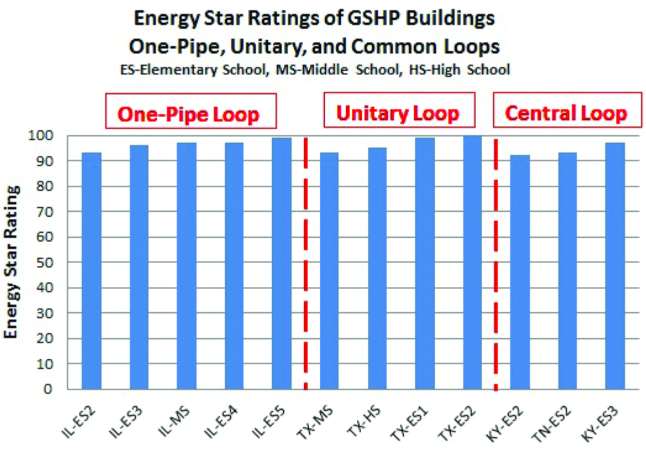

Figure 1 *Highest ENERGY STAR results for GSHPs in 2011–12 Survey (Kavanaugh and Kavanaugh 2012).*

loop pump provides flow continuously through the building and a vertical ground heat exchanger loop while the secondary pumps at each heat pump provides flow to the heat pump on demand. The One-Pipe Loop system is a type of primary-secondary piping system.

The buildings listed under the Unitary Loop heading are schools constructed between 1998 and 2003 with GSHP systems comparable to common residential design. Each classroom and office is conditioned by a water-to-air heat pump, which is connected to an individual vertical ground heat exchanger loop. Water flow is provided by an on-off circulator pump. Large spaces are conditioned by air-cooled equipment. Ventilation air is delivered via dedicated outdoor air systems (DOASs) with energy recovery units (ERUs) supplemented by air-cooled equipment.

The buildings listed under the Central Loop heading are two older schools built in 1926 and 1941 and a new school (KY-ES3) constructed in 2007. All buildings are heated with unitary water-to-air heat pumps connected to a central vertical ground heat exchanger network. The older schools have variable-speed drive pumps, and the new school has on-off circulator pumps on each unit. Ventilation air is provided by DOAS units connected to water-to-water heat pumps.

Thirteen Steps to Low Energy GSHPs with Low Cost Premiums

The design approach for the successful buildings in the survey followed alternatives recommended in the ASHRAE publication *Geothermal Heating and Cooling: Design of Ground-Source Heat Pumps Systems* (Kavanaugh and Rafferty 2014a). The text provides more detail than the following summary. A 13 step procedure emphasizes simplicity as the means to high efficiency, low maintenance, and low installation cost premiums.

The steps are:

1. Calculate peak zone cooling and heating requirements and provide a summary that can be reviewed by building owners and architects.
2. Compare peak loads results to values for high performance building in terms of building floor area per unit of load/loss (ft^2/ton [m^2/kW]) or the inverse load/loss per floor area (Btu/h·ft^2 [kW/m^2]) (Kavanaugh et al. 2006). Provide suggestions to reduce building envelope, lighting, and ancillary loads with estimates of reduction in HVAC and ground-loop costs. Implementation of DOAS with energy recovery units (ERUs) supplemented with GSHP equipment is encouraged.
3. Estimate off-peak, monthly, and annual cooling and heating requirements so that the annual heat addition to and removal from the loop field can be determined to account for potential ground temperature change.
4. Conduct a site survey to determine ground thermal properties and drilling conditions. This may include an *in situ* formation thermal conductivity test by installing a ground heat exchanger, imposing a thermal load, and measuring time versus temperature change (ASHRAE 2015). Results will include undisturbed deep ground temperature, thermal conductivity, and thermal diffusivity. The procedure will also provide valuable formation drilling conditions to potential loop installers.
5. Select the preliminary loop operating temperatures and flow rate to begin optimization of first cost and efficiency. For commercial building applications, the recommended cooling mode entering liquid temperature (ELT) into the heat pump is 20 to 30°F (11 to 17°C) above the deep ground temperature provided in Step 4. Heating mode ELT into the heat pump should be 10 to 16°F (6 to 9°C) below the deep earth temperature. Flow rate should be 2.5 to 3.0 gpm/ton (2.7 to 3.2 lpm/kW). Note: Selecting temperatures near the normal ground temperature will result in high efficiencies but larger and more costly ground loops).
6. Correct heat pump performance at rated conditions to design conditions. The standards for rating water-to-air heat pumps (ISO 1998a) and water-to-water heat pumps (ISO 1998b) do not include corrections for fan and pump power to distribute air and water along with a host of idealized conditions that do not provide comfort in actual applications.
7. Select heat pumps to meet cooling and heating loads and locate units to minimize duct cost, fan power, and noise.
8. Arrange heat pumps into the ground-loop field arrangement (unitary, one-pipe, common loop, or central loop) to minimize system cost, pump energy, and demand.
9. Determine and evaluate possible loop field arrangements that are likely to be optimal for the building and site (bore depth, separation distance, completion methods, annulus grout/fill, and header arrangements). Options include

