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Assessment of Hybrid Geothermal Heat Pump Systems

Geothermal heat pumps offer attractive choice for space conditioning and water heating

Technology Installation Review

A case study on energy-efficient technologies

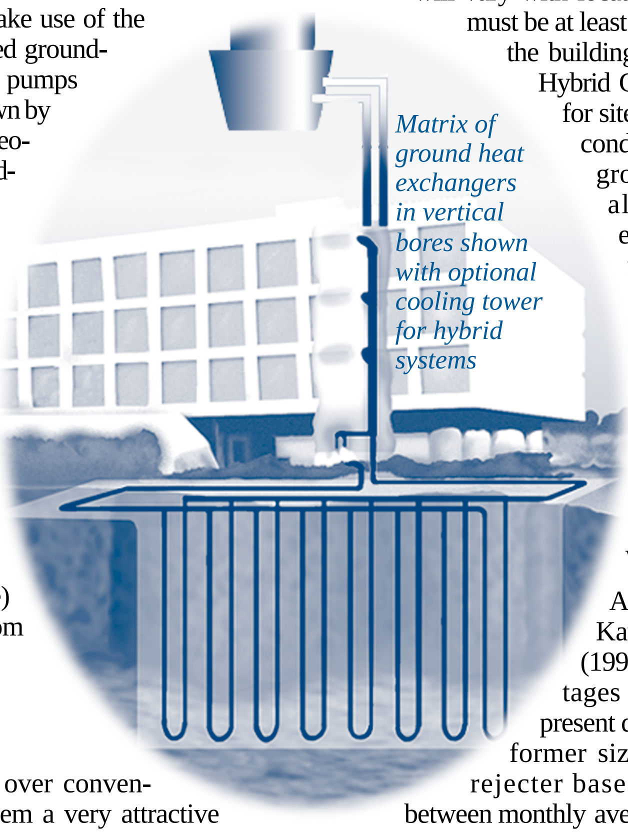
Prepared by the New Technology Demonstration Program

Introduction

The purpose of this *Technology Installation Review* is to provide an overview of hybrid geothermal heat pump systems. It presents the results of recent research on these systems, looks at system types, energy savings, maintenance considerations, and measured technology performance from several examples.

Using the ground as a thermal energy source and/or a heat sink for heat pumps has long been recognized to have a number of advantages over the similar use of ambient air. Ground temperatures at about 3-ft depth or lower are much less variable than ambient air temperatures. Further, soil or rock at these depths is usually warmer than ambient air during the coldest winter months and cooler than ambient air during the summer months. This fact leads directly to cooler condensation temperatures (during cooling operation) and warmer evaporating temperatures (during heating) for a heat pump with consequent improved energy efficiency. It also results in increased heating and cooling capacity at extreme temperatures, thereby reducing or eliminating the need for auxiliary heat.

Heat pump systems that make use of the ground in this way are called ground-source or geothermal heat pumps (GHPs). GHPs are also known by a variety of other names: geo-exchange heat pumps, ground-coupled heat pumps, earth-coupled heat pumps, ground-source systems, ground-water source heat pumps, well water heat pumps, solar energy heat pumps, and a few other variations. Some names are used to describe more accurately the specific application; however, most are the result of marketing efforts and the need to associate (or disassociate) the heat pump systems from other systems.



Matrix of ground heat exchangers in vertical bores shown with optional cooling tower for hybrid systems

Why Hybrid GHPs?

The advantages of GHPs over conventional alternatives make them a very attractive choice for space conditioning and water heating for both residential and commercial/institutional buildings. However, GHPs often have higher first costs than conventional systems making short-term economics unattractive. This disadvantage can be magnified in commercial buildings, many of which have much larger cooling needs than heating needs, especially for buildings located in climates typical of the southern United States. For GHP systems using closed-loop vertical ground heat exchangers, this load imbalance can result in a ground temperature increase over time causing system performance deterioration. Increasing the size of the ground heat exchanger or increasing the distance between adjacent heat exchanger boreholes can postpone the temperature increase problem but will also result in higher system cost. An alternative, lower cost approach for such applications can be use of a hybrid GHP design. In hybrid GHPs, the ground heat exchanger size is reduced and an auxiliary heat rejecter (e.g., a cooling tower or some other option) is used to handle the excess heat rejection loads during building cooling operation. The extent to which the ground heat exchanger size can be reduced in a hybrid GHP system will vary with location and climate, but it must be at least large enough to handle the building heating requirements. Hybrid GHPs can also be used for sites where the geological conditions or the available ground surface will not allow a ground heat exchanger large enough for the building cooling loads to be installed.

A number of recent reports and research papers have been published that deal with both design of hybrid GHPs and operating experience with a few installations.

ASHRAE (1995) and Kavanaugh and Rafferty (1997) both discuss advantages of hybrid GHPs and present design procedures. The former sizes the auxiliary heat rejecter based on the difference between monthly average heating and cooling needs of the building and offers general guidelines for integration of the heat rejecter into the system piping. The latter bases heat rejecter sizing on peak loads at design conditions and the difference between required ground heat exchanger borehole lengths for heating and cooling.

Kavanaugh (1998) revises and extends the design procedures presented in the above two publications. In addition, a control method is proposed for balancing the cooling and heating loads on the ground heat exchanger to limit long-term temperature increase. The revised procedure is applied to an office building in three climates, and first cost and operating cost issues are discussed.

Yavuzturk and Spitler (2000) present a comparative study investigating several control strategies for hybrid GHP systems. The strategies investigated include set point control (operating the auxiliary rejecter whenever the heat pump entering or exiting fluid temperature exceeds a set temperature), differential temperature control (operating the auxiliary rejecter whenever the difference between heat pump fluid temperature and ambient air temperature exceeds a set value), and operation of the auxiliary rejecter to remove heat from the ground heat exchanger field during nighttime hours. The purpose of the last strategy is to use the tower to attempt to balance the annual heat rejection and heat absorption loads on the ground heat exchanger. A 20-year life-cycle cost analysis is conducted to compare each control strategy.

Thornton (2000) performed an analysis of a hybrid GHP for a building at the U.S. Navy's Oceana Naval Air Station. Overall system performance was compared for similar control strategies as studied by Yavuzturk for both 1-year and 10-year performance periods.

A few studies of actual hybrid GHP installations have been reported as well. Phetteplace and Sullivan (1998) describe a system installed in an administration building at the U.S. Army's Fort Polk facility. The paper presents performance data over a 22-month period. Singh and Foster (1998) explore first-cost savings resulting from hybrid GHP designs in two buildings—an office building and an elementary school. Both of these cases are examples of installations where site geological characteristics or surface area limitations precluded use of a ground heat exchanger large enough to handle the total cooling needs.

