FINAL REPORT

Full-Scale Evaluation of Energy Foundations for Buildings

ESTCP Project EW-201153

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Eight deep (drilled-shaft) energy foundations were constructed as the structural support system for a new shower facility at the United States Air Force Academy. These foundations contain HDPE tubing to circulate heat transfer fluid in order to use the subsurface concrete foundation and adjacent soil or rock as a heat source and sink. The heat transfer fluid is circulated to a ground source heat pump in order to provide heating to the building. The construction costs are favorable compared to drilling boreholes for ground source heat pumps, provided the deep foundations are required for structural reasons. A life cycle cost analysis, based on operational estimates of building heat load, indicates that the life cycle costs of the energy foundation heat pump hybrid with a gas boiler is comparable to a high efficiency gas boiler alone. The carbon emissions of the Energy Foundation heat pump system are estimated to exceed those of the gas boiler alone. This is related to the fact that the source of 89% of the electrical power is a coal.

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TABLE OF CONTENTS

		Page
EXECUTIVE SUMMARY		ES-1
1.0	INTRODUCTION	1
1.1	OVERVIEW	1
1.2	BACKGROUND	2
1.3	DEMONSTRATION OBJECTIVES	3
1.4	REGULATORY DRIVERS	4
2.0	ENERGY FOUNDATION TECHNOLOGY DESCRIPTION	7
2.1	TECHNOLOGY DESCRIPTION	7
2.2	TECHNOLOGY DEVELOPMENT	11
2.3	ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY	14
3.0	PERFORMANCE OBJECTIVES	17
3.1	OVERVIEW	17
3.2	QUALITATIVE PERFORMANCE OBJECTIVES	17
3.3	QUANTITATIVE PERFORMANCE OBJECTIVES	18
4.0	FACILITY/SITE DESCRIPTION	22
4.1	INTRODUCTION	22
4.2	FACILITY/SITE LOCATION AND OPERATIONS	22
4.3	GEOTECHNICAL CONDITIONS	23
4.4	FOUNDATION DESIGN	25
5.0	TEST DESIGN	26
5.1	INTRODUCTION	26
5.2	HEAT TRANSFER LOOP DESIGN	26
5.3	FOUNDATION CONSTRUCTION	27
5.4	TEST DESIGN OVERVIEW	32
5.5	INSTRUMENTATION AND DATA COLLECTION	33
5.6	THERMAL TESTING OF THE FOUNDATIONS	33
6.0	PERFORMANCE ASSESSMENT – HEAT SUPPLIED BY EFHP SYSTEM VS. GAS BOILER SYSTEM	37
6.1	OVERVIEW	37
6.2	BUILDING HEAT DEMAND ESTIMATE USING HVAC-CALC, COMMERCIAL 4.0	37
6.3	HEAT REQUIRED BY THE BUILDING FOR AN AVERAGE WINTER	41
6.4	ESTIMATE OF COST PER MILLION BTU/HR OF HEATING (QUANTITATIVE OBJECTIVE 1)	42
6.5	CARBON EMISSIONS REDUCTION (QUANTITATIVE OBJECTIVE 2)	43

TABLE OF CONTENTS (continued)

Page

6.6 COEFFICIENT OF PERFORMANCE AND HEATING SEASON ERFORMANCE FACTOR OF THE GROUND SOURCE HEAT PUMP (QUANTITATIVE OBJECTIVE 3) 43
6.7 CONSTRUCTION COSTS OF THE ENERGY FOUNDATION VS. SEPARATE BOREHOLE FIELD (QUANTITATIVE OBJECTIVE 4) 44
6.8 ENERGY FOUNDATION RETROFIT DISCUSSION (QUANTITATIVE OBJECTIVE 6) 45

7.0 COST ASSESSMENT 47
7.1 OVERVIEW 47
7.2 CONSTRUCTION COSTS OF THE ENERGY FOUNDATIONS 47
7.3 LIFE CYCLE COST COMPARISON 48

8.0 IMPLEMENTATION ISSUES 51

9.0 REFERENCES 53

APPENDIX A POINTS OF CONTACT A-1
APPENDIX B BORING LOGS GENERATED DURING THE GEOTECHNICAL SITE INVESTIGATION PERFORMED FOR THIS PROJECT B-1
APPENDIX C EVALUATION OF THERMO-MECHANICAL AND THERMAL PERFORMANCE OF FULL-SCALE ENERGY FOUNDATIONS C-1
APPENDIX D THERMO-MECHANICAL CHARACTERIZATION OF FULL-SCALE ENERGY FOUNDATIONS D-1
APPENDIX E GROUND LOOP DESIGN AND HEAT PUMP SIZING INFORMATION PROVIDED BY FARRIS ENGINEERING E-1
APPENDIX F INDEPENDENT GOVERNMENT ESTIMATE FOR CONSTRUCTION OF ENERGY FOUNDATIONS F-1

LIST OF FIGURES

Page

Figure 1. Schematic of the heat pump cycle. 7
Figure 2. Schematic of building with energy foundations (inset) and connection of heat pump cycle to the energy foundation. 9
Figure 3. Photo of energy foundation construction for this demonstration in April 2012..... 9
Figure 4. Photo of grade beam construction for this project in May 2012..... 10
Figure 5. Air photo and map of the United States Air Force Academy showing the location of the shower/shave building prior to construction..... 22
Figure 6. Plan view of the sleeping quarters area of the FERL site, showing the location of the Shower/ Shave building (circled in red). 23
Figure 7. Photograph showing Shower/ Shave building from the south (foreground) and sleeping quarters to the west (left). 23
Figure 8. Sketch of soil profile and foundation used in the deep foundation design. 24
Figure 9. Plan view of the Shower/ Shave building showing the deep foundations (labeled 1 through 8) and instrumentation locations..... 25
Figure 10. Locations of instrumentation in drilled shaft foundations. 27
Figure 11. Photo showing attachment of HDPE tubing to rebar cage. 28
Figure 12. Construction photos. 29
Figure 13. Photo of PVC tubing, placed in reinforcement cage, used to simulate bored hole inside Foundation 8. 30
Figure 14. Photo showing horizontal placement of heat exchanger tubing in the grade beam formwork. 31
Figure 15. Photo showing concrete slab on grade before building wall placement. 31
Figure 16. Diagram excerpted from mechanical drawings of the shower/shave, showing the plumbing of the heat pump (GHP) and gas boiler (B) to the radiant in-floor heating system. 32
Figure 17. Photo of the manifold showing control valves for the eight foundations. 33
Figure 16. HVAC-Calc output for FERL Shower/Shave building for 2°F outdoor temperature. 40
Figure 17. Building life cycle cost analysis as output by BLCC 5.3 (2015) that compares the life cycle costs of heating the FERL Shower/ Shave with a high efficiency gas boiler (Base Case) to the Energy Foundation Heat Pump System, which is a hybrid of the ground source heat pump with the gas boiler to supply additional heat at times of high demand. 49

LIST OF TABLES

Page

Table 1a. List of journal articles, magazine article and conference papers resulting from this project. 12
Table 1b. List of posters and presentations resulting from this project. 13
Table 2a. Qualitative performance objective for the demonstration of energy foundations. 17
Table 2b. Quantitative performance objective for the demonstration of energy foundations. .....**Error! Bookmark not defined.**18
Table 3. Soil layer geometry and engineering properties assumed for design based on geotechnical site investigation. 24
Table 3. Summary of thermal response tests conducted on the foundations. 35
Table 4. Bin Analysis information indicating how much heat is supplied by the heat pump and the gas boiler for each temperature bin for the FERL Shower/Shave facility. 41
Table 5. Borehole cost estimates (From May of 2013) for drilling ground source heat pump system. 45

ACRONYMS AND ABBREVIATIONS

BLCC	Building Life Cycle Cost
DoD	Department of Defense
DOE	Department of Energy
EFHP	Energy foundation heat pump
ESTCP	Environmental Security Technology Certification Program
FERL	Field Engineering Readiness Laboratory (refers to the field site at the Air Force Academy and the undergraduate course of the same name)
GHG	Green house gas
GSHP	Ground source heat pump
HDPE	High density polyethylene
HSPF	Heating season performance factor
HVAC	Heating, ventilation and air conditioning
LCC	Life cycle cost
NREL	National Renewable Energy Laboratory
NZEI	Net Zero Energy Initiative
OMB	Office of Management and Budget
OSD	Office of Secretary of Defense
RED HORSE	Rapid Engineer Deployable Heavy Operations Repair Squadron Engineer
SABER	Simplified Acquisition Base Engineering Requirement
USAFA	United State Air Force Academy
WSHP	Water Source Heat Pump

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EXECUTIVE SUMMARY

Energy foundations are a relatively newly commercialized technology, and this project demonstrates this new technology. The overarching goal of this project was to determine energy cost savings and carbon emission reductions from a heating system for a building that utilized energy foundations in conjunction with a ground source heat pump vs. use of a high efficiency gas boiler to supply heat.

Eight deep (drilled-shaft) energy foundations were constructed as the structural support system for a new shower facility at the Field Engineering Readiness Laboratory (FERL) site in Jack's Valley of the United States Air Force Academy. These foundations contain high density polyethylene (HDPE) tubing to circulate heat transfer fluid in order to use the subsurface concrete foundation and adjacent soil or rock as a heat source and sink. The heat transfer fluid is circulated to a water source heat pump (WSHP) in order to provide heating to the building. Because of the ability to incorporate heat transfer tubing into the foundations of buildings being constructed, the installation costs of the system are favorable compared to traditional ground source heat pump (GSHP) systems for which boreholes (separate from the building) must be drilled.

Due to incomplete installation of the building's heating, ventilating and air conditioning (HVAC) systems, as well as other construction delays, neither one of the HVAC systems were ever fully operational, and ESTCP ended the project prior to the collection of performance data related to electrical power consumption that would have allowed a direct comparison of the energy costs of the two HVAC systems. In lieu of actual performance data, a life cycle cost (LCC) analysis comparing the two heating systems was performed. The LCC analysis utilizes a basic assessment of building heat requirements for one year in order to estimate energy costs associated with the operation of each system.

There were three qualitative performance objectives: 1) Ease of construction of the energy foundations. This objective was met—no special training of the construction crew was required for installation of the foundations. 2) Ease of energy foundation retrofit. This objective was not evaluated, as it was deemed impractical to jack the building up once constructed. 3) Ease of maintenance of the energy foundation heat pump (EFHP) system. This objective was not fully evaluated, but had it been, it would likely have been met as it is logical that the maintenance would be similar to other currently installed HVAC systems.

There were five quantitative performance objectives that were evaluated in some form:

1. Reduced cost of fuel per unit of heat energy of the EFHP system compared to the natural gas boiler. The performance objective was set at 70% of the fuel costs. However, the estimated energy costs of the EFHP system are % of those of the natural gas boiler. Although there is a fuel cost savings, the performance measure was not met.
2. Reduced carbon emissions. In the estimates of carbon emissions that we made for the 89% coal-fired electricity source at the US Air Force Academy, this objective was not met. The EFHP system would generate 7790 pounds of additional carbon compared to

heating with the natural gas boiler alone. In order for this objective to be met, the electrical source would have to experience considerable de-carbonization.

3. Energy efficiency. We determined the heating season performance factor (HSPF) of a 'typical' high-efficiency air source heat pump de-rated for the climate of Colorado, and estimated that Objective 3.0 would be met, as we calculated an HSPF of 10.7 for the installed heat pump and a typical air source heat pump installed in the Front Range would have an HSPF of 6.4.

4. Construction costs compared to a geothermal borehole system for ground source heat pumps. For this project, we estimated that a single borehole providing the equivalent heat exchange capability to the eight foundations would cost about $4.9k, whereas the cost of installing the heat transfer pipe into the foundations and the extra pipe required to route to the manifold would cost $2.3k for a savings of $2.6k. Hence, the performance objective was met.

5. Life cycle cost compared to a natural gas boiler. The BLCC 5.3-15 software was used to perform a life cycle cost analysis of the two systems. The as-built and as-used conditions of the building were modeled. The life cycle cost of the EFHP system was estimated at $43,545 and that of the gas boiler only was $37,507. Hence the EFHP system estimated life cycle cost is 116% of that of the gas boiler system, so the objective of costing less than was 70% of the gas boiler system was not met. However, with increased building use in the winter, the life cycle costs would become more favorable to the EFHP system. The analysis results also suggest that the EFHP system would be worth evaluating in new construction projects where deep foundations will be used.

1.0 INTRODUCTION

1.1 OVERVIEW

'Energy foundation' refers to a structural foundation that contains high density polyethylene (HDPE) tubing to circulate heat transfer fluid in order to use the subsurface concrete foundation and adjacent soil or rock as a heat source and sink. The heat transfer fluid is used in conjunction with a ground source heat pump in order to provide heating and cooling.

The overarching goal of this project was to determine energy cost savings and carbon emission reductions from a heating system for a building that utilizes an energy foundation heat pump (EFHP) system (which uses a supplemental gas boiler at times of high heat demand) vs. use of a high efficiency gas boiler alone to supply heat, thus demonstrating the technology to the DoD. The building in which this technology was demonstrated is a newly-constructed shower facility to serve 100 people in Jack's Valley of the U.S. Air Force Academy (USAFA). Other objectives related to this project, such as demonstrating the ease of construction of the energy foundations, are described in Section 1.2.

Eight deep (drilled-shaft) energy foundations connected by a horizontal grade beam were constructed as the structural support system for the building located at the Field Engineering Readiness Laboratory (FERL) site of USAFA. There were two systems installed to provide heating of the building—one is a high efficiency, condensing gas boiler, sized to satisfy all heating requirements for the building. The second system is an EFHP system. The heat pump was sized by the mechanical designer of the building to provide all of the heat from building envelope heat loss and infiltration. The condensing gas boiler will provide the heat required at times of very high demand—i.e., very low air temperature and high occupancy rate of the building.

Note that the EFHP system installed in the new shower facility will run in reverse to provide cooling in the summer. However, this project compared the two systems in heating mode only because there is no other source of cooling to utilize as a baseline.

Due to numerous delays in construction, and inadequate installation of the building's heating, ventilating and air conditioning (HVAC) systems, neither one of the HVAC systems have been operated to date, and ESTCP ended the project. This report summarizes the results of the project. In lieu of performance data, a life cycle cost (LCC) analysis was used to compare the two heating systems. The LCC analysis utilizes estimated building heat requirements for one year in order to approximate annual energy costs associated with the operation of each system.

At the time of the writing of this report, plans are being made to provide the necessary repairs to the building and the HVAC systems and it is anticipated that at least one of the systems will be operational in January of 2016. Currently the instrumentation required to document the performance of the systems is functioning, and it is the intent of the US Air Force Academy to complete the study of the two HVAC systems after they become operational.

1.2 BACKGROUND

Energy security, surety and reliability are critical for the DoD and national security. Hence, technologies to improve the energy efficiency of buildings, renewable energy sources, HVAC systems that efficiently operate on electricity (providing power source flexibility) and sustainable building design are being tested and validated. Assurance of energy to support the DoD mission is the objective of the DoD-DOE Initiative entitled 'Net Zero Energy Installations (NZEI).' The overall program objective of NZEI is creating a template for planning and developing net zero energy installations across the United States Armed Services. This project is aligned with the objective of NZEI.

Current State of Technology in DoD: The technology demonstrated is referred to herein as 'energy foundations.' Energy foundations utilize a ground source heat pump (GSHP) system with the heat exchangers embedded inside deep foundations (in this case, drilled shafts).

The cost associated with heat pump operation is the power required for the refrigerant compressor and for the circulation systems for the heat transfer fluid and for the heating/cooling system inside the building. In a GSHP system, heat is absorbed and/or shed to the ground—which is at a relatively constant temperature below depths as shallow as 2m (6 ft). The DoD has utilized GSHP systems since the 1980s, and found them to be cost-effective compared to other means of heating indoor space (Office of the Secretary of Defense [OSD], 2007). They are used primarily in the eastern half of the United States in family housing units. However, modeling indicates that GSHP-conventional heating hybrid systems are cost-effective in the Northeast, Southwest, Western mountain, Northwest and West coast regions of the U.S.

Energy foundations are an innovative variation of the GSHP systems because they use existing deep foundations that are (already) required to provide structural support for the secondary purpose of housing heat transfer loops to supply a GSHP. Hence, they improve the energy efficiency of building HVAC systems, provided they were not already GSHP systems. Since they are installed while the building is being constructed they offer considerable capital savings compared to drilling separate boreholes for heat transfer loops.

Deep foundations are those that receive some or all of their support from soil strata at a depth where the Depth of bearing/Base width of footing ratio is greater than 5 (UFC 3-220-01A, 2004). Whether a deep or shallow foundation is selected to provide structural support depends on a number of factors, including the structural load of the building, the direction of the structural loads and the subsurface conditions—especially soil strength and compressibility. Deep foundations are often the only logical choice to support a building in regions where shallower soils cannot bear the structural loads of the building—such as in regions with soils that have high clay content and/or in coastal regions (e.g., the recently-constructed U.S. Central Command headquarters building at MacDill AFB, FL).

In this project, deep foundations were constructed for a building that did not require them. This was done in order to examine ease of construction of energy foundations and to document heat transfer characteristics of the energy foundation system. However, energy foundations should be adapted from foundations that are structurally required by the building. Energy foundations promise to be an important strategy that can be utilized by the DoD to improve energy-efficiency

and sustainable building operation. If energy foundations are combined with renewable electric power to run the heat pump(s), this technology could provide 100% renewable energy for building HVAC.

1.3 DEMONSTRATION OBJECTIVES

The project's objectives were to document the performance, costs and benefits of energy foundations by:

1) Monitoring energy usage of the EFHP system for heating the building for one year and then operating the gas boiler for the following year, and comparing the power consumption (correcting for occupancy and different heating seasons). This was the overarching project objective – to use operational data in the performance comparison. Hence, the circuits powering the components of both systems are wired with sensors to measure power consumption over the course of each year.

   Because the HVAC systems were not operational, we could not accomplish this comparison by monitoring. Instead, we used available information about the building and its components (i.e., heat transfer information efficiencies of the boiler and heat pumps) and information about an average heating season in Colorado Springs in order to provide these estimates based on a building energy analysis.

2) Measuring thermally-induced movements of the foundations to validate their structural performance.

   We performed thermal response testing of the foundations, in which we heated the foundations and let them cool naturally. These tests validated that neither the movements nor the stresses induced by foundation heating and/or cooling compromise the structural performance of the foundations (Murphy, 2013; Murphy, et al., 2014a; Murphy et al. 2014b, Murphy et al., 2015, McCartney et al., 2015).

3) Measuring in-ground temperature changes related to the use of the energy foundations. This was meant to help estimate permanent changes in ground temperature, which could affect the operating efficiency of the life-cycle costs of the energy.

   We were not able to examine long-term temperature changes due to the fact that the EFHP system has not been operational. However, short-term thermal response testing provided some information on the heat transfer characteristics of the surrounding soil.

4) Estimating GHG (carbon) emissions associated with both types of HVAC systems.

   Using data for an average heating season in Colorado Springs we were able to make an estimate of carbon emissions.

5) Estimating the total life-cycle costs of both the energy-foundation HVAC system and the conventional system.

   We utilized BLCC5.3-15 to do a comparison of the two systems.

In addition to the above-described objectives, we documented the construction costs of the energy foundations.

1.4 REGULATORY DRIVERS

Drivers for this technology include:

1) **Executive Order 13423**, 'Strengthening Federal Environmental, Energy, and Transportation Management,' January 2007, provides the following goal for Federal agencies:

   Sec. 2. Goals for Agencies. In implementing the policy set forth in section 1 of this order, the head of each agency shall:

   (a) <u>improve energy efficiency and reduce greenhouse gas emissions of the agency</u>, through reduction of energy intensity by (i) 3 percent annually through the end of fiscal year 2015, or (ii) 30 percent by the end of fiscal year 2015, relative to the baseline of the agency's energy use in fiscal year 2003 ….

   (f) ensure that (i) new construction and major renovation of agency buildings comply with the Guiding Principles for Federal Leadership in High Performance and Sustainable Buildings set forth in the Federal Leadership in High Performance and Sustainable Buildings Memorandum of Understanding (2006), and (ii) 15 percent of the existing Federal capital asset building inventory of the agency as of the end of fiscal year 2015 incorporates the sustainable practices in the Guiding Principles;

   Generally, ground source heat pumps help improve the (energy) efficiency of heating and cooling buildings, thus also reducing greenhouse gas emissions.

2) **Executive Order 13514**, 'Federal Leadership in Environmental, Energy, and Economic Performance,' October 2009. This EO expands on the energy reduction and environmental performance requirements for Federal agencies identified in EO 13423. The goal of EO 13514 is "to establish an integrated strategy towards sustainability in the Federal Government and to make reduction of greenhouse gas emissions (GHG) a priority for Federal agencies."

   Sec. 1. Policy. In order to create a clean energy economy that will increase our Nation's prosperity, promote energy security, protect the interests of taxpayers, and safeguard the health of our environment, <u>the Federal Government must lead by example.</u> It is therefore the policy of the United States that <u>Federal agencies shall increase energy efficiency; measure, report, and reduce their greenhouse gas emissions from direct and indirect activities;</u>….

   …and prevent pollution; leverage agency acquisitions to foster markets for sustainable technologies and environmentally preferable materials, products, and services; design, construct, maintain, and operate high performance sustainable buildings in sustainable locations; strengthen the vitality and livability of the communities in which Federal facilities are located; and inform Federal employees about and involve them in the achievement of these goals.

   This project provides the US Air Force (and the DoD) the opportunity to lead by example with regards to demonstrating the energy and GHG savings associated with energy foundations.

Sec. 2. Goals for Agencies. In implementing the policy set forth in section 1 of this order, and preparing and implementing the Strategic Sustainability Performance Plan called for in section 8 of this order, the head of each agency shall:….

(i) beginning in 2020 and thereafter, ensuring that all new Federal buildings that enter the planning process are designed to achieve zero-net-energy by 2030;…..

(iv) pursuing cost-effective, innovative strategies, such as highly reflective and vegetated roofs, to minimize consumption of energy, water, and materials;

(v) managing existing building systems to reduce the consumption of energy, water, and materials, and identifying alternatives to renovation that reduce existing assets' deferred maintenance costs;…..

(vii) ensuring that rehabilitation of federally owned historic buildings utilizes best practices and technologies in retrofitting to promote long term viability of the buildings;

This project promotes energy conservation, which is an important contributor to our 2030 zero-net-energy goal. In rare cases, buildings must be retrofit with deep foundations (in a process called underpinning). If that occurs, then there is a possibility of installing the deep foundations as energy foundations.

3) DoD Policy - Energy Security MOU with DOE

Section IV. Activities

Specific activities covered under this MOU include, but are not limited to:

A. Evaluate energy systems and technology management solutions that meet DoD objectives including developing energy technologies that meet DoD energy requirements. Work collaboratively to identify a strategy for their development and deployment.

B. Maximize DoD access to DOE technical expertise and assistance through cooperation in the deployment and pilot testing of emerging energy technologies.

We have provided our thermal testing publications to an information clearinghouse managed by the Geothermal Academy, of the National Renewable Energy Laboratory (NREL), which is a DOE organization.

4) Air Force Energy Plan

Section 4 Creating a Framework for Energy Management Across the Air Force

Below is a synopsis of the overarching goals of the Air Force Energy Plan:

Reduce Demand: Through energy efficiency and conservation measures, and by raising awareness of the need to reduce Air Force energy consumption.

Increase Supply: By researching, testing, and certifying new technologies, including renewable, alternative, and traditional energy sources, the Air Force can assist in creating new domestic energy supplies.

This project directly addresses two of the three pillars of the Air Force Energy Plan (underlined text above).

5) **Metering:** According to the Air Force Civil Engineering Service Agency (AFCESA), Measurement and Verification Handbook, Section 5.1

Energy measurement and verification goals may vary significantly depending on the project type, location, funding source, project cost, anticipated savings, economic project life, and other factors. In general, the goals should accomplish the following:

1 establish economic feasibility of the ECM (energy conservation measure);

2 provide a method to obtain a cost effective baseline;

3 establish procedures for adjusting baselines on changes in the facility use which might impact the project; and

4 establish the physical requirements for in-line items that require installation as part of the ECM.

The performance goals of this project directly address items 1 and 4 of the above list. Further, we are documented construction costs associated with this technology.

2.0 ENERGY FOUNDATION TECHNOLOGY DESCRIPTION

2.1 TECHNOLOGY DESCRIPTION

Energy foundations use the structural supports of a building for emplacement of heat transfer tubing that exchanges heat with the foundation and adjacent ground. The tubing is connected to a water source heat pump to provide heating and cooling for a building. Energy foundations offer an energy-efficient means of heating and cooling buildings that requires only electrical energy (vs. oil or gas)—hence, they offer the same advantages as all ground source heat pumps.

Description: In a heat pump, refrigerant is circulated through a loop and transfers heat primarily by changing phases—giving up heat when it condenses from a gas to a liquid and absorbing heat when it evaporates (Fig. 1). In the heating phase, the refrigerant in the evaporator absorbs heat from a source (e.g., ground, water or air), and changes phase from a liquid to a gas in the evaporator. The refrigerant gas is then compressed, raising its temperature and pressure. As the hot gas circulates through the condenser in the heating system, it gives off heat, causing it to condense to the liquid phase. The expansion valve then lowers the pressure (and hence the temperature) of the liquid which then absorbs heat and the cycle repeats. In winter the heat extracted by the heat pump is used to warm the building. The system is run in reverse in the summer and the ground becomes a heat sink.

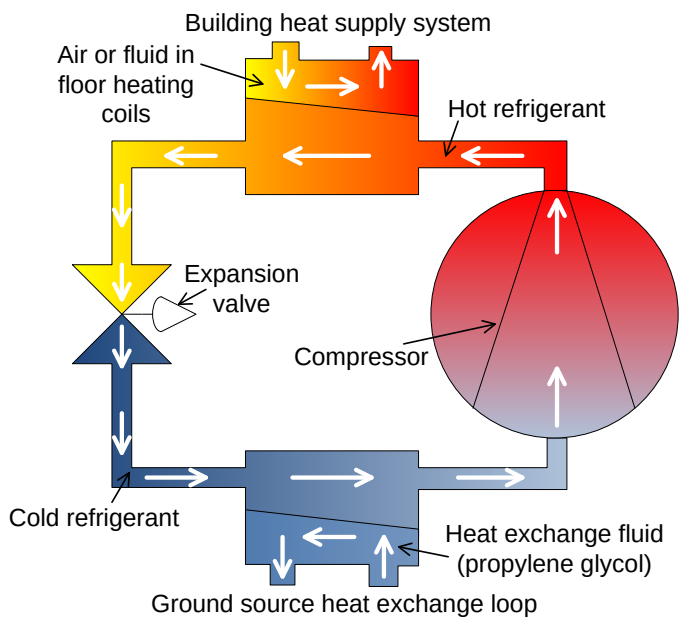

Figure 1. Schematic of the heat pump cycle.

Minimizing the temperature difference between the heat source and the sink increases the coefficient of performance (COP), defined as the ratio of heat energy output over energy input. Heat pumps use the air, ground or water as the heat source and sink for heating and cooling, respectively. For air source heat pumps, the power required to operate the compressor depends on the exterior air temperature, which is highly variable over time in temperate and cold climates. Further, the air temperature is low when the heating demand is the greatest and high when the cooling demand is the greatest. In a GSHP system, heat is absorbed and or rejected to

the ground—which is typically at a relatively constant temperature even at depths as shallow as 2 m (6 ft). Although the subsurface temperatures vary with geologic setting throughout the U.S., the average temperature of the ground below a depth of 1.3 m (4.5 ft) is approximately 10-13˚C (50 to 55 ˚F) year-round (Omer 2008). For the most effective performance, the heat transferred from the source via the heat pump is used to heat liquid in an in-floor radiant heat (hydronic) system (i.e., there is a relatively low temperature difference between the heat source and sink).

Ground source heat pump systems typically utilize high density polyethylene (HDPE) tubing that is installed to depths up to 120 m (400 ft, http://energy.gov/energysaver/articles/geothermal-heat-pumps), although the authors know of 180-m-deep installations (e.g., at the U.S. Air Force Academy). The size of the tubing varies, but typical diameters are 20 to 25 mm (0.75 to 1.0 in) (Brandl, 2006). The heat exchanger tubes are filled with a propylene glycol-water mixture, and a pump is used to cycle the liquid through the closed loop in the ground. For best heat transfer with the ground the fluid should be circulated such that there is turbulent flow of heat transfer fluid in the HDPE tubing.

Like GSHP systems, EFHP systems exploit the constant ground temperature at depth to maximize the COP. Figure 2 is a schematic of a typical EFHP system. The foundations are constructed by auguring a 0.5- to 1.8-m (18- to 72-in) diameter hole, lowering a steel reinforcement cage into the hole, and backfilling the hole with concrete. Prior to placement in the drilled holes or borings the cages have heat exchange tubing loops that are attached to them. The heat transfer tubes are then tied together with header pipes at the ground surface and connected to the heat pump (Figs. 3 and 4). In an alternative to drilled shaft energy foundations, steel energy piles are also constructed and then screwed or driven into the ground (e.g., Nagano, 2007).

Finally, optimal heat pump sizing for energy conservation usually involves an additional source of heat for times of high heat demand. As a rule of thumb, for a heat pump to be operated most economically, it should operate for 3,000-4,000 hours per year at full load (Koen and Geelen, 2000). One way to accomplish this is to reduce the size of the heat pump so that peak load demands (e.g., approximately 10-20% of the heating demand when the temperatures are very cold) must be met with a different heating device (such as a boiler).

Comparison to existing technology: For new construction, the capital costs of the heat exchangers of an energy foundation are that of the HDPE tubing and the labor of connecting the tubing to the steel reinforcement. In comparison, for GSHPs drilling equipment must be mobilized to the site and boreholes drilled and backfilled with thermally conductive grout. Energy foundations also require significantly less, if any, open land compared to boreholes.

Most energy foundation projects involve large structures that require deep foundations and the designers included energy foundations in order to reap the benefits usually supplied by GSHP systems without the additional installation costs (Brandl, 2006). Brandl (2006), in reviewing several case-studies of energy foundations, noted that due to the superior thermal properties of concrete (thermal conductivity and heat storage capacity) and geometry of heat transfer tube placement, the heat transfer rate is often higher in the energy foundations than in boreholes.