unitary, one-pipe, and common loop (several circuits in a building with multiple heat pumps on each circuit that serves a section of a large building). Central loops are discouraged in large footprint buildings (i.e., 1 to 3 stories) as interior piping cost and pump power typically offsets cost and power savings. Include subheader circuits (typically 5 to 15 U-bend assemblies on each) with isolation valves to permit air and debris flushing of sections of the loop field through a set of full-port purge valves.

10. Determine ground heat exchanger dimensions. Recognize one or more alternatives (depth, number of bores, grout/fill material, loop field arrangement, hybrid designs, etc.) may provide equivalent performance and yield more competitive bids.
11. Iterate to determine optimum operating temperatures, flows, loop field arrangement, depth, bores, grout/fill materials, heat pump equipment, etc.
12. Layout interior piping and exterior piping network, compute head loss through critical path, and select pump(s) to provide the recommended flow rates. A measure of success for closed-loop GSHPs is a pump motor power of 5 hp/100 tons (10.5 W/kWt), which is recognized as high performance, and 7.5 hp/100 tons (16 W/kWt) is acceptable (Kavanaugh and Rafferty 2014a).
13. Verify system performance of the final design using the system efficiency. If the system cooling energy efficiency ratio (EER) is less than 12 Btu/W·h (COPc < 3.5) or system heating COP is less than 3.5 at design conditions, consider the following options:

    - Modify the water distribution system if pump demand exceeds 15% of the total system demand.
    - Revise the air distribution system if fan demand exceeds 20% of the total system demand.
    - Replace the heat pumps if they do not meet the recommendations listed in the publication by Kavanaugh and Rafferty (2014).
    - Redesign the ground heat exchanger to improve ELTs.

The highly successful closed-loop GSHP system includes a reliable, low head loss, extended length ground heat exchanger. HDPE with 100% thermally fused below grade joints is critical to success. Additionally, HDPE for interior piping has the advantages of low cost and low maintenance, especially for building owners with limited resources for maintenance since pipe corrosion issues are eliminated. Thermally fused fiber-core polypropylene is a higher cost interior option without the large thermal expansion issues of HDPE.

Vertical ground heat exchangers with HDPE U-bend assemblies have been the backbone of the industry for commercial/institutional building GSHPs. Countless individuals have promoted more complex designs and promised dramatic loop length reductions, thus lower drilling cost. This includes a variety of piping materials, multiple pipes, turbulence inducers, and high conductivity “super grouts” in the bore annulus.

None have proven to be better alternatives than single U-bend assemblies when cost, durability, and speed of installation are considered. (Double U-bend assemblies are an alternative in high drilling cost formations.) These alternatives fail to consider that the primary thermal resistance to heat flow is the ground itself. This, coupled with the fact that reduced bore length will increase the potential for long-term ground temperature change because of the reduced thermal capacity of the ground surrounding the shorter loop.