Technology Description

GHP system types

There are several types of geothermal heat pump systems that can be used for building space conditioning and water heating. The common denominator is that water source heat pumps exchange heat between indoor air (for space heating or cooling) or water (for heating or chilling water) and a liquid (either water or a water-coolant mixture) flowing in a closed loop. The liquid in the closed loop is "conditioned" by exchanging heat with one or more geothermal heat sources or sinks, such as the ground, groundwater, surface water, wastewater streams, or potable water supplies (where allowed). Figure 1 illustrates the various types of geothermal source/sinks that may be used in GHP systems. Hybrid GHP system designs using outdoor air as a supplement heat sink can be configured with any of these GHP source/sinks. Figure 2 is a schematic illustration of a hybrid GHP using a closed loop vertical ground heat exchanger and a cooling tower as an auxiliary heat rejecter.

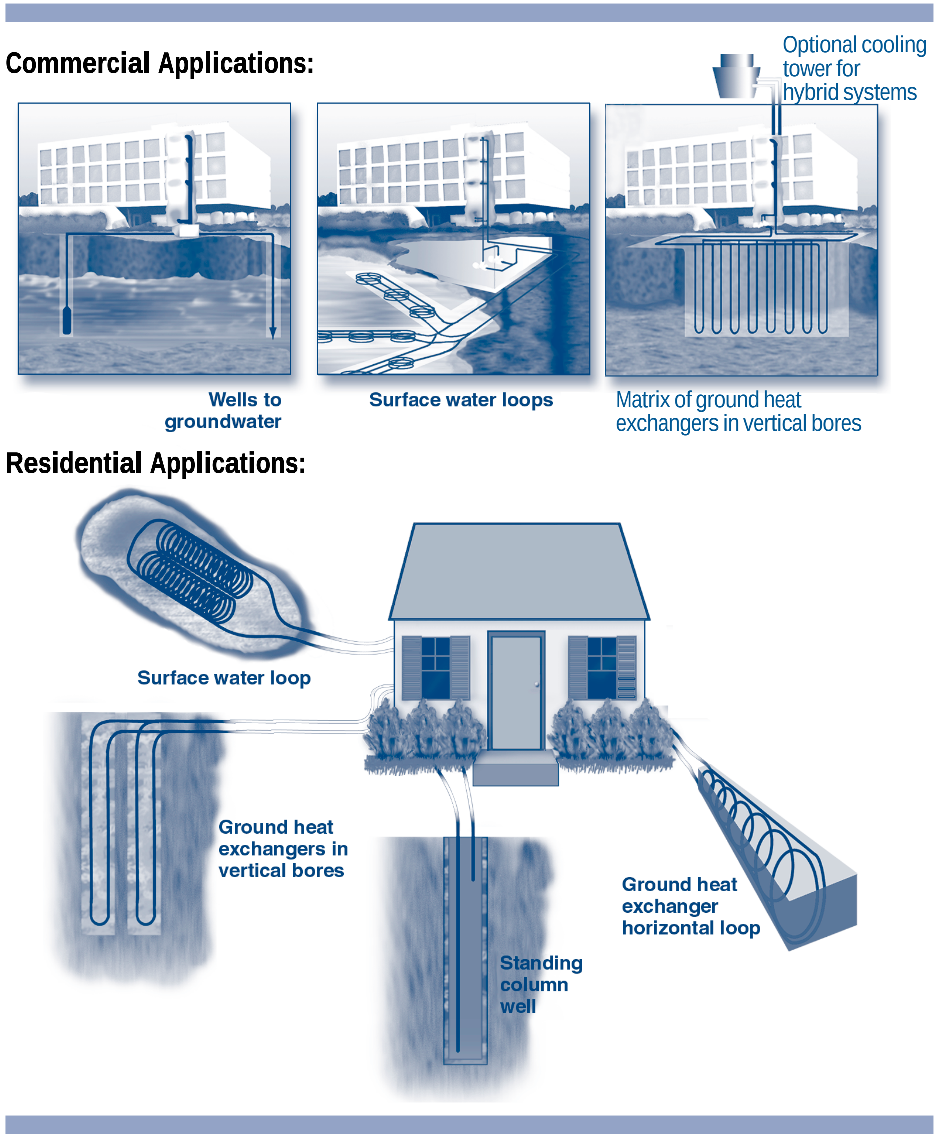


Figure 1. Various geothermal source/sinks that can be applied to geothermal heat pump systems in commercial or residential applications.

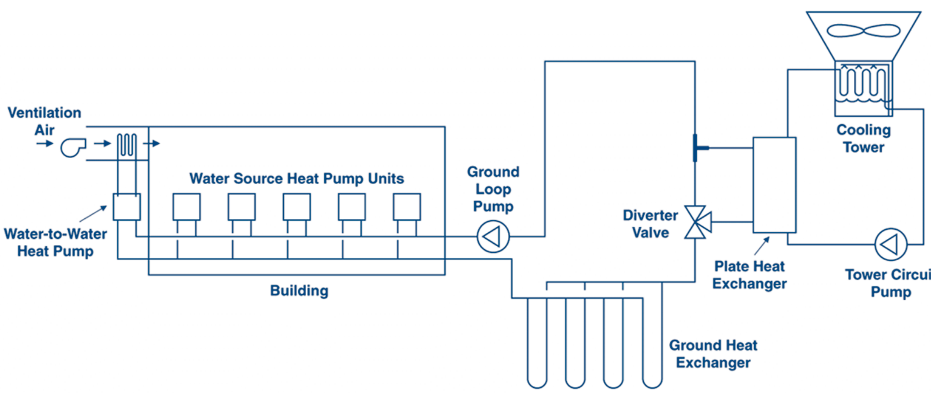


***Figure 2**. Hybrid GHP system schematic—tower isolated from building and ground loop.*

The closed loop in a GHP system may serve one or many heat pumps, depending on the application. For example, military family housing might be served with systems having one heat pump per living unit, each with its own vertical ground heat exchanger (GHX). Larger facilities might have many heat pumps on a common loop with a central variable-speed pumping station and one large vertical GHX. The schematic in Figure 2 is an example of a large central system type. Individual water source heat pump units provide heating and cooling to each zone within the building. These units are connected to a common interior building pipe loop, which is used as a heat source or sink as needed. Dedicated water-to-water heat pumps may also be connected to the loop to meet building water heating needs or to preheat or cool ventilation air as shown in this example. The building loop is connected to the ground source/sink system (a vertical ground heat exchanger in this case) via a central pumping station. The pumping station may be configured with a few large or several small single-speed pumps in parallel or with variable-speed pumps. Multiple parallel pumps or variable speed pumps offer the possibility of reducing pumping power during periods when building load is lower than the design values. In this hybrid system example, the cooling tower (or other heat rejection unit) is connected in series with the ground heat exchanger and is isolated from the building and ground piping loops with a plate heat exchanger. A wet or evaporative tower is shown in the example, but dry towers may also be used. Systems using dry towers would consume more energy because the tower would have to reject heat to the ambient air dry bulb temperature rather than the lower wet bulb temperature, as is the case with evaporative towers.