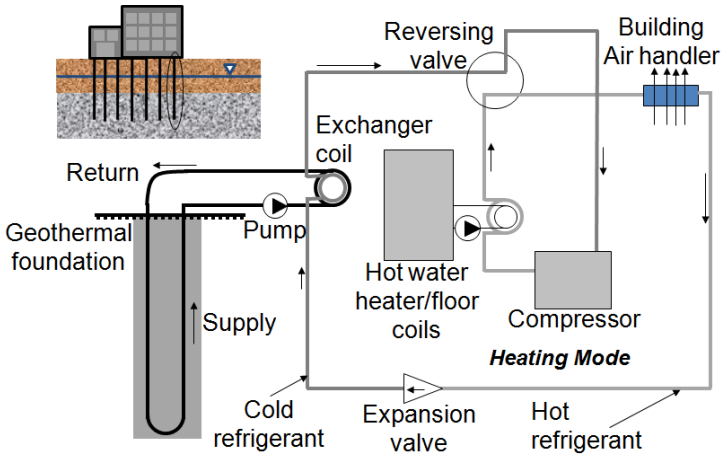

Figure 2. Schematic of building with energy foundations (inset) and connection of heat pump cycle to the energy foundation.
(From McCartney et al. 2010)

Figure 3. Photo of energy foundation construction for this demonstration in April 2012.
The HDPE heat transfer tubing was placed inside the rebar cage, attached to the cage via zip ties and charged with an 80/20% water/ propylene glycol mixture prior to emplacement. The tubes were capped with pressure gages to assure no loss of fluid during construction.

Figure 4. Photo of grade beam construction for this project in May 2012.
The HDPE heat transfer tubing was routed from each foundation through the grade beam before the concrete was placed. In the middle of the photo, workers are bringing each foundations heat transfer tubing to a manifold inside the (to be constructed) mechanical room.

The thermal design and testing of energy foundations is currently the focus of considerable research (e.g., Cecinato and Loveridge, 2015). Brandl (2006) noted that for foundations with diameters of 0.3m to 0.5 m (12in to 20in), 40 to 60 W/m (42 to 62 Btu/h per ft) vertical length can typically be extracted, whereas if the foundations have diameters greater than or equal to 0.6 m (2 ft), 35 W/m^2 (12 Btu/[hr ft^2]) in contact with the soil can be used (for a 0.6-m-diameter foundation, this is equal to 132 W/m length). These are quite similar to those used for vertical borehole heat exchanger design, which are listed by Sailer, et al. (2015) as 35 to 60 W/m (36 to 62 Btu/h per ft).

Thermal conductivity values listed by the Ground Source Heat Pump Association of the United Kingdom are 0.3 to 5.0 W/m°K (0.2-2.7 Btu-ft/[hr ft^2 °F]) for soil, 1.7 to 7.4 W/m°K (1.0-4.3 Btu-ft/[hr ft^2 °F]) for rock, and 1.4 to 3.6 W/m°K (0.8-2.1 Btu-ft/[hr ft^2 °F]) for concrete, depending on the specific constituents of concrete. Hence, the thermal conductivity of concrete is generally somewhat lower than most rock material and approximately equal to that of soil. However, the thermal performance of energy foundations can be optimized compared to borehole heat exchangers by placing heat transfer loops towards the outer edges of the foundations to minimize conductive heat transfer between tubes containing downward flowing and upward flowing heat transfer fluid (Cecinato and Loveridge, 2015).

Thus, the thermal performance of energy foundations compared to a separately installed borehole field will be site and project specific (e.g., what is the optimal pile size for the structural requirements of the building?), and field thermal conductivity testing is often used to verify the actual values of the thermal properties in contact with the foundations to be used in system design. Typically only a portion of the installed deep foundations are utilized as energy foundations (i.e., Brandl, 2006).

Various modifications are sometimes used to make this technology economical in specific climate zones (e.g., Brandl, 2006). For example, if the heating season exceeds the cooling season by a significant amount, then configurations of the heat transfer loop could take advantage of waste heat; or, the ground heat could be recharged with solar energy. If the cooling season exceeds the heating season demand, resulting in ground temperature increases, the ground heat could also be used to heat domestic hot water.

2.2 TECHNOLOGY DEVELOPMENT

The earliest construction of energy foundations (including shallow mat foundations followed by deep foundations) occurred in the 1980's in Switzerland and Austria (Brandl, 1998). More than 6,000 energy foundations (piles) were installed in Austria between 2005 and 2009 (Brandl, 2009). Their use has grown exponentially in the UK, mainly driven by the code for sustainable buildings that requires the construction of zero-carbon buildings by 2019 (Boënnec 2009).

Several full-scale projects have been constructed in Europe (Brandl 2006; Desmedt and Hoes 2007); Japan (Ooka et al. 2007; Nagano, 2007) and the UK (Amis et al. 2009; Boënnec 2009) in which energy foundations (also termed thermo-active foundations) provided heating and cooling to the structures that they founded. These projects all concluded that the energy foundations provide sustainable heat output, long-term reductions in heating and cooling costs and helped to meet carbon emission reduction goals.

At the time this demonstration began (2011), one energy foundation construction project had been successfully completed in the United States by Kulchin Drilling, of Redmond, WA, for a residential building named Art Stable in Seattle (Redmond Reporter 2010). Upon completion of the construction, Kulchin Drilling estimated "saving between 30-50 percent of heating and cooling energy usage, depending on the season." (Note: the HVAC system to which the comparison was made was not identified.) Further, no instrumentation was included in this system to monitor either the thermal response or the thermo-mechanical deformation response.

Another project was completed in 2011 in Denver, Colorado, in which two of 60 drilled shaft foundations for an eight-story building, were constructed as energy foundations in order to demonstrate their feasibility (Zitz et al. 2011; Murphy and Mc Cartney, 2012; McCartney and Murphy, 2012; Murphy and McCartney 2015). The two foundations were linked to a 'traditional' deep borehole field to supply heating and cooling to the building with a ground source heat pump and were end-bearing on shale.

This project was the third operational installation of energy foundations in the United States (some have been installed for thermal and mechanical testing purposes), the second to include instrumentation embedded in the energy foundations, and the first to include comprehensive instrumentation to assess the role of the EFHP system in the thermal structural response of the building system. At the time of writing of this report there are no design standards for the installation of energy foundations.

We were able to perform considerable thermal testing to help validate this technology to the geotechnical engineering design community as well as providing data on the actual thermal performance of the foundations. A list of publications and presentations is given below (Tables

1a and b, respectively) that resulted from this project. Two of the publications are provided as appendices to this report.

Table 1a. List of journal articles, magazine article and conference papers resulting from this project.

The publications are listed in reverse order of their publication date.

Publication	Description/ contribution
McCartney, J.S.; K.D. Murphy and K.S. Henry (2015) Response of an Energy Foundation to Temperature Fluctuations. In Proceedings, International Foundations Congress and Equipment Exposition, March 17-21, Iskander, Suleiman, Anderson and Lafer, eds. pp. 1691-1700 http://dx.doi.org/10.1061/9780784479087.153	We estimated the coefficients of thermal expansion of the foundations based on automated strain and temperature readings in the shower/shave during a time in which no testing was conducted or HVAC equipment was operating. (Presented by K. Henry.)
The Military Engineer, March-April, 2015 issue: Energy and Sustainability News, No. 694 http://themilitaryengineer.com/index.php/staging/item/447-tme-march-april-2015	The demonstration project was described for the military engineering community. It was highlighted under a section entitled Foundations of Energy. (K. Henry contributed to the article.)
Murphy, K.D., J.S. McCartney and K.S. Henry (2015) Evaluation of Thermo-Mechanical and Thermal Behavior of Full-Scale Energy Foundations, Acta Geotechnica, Vol. 10, No. 2, pp. 179-195. (Appendix B of this report) http://dx.doi.org/10.1007/s11440-013-0298-4	This article summarizes Murphy's thesis results for this project. Thermal testing indicated that the maximum displacement induced by foundation heating was less than 2.0 mm and is not a concern with respect to structural performance. It also showed that heat is lost from the horizontal tubing in the grade beam, and a correction factor for this loss was determined. Heat extraction rates ranged from 65 to 108 W/m, depending on the heat transfer loop configuration. The thermal conductivity of the surrounding soil was estimated at 2.0 W/m°K
Nicholson, D.; P. Smith, G. A. Bowers, F. Cuceoglu, C. G. Olgun; J. S. McCartney, K.S. Henry, L. L. Meyer, F. A. Loveridge (2014) Environmental impact calculations, life cycle cost analysis, The Journal of the Deep Foundations Institute, Vol 8, No 2, pp. 130-146 http://www.maneyonline.com/doi/abs/10.1179/1937525514Y.0000000009	This article summarizes and extends work accomplished at the International Workshop on Thermoactive Geotechnical Systems for Near-Surface Geothermal Energy. It explains that methods for the sustainability evaluation of thermoactive geotechnical systems still need to be developed, but that the development can be done within larger regulatory frameworks (various systems are described). Life Cycle analyses utilizing ground source heat pumps provide valuable insight into the indirect operational environmental impacts of these systems.
Murphy, K.D., K.S. Henry, and J.S. McCartney. (2014). "Impact of horizontal run-out length on the thermal response of full-scale energy foundations." Proceedings of GeoCongress 2014 (GSP 234), M. Abu-Farsakh and L. Hoyos, eds. ASCE. pp. 2715-2714..	This paper published results of the thermal response test performed on four of the foundations for 21 days when a constant rate of heat input was applied. We observed that the longer the heat transfer tubing runs horizontally above ground, the more heat loss occurs. (Presented by J. McCartney)

Table 1a. List of journal articles, magazine article and conference papers resulting from this project (continued).

Publication	Description/ contribution
Murphy, K.D., J.S. McCartney, and K.S. Henry. (2014). "Thermo-mechanical characterization of full-scale energy foundations." From Soil Behavior Fundamentals to Innovations in Geotechnical Engineering: Honoring Roy E. Olson (GSP 233). M. Iskander, J.E. Garlanger, M. Hussein, eds. pp. 617-628.	This paper reports the results of the first heating test performed, which was on Foundation 4 only. The estimated 'system' thermal conductivity was found to be 3.3 W/m°K based on this initial test.
Murphy, K.D. (2013) Evaluation of thermo and thermo-mechanical behavior of full-scale energy foundations, Master's Thesis, University of Colorado, Boulder, Department of Civil, Environmental and Architectural Engineering, 117 p.	Murphy established that side shear stresses on constructed energy foundations at Denver and USAFA provide resistance to thermally induced movements, because measured strains during testing of the shower/shave foundations are less than the theoretical thermal expansion and contraction of the reinforced concrete. Such movements should not cause structural or aesthetic damage of the building.

Table 1b. List of posters and presentations resulting from this project.
(in reverse chronological order)

Presentation/Poster Citation	Description/ contribution
K. Henry (2015), Introductions to Energy Foundations and Thermo-mechanical test results from the US Air Force Academy Demonstration, Presentation, Oregon State University, School of Construction and Civil Engineering, Feb 19.	This was an undergraduate/ graduate student seminar given at Oregon State which introduced heat pumps, GSHP systems and energy foundations and presented thermo-mechanical testing results with a focus on mechanical performance.
LaPrade, K., K. Henry, A. Hoisington and A. Laffely (2014) Energy Foundations, Poster, Defense Energy Summit, Austin TX, November 11-13.	This poster describes the demonstration project at USAFA as well as some estimates that 2nd Lt LaPrade made regarding potential energy cost savings.
Henry, K. (2014) Energy Foundations: Full-Scale Evaluation at the US Air Force Academy, Poster, presented at Corona weekend, United States Air Force Academy	This poster describes the demonstration project at USAFA and was part of the USAFA research poster session presented to visiting General Officers.
Murphy, K.D.; K.S. Henry and J.S. McCartney (2013) Impact of Horizontal Run-out Length on the Thermal Response of Full-Scale Energy Foundations, Poster, GeoCongress, Atlanta, GA,	This poster reports our initial thermal testing in which we were able to evaluate the impact of this horizontal runout length on the thermal response of the energy foundation. An empirical relationship was developed to account for the effects of horizontal run-out length. (Presented by J. McCartney)
Henry, K.S. and K. Baker (2014) Building Energy Simulation: Energy Foundations with HP vs. Natural Gas Boiler, Presentation, Critical Infrastructure Symposium, Colorado Springs Available from: http://www.tisp.org/index.cfm?pid=13324	This presentation described 2nd Lt Baker's independent study project in which he utilized BEOpt and GLHEPro to model and predict building energy usage for the shower/shave, comparing the EFHP system to the gas boiler. GLHEPro was used to extend work described below.
Baker, K. and K.S. Henry (2013) Building Energy Simulation: Energy Foundations with Heat Pump vs. Natural Gas Boiler, Poster, Defense Energy Summit, Austin TX, November 11-13.	This presentation described 2nd Lt Baker's independent study project in which used BEOpt (after attempting to use EQUEST) to model carbon emissions and energy consumption of the EFHP system and the gas boiler system for the shower/shave building.

2.3 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

There are two means by which to compare energy foundations to alternative technologies. One way is to compare the HVAC system associated with the energy foundation—that of a ground source heat pump plumbed to the hydronic heating system of the building with another high-efficiency HVAC system—in our case, this is a high-efficiency gas boiler. The second basis is that of installing heat transfer tubing into the foundations vs. installing heat transfer tubing into boreholes or other ground installations such as trenches. In order for this second comparison to be made, we must assume that energy foundations can meet the same demand as that of the boreholes drilled for GSHP systems. This is generally true, as discussed in Section 2.1.

With regard to the HVAC system comparison, the advantages of the energy foundation heat pump system compared to other HVAC systems are the same as those for ground source heat pump systems compared to traditional heating and cooling systems (gas, oil, air conditioners) and include considerable energy cost savings, deriving from the relatively constant-temperature ground heat source and sink. Because most ground source heat pumps operate on electricity, as the electrical grid becomes decarbonized, heating and cooling with energy foundations will automatically incorporate the emissions savings. The expected Coefficient of Performance (ratio of heat energy produced to electrical energy required) is estimated to be 2.5 to 4.0.[1]

Operations and maintenance costs compared to conventional HVAC systems are hypothesized to be similar. Because of the ability to incorporate the heat transfer tubing into foundation elements already required for structural support of the building, installation costs are low compared to GSHP systems. As noted in Section 2.1, the heat transfer characteristics of vertical foundations are similar to boreholes, and as the width of foundations increase, the heat transfer characteristics improve over those of boreholes.

With regard to construction cost comparison, the principal capital cost of the heat exchange component of an energy foundation (i.e., beyond that of the cost of a typical drilled pier) is that of the HDPE tubing and the labor of connecting the tubing to the steel reinforcement of the drilled shaft foundation, providing considerable construction savings compared to installation of boreholes. Although there is labor related to attaching the tubing to the rebar cages, the additional expense of drilling a separate borehole (or borehole field) is completely avoided.

Another benefit of energy foundations over conventional borehole GSHP systems is that energy foundations require less open land outside the building footprint, which can be a major issue in metropolitan and other built-up areas. In the relatively rare case of a building needing to be retrofitted with deep foundations, there is the possibility of having the new foundations be installed as energy foundations.

Potential risks associated with energy foundations are related to the design and construction of the heat transfer portion of the system. If improperly designed for the building heating load, the energy foundation system may permanently increase or decrease the ground temperature, thus compromising the efficiency of the system. For best operational energy efficiency, the energy foundation heat pump system, like all ground source heat pump systems, should be sized to carry

[1] http://www.greenspec.co.uk/ground-source-heat-pumps.php

only a portion of the peak heat demand load in order to avoid having the heat pump cycle on/ off frequently. Given the equivalency (or better) in thermal performance to GSHP systems, the supplemental heating system should cost no more than that for the standard GSHP system.

There is a risk of damage to the heat transfer system during construction. Construction difficulties that were anticipated on this project included damage to the heat transfer tubing, which would cause leaks, and render the loop useless. No damage occurred during construction. Pressure testing of the water-filled tubing during and after foundation installation verified this.

Another potential issue related to construction is reduced heat transfer characteristics resulting from the formation of gaps and holes around the heat transfer tubing due to improper or incomplete placement of concrete around the rebar cage and tubing. If contact between the concrete and heat transfer tubing is not complete (i.e., air gaps form) there will be decreased thermal performance compared to the design. Contractor skill and patience during the concrete placement and the consistency of the mix (specifically the slump), is important in avoiding this issue. For this project, we observed the construction of each foundation, and found that with the use of a mirror to assist in viewing to the depth of concrete placement, and with high slump concrete, there was good contact between the concrete and tubing and the concrete and soil on each foundation.

We anticipate little maintenance associated with the heat transfer fluid circulation in the foundations; the chances of damage in the foundation are lower than those in vertical boreholes as the tubing is encapsulated in concrete. However, should something malfunction within the foundations, it would be difficult to service in an economical manner.

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3.0 PERFORMANCE OBJECTIVES

3.1 OVERVIEW

The qualitative performance objectives of this demonstration are listed in Tables 2a and b. The qualitative objectives (Table 2a, Section 3.2) relate to how easily this technology could be implemented using state-of-practice construction techniques.

The quantitative objectives (Table 2b, Section 3.3) are linked to energy costs, construction costs, life cycle costs and carbon emissions. Our plan was to monitor electrical power consumption to help evaluate five of the six quantitative objectives. Because the HVAC systems have not been operational as of the writing of this report, we instead estimated the power consumption of the systems for an average heating year. Details on how these objectives were evaluated are found in Sections 6.0 and 7.0.

3.2 QUALITATIVE PERFORMANCE OBJECTIVES

The first objective, ease of construction of the energy foundations, was met as the construction crew was able to complete the construction of the energy foundations with no additional training. A preliminary meeting among the contractors (including the geothermal contractors), and the authors of this report to describe this project and objectives helped assure success.

The constructability of the retrofit was not evaluated because shortly before construction we determined that jacking up a newly constructed building was impractical. The only potentially practical retrofit of an energy foundation would occur if a damaged foundation had to be underpinned.

Since the HVAC system was never operational, we could not fully evaluate qualitative to the ease of maintenance of the EFHP system (Objective 3). Nonetheless, performing system pressure checks on the heat transfer tubing component was straightforward; and filling and checking the heat transfer tubing was done without complication when the heat pump was installed. The maintenance of the gas boiler, heat pump and all other system components that are located in the mechanical room of the shower building are expected to be routine.

Table 2a. Qualitative performance objective for the demonstration of energy foundations.

Performance Objective	Metric	Data Requirements	Success Criteria	Results
Ease of construction (1)	Ability of construction crew to construct the foundations	Documentation of foundation construction	Able to construct with 3 days or less additional training	**Objective met**
Ease of energy foundation retrofit (2)	Ability of construction crew to construct the retrofit	Documentation of foundation construction	Able to retrofit with 3 days or less additional training	**Objective not evaluated**
Ease of maintenance (3)	Ability of technician to perform necessary repairs on the system	Feedback from technician performing maintenance	Similar in difficulty to maintaining a 'conventional' system	**Objective not evaluated**

3.3 QUANTITATIVE PERFORMANCE OBJECTIVES

The quantitative performance objectives are listed in Table 2b.

Table 2b. Quantitative performance objective for the demonstration of energy foundations.

Performance Objective	Metric	Data Requirements	Success Criteria	Results
Reduced energy costs of system (1)	Cost per Btu (kWh) of heating	Electrical consumption and costs of EFHP systems, Heating output of both HVAC systems, Fuel use and cost of conventional HVAC system	The energy foundation system costs < 70% of conventional heating system	**Objective not met**
Reduced carbon emissions (2)	Carbon emissions per Btu (kWh) of heating	Electrical usage of both HVAC systems, Electrical power source and electrical generation efficiency, Efficiency of conventional HVAC system	> 50% reduction in carbon emissions compared to conventional heating/cooling system	**Objective not met**
Increased energy efficiency compared to air source heat pump (3)	Coefficient of Performance	Electrical usage of both HVAC systems, Heating output of both HVAC systems including a measure of the heat output for energy input of each individual foundation	> 40% improvement in COP compared with air source heat pump	**Objective met using estimates of HSPF values and not measured COPs.**
Construction costs of energy foundation vs. boreholes (4)	Construction costs	Construction and installation costs of energy foundation system, Estimated construction costs of conventional borehole system*	>50% decrease in cost compared to a conventional GSHP bore fields	**Objective met**

Table 2b, continued. Quantitative performance objective for the demonstration of energy foundations.

Performance Objective	Metric	Data Requirements	Success Criteria	Results
Reduced life-cycle costs (5)	Life cycle cost of heating systems	Construction costs, Electrical usage and cost of both HVAC systems, including a measure of the efficiencies of each individual foundation	> 30% decrease in life cycle heating system costs compared to conventional HVAC system	**Objective not met**
Retrofit life-cycle costs (6)	Life cycle costs of heating systems	Life cycle cost estimate of EFHP system based on installing heat transfer loops in foundations being repaired	Cost of adding heat transfer loops to foundation repaired is paid for in reduced life cycle costs with a 30% margin	**Objective not evaluated**

The motivation for Objective 1 is based primarily on the fact that the DoD is the Federal government's largest energy consumer.[2] Facility energy is about 20-25% of the DoD's energy consumption, and the cost of it is of primary importance.[3] As outlined in Section 1.4, the Objective aligns with Executive Orders 13423 and 13514.

To evaluate Objective 1, we used an average year temperature bin data and HVAC-Calc software to determine the total heating demand of the building. Using current rates paid by the US Air Force Academy for natural gas and electricity, we estimated that the cost per million Btu of the gas boiler system is $8.47 and that for the EFHP system is $7.40. Since the estimated energy costs of the EFHP system are 87% of those of the natural gas boiler, the performance measure was not met, even though it represents an energy cost savings.

Objective 2 aligns with Executive Orders 13423 and 13514. The DoD needs to maintain operability in the face of climate change; and, has aggressive goals with regard to emissions reduction.[4]

In the estimates of carbon emissions that we made for the 89% coal-fired electricity source at the US Air Force Academy, this objective was not met. The EFHP system would generate 5,889 pounds of additional carbon compared to heating with the natural gas boiler alone. In order for

[2] http://www.eia.gov/totalenergy/data/annual/txt/ptb0113.html
[3] http://www.acq.osd.mil/ie/energy/library/FY.2011.AEMR.PDF
[4] http://www.acq.osd.mil/ie/download/green_energy/dod_sustainability/2012/DoD%20SSPP%20FY12-FINAL.PDF

this objective to be met, the electrical source would have to experience considerable de-carbonization.

The coefficient of performance (COP) is the primary means of measuring the efficiency of ground source heat pumps, per Objective 3. Ground source heat pumps are often advertised and sold on the basis of the coefficient of performance. Hence, the COP was originally selected for comparison in this project. Air source heat pumps energy efficiency is usually measured in heating seasonal performance factors (HSPF), which is defined as the total Btus supplied by the heat pump divided by the total Watt-hours required to run them. We ultimately compared the HSPFs of the purchased heat pump, utilizing the COP provided by the manufacturer, and an air source heat pump. We determined the HSPF of a 'typical' high-efficiency air source heat pump de-rated for the climate of Colorado, and estimated that Objective 3.0 would be met, as we calculated an HSPF of 10.7 for the installed heat pump and a typical air source heat pump installed in the Front Range would have an HSPF of 6.4.

Objective 4 addresses the potential to obtain near-surface geothermal heat for very low cost by simply inserting heat transfer elements in foundations that are already required for building support. The primary cost is the labor required to assemble and place the heat transfer tubing in the foundations. There is no need to mobilize extra drilling equipment for borehole development and to coordinate that with other construction activities.

For this project, we estimated that a single borehole providing the equivalent heat exchange capability to the eight foundations would cost about $4.9k, whereas the cost of installing the heat transfer pipe into the foundations and the extra pipe required to route to the manifold would cost $2.3k for a savings of $2.6k. Hence, the performance objective was met.

Federal buildings must be designed to achieve energy consumption levels that are at least 30 percent below the levels established in the referenced codes, if life-cycle cost-effective.[5][6] Hence, a life-cycle cost analysis is now a part of all Federal construction projects. The National Institute of Standards and Technology (NIST) developed the Building Life Cycle Cost (BLCC) Programs to provide computational support for the analysis of capital investments in buildings. It is used throughout the Federal Government, and we utilized it to compare the life cycle costs of the two HVAC systems.

The BLCC 5.3-15 software was used to perform a life cycle cost analysis of the two systems. The life cycle cost of the EFHP system was estimated at $43,545 and that of the gas boiler only was $37,507. Hence the EFHP system estimated life cycle cost is 116% of that of the gas boiler system, so the objective was not met. This analysis was based on the near-term projected use of the building, which will have minimal use during the heating season with a resulting setback temperature of 55°F (12.8°C). With higher occupancy in the winter, the life-cycle costs would begin to favor the EFHP system due to the lower costs of heating. The analysis results also suggest that the EFHP system would be worth evaluating in new construction projects where deep foundations would be used.

[5] http://www.wbdg.org/pdfs/10cfr435.pdf
[6] http://www.wbdg.org/resources/energycodes.php

The project was originally designed to evaluate the cost effectiveness of retrofitting foundations to become energy foundations, which is indicated by Objective 6. It is improbable that it would be cost-effective to retrofit foundations only for the sake of adding heat exchangers. However, one of the foundations was constructed in order to be able to test the concept of a deep foundation that has been converted into a geothermal heat exchanger after being repaired for another reason. The foundation was configured with heat transfer tubing placed in a bore in the middle of the foundation. Although this permitted evaluation of the thermal response of a retrofitted energy foundation, the construction process of retrofitting was not evaluated. Specifically, the final design of the shower/shave building included the attachment of a concrete grade beam to the deep foundations, which precluded any post-construction activities.

Reasons that a deep foundation would be repaired or be newly constructed under an existing building (which would involve lifting the building) include that the deep or shallow foundation is not performing well (i.e., settlement is occurring) or that the building is being expanded and the structural support needs to be enhanced. One type of repair on a deep foundation is to core through the foundation and grout the base. If this were being done, a single loop of heat transfer tubing could be installed during the grouting process, per our demonstration foundation. Another type of repair would be the need to lift a building off of a shallow foundation for the purpose of installing deep foundations. In this case, the potential benefits would be similar to those for new construction, which would involve placing the heat transfer loops towards the outer edges of the foundations (e.g., this project) to maximize thermal performance.

4.0 FACILITY/SITE DESCRIPTION

4.1 INTRODUCTION

This demonstration took place at the United States Air Force Academy, which is located in Colorado Springs, Colorado. The region is in a semi-arid climate zone. The lowest average monthly temperatures in Colorado Springs occur in December and January, with the average daily lows around 18ºF and average daily highs around 43ºF, respectively. The specific site for the demonstration is located in Jack's Valley, which is most well-known as the field encampment and training site for the second half of cadet basic training for the United States Air Force Academy (Fig. 5).

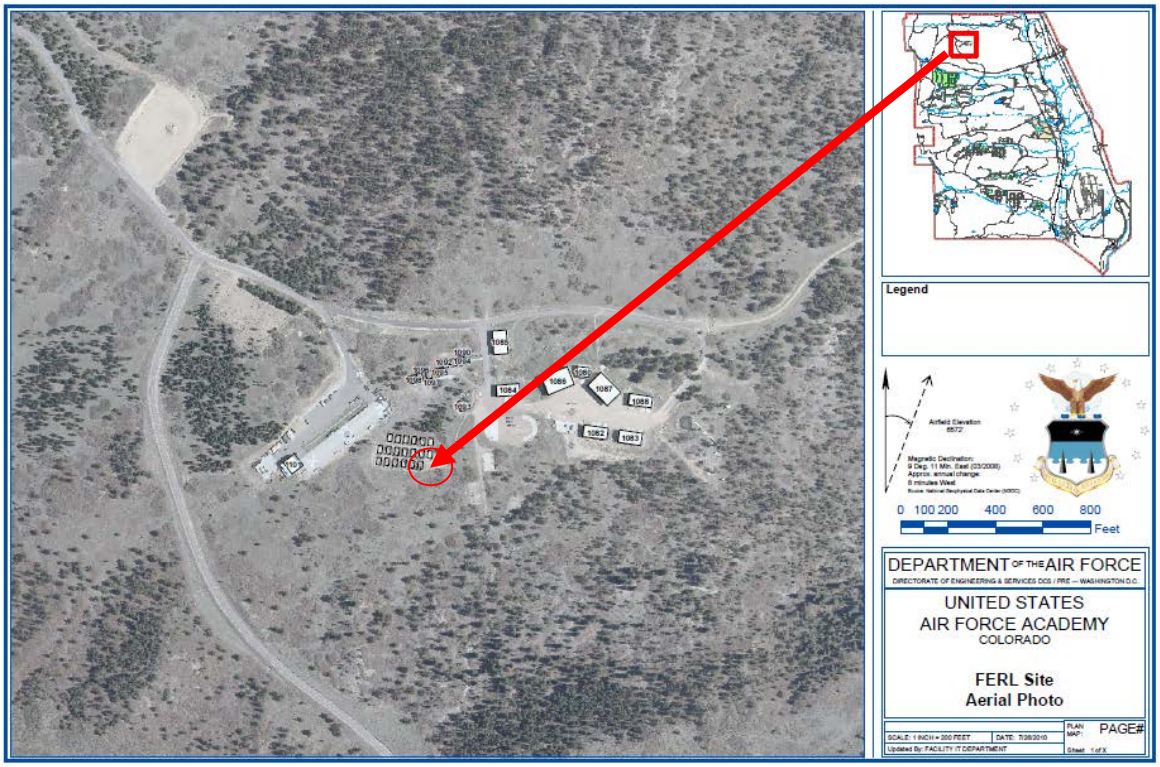

Figure 5. Air photo and map of the United States Air Force Academy showing the location of the shower/shave building prior to construction.

4.2 FACILITY/SITE LOCATION AND OPERATIONS

The elevation of the site is 6980 ft, and it is located on a hill that slopes down to the north. Presently, the FERL site, and the Shower/ Shave facility is used heavily May through July by cadets attending the Field Engineering Readiness Program, a three-credit hands-on academic course that introduces surveying, construction materials, design of concrete mixes, construction and environmental systems. Typically 80 to 100 cadets from the Air Force Academy, the other service academies and ROTC cadets attend this course. All are engineering majors. Following FERL, there is a one-week Society of American Military Engineers (SAME) camp that introduces approximately 100 high school students to military construction and engineering through hands-on activities.

