2010

Mechanical Option
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Manoa Elementary School

[APPLICATION ANALYSIS OF GROUND SOURCE AND AIR SOURCE HEAT PUMPS]

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Executive Summary

Manoa Elementary School’s mechanical system was originally designed as a central plant system that included air cooled condensing units to provide cooling and dual fuel boilers when heating was necessary. Air distribution was

provided by five rooftop variable air volume air handling units which utilized an energy recovery unit ventilator on the exhaust. Each zone is equipped with a series fan powered box to limit space conditioning.

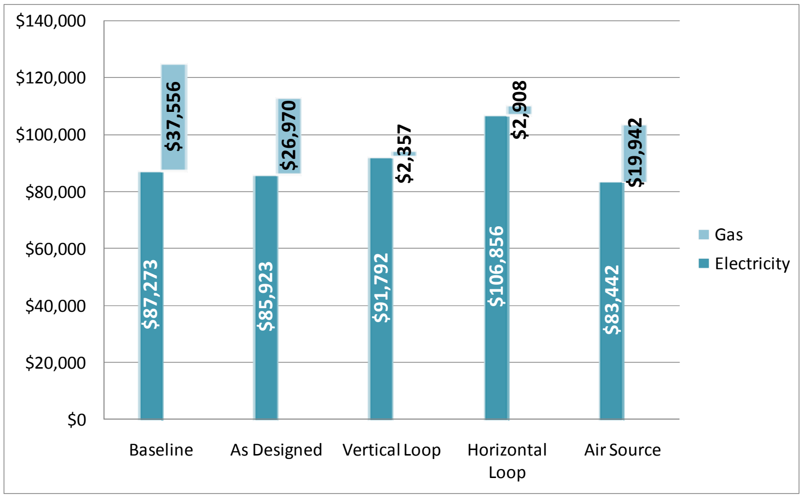
The system redesign looked into exploring the results of three heat pump systems to determine their effects on the building as well as model the differences between the types. The impact of selecting a higher first cost system with improved energy performance will be analyzed throughout the process.

A vertical loop ground source heat pump system was selected as the first alternative. Water source heat pumps were selected to replace the rooftop air handling units. These heat pumps were designed to operate in parallel with dedicated outdoor air units to decouple the sensible and latent loads. The required loop length was calculated and then optimized to minimize the construction cost.

A horizontal loop ground source heat pump system was selected as the second alternative. This system was designed with the same parameters as the vertical loop system. The purpose of this analysis was to compare the performance of this system, whose ground loop is relatively inexpensive, with the expensive vertical ground loop.

An air source heat pump system was selected as the third and final alternative. This system was selected to compare cost and performance with the ground source heat pumps.

Trane Trace 700 was used to model all the systems and determine their annual energy use. The results from this analysis showed the costs and benefits of utilizing the different heat pump systems. Total energy costs of the three proposed designs were compared to the designed system and a baseline model is shown below. Research was also performed on the façade. The design and performance of vertical and solar shading devices and the impact they have on the total energy cost was also analyzed.



Building Design Background

Manoa Elementary School is a recently constructed, multi-level, 85,000 square foot elementary school located in the Philadelphia suburbs. The building includes classrooms for grades K-5, faculty office space, music and art rooms, a multi-purpose gymnasium space, and a cafeteria/kitchen. McKissick Architects of Harrisburg designed the building to maximize the amount of playing field space available to the community. Construction of the facility was supervised by John S. McManus, Inc of Chester Heights, PA at a total cost of $21.2 million following a design-bid-build project delivery method.

Building Envelope

A reinforced masonry bearing and pre-cast concrete plank structural system was utilized for the classroom wing to substantially reduce construction time and to limit the overall height of the building to 30-feet to meet the local zoning requirements. The exterior skin utilizes a mixture of reflective zinc colored metal panels allowing the classroom and gymnasium wings to assume the color of the surrounding environment.

Structural System

Concrete masonry units, concrete and steel compose most of Manoa Elementary's structural system. Concrete strip footings and a slab on grade serve as the building's foundation. Exterior walls are constructed from 12" CMU blocks reinforced with rebar and filled with concrete. Concrete columns form the internal grid of the structure with steel wide flange beams running atop. The roof is a modified bitumen roofing system with two layers of R-10 rigid insulation and supported by a system of steel trusses. Structural System design was performed by Baker, Ingram and Associates of Lancaster, PA.

Lighting System

Lighting design for this facility was performed by H.F. Lenz Company of Johnstown, PA. Indirect pendant fixtures with T-8 fluorescent lamps were used to light classroom and educational spaces. Specifications called for an average rated life of 24,000 hours, minimum of 3,000 lumens and a minimum CRI of 85 for all T-8 lamps. Office and conference spaces utilize recessed parabolic two lamp T-8 fixtures. The multipurpose gymnasium space is lit by low profile industrial T-5 pendants. Linear T-5 fluorescent lamps are to have an average rated life of 20,000 hours and a minimum CRI of 82. Compact fluorescent pendant fixtures are used in the lobby areas with T-5 lamps that have a CRI of 82. All lamps are to have a color temperature of 3500 K.

Electrical System

Electrical service comes into the building through a 1600 Amp, 3-phase, 480Y-277 Volt main distribution switchboard which serves the mechanical, electrical and plumbing equipment. 30kVA and 15kVA transformers step the voltage down from the distribution panel to 280Y/120 Volts which serve the computers and emergency and kitchen equipment. A 300kVA dry type transformer steps the voltage from the main distribution panel to the 1200 Amp, 3-phase, 208Y/120 Volt sub distribution switchboard. An 80 kW, 3-phase, 480Y/277 Volt generator supplies the emergency power to the building. Electrical design was performed by H.F. Lenz Company, Johnstown, PA.