Energy Saving Mechanisms and Benefits

GHPs save energy and money because the equipment operates more efficiently than in conventional systems. The compressors in the individual heat pump units of a GHP system operate much more efficiently than those in air source units because the geothermal source/sink temperature is far more stable than that of outdoor air and has much less severe high and low extremes. In addition, air need be moved only on one side of the GHP, and less power is needed to move the liquid on the other side than would be needed to move air. Unlike air source units, GHP systems do not need defrost cycles or backup electric resistance heat at low outdoor air temperatures.

Common loop GHP systems recover heat as part of their design. In cooler weather, the heat pumps serving the building perimeter extract heat from the common loop to provide space heating, while units serving core areas are cooling space and rejecting heat to the common loop. When the common loop is in balance, no net conditioning is required from the geothermal source; under some operating conditions, the offset between heating and cooling units reduces the thermal load on the source. Recovered heat also can be used to heat water, using either desuperheaters on the heat pumps or, where large amounts of hot water are needed, dedicated water-to-water units.

GHP systems save money because they use less energy and improve energy consumption patterns. The 4003 GHPs in family housing at Fort Polk reduced the summer electric peak demand of that city of 12,000 people by 43% and increased the annual electric load factor from 0.52 to 0.62. Federal sites can purchase electricity at lower costs when their load characteristics improve so dramatically. (For more details on the Fort Polk story see www.eren.doe.gov/femp/financing/tecspec.html. Click on "Geothermal Heat Pumps." Also see Hughes and Shonder [1998].)

Maintenance Considerations—Cooling Towers

For hybrid GHPs using cooling towers as the auxiliary heat rejecter, tower maintenance is an issue that must be considered. Cooling towers add additional maintenance time and cost to the HVAC system. ASHRAE (1996) offers recommendations for a tower maintenance program including daily and weekly visual inspections for cleanliness, control component functioning, and sump water levels. These recommendations are intended to encourage tower maintenance and operating practices to reduce Legionella risks.

Geothermal heat source/heat sink options

For the government to receive the best value from GHP technology, installation contractors and Federal site personnel need to determine which geothermal heat source/sink type or combination of types is most economical for each site. The order of preference is not universal, but it generally is as follows.

Groundwater already being pumped. Is groundwater currently being pumped to the surface? Some Federal sites pump groundwater to the surface, treat it, and re-inject it as a part of groundwater remediation projects in areas near buildings. Tapping into such an already existing heat source/sink may be economical. A plate and frame heat exchanger can be used to transfer heat between the groundwater and a common loop serving individual heat pump units in nearby buildings. After remediation is completed, the pumping on the groundwater side of the heat exchanger can be re-optimized for the HVAC application and continued using the same supply and reinjection wells.

Stationary surface water. Are there large volumes of stationary surface water on the site, owned by the government and with government use restrictions, near buildings with significant heating and cooling loads? Heat exchange with surface water impoundments such as reservoirs, runoff retention basins, reflecting pools, ponds, and lakes, may be economical. A common loop serving individual heat pump units in nearby buildings can be submerged directly into the body of water. If the loop pipe material could be subject to damage from local wildlife, or if the water is used for recreational or other purposes that might interfere with this approach, an on-shore pump house with a plate and frame heat exchanger and protected intake from and discharge to the body of water could be considered. The issue of sensitivity of local fish to water temperature changes may need to be considered as well.

Moving surface water. Are large volumes of reliable moving surface water (e.g., large rivers with reliable flow and modest current), owned by the government and with government use restrictions, on the site near buildings with substantial space? Use of this type of water for heat exchange with a submerged pipe loop may be economical. If use of a submerged loop is not feasible, an on-shore pump house with a plate and frame heat exchanger and protected intake from and discharge to the moving body of water could be considered. Issues such as historical high and low water conditions, debris flow, sensitivity of aquatic life to temperature changes, and commercial and recreational traffic would require serious attention.

Wastewater streams. Does the site have large-volume, reliable flowing wastewater streams near buildings with significant square footage? If so, those streams may offer economical heat exchange. A common loop serving individual heat pump units in nearby buildings could be conditioned by a plate and frame heat exchanger in contact with the wastewater. Heat exchanger maintenance must be considered, as well as the stability of the missions of the facilities that are the source of the wastewater.

Groundwater. Are large quantities of groundwater available at a reasonable depth at the site, as well as an acceptable and economical means of disposal, near buildings with significant heating and cooling loads? Heat exchange with groundwater may be economical even when the project must bear the cost of developing the supply and discharge wells. The groundwater can be used with a plate and frame heat exchanger to condition a common loop serving individual heat pump units in nearby buildings. Poor water quality might require the use of expensive heat exchanger materials, and additional maintenance and aquifer re-injection in some formations might be expensive. Local environmental regulations on the use of groundwater need to be considered. In some cases, a double-walled heat exchanger may be required to minimize the risk of contamination of the ground-water with the fluid used in the common building loop.

Standing column well. Standing column well GHP systems are similar to standard groundwater GHPs, but since water is re-circulated between the well and the building, only one well may be required (larger projects may have several wells in parallel). Standing column wells are feasible in areas with near surface bedrock. Deep bores are drilled, creating a long standing column of water from the static water level down to the bottom of the bore. Water is recirculated from one end of the column to the other. During peak heat rejection or extraction periods, the system can bleed part of the water to the surface (lake, pond, stream, etc.) rather than reinjecting it all, causing water inflow to the column from the surrounding rock formation. This cools the column during heat rejection (building cooling), heats it during heat extraction (building heating), and reduces the required bore length.

Ground heat exchangers. Does the site have sufficient land area to accommodate ground heat exchangers near buildings with significant square footage? If so, heat exchange with the ground, using vertical or horizontal loops, may be economical. A central ground heat exchanger can condition a common loop serving individual heat pump units in nearby buildings. Alternatively, each heat pump, or small group of heat pumps, can have its own ground loop. Horizontal loops require considerably more land area but may be less expensive to install, depending on the types of soil and rock formations encountered in drilling. Ground heat exchangers are an option almost anywhere. They are placed last in this list not because they are less economical than other geothermal options, but merely to ensure that other options are considered where they exist.