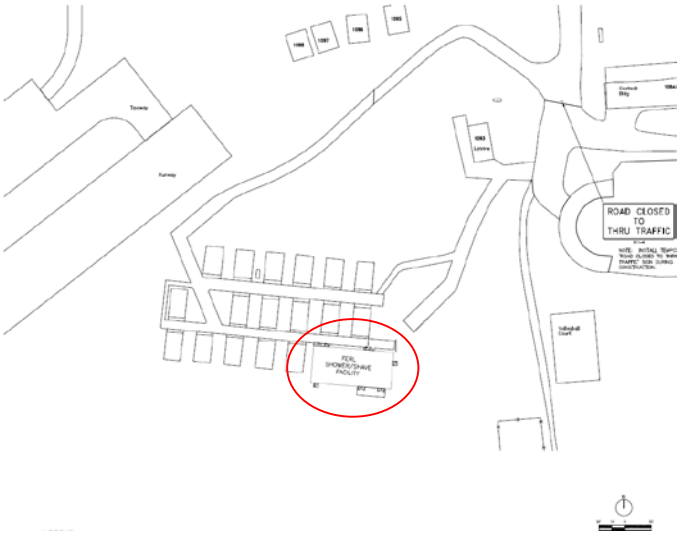

Figure 6. Plan view of the sleeping quarters area of the FERL site, showing the location of the Shower/ Shave building (circled in red).

The shower facility is now a part of the Field Engineering and Readiness Laboratory (FERL), site. It is located in the southeast corner of the sleeping quarters' area (Fig. 6). The sleeping quarters consist of 17 small, wood-framed sleeping units that can be utilized any time of the year. The reason this site was chosen for the energy foundation demonstration is that engineering cadets would be exposed to this potential energy-saving technology, in a building that they use daily, as part of their academic course. Figure 7 is a photograph of the constructed shower shave in June 2015.

Figure 7. Photograph showing Shower/ Shave building from the south (foreground) and sleeping quarters to the west (left).

4.3 GEOTECHNICAL CONDITIONS

The Air Force Academy is located on the Front Range of Colorado and the Rampart Range Fault runs through to Academy property—to the west of Jack's Valley. The Academy lies at the (eastern) base of Rampart Range, which demarcates the eastern edge of Pikes Peak Granite (Varnes and Scott, 1967). The Air Force Academy has five landforms: 1) the steep slopes of the

Rampart Range on the west, 2) sedimentary rock ridges parallel to the range, 3) mesas and foothill ridges separated by broad valleys extending eastward from the base of the mountains, 4) the Monument Creek Valley, and 5) an even to gently rolling area that slopes southwestward toward Monument Creek (Varnes and Scott, 1967). The FERL site is in one of the broad valleys.

The geotechnical conditions of the site are highly favorable for construction of drilled shaft foundations—the construction site was overlain by 0.6 m to 1 m (2-3 ft) of dense granular fill which is underlain by very dense native sand, silt and gravel (typically poorly graded silty sand, SP-SM) overlying Dawson Arkose sandstone. The Dawson Formation is further described as light-gray, coarse sandstone with sandy ironstone layers that cap monument-like erosional remnants (Terracon, 2011). Cross-bedding and cut-and-fill channel deposits are found throughout the formation. The soil properties assumed for design of the foundations are shown in Table 3, and the soil profile used for the foundation design, along with a sketch of one of the deep foundations is shown in Figure 8. The boring logs generated from the site investigation are included as Appendix B.

Table 3. Soil layer geometry and engineering properties assumed for design based on geotechnical site investigation.

Layer	Soil Layer Thickness (m/ft)	Depth from Surface to Bottom (m/ft)	Description	Soil Classification (USCS)	SPT N	Total Unit Weight (kN/m^3/ pcf)	Unconfined Compressive Strength (kPa/ psf)	Drained Friction Angle (°)	Thermal Conductivity (W/mK)
1	1.2/ 4.0	1.2	Backfill	SC	64	120/ 18.9	n/a	30	1.1
2	1.2/ 4.0	2.4	Silty Sand	SM	72	120/ 18.9	n/a	30	0.8
3	3.7/ 12.0	6.1/ 20.0	Tan-Red Clay with SP sand seams	CL	25	105/ 16.6	306/ 6400	n/a	1.2
4	3.1 /10.0	varies	Weathered bedrock	n/a	n/a	20.5/ 130	480/ 10000	n/a	1.2
5	n/a	n/a	Bedrock	n/a	n/a	23.7/ 150	570/ 12000		1.2

Note: Thermal conductivity values of soil were obtained from single needle tests, values for bedrock were assumed to be consistent with CL soil for conservatism.

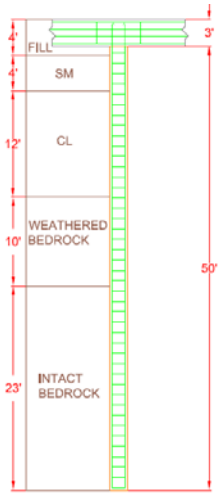

Figure 8. Sketch of soil profile and foundation used in the deep foundation design.

4.4 FOUNDATION DESIGN

Eight drilled shafts, each 15.2-m-deep by 0.61-m-diameter, provide the foundation for the structure (Fig. 9). The purpose of incorporating the drilled shafts into the building (vs. using a shallow foundation) was to evaluate the EFHP system and the structural performance of the foundations as influenced by being heated and cooled. Each foundation contains a 0.46-m-diameter steel reinforcing cage that extends the full length of the shaft. The reinforcing cages are composed of six #7 longitudinal bars with #5 radial hoops spaced at 0.3 m on center throughout the length of the cage. Each foundation contains one, two, or three heat exchanger loops configured in different ways to exchange heat with the concrete and adjacent soil, as well as to test the efficacy of the loop configuration.

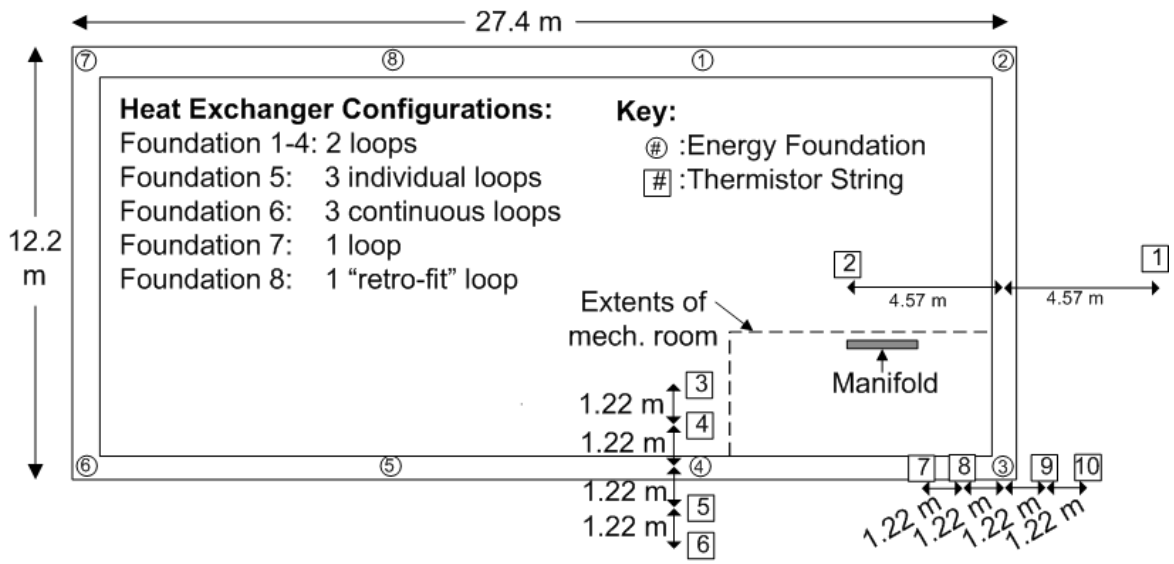

Figure 9. Plan view of the Shower/ Shave building showing the deep foundations (labeled 1 through 8) and instrumentation locations.

5.0 TEST DESIGN

5.1 INTRODUCTION

This project addressed engineering questions related to the foundations as structural elements and the ability of the ground and foundations to deliver heat to the heat pump. Instrumentation was installed on the foundations to measure temperature and strain, and the ground was also instrumented to measure temperature. Hence, this section of the report focuses on the testing performed to measure the thermal and mechanical response of the foundations and the thermal response of the ground to the foundations being heated and cooled.

The tests conducted and the results of the testing are described in detail in Murphy (2013), a Master's Thesis from the University of Colorado at Boulder, Murphy et al. (2015), which summarizes results of the thermal testing in this project (Appendix C), and in Murphy et al., (2014) (Appendix D). A summary of the results are provided in the following sections.

The publications summarized in this section require SI units. Hence, the analyses were performed using SI units, and the summaries provided in this section provide SI units first, with Imperial units provided parenthetically.

5.2 HEAT TRANSFER LOOP DESIGN

Each foundation has some combination of heat transfer loops incorporated into it. The loops consist of 19 mm-diameter (3/4-in) HDPE tubing that are plumbed into a manifold located in the mechanical room. At the top of each foundation, which is 1 m (3.3 ft) below grade, the heat exchanger loop is connected with tubing which is routed through the grade beam into a manifold within the mechanical room of the building. The top of the shafts are spliced into a 0.91 m-deep by 0.61 m-wide (3 ft deep by 2 ft wide) grade beam that extends around the perimeter of the building.

Foundations 1 through 4 have identical heat exchanger configurations, with two continuous heat exchanger loops attached to the inside of the steel reinforcement cage. The inlet and outlet tubes are separated diametrically by at least 90°, which minimizes thermal short circuiting where heat is lost by direct transmission from the inlet to outlet tubes. Foundation 5 has three individual loops; each having a supply and return line running to the mechanical room, permitting any combination of the three loops to be operational. Foundation 6 has three continuous heat exchanger loops with only one supply and return line extending to the manifolds. Foundation 7 contains one loop connected to the interior of the reinforcing cage. Foundation 8 has a single loop in the center of the foundation to simulate a retrofit where a heat exchanger would be inserted into a hole bored into an existing foundation.

Instrumentation was incorporated into three of the eight energy foundations to capture the distribution of axial strain and temperature with depth (Fig. 10). Foundations 1 and 3 contain six Geokon Model 4200 vibrating wire strain gauges (VWSGs), while Foundation 4 contains twelve. Foundation 4 has twice the number of gauges with the intent of capturing detailed strain and temperature distribution. At three locations within Foundation 4, gauges were located at the same

depth on opposite sides of the reinforcing gage to gain redundancy in temperature and strain readings and to capture any differential strain across the shaft (horizontally).

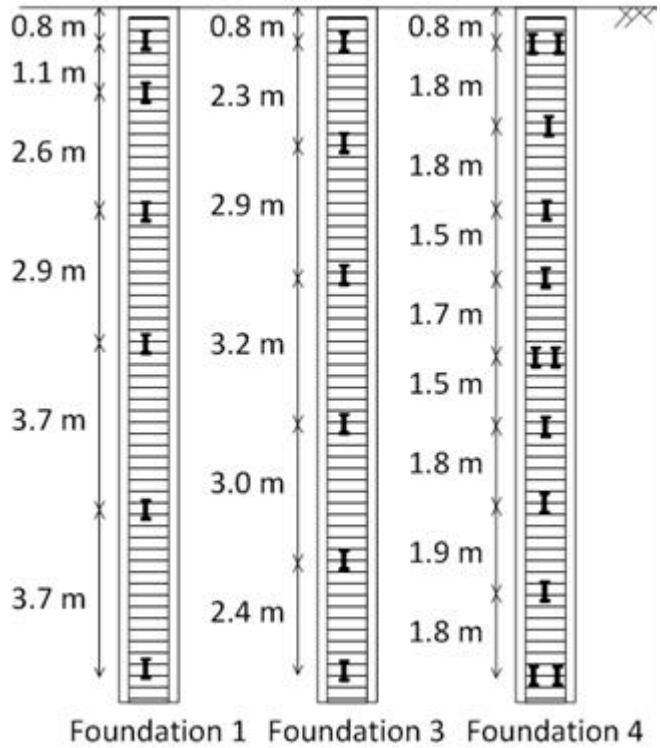

Figure 10. Locations of instrumentation in drilled shaft foundations.

5.3 FOUNDATION CONSTRUCTION

The reinforcing cages were assembled on site prior to construction (Fig.11). Once the cages were constructed, the heat transfer tubing and instrumentation were attached. The tubing was fastened to the inside of the reinforcing cages with zip-ties at a distance of at least 70 mm (2.75 in) from each vertical reinforcing member. U-shaped couplings were used to connect the inlet and outlet tubes so that the tubing does not cross the bottom of the cage. Figure 12 (a) and (b) show the reinforcing cages and heat exchangers, and 12 (c) shows a mounted vibrating wire strain gage. Cables for the instrumentation embedded in the foundation were bundled at the top of the cage until placement in the uncased hole [Fig. 12(c)].

Figure 11. Photo showing attachment of HDPE tubing to rebar cage.

The foundations were drilled, reinforcing cages placed and concrete pumped into the holes in one day. The ground and subsurface material were competent enough to avoid sloughing and no groundwater was present, so the dry-hole drilling method was used—and all eight borings stood open. The reinforcing cages were lifted with a 3-point pick to minimize bending [Fig. 12(d)], and the cages were lowered into the hole with a crane [Fig. 12(e)]. The cages were suspended on wooden beams to ensure that the top of the cage was at the base of the grade beam.

Figure 12. Construction photos.
(a) Reinforcing cages with heat exchangers; (b) Inside view of cage;
(c) Vibrating wire strain gauge; (d) Lifting with 3-point pick; (e) Lowering into uncased hole;
(f) Concrete tremie; (g) Finished foundation; (h) Tubing in grade beam;
(i) Completed grade beam and heat exchanger manifold

A concrete pump truck was used to place high-slump 21 MPa (3 ksi) concrete in the holes following placement of the reinforcing cages. A tremie pipe was used to avoid excessive segregation of the concrete during free-fall [Fig. 12(f)]. Note that Foundation 8 was constructed with a 100 mm-(4-in) diameter plastic sleeve in the center of the foundation. After curing, a single heat exchanger loop was inserted into the plastic sleeve and the hole was grouted with sand bentonite grout (Fig. 13).

Figure 13. Photo of PVC tubing, placed in reinforcement cage, used to simulate bored hole inside Foundation 8.

After the foundation was placed, the PVC tube shown was retrofitted with one loop of heat transfer tubing and grout.

In addition to preventing concrete segregation, the use of the tremie pipe minimized the risk of damage to the heat exchanger loops and embedded instrumentation, and no damage occurred. All heat transfer loops were filled and pressurized, and capped with pressure gages before construction. After construction, there was no loss of pressure, and the loops were easily connected to the heat pump and the heating device used for subsequent testing. The strain gauges gave reasonable readings after placement of the concrete foundations, and produced reasonable readings in the subsequent testing program.

The grade beam was constructed around the foundations [Fig. 12(g)] after the foundation concrete had cured, and the heat exchangers were routed through the grade beam [Fig. 12(h)] into a manifold in the utility room [Fig. 12(i)]. Figure 14 shows the formwork that was placed to form the grade beam, the steel reinforcement in the grade beam and the routing of the heat transfer tubing from each foundation through the reinforcement to the mechanical room. Once the grade beam was poured, the contractor work was completed, and the REDHORSE squadron poured the concrete slab floor, incorporating radiant-in-floor heating (Fig. 15). The radiant in-floor heating can be supplied by both the gas boiler and the EFHP system (Fig 16).

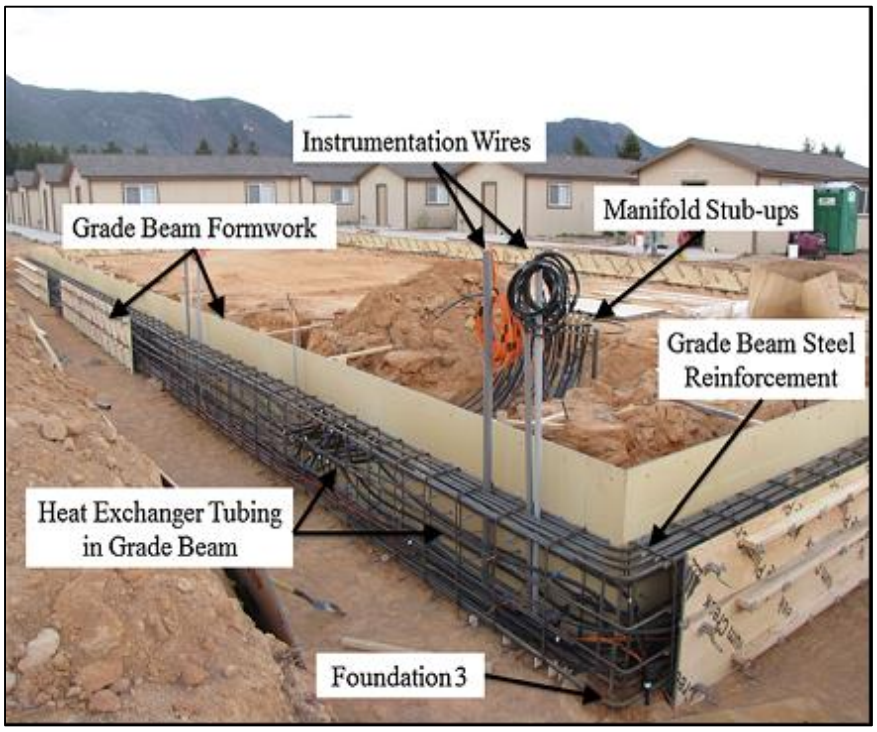

Figure 14. Photo showing horizontal placement of heat exchanger tubing in the grade beam formwork.

Figure 15. Photo showing concrete slab on grade before building wall placement.

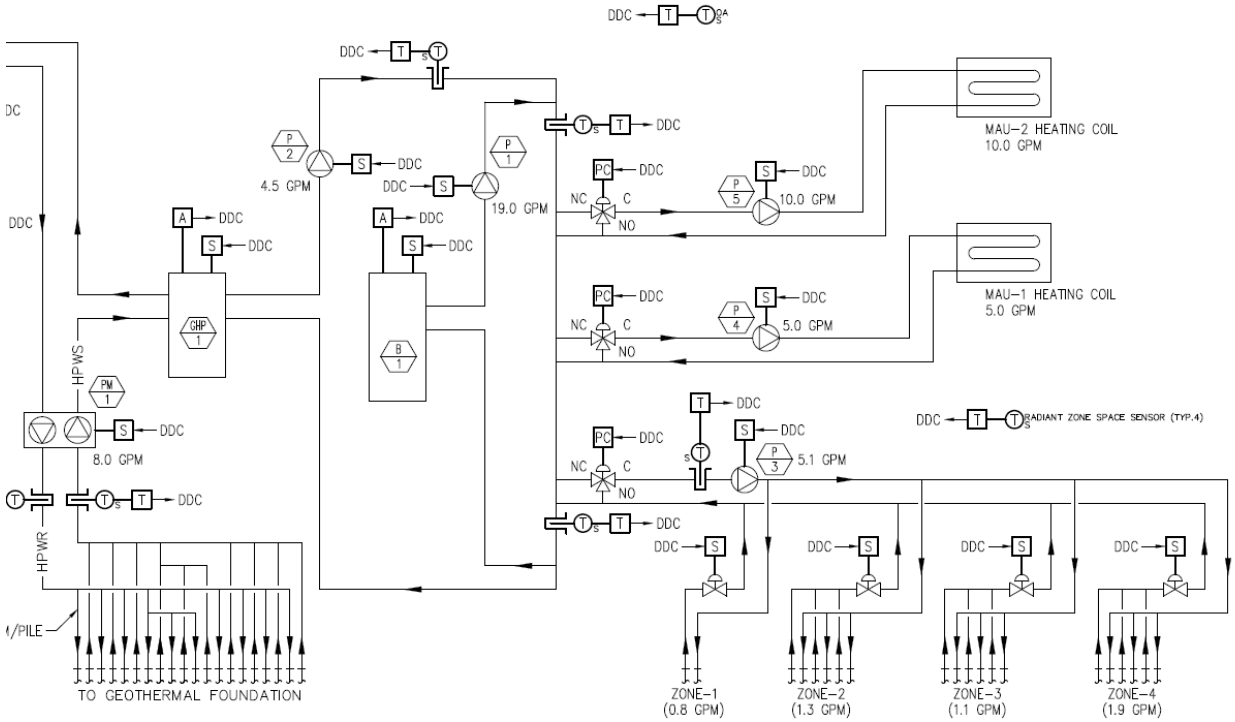

Figure 16. Diagram excerpted from mechanical drawings of the shower/shave, showing the plumbing of the heat pump (GHP) and gas boiler (B) to the radiant in-floor heating system.

5.4 TEST DESIGN OVERVIEW

Thermal tests were performed on the foundations to measure thermal properties and to make stress measurements on the foundations during heating and cooling. When the HVAC systems are functioning properly, we will be able to measure and monitor long-term changes in temperatures, stresses and strains in the foundations, as well as temperature changes in the ground.

As a deep foundation is loaded mechanically, the axial stress is expected to be highest at the head and decrease with depth as side shear resistance is mobilized at the soil– foundation interface. The axial stress will decrease to zero if the side shear resistance is sufficient to support the building load; if not, it will decrease to a nonzero value, and there will be end-bearing resistance in the material underlying the toe of the foundation. As an energy foundation is heated or cooled, the reinforced concrete will tend to expand or contract axially and radially. It is important to establish to what degree the mechanically- and thermally-induced stresses and strains affect the structural performance of the foundations.

Thermal response tests were performed after construction, in which the 20% propylene glycol–water heat transfer mixture was heated and circulated through the foundations. During these tests, the temperatures and strains in the foundations and the temperatures in ground near the foundations were monitored. This enabled validation that there are no structural concerns and

allowed measurement of thermal properties of the foundations. The details of the testing and results are reported in Murphy et al. (2015), and are summarized below (Section 5.6).

5.5 INSTRUMENTATION AND DATA COLLECTION

Foundations 1 and 3 contain six Geokon Model 4200 vibrating wire strain gauges (VWSGs), and Foundation 4 contains twelve. Each of the strain gages includes a temperature sensor. Inlet and outlet temperatures of the heat exchanger fluid for each foundation were continuously monitored using pipe plug thermistors installed within special ball valves on the manifold (Fig. 17).

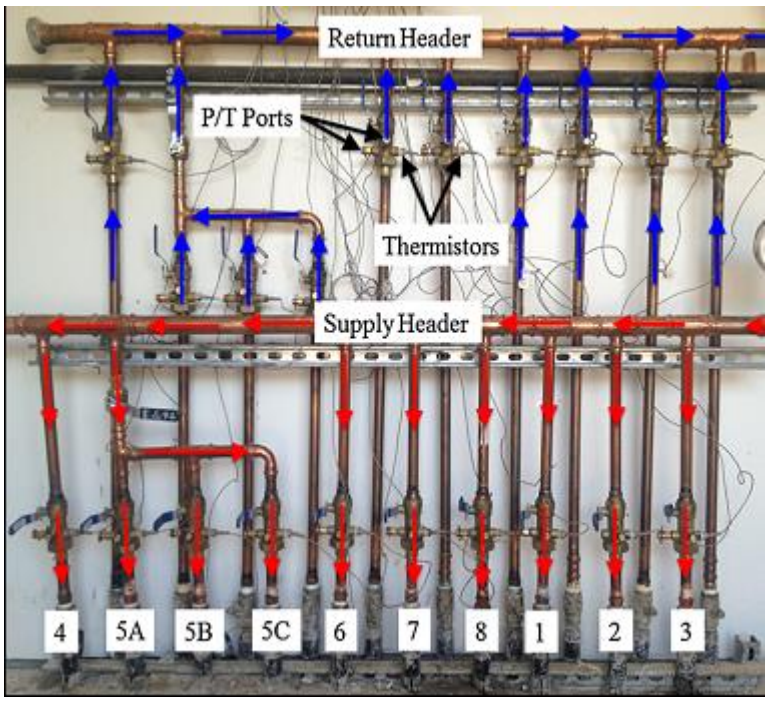

Figure 17. Photo of the manifold showing control valves for the eight foundations.

Temperature variations in the soil surrounding the energy foundations were monitored using a series of ten Geokon model 3810 thermistor strings that each have six sensors, installed in 14.5-m-deep boreholes that were then backfilled with CETCO high thermal conductivity grout. Note that the temperatures around Foundations 3 and 4 are monitored using four thermistor strings each, another thermistor string lies beneath the floor slab to observe any long-term changes in the ground temperature beneath the slab, and one thermistor string is located outside the building footprint to observe seasonal variations in ground temperature. A Geokon, Inc. datalogger (Model 8002-16 LC-2×16) was used to record data every 30 minutes.

5.6 THERMAL TESTING OF THE FOUNDATIONS

Heating of the foundations was done in order to estimate the maximum stresses and displacements induced, to estimate the heat exchange rate per meter length of each foundation, to estimate heat loss from the horizontal lengths of the heat transfer tubing that run from the foundations through the grade beam to the manifold, and to measure the thermal conductivity of

the subsurface soil surrounding the foundations. The foundations were heated with GeoCube thermal conductivity test equipment by heating the heat transfer fluid.[7] Refer to Appendices C and D for test details.

During testing, the rate of heat input was somewhat greater than that expected to be exchanged with the foundation/ground when the system is used to heat the building. The system was designed using a maximum heat exchange rate of 9.0 kW (30.7 kBtu/hr), and 11.0 kW (37.5 kBtu/hr) of heating was the maximum heat energy input during these tests. Hence, the test was conservative for the purposes of estimating stresses than strains that will be induced during operation of the EFHP system.

The heated fluid passed into the supply header, circulated through the foundations, and then passed out of return header back to the test unit. The flow rate of each foundation was measured at one instance during the test on each foundation from the pressure/temperature ports (P/T ports) using a differential pressure meter at a fluid temperature of 30°C (86°F). The differential pressure was then used to compute the flow. During the test, the inlet and outlet temperatures of the heat exchanger fluid for each foundation were continuously monitored, and the heat transfer rate was estimated according to the equation:

$$Q = \Delta T_{\text{fluid}} \dot{V} \rho_{\text{fluid}} C_{\text{fluid}}$$

where ΔT_{fluid} is the difference between the supply and return fluid temperatures in K (T_{supply} and T_{return}, respectively), V is the volumetric fluid flow rate, q_{fluid} is the mass density of the fluid, and C_{fluid} is the specific heat of the fluid.

A series of seven stages were carried out to investigate the thermal response of various components of the energy foundation system at USAFA (Table 4). In each stage, a nominal heat input was selected to avoid heating any foundation component too rapidly. Stage 1 involved heating Foundations 1–4 simultaneously. Stage 1 operated for 498 h with the intent of allowing sufficient time to increase the temperature of the soil surrounding the foundations, permitting the soil thermal conductivity to be estimated. Stages 2–4 were conducted on Foundations 6–8 individually with a nominal heat input to the fluid of 5 kW (17.1 kBtu/hr) and duration of approximately 1 week for each stage. Stages 5–7 were conducted on Foundation 5, which has three individual loops that can be turned on and off at the manifold. Stage 5 operated on only Loop 5A. During stage 6, Loop 5B was activated while continuing to pass fluid through Loop 5A. In stage 7, all three loops in Foundation 5 were switched open so that flow was permitted to pass through all three loops. Stages 5–7 utilized a 2.5-kW heater in the thermal response test unit.

The estimated stresses due to expansion were far below those of the compressive strength of the concrete (maximum of 5 MPa [0.73 ksi] compared to a compressive strength of the concrete of 21 MPa [3 ksi]). The maximum displacement induced by foundation heating was less than 2.0 mm and therefore is not a concern with respect to building displacements during operation of the building (Murphy et al., 2015).

[7] http://www.precisiongeothermal.com/geocube.htm.

It is extremely difficult to individually measure the thermal properties of heat transfer components of the energy foundation systems. Hence, they are characterized by using a system value. Table 3 lists the results of the heating tests in terms of the overall system heat transfer rate per unit length of the foundation. The corrected values refer to the heat transfer rate once corrected for heat loss that occurred through the horizontal portion of the heat transfer tubing between the foundation and the manifold. These values are consistent with those of other full-scale tests of foundations (e.g., Hamada, et al., 2007; Ooka et al., 2007 and Gao et al., 2008) and demonstrate that the energy foundations will perform as designed when the heat pump is utilized to heat the building. Of particular importance is the good performance of the foundations with single heat transfer loops, including the simulated retrofitted loop. It is noted here, though, that the apparently high heat transfer rates for the tests that were conducted for less than 200 hours, may be an overestimate of the performance of the system because steady state conditions may not have been fully met.

Thermal conductivity of the soil near the end of heating in stage 1 was calculated to be 2.0 and 2.3 W/mK (1.2 and 1.4 Btu-ft/[hr ft^2 °F]) for heat flow through the subsurface, which is in the range of values reported in the literature (e.g., Gao et al., 2008 and Lennon et al., 2009).

Table 3. Summary of thermal response tests conducted on the foundations.
Heat applied refers to the heaters used in the thermal test unit.

Test	Foundation	Configuration	Dates Tested	Duration (h)	Heat Applied (kW, kBtu/hr)	Measured Heat Output from Foundation (kW, kBtu)	Q/L (W/m, Btu/[hr ft])	Q/L Corrected (W/m, Btu/[hr ft])
1	1	2 loops	6/18/13-7/9/13	498	11.0, 37.5	3.133, 10.69	73.5, 76.4	105.2, 109.4
	2					2.696, 9.20	80.5, 83.7	101.6, 105.7
	3					2.180, 7.44	102.3, 106.4	109.4, 113.8
	4					2.081, 7.10	88.2, 91.7	97.9, 101.8
2	6	3 loops	7/11/13-7/18/13	175	5.0, 17.1	4.534, 15.47	108.5, 112.8	139.2, 144.8
3	7	1 loop	7/18/13-7/25/13	167	5.0, 17.1	4.431, 15.12	82.1, 85.4	126.9, 132.0
4	8	Retrofit – 1 loop	7/25/15 – 8/1/13	165	5.0, 17.1	4.075, 13.90	64.6, 67.2	120.0, 124.8
5	5A	1 loop	8/1/13-8/5/13	119	2.5, 8.5	2.285, 7.80	69.9, 72.7	90.1, 93.7
6	5A		8/5/13-8/28/13	530	2.5, 8.5	1.164, 3.97	35.6, 37.0	55.8, 58.0
	5B	1 loop				1.150, 3.92	35.2, 36.6	55.4, 57.6
7	5A	1 loop	8/28/13-9/4/13	163	2.5, 8.5	0.797, 2.72	24.4, 25.4	44.6, 46.4
	5B	1 loop				0.803, 2.74	24.6, 25.6	44.8, 46.6
	5C	1 loop				1.201, 4.10	36.7, 38.2	56.9, 59.2

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6.0 PERFORMANCE ASSESSMENT – HEAT SUPPLIED BY EFHP SYSTEM VS. GAS BOILER SYSTEM

6.1 OVERVIEW

This section provides details on the analyses that form the basis of this report. A performance-data-based life cycle cost analysis was one of the main goals of this project. Since the operational cost and performance data could not be obtained for the two HVAC systems, we estimated energy consumption and the costs associated with operating the systems using the best available information.