Mechanical System

Manoa Elementary School is serviced by 5 air handling units: two serving the classroom wing, one serving the library and administrative offices, one serving the multipurpose gymnasium and the last serving the kitchen and cafeteria spaces. The air handling units are direct expansion systems equipped with rooftop energy recovery ventilators. Two dual fuel boilers are used for perimeter heating through fin tubes and horizontal unit heaters. The mechanical system was designed by H.F. Lenz Company of Johnstown, PA. More information on the mechanical systems can be found in the section Existing Mechanical Equipment.

Fire Protection System

Manoa Elementary is completely sprinklered and its occupancy is subdivided into five categories. The walk in freezer and refrigerator and all other areas not listed below are a wet type sprinkler system with a minimum temperature rating of 135°F and a K Factor of 5.5. the mechanical and electrical areas and storage and building service areas are also a wet type sprinkler system with a minimum temperature rating of 155°F and a K Factor of 5.5. the elevator machine room is a wet system with a minimum temperature rating of 200°F and a K Factor of 5.5. The fire protection system was designed by H.F. Lenz Company of Johnstown, PA.

Transportation

There are two stairwells and one elevator that provide the vertical transportation through the building. These stairwells connect levels one through three and are located in the classroom wing since it is the only multi-level wing of the building.

Existing Mechanical System

Design Factors

The mechanical design objectives for Manoa Elementary School were relatively straight forward. The primary design objective for the HVAC system was to provide adequate heating and cooling to the conditioned spaces while complying with ASHRAE Standards 55, 62.1 and 90.1. Another primary design objective was to control the humidity of the building in order to decrease mold and mildew growth and improve the indoor air quality of the space.

The design of the HVAC system was also limited by two factors. The location of the building in the heart of a suburban community created several design limitations. First of all, developers wanted the building footprint to be as small as possible yet not exceed zoning height requirements in order to maximize the amount of recreation field available to the neighborhood. The level of noise pollution generated by the mechanical equipment was also of great concern for designers. Another design limitation was the project budget for the mechanical system. Manoa Elementary School is one of five elementary schools in the Haverford Township School District. As a public school, all funds for the construction of the new building were obtained through tax dollars or private donations. As such, the total cost of the building was limited to the amount allotted by the Pennsylvania Department of Education.

System Summary

Several different types of systems were utilized due to the fact that Manoa Elementary School is composed of many different space types. As seen in Figure 1 below, AHU-1 and AHU-2 both serve the classroom wing. These units are rooftop variable air volume units that utilize a total enthalpy wheel to recover heat from the exhaust stream. Conditioning to the classroom wing is provided by direct expansion cooling or baseboard hot water heating.

AHU-3 operates in the same way as AHU-1 and AHU-2 but serves the administrative office spaces and the library. This system is also a rooftop variable air volume system that utilizes a total enthalpy wheel. Cooling is provided to these spaces via direct expansion cooling coils and heating is provided via baseboard hot water.

AHU-4 is a constant volume indoor unit which serves the multipurpose gymnasium. This 100% outdoor air unit conditions the gymnasium through direct expansion cooling and heating.

AHU-5 is a constant volume rooftop unit that serves the kitchen and cafeteria spaces. This unit conditions 100% outdoor and through direct expansion cooling and heating.

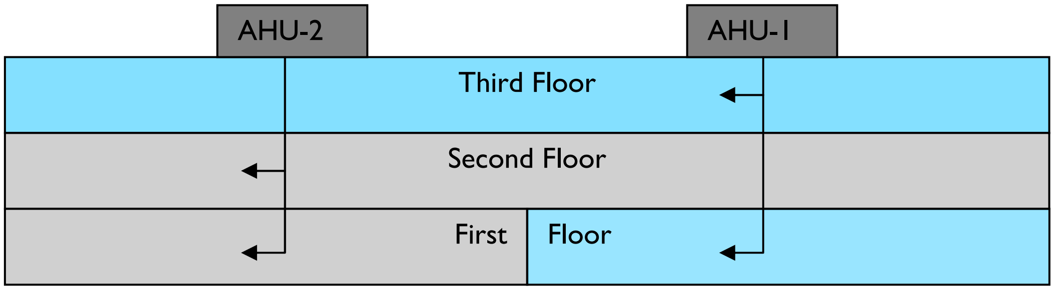


Figure 1: Wing A Classroom AHU Air Distribution Schematic

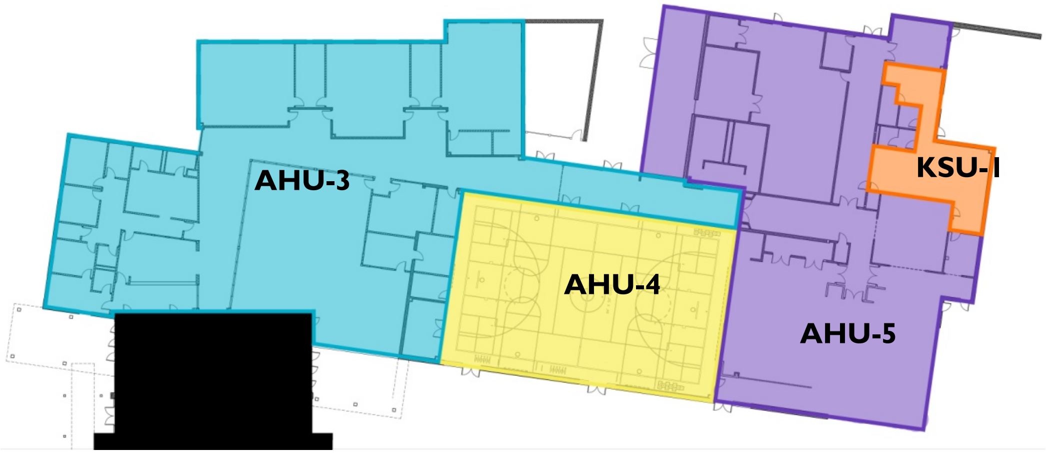


Figure 2: Wing B AHU Air Distribution Schematic

Mechanical Equipment Summary

A full list of all mechanical equipment can be found in Appendix A.