Specific hybrid system considerations

Sites should be examined to determine whether a hybrid GHP system might be advantageous. For applications where the required geothermal heat sink capacity for cooling is much greater than the required heat source capacity for heating, hybrid systems can lead to significantly reduced installation costs. This is particularly true for commercial or institutional buildings in warm climates. A rule of thumb suggested by Kavanaugh (1997) for defining a warm climate location is one where the average ground temperature at 30-ft depth exceeds 60°F. Hybrid designs may also have economic advantages in such buildings in more moderate climates (30-ft ground temperature between 50-60°F) particularly for buildings with low ventilation air requirements or where heat recovery units or other conditioning means are used to reduce ventilation air heat gains/losses. Hybrid designs can also allow use of GHP systems (and access to most of their advantages) where site subsurface geological conditions or surface area limitations prevent installation of geothermal source/sink systems with sufficient capacity to fully meet the building heat rejection needs for cooling. Auxiliary heat rejecter location and maintenance requirements must be considered.

Technology Performance

Building 1562 – Fort Polk, LA

In 1993, Building 1562, a 24,000-ft^2 administration building at Fort Polk, LA, was renovated including conversion of the existing HVAC system to a hybrid GHP system. The new system consisted of 14 water source heat pumps (total cooling capacity of about 120 tons) connected to a common building loop that was conditioned by a vertical ground heat exchanger grid with seventy, 200-ft-deep boreholes on 10-ft centers and a 78-ton wet cooling tower. (Kavanaugh and Rafferty [1997] recommend that bore-to-bore spacing in vertical GHX grids be at least 20-25 ft for applications that are cooling load dominated to minimize long-term ground temperature rise effects.) A hybrid system was selected by the designer primarily because of limited space available for borehole installation and because high internal personnel and computer loads together with the warm climate location led to design cooling loads much greater than heating loads. Phetteplace and Sullivan (1998) presented operating data collected over a 22-month period. Cooling tower operation was initiated whenever the common loop fluid temperature exceeded 97°F and was terminated when the loop temperature fell below 95°F.

The observed data show that, over the period of monitoring, the amount of heat rejected to the ground (in cooling) was about 43 times as great as that extracted during heating—an indication that the tower was not used effectively to reduce the thermal load on the ground in this installation. Phetteplace and Sullivan noted that some increase in ground temperature occurred between the two summers over which the data were taken. This is attributed to the large imbalance between cooling and heating loads on the ground loop and the close spacing of the boreholes. They recommended that the tower setpoint controls be revised to either initiate tower operation at a lower fluid setpoint temperature or to operate the tower whenever possible to minimize the ground heat rejection load. Even though this would result in increased tower energy consumption, it is estimated that system energy consumption would be reduced because the heat pumps would operate at higher efficiency (due to lower entering fluid temperatures). The data showed that the tower fan and pump only accounted for 4% of the system energy over the 22-month monitoring period while the heat pumps used 77% of the total. Thus, improved efficiency of the heat pumps could more than compensate for even large increases in tower energy.

It was also noted that the building loop circulation pumps accounted for 19% of the total system energy use over the monitored period. Loop circulation is provided by two 15-hp pumps, one of which operates continuously. The system could be modified to use solenoid valves at each heat pump (to shut off fluid flow when the heat pump is off) and variable speed loop pumps to reduce loop flow during low load periods. Phetteplace and Sullivan estimated that such a pump control strategy could have reduced the loop pumping power by 45% over the study period resulting in a 8.5% reduction in system energy use.

As of this writing, the system at Ft. Polk's building 1562 has not been modified to incorporate any of the recommendations made by Phetteplace and Sullivan. However, they are preparing to retrofit a group of their buildings with GHP systems under FEMP's new GHP Super ESPC (see sidebar below) and this may include

GHP Super ESPC

The Federal Energy Management Program (FEMP) has implemented a "Super ESPC" to streamline the process of procuring GHP-centered energy saving retrofit projects for Federal facilities. In an ESPC (energy savings performance contract), an energy services contractor (ESCO) bears the costs of implementing energy-saving measures in exchange for fixed (annual or monthly) payments from the resulting cost savings. Under the Super ESPC, a GHP system must be the major focus but other energy saving measures (e.g., lighting improvements) can be included if they make the project more economical. FEMP has selected and preapproved a pool of ESCOs with which Federal agencies can contract. Under the Super ESPC, delivery orders can be awarded quickly, and facility managers have the assurance that all of the selected ESCOs are qualified to deliver top-quality GHP-centered energy efficiency projects.

The following contractors have been selected for this Super ESPC:

- Constellation Energy Source, Baltimore, MD; www.cesource.com
- Duke Solutions, Charlotte, NC; www.dukesolutions.com
- Energy Performance Services, Inc., King of Prussia, PA; www.energy-assets.com
- Enron Energy Services Operations, Inc., Alpharetta, GA; www.enron.com
- Trane Company Asset Management Services, St. Paul, MN; www.trane.com

Among the advantages of GHP-centered projects under the Super ESPC are:

- Alignment with ESPC statutory authority and full compliance with all Federal procurement regulations is assured.
- New GHP-based HVAC and water heating systems can be acquired at no capital cost to the Federal facility.
- Super ESPC contracts were awarded to large financially stable ESCO teams that can offer financing at low rates. In addition, these ESCOs had to demonstrate their GHP capabilities through past performance and a specific proposal for a large initial project.
- ESPC project cost savings are guaranteed to exceed payments to the ESCO for services and debt.

upgrading the controls of the existing hybrid GHP system (Phetteplace 2001).

Paragon Center – Allentown, PA

The Paragon Center in Allentown, PA, is an 80,000-ft^2, four-story office building. It was intended to have a full GHP system for building HVAC with a ground heat exchanger consisting of fifty-five, 500-ft deep boreholes to meet a 200-ton design capacity (Singh and Foster 1998). Although an early test bore indicated that the site could accommodate the deep bores, subsequent drilling in the intended ground loop location was unable to go lower than about 110-125 ft due to high water flow in a limestone strata. Drilling at that location would require casing the boreholes. For the original 500-ft borehole design casing would have increased installation costs beyond the allowable budget. It was determined that a hybrid GHP design with eighty-eight, 125-ft cased boreholes and a 120-ton cooling tower could be built within the budget allowing the building to enjoy most of the advantages of GHP technology. Singh and Foster note that the building HVAC system also employs heat recovery units to reduce heat losses and gains from ventilation air and uses variable speed pump control to limit pump energy at off-peak conditions. The building operating energy cost is reported to be less than \$1.00/ft^2 annually, including demand charges.

Elementary School – West Atlantic City, NJ

Singh and Foster (1998) also discussed a planned expansion of an elementary school in West Atlantic City, NJ. The expanded structure will have 85,000 ft^2 of conditioned area and will be occupied 9 months of the year. Total cooling load including ventilation air is 275 tons. Heat recovery equipment included in the HVAC design covers 25 tons of the load, leaving 250 tons to be covered by the main HVAC system. It was intended to use a full GHP system with ninety, 400-ft bores. However, the relatively small site (210 ft by 580 ft) was not large enough to fit all of the boreholes needed. A hybrid GHP will be installed with a ground heat exchanger system of sixty-six, 400-ft bores covering 133 tons of the design load and a 117-ton cooling tower to make up the difference. Ground heat exchanger installed cost is about \$9.70 per bore ft (\$255,600 total). No operating data is reported for the system, but Singh and Foster estimated that the hybrid GHP would generate annual energy cost savings of about \$4500 and maintenance savings of \$5000 compared to a conventional boiler/tower water loop heat pump system. The estimated installation cost of the hybrid GHP is \$1,139,100 compared to \$1,118,300 for the conventional alternative, so the estimated simple payback is 2.2 years.