Section 6.2 describes the input values for the computer software used to determine the building heat load. Section 6.3 describes the process of using a temperature bin analysis (for the Colorado Springs area) to determine the total seasonal heat demand. Sections 6.4 and 6.5 summarize the process used to estimate cost per unit of heat provided and carbon emissions for both systems. Section 6.6 discusses the energy efficiency of the water source heat pump installed in this project compared to an air-source heat pump, and Section 6.7 is a summary of the construction costs of the energy foundations as compared to the cost of drilling geothermal boreholes to provide the same amount of heat.

The software utilized requires input values in Imperial units. Hence for this section of the report, the Imperial units are provided first, with SI units provided parenthetically. The R-values provided have units of (ft^2 °F hr)/Btu, and to convert the R-value to the SI units of Kelvins/Watt, multiply by 5.6783.

6.2 BUILDING HEAT DEMAND ESTIMATE USING HVAC-CALC, COMMERCIAL 4.0

Commercially available software, HVAC-Calc Commercial 4.0, was used to perform a heating load estimate for the facility. This software is used to estimate heating and cooling loads in order to size HVAC systems for commercial and industrial buildings.[8] We input as-built conditions of the building and the anticipated fall/ winter use of the building in the near term (i.e., next 3-10 years). At this time, the only anticipated use of the building during heating season will be for a few hours each week to utilize the laundry. Hence, the ventilation system related to shower use is assumed to be turned off, and the indoor temperature of the building is expected to be set to 55°F (12.8°C)[9].

The following, building-specific information was entered into HVAC-Calc. The specific input values are highlighted ***in bold italics.*** Each input is followed by a brief explanation as to why that input was chosen:

<u>Outdoor design conditions:</u> For the bin analysis (described in Section 6.3), the outdoor temperature was varied to reflect the heat demand for the bin being studied. The temperatures input into the outdoor design conditions ranged from ***-2° to 53°F (-18.8 to 11.7°C***), in 5°F

[8] The software was purchased at www.hvaccalc.com

(2.8°C) increments**.** (The default design outdoor temperature for Colorado Springs is 2°F, or -16.7°C, for the purpose of sizing HVAC systems.)

Indoor design conditions: We used an indoor design air temperature of ***55°F*** (12.8°C)**.** This is the ASHRAE recommended indoor setback temperature for temporarily unoccupied buildings in the winter.

Floor description: The floor area used is ***90' x 40'9"*** (27.4 3m x 12.42 m)**.** This is the interior footprint of the building. In HVAC-Calc, partitions refer only to walls adjacent to unheated space; in addition, different heating zones are not accounted for. Hence, only the rectangular shape of the building was used (no partitions).

We selected ***concrete slab on grade*** as well as ***2-in*** (51-mm) ***edge insulation, R-11*** because the floor is in direct contact with the insulated concrete form walls, which have an R-22 value; however, R-11 value is the highest R-value offered by HVAC-Calc. The choice of this floor type results in an estimated heat loss through the floor at design temperatures of 2,998 Btu/hr (0.8786 kW).

Wall descriptions: The north and south wall areas used were ***90' by 8'*** (27.43 m x 2.44 m)**.** The east and west wall dimensions are ***40'9" x 8'*** (12.42m x 0.38m)**.** These are the interior building dimensions. The walls type selected was ***insulated concrete forms*** with an R-24 value. Although the value provided by the manufacturer is R-22, an analysis that includes the thermal resistivity of the interior and exterior air films, the concrete and interior gypsum wallboard with exterior fiber cement siding results in results in an R-23.8 value.[10]

Window descriptions: There are 12 windows each on the north and south walls and 8 windows on the west wall. The east wall has no window. Each window is ***3'6" by 1'4"*** (1.07 m by 2.44 m)**.** We selected ***double pane, 1/8"(32 mm)-thick-glass, no shading on the inside*** with ***30% of the window being always in the shade***. The shading was a judgement call, and there is some shading provided by the roof overhang.

Door descriptions: The door choices offered by HVAC-Calc are glass single, glass double, wood single, metal single, revolving door, and three types of overhead doors. The best match to the shower building is to select ***metal single door***. Four doors were assigned to the north wall, with only ***one being opened once per hour during time of peak load***. Five doors were assigned to the south wall, and one door was assigned to the east wall.

Ceiling description: The ceiling area used is the same as the floor area at ***90' by 40'9"*** (27.43 m by 12.42 m)**.** The ceiling type is ***below unconditioned space*** to reflect construction. A drop ceiling was installed using Armstrong fine textured contractor ceiling tile (2' x 2', or 0.61 m x 0.61 m) comprising mineral fiber.[11]

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[10] Personal communication (email) Mr. Kelvin Doerr, PE, Director of Engineering and Technical Services, Fox Blocks

[11] http://www.armstrong.com/residential-ceilings/ceiling/classic-fine-textured-954-panel/14145-45154

One of the HVAC-Calc inputs required for a ceiling below unconditioned space is the temperature difference (ΔT) between the heated and unheated space. In order to estimate this, we performed a heat balance in the unconditioned space using an inside temperature of 55°F (12.2°C) and varying the outside temperature from -2.5°F to 57.5°F (-19.2℃ to 14.2℃) in 5 degree Fahrenheit increments (to match with the bin analysis performed). The following U values (inverse of R-values) (Btu/[hr ft^2°F]), were used in the calculations: drop ceiling tile with overlying batt insulation (R-value of 38): 0.026, gables: 0.64 (1"- [25mm], thick wood), roof 0.325 (typical value of metal roofing assemblies[12]).

The heat transfer analysis resulted in temperature differences between the heated room and unheated attic space ranging from 54°F (30°C) at -2.5°F (-19.2 ℃) outdoor temperature to 2°F (1.1°C) at 57.5°F (14.2℃) outdoor temperature. HVAC-Calc only offers 5°F (2.8°C) ΔT increments ranging from 0°F to 50°F (0°C to 27.8°C). The values input to HVAC-Calc for temperature difference were: ***50°F*** (27.8°C) ***at outdoor temperatures of -2.5°F*** (-19.2°C) ***and 2.5°F*** (-16.4°C)***, 45°F*** (25.0°C) ***at 7.5°F*** (-13.6°C)***, 40°F*** (22.2°C) ***at 12.5°F*** (-10.8°C)***, and so forth…decreasing ΔT by 5°F*** (2.8°C) ***for every 5°F*** (2.8°C) ***increase in outdoor temperature until 57.5°F*** (14.2°C) ***outdoor temperature, at which point the temperature difference is zero.***

Duct description: The ducts run above the ceiling in unconditioned space. All of the ducts are insulated per the project's Bill of Materials (BOM), although no R-values are given for the insulation. The values offered by HVAC-Calc for duct insulation are R-2, 4 and 6; hence, we selected R-4 because it's the mean value and we have no other information. The values input were: ***100% supply and 100% return ducts are insulated, R-4 value.***

People/vent description: There is a list of application types in this section of HVAC-Calc, and we selected ***locker rooms***. The program determined that there is space for 244 people and recommends a ventilation rate of 30 ft^3/min (51 m^3/hr) of fresh air per person. We anticipate that in the near future, the building will be largely unoccupied in the winter, except for weekly use of the laundry facilities by one of the laboratory personnel. Hence, we inserted ***1 person*** and a ventilation rate of ***1 ft^3/min*** (1.7 m^3/hr) with an activity level of ***standing, slow walk, light work***.

Infiltration/exhaust : There is ***39,600 ft^3*** (1120 m^3) of building volume (per HVAC-Calc). The choices for building tightness are tight, average, poor and loose. We opine that ***average*** best describes the shower building. We used ***0.3 air changes per hour*** in the winter. In order to simulate 2 hours of laundry per week, with the associated need to heat the exhaust air, we multiplied the exhaust rate of the laundry facility (1800 ft^3/min, or 3058 m^3/hr) times 0.0119 (2 hrs per week) to obtain a ***forced exhaust of 21 ft^3/min*** (35.7 m^3/hr).

Figure 16 shows the output of HVAC-Calc 4.0 for the Colorado Springs design conditions of outdoor temperature of 2°F (-16.7 °C) and all other input conditions as described above.

[12] http://www.energy.ca.gov/title24/2008standards/rulemaking/documents

Component	Heat Loss (BTUH)
Ceiling	11,002
Total for building	70,437
Floors	2,998
Walls	5,232
Windows	5,699
Doors	7,720
Door Leakage	15,566
Partitions	0
Ceilings	11,002
Skylights	0
Duct	9,453
People	0
Ventilation	58
Infiltration	12,709
Lights	0
Miscellaneous	0

Figure 16. HVAC-Calc output for FERL Shower/Shave building for 2°F outdoor temperature.

Farris Engineering, Inc., the firm hired by the 10th Civil Engineering Squadron to design the HVAC systems, sized the heating system to meet the full heat demand for the building at design conditions when both make-up air units are fully operating. Under these conditions, they estimated the heat load at 187,037 Btu/hr (54.8151 kW). Their estimates for the make-up air unit for the shower area that includes an energy recovery wheel (exhausts 2800 ft^3/min or 79.3 m^3/hr) requires 47,600 Btu/hr (13.95 kW), and the make-up air unit for the laundry area requires 115,200 Btu/hr (33.76 kW), at design heat conditions.

The Farris Engineering documentation indicates an estimate of 24,237 Btu/hr (7.1031 kW) for design conditions for building envelope and infiltration losses only, and they selected the heat pump on that basis. This is approximately 34% of that estimated by HVAC-Calc (70,437 Btu/hr or 20.643 kW) for very similar conditions. Since the documentation provided by Farris Engineering, Inc., for the 24,237 Btu/hr (7.103 kW) determinations was not provided, the source of discrepancy could not be investigated.

6.3 HEAT REQUIRED BY THE BUILDING FOR AN AVERAGE WINTER

We determined that the total heat required by the building for an average winter is 122,806 KBtu (35990.9 kWh) as follows:

Temperature bins were obtained from BinMaker PRO v3.0.1 software.[13] They were in five degree Fahrenheit increments from -5°F (-20.6°C) through 100°F (37.8°C), and included a list of the number of hours that Colorado Springs experiences in each temperature bin. We used the average temperature of each bin (rounded up to the nearest whole number) and utilized HVAC-Calc, with the inputs as described above, to estimate the heat demand (rate of heat loss) for each temperature bin. The heat demand (rate) was then multiplied by the number of hours in the respective bin in order to estimate the total heat required at that average temperature.

The heat pump provides a maximum of 27,400 Btu/hr (8.03 kW), so when the heat demand rate is higher than that, the gas boiler must make up the difference. Table 4 lists the average temperature used in each bin for the determination of the heat demand, the total number of hours in each bin, the total heat required for each temperature bin, the heat for each bin that can be provided by the heat pump, and the heat that must be made up with the natural gas boiler.

Table 4. Bin Analysis information indicating how much heat is supplied by the heat pump and the gas boiler for each temperature bin for the FERL Shower/Shave facility.

Ave Temp of Bin (°F)	Rate of heat demand at Ave Temp (Btu/hr)	Number of hours in bin	Total heat required (KBtu/ kWh)	Heat provided by 27,400 Btu/hr Heat Pump (KBtu/ kWh)	Heat provided by Natural Gas Boiler (KBtu/ kWh)
53	2188	767	1678/ 491.8	1678/ 491.8	
48	8892	591	5255/ 1540.0	5255/ 1540.0	
43	15594	721	11243/ 3295.0	11243/ 3295.0	
38	22334	874	19520/ 5720.7	19520/ 5720.7	
33	29034	675	19598/ 5743.6	18495/ 5420.3	1103/ 323.3
28	35771	390	13951/ 4088.6	10686/ 3131.8	3265/ 956.9
23	42470	466	19791/ 5800.2	12768/ 3741.9	7023/ 2058.2
18	49211	360	17716/ 5192.0	9864/ 2890.8	7852/ 2301.2
13	55913	113	6318/ 1851.6	3096/ 907.3	3222/ 944.3
8	62615	80	5009/ 1468.0	2192/ 642.4	2817/ 825.6
3	69352	35	2427/ 711.3	959/ 281.1	1468/ 430.2
-2	74784	4	299/ 87.6	110/ 32.2	190/ 55.7
Total			**122,806/ 35,991**	**95,866/ 28,095**	**26,940/ 7,895**

[13] http://www.interenergysoftware.com/

6.4 ESTIMATE OF COST PER MILLION BTU/HR OF HEATING (QUANTITATIVE OBJECTIVE 1)

An estimate for one average year of heating in the shower building was developed using the bin analysis described above (Section 6.2 & 6.4), the HVAC equipment specifications, and the price of electricity and natural gas paid by the United States Air Force Academy to Colorado Springs Utilities. The annual maintenance costs for the systems were not included in this estimate, but they were included in the life cycle cost analysis (Section 6.6).

The ground source heat pump installed in the building is a ClimateMaster Tranquility® water to water Model TMW036 – 340, 60Hz - HFC-410A, purchased in 2013. The manufacturer's information indicates that with a 9 gpm (0.034 m^3/min) source, the COP is 3.1 with an entering water temperature of 40°F (4.4°C). ClimateMaster also lists a COP of 3.2 for the same conditions with water only as the heat transfer fluid and the entering water temperature at 50°F (10°C) and a hydronic heating system entering water temperature of 120°F (49°C), which is the condition for the shower facility (note that the average ground temperature is approximately 54°F, or 12°C). For a 15% methanol solution at an entering water temperature of 40°F (4.4°C) for the same condition, ClimateMaster lists a COP of 2.9. The heat transfer fluid circulated in the foundation is 80% water 20% glycol. In consideration of the above listed information, we used a COP of 3.1 in estimating the electrical cost.

Farris Engineering selected a Lochinvar KBN 286 Boiler based on their estimated peak heat demand of 187,037 Btu/hr (54.8151 kW). Accounting for altitude, they estimated that the building required a 281,259 Btu/hr (82.4289 kW) boiler (although no calculations were presented). Efficiency curves for the Knight boilers, provided by the manufacturer indicate a 93% efficiency at return water temperatures of 130°F (54°C), which is our hydronic system design. In addition, there is a 14% high altitude de-rate for the altitude of our site (6,001 -7,000 ft, or 1829 – 2134 m). Hence, the overall efficiency assigned to the gas boiler for this analysis was 80%.

The steps involved in performing this analysis for that hybrid EFHP system are as follows:

1. To determine the cost per Btu, the following steps were completed:
    a. The total heat to be supplied by the heat pump is 95,867 kBtu (28096 kWh). Dividing the heat required by the COP results in the need for 9,063 kWh to run the heat pump and an additional 851 kWh (1/6 horsepower) to run the circulation pump to the foundations. Multiplying the KWh times the average rate paid by the US Air Force Academy of 0.06 per KWh results in a total annual cost of $595.
    b. When the rate of heat demand is more than 27,400 Btu/hr (8.03 kW), the gas boiler must supply the remaining heat.

    Dividing the heat supplied by the boiler, by its efficiency (0.80) determined the required heat to be supplied by natural gas. Using the assumed heat content of natural gas (850 Btu/ft^3 [31650 kJ/m^3], per Colorado Springs Utilities), the quantity of natural gas required to supply the demanded of the boiler is 39617 ft^3 (1121.8 m^3) of natural gas. Using the current rate that the Air Force Academy pays for

natural gas ($5.15 per Mcf), and adding on the annual access and meter fees for the natural gas of $110 per year yields a total annual cost of $314.03 for a total combined electricity and natural gas cost of $909 or $7.40 per million Btu ($25.17/ MWh) of heat.

The annual cost of supplying the required 122,806 kBtu of heat is $1040 or $8.47 per million Btu ($28.90/MWh) of heat. Hence the hybrid system costs per unit of heat are 87% of the gas boiler.

6.5 CARBON EMISSIONS REDUCTION (QUANTITATIVE OBJECTIVE 2)

Using the information provided by the United States Energy Information Administration (http://www.eia.gov/tools/faqs/faq.cfm?id=73&t=11), we assumed that 215 lb (97.5 kg) of carbon dioxide (henceforth referred to as carbon) is produced by burning 1 million Btu (293 kWh) of coal, and burning the same amount of natural gas produces 117 lb (53.1 kg) of carbon. The United States Air Force Academy supplies 11% of its electrical power by solar panels and receives 89% of its power from the coal-fired Martin Drake Power Plant in Colorado Springs.

The estimated annual electrical consumption of 9,914 kWh required by the heat pump would have 8,824 kWh generated by coal burning. With a generation efficiency of 32.6%, this would require 27,066 kWh (92.35 million Btus) of 'coal heat,' generating 19,856 lb (9,007 kg) of carbon. The amount of carbon generated by the natural gas of this hybrid system is 3,939 lb (1,787 kg). Thus, the hybrid system, with a coal-fired source of 89% of its electrical power, will produce approximately 23,795 lb (10,793 kg) of carbon in an average year.

For all of the heat being provided by the gas boiler alone, which requires 153.508 million Btu (44,989 kWh) of heat from gas 17,906 lb (8,122 kg) of carbon would be generated. To have the two systems be carbon equivalent, the renewable electricity would have to eliminate 5,835 lb (2,647 kg) of carbon in the hybrid system, or 22,307 kWh, which would require approximately 82% of renewable electrical power.

6.6 COEFFICIENT OF PERFORMANCE AND HEATING SEASON ERFORMANCE FACTOR OF THE GROUND SOURCE HEAT PUMP (QUANTITATIVE OBJECTIVE 3)

The coefficient of performance could not be measured for this project. Furthermore, even though air source heat pumps are being developed for use in cold climates, it is not a recommended practice. A simple analysis was performed in an attempt to compare the ground source heat pump and a cold climate air source heat pump in the heating mode for this project.

The Department of Energy notes that the energy efficiency of air source heat pumps falls considerably when the outdoor temperature is below 4.5°C (40°F), and they do not recommend use of air source heat pumps in cold regions.[14] However, cold climate air source heat pumps have been manufactured that list Heating Season Performance Factors (HSPF) as ranging from 8 to 10. The HSPF is defined as the total heat (in Btus) supplied by the heat pump divided by the total Watt-hours required to run them. However, HSPF values are determined for heat pumps in

[14] http://energy.gov/energysaver/articles/air-source-heat-pumps

milder climates than that of Colorado and the US Energy Information Administration provides guidance that an HSPF of 10 reduces to 6.4 in Denver, Colorado, the nearest city to the Air Force Academy for which a reduction factor is available.[15] A 40% improvement for the HSPF of 6.4 would result in an HSPF of 9.0.

Applying the manufacturer's COP of 3.1 to the total heat in Btus (95,866,758) supplied by the heat pump in an average heating season results in an HSPF of 10.6 for the heat pump. Hence, for most air source heat pumps operating with an HSFP of 6.4 or lower in this region of the country, this objective would be met.

6.7 CONSTRUCTION COSTS OF THE ENERGY FOUNDATION VS. SEPARATE BOREHOLE FIELD (QUANTITATIVE OBJECTIVE 4)

The mechanical engineering contractor, Farris Engineering, used ground loop design software to estimate the thermal capacity of the foundations (see Appendix D for assumed input values). Their software-based estimate was that the foundations would produce 9.5 W/m (9.9 Btu/hr ft), and that the total system could produce a peak demand of 3.0 kW (3.4 kBtu/hr). A local geothermal contractor indicates that they can obtain 51 W/m (53 Btu/hr ft) in the foothills of the Front Range of Colorado (which seems high).[16] Using this estimate, the 'equivalent single borehole length' is 61 m (200 ft).

The construction cost comparison comprises the cost of installing HDPE pipe in the drilled shaft foundations and running the pipe through the grade beam to the heat pump system manifold vs. the installation of a single borehole and connecting it to the manifold to provide the heat required for the heat pump.

We contacted a local geothermal contractor, Can-America Drilling, Inc., in 2013 in order to provide an estimate of borehole drilling costs, and their estimate is provided in Table 5. Note that all of the estimates are based on the assumption of 'soft' drilling conditions (meaning no hard rock, which matches our site), with no thermally conductive grout added to the borehole. Based on the estimates summarized in Table 5, and an assume heat extraction rate of 51 W/m (53 Btu/hr ft), the single borehole required is estimated to cost $4.9k (minimum) to approximately $5.5k. To meet this objective, the cost associated with installing the tubing in the foundation would have to save $2.4k.

Assembling and attaching the tubing into the reinforcement cages of the drilled shafts prior to construction took approximately 35 hours of labor. The governmental cost estimates for plumbers hourly rate on this job was $54.60.[17] Adding to that approximately 300 m (1000 ft) of extra HDPE piping to run horizontally in the grade beam to the manifold for approximately $400 yields a total cost of $2.3k for a savings of $2.6k. Hence, the performance objective is met. The construction cost savings would be greater if the borehole was developed using thermally conductive grout and/or if more than one borehole were required to meet the same thermal output as the foundations.

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[15] www.**eia**.gov/tools/faqs/**heat**calc.xls
[16] www.cogeothermal.com
[17] Information obtained from Farris Engineering preliminary cost estimate dates 20 March 2012

Table 5. Borehole cost estimates (From May of 2013) for drilling ground source heat pump system.

Diameter (cm/ in.)	Depth (m/ ft.)	Pipe diam. (cm/ in.)	Total cost ($)
12.1/ 4.75	61/ 200	0.19/ 0.75	4,934
12.1/ 4.75	91/ 300	2.54/ 1.00	5,589
12.7/ 5.00	122/ 400	5.18/ 1.25	6,479
13.3/ 5.25	152/ 500	5.18/ 1.25	7,188

6.8 ENERGY FOUNDATION RETROFIT DISCUSSION (QUANTITATIVE OBJECTIVE 6)

The project was originally designed to evaluate the cost effectiveness of retrofitting foundations to become energy foundations (Objective 6). It is highly unlikely that it would be cost-effective to retrofit foundations only for the sake of adding heat exchangers. However, one of the foundations was constructed in order to be able to test the concept of a deep foundation being repaired for another reason, such that heat transfer tubing could be placed in a bore in the middle of the foundation. The final design of the shower/shave building included the attachment of a concrete grade beam to the deep foundations, which precluded any post-construction activities, and the actual construction process and costs of a retrofit could not be evaluated.

Reasons that a deep foundation would be repaired or be newly constructed under an existing building (which would involve lifting the building) include that the deep or shallow foundation is not performing well (i.e., settlement is occurring) or that the building is being expanded and the structural support needs to be enhanced.

One type of repair on a deep foundation is to core through the foundation and grout the base. Mullins, et al. (2000) describes this process. If this were being done, a single loop of heat transfer tubing could be installed during grouting. Another type of repair would be the need to lift a building off of a shallow foundation for the purpose of installing deep foundations (this is called underpinning). In this case, the potential benefits would be similar to those for new construction, which would involve placing the heat transfer loops towards the outer edges of the foundations (e.g., this project) to maximize thermal performance.

The thermal testing of Foundation 8 indicated that it will perform effectively to transfer heat to the heat pump, and this makes sense as the foundation and heat transfer loop configuration is similar to that of vertical boreholes commonly used with heat pump systems. However, we decided not to attempt a life-cycle cost analysis of this process, deeming it a rare circumstance with too many unknowns to generate estimates with any degree of confidence.

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7.0 COST ASSESSMENT

7.1 OVERVIEW

Implementation costs and life-cycle savings from installing energy foundations and using them in combination with a ground source heat pump will vary with region within the United States. Goetzler, et al. (2009) conducted a study on the status of GSHP technology and to estimate their energy saving potential. Ground source heat pumps result in more energy savings than air source heat pumps in every region of the country, but the savings are particularly great in the South Atlantic and East South Central regions. They found that savings are in the range of 30 to 60 percent of space-conditioning energy consumption; but that installation costs generally delay the payback period to the point that the GSHP systems are not typically installed.

The construction of the deep foundation and grade beam system for the FERL shower/shave facility was awarded to a SABER (Simplified Acquisition Base Engineering Requirement) contractor. In order to validate the quotes submitted for the completion of the work, the 10th Civil Engineering Squadron prepared their own construction cost estimate. The final independent government estimate for this work is provided in Appendix E. The costs associated with installing the HDPE tubing and the manifold are listed in items 26 through 28.

7.2 CONSTRUCTION COSTS OF THE ENERGY FOUNDATIONS

This demonstration combined state-of-practice construction techniques and HVAC technologies such that estimating the cost of a similar project is straightforward. The total cost for the installation of eight drilled shaft foundations, the grade beam to which they are attached and placement of the heat transfer tubing was $162,400 in April of 2012.[18] This included:

- Assembly of reinforcement cages
- Placement of the heat transfer tubing inside the cages
- Filling the tubing with heat transfer fluid, pressurizing the fluid and capping the tubes with pressure gages
- Drilling the boreholes, placing the cages in the boreholes and pumping concrete into the shafts
- Assembling the grade beam forms and reinforcement
- Routing the heat transfer tubing through the grade beams (and within the grade beam reinforcement)
- Placing the concrete in the grade beam

[18] From DDForm 1155 dated 2012, 30 March, Order 5Q21

7.3 LIFE CYCLE COST COMPARISON

The software used to perform the life cycle cost analysis of the shower building is BLCC 5.0, and was downloaded from: http://www.energy.gov/eere/femp/building-life-cycle-cost-programs .

We ran a MILCON Analysis for a non-energy project because this best described the Shower/ Shave construction. This utilizes a constant-dollar analysis (which also represents new construction, paid at once). For DoD projects, the annual recurring costs are discounted from the middle of the year to the base date, and OMB (Office of Management and Budget) discount rates are used.

Below are the inputs that we provided BLCC 5.3-15 in performing the life cycle cost analysis with justifications for their selection:

1. Base date: January 2016, the construction of the building was complete in January of 2014, and the HVAC systems were functional except for the control units. However BLCC 5.3-15 does not permit a base date earlier than April of 2015. The building is scheduled for repairs during the autumn of 2015, and is expected to have operational HVAC in January of 2016.
2. Length of study period: 20 years, as this is a reasonable period of time for which at a minimum, the Shower/ Shave building will be used as it is currently being used with the building being used primarily in the summer and set to low temperatures with little use in the winter.
3. Investment cost for the Lochinvar High Efficiency Gas Boiler: $8450, from a Building Material List supplied by RED HORSE. This quote is higher than prices found on-line in 2015, so we input the $8450 cost. The costs for the water piping, gas piping, controls, labor for installation, materials for venting exhaust gasses, electrical connection, etc, are assumed equal for the gas boiler on both projects, so that they were not input.
4. For the investment cost for the ground source heat pump, we used $7,200, based on the quote that was accepted by the U.S. Air Force Academy contracting office. This quote is higher than prices found on-line in 2015, so we did not increase that amount for input in January 2016. We also added $7,230 to this investment to account for the construction cost of the plumbing related to installing the heat transfer tubing in the foundations as well as connection to the manifold and radiant heating system per the independ government estimate (line item 28, Appendix E). We added the cost of the gas boiler (step 3 above) because this system is hybrid, and the practice of having a secondary heat supply is common with ground source heat pump installation. Thus, the total investment for the hybrid system was $22,880.
5. There is a 20 year life-expectancy for the ground source heat pump (per: http://energy.gov/sites/prod/files/guide_to_geothermal_heat_pumps.pdf). According to an ASHRAE service life and maintenance cost database, a reasonable life-expectancy for the gas boiler is 18 years (http://xp20.ashrae.org/publicdatabase/). We replaced the gas boiler at 18 years in both systems. We did not assign a residual value to the gas boilers.

6. No information is available on maintenance costs for either system, and ASHRAE lists maintenance costs by building type. Since it is the same building with both systems, and due to lack of reliable information on this topic, we assume that all maintenance and repair costs are equal on the gas boiler, and thereby left them out of the life-cycle cost analysis. A local geothermal contractor estimates the annual maintenance cost of the ground source heat pump at $40 for replacement filter.[19]

NIST BLCC 5.3-15: Summary LCC

Consistent with Federal Life Cycle Cost Methodology in OMB Circular A-94

General Information

File Name:	C:\Users\karen.henry\Desktop\FinalLCC.xml
Date of Study:	Wed Jul 22 16:32:07 MDT 2015
Analysis Type:	MILCON Analysis, Non-Energy Project
Project Name:	Final LCC
Project Location:	Colorado
Analyst:	Karen Henry
Base Date:	January 1, 2016
Beneficial Occupancy Date:	January 1, 2016
Study Period:	20 years 0 months (January 1, 2016 through December 31, 2035)
Discount Rate:	1.2%
Discounting Convention:	Mid-Year

Discount and Escalation Rates are REAL (exclusive of general inflation)

Alternative: Natural Gas Boiler

LCC Summary

	Present Value	Annual Value
Initial Cost Paid By Agency	$8,450	$478
Energy Consumption Costs	$19,911	$1,126
Energy Demand Costs	$2,329	$132
Energy Utility Rebates	$0	$0
Water Usage Costs	$0	$0
Water Disposal Costs	$0	$0
Routine Annually Recurring OM&R Costs	$0	$0
Routine Non-Annually Recurring OM&R Costs	$0	$0
Major Repair and Replacement Costs	$6,817	$385
Less Remaining Value	$0	$0
	---	---
Total Life-Cycle Cost	$37,507	$2,121

Alternative: EFHP System

LCC Summary

	Present Value	Annual Value
Initial Cost Paid By Agency	$22,880	$1,294
Energy Consumption Costs	$10,807	$611
Energy Demand Costs	$2,329	$132
Energy Utility Rebates	$0	$0
Water Usage Costs	$0	$0
Water Disposal Costs	$0	$0
Routine Annually Recurring OM&R Costs	$712	$40
Routine Non-Annually Recurring OM&R Costs	$0	$0
Major Repair and Replacement Costs	$6,817	$385
Less Remaining Value	$0	$0
	---	---
Total Life-Cycle Cost	$43,545	$2,462

Figure 17. Building life cycle cost analysis as output by BLCC 5.3-15 that compares the life cycle costs of heating the FERL Shower/ Shave with a high efficiency gas boiler (Base Case) to the Energy Foundation Heat Pump System, which is a hybrid of the ground source heat pump with the gas boiler to supply additional heat at times of high demand.

[19] www.cogeothermal.com , personal communication

With all of the assumptions as stated in the building energy modeling to predict heat load (Sections 6.1 and 6.2), and with the inputs as described above, the life cycle cost of the EFHP system is $43,545 and that of the gas boiler only is $37,507. Hence the EFHP system estimated life cycle cost is 116% of that of the gas boiler system. The performance objective was set at 70% of the costs, so the objective was not met for the current and projected utilization of the building during heating season. However, in the case that the building were to be used such that the inside temperature were to be increased, the energy savings costs associated with the EFHP system will become more advantageous.