System Operation

AHU-1, AHU-2 and AHU-3 all follow the same sequence of operation. These air handling units operate in the following control modes based on time of year and time of day: Summer Occupied, Summer Unoccupied, School Year Occupied, School Year Unoccupied, and Stand-by. In order for the spaces to reach their occupied setpoints the air handling units are programmed to begin operating before the occupants arrive. The units serve variable air volume boxes and are therefore equipped with variable frequency drives to modulate the supply fan speed in order to maintain the static pressure above the minimum 1.3" of water. The system return fans operate in unison with the supply fans and are also equipped with variable frequency drives that operate simultaneously with the supply fan variable frequency drive. A fixed supply air temperature of 55˚F for cooling and 75˚F for heating maintains the temperature of the spaces served at 72˚F for cooling and 70˚F for heating. An air side economizer is used to maintain a setpoint of 2˚F less than the supply air temperature and is enabled when the outside air temperature falls below 70˚F, the outside air enthalpy is less than 25 BTU/lb, the outside air temperature is less than the return air temperature, the outside air enthalpy is less than the return air enthalpy and the supply fan status is on. The economizer is programmed to close when the freezestat is on or when the supply fan is no longer operating. These air handling units are also equipped with energy recovery ventilators. These ventilators as well as their supply and exhaust fans are enabled when the air handling units are in occupied mode. The speed of the when is controlled to maintain a supply air temperature based off of outdoor air temperature.

AHU-4 which serves the multipurpose room is designed to maintain an occupied temperature of 74˚F during occupied mode and 85˚F during unoccupied mode whenever cooling and 70˚F and 55˚F whenever heating. This system is designed to optimize the starting of the unit by minimizing the unoccupied warm-up or cool-down periods while maintaining comfortable thermal conditions for occupants. The constant volume supply fan is programmed to operate whenever the unit is running. An air side economizer is designed to operate whenever the outside air temperature is less than 65˚F, the outside air enthalpy is less than 22 BTU/lb, the outside air temperature is less than the return air temperature, the outside air enthalpy is less than the return air enthalpy and the supply fan status is on. The economizer will shut down when the freezestat is on or the supply fan is no longer running.

AHU-5 is designed to maintain a temperature of 74˚F during occupied mode and 85˚F during unoccupied mode whenever cooling and 70˚F and 55˚F whenever heating. This system is designed to optimize the starting of the unit by minimizing the unoccupied warm-up or cool-down periods while maintaining comfortable thermal conditions for occupants. The supply and return air fans are programmed to run whenever the unit is in operation. The return fan variable frequency drive will decrease the return airflow when exhaust fans are in use. An air-side economizer is used to maintain a setpoint of 2˚F less than the zone cooling temperature. The economizer is designed to operate when the outside air temperature is less than 65˚F, the outside air enthalpy is less than 22 BTU/lb, the outside air enthalpy is less than the return air enthalpy, and the supply air fan is operating. The economizer shall be disabled when the freezestat is on or the supply air fan is not operating.

ASHRAE Standard 62.1 Compliance Summary

ASHRAE Standard 62.1 is a prescribed method for analyzing the effects of equipment on the indoor air quality of the building and contains a prescriptive method to calculate the minimum outdoor air flow required for the occupancy type and density for a space. All systems were used for the calculation of required outdoor air intake. Compliance to Sections 5 and 6 of this standard is briefly described in the tables below.

Section 5	
5.1 Natural Ventilation	Yes
5.2 Ventilation Air Distribution	Yes
5.3 Exhaust Duct Location	N/A
5.4 Ventilation System Controls	Yes
5.5 Airstream Surfaces	Yes
5.6 Outdoor Air Intakes	Yes
5.7 Local Capture of Contaminants	Yes
5.8 Combustion Air	Yes
5.9 Particulate Matter Removal	Yes
5.10 Dehumidification Systems	Yes
5.11 Drain Pans	Yes
5.12 Finned-Tube Coils and Heat Exchangers	Yes
5.13 Humidifiers and Water-Spray Systems	N/A
5.14 Access for Inspection, Cleaning and Maintenance	Yes
5.15 Building Envelope and Interior Surfaces	Yes
5.16 Buildings with Attached Parking Garages	N/A
5.17 Air Classification and Recirculation	Yes
5.18 Requirements for Buildings Containing ETS Areas and ETS-Free Areas	N/A

Table 1: ASHRAE Standard 62.1 Section 5 Compliance Summary

Section 6				
	Calculated Outdoor Air	Design Supply Air Flow	Design Minimum Outdoor Air	ASHRAE 62.1 Compliance
AHU-1	8,051 cfm	20395 cfm	7,000 cfm	No
AHU-2	7,250 cfm	20750 cfm	8,000 cfm	Yes
AHU-3	2,565 cfm	13600 cfm	5,300 cfm	Yes
AHU-4	5,192 cfm	5800 cfm	3,000 cfm	No
AHU-5	3,579 cfm	8090 cfm	4,500 cfm	Yes

Table 2: ASHRAE Standard 62.1 Section 6 Compliance Summary

ASHRAE Standard 90.1 Compliance Summary

ASHRAE Standard 90.1 is the prescriptive method for analyzing the energy efficiency of a building. This standard focuses on defining energy efficient measures to be applied to the building envelope, heating, ventilating and air conditioning systems, service hot water heating systems, power and lighting of a building. Manoa Elementary School did not meet all the prescriptive requirements of this section.