GSHPS AND NET ZERO ENERGY BUILDINGS

The net zero energy building movement has evolved from low-energy building design standards and rating systems through international influences from R-2000 (NRCan 1982), German passive house standards, and others, as the best approach to reducing energy consumption in the United States. From ASHRAE’s Vision 2020: “Buildings consume 40% of the primary energy and 71% of the electrical energy in the United States. Driven by economic expansion and population growth that require more and more facility space each year, energy use in the U.S. commercial sector is expected to grow by 1.6% per year. This is resulting in an energy impact that is increasing faster than all other energy conservation measures being taken and retrofits being made to buildings” (ASHRAE 2007).

Just as there are many different names for geothermal heat pumps, the approach to providing buildings which achieve net zero energy consumption over the course of a year has many different names and definitions. ASHRAE has chosen to define a net zero energy building (NZEB) as “a building that produces as much energy as it uses when measured at the site. On an annual basis, it produces or consumes as much energy from renewable sources as it uses while maintaining an acceptable level of service and functionality. NZEBs can exchange energy with the power grid as long as the net energy balance is zero on an annual basis” (ASHRAE 2007).

A Pathway to Net Zero Energy in Commercial Buildings

A research project (ASHRAE 2016) to determine the maximum energy targets for ultra-low energy use commercial buildings was completed in 2015. Energy simulations were performed for a variety of building construction techniques and HVAC technologies without consideration of cost. A conclusion was that near net-zero energy was possible with a variety of the options if solar photovoltaics (PV) were added.

The most common building type encountered during the EPRI/SoCo/TVA GSHP survey was elementary schools. RP-1651 determined the maximum technically achievable target for primary schools in Chicago is 27.1 kBtu/ft^2•y (85.5kWh/m^2•y) and 25.5 kBtu/ft^2•y (80.4kWh/m^2•y) in Houston. Figure 2 demonstrates these targets have already been achieved with 2006 GSHPs retrofits of 1950 vintage elementary schools 130 miles (210 km) southwest of Chicago and 2008 vintage elementary schools 180 miles (290 km) west of Houston.

Equally important are the relatively low HVAC costs (which include the ground heat exchanger) that are possible. These milestones were achieved with a combination of design engineers who value simplicity and quality, an involved client with high expectations, and experienced ground heat exchanger and mechanical contractors. These low costs make the addition of solar PV more economically feasible. Finally, note the potential for further reduction to achieve net zero energy in Illinois with application to new lower energy construction (compared to 1950s construction) and in Texas with the replacement of large zone and ERU supplement air-cooled equipment with GSHPs.

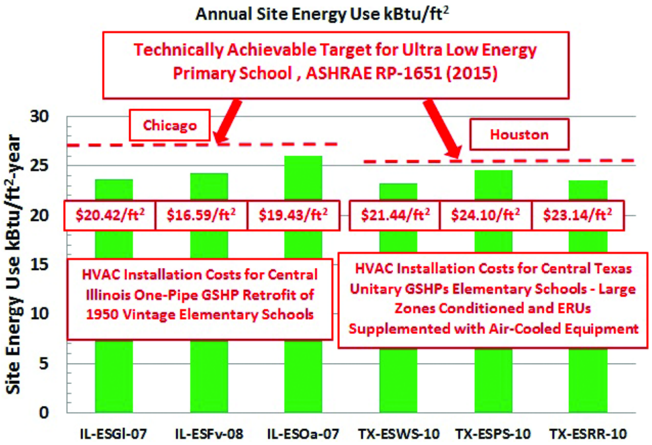

Figure 2 *HVAC costs for GSHPs lower than ASHRAE RP-1651's ultra-low energy target (ASHRAE 2016).*

A Pathway to Net Zero Energy for Multifamily Housing

In a report prepared for the National Multi Housing Council (Newport Partners 2008), the results of a study which evaluated several energy efficiency measures for multifamily apartment buildings in Atlanta, Chicago, and Houston are presented. The goal was to provide energy efficiency measures which would exceed ANSI/ASHRAE/IES Standard 90.1 (ASHRAE 2004) by 15%, 30%, and 50%. The study showed that in two of the locations that very little impact was made by improving building efficiency through improving envelope construction. This was mainly because apartments are high density and already use efficient building systems because of their role in providing affordable housing. For Chicago and Houston, 15% better than Standard 90.1 was achieved through high-efficiency gas furnaces and envelope improvements; however, in Atlanta the only way to get to this 15% improvement was through the use of GHPs. For Chicago and Houston, the installation of GHPs allowed the multifamily apartment buildings to perform more than 30% better than Standard 90.1; however, none of the buildings in this study were able to achieve 50% better.