Technology Demonstration

Detailed comparative analyses have been performed on full and hybrid GHP systems by Yavuzturk and Spitler (2000) on a small office building in two locations and by Thornton (2000) on a Navy training center building.

Yavuzturk and Spitler consider a small office building (14,205-ft^2 conditioned space) in Houston, TX, and Tulsa, OK, climates. Annual loads for this building in Houston were calculated to be 7.5 million Btus heating and 181.6 million Btus cooling. For the Tulsa location, the calculated annual loads were 50.1 million Btus heating and 133.8 million Btus cooling. Design cooling loads for the building were estimated to be about 15 tons in both locations. The hybrid GHP system layout is based on the schematic in Figure 2 where the cooling tower is isolated from the ground heat exchanger and building loops with a plate heat exchanger. The plate heat exchanger is plumbed in series with the ground heat exchanger. The ground loop is modeled using a short time step approach developed by Yavuzturk and Spitler (1999). Total system simulation for both full and hybrid GHP cases is done using the TRNSYS code (Klein et al. 1996) with the ground loop model incorporated into a TRNSYS module. Eight different hybrid GHP system control strategies within three main categories were investigated to determine their impacts on system energy consumption and overall system operation. The specific strategies within each main category that yielded the lowest system (building heat pumps plus tower pump and fan) energy use and life-cycle cost are summarized in this review. System maintenance costs were not quantified for the life-cycle cost estimates in these studies and no annual electricity escalation rate was considered.

Hybrid Case 1. The cooling tower is activated when the fluid temperature leaving the heat pumps exceeds a specified set point. In this study, the set point temperature was 96.5°F.

Hybrid Case 2. This approach uses the difference between the heat pump fluid exit temperature and the ambient wet-bulb temperature. Cooling tower operation is initiated whenever the temperature difference exceeds 3.6°F and is stopped when the difference falls below 2.7°F .

Hybrid Case 3. This strategy is based on using the cooling tower to reject heat from the ground to avoid long-term temperature rise. This effect is achieved by operating the tower for six hours daily (from midnight to 6 a.m.) year-round. To avoid high loop temperatures, a secondary set point control is included to operate the tower whenever the fluid temperature entering the heat pumps exceeds 96.5°F.

Summary results for the subject building in the Houston and Tulsa locations are given in Tables 1 and 2, respectively, and also in Figures 3 and 4. Case 1 results in the least usage and energy consumption for the cooling tower of the three hybrid control approaches. Case 2 yields the lowest values for annual system energy use and life-cycle cost for both locations while case 3 has the lowest system first cost. The case 2 strategy operates the tower a very large number of hours and generally under advantageous outdoor ambient (lower temperature) conditions. This approach tended to cool the ground over time resulting in lower ground loop fluid temperature. This resulted in lower heat pump energy use due to more efficient heat pump operation in the cooling season. Tower usage and energy consumption is greatest for this approach, but overall system energy use compared to the full GHP design is 18% lower for the Houston location and 6% lower for the Tulsa location. Clearly, the hybrid approach yields greater energy saving benefits in the warmer (higher cooling load) location. Energy use for the ground loop and building loop circulation pump is

***Table 1**. Summary of Hybrid GHP case study for 14,025 ft² office building in Houston, Texas (from Yavuzturk 2000)*

Heating degree-days = 1434; Cooling degree-days = 2889   Annual heating load = 7.5 million Btus   Annual cooling load = 181.6 million Btus*

	Base case—no cooling tower	Hybrid Case 1[1]	Hybrid Case 2[2]	Hybrid Case 3[3]
Number of boreholes in ground heat exchanger	36 @ 250 ft	12 @ 250 ft	12 @ 250 ft	12 @ 250 ft
Cost of ground heat exchanger[4]	$54,000	$18,000	$18,000	$18,000
Maximum fluid temperature entering heat pumps in 20-year period (°F)	96.6	96.3	80.5	96.0
Minimum fluid temperature entering heat pumps in 20-year period (°F)	71.3	67.3	40.5	54.1
Design capacity of cooling tower (tons)	22.5	11.5	8.5	
Cost of cooling tower and plateheat exchanger including controls and auxiliary equipment[5]	-	$8,662	$4,427	$3,272
Total cost of ground heat exchanger and cooling tower equipment	$54,000	$26,662	$22,427	$21,272
Present value of 20 years of electricity costs[6]	$19,611	$19,413	$16,011	$20,573
Present value of total costs	$73,611	$46,075	$38,438	$41,845
Annual energy use (kWh)				
Heat pumps	24,425	23,877	17,792	24,453
Cooling tower fan	-	260	1,847	1,006
Cooling tower pump	-	42	302	164
Total system	24,425	24,179	19,941	25,623

* From Air Force Manual AFM 88-29, "Engineering Weather Data," July 1978.
[1] Set point control to limit fluid temperature exiting heat pumps to 96.5°F or less.
[2] Differential temperature control activates tower when difference between heat pump exiting fluid temperature and air wet-bulb temperature exceeds 3.6°F and turns tower off when this difference falls below 2.7°F.
[3] Tower operated between midnight and 6 a.m. year-round to cool ground heat exchanger field (attempt to balance heating and cooling loads on ground); secondary set point control to limit fluid temperature entering heat pumps to 96.5°F or less.
[4] Estimated at $6.00/ft of borehole, including horizontal runs and connections (Kavanaugh and Rafferty 1997).
[5] Estimated at $385/ton of tower design capacity based on data from Means (1999).
[6] Assumes $0.07 per kWh cost of electricity; no price escalation rate assumed. A 6% discount rate is used for present value computation.

also a significant factor in total system energy consumption as noted above in discussion of the Ft. Polk system. In analysis of the Yavuzturk and Spitler case study for this review, however, it is assumed to be the same for the full GHP and the hybrid GHP cases. The building heat pump flow requirements will be the same for all systems and the total pressure loss for the GHX and tower loops is assumed not to vary significantly among the four cases studied.

Figure 4 shows the comparison in system first cost between full and hybrid GHP designs for both locations. First cost of the ground heat exchanger plus auxiliary heat rejecter for the hybrid cases is lower than for the full GHP ground loop in both locations. This difference is most dramatic in Houston where the hybrid system reduces installation costs by more than 50%.