Building Envelope

Section 5 of this standard is dedicated to describing the performance requirements for a structure's building envelope. These requirements are dependent on both the location of the building and the space conditioning category. Using the Standard's appendices the climate zone for Havertown PA is classified as Climate Zone 4A and a non-residential occupancy fully conditioned building.

In order to use this section to analyze the performance of a building, first the total vertical fenestration area cannot exceed 40% of the total wall area and secondly skylight fenestration cannot exceed 5% of the gross roof area. Table 3 below summarizes compliance.

Window Area Summary			
	Fenestration Area	Wall Area	% Glazing
Walls	7,052	44,336	16%
Roof	-	49,650	0%

Table 3: ASHRAE Standard 90.1 Section 5.5 Prerequisite Compliance

Table 5.5 in conjunction with the above mentioned climate zone and occupancy category can then be used to determine the baseline U-, C- and F-factors for opaque surface. Compliance of the designed insulation compared to the prescribed insulation values can be seen in the table below. Actual envelope construction is as follows:

- Exterior Walls
  8" CMU, ½" sheathing, 2" rigid insulation, 3" airspace, 4" face brick
- Glazing
  Double pained, argon filled and Low-E4 coating for a maximum U-value of 0.29 and a Solar Heat Gain Coefficient of 0.425
- Roof
  2" acoustic deck, ½" cover board, 2 layers of tapered R-10 rigid insulation, ¼" cover board, modified bitumen roof system.

Insulation Requirements			
	Required	Designed	Compliance
Wall R- Value	9.5	11	Yes
Roof R-Value	20	20	Yes
Fenestration U-Value	0.55	0.29	Yes
Fenestration Max SHGF	0.4	0.425	Yes

Table 4: Building Envelope Compliance

Although both the walls and the vertical fenestration meet the requirements of this standard, the insulation value of the walls could be increased for better building performance. The roof, however, just barely meets the required value.

Heating Ventilating and Air-Conditioning

Section 6 of this standard prescribes the minimum efficiencies for the mechanical equipment in a newly constructed building as well as the thickness of piping insulation. Using the tables in this standard, the tables below show that the majority of the air handling units do not meet the minimum EER prescribed, however all of the system piping has adequate insulation.

HVAC Compliance

Air Conditioners, Air-Cooled

	Required EER	Actual	Compliance
AHU-1	9.2	9.6	YES
AHU-2	9.2	9.6	YES
AHU-3	9.3	8	NO
AHU-4	9.3	7.4	NO
AHU-5	9.3	6.7	NO

Pipe Insulation

	Nominal Pipe Diameter	Required Insulation Thickness	Actual Thickness	Compliance
Heating Systems 141-200°F Operating Temperature	<1"	1	1.5	YES
	1" to 1-1/2"	1	1.5	YES
Domestic and Hot Water Service Systems	<1"	0.5	1	YES
	1" to 1-1/2"	0.5	1	YES
	1-1/2" to 4"	1	1	YES
Cooling Systems 40-60°F Operating Temperature	<1"	0.5	1	YES
	1" to 1-1/2"	0.5	1	YES

Table 5: Air Handling Unit and Pipe Insulation Compliance

Service Hot Water Heating

This section prescribes a method to analyze the building's service hot water heating system. A minimum 80% efficient hot water gas and oil supply boiler is specified; however Manoa Elementary School has two dual fuel boilers each with 79% efficiency.

Power

This section prescribes the allowable voltage drop for a building's power system. The building designer designed based on this standard and sized all feeders and branch circuits to comply with the required 2% and 3% respective voltage drop at the design load.

Lighting

This standard defines the maximum allowable lighting power densities allowable for a specific building type. This section outlines two means of analysis: the building area method which allows you to give one specific lighting power density value for the building as a whole and the space-by-space method which defines a specific lighting power density for each specific space type and the usage is analyzed based on that. If the requirements of the analysis aren't met using the building area method, the space-by-space method is used to get more specific results. Table 9.5.1 of this section classifies Manoa Elementary School in the school/university category and compliance is shown in the table below.

Lighting Power Density			
	Maximum from Standard	Actual	Compliance
First Floor	1.2	1	YES
Second Floor	1.2	0.8	YES
Third Floor	1.2	1.1	YES
Total	1.2	0.96	YES

Table 6: Lighting Power Density Compliance

As shown in the results, Manoa Elementary School performs much better than what is prescribed in this standard. Because the building area method resulted in a lighting power density much lower than the maximum allowable, the more detailed space-by-space analysis is not required.

Proposed Mechanical System Redesign

Redesign Goals

Several different goals drove the selection of systems for further analysis. The primary design goal in choosing systems for analysis was to select systems where the overall life cycle cost is less than that of the designed system. An important factor in improving the life cycle system cost will be designing energy efficient systems. As seen in Table 5, the current mechanical systems either don't meet or barely meet the minimum efficiency requirements prescribed in ASHRAE 90.1. Although it is likely that the redesign systems will initially cost more than the current design, it is important that in the long run they will be less expensive due to better efficiencies.