8.0 IMPLEMENTATION ISSUES

Because energy foundations require only state-of-practice construction techniques and HVAC technologies, no significant implementation issues are expected other than those already faced by GSHP systems in general. For this demonstration, the construction contractor and skilled crew did not need any special training, and one pre-construction meeting in which goals of the project were described helped assure success with respect to the construction of the foundations.

Skilled HVAC design and construction are also required for a successful implementation of the energy foundations into their intended use in building space conditioning. This is very similar to other ground source heat pump installations, and with proper design inputs, local geothermal contractors should be able to perform the design and oversee construction. Unfortunately, for this project, integrating the energy foundations and the natural gas boiler into a hybrid system was beyond the skill of the REDHORSE Squadron, whose primary construction experience is “rapid” and not very sophisticated.

The life cycle cost analysis related to heating via the EFHP system indicates that this approach deserves consideration in future DoD construction projects. With aggressive goals towards carbon emissions reduction and building sustainability, they would be particularly worthy of consideration in regions where the electrical power source is relatively decarbonized.

In warmer regions, and with large structures that are cooling-load dominated, this technology could be tested and/or demonstrated for the purposes of cooling buildings.

Goetzler, et al. (2009) concluded that GSHPs face three key barriers—1) high initial equipment costs, 2) cost and difficulty of evaluating the suitability of individual installation sites and 3) space requirements for ground coupling can be problematic in densely built areas. They specifically mention maximizing the use of excavation required for new construction of building foundations and ‘coupling the ground loop to the foundation’ as a potential solution to help reduce initial costs of the GSHP systems. This project demonstrated the cost-effectiveness of such practice.

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APPENDIX A

POINTS OF CONTACT

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Dr. John McCartney, PE	Department of Structural Engineering University of California, San Diego 9500 Gilman Dr, SME 442J La Jolla, CA 92093	Phone: 858-534-9630 (office) 303-475-373 (mobile) E-mail: mccartney@eng.ucsd.edu	Associate Investigator & Lead on geotechnical design and analysis
Mr. Kyle Murphy, EIT	Shannon and Wilson, Inc. 1321 Bannock St. Suite 200 Denver, Colorado 80204	Phone: 303 825-3800 (office) Fax: 303 825-3801 E-mail: kdm@shanwil.com	Graduate Student and lead author on geotechnical and thermal test results

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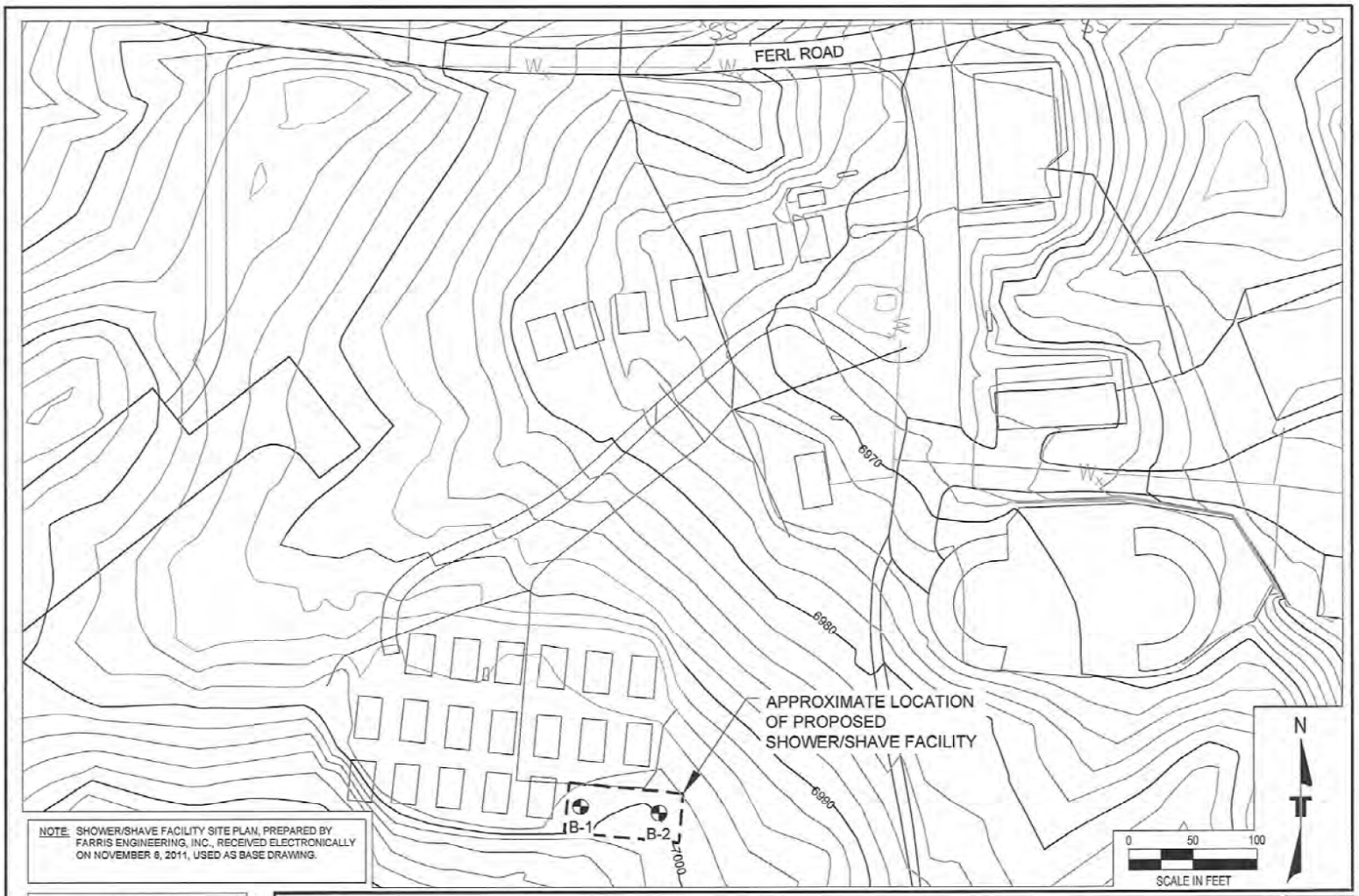
APPENDIX B

BORING LOGS GENERATED DURING THE GEOTECHNICAL SITE INVESTIGATION PERFORMED FOR THIS PROJECT

These are excerpted from the Geotechnical Engineering Report prepared by Prepared by:

Terracon Consultants, Inc., Colorado Springs, Colorado, for Farris Engineering, Colorado Springs, CO, November 10, 2011, Project No. 23115034.



NOTE: SHOWER/SHAVE FACILITY SITE PLAN, PREPARED BY FARRIS ENGINEERING, INC., RECEIVED ELECTRONICALLY ON NOVEMBER 8, 2011, USED AS BASE DRAWING.

LEGEND

B-1 — APPROXIMATE LOCATION OF TEST BORING

DIAGRAM IS FOR GENERAL LOCATION ONLY, AND IS NOT INTENDED FOR CONSTRUCTION PURPOSES.

Project Mngr:	RWF
Drawn By:	RMH
Checked By:	RWF
Approved By:	RWF

Project No.	23115034
Scale:	AS SHOWN
File No.	Fig1-BLP
Date:	11-09-2011

Terracon
Consulting Engineers and Scientists
4172 Center Park Drive, Colorado Springs, Colorado 80916
PH. (719) 597-2116 FAX. (719) 597-2117

BORING LOCATION PLAN
Farris Engineering, Inc.
FERL SHOWER/SHAVE FACILITY - XQPZ 11-60543
EAST OF PARADE LOOP AND FERL ROAD
UNITED STATES AIR FORCE ACADEMY COLORADO

Ex. No.
A-2

BORING LOG NO. B-1

CLIENT
Farris Engineering

SITE **East of Parade Loop and FERL Drive**
United States Air Force Academy, Colorado

PROJECT
Shower/Shave Facility

Approx. Surface Elevation: 6999 ft

GRAPHIC LOG	DESCRIPTION		DEPTH, ft.	USCS SYMBOL	SAMPLES NUMBER	TYPE	RECOVERY, in.	BLOWS / ft.*	TESTS WATER CONTENT, %	DRY UNIT WT, pcf	UNCONFINED STRENGTH, psf	PERCENT FINES ATTERBERG LIMITS, %
	FILL-POORLY GRADED SAND, with silt and gravel; brown to reddish brown, fine to coarse grained, very dense.	3 / 6996			1	BS						
				SP	2	RS	6	50/6"	7	112		
				SM	3	SS	16	85	9			
	POORLY GRADED SAND, with silt and gravel; brown to reddish brown, fine to coarse grained, very dense.	6 / 6993	5	SP								
				SM	4	RS	6	50/6"	9	116		
	SILTY SANDSTONE: brown to reddish brown, fine grained, hard to very hard.			SP								
				SM	5	RS	6	50/6"	14	103		-200 = 25
					6	SS	18	59	14			LL = NV
			10									PI = NP
					7	RS	6	50/6"	11	120		
			15		8	RS	3	50/3"	10	93		
			20		9	SS	3	50/3"	9			
			25		10	SS	1	50/1"	10			
			30		11	SS	0.5	50/1"	8			
			35		12	SS	0.5	50/1"	4			
		39 / 6960										
	BOTTOM OF BORING				13	SS	3	50/3"	8			

The stratification lines represent the approximate boundary lines between soil and rock types: in-situ, the transition may be gradual.

* 140lb. SPT automatic hammer
4" diameter solid stem auger

WATER LEVEL OBSERVATIONS, ft			
WL	None	WD	None AB
WL			

Terracon

BORING STARTED	10-27-11		
BORING COMPLETED	10-27-11		
RIG	CME-55	LOGGED	LKC
APPROVED RWF		PROJ. NO.	23115034

BOREHOLE WITH ATTERBERG LIMITS 23115034.GPJ DENVER TEMPLATE 8-5-11.GDT 11/9/11

BORING LOG NO. B-2

CLIENT
Farris Engineering

SITE **East of Parade Loop and FERL Drive**
United States Air Force Academy, Colorado

PROJECT
Shower/Shave Facility

Approx. Surface Elevation: 7000 ft

GRAPHIC LOG	DESCRIPTION		DEPTH, ft.	USCS SYMBOL	SAMPLES NUMBER	TYPE	RECOVERY, in.	BLOWS / ft.*	TESTS WATER CONTENT, %	DRY UNIT WT, pcf	UNCONFINED STRENGTH, psf	PERCENT FINES ATTERBERG LIMITS, %
	2 **FILL-POORLY GRADED SAND**, with silt; brown to reddish brown, fine to coarse grained, trace gravel.	6998			1	BS						
				SP	2	RS	5	50/5"	3	122		-200 = 11
	POORLY GRADED SAND, with silt; brown to reddish brown, fine to coarse grained, dense to very dense, trace gravel.			SM	3	SS	18	71	5			LL = NV
			5	SP								PI = NP
				SM	4	RS	9	50/9"	5	124		
				SP								
	9	6991		SM	5	RS	5	50/5"	3	118		
	SILTY SANDSTONE; brown to reddish brown, fine grained, very hard.				6	SS	16	87/10"	7			
			10		7	RS	2	50/2"	8	126		
			15		8	RS	1	50/1"	15	119		
			20		9	SS	6	50/6"	11			
	24	6976										
	BOTTOM OF BORING				10	SS	1	50/1"	11			

The stratification lines represent the approximate boundary lines between soil and rock types: in-situ, the transition may be gradual.

* 140lb. SPT automatic hammer
4" diameter solid stem auger

WATER LEVEL OBSERVATIONS, ft			
WL	None	WD	None AB
WL			

Terracon

BORING STARTED	10-27-11
BORING COMPLETED	10-27-11
RIG CME-55	LOGGED LKC
APPROVED RWF	PROJ. NO. 23115034

BOREHOLE WITH ATTERBERG LIMITS 23115034.GPJ DENVER TEMPLATE 8-5-11.GDT 11/2/11

APPENDIX C

EVALUATION OF THERMO-MECHANICAL AND THERMAL PERFORMANCE OF FULL-SCALE ENERGY FOUNDATIONS

Citation: Murphy, K.D., J.S. McCartney and K.S. Henry (2015) "Evaluation of Thermo-Mechanical and Thermal Behavior of Full-Scale Energy Foundations." Acta Geotechnica, Vol. 10, No. 2, pp. 179-195. DOI 10.1007/s11440-013-0298-4

Acta Geotechnica
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RESEARCH PAPER

Evaluation of thermo-mechanical and thermal behavior of full-scale energy foundations

Kyle D. Murphy · John S. McCartney · Karen S. Henry

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Abstract Eight full-scale energy foundations were constructed for a new building at the US Air Force Academy. The foundations are being used to demonstrate this technology to the United States Department of Defense and have several experimental features in order to study their thermal–mechanical behavior. Three of the foundations are instrumented with strain gages and thermistors, and their thermo-mechanical response during a heating and cooling test was evaluated. For a temperature increase of 18 °C, the maximum thermal axial stress ranged from 4.0 to 5.1 MPa, which is approximately 25 % of the compressive strength of concrete (estimated at 21 MPa), and the maximum upward displacement ranged from 1.4 to 1.7 mm, which should not cause angular distortions sufficient enough to cause structural or aesthetic damage of the building. The end restraint provided by the building was observed to change depending on the location of the foundation. The heat flux per meter was measured by evaluating the temperatures and flow rates of a heat exchanger fluid entering and exiting the foundations. The heat flux values were consistent with those in the literature, and the foundation with the three continuous heat exchanger loops was found to have the greatest heat flux per meter. The transient thermal conductivity of the subsurface measured using the temperatures of the subsurface surrounding the foundation ranged from 2.0 to 2.3 W/mK, which is consistent with results from thermal response tests on energy foundations reported in the literature.

Keywords Deep foundations · Geothermal heat exchange · Thermal response test · Thermo-mechanical behavior

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1 Introduction

Heating and cooling of buildings comprises nearly 50 % of the total building energy usage in the USA (Energy Information Administration) [8]. Ground-source heat exchange (GSHE) systems are an approach to reduce the energy demand of heating and cooling systems compared with conventional air-source heat pump systems. The most common GSHE system involves the use of a closed-loop heat exchanger to transfer heat between the subsurface soil or rock and an overlying structure, taking advantage of the relatively constant natural ground temperature below the depth of seasonal variation [6]. The subsurface below a depth of 4 m generally has a relatively constant temperature approximately equal to the mean annual air temperature at a given location which contributes to making the efficiency of a GSHE system higher than that of an air-source heat exchange system [13].

Although conventional ground-source heat exchange (GSHE) systems have been used for many years, the additional cost of drilling deep boreholes for the sole purpose of exchanging heat with the ground has rendered this technology cost-prohibitive in some situations [12]. Energy foundations are a feasible approach to enhance implementation of GSHE systems by reducing installation

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costs through taking advantage of initial construction activities [1, 6]. In this study, energy foundations refer to drilled shaft foundations constructed with a set of closed-loop heat exchangers attached to the inside of the reinforcement cage so that they can serve the dual purposes of providing structural support and providing access to ground thermal energy. While energy foundations are gaining popularity throughout the world, further research is required to fully understand their performance in terms of thermal response and thermo-mechanical behavior in different soil profiles. This paper focuses on the characterization of a series of eight energy foundations installed in an unsaturated sandstone deposit.

2 Background

2.1 Thermo-mechanical Behavior

As a deep foundation is loaded mechanically, the axial stress is expected to be highest at the head and decrease with depth as side shear resistance is mobilized at the soil–foundation interface. The axial stress will decrease to zero if the side shear resistance is sufficient to support the building load; if not, it will decrease to a nonzero value, and there will be end-bearing resistance in the material underlying the toe of the foundation. As an energy foundation is heated or cooled, the reinforced concrete will tend to expand or contract axially about a point referred to as the "null point" [14]. The null point is the point of zero axial displacement during heating or cooling, and its location depends on the stiffness of the end boundaries imposed by the overlying superstructure and the material beneath the toe, as well as the distribution of mobilized side shear resistance [2, 4]. It is also likely that radial expansion of the foundation will occur as the foundation is heated [15], which may result in a net increase in ultimate side shear resistance [21, 26].

The upper limit on the thermal axial strain ε_T in an energy foundation is the free-expansion (i.e., unrestrained) thermal axial strain $\varepsilon_{T,free}$, defined as follows:

$$\varepsilon_{T,free} = \alpha_c \Delta T \quad (1)$$

where α_c is the coefficient of linear thermal expansion of reinforced concrete and ΔT is the change in temperature. For geotechnical engineering purposes, the thermal axial strain is defined as positive during compression. Accordingly, α_c is defined as negative because structural elements expand during heating (i.e., positive ΔT). For the case that an energy foundation is restrained from moving such that the actual thermal axial strain ε_T is less than that predicted by Eq. 1, the thermal axial stresses σ_T can be calculated as follows:

Table 1 Results of previous studies on thermo-mechanical behavior of energy foundations

Case	Laloui et al. [15]	Bourne-Webb et al. [4]	McCartney and Murphy [20]; Murphy [23]
Site stratigraphy	Alluvial soil, sand, and gravel, founded in soft sandstone, groundwater table near surface	Granular fill and sand, founded in stiff fissured silty clay, groundwater table at a depth of 3 m	Urban fill, sand, and gravel, founded in shale, locations of perched groundwater
Load mechanism at foundation head	Free expansion, building dead load	Load frame	Building dead load
Foundation diameter (m)	0.88	0.56	0.91
Foundation length (m)	25.8	23	14.8 (A), 13.4 (B)
Mechanical load during heating test(s) (kN)	0, 1300	1200	3840 (A), 3640 (B)
Range of ΔT (°C)	+20.9, +13.4	−19.0 to +29.4	−5.0 to +14.0
Depth of minimum thermal axial strain during heating (m)	21.0	17.0	11.6
Minimum/ maximum thermal axial stress (MPa)	2.1	−0.8 to 1.9	−1.0 to 4.0
Maximum increase in thermal axial stress with temperature (kPa/ °C)	104	192	285
Range in head displacements (negative is upward) (mm)	−4.2, not measured	4.0 to −2.0	0.4 to −0.8

$$\sigma_T = E(\varepsilon_T - \alpha_c \Delta T) \quad (2)$$

where E is the Young's modulus of reinforced concrete. For energy foundations, soil–structure interaction mechanisms will restrict the movement of the foundation during heating. The side shear resistance, end bearing, and building restraint will influence the distribution in thermally induced stresses and strains [22]. Soil–structure interaction mechanisms of energy foundations have been studied in centrifuge-scale tests for simplified soil profiles

[21, 30]. However, evaluation of full-scale foundations imposes a set of real boundary conditions and soil strata. Several full-scale energy foundations have been evaluated to study the thermo-mechanical stresses and strains during mechanical loading, heating, and cooling [2, 4, 15, 16, 20] (Table 1). The thermal axial stress ranges from −1 to 5 MPa, and the thermal axial displacement of the foundation head ranges from −4.2 mm upward to +4.0 downward. The axial stresses are well within the compressive strength of reinforced concrete, and the axial displacements of the foundation would not lead to significant angular distortions to cause architectural damage for most buildings.

2.2 Thermal behavior

The thermal behavior of energy foundations depends on many factors, including the thermal properties of individual materials in the GSHE, site stratigraphy, groundwater and its flow, heat exchanger configuration within foundation and dimensions of the energy foundation, and thermal demands of the building [6]. To optimize the design of GSHE, the system thermal conductivity, specific heat capacity, borehole resistance, and heat exchange rate must be evaluated accurately [27]. For the purposes of this study, the primary mode of heat transport in the soil surrounding energy foundations is assumed by conduction. There is little to no groundwater present in the soil profile of the foundation installations; hence, groundwater flow (and convective heat transfer) is considered to be negligible. The heat flux from an infinitely long cylindrical source is given by:

$$Q = -2\pi R l \lambda \frac{\mathrm{d}T}{\mathrm{d}r} \tag{3}$$

where Q is the heat flux in Watts being supplied to the energy foundation, R is the radius of the energy foundation, l is the length of the energy foundation, λ is the thermal conductivity of the medium in contact with the cylindrical source, and $\mathrm{d}T/\mathrm{d}r$ is the temperature gradient in the radial direction. As the fluid flow rate through the heat exchanger pipes is sufficient to lead to a turbulent flow pattern, convection is assumed to be the predominant mechanism of heat transfer within the fluid. Conduction is assumed to be dominant through the heat exchanger pipe walls, concrete, and into the ground. As it is difficult to measure the thermal properties of the individual soil layers and materials in energy foundations, they are typically characterized using a system value.

Thermal response tests (TRTs) are the most common method of determining thermal properties of the subsurface and energy foundation system [6]. Thermal response testing of geothermal borehole heat exchangers has been in use for several years [28] and involves circulating a fluid through a heat exchanger while supplying a constant amount of power to the fluid. During a TRT, the temperatures of the fluid entering and exiting the foundation are monitored over a period of several days. The measured values of the fluid supply and return temperatures and the mass flow rate through each foundation can be used to calculate the input heat flux in Watts, as follows:

$$Q = \Delta T_{\mathrm{fluid}} \dot{V} \rho_{\mathrm{fluid}} C_{\mathrm{fluid}} \tag{4}$$

where $\Delta T_{\mathrm{fluid}}$ is the difference between the supply and return fluid temperatures in K (T_{supply} and T_{return}, respectively), $\dot{V}$ is the fluid flow rate in $\mathrm{m^3/s}$, ρ_{fluid} is the mass density of the fluid $\mathrm{kg/m^3}$, and C_{fluid} is the specific heat capacity of the fluid in J/(kgK). The heat flux density can be calculated by dividing Eq. (4) by the cross-sectional area of the heat exchanger tubing.

Several studies have used simple analytical solutions to investigate the thermal behavior of full-scale energy foundations in different soil types with various heat exchanger loop configurations and foundation geometries [7, 9, 10, 17, 25]. The results of these studies are summarized in Table 2. The system thermal conductivity values reported in these studies range from 2.4 to 6.0 W/mK, which is much higher than the thermal conductivity of most geological and structural materials, suggesting that the thermal conductivity values may incorporate the effects of the heat capacity of the concrete and may not represent steady-state conditions [18]. In these studies, the TRT was performed at the head of the foundation before the building has been constructed. However, there has not been a thorough evaluation of TRT results on foundations after construction and plumbing is complete. The fact that the tubing used to connect the energy foundation to the heat pump is often not insulated for practical construction purposes means that the heat exchange response of the energy foundation system may be affected by ambient surface fluctuations.

3 Project description

3.1 Building description

A one-story, shower-shave building was constructed at the Field Engineering and Readiness Laboratory (FERL) of the US Air Force Academy (USAFA) beginning in March 2012. The building provides restrooms, showers, and laundry facilities for 100 people. The building will also be used to evaluate the performance of energy-efficient technologies to aid in the development of "net zero"-energy-consuming structures for the US Department of Defense (DoD). These technologies include energy foundations, a radiant in-floor heating system, solar photovoltaic panels,

Table 2 Summary of TRT results from previous studies

Case	Hamada et al. [10]	Ooka et al. [25]	Gao et al. [9]	Lennon et al. [17]	Brettmann and Amis [7]
Foundation type	26 × DP	2 × DS	1 × DS	4 × DP	3 × ACIP
Foundation length (m)	9	20	25	12-17	18.3
Foundation diameter (mm)	300 (square)	1500	600	244 (round), 270 (square)	300-450
# Heat exchanger loops	1,2, Indirect/ Direct Pipe	8	1-3	1	2
TRT analysis method	N/A	N/A	Num. method	Line source	Line source
Thermal conductivity (W/mK)	N/A	N/A	5.8–6.0	2.4–2.6	2.5–2.6
Heat exchange rate (W/m)	54–69 (ext.)	100–120 (rej.) 44–52 (ext.)	57–108 (rej.)	N/A	73–80 (rej.)

DS drilled shaft, *ACIP* auger cast in place pile, *DP* driven pile, *Rej* heat rejection into foundation, *Ext* heat extraction from foundation

and a solar water heating system. Each component will be continuously monitored to evaluate the energy usage or output of each technology. In addition to the ground-source heat pump coupled with the energy foundations, the building contains a natural gas boiler heating system. Having both conventional and ground-source HVAC systems permits comparison of their energy efficiencies under similar environmental conditions.

3.2 Subsurface conditions

A site investigation was performed in September 2011 by Hernandez [11], which consisted of two 102-mm-diameter borings located within the building footprint, extending 12 and 7 m below the ground surface. At selected intervals, disturbed samples were obtained by driving split-spoon with a 622.75 N hammer falling 762 mm. Penetration resistance measurements were made during driving. Exploration results from both boreholes were similar and showed three prominent strata, and relevant data are shown in Table 3. The thermal conductivity values were measured on the split-spoon samples of soil using a thermal needle and provide a preliminary estimate of the thermal conductivity of the subsurface strata. The top layer is approximately 1 m thick and consists of sandy fill. Beneath the fill is a very dense 1-m-thick sandy gravelly layer. The bedrock is Dawson–Arkose (sandstone) extending to the maximum depth explored. No groundwater was encountered during the site investigation or foundation installation, so it is assumed to be at a depth greater than 16 m.

3.3 Energy foundation descriptions

Eight drilled shafts, each 15.2 m deep by 0.61 m diameter, provide the foundation support for the structure, as shown in Fig. 1a. The one-story building could have been constructed with a shallow foundation, so the main purpose of incorporating the deep drilled shafts into the building was to evaluate the thermo-mechanical response of the energy foundations for this research project. Each foundation contains a 0.46-m-diameter steel reinforcing cage that extends the full length of the shaft. The reinforcing cages are composed of six #7 longitudinal bars with #5 radial hoops spaced at 0.3 m on center throughout the length of the cage. The top of the shafts is spliced into a 0.91 m deep by 0.61 m wide grade beam that extends around the perimeter of the building. Each foundation contains a heat exchanger loop consisting of 19-mm-diameter HDPE tubing. At the top of each foundation (i.e., 1 m below grade), the heat exchanger loop is connected with tubing, which is routed through the grade beam (Fig. 1b) into a manifold within the mechanical room of the building (Fig. 1c).

Table 3 Summary of stratigraphy encountered during subsurface exploration at USAFA

Layer	Depth to bottom of stratum (m)	Material encountered	Gravimetric water content (%)	Dry unit weight (kN/m^3)	SPT N-Value (blows/300 mm)	Thermal Conductivity (W/mK)
1	1	Sandy fill w/silt, gravel	5	18.4	70	1.118
2	2	Dense sands, silt, gravel	7	19.2	85	0.785
3	12+	Sandstone	N/A	N/A	50/25.4 mm	1.233

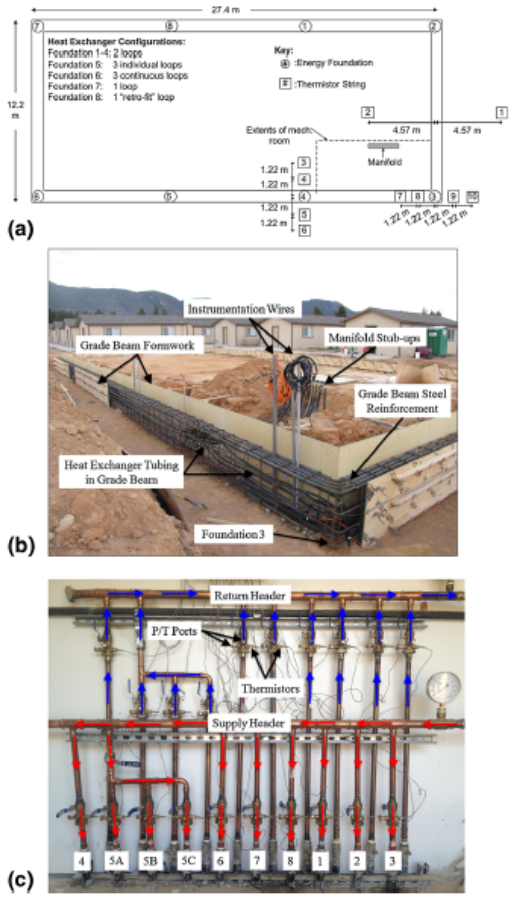


Fig. 1 **a** Plan view of the building with the locations of the different energy foundations; **b** heat exchanger tubing configuration in grade beam prior to concrete placement; **c** manifold detail prior to installation of insulation

The heat exchange tubing was attached to the inside of the reinforcing cages such that the inlet and outlet tubes were separated diametrically by at least 90°, which minimizes thermal short circuiting from the inlet to outlet tubes. The reinforcing cages were lifted with a 3-point pick to minimize bending, and the cages were lowered into the hole with a crane and were suspended on wooden beams to ensure that the top of the cage was at the base of the grade beam. A concrete pump truck was used to place high-slump concrete with a compressive strength (f'_c) of 21 MPa in the holes following placement of the reinforcing cages. A tremie pipe was used to avoid excessive segregation of the concrete during free fall. The use of the tremie also minimized the

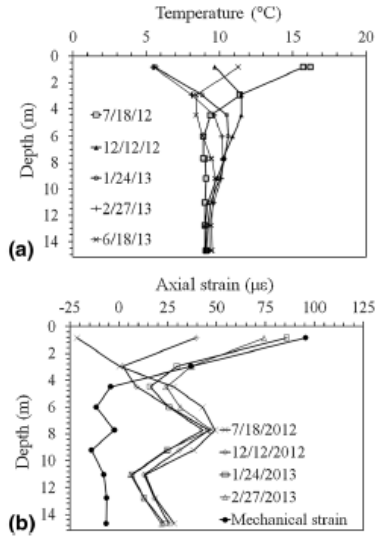


Fig. 2 Measurements from Foundation 4 during building construction: **a** profile of seasonal temperature variations; **b** profiles of axial strain during foundation curing and building loading, with strains due to mechanical loading

risk of damage to the heat exchanger loops and embedded instrumentation.

Each shaft has one, two, or three heat exchanger loops configured in different ways (Fig. 1a). Foundations 1 through 4 have identical heat exchanger configurations, with two continuous heat exchanger loops attached to the inside of the steel reinforcement cage. Foundation 5 has three individual loops, each having a supply and return line running to the mechanical room; this permits any combination of the loops to be operational in order to evaluate the efficiency of multiple loops in a single foundation. Foundation 6 has three continuous heat exchanger loops with only one supply and return line extending to the manifolds. Foundation 7 contains one loop connected to the interior of the reinforcing cage. Foundation 8 has a single loop in the center of the foundation to simulate a retrofit where a heat exchanger would be inserted into a core hole bored into an existing foundation. This was constructed with a 100-mm-diameter plastic sleeve in the center of the foundation. After curing, a single heat exchanger loop was inserted into the plastic sleeve and the hole was grouted with sand bentonite grout.