Thornton (2000) performed a comparative analysis of hybrid and full GHP systems for Building 137 at the U.S. Navy Oceana Naval Air Station. Building 137 is a training facility with about 21,000 ft² of office and classroom space. In addition, there are a number of large, open-bay hangars attached to the building. The building is presently heated and cooled using a combination of steam from a central base steam generating station (for the hangar areas) and water source heat pumps connected to a common building water loop (for the classroom/office area). When the building is being cooled, condenser heat from the heat pumps is rejected through a 100-ton cooling tower. The HVAC system for the office/classroom portion of the building will be renovated to a GHP-based system under an energy savings performance contract (ESPC). This will be one of the first such arrangements to be put in place under the GHP "Super ESPC" recently approved by FEMP (see sidebar, page 5).

In Thornton's analysis, the TRNSYS code was used to model the building and all HVAC system components. The annual heating load for the office/classroom portion of the building was calculated to be 199.6 million Btus while the annual cooling load was 439.1 million Btus. There are 21 individual water source heat pumps used to provide heating and cooling with a total nominal cooling capacity of about 75 tons. Total length of the ground heat exchanger for the full GHP baseline case was 11,400 ft. The ground heat exchanger was simulated using the DST algorithm (Pahud and Hellstrom 1996) which was cast as a TRNSYS module. Thornton considered several different hybrid system configurations and control strategies based on using the existing cooling tower as the

Table 2. Summary of Hybrid GHP case study for 14,025 ft² office building in Tulsa, Oklahoma (from Yavuzturk 2000)
Heating degree-days = 3680; Cooling degree-days = 1949 Annual heating load = 50.1 million Btus Annual cooling load = 133.8 million Btus*

	Base case—no cooling tower	Hybrid Case 1[1]	Hybrid Case 2[2]	Hybrid Case 3[3]
Number of boreholes in ground heat exchanger	16 @ 240 ft	9 @ 240 ft	9 @ 240 ft	9 @ 240 ft
Cost of ground heat exchanger[4]	$23,040	$12,960	$12,960	$12,960
Maximum fluid temperature entering heat pumps in 20-year period (°F)	96.4	96.9	79.0	97.9
Minimum fluid temperature entering heat pumps in 20-year period (°F)	50.2	39.8	24.2	39.2
Design capacity of cooling tower (tons)	-	17.0	11.0	5.5
Cost of cooling tower and plate heat exchanger including controls and auxiliary equipment[5]	-	$6,545	$4,235	$2,118
Total cost of ground heat exchanger and cooling tower equipment	$23,040	$19,505	$17,195	$15,078
Present value of 20 years of electricity costs[6]	$15,999	$15,988	$14,976	$17,595
Present value of total costs	$39,039	$35,493	$32,171	$32,672
Annual energy use (kWh)				
Heat pumps	19,927	19,813	16,463	20,769
Cooling tower fan	-	86	1,882	984
Cooling tower pump	-	14	308	161
Total system	19,927	19,913	18,653	21,914

* From Air Force Manual AFM 88-29, "Engineering Weather Data," July 1978.
[1] Set point control to limit fluid temperature exiting heat pumps to 96.5°F or less.
[2] Differential temperature control activates tower when difference between heat pump exiting fluid temperature and air wet-bulb temperature exceeds 3.6°F and turns tower off when this difference falls below 2.7°F.
[3] Tower operated between midnight and 6 a.m. year-round to cool ground heat exchanger field (attempt to balance heating and cooling loads on ground); secondary set point control to limit fluid temperature entering heat pumps to 96.5°F or less.
[4] Estimated at $6.00/ft of borehole, with horizontal runs and connections (Kavanaugh and Rafferty 1997).
[5] Estimated at $385/ton of tower design capacity based on data from Means (1999).
[6] Assumes $0.07 per kWh cost of electricity; no price escalation rate assumed. A 6% discount rate is used for present value computation.

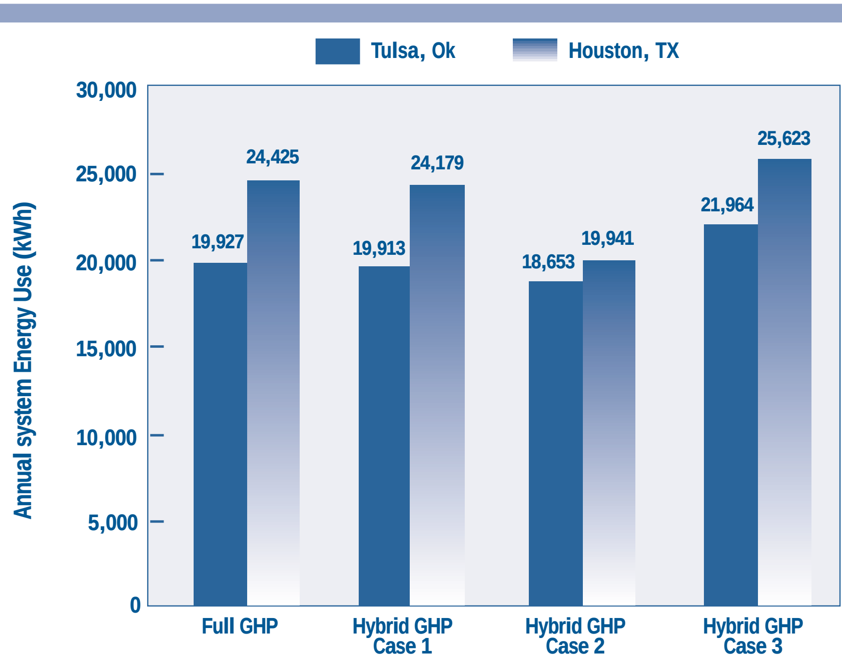


Figure 3. Full vs. hybrid GHP system (heat pumps, tower pump, and tower fan) energy use for 14,025-ft² office building—Houston, Texas, and Tulsa, Oklahoma, locations.

auxiliary heat rejecter. The three that produced the lowest hybrid GHP system (building heat pumps plus tower fan and circulating pump) energy usage are summarized below.

Oceana Hybrid Case 1. For this system, the tower is piped in series with the ground heat exchanger and is not isolated from the GHX loop as shown in Figure 5. The tower is activated when the fluid temperature in the system fluid loop exceeds a specified set point. In this case, the set point temperature was 80°F. Ground heat exchanger size for this case was 7,500 ft vs. 11,400 ft for the base case.