Cost savings, however, was not the only parameter considered. The other outcome I wanted to come from detailed analysis was to develop an understanding the performance and design differences between different types of systems.

Masters Application

Central Cooling Systems

Knowledge obtained from this course will be used to both design and analyze the three proposed mechanical systems. Information about heat pump cycles, COP and EER, pumping and piping design and life cycle cost analysis was utilized to generate this analysis. More information on the topics listed above are detailed more thoroughly in later sections.

Indoor Air Quality

Total emissions of Greenhouse Gasses by the mechanical equipment is becoming of greater concern due to global warming. Also, some emissions can have adverse effects on humans. Since Manoa Elementary School is located in the heart of a residential community, an analysis of the emissions performed will be done with a focus on attempting to drastically cut the impact the school has on its surroundings.

Preliminary Ideas

The goals detailed above led to several alternative systems to be considered for application to Manoa Elementary School. The possibilities that were not chosen for further analysis are described below.

Combined Heat and Power

Combined heat and power was a system preliminarily considered for implementation in Manoa Elementary School. Although generally this system results in a more efficient mechanical system, it requires the electrical and thermal load profiles to be relatively constant, which is not the case here. The building occupancy varies hourly and seasonally, being fully occupied during the hours of 8 a.m. and 7 p.m. during the fall, winter and spring and being only lightly used in the summer. Because of this, thermal and electric loads are at a minimum when the building is unoccupied and at a maximum when school is in session. This wide variation in loads causes combined heat and power to be inapplicable in this situation.

Water Cooled Systems

The use of a cooling tower to reject heat was also considered for application to this building. This application was considered to compare the benefits and costs of this system to the designed air cooled system. Benefits of this system come from the use of evaporation to bring the water temperature down to its dew point before entering the chiller and the cost of fan and pump energy. This system was not chosen for final design based on many factors. Firstly, noise pollution was a big system design consideration and cooling towers inherently produce a great deal of noise because of the fan required to draw air through the tower. Secondly, these systems require a great deal of maintenance to prevent freezing and keep the water used healthy.

Automated Natural Ventilation

Currently Manoa Elementary School is designed using manually operated windows as a natural ventilation system. This was done by the designer to give the occupant a sense of control over their environment. Preliminary investigation led to research for implementing mechanized control for this system and removing user control. This system was not chosen because the technology is still very unreliable. Optimum outdoor conditions for the use of natural ventilation are extremely specific and complex and rely on both the temperature and humidity of the outdoors and the space. Controlling this type of system is both expensive and unreliable and therefore the system was not considered for redesign.

Selected Systems

Ground Source Heat Pump

A ground source heat pump system was selected for further analysis because of its many efficiency and cost saving features. The ground source heat pump is that it utilizes the nearly constant temperature of the ground to facilitate heating and cooling of the building. This allows the system to consume less energy while conditioning the spaces. There are several other benefits to using this system. First of all, the system equipment cost is lower than most systems since there are no cooling towers, boilers, sump heaters, tower water chemicals and make-up water. Because none of this equipment is used, building mechanical rooms do not need to be as large as traditional mechanical rooms, freeing up more unable floor area. The heat pump equipment, which comes in a wide variety of shapes and sizes and can be installed either horizontally or vertically at the zone it serves and carries a lifespan of approximately 50 years. This decentralization of the mechanical equipment eliminates long duct runs and simplifies system maintenance. These systems, when coupled with a dedicated outside air unit which serves the building ventilation needs, can if properly designed improve the indoor air quality of the building. Two different loops will be analyzed.

- Vertical Loop

  The vertical loop system, shown in Figure 3, is composed of two small diameter tubes, fused at the end into a U-bend, which are placed into a vertical borehole and then filled with grout. Vertical boreholes are usually drilled between 50 and 600 feet where at these depths the ground temperature is relatively constant year-round. Water will be circulated through the tubes, using the earth as a thermal reservoir. This thermal reservoir will remove the building heat from the water in the loop during the summer months and will add that heat the water in loop during the winter months. In order for the earth to perform in both summer and winter months, the building's heating and cooling loads must be fairly close from year to year.

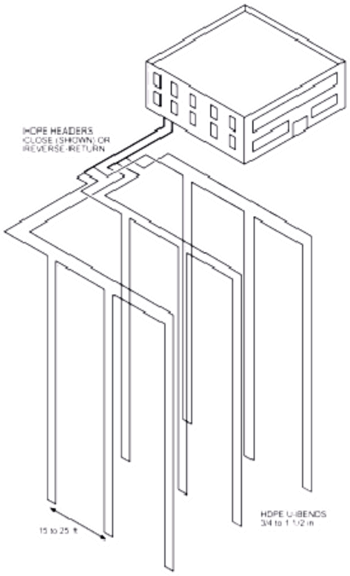


Figure 3: Ground Source Heat Pump Vertical Loop Diagram

Figure 4 below schematically shows how a geothermal heat pump operates. This operation is the same for both vertical and horizontal loop systems. In this system, water from the ground loop is pumped to each heat pump. Here, the solution is circulated through a heat exchanger, which functions similarly to a traditional evaporator. The method of conditioning, either heating or cooling, in conjunction with a reversing valve, dictates how the refrigerant circulates through the rest of the system.