A Pathway to Net-Zero Energy Homes

Since 2006, the landscape for low-carbon buildings has been transformed, and building with sustainability and high performance in mind has become the standard approach. NZEBs have gone from being prototypes and experiments to being widely built and, in the case of California, being the standard that has been adopted for new residential buildings in 2020.

In California, there are two challenges to overcome for homeowners and developers who want to install a GHP system as part of their strategy for achieving a net zero energy home. The state of California created its own building energy efficiency standard using ASHRAE Standard 90-1975's approach as a basis for design in 1978. Within the compliance algorithms for the software most designers use to prove their buildings comply with this standard, there is poor representation of the true efficiency of a geothermal heat pump. This is primarily due to the California Energy Commission's (CEC) inability to comfortably model the ground heat exchanger in the algorithm from within the organization. The poor representation of the geothermal heat pump is to model it as an air-source heat pump in the compliance software, thereby reducing the opportunity to show true energy savings by a geothermal heat pump in both warmer and colder regions. The second challenge is that there are 58 counties responsible for permitting "ground-heat exchange wells" under the State's Water Code (CWC 1997). Each county applies their own interpretation of the water code, although, as of this date, there is no standard in place in the state of California for its construction.

Despite the challenges facing GHP technology in California, there are several examples for which the technology is successfully paired with PV panels to work toward the state's goal of net zero energy homes. Two case studies are provided here by home builders who were forward-thinking in their projects, employing elements of net zero energy construction strategies prior to the state of California establishing its solar-ready requirements for rooftop PV panels or the current, more stringent mandatory measures. California has 16 different climate zones. The case studies that follow are in Quincy, which is in climate zone 16, high in the northern Sierra Nevada mountains, and in Jamestown, which is in climate zone 12 and borders the great Central Valley in the eastern foothills.

It is important to note here that the most recent California Residential Appliance Saturation Study (CEC 2010) states that for the average single-family home in California, the total electric consumption is 7605 kWh. This is for an average single-family dwelling size of 1882 ft^2 (175 m^2). In the same study, for single-family homes, there is listed a total average natural gas consumption of 425 therms (12,452 kWh). The total annual energy (electricity and gas) consumption for the

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average single family home is 20,057 kWh. This information is provided as a basis for comparing the following data.

Quincy, CA. Quincy is the county seat of Plumas. It sits 3500 feet (1067 m) above sea level and base is listed by the National Oceanic and Atmospheric Administration (NOAA) at 5852 HDD and 500 CDD (65°F [18.3°C]). The summer design day is 93°F (33.9°C) and the winter design day is 10°F (–12.2°C) with record extremes of –24°F to 114°F (–31.1°C to 45.6°C). During design, the homeowner took special care to use construction materials and methods to reduce the heat transfer between the conditioned space and the environment based on experience of building homes in this region over the previous 41 years (Martin 2018). The goal for this homeowner was to achieve a carbonless building that produces as much energy as it needs over the course of a year. The home was completed in 2014 and now has four years of data shared and is summarized in Table 1.

- Home square footage: 3265 ft^2 (303 m^2)
- Heat pump size: 3 ton (10kW) nominal
- Ground loop: Four ¾ in. (1.91 cm) HDPE 800 ft (243.8 m) slinky at 7 ft (2.1 m) depth
- Working fluid: 20/80 methanol/water
- PV array: 7.4 kW AC
- Occupants: 2, retired

Table 1. Quincy Home Four Year Energy Summary

Month	2014 (no PV)	2015 (PV)	2016 (PV)	2017 (PV)
Jan	1957	1052	1451	1653
Feb	1609	699	1062	1312
Mar	1122	138	531	939
Apr	999	–253	–92	376
May	768	–427	–328	–516
Jun	659	–664	–704	–706
Jul	765	–677	–754	–647
Aug	890	–753	–606	–486
Sep	730	–639	–615	–532
Oct	745	–617	–339	–152
Nov	1065	297	293	306
Dec	1157	1053	1061	1057
Net consumption, kWh	12,807	–791	960	2604