Oceana Hybrid Case 2. For this system, the tower is isolated from the ground heat exchanger with a plate heat exchanger as shown in Figure 6. The auxiliary heat rejection circuit (tower) operates when the fluid temperature in the tower fluid loop

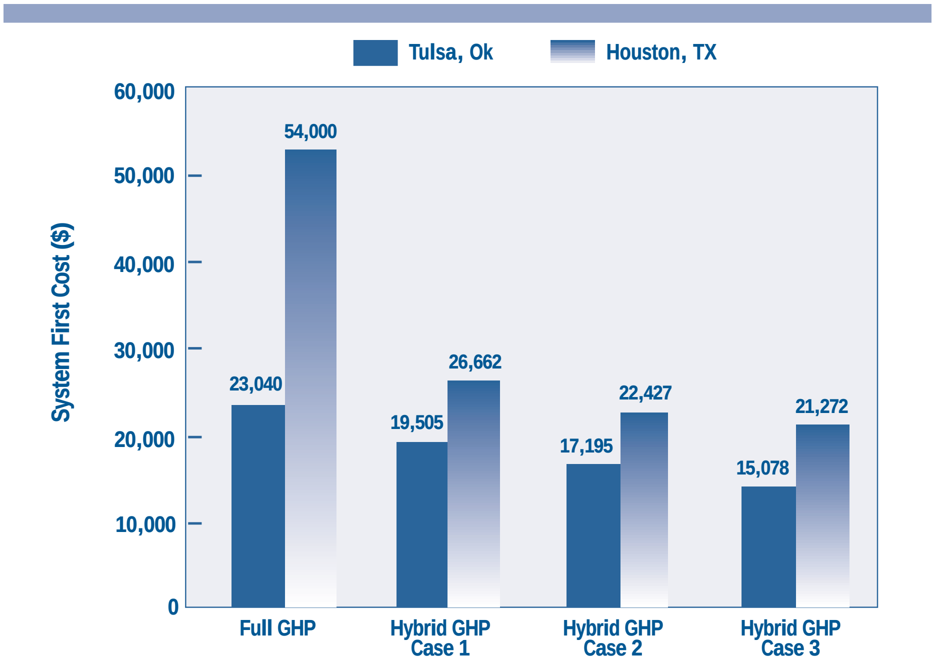


Figure 4*. Full vs. hybrid GHP system first cost for 14,025-ft^2 office building—Houston, Texas, and Tulsa, Oklahoma, locations.*

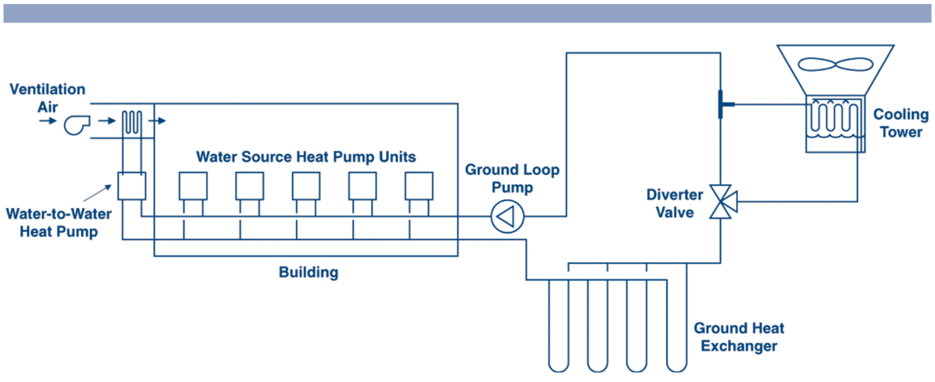


Figure 5*. Hybrid GHP system schematic—tower unisolated from ground and building loop.*

exceeds 70°F. Main loop flow was split between the plate and ground heat exchangers such that the total heat rejection to the ground in summer equaled the heat extraction in winter. The required split in loop flow to achieve ground thermal load balance for this case was 90% to the plate heat exchanger. Ground heat exchanger size for this case was 4,650 ft vs. 11,400 ft for the base case.

Oceana Hybrid Case 3. For this system, the tower is isolated from the ground heat exchanger with a plate heat exchanger as shown in Figure 6. The auxiliary heat rejection circuit (tower) operates when the fluid temperature in the tower fluid loop exceeds 70°F. Main loop flow was split between the plate and ground heat exchangers so that the maximum fluid temperature entering the building heat pumps was kept below 95°F. The required split in loop flow for this case was 42% to the plate heat exchanger. Ground heat exchanger size for this case was the same as for case 2.

Summary results for Thornton's ten-year analysis for the full GHP base case and the three hybrid GHP cases are presented in Table 3. As in Yavuzturk and Spitler's analysis, the setpoint control strategy of case 1 results in the least tower usage and energy consumption. Case 3 yields the lowest value for both first cost and life-cycle cost. For this case study, the first cost is taken to be the GHX cost plus the cost of the plate heat exchanger and tower loop circulation pump. Tower cost is not included because a tower already exists for this building. All other system costs (for the internal building systems and controls, GHX pump and controls, etc.) are assumed to be the same for all systems examined.

For the Oceana site, annual energy use for the building heat pumps is almost the same for all cases (full and hybrid GHPs) in contrast to the results seen for the previous case study assessment for Houston and Tulsa locations. At Oceana, the cooling-to-heating (C/H) load ratio for the building studied was about 2.2—about 20% lower than for the office building studied in Tulsa (C/H ratio about 2.7) and much lower than for the building studied in Houston (C/H ratio about 24.2). Thornton's Oceana study results show that in the hybrid GHP cases, the building heat pumps used more energy in the heating season than for the base case full GHP due to the lower minimum fluid temperatures. Cooling season heat pump energy use ranged from slightly lower to about the same for the hybrid GHP systems. With the added energy use of the tower fan and pumps, overall system energy use for the hybrid GHP cases studied at Oceana ranges from 1% to 13% higher than for the base case.

Figure 7 shows the comparison of first cost between the full and hybrid GHPs for the Oceana study. For case 1 (with tower not isolated from GHX and building), the GHX size and system first cost are both reduced by about 34%. In cases 2 and 3, with an isolated tower circuit, it is possible

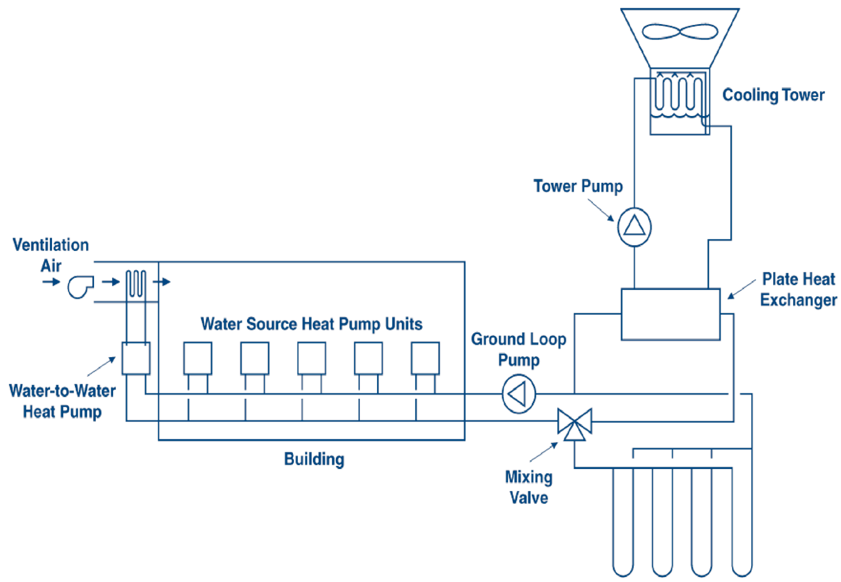


Figure 6. Hybrid GHP system schematic for Oceana analysis cases 2 and 3—tower isolated from building and GHX and piped in parallel with GHX.

to operate with lower temperatures in the GHX (using an antifreeze solution). The GHX size is reduced about 59% and system first cost by about 55% in these cases. The hybrid systems had life-cycle costs from 26% lower (for case 1) to 40% lower (for case 3) than that for the base case.