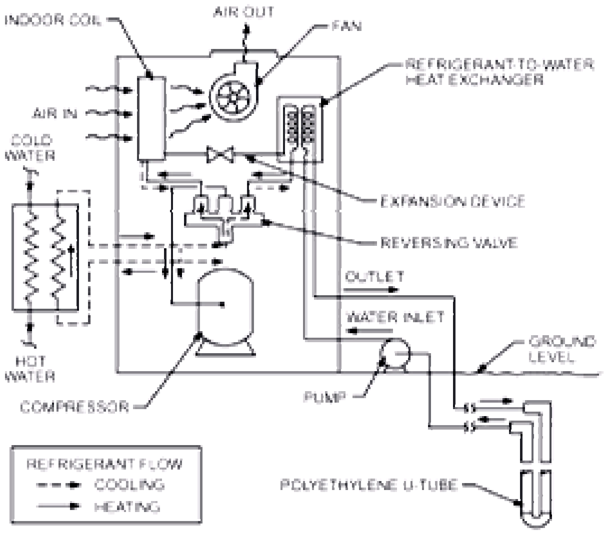


Figure 4: Ground Source Heat Pump Schematic

- Horizontal Loop

This system, shown in Figure 5, operates very similarly to the vertical option above, but the ground loop is laid out horizontally instead of vertically. The primary benefit of this system as opposed to the vertical system is in the cost of excavation. However, this system requires much more horizontal area for the loop as well as a more pumping energy. Another major drawback to this layout is that the ground temperature at shallower depths is not constant year-round.

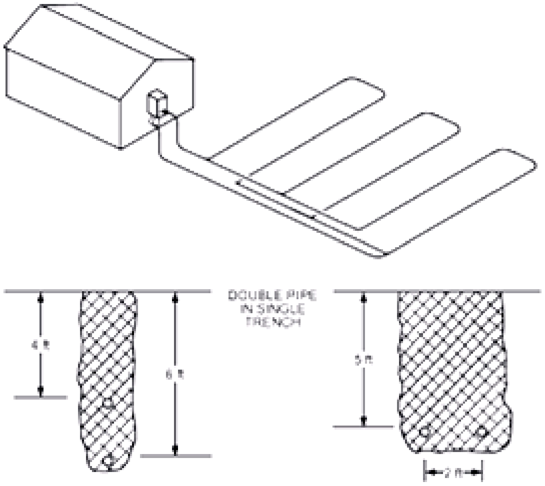


Figure 5: Ground Source Heat Pump Horizontal Loop Diagram

Air Source Heat Pump System

An air-source heat pump system was selected for analysis to understand and analyzed what makes a geothermal system more beneficial than the air source version of the same type of system. Air source heat pumps have many of the same advantages of ground source heat pumps since this system is also decentralized and the units are placed at the zones which they serve. However, this system has many disadvantages. One of the main disadvantages is that it utilizes electricity to facilitate space conditioning which adds additional cost to the system operation. Despite this, the estimated system performance in mild weather can be approximated to have a COP of 4 where the designed system only has a COP of 2.7. This improved efficiency results in energy that makes this system a viable research option. Also, this system does not require the extensive excavation or underground piping requirements that the ground source heat pumps utilize therefore initial cost of the system would appear to be less that ground source heat pumps. A comparison of the life cycle cost of this system compared to that of the two ground source heat pumps described above is a major interest in the design.

Systems Benefits

In conjunction with the equipment benefits listed above, the addition of a dedicated outdoor air unit to serve the ventilation loads creates additional savings. By using the DOAS unit in parallel with the ground source heat pumps, the size of the rooftop air handling units is greatly reduced. This size reduction leads to less difficulty in installation, replacement and possibly a reduction in the structure required to support them.

Systems to be Replaced

The heat pumps and dedicated outdoor air units described above will be used to replace the current variable air volume boxes and air handling units for all the currently designed systems, excluding the kitchen make-up air unit. This unit is relatively small and is used solely to replace the outdoor air exhausted from the kitchen area therefore there is no need to replace it with another dedicated outdoor air unit of the same size.

Ground Source Heat Pump: Vertical Loop

Load Analysis

Assumptions

Trane Trace 700 was used to model Manoa Elementary School in order to calculate the design cooling and heating loads. All required input parameters were obtained from the architectural and engineering design documents. The major input assumptions are detailed below.

- Outdoor Ventilation Rates
  Ventilation rates were specified by the design engineer in the mechanical equipment schedules in the mechanical design documents. These values, which are the same as those used in Technical Report I are summarized in Appendix A for reference.
- Lights and Equipment Loads
  Because Manoa Elementary School is a relatively small building, it was possible to use the designed lighting power densities in the model instead of that prescribed in ASHRAE 90.1. These numbers, which can be seen in Appendix B, were entered into Trace on a watts-per-square-foot basis. Heat gain due to lighting was scheduled based on space type. All spaces except the following were modeled based on the classroom schedule summarized below in Table 1. Table 2 summarizes the schedule used for the multipurpose room and Table 3 summarizes the schedule for spaces served by AHU-5. This utilization schedule is defined in Table 1 below.

School Year- Weekday	
Times	%
12am 6am	0
6am 7am	10
7am 8am	50
8am 11am	100
11am 12pm	80
12pm 1pm	20
1pm 3pm	100
3pm 5pm	30
5pm 12am	0

Summer	
Times	%
12am 7am	0
7am 8am	10
8am 3pm	30
3pm 5pm	10
5pm 12am	0

Weekend	
Times	%
12am 12pm	10

Table 7: Lighting Schedule- Elementary School Classroom

School Year- Weekday	
Times	%
12am 7am	0
7am 8am	50
8am 7pm	100
7pm 12am	0

Summer	
Times	%
12am 7am	0
7am 3pm	10
3pm 12am	0

Weekend	
Times	%
12am 12pm	0

Table 8: Lighting Schedule- Elementary Gym

School Year- Weekday		
Times		%
12am	7am	0
7am	3pm	100
3pm	5pm	50
7pm	12am	0

Summer		
Times		%
12am	7am	0
7am	1pm	10
1pm	12am	0

Weekend		
Times		%
12am	12pm	0

Table 9: Lighting Schedule- Elementary Kitchen

Electrical equipment loads were input based on recommendations by the design engineer. Manoa Elementary School is a high-tech school and utilizes a significant amount of computer equipment. Table 4 below outlines the entered values for specific space-types of the building on a watts-per-square-foot basis. These loads were assigned to the elementary school schedule for miscellaneous loads to determine the heat gain to the space. This utilization schedule is outlined in Table 5 below.