3.4 Instrumentation

Instrumentation was incorporated into three of the eight energy foundations to capture the distribution of axial strain and temperature with depth. Foundations 1 and 3

contain six Geokon Model 4200 vibrating wire strain gauges (VWSGs), while Foundation 4 contains twelve, at the depths shown in the legend of Fig. 4. Foundation 4 has twice the number of gauges to capture detailed strain and temperature distribution. At three locations within Foundation 4, gauges were located at the same depth on opposite sides of the reinforcing gage to gain redundancy in temperature and strain readings and to capture any differential strain measurements across the width of the shaft. All of the gauges were oriented vertically and attached to brackets welded to longitudinal steel reinforcing bars. The sensor cables were routed to the mechanical room where they are connected to the data acquisition system. Temperature variations in the soil surrounding the energy foundations are monitored using a series of ten Geokon model 3810 thermistor strings that each has six thermistors spaced equally over the same length as the foundation, installed in boreholes that were then backfilled with CETCO high thermal conductivity grout at the locations shown in Fig. 1a. The temperatures around Foundations 3 and 4 are monitored using four thermistor strings each, with additional thermistor strings located beneath the floor slab and outside the building footprint.

3.5 Ambient ground temperatures and construction strains

Seasonal temperature versus depth in Foundation 4 was recorded at various times over the course of a year (Fig. 2a), as were the axial strains (Fig. 2b). The depths in this figure (and other figures) are measured from the bottom of the grade beam, which is 0.91 m below the ground surface. Ground temperatures fluctuate between 5 and 16 °C near the surface and then become relatively stable at a temperature of 9 °C at depths below 4 m. The axial strains measured in July 2012 reflect the impact of concrete curing, with some tensile strains observed near the head of the foundation. Construction of the floor slab, walls, and roof occurred in Fall 2012, reflected in the increase in axial strain at the head of the foundation. The difference in the strain profiles between February 2013 and July 2012 was assumed to be equal to the mechanical strain in the foundation due to the majority of the building load. The strain decreases with depth as expected, with a maximum strain corresponding to an axial load of 833 kN. Similar behavior was noted from the temperatures and strains measured in Foundations 1 and 3.

3.6 Testing scheme

A series of thermal response tests were performed on individual and groups of foundations after the building was constructed. Specifically, an 11 kW thermal response test unit was used to circulate and heat a 20 % propylene glycol–water mixture through the foundations. The TRT unit is comprised of four heaters, two rated at 2.5 kW and two at 3 kW. A combination of heaters may be activated to achieve a nominal heat input to the heat exchange fluid ranging from 2.5 to 11 kW. Fluid properties of the glycol mixture are shown in Table 4. The heated fluid passed into the supply header, circulated through the foundations, and then passed out of return header back to the test unit. The flow rate of each foundation was measured at one instance during the test on each foundation from the pressure/temperature ports (P/T ports) using a differential pressure meter at a fluid temperature of 30 °C. The differential pressure was then used to compute the flow. During the test, the inlet and outlet temperatures of the heat exchanger fluid for each foundation were continuously monitored using pipe plug thermistors installed within ports on the manifold.

Table 4 Heat exchange fluid properties

Water-to-propylene glycol ratio	Molar heat capacity (J/molK)	Molecular weight (g/mol)	Specific heat capacity (J/kgK)	Fluid density (g/ml)
5:1	98	30	3267	1.008

A series of seven test stages were performed to investigate the thermal response of various components of the energy foundation system at USAFA, as summarized in Table 5. In each stage, a nominal heat input was selected to avoid heating any foundation component too rapidly. Stage 1 involved heating Foundations 1–4 simultaneously. Since each of these foundations has an identical loop configuration within the foundation itself, the effects of the horizontal length of tubing required to connect each foundation to the manifold (called "run-out length") were documented [24]. Stage 1 operated for 498 h with the intent of allowing sufficient time to increase the temperature of the soil surrounding the foundations and to observe the temperature rise in the boreholes 3–10. Stages 2–4 were conducted on Foundations 6–8 individually with a nominal heat input to the fluid of 5 kW and duration of approximately 1 week for each stage. Stages 5–7 were conducted on Foundation 5, which has three individual loops that can be turned on and off at the manifold. Stage 5 operated on only Loop 5A. During stage 6, Loop 5B was activated while continuing to pass fluid through Loop 5A. In stage 7, all three loops in Foundation 5 were switched open so that flow was permitted to pass through all three loops. Stages 5–7 utilized a 2.5-kW heater in the thermal response test unit. The input heat flux was calculated using Eq. (4) for each heat exchanger loop during each stage.

Table 5 Summary of thermal response testing stages and heat input details

Testing stage	Foundation	Testing dates	Approximate duration (hours)	Nominal heat flux applied (kW)	Measured heat flux Q (kW)
1	1	6/18/13–7/9/13	498	11.0	3.133
	2				2.696
	3				2.180
	4				2.081
2	6	7/11/13–7/18/13	175	5.0	4.534
3	7	7/18/13–7/25/13	167	5.0	4.431
4	8	7/25/13–8/1/13	165	5.0	4.075
5	5A	8/1/13–8/5/13	119	2.5	2.285
6	5A	8/5/13–8/28/13	530	2.5	1.164
	5B				1.150
7	5A	8/28/13–9/4/13	163	2.5	0.797
	5B				0.803
	5C				1.201

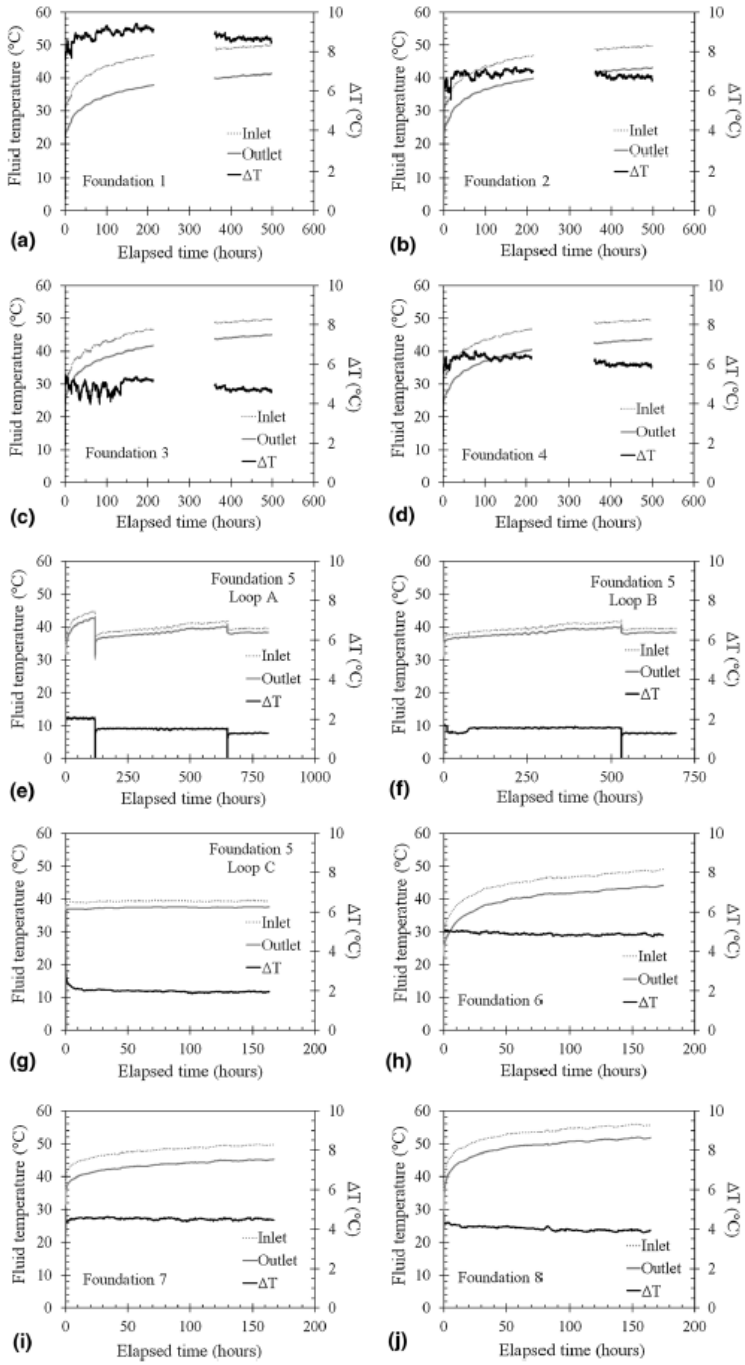
4 Thermal response test results

The fluid temperatures versus elapsed time plots are shown in Fig. 3. The differences in fluid temperatures, ΔT_{fluid}, are also plotted on the right vertical axis for each foundation. In all cases, a relatively rapid rise in temperature was observed in the first 25 h. At one segment during stage 1, the data acquisition system malfunctioned and is represented by a gap in the data (Fig. 3a–d). A constant ΔT_{fluid} value reflects uniform heat input energy into the system, and these conditions prevailed after about 100 h of testing in each stage. Note that the differential temperature is greater for longer horizontal run-out lengths, indicating that heat exchange occurs in the grade beam and can have an impact on heat exchange performance.

The temperatures of the three instrumented foundations at different depths are shown in Fig. 4a–c. The thermistor at the bottom of each of the foundations showed a substantially lower increase in temperature than in the rest of the foundation. This may be due to denser rock at the toe of the foundation, potential rises in the water table at the time of testing, or the geometry of how the heat exchangers were routed to the U-connector at the base of the foundation. After approximately 498 h of heating, fluid circulation in Foundations 1–4 was stopped, and the temperatures in the foundation were monitored during the cooling process. The deeper portions of the foundations cooled more rapidly, as they were not influenced by the warm ambient air temperature at the ground surface. The foundations returned to their original temperatures after approximately 700–1,000 h after the end of heating. Fluctuations in the uppermost thermistors during cooling reflect the impact of the seasonal ground temperature fluctuations.

Foundation heating led to an increase in ground temperatures measured by the thermistor strings. The temperatures measured in Borehole 1, located at a distance of 4.6 m outside of the building footprint, are shown in Fig. 5a. The temperature fluctuations occur only near the surface and appear to be due to hot weather. The temperatures measured in Borehole 2, located under the building slab in the center of Foundations 1–4, are shown in Fig. 5b. Although some changes in temperature near the top of the borehole appear to correspond with the increase in surface temperature during the summer, the temperature of the subsurface at the bottom of the borehole experienced an increase in temperature by about 2 °C below a depth of 8 m likely due to the heating of the subsurface due to the operation of Foundations 1–4. After stage 1 ended, the borehole temperature slightly decreased and remained nearly unchanged from 8/15/13 to 9/4/13.

The temperatures measured in Boreholes 3 through 6, which are located at different radial distances from Foundation 4, are shown in Fig. 6. The temperatures at 1.2 m from the center of Foundation 4 (Fig. 6a, b) increase more rapidly than those located at 2.4 m from the center of the foundation (Fig 6c, d). The temperatures under the building slab were affected less by changes in the surface temperature than those that were not under the building slab. This suggests that the floor slab acts as an insulator. This effect may be enhanced after the heating system in the building is used to maintain a constant temperature within the building envelope. Although the results shown in Table 6 provide a preliminary evaluation of the thermal response of energy foundations, a more in-depth analysis of the thermal resistance of the different energy foundations will be investigated in the future using the concepts of thermal


(a)
Foundation 1
(b)
Foundation 2
(c)
Foundation 3
(d)
Foundation 4
(e)
Foundation 5
Loop A
(f)
Foundation 5
Loop B
(g)
Foundation 5
Loop C
(h)
Foundation 6
(i)
Foundation 7
(j)
Foundation 8
Inlet
Outlet
ΔT
Fluid temperature (°C)
ΔT (°C)
Elapsed time (hours)

◀**Fig. 3** Fluid temperatures during thermal response testing on Foundations: **a** 1 (stage 1); **b** 2 (stage 1); **c** 3 (stage 1); **d** 4 (stage 1); **e** 5, Loop A (stage 5,6,7); **f** 5, Loop B (Stages 6 and 7); **g** 5, Loop C (Stage 7); **h** 6 (Stage 2); **i** 7 (Stage 3); **j** 8 (Stage 4)

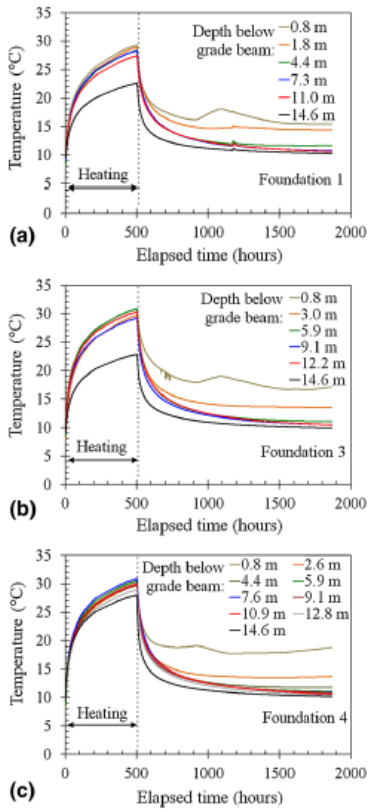


Fig. 4 Foundation temperatures during thermal response testing. **a** Foundation 1; **b** Foundation 3; **c** Foundation 4

resistance and shape factors described by Loveridge and Powrie [19].

5 Evaluation of Thermo-mechanical Behavior

To evaluate the thermo-mechanical response of the energy foundations, the resonant frequency values, f, from the VWSGs during the heating test were first converted into axial strain ε, as follows:

$$\varepsilon = -Gf^2 \tag{5}$$

where G is the gage factor equal to 3.304×10^{-3} and the units of ε are micro-strain. The negative sign follows

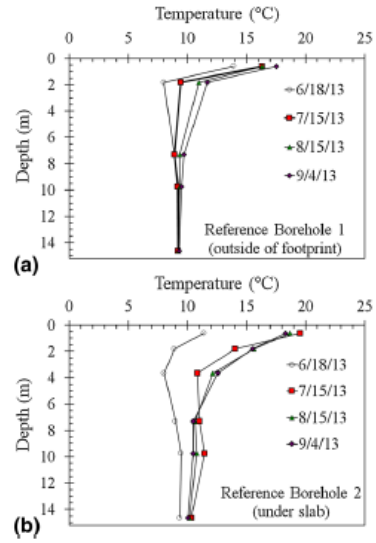


Fig. 5 Temperatures of the subsurface during thermal response testing: **a** Reference Borehole 1; **b** Reference Borehole 2

the geotechnical sign convention where compressive strains are defined as positive. The strain values calculated with Eq. (5) were then converted to thermal strains, as follows:

$$\varepsilon_T = [(\varepsilon_i - \varepsilon_0)B + \alpha_s \Delta T] \tag{6}$$

where B is the batch calibration factor of 0.975, ε_i is the measured axial strain at time i, ε_0 is the initial value of axial strain at the end of building construction (i.e., ambient temperature), ΔT is the change in temperature between the initial reading and the value at time i, and α_s is the coefficient of thermal expansion of the steel wire of -12.2 $\mu\varepsilon/$ °C. This equation accounts for the elongation of the steel wire in the gage during heating.

The thermal axial strains calculated using Eq. (6) are shown in Fig. 7a–c. As the temperature increases in the foundations, the thermal axial strains become more negative, indicating expansion. The fluctuations in thermal axial strain after heating was stopped correlate well with the observed changes in foundation temperature due to the changes in surface temperature. The strain gauges near the top of each instrumented foundation display the greatest variation, as this is the depth range that is subjected to the greatest change in temperature.

Instances in time corresponding to average changes in foundation temperature of 6 °C during heating and cooling were selected to generate thermo-mechanical profiles for each foundation. The profiles of foundation temperature in Fig. 8 show that the temperature is relatively constant in

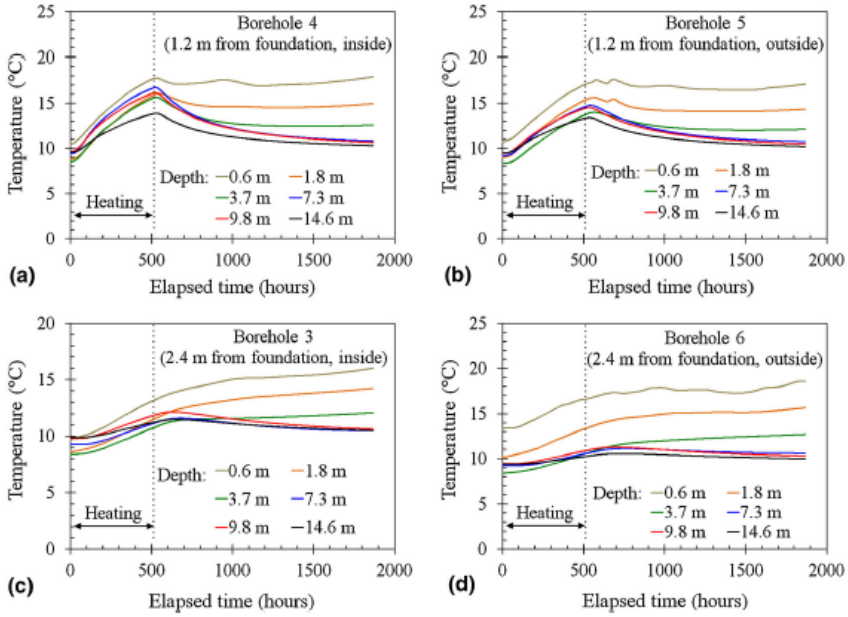


Fig. 6 Subsurface temperatures surrounding the foundations during thermal response testing: **a** Borehole 4; **b** Borehole 5; **c** Borehole 3; **d** Borehole 6

the foundation, except for the base of the foundations, and slight variations in the shape of the temperature profile with time are observed in the top of the foundation due to surface temperature effects. The corresponding changes in thermal axial strain are shown in Fig. 9. The shapes of the thermal axial strain profiles are relatively consistent for each foundation. A large thermal axial strain at the toe of each foundation was observed even through the change in temperature was not significant. Although this could be due to issues with the temperature measured by the thermistors at these depths, it could also reflect the possibility that the toe of the foundations may be relatively soft. This would be the case if the loose sandstone cuttings were not thoroughly removed from the bottom of the holes during construction. The distributions in thermal axial strain in Fig. 9 reflect that soil–structure interaction due to mobilization of side shear resistance leads to a nonlinear distribution in thermal strain with depth, similar to the observations of Laloui et al. [15] and Bourne-Webb et al. [4] during the heating portions of their tests.

Profiles of thermal axial stress were calculated using Eq. (2) with a Young's modulus of 30 GPa (Fig. 10). If the foundations were completely restrained, the maximum thermal axial stress that could be generated for an increase in temperature of 18 °C is 6.48 MPa. As the strain gage measurements indicate that some strain occurs in the foundations during heating, the thermal axial stresses in the foundations are all lower than this value. The thermal axial stress generally increases with depth for each of the foundations, although the stress appears to decrease below a depth of 11–12 m in each of the foundations. As the point of maximum thermal axial stress typically coincides with the point of zero axial displacements, it is possible that the null point in the foundations occurs at a depth of 11–12 m below the grade beam. The thermal axial stresses in Foundation 3 were observed to be nearly 1 MPa lower than in the other two foundations. This could be attributed to the lower amount of restraint provided by the corner of the building compared with the center of the grade beam. Further, Foundations 5 and 8 were not heated, so they may provide greater constraint to Foundations 1 and 4 than to Foundation 3. The thermal axial stresses observed in these three foundations are below 33 % of the compressive strength of reinforced concrete ($f'_c = 21$ MPa). Even if the foundations were fully restrained (i.e., the case where the measured thermal axial strain is close to zero), the maximum thermal axial stress of 6.48 MPa would be less than this limit.

The mobilized side shear stress due to changes in foundation temperature was calculated from the difference in thermal axial stress values at different heights in the soil layer, as follows:

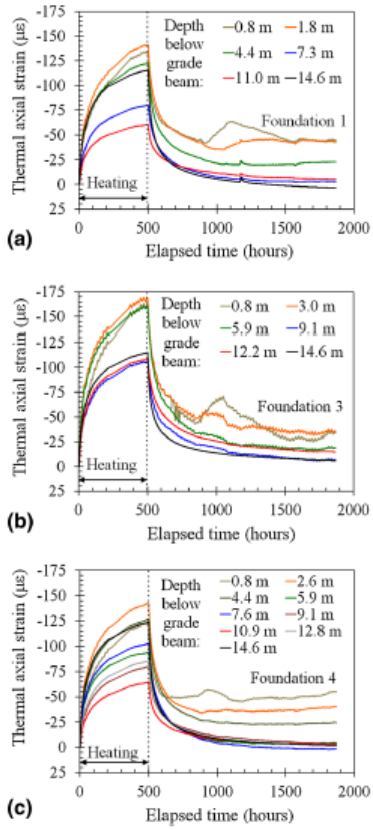


Fig. 7 Time series of thermal axial strains during thermal response testing and subsequent cooling: **a** Foundation 1; **b** Foundation 3; **c** Foundation 4

$$f_{s,\mathrm{mob},j} = \frac{(\sigma_{T,j} - \sigma_{T,j-1})D}{4\Delta l} \tag{7}$$

where D is the shaft diameter and Δl is the distance between gages. The sign convention for the mobilized side shear stress implies that positive side shear stresses are upward (in the same direction as those mobilized during mechanical loading), while negative side shear stresses are downward (in the opposite direction as those mobilized during mechanical loading). The mobilized side shear stress profiles calculated for the greatest change in temperature of 18 °C for all three foundations are shown in Fig. 11. The results indicate that a negative (downward) side shear stress was observed in the upper portion of the foundation and a positive (upward) side shear stress was observed in the lower portion of the foundation. The point at which the signs of the mobilized side shear stress change is in the region of the maximum thermal axial stress and

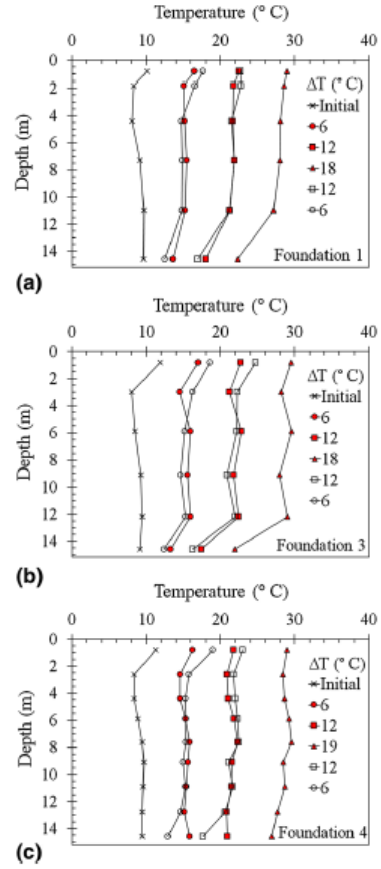


Fig. 8 Profiles of temperature for different average changes in foundation temperature during heating (*red*) and cooling (*open*): **a** Foundation 1; **b** Foundation 3; **c** Foundation 4

corresponds to the position of the null point. The mobilized side shear stress increases with depth as expected, and the magnitude (upward or downward) is less than 200 kPa, which is reasonable for a weakly cemented sandstone.

Although the actual displacements of the toe and head of the foundations were not measured, the relative thermal axial displacements to the bottom of the foundations could be calculated by integrating the thermal axial strain profiles, as follows:

$$\delta_{T,i} = \delta_{T,i-1} + \frac{1}{2}(\varepsilon_{T,i-1} + \varepsilon_{T,i})\Delta l \tag{8}$$

where $\delta_{T,i}$ is the thermal axial displacement at the midpoint between gages and $\varepsilon_{T,i}$ is the thermal axial strain at the location of gage i. The profiles of thermal axial displacement for the three foundations suggest that Foundation 3

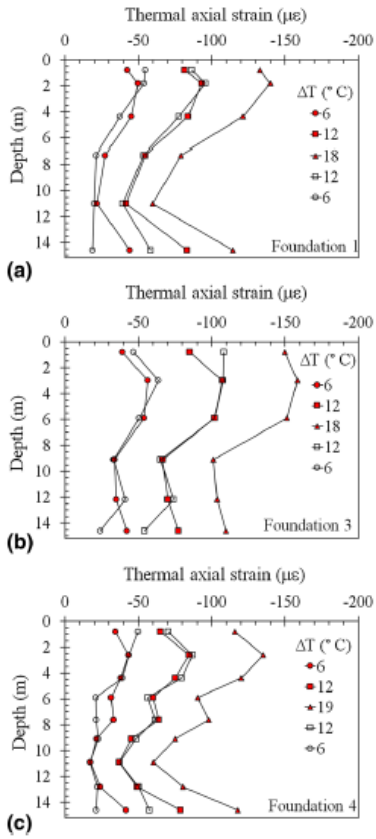


Fig. 9 Profiles of thermal axial strain for different average changes in foundation temperature during heating (*red*) and cooling (*open*): **a** Foundation 1; **b** Foundation 3; **c** Foundation 4

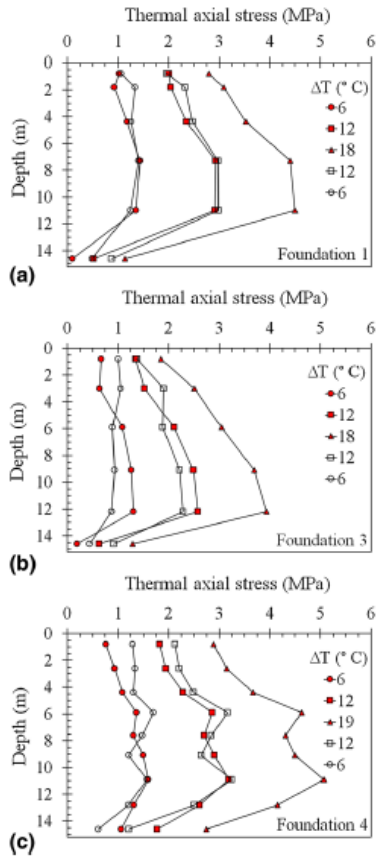


Fig. 10 Profiles of thermal axial stress for different average changes in foundation temperature during heating (*red*) and cooling (*open*): **a** Foundation 1; **b** Foundation 3; **c** Foundation 4

experienced a greater displacement at the head of the foundation than the other two foundations (Fig. 12), likely for similar reasons contributing to the lower thermal axial stress in it. Although the relative displacement at the toe is assumed to be zero for the purposes of calculating the thermal axial displacements, this does not assume that the null point is at the toe. For a rigid, end-bearing foundation, it is expected that the null point should be close to the toe as by definition it should not be able to move downward. If this were the case, then the maximum upward movement of the head would range from −1.3 to −1.7 mm during a change in temperature of about 18–19 °C. On the other hand, if loose cuttings are present at the toe, it is possible that the null point would move upward. If the null point is assumed to be at a depth of 11–12 m, then the point of zero axial displacement can also be assumed to occur at this depth, shifting the profiles of displacement to the left. In

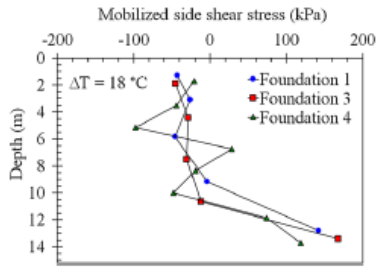


Fig. 11 Profiles of mobilized side shear for a change in temperature of 18 °C for Foundations 1, 3, and 4

this case, the upward displacement at the foundation head would range from −1.0 to −1.4 mm, and the downward displacement at the foundation toe would range from 0.2 to

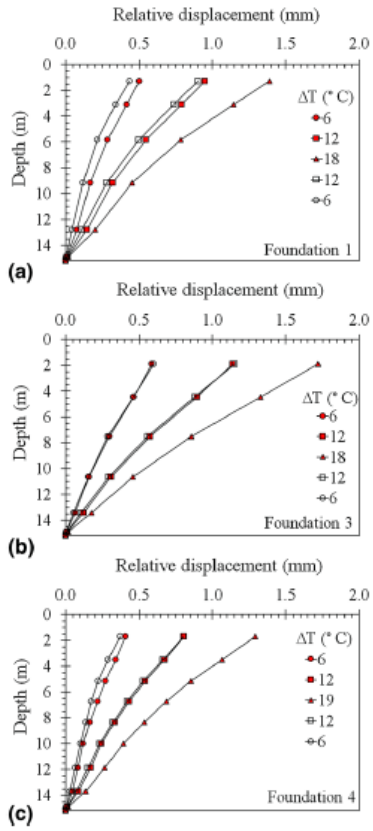


Fig. 12 Profiles of thermal axial displacement for different average changes in foundation temperature during heating (*red*) and cooling (*open*): **a** Foundation 1; **b** Foundation 3; **c** Foundation 4

0.3 mm. If the toe does not move, the maximum upward displacements will lead to an angular distortion δ/L_s, where δ is the difference in displacements of two adjacent energy foundations and L_s is the horizontal spacing between the foundations, of less than 1/5,000. This value is lower than the limit expected to cause architectural damage in the building [3, 29].

The foundations experienced linear changes in thermal axial strain with changes in temperature (Fig. 13). During the cooling phase, the strain for each foundation was observed to nearly return to the values that were experienced during the heating portion of the test, further indicating linear elastic behavior of the reinforced concrete. Relatively little hysteresis was observed, indicating that the mobilized side shear resistance during the heating test did not lead to locked-in plastic strains at the interface. The slope of each trend was defined as the mobilized coefficient of thermal expansion, and the profiles of this coefficient with depth are plotted in Fig. 13d. For each foundation, the mobilized coefficient of thermal expansion was less than that of free expansion ($\alpha_c = -12$ με/ °C), indicating that side shear resistance and the end restraint boundary conditions prevented the foundation from expanding as much as it possibly could in free-expansion conditions. The lowest value of the mobilized coefficient of thermal expansion in each of the foundations was observed at a depth of 11–12 m, consistent with the location of the maximum thermal axial stress. Foundation 3 exhibited slightly greater mobilized coefficients of thermal expansion likely due to the lower amount of restraint provided by the corner of the building.