Summary. Based on the results from the two case studies analyzed for this review, the following observations are made.

- Hybrid GHP systems can significantly reduce system first costs even when a tower needs to be purchased. Costs can be reduced by more than 50% for very highly cooling dominated applications such as the small office building in Houston (cooling-to-heating load ratio of 24:1).

Table 3. Summary of Oceana Hybrid GHP case study - existing tower (from Thornton 2000)

Heating degree-days = 3639; Cooling degree-days = 1485   Annual heating load = 199.6 million Btus   Annual cooling load = 439.1 million Btus*

	Base case—no cooling tower	**Hybrid Case 1**[1]	**Hybrid Case 2**[2]	**Hybrid Case 3**[3]
Number of boreholes in ground heat exchanger - ten-year design	76 @ 150 ft	50 @ 150 ft	31 @ 150 ft	31 @ 150 ft
Cost of ground heat exchanger[4]	$92,454	$60,825	$37,712	$37,712
Maximum fluid temperature entering heat pumps in ten year period (°F)	94.9	84.6	92.5	95.1
Minimum fluid temperature entering heat pumps in ten year period (°F)	63.3	53.7	35.5	44.4
Existing cooling tower capacity (tons)	-	100.0	100.0	100.0
Cost of plate heat exchanger and tower circuit pump[5]	-	-	$3,800	$3,800
Total cost of ground heat exchanger, plate heat exchanger, and tower pump	$92,454	$60,825	$41,512	$41,512
Present value of 10 years of electricity costs[6]	$29,069	$29,492	$32,898	$31,906
First-year electricity costs[6]	$3,950	$4,007	$4,470	$4,335
Present value of first costs plus electricity costs	$121,523	$90,317	$74,410	$73,418
Annual energy use (kWh)				
Heat pumps	70,027	69,083	72,234	71,632
Cooling tower fan	-	573	3,115	1,379
Cooling tower pump	-	1,391	3,902	3,840
Total system	70,027	71,047	79,251	76,861

* From Air Force Manual AFM 88-29, "Engineering Weather Data," July 1978.
[1] Unisolated tower; tower operated whenever loop temperature exceeds 80°F.
[2] Isolated tower with plate heat exchanger; tower operated to achieve balance between heating and cooling loads on ground heat exchanger.
[3] Isolated tower with plate heat exchanger; tower operated with setpoint control to keep maximum fluid temperature entering heat pumps at or below 95°F.
[4] Actual cost of test bores drilled at Oceana site for ground thermal conductivity testing was $8.11 per ft of borehole, including horizontal runs and connections (personal communication with B. Koshka, Trane Co. December, 2000).
[5] Plate heat exchanger estimated at $25.50 per ton based on data presented by Kavanaugh and Rafferty 1997; tower circuit pump cost estimated at $1250.
[6] Electricity cost $0.0564 per kWh (rate charged to Oceana buildings by U.S. Navy Public Works Center - Norfolk); no price escalation rate assumed. A 6% discount rate is used for present value computation.

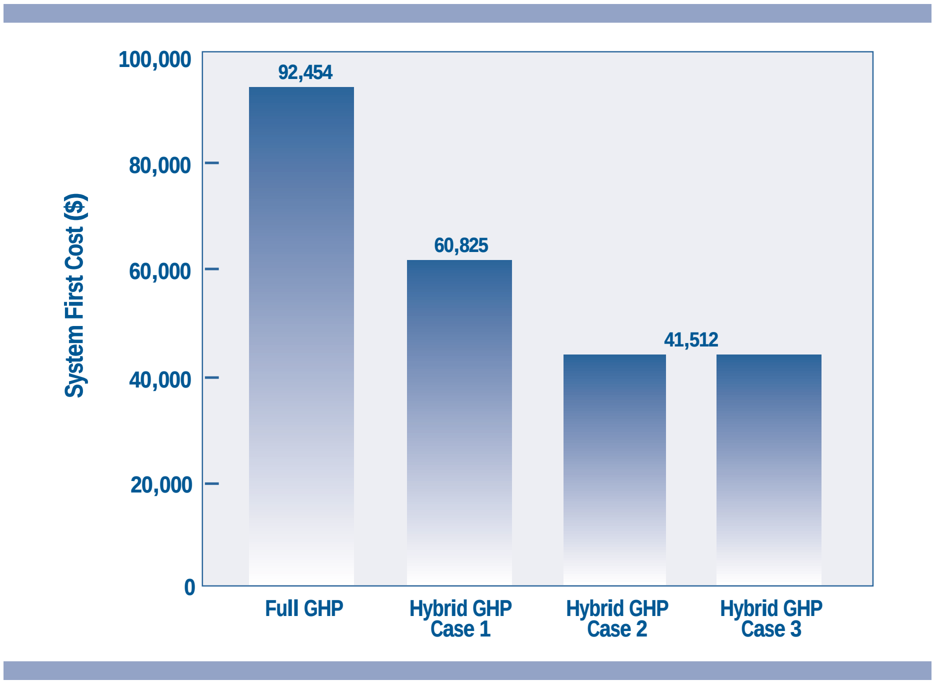


***Figure 7**. Full vs. hybrid GHP system first cost comparison for Bldg 137 Oceana NAS, Virginia (existing cooling tower).*

- For applications where a suitable tower already exists (as at the Oceana study site), a hybrid system can result in system cost reductions of more than 50% even when the building is not overly cooling load dominated.
- For heavily cooling dominated sites, hybrid GHPs can result in heat pump and system energy savings compared to full GHPs when the supplementary heat rejecter is operated enough hours to reduce the average heat pump entering fluid temperature during the cooling season.
- The authors of both case studies point out that none of the hybrid system designs they examined have been optimized. A design optimization method is needed to balance GHX size, supplemental heat rejecter size and type, control strategy, and electric rate structure to achieve lowest life-cycle or first cost designs for a given location.

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