Trace Miscellateous Loads							
Classroom	Corridor	Office	Vestibule	Storage	Restrooms	Library	Multipurpose
1000 W	0 W/sf	0 W/sf	0 W/sf	0 W/sf	0 W/sf	2800 W	0 W/sf

Table 10: Entered Miscellaneous Electrical Loads for Space Type

School Year- Weekday		
Times		%
12am	6am	0
6am	7am	10
7am	8am	50
8am	11am	100
11am	12pm	80
12pm	1pm	20
1pm	3pm	100
3pm	5pm	30
5pm	12am	0

Summer		
Times		%
12am	7am	0
7am	8am	10
8am	3pm	30
3pm	5pm	10
5pm	12am	0

Weekend		
Times		%
12am	12pm	10

Table 11: Miscellaneous Electrical Load Utilization Schedule

- Occupancy

  The number of occupants per space was determined in Technical Report 1 based on the architectural design documents and the ASHRAE 62.1 analysis performed. The occupancy load for all classroom and office spaces is based on moderate activity levels which produce a sensible load of 250 BTU/hour and a latent load of 200 BTU/hour. The multipurpose room is modeled for a high level activity which provides a sensible and latent load of 275 BTU/hour each. The occupancy schedules for classrooms, the multipurpose room and kitchen spaces are summarized in Tables 6, 7 and 8 respectively.

School Year- Weekday	
Times	%
12am 7am	0
7am 8am	50
8am 11am	100
11am 12pm	80
12pm 1pm	20
1pm 3pm	100
3pm 5pm	30
5pm 12am	0

Summer	
Times	%
12am 7am	0
7am 8am	10
8am 3pm	30
3pm 5pm	10
5pm 12am	0

Weekend	
Times	%
12am 12pm	10

Table 12: Occupancy Schedule- Classrooms

School Year- Weekday	
Times	%
12am 7am	0
7am 8am	50
8am 3pm	100
3pm 5pm	50
5pm 7pm	20
7pm 12am	0

Summer	
Times	%
12am 7am	0
7am 3pm	10
3pm 12am	0

Weekend	
Times	%
12am 12pm	0

Table 13: Occupancy Schedule- Multipurpose Room

School Year- Weekday	
Times	%
12am 7am	0
7am 11am	20
11am 1pm	80
1pm 3pm	20
3pm 12am	0

Summer	
Times	%
12am 7am	0
7am 1pm	10
1pm 12am	0

Weekend	
Times	%
12am 12pm	0

Table 14: Occupancy Schedule- Kitchen

- ASHRAE Design Indoor and Outdoor Air Conditions

  Outdoor air conditions are specified in the ASHRAE Handbook of Fundamentals and are based on location. Manoa Elementary is located in a suburb of Philadelphia Pennsylvania therefore weather information for Philadelphia as noted in Table 9 was used in the model. Indoor design temperatures came from the design engineer's specifications and are also included in the table below.

Design Temperatures	
ASHRAE 0.4% Cooling Dry Bulb	92.7 ˚F
ASHRAE 0.4% Cooling Wet Bulb	75.6 ˚F
ASHRAE 99.6% Heating Dry Bulb	11.6 ˚F
Indoor Cooling Dry Bulb	75 ˚F
Indoor Heating Dry Bulb	70 ˚F

Table 15: Design Indoor and Outdoor Air Conditions

- Infiltration

Manoa Elementary in a newly constructed building and it was assumed to be tightly constructed for this analysis. This assumption defines the infiltration rate as 0.3 air changes per hour.

- System Zoning
  Zoning for all of the heat pump systems was almost on a room by room basis with only a few exceptions. Some of the smaller rooms were combined on one heat pump for practicality purposes.
- Additional Assumptions
  For the purpose of modeling, all wall and roof construction types were based off the architectural design documents. The amount of glazing was entered in based on take-off areas from the design documents. Appendix B summarizes these and other assumptions made for each typical space.

Results

For this analysis, the rooftop variable air volume units were replaced with ground source heat pumps in conjunction with a rooftop dedicated outdoor air unit. Because a new mechanical system was implemented to replace the designed system, the rooftop air handling units designated as AHU have been renamed for this analysis to VWSHP. Zoning of this system, as well as the cooling, heating and ventilation load for each heat pump unit is given in Tables 16 through 20.