Jamestown, CA. Jamestown is a former Gold Rush town and is now a California Historic Landmark. Jamestown is located at 1427 ft (435 m) elevation east of Stockton, CA. The Boulders development in Jamestown provides homes that exceed the state's Building Energy Standards (CEC 2013). The homes use GHPs for heating and cooling and preheating domestic hot water. They also have a 6 kW south-facing PV array on each rooftop. The total heating and cooling days are 3364 and 1100, respectively. While Jamestown is still heating dominated with a winter design temperature of 20°F (–6.7°C), the number of cooling hours are significant and the summer design temperature is 100°F (37.8°C). Energy data for the first homes sold in this development is provided for two lots with the same floor plan. While it hasn't yet been occupied for a year, the data is trending positively. Propane gas is provided for cooking only in these homes.

- Home square footage: 1859 ft^2 (173 m^2)
- Heat pump size: 3.5 ton (12.3 kW) nominal
- Ground loop: Two 1 in. (2.54 cm) HDPE 300 ft (91.4 m) vertical loops
- Working fluid: Water
- PV array: 6.0 kW AC
- Occupants: 1, retired

Figure 3 Slinky loop installation.

During the planning phase of this housing development, it was determined that the total kWh of energy consumed, on average, would be 32% less for these homes than the equivalent home built to the state's minimum Building Energy Standards (CEC 2013). Since the mechanical system and domestic hot-water heating are all electric, a PV array was provided with each home to offset the estimated baseline all-electric consumption for each home. The estimated electrical production required to cover this base load annually is 5905 kWh. The data in Table 2 shows that for the months monitored the PV array is well on its way to meeting this 5905 kWh estimate at 90%* and 76%**, respectively, after the first five months of monitoring.

Table 2 shows the consumption and net generation data provided by the utility company for each month of electrical service. The production value is also provided by the monitoring company and reflects the total gross production of the installed PV array.

Comparing the of 7906 kWh total for Lot 5 to the previously cited CEC study shows that the home is close to the annual average electrical consumption value of 7605 kWh for single-family homes in California. However, since the home is all electric (except for cooking), the total energy consumption of this home is 40% of the 20,0257 kWh total combined (gas and electric) energy use for the average single-family dwelling. Lot 11 used more energy than Lot 5 but is still less than half of 20,057kWh. This case study also illustrates how energy consumption varies from household to household.

CODE AND STANDARD DEVELOPMENT

Since 1997, the *Closed-Loop/Geothermal Heat Pump Systems—Design and Installation Standards* (IGSHPA 2017) have led the U.S. industry in best practices for the ground heat exchanger installation of a geothermal heat pump system. The Standards Committee was initially chaired by Phil Albertson and then Allan Skouby, who chaired the committee for much of its existence and guided it to its most current format and content.

In 2013, the International Association of Plumbing and Mechanical Officials (IAPMO) adopted proposals to include geothermal heat pump systems in the *Uniform Solar Energy and Hydronics Code* (IAPMO 2015). While the code is not as prevalent in the industry as the other Uniform codes, it is the first time a code-writing organization sought to address the technology in a dedicated chapter. The revision to this code was updated, and its new title became the *Uniform Solar, Hydronics, and Geothermal Code* (IAPMO 2018b). Previously, the International Code Committee adopted Section 1210 in the International Mechanical Code to address the installation and testing of ground heat exchanger piping (ICC 2009).

The Canadian Standards Association (CSA) approached several geothermal industry organizations in the United States and Canada during 2013 with the goal of collaborating on a binational standard. The pooling of resources and experts in the US and Canada made good business sense, and a technical committee was formed to revise the then recently published C448 Series-13, *Design and Installation of Earth Energy Systems* (CSA 2013). The binational effort resulted in a collaboration of IGSHPA's standards and the National Groundwater Association's (NGWA) Water Well Construction Standard and its Guidelines for the Construction of Loop Wells for Vertical