The ranges in stress in Foundations 1, 3, and 4 are consistent with those observed from the other full-scale foundations reported in the literature (Table 1). The change in thermal axial stress with the change in temperature for Foundations 1, 3, and 4 is shown along with published data from the literature in Fig. 14. The depth corresponding to the greatest increase in thermal stress within each foundation was used to define the maximum rates of axial stress during heating. The depths shown correspond to the null point of each foundation and show the greatest thermal axial stress rate. Rates of $\sigma_t = 210\Delta T$ to $260\Delta T$ were determined from the results in this study, which are slightly higher than values from Laloui et al. [15] and Bourne-Webb et al. [4], but are consistent with those calculated from the results of McCartney and Murphy [20]. This may be due to the greater coefficient of thermal expansion of the reinforced concrete used in this study (−12 με/ °C), which is slightly higher than the value of −9.5 με/ °C used in the studies of Laloui et al. [15] and Bourne-Webb et al. [4].

6 Evaluation of thermal behavior

The details of each heating stage and results from the thermal response tests are summarized in Table 6. The measured heat input for each heat exchanger configuration was normalized over the effective length of the energy foundation system element to define the heat flux per unit meter of heat exchanger Q/L. The effective length, L, is defined as the distance from the manifold to the tip of the foundation. The effective length includes the horizontal run-out length of tubing cast in the grade beam in addition to the 15.2 m length of each foundation. The heat exchange rate is used in this study to assess the relative heat exchange behavior of each foundation because of the geometry of the horizontal connection between the energy foundations and the manifold, which does not satisfy the assumptions of the available analytical methods. The values of Q/L range from 24.4 to 108.5 W/m, which are within

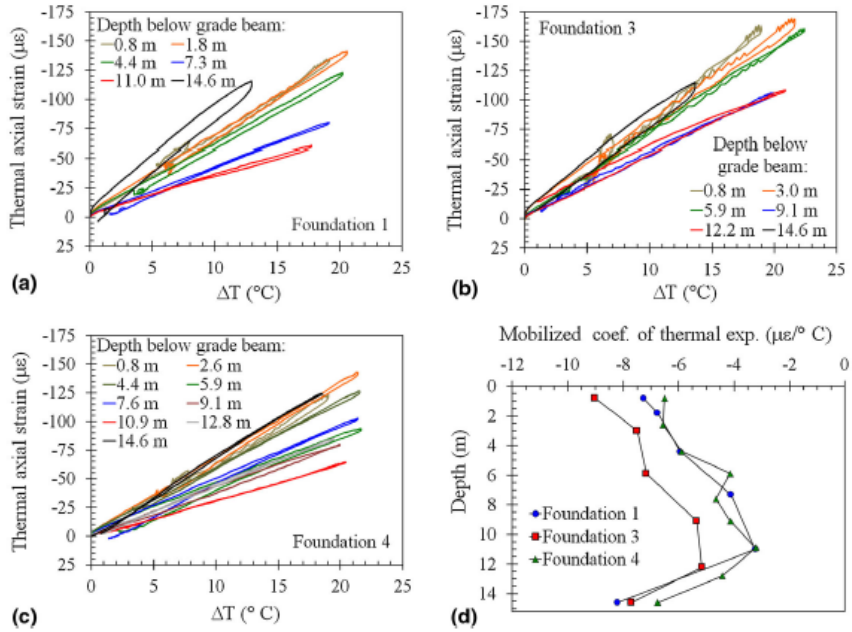


Fig. 13 Thermal axial strain with change in foundation temperature at each depth: **a** Foundation 1; **b** Foundation 3; **c** Foundation 4; **d** mobilized coefficient of thermal expansion with depth for the three instrumented energy foundations

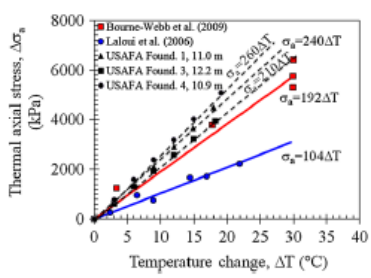


Fig. 14 Comparison of the slope of maximum thermal axial stress with change in temperature for the USAFA foundations and those from previous studies

the range reported by Bourne-Webb [5]. The value of Q/L was found to be highly dependent on the effective length and nominal heat input, with a decrease in Q/L with increasing effective length. The response is similar to the decrease in heat flux for increasing length-to-diameter ratios observed by Bourne-Webb [5].

As the horizontal run-out length is increased, the heat exchange rate is observed to decrease as some heat loss or gain occurs in the grade beam [24]. The effect of the horizontal run-out length can be assessed by evaluating the Q/L results from Foundations 1 through 4, as shown in Fig. 15. These foundations have different horizontal run-out lengths, but have the same heat exchanger configuration and were tested together in the same test. A linear relationship was used to estimate the corrected value of Q/L representing the response of a foundation without the effect of horizontal run-out length, as follows:

$$(Q/L)_{\text{corrected}} = Q/L - m_{\text{HR}} \times H_{\text{RO}} \quad (9)$$

where m_{HR} is the run-out length correction factor in (W/m)/m and H_{RO} is the horizontal run-out length in meters. A value of m_{HR} of −1.16 (W/m)/m was obtained from the slope of the line in Fig. 15. The corrected values of Q/L are reported in Table 6. After the correction is applied, values of Q/L for Foundations 1 through 4 ranged from 97.9 to 109.4 W/m. The small differences after correction may be due to the slight difference in flow rate through each of the foundations. The correction approach was applied to the other foundations at the site to eliminate the impact of horizontal run-out length to evaluate the thermal properties of the foundation–soil system alone. The results in Table 6 indicate that Foundation 6 had the highest value of Q/L of 139.2 W/m; and it had the longest continuous length of heat exchanger within the foundation. However, Foundations 7 and 8 both have similar high values of Q/L of 126.9

Table 6 Summary of results from thermal response testing for each stage (note: all foundations have a length of 15.2 m)

Testing stage	Foundation	Heat exchanger configuration	Effective length, L (m)	Flow rate (ml/s)	Average ΔT_{fluid} (°C)	Measured heat flux, Q (W)	Q/L (W/m)	Corrected Q/L (W/m)
1	1	2 Loops	42.6	108	8.8	3133	73.5	105.2
	2		33.5	119	6.9	2696	80.5	101.6
	3		21.3	137	4.8	2180	102.3	109.4
	4		23.6	106	6.0	2081	88.2	97.9
2	6	3 Loops	41.8	144	4.8	4,534	108.5	139.2
3	7	1 Loop	54.0	108	4.5	4,431	82.1	126.9
4	8	1 Loop in center	63.1	126	3.9	4,075	64.6	120.0
5	5A	1 Loop	32.7	347	2.0	2,285	69.9	90.1
6	5A	1 Loop	32.7	226	1.6	1,164	35.6	55.8
	5B			226	1.6	1,150	35.2	55.4
7	5A	1 Loop	32.7	189	1.3	797	24.4	44.6
	5B			189	1.3	803	24.6	44.8
	5C			189	1.9	1,201	36.7	56.9

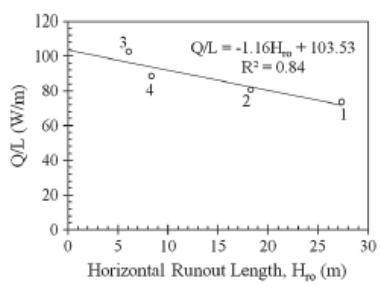


Fig. 15 Trends in heat flux per unit meter (Q/L) for Foundations 1 through 4 as a function of horizontal run-out length

and 120 W/m even though they only have one continuous heat exchanger. It is possible that these tests were not performed for a long-enough duration so that the effect of the heat capacity of the concrete could be overcome [18]. The *Q*/*L* for Foundation 5 when only loop 5A was included was lower, but this could have been due to the much higher flow rate used in this test. The flow rate decreased when the valves for loops 5B and 5C were opened as flow was distributed among the three loops.

The thermal conductivity of the subsurface surrounding the foundations could be assessed using the temperatures of the subsurface measured using the thermistor strings in the boreholes. The temperatures of Foundation 4 and the surrounding subsurface were plotted at different instances in time, as shown in Fig. 16a. The vertical line in this figure denotes the outside limit of the building slab, and the distances are measured from the center of the foundation. As expected, as Foundation 4 heats up, the temperature of the soil also increases. The thermal conductivity as a function of time at a depth of 7.3 m was calculated using

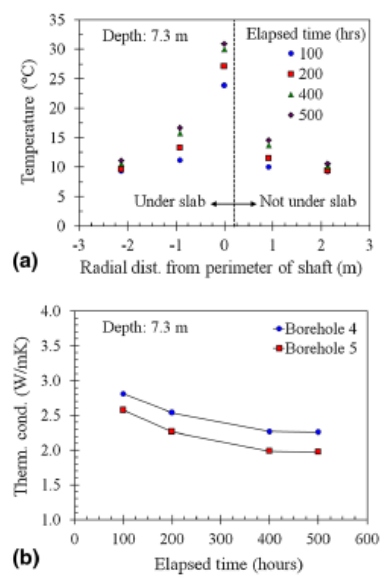


Fig. 16 **a** Temperatures of Foundation 4 and surrounding soil; **b** thermal conductivity over the duration of heating from the thermal gradient between the foundation and Boreholes 4 and 5

the temperatures from Boreholes 4 and 5 using Eq. (3), as shown in Fig. 16b. For greater times, the temperature gradient, dT/dr, between the foundation and adjacent boreholes became steadier, which produced thermal conductivity values that were constant between 400 and 500 h. Thermal conductivity of the soil near the end of heating in stage 1 was calculated to be 2.0 and 2.3 W/mK for heat flow through the subsurface in the directions of Boreholes

4 and 5, respectively. These values of thermal conductivity are consistent with the corrected system thermal conductivity values reported by Murphy et al. [24] using the line source method to analyze the heating response data reported for stage 1, even though the details of the foundation system do not satisfy the assumptions of this analysis.

7 Conclusions

A series of thermal response tests were carried out on eight full-scale energy foundations with various heat exchanger configurations after construction in a new building. Three of eight energy foundations were instrumented with embedded strain gauges and thermistors to capture the thermo-mechanical behavior during heating, while the inlet and outlet fluid temperatures were monitored for each of the foundations to capture their thermal response. Relevant conclusions related to the thermo-mechanical behavior of the energy foundations are as follows:

- During heating over a change in temperature of 18 °C, Foundations 1, 3, and 4 experienced a relatively uniform change in temperature with depth.
- The increase in temperature led to expansive thermal axial strains in each foundation that were smaller than the estimated free-expansion strain. The maximum strains in each foundation occurred near the top and bottom.
- The location of the maximum compressive thermal axial stress, which ranged from 4.0 to 5.1 MPa, was located between a depth of 11 and 12 m (at a normalized depth of 0.72–0.78). The thermal axial strains were used to calculate the thermal axial stresses induced in each foundation during heating.
- The relative displacement between the head and toe of each instrumented foundation was found to increase nonlinearly upward. If the toe of the foundation was assumed not to move, the upward displacement of the head of the foundation was estimated to range from −1.3 to −1.7 mm for the maximum increase in temperature. However, if the toe of the foundation was assumed to move downward (which would be the case if the hole was not adequately cleaned) and the null point was colocated with the depth of the maximum thermal axial stress, the upward displacement of the head of the foundation was estimated to range from −1.0 to −1.4 mm. In either case, the thermal axial movements are not sufficient to induce structural or aesthetic damage to the building.
- The end restraint boundary conditions were found to play an important role in the thermal axial stress and displacement profiles in the energy foundations. Foundation 3 was located at the corner of the building and had the lowest end restraint at the top compared with Foundations 1 and 4 which are located beneath the middle of the grade beam, especially considering the fact that Foundations 1 and 4 were also expanding during the same test. The lower head stiffness was found to lead to a lower thermal axial stress in Foundation 3, along with a slightly greater displacement.
- The thermal axial strains, stresses, and displacements during cooling were similar to those during heating, indicating linear thermo-elastic behavior. Little hysteresis was observed, which indicates that permanent thermo-plastic deformations did not occur at the foundation–subsurface interface.

The results from the temperature measured for various system components in each heating stage were analyzed to determine system thermal behavior. Relevant conclusions related to the thermal behavior of the energy foundations are as follows:

- The heat flux ranged from 64.5 to 108.5 W/m for the foundations considering the role of the horizontal run-out length of tubing connecting the foundations to the manifold, although lower values of 34.5 W/m were measured when performing staged heating tests on Foundation 5.
- Heat exchange through the horizontal portion of the loop contributes to the efficiency of heat exchange and may play an important role in the design of the plumbing of energy foundations. After application of a correction factor to consider the effects of the horizontal run-out length, the heat flux ranged from 90.1 to 139.2 W/m, and it was possible to consider the relative impacts of different heat exchange configurations. The foundations with a single heat exchanger loop had relatively high values of heat flux per meter, nearly as high as that of a foundation with three continuous heat exchangers. This may be due to the large thermal mass that the single heat exchanger must overcome, leading to a higher Q/L than expected in a long-term test.
- The building slab was observed to lead to an insulating effect that led to more stable temperatures in the subsurface. This insulating effect may change when the temperature of the building is maintained at a constant temperature, and is a topic of further study in the future.
- The temperatures of the subsurface measured using thermistor strings in boreholes surrounding Foundation 4 were used to calculate thermal conductivity of the subsurface. The thermal conductivity at a depth

of 7.3 m was observed to range from 2.0 to 2.3 W/mK.

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APPENDIX D

THERMO-MECHANICAL CHARACTERIZATION OF FULL-SCALE ENERGY FOUNDATIONS

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Impact of Horizontal Run-out Length on the Thermal Response of Full-Scale Energy Foundations

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ABSTRACT: This paper includes the results of a combined thermal response test performed simultaneously on four full-scale energy foundations beneath a new building at the U.S. Air Force Academy. The temperatures of the fluid circulating in and out of each of the closed loop heat exchangers in the drilled shaft foundations were monitored over the course of 21 days during application of a constant input energy. The temperatures of the foundations at different depths were also monitored. The horizontal length of pipe connecting each energy foundation to the manifold through the grade beam of the building was different. The results of the tests indicate that a longer horizontal run-out length leads to a lower apparent thermal conductivity, potentially due to the greater mass of concrete being heated, or lower heat transfer in the grade beam due to the higher temperatures of the ground surface during testing.

INTRODUCTION

Energy foundations are structural elements that incorporate a series of geothermal heat exchanger loops embedded in reinforced concrete, and are used for the purpose of exchanging heat between the subsurface and a building. Heat is transferred from the subsurface, which has a relatively steady temperature compared to the ground surface, to a fluid circulating through the heat exchanger loops, to a refrigerant circulating within a heat pump in the building. The heat exchange capacity of an energy foundation can be characterized using a thermal response test (TRT). These tests consist of injecting heat at a constant rate into the fluid circulating through the loops. TRTs are often performed on a foundation soon after installation, in which case heat is only transferred into the reinforced concrete and surrounding subsurface. However, these tests neglect the horizontal portion of the heat exchange loop within the building slab or grade beam that connects the foundation to the manifold and heat pump. In most cases, this horizontal run-out length is not insulated because of economical and time constraints and may be affected by surficial temperature fluctuations. Accordingly, the run-out length may affect the heat exchange capacity of the system. This paper presents an evaluation of the impact of horizontal run-out length through evaluation of the results of a thermal response test performed on four identical energy foundations installed beneath a building.

BACKGROUND

Thermal response testing of geothermal borehole heat exchangers has been in use for several years (Sanner et al. 2005), including development of testing standards and analysis approaches (Loveridge and Powrie 2012). Energy foundations differ from borehole heat exchangers in that the reinforced concrete can store heat during a thermal response test, and the geometry of the foundations and embedded heat exchangers do not satisfy the assumptions of most simple thermal response test analyses. Several investigations have been conducted to characterize the thermal performance of energy foundations, in terms of either the heat pump efficiency (Wood et al. 2009) or the system thermal conductivity (Brettmann and Amis 2011; Ozudogru et al. 2012; Loveridge and Powrie 2012). The heat exchange characteristics of energy foundations depend on the thermal properties of the different structural materials and geologic strata, groundwater flow, foundation dimensions, thermal response test procedures, and the analysis method. The heat exchange response during operation of a building depends on the heating or cooling load applied to the foundation (Sanner 2001). Loveridge and Powrie (2012) and Bourne-Webb (2013) collected data from a number of studies and observed that foundations with a low length to diameter ratio have a greater heat flux per unit meter (Q/L). Further, they found that transient heating tests lead to a greater Q/L than steady-state heating tests. This was attributed to the thermal mass of the concrete, which has a higher specific heat capacity than the surrounding soil.

ENERGY FOUNDATION SYSTEM

Building and Project Description

A new building at the US Air Force Academy (USAFA) was constructed to evaluate the long-term performance of energy efficiency technologies to aid in the development of “net zero” energy consuming structures for the U.S. Department of Defense (DoD). These technologies include energy foundations with different heat exchanger configurations, a radiant in-floor heating system, solar photovoltaic panels, and a solar water heating system. The building contains a conventional gas-powered heating system which will be used to provide back-up heating to the ground-source heat pump coupled with the energy foundations, and will also permit comparison of the energy efficiencies of the two systems under similar environmental conditions.

Subsurface Conditions

Relevant data from a site investigation within the building footprint is shown in Table 1. Three strata were identified: an approximately 1 m-thick layer of sandy fill, underlain by a very dense 1 m-thick sandy gravelly layer, underlain by Dawson-Arkose sandstone bedrock. No groundwater was encountered during the site investigation or foundation installation, so it is assumed to be at a depth greater than 16 m. Field classification tests indicate that all materials are non-plastic and non-expansive. Thermal conductivity of each layer was measured on site in disturbed samples recovered from a split-spoon sampler using a thermal needle (KD2Pro from Decagon Devices of Pullman, WA).

Table 1. Summary of stratigraphy encountered during subsurface exploration.

Layer	Depth to Bottom of Stratum (m)	Material Encountered	Gravimetric Water Content (%)	Dry Unit Weight (kN/m^3)	Thermal Conductivity (W/mK)
1	1	Sandy fill w/ silt, gravel	5	18.4	1.118
2	2	Dense sands, silt, gravel	7	19.2	0.785
3	12+	Sandstone	N/A	N/A	1.233

Energy Foundations and Heat Exchanger Configurations

Eight drilled shafts provide support for the structure, each having a depth of 15.2 m and a diameter of 0.61 m. Although the one-story building could have been constructed with a shallow foundation, the drilled shafts were incorporated to evaluate the thermal and mechanical response of the energy foundations as part of this research study. Each shaft contains a 0.46-m-diameter steel reinforcing cage that extends the full length of the shaft. The reinforcing cages are composed of six #7 longitudinal bars with #5 radial hoops spaced at 0.3 m on center throughout the length of the cage. The top of the shafts are spliced into a 0.91 m-deep by 0.61 m-wide grade beam that extends around the perimiter of the building. The shafts were constructed using the dry hole method due to the lack of groundwater and the competency of the subsurface material.

Each foundation contains a closed-loop heat exchanger constructed from 19 mm-diameter high density polyethylene (HDPE) tubing. Each shaft has either one, two, or three heat exhanger loops configured as shown in Fig. 1. The tubing is routed from the foundation to the mainfold in the mechanical room through the grade beam. The heat exchange tubing was attached to the inside of the reinforcing cages with zip-ties at a distance of at least 70 mm from the vertical reinforcing members. The inlet and outlet tubes were seperated diametrically by at least 90° to minimize thermal short-circuiting where heat is lost by direct transmission from the inlet to outlet tubes. U-shaped couplings were used to connect the inlet and outlet tubes so that the tubing does not cross the bottom of the cage where it could cause concrete segregation. A concrete pump truck was used to place high-slump concrete having a compressive strength of 21 MPa in the holes following placement of the reinforcing cages.

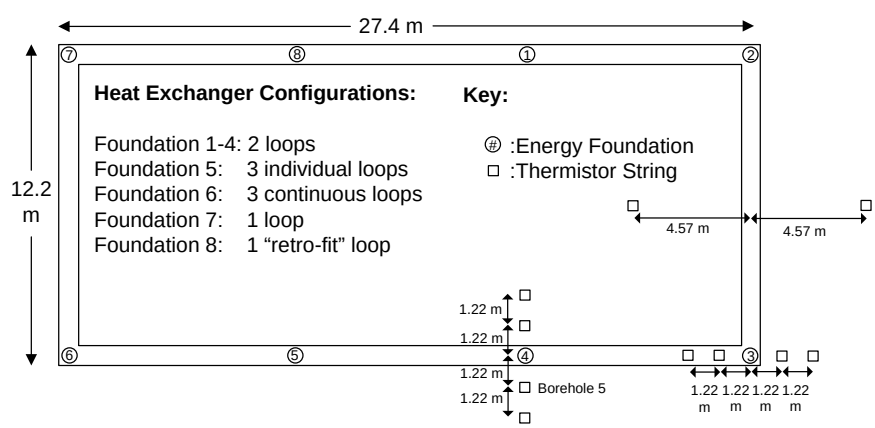
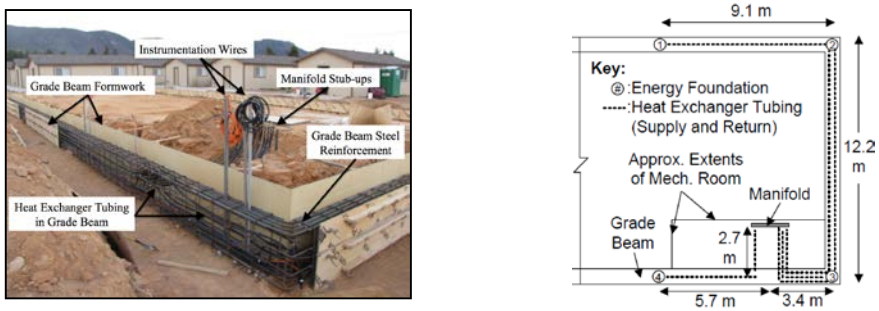


Figure 1. Heat exchanger loop configurations in the energy foundations.

This study focuses on the behavior of Foundations 1 through 4, each of which has identical heat exchanger configurations with two continuous loops arranged in a W-shape. Each of the four shafts contain a total of 61 meters of heat exchanger tubing, but each has a different horizontal run-out length. The grade beam was constructed around the foundations and the heat exchangers were routed through the grade beam into a manifold in the mechanical room. A photo illustrating the run-out tubing in the grade beam prior to concrete placement is shown in Fig. 2(a). The routing of the run-out pipes and lengths are shown in plan view in Fig. 2(b).



(a) **(b)**

Figure 2. (a) Run-out tubing in grade beam prior to concrete placement, (b) Plan view of run-out tubing connecting foundations 1-4 to the manifold.

Instrumentation

Vibrating wire strain gages and thermistors were incorporated into Foundations 1, 3, and 4 at different depths in order to capture the distribution of temperature and axial strain with depth. The locations of the sensors are shown in Fig. 3. Foundations 1 and 3 contain six thermistors, while Foundation 4 contains twelve. Foundation 4 has twice the number of gauges with the intent of capturing a more discretized temperature distribution with depth. At three locations within Foundation 4, gauges were located at the same depth on opposite sides of the reinforcing gage to gain redundancy in temperature readings and to capture any differential temperature measurements across the width of the shaft. All of the thermistors were attached to brackets welded to longitudinal steel reinforcing bars. The sensor leads were routed to the mechanical room where they are connected to the data acquisition system.

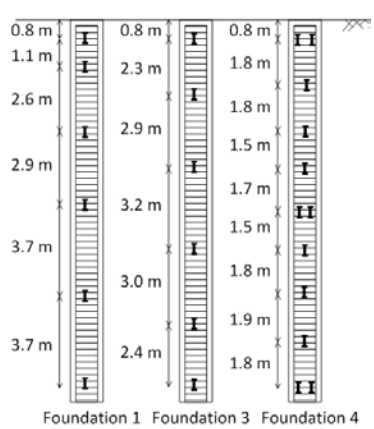


Figure 3. Locations of thermistors in each instrumented foundation.

Temperature variations in the subsurface around the energy foundations were monitored using a series of ten Geokon model 3810 thermistor strings that each have six sensors, installed in boreholes that were then backfilled with CETCO high thermal conductivity grout at the locations shown in Fig. 1. The subsurface temperatures around Foundations 3 and 4 are monitored using four thermistor strings, with two under the slab and two outside. Two thermistor strings are used to monitor ground temperatures under the center of the slab and outside of the building.

Experimental Setup and Procedures for the Thermal Response Test

A heating test was conducted to evaluate the thermal response of Foundations 1 through 4. As these foundations have identical heat exchanger configurations, the impact of the run-out pipe length on the apparent thermal conductivity could be assessed. A photo of the manifold system is shown in Figure 4. The manifold was insulated during the test to reduce the influence of ambient outside air temperatures on thermistor readings. An 11 kW thermal response test unit was used to circulate and heat a 20% propylene glycol-water mixture. Fluid properties of the glycol mixture are shown in Table 2. The heated fluid passed into the supply header, circulated through the foundations, and then passed out of return header back to the test unit. The fluid rate out of each foundation was measured when the fluid temperature was 30 °C using a differential pressure meter inserted into a pressure and temperature port (P/T ports). The P/T port includes a Venturi balancing valve for calculation of the flow rate from the differential pressure. The ball valves were adjusted with the goal of maintaining the same flow rate through each foundation, but the accuracy of the meter only permitted the flow rates to be within 30 ml/s of each other. During testing, the inlet and outlet fluid temperatures for each foundation were monitored using pipe plug thermistors installed in the P/T ports.

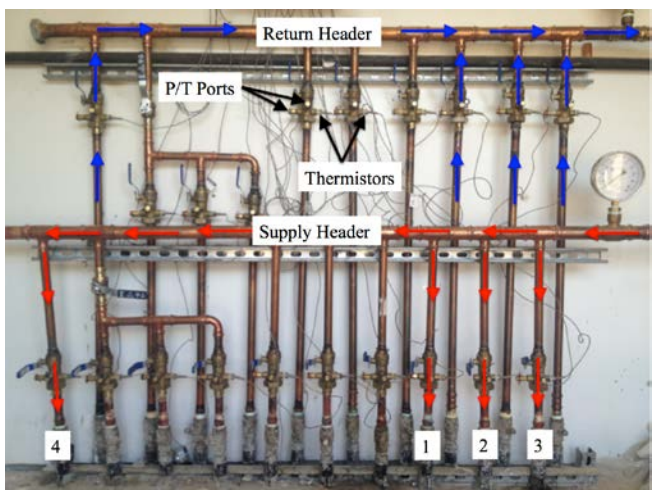


Figure 4. Energy foundation manifold configuration prior to insulation.

Table 2. Heat exchange fluid properties.

Water to Propylene Glycol Ratio	Molar Heat Capacity (J/molK)	Molecular Weight (g/mol)	Specific Heat Capacity (J/kgK)	Fluid density (g/ml)
5:1	98	30	3267	1.008

RESULTS

Seasonal temperatures vs. depth were recorded at various times over the course of a year, as shown in Figure 5. Ground temperature fluctuates between 5 °C and 16°C near the surface then becomes relatively stable at a temperature of 9 °C at depths below 4 m. The depths in this figure (and other figures) are measured from the bottom of the grade beam, which is 0.91 m below the ground surface.

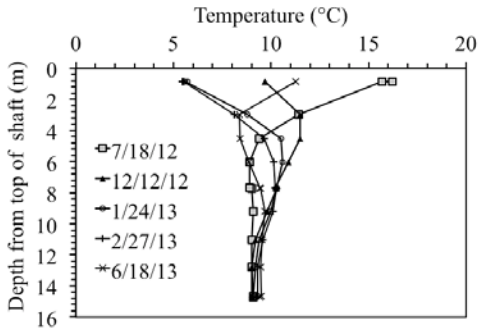


Figure 5. Seasonal temperature profile of Foundation 4.

Figure 6 shows the inlet and outlet fluid temperatures for the four foundations. In all cases, a relatively rapid rise in temperature was observed in the first 25 hours before reaching more steady conditions. The differences in fluid temperatures, □T, are also plotted on the right vertical axis for each foundation. A constant value of □T reflects a system. Although the data acquisition system malfunctioned over a weekend causing a gap in the data, the trends are clear.

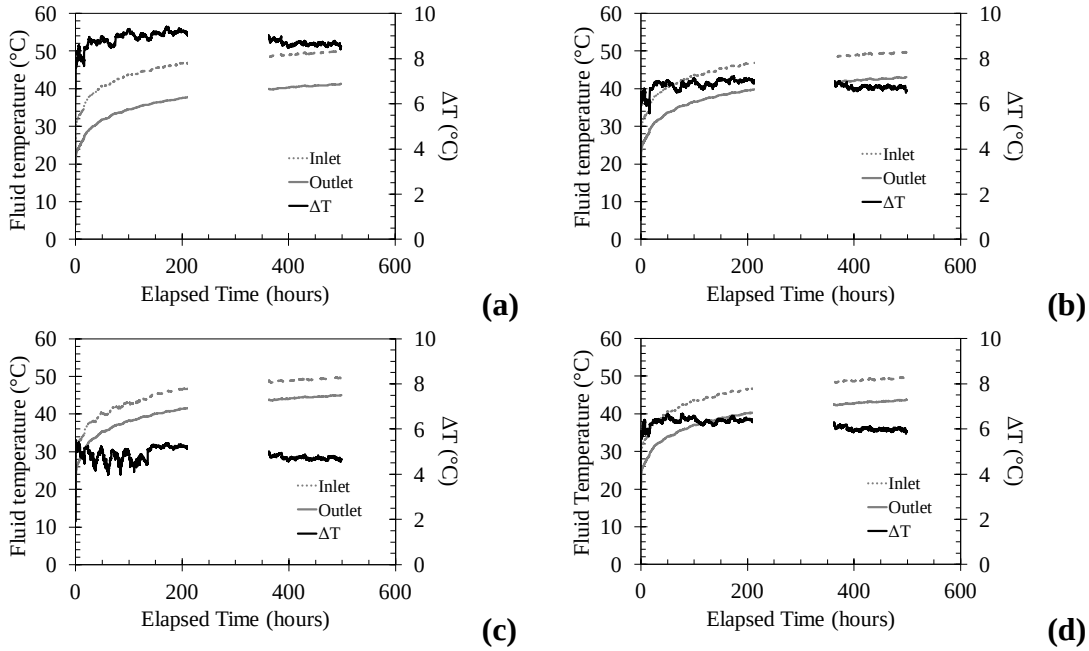


Figure 6. Temperature rise curves and differential temperature during testing: (a) Foundation 1; (b) Foundation 2; (c) Foundation 3; (d) Foundation 4.

The temperatures of Foundations 1, 3 and 4 as well as the thermistor borehole strings were monitored during the test. The time series and temperature profiles for Foundation 4 and Borehole 5 (located 1.2 m from the center of Foundation 4) are shown in Figure 7. The temperature rise in Foundation 4 is relatively uniform with depth during heating. An increase in temperature does not occur in Borehole 5 until 50 hours after the test is started, after which the temperature rises steadily indicating uniform heat flux. The sensor at 0.61 m is warmer due to its proximity to the surface.

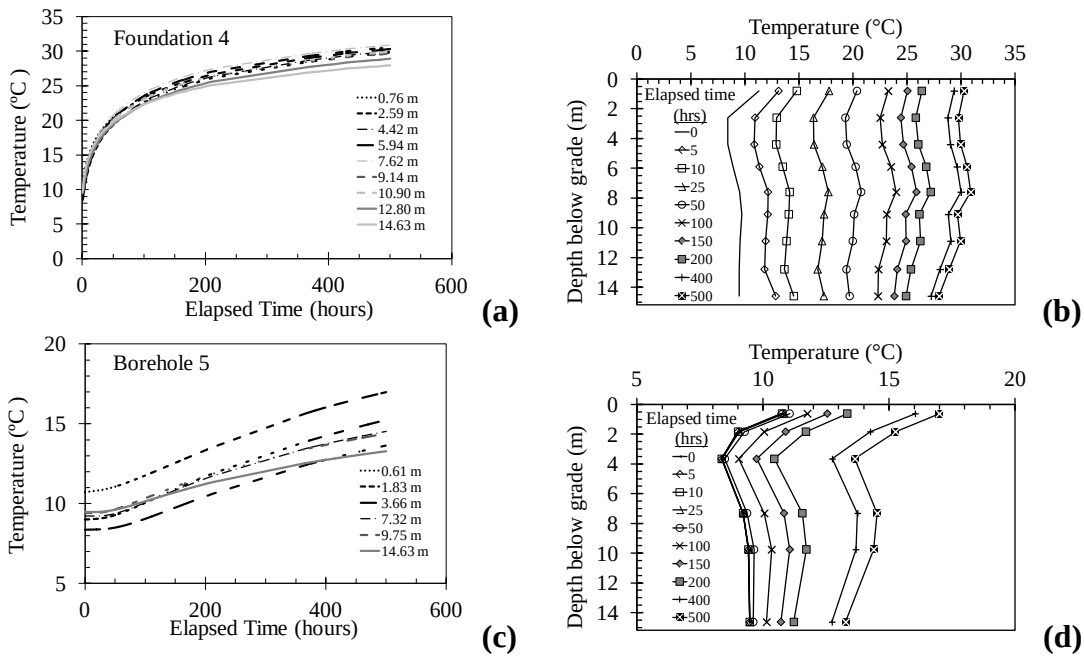


Figure 7. Temperatures: (a) Foundation 4 time series; (b) Foundation 4 profiles; (c) Borehole 5 time series; (d) Borehole 5 profiles.

ANALYSIS

The measured values of the fluid supply and return temperatures and the mass flow rate through each foundation can be used to calculate the heat flux, as follows:

$$Q = \Delta T \dot{V} \rho_{fluid} C_{fluid} \qquad (1)$$

where Q is the heat flux in W,)T is the difference between the supply and return fluid temperatures in K (T_{supply} and T_{return}, respectively), $\dot{V}$ is the fluid flow rate in ml/s, Δ_{fluid} is the mass density of the fluid kg/ml, and C_{fluid} is the specific heat capacity of the fluid in J/(kgK). The value of)T was defined using the average of the time series shown in Fig. 6 after reaching steady state.

The most rigorous approach to estimate the thermal conductivity of the energy foundation-soil system would be to solve Fick's second law inversely considering the boundary conditions and optimizing the layer thermal properties to match the data in Figure 6. However, it may be impossible to find a unique solution for such a complex system. Several analytical solutions to

Fick's second law are available for simplified heat exchanger geometries, including the infinite or finite line or cylinder sources. Analytical solutions have the shortcoming that the thermal heat capacity of the different materials cannot be considered, an issue that is relevant in transient heating and cooling of energy foundations (Bourne-Webb 2013). However, these solutions provide a simple approach to assess the role of horizontal run-out length. The infinite line source equation was used in this study for simplicity, acknowledging the fact that the heat exchanger is not a linear element. The line source method involves prediction of the change in temperature of a medium surrounding a line heat source with constant heat input energy. The change in temperature of medium at a radial distance of r away from the line source can be calculated as follows:

$$\mathrm{T(t,r)} = -\frac{\mathrm{Q/L}}{4\pi\lambda}\mathrm{Ei}\left(-\frac{\mathrm{r}^2}{4\alpha\mathrm{t}}\right) \tag{2}$$

where r is the distance from the source in m, Q/L is the heat input energy per unit length (W/m), 8 is the thermal conductivity in W/mK, ∀ is the thermal diffusivity, and t is the time from the start of heating. Ei is the solution to the following integral, which can also be presented in a linearized form for small values of r, as follows:

$$-\mathrm{Ei}(-\mathrm{x}) = \int_{\mathrm{x}}^{\infty}\frac{\mathrm{e}^{-\mathrm{t}}}{\mathrm{t}}\mathrm{dt} \cong -0.58 - \ln(\mathrm{x}) \tag{3}$$

where x is the term in parentheses in Eq. (2). After inserting Eq. (3) into Eq. (2), the differential form of Eq. (2) can be rearranged to define the system thermal conductivity, as follows:

$$\lambda_a = \frac{Q}{4\pi L}\left[\frac{dT}{d(\ln t)}\right]^{-1} \tag{4}$$

where 8_a is the apparent thermal conductivity of each foundation in W/mK, L is the effective length of each foundation system in meters (representing the distance from the manifold to the tip of the foundation), and the term in brackets represents the slope of the change in mean fluid temperature versus the logarithm of time. The mean fluid temperature vs. logarithmic time is plotted in Fig. 8 and a constant slope is observed for each of the four foundations. The slope is calculated at large times after which it is assumed that the heat capacity of the concrete has been reached and heat is being transferred by conduction into the surrounding subsurface.

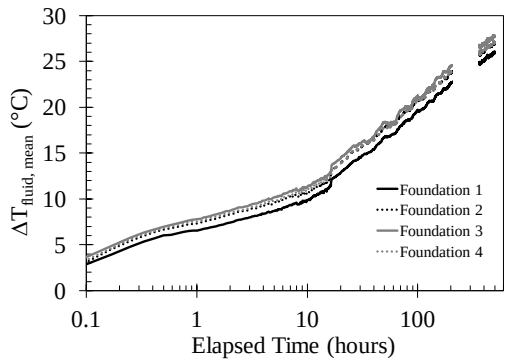


Figure 8. Mean fluid temperature rise vs. logarithm of elapsed time.

Details of each foundation and TRT results are summarized in Table 3. As each of the four foundations has the same length and heat exchanger tubing, the only difference is the horizontal run-out length. Foundation 1 has the longest horizontal run-out length (and largest L), and has the highest heat input energy consumption, Q, and the highest average value of)T. However, the heat transfer per unit length, Q/L, is the lowest. Foundation 3 has the shortest run-out length and the lowest heat energy consumption but the highest heat transfer per unit effective length.

Table 3. Details of loop lengths and summary of results.

Foundation #	1	2	3	4
Run-out length, H_{ro} (m)	27.4	18.3	6.1	8.4
Effective length, L (m)	42.6	33.5	21.3	23.6
Flow rate (ml/s)	109	119	137	106
Q (W)	3133	2696	2180	2081
Q/L (W/m)	73.5	80.5	102.3	88.2
dT/d(ln t)	4.01	3.96	4.10	4.05
8_a (W/mK)	1.5	1.6	2.0	1.7
$8_{a,\ corrected}$ (W/mK)	2.0	2.0	2.1	1.9

Note: Each foundation is 15.2 m long and contains a length of 61.0 m of tubing.

The apparent thermal conductivity and heat transfer versus effective length for each of the four foundations are shown in Fig. 9. For greater effective lengths, the thermal conductivity and heat input energy per unit length decreases by nearly 0.6 W/mK. The response is similar to the decrease in heat transfer for increasing length to diameter ratios observed by Bourne-Webb (2013). This is potentially due to the greater mass of concrete being heated, or lower heat transfer in the grade beam due to the higher temperatures of the ground surface during testing. This indicates that in the design phase of an energy foundation system, consideration for energy loss through the horizontal portion of the geothermal loop needs to be considered. In practice, energy foundations may be connected in series to reduce this effect. The system described in this study was plumbed in parallel in order to characterize and operate each energy foundation individually.

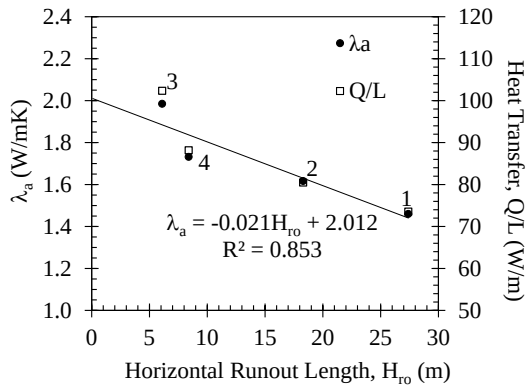


Fig. 9. Trends in apparent thermal conductivity and heat flux per unit length.

A linear relationship was used to estimate the value of apparent thermal conductivity representing the case of a foundation without the effect of horizontal run-out length, as follows:

$$\lambda_{a,corrected} = \lambda_a - m_{HR} \times H_{RO} \qquad (5)$$

where $8_{a,\ corrected}$ is the thermal conductivity of the foundation-soil system without the impact of the horizontal run-out length in W/mK, 8_a is the apparent system conductivity calculated from Eq. (4) in W/mK, m_{HR} is the run-out length correction factor in (W/mK)/m, and H_{RO} is the horizontal run-out length in meters. Use of this equation assumes that the thermal conductivity of each of the foundations is the same, which is reasonable as there is no significant change in stratigraphy between the foundation locations. After the correction is applied, values of apparent thermal conductivity range from 1.9 to 2.1 W/mK. This approach can be used for the other foundations at the site to eliminate the impact of horizontal run-out length on system conductivity to evaluate the thermal properties of the foundation-soil system alone.

CONCLUSIONS

The impact of the length of horizontal tubing connecting an energy foundation to the manifold and heat pump on the heat exchange characteristics of the energy foundation system was investigated in by measuring the temperatures of four foundations and surrounding soil boreholes during a 21 day-long thermal response test. The thermal conductivity and heat transfer per unit length results indicate that foundations with lower effective lengths (lower horizontal run-out lengths) may have greater normalized heat transfer performance. An empirical relationship was developed to account for the effects of horizontal run-out length, and corrected values of the apparent thermal conductivity ranged from 1.9 to 2.1 W/mK.

ACKNOWLEDGEMENTS

Support from DoD ESTCP project EW-201153 is gratefully acknowledged, as are the contributions of the 819th Air Force RED HORSE Squadron, who provided support for the heating test. The views in the paper are those of the authors alone.

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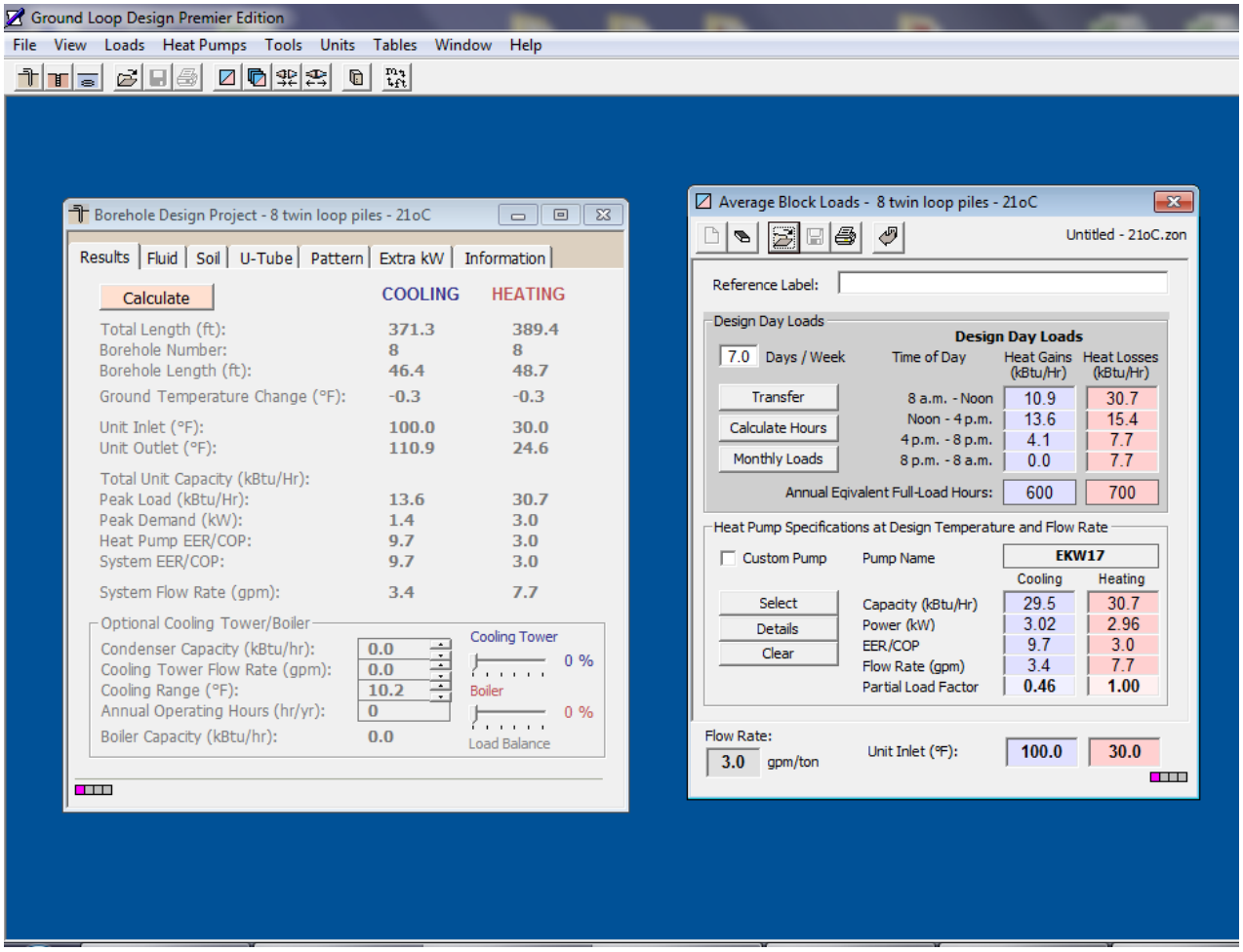
APPENDIX E

GROUND LOOP DESIGN AND HEAT PUMP SIZING INFORMATION PROVIDED BY FARRIS ENGINEERING



Ground Loop Design

Borehole Design Project Report - 15/02/2012

Project Name:			
Designer Name:			
Date:	20/05/2011	**Project Start Date:**	20/05/2011
Client Name:			
Address Line 1:			
Address Line 2:			
City:		**Phone:**	
State:		**Fax:**	
Zip:		**Email:**	

Calculation Results

	COOLING	HEATING
Total Length (ft):	370.9	388.7
Borehole Number:	8	8
Borehole Length (ft):	46.4	48.6
Ground Temperature Change (°F):	-0.3	-0.3
Unit Inlet (°F):	100.0	30.0
Unit Outlet (°F):	110.9	24.6
Total Unit Capacity (kBtu/Hr):	29.5	30.7
Peak Load (kBtu/Hr):	13.6	30.7
Peak Demand (kW):	1.4	3.0
Heat Pump EER/COP:	9.7	3.0
System EER/COP:	9.7	3.0
System Flow Rate (gpm):	3.4	7.7

Input Parameters

Fluid		Soil	
Flow Rate:	3.0 gpm/ton	Ground Temperature:	69.8 °F
Fluid:	20% Propylene Glycol	Thermal Conductivity:	0.58 Btu/(h*ft*°F)
Specific Heat (Cp):	0.97 Btu/(°F*lbm)	Thermal Diffusivity:	0.48 ft^2/day
Density (rho):	63.7 lb/ft^3		

Piping	
Pipe Type:	3/4 in. (20 mm) - SDR11
Flow Type:	Turbulent
Pipe Resistance:	0.072 h*ft*°F/Btu
U-Tube Configuration:	Double
Radial Pipe Placement:	Average
Borehole Diameter:	24.00 in
Grout Thermal Conductivity:	0.62 Btu/(h*ft*°F)
Borehole Thermal Resistance:	0.571 h*ft*°F/Btu

Design Software Gaia Geothermal

1 / 2

Input Parameters (Cont.)

Pattern		Modeling Time Period	
Vertical Grid Arrangement:	4 x 2		
Borehole Number:	8	Prediction Time:	100.0 years
Borehole Separation:	29.9 ft	Long Term Soil Temperatures:	
Boreholes per Parallel Circuit:	1	*Cooling:*	69.5 °F
Fixed Length Mode	Off	*Heating:*	69.5 °F
Grid File	None		
File:			

Heat Pumps			Optional Boiler/Cooling Tower		
Manufacturer:	WaterFurnace			Tower	Boiler
Series:	EW Hydronic International 50hz		Load Balance	0 %	0 %
Design Heat Pump Inlet Load Temperatures:			Capacity (kBtu/Hr)	0.0	0.0
	Cooling (WB)	*Heating (DB)*	Cooling Tower Flow Rate (gpm):	0.0	
Water to Air:	67 °F	70 °F	Cooling Range (°F):	10.2	
Water to Water:	55 °F	100 °F	Annual Operating Hours (hr/yr):	0	

Extra kW		Loads File
Pump Power:	0.0 kW	*Untitled - 21oC.zon*
Cooling Tower Pump:	0.0 kW	
Cooling Tower Fan:	0.0 kW	
Additional Power:	0.0 kW	

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APPENDIX F

INDEPENDENT GOVERNMENT ESTIMATE FOR CONSTRUCTION OF ENERGY FOUNDATIONS

CH2MHILL
Academy Services LLC
A CH2MHILL/KIRA Company

Final Estimate
Jerry Branesky

FA2517-10-D-501X - 2010 Front Range SABER
FERL Shower and Shower - XQPZ11-60543R
Jerry Branesky

Estimator: Jerry Branesky | **FERL Shower and Shower**

Division Summary (MF04)

01 - General Requirements		26 - Electrical	$558.95
02 - Existing Conditions		27 - Communications	
03 - Concrete	$58,756.33	28 - Electronic Safety and Security	
04 - Masonry	$1,237.50	31 - Earthwork	$73,839.55
05 - Metals		32 - Exterior Improvements	
06 - Wood, Plastics, and Composites		33 - Utilities	
07 - Thermal and Moisture Protection	$1,080.00	34 - Transportation	
08 - Openings		35 - Waterway and Marine Transportation	
09 - Finishes		41 - Material Processing and Handling Equipment	
10 - Specialties		44 - Pollution Control Equipment	
11 - Equipment		46 - Water and Wastewater Equipment	
12 - Furnishings		48 - Electric Power Generation	
13 - Special Construction		Alternates	$49,756.00
14 - Conveying Equipment		Trades	
21 - Fire Suppression		Assemblies	
22 - Plumbing	$2,937.60	**MF04 Bare Total (Without totalling components)**	**$198,075.93**
23 - Heating, Ventilating, and Air-Conditioning (HVAC)	$9,910.00		

Totalling Components

FRS Priced Line Items	$198,075.93	FRS Nonpriced Line Items	
RSMeans COLORADO SPRINGS, CO CCI 2012Q1, 93.80%	$(12,280.71)	FRS USAFA SABER Nonpriced Coefficient (19.0000%)	
2012 FRS USAFA SABER Standard-Nonsecured < $750k (-11.0000%)	$(20,437.47)		

Material, Labor, and Equipment Totals (No Totalling Components)

Material:	$47,410.35
Labor:	$117,778.61
Equipment:	$39,511.30
Other:	$(6,624.33)
Laborhours:	1,687.92
Green Line Items:2	$17,760.00

Priced/Non-Priced

Total Priced Items:	32	$198,075.93	
Total Non-Priced Items:	0	$0.00	0.00%
	32	$198,075.93	

Grand Total **$165,357.75**

Printed 29 MAR 2012 7:25AM | Page 1 of 5 | FERL Shower and Shower - XQPZ11-60543R

Estimator: Jerry Branesky

Totalling Component Details

Description	Item Count	Applicable Amount	Applied Amount	Applied Result	Balance
FRS Priced Line Items Included in Total: Yes Type:Total, Master Format Type: MF04 Values:Total Includes: Priced Filtering: (none)	32	$198,075.93		$198,075.93	$198,075.93
RSMeans COLORADO SPRINGS, CO CCI 2012Q1, 93.80% Included in Total: Yes Type:RSMeans CCI (Estimate Level) Subtotal based on 1 items: "FRS Priced Line Items"		$198,075.93	(6.2000)%	$(12,280.71)	$185,795.22
2012 FRS USAFA SABER Standard-Nonsecured < $750k Included in Total: Yes Type:Percentage Subtotal based on 2 items: "FRS Priced Line Items", "RSMeans COLORADO SPRINGS, CO CCI (Current)"		$185,795.22	(11.0000)%	$(20,437.47)	$165,357.75
FRS Nonpriced Line Items Included in Total: Yes Type:Total, Master Format Type: MF04 Values:Total Includes: Non Priced Filtering: (none)					$165,357.75
FRS USAFA SABER Nonpriced Coefficient Included in Total: Yes Type:Percentage Subtotal based on 1 items: "FRS Nonpriced Line Items"			19.0000 %		$165,357.75

Note: It appears that at least one of these totalling components is set to "Amount is at Estimate Level". This can cause some of the Project totalling components that share the same characteristics to have the appearance of not adding up correctly on this detailed report page.

	Item	Description	UM	Quantity	Unit Cost	Total	Book	
03 - Concrete								
1	03-11-13-45-1500-2250	Forms in place, footings, for keyway hung from supports, add (Modified using 03 -11-13-45-2250)	L.F.	540.0000	$3.09	$1,668.60	RSM12MCOM M, L, B	P
2	03-11-13-50-0020	Forms in place, grade beam, includes erecting, bracing, stripping and cleaning, job-built plywood, 1 use	SFCA	3,700.0000	$6.16	$22,792.00	RSM12MCOM M, L, B, CCI 808 Q1 WA/T	P
3	03-21-10-60-0330	Reinforcing in place, 50 to 60 ton lots, A615 Grade 60, includes labor, but not material cost, to install accessories, columns, spirals, hot rolled, 24" to 36" diameter	Ton	8.0000	$2,085.00	$16,680.00	RSM12MCOM Gm, M, L, B	P
4	03-31-05-35-0200	Normal weight concrete, ready mix, delivered, includes local aggregate, sand, portland cement, and water, excludes all additives and treatments, 3500 PSI	C.Y.	150.0000	$99.50	$14,925.00	RSM12MCOM M, B	P
5	03-31-05-70-3200	Placing concrete, includes labor and equipment to place, strike off and consolidate, grade beams, direct chute	C.Y.	19.0740	$11.31	$215.73	RSM12MCOM L, E, B, CCI 808 Q1 WA/T	P
6	03-31-05-70-4300	Placing concrete, includes labor and equipment to place, strike off and consolidate, slab on grade, up to 6" thick, direct chute	C.Y.	150.0000	$16.50	$2,475.00	RSM12MCOM L, E, B	P
		03 - Concrete Total				**$58,756.33**		
04 - Masonry								
7	04-05-16-30-2000	Grouting, grout, C476, for bond beams, lintels and concrete masonry unit (CMU) cores Grout to fill 6 test holes 4" round and 50' deep per structural drawings.	C.F.	150.0000	$8.25	$1,237.50	RSM12MCOM M, L, E, B	P
		04 - Masonry Total				**$1,237.50**		
07 - Thermal and Moisture Protection								
8	07-21-13-13-0700	Foam board insulation, polystyrene, expanded, 2" thick, R8	S.F.	1,000.0000	$1.08	$1,080.00	RSM12MCOM Gm, M, L, B	P
		07 - Thermal and Moisture Protection Total				**$1,080.00**		
22 - Plumbing								
9	22-11-13-78-0054	Pipe, high density polyethylene plastic (HDPE), standard length is 40', add a weld for each joint, excluding hangers, trenching, backfill, hoisting or digging equipment, single wall, straight, 1" diameter DR 11	L.F.	1,900.0000	$0.68	$1,292.00	RSM12MCOM M, B, CCI 808 Q1 WA/T	P
10	22-11-13-78-0304	Pipe, high density polyethylene plastic (HDPE), add a weld for each joint, excluding hangers, trenching, backfill, hoisting or digging equipment, single wall, 90° elbow, 1" diameter DR 11	Ea.	110.0000	$5.02	$552.20	RSM12MCOM M, B, CCI 808 Q1 WA/T	P
11	22-11-13-78-4030	Pipe, high density polyethylene plastic (HDPE), single wall, welding labor per joint, excluding welding machine, pipe joint size (cost based on thickest wall for each diameter), 1" pipe size	Ea.	220.0000	$4.97	$1,093.40	RSM12MCOM L, B, CCI 808 Q1 WA/T	P

22 - Plumbing

	Item	Description	UM	Quantity	Unit Cost	Total	Book	
		22 - Plumbing Total				**$2,937.60**		
23 - Heating, Ventilating, and Air-Conditioning (HVAC)								
12	23-05-93-50-0180	Piping, testing, nondestructive testing, nondestructive hydraulic pressure test, isolate and one hour hold, 1" to 4" pipe, 500 to 1000 L.F.	Ea.	12.0000	$705.00	$8,460.00	RSM12MCOM L, B	P
13	23-23-23-10-2000	Anti-freeze, inhibited, propylene glycol, for solar heat, 55 gallon drums, small quantities	Gal.	100.0000	$14.50	$1,450.00	RSM12MCOM M, B	P
		23 - Heating, Ventilating, and Air-Conditioning (HVAC) Total				**$9,910.00**		
26 - Electrical								
14	26-05-26-80-0700	Grounding, wire ground, bare copper wire, stranded, 1/0 UFER	C.L.F.	0.3000	$294.53	$88.36	RSM12MCOM M, L, B, CCI 808 Q1 WA/T	P
15	26-05-26-80-2730	Grounding, exothermic weld, 4/0 wire to 1" ground rod UFER	Ea.	1.0000	$66.08	$66.08	RSM12MCOM M, L, B, CCI 808 Q1 WA/T	P
16	26-05-26-80-2790	Grounding, exothermic weld, mold, reusable, for above UFER	Ea.	1.0000	$128.51	$128.51	RSM12MCOM M, B, CCI 808 Q1 WA/T	P
17	26-05-39-30-3250	Conduit in concrete slab, including terminations, fittings and supports, PVC, schedule 40, 3/4" diameter	L.F.	100.0000	$2.76	$276.00	RSM12MCOM M, L, B	P
		26 - Electrical Total				**$558.95**		
31 - Earthwork								
18	31-23-16-13-0500	Excavating, trench or continuous footing, common earth, excluding sheeting and dewatering, 6' to 10' deep, 3/4 C.Y. excavator	B.C.Y.	550.0000	$5.47	$3,008.50	RSM12MCOM L, E, B, CCI 808 Q1 WA/T	P
19	31-23-16-13-0500	Excavating, trench or continuous footing, common earth, excluding sheeting and dewatering, 6' to 10' deep, 3/4 C.Y. excavator	B.C.Y.	350.0000	$5.47	$1,914.50	RSM12MCOM L, E, B, CCI 808 Q1 WA/T	P
20	31-23-16-16-6030	Structural excavation for minor structures, machine excavation, for spread and mat footings, elevator pits, and small building foundations, common earth, hydraulic backhoe, 1/2 C.Y. bucket	B.C.Y.	143.0560	$17.63	$2,522.08	RSM12MCOM L, E, B, CCI 808 Q1 WA/T	P
21	31-23-16-46-3010	Excavating, bulk, dozer, open site, 105 H.P., 50' haul, sandy clay and loam	B.C.Y.	2,500.0000	$1.46	$3,650.00	RSM12MCOM L, E, B, CCI 808 Q1 WA/T	P
22	31-23-23-14-2020	Backfill, structural, dozer or front end loader, from existing stockpile, no compaction, 80 H.P., 50' haul, common earth	L.C.Y.	124.0000	$0.92	$114.08	RSM12MCOM L, E, B, CCI 808 Q1 WA/T	P

31 - Earthwork

	Item	Description	UM	Quantity	Unit Cost	Total	Book	
23	31-23-23-20-2310	Hauling, spotter at fill or cut, if required	Hr.	40.0000	$32.83	$1,313.20	RSM12MCOM L, B, CCI 808 Q1 WA/T	P
24	31-23-23-20-2500	Hauling, dust control, light	Day	5.0000	$691.31	$3,456.55	RSM12MCOM L, E, B, CCI 808 Q1 WA/T	P
25	31-63-26-13-0200	Fixed end caisson piles, includes excavation, concrete, 50 lb. reinforcing per C.Y., excluding mobilization, boulder removal, disposal, casings or ground water, open style, machine drilled, to 50' deep, in stable ground, 24" diameter, 0.116 C.Y. per L.F.	V.L.F.	400.0000	$34.94	$13,976.00	RSM12MCOM M, L, E, B, CCI 808 Q1 WA/T	P
26	31-63-26-13-0200-3650	Fixed end caisson piles, for rock excavation, sockets, add, average (Modified using 31-63-26-13-3650)	C.F.	628.0000	$69.88	$43,884.64	RSM12MCOM L, E, B, CCI 808 Q1 WA/T	P
		31 - Earthwork Total				**$73,839.55**		

Alternates

27	Fusion Weld Machine	Includes Cost of Machine	LSUM	1.0000	$3,000.00	$3,000.00	CUSTOM E	P
28	Geothermal Loop	Includes HDPE pipe, pipe fittings suchas elbows & reducers, manifold and the associated labol	LSUM	0.0000	$7,230.00		CUSTOM M, L	P
29	Loop Cleaning	Includes hose connections, pump rental, water, etc.	LSUM	2.0000	$750.00	$1,500.00	CUSTOM M, L, E	P
30	Loop Fiel Testing & Comm	Includes witnessing the koop fiel installation, testing the system and providing some commissioning.	LSUM	0.0000	$3,990.00		CUSTOM L	P
31	Loop Testing	Pressure Test loops	LSUM	2.0000	$350.00	$700.00	CUSTOM M, L, E	P
32	Misc General Conditions	Includes miscellaneous costs such as utilities, porta potles, equipment rental, miscellaneous haul off, project administration, etc.	LSUM	1.0000	$44,556.00	$44,556.00	CUSTOM L, B	P
		Alternates Total				**$49,756.00**		

Estimate Grand Total **165,357.75**