Table 2. Jamestown First Year Energy Production

Statement Date	Consumption per Utility Statement, kWh	Net Generation per Utility Statement, kWh	Production Monitored by Solar Co., kWh	Consumption per Utility Statement, kWh	Net Generation per Utility Statement, kWh	Production Monitored by Solar Co., kWh
Sep-2017	1288.00	52.308	(no monitor)	823.000	(no PV)	(no monitor)
Oct-2017	529.060	290.462	(no monitor)	716.190	460.022	(no monitor)
Nov-2017	593.000	178.618	(no monitor)	874.4175	307.529	(no monitor)
Dec-2017	837.479	163.011	(no monitor)	865.934	292.317	(no monitor)
Jan-2018	884.628	101.193	(no monitor)	971.136	180.354	(no monitor)
Feb-2018	744.959	250.205	(no monitor)	979.204	352.916	(no monitor)
Mar-2018	729.369	338.690	(no monitor)	1097.836	343.902	(no monitor)
Apr-2018	560.312	565.680	959	942.008	492.049	1033
May-2018	333.136	713.250	1121	655.585	628.585	1187
Jun-2018	372.810	528.916	1184	749.000	578.010	693
Jul-2018	488.288	528.916	1052	957.156	468.962	502
Aug-2018	545.185	303.169	976			1046
Total	7906.225	4193.005	5292	8808.466	4104.646	4416
	Lot 5		90%*	Lot 11		76%**

Closed-Loop Ground Source Heat Pump Systems (NGWA 2014) and content from Chapter 34, "Geothermal Energy" in *ASHRAE Handbook—HVAC Applications* (ASHRAE 2015). The final document was published as ANSI/CSA C448 Series-16, *Design and Installation of Ground-Source Heat Pump Systems for Commercial and Residential Buildings* (CSA 2016).

Since IGSHPA is not an accredited Standards Development Organization (SDO), a partnership was reached in 2017 between CSA and IGSHPA for further development and support of the binational standard and its future revisions. The updated title of this standard is ANSI/CSA/IGSHPA C448-Series 16, *Design and Installation of Ground-Source Heat Pump Systems for Commercial and Residential Buildings* (2016). IGSHPA will sunset their standards.

The Uniform Mechanical Code (IAPMO 2018a) is currently going through revision and will include a new Appendix F with mandatory language references to ANSI/CSA/IGSHPA C448 (2016).

There are other ANSI and ISO standards related to the geothermal heat pump equipment ratings; however, they will not be covered by this paper.

SUMMARY AND DISCUSSION

In addition to providing a historical perspective of the now mature geothermal heat pump technology, the goal of this paper was to emphasize that the simple efficiency of these systems is what drives their rising popularity in the HVAC industry. For commercial/institutional and residential building, efficiency and energy savings are only realized by applying good design practices through proper equipment selection, reasonably sized open- or closed-loop heat exchangers, simple pumping strategies, and basic controls. The commercial/institutional sector has already proven the economic value of this approach. Applying this technology to a central plant system by removing the cooling tower and installing a ground loop doesn't achieve the same level of efficiency as the simple yet elegant building system designs featured in this paper. It was shown that, for many locations, applying GHP technology with appropriate site electrical generation, and some conservation by building occupants, is one of the best methods for achieving the industry's net zero energy building goals.

As benchmarking efforts continue across the country using tools such as EPA's ENERGY STAR Portfolio Manager (EPA 2018), and as the industry pushes to meet the call for net zero energy buildings, there may be a better way of planning and designing for energy efficiency. Instead of providing energy efficiency by building components, HVAC systems, and lighting, perhaps a holistic building system efficiency approach is a prudent alternative (Kavanaugh et al. 2006). This would begin with minimizing total contributions of envelope heat gains/losses, lighting power density, and plug loads (Btu/h·ft^2 [W/m^2]). The current approach of dictating minimum efficiency for each component would be replaced with a HVAC system efficiency (EER or COP). Buildings with low requirements (Btu/h·ft^2 [W/m^2]) combined with high system efficiency GSHPs will have input power density (W/ft^2 [w/m^2]) values necessary for net zero energy buildings.

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DISCUSSION

Frank Pucciano, Solutions Architect, Schneider Electric, Lilburn, GA: Excellent presentation. A+.

Lisa Meline: Thank you.

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