VWSHP-1 Zoning						
Zone	Rooms	Sensible Load (MBH)	Latent Load (MBH)	Heating Load (MBH)	Heating Ventilation Load (MBH)	CFM
1	101 SEM Classroom	21.6	8	34.9	17.5	901
2	102 SEM 2 Classroom	12.7	8.5	34.4	17.5	778
3	105 SE 6 Resource Classroom	16	6.6	27.9	13.2	772
4	106 Kindergarten Classroom 1 111 Corridor 124 Faculty Workroom 126 Vestibule	26.2	13	56.60	22.5	1700
5	301 SE 4	24.1	7.2	32.3	15.4	776
6	302 Fourth Grade Classroom 2 304 Storage	22.2	7.9	35.1	15.9	827
7	305 Fifth Grade Classroom 1	17.6	3.8	34.5	17.5	779
8	306 Restroom	10.3	1	6.8	0	462
9	307 Corridor	35.9	5.4	32.3	7.9	681
10	309 Fifth Grade Classroom 3	18.1	3.3	27.5	13.2	703
11	310 Fifth Grade Classroom 4	11.3	9.8	34.3	17.5	776
12	314 Fourth Grade Classroom 1	10.5	4.5	34	17.5	772
13	315 Reading Seminar	18.4	3.9	31.6	15.9	723
14	316 SE Classroom	11.4	9	31.5	15.9	711
15	318 Corridor 322 Faculty Meeting	17.7	4.1	19.8	7.4	674
16	326 Storage 323 Faculty Planning	8.7	3.1	14.5	5.7	424
17	324 Fourth Grade Classroom 2	11.5	9.7	33.9	17.5	770
18	325 Fourth Grade Classroom 1	18.6	4	33.9	17.5	770
19	327 SE 5 Classroom	18.8	3.8	35.9	17.5	803
20	Fourth Grade	18.6	4	34.1	17.5	773

Table 16: System Zoning and Dedicated Outdoor Air Loads for VWSHP-1

VWSHP-2 Zoning

Zone	Rooms	Sensible Load (MBH)	Latent Load (MBH)	Heating Load (MBH)	Heating Ventilation Load (MBH)	CFM
1	107 First Grade Classroom 1	12.9	4.4	31	16.4	740
2	109 First Grade Classroom 2	13.1	3.9	31.1	16.4	754
3	112 Kindergarten Classroom 2 113 Conference 115 Storage	15.4	10.6	36.4	18.4	937
4	117 First Grade Classroom 3	13.1	3.9	31.00	16.4	752
5	118 Kindergarten Classroom 3	12.7	8.9	31.4	14.9	717
6	119 First Grade Classroom 1 120 Faculty Workroom 121 Corridor	19.7	5.8	40.1	18.5	1027
7	201 SE 3	11.5	3.2	28.7	14.4	667
8	202 Second Grade Classroom 2 204 Storage	9	8.6	29.5	14.8	714
9	205 Second Grade Classroom 1 206 Restroom 207 Corridor	24.4	16.8	42.2	18.3	1412
10	209 Second Grade Classroom 3	12.8	4.2	30.8	16.4	741
11	210 Second Grade Classroom 4	9.6	9.4	31.2	16.4	734
12	213 Third Grade Classroom 3	12.8	10.6	31.1	16.4	732
13	214 Third Grade Classroom 4	9	9.4	31	16.4	732
14	215 SEM	12.6	3.5	28.7	14.9	705
15	216 Seminar Learning Support 222 Faculty Meeting 223 Faculty Planning	11.8	12.5	44.3	24.1	1053
16	224 Third Grade Classroom 2	9.4	8	27.8	14.4	651
17	225 Third Grade Classroom 1 226 Storage	17.1	3.7	32.6	19.2	920
18	227 SE 2 Classroom	-7.6	33.3	41	18.8	1076

Table 17: System Zoning and Dedicated Outdoor Air Loads for VWSHP-2

VWSHP-3 Zoning

Zone	Rooms	Sensible Load (MBH)	Latent Load (MBH)	Heating Load (MBH)	Heating Ventilation Load (MBH)	CFM
1	129 Administration	4.6	0.4	2.5	0.7	190
2	130 Reception 131 Hallway	5.2	2.2	7.4	3	288
3	132 Nurse 132.2 Exam	4.8	2.1	8	3.5	291
4	133 Hallway 134 Conference 135 Conference	6.4	8.8	25.4	12.8	650
5	136 Guidance	2.8	2.6	9.2	4.8	245
6	139 IST	3.5	1.9	7	3.4	232
7	140 Principal 141 Corridor	10.1	1.2	10.2	2	490
8	142 Library High	41.6	8.2	49.7	16.3	2004
9	142 Library Low 142.2 Storage	17.5	12	33.1	14.6	1051
10	143 Office 144 Workroom	5.6	1.8	5	2.1	271
11	145 Music Room 145.1 Storage 146 Faculty Dining	17.7	10.5	54.8	21.9	1217
12	147 Music Room 147.1 Storage	10.7	11.4	35.2+3.9	15.2	918
13	139 Art Room 149.1 Art Storage	17.3	5.4	62.2	30.4	1130
14	150 Corridor	17	1.1	16.5	3	1030
15	151 Corridor	13.4	0.6	10.7	1.3	594
16	152.1 Gym Office	4	0.6	1.9	0.7	189

Table 18: System Zoning and Dedicated Outdoor Air Loads for VWSHP-3

VWSHP-4 Zoning

Zone	Rooms	Sensible Load (MBH)	Latent Load (MBH)	Heating Load (MBH)	Heating Ventilation Load (MBH)	CFM
1	Multipurpose Room	26.475	43.2	64.3	24.7	1395.75
2	Multipurpose Room	26.475	43.2	64.3	24.7	1395.75
3	Multipurpose Room	26.475	43.2	64.3	24.7	1395.75
4	Multipurpose Room	26.475	43.2	64.3	24.7	1395.75

Table 19: System Zoning and Dedicated Outdoor Air Loads for VWSHP-4

VWSHP-5 Zoning						
Zone	Rooms	Sensible Load (MBH)	Latent Load (MBH)	Heating Load (MBH)	Heating Ventilation Load (MBH)	CFM
1	155 Ramp	6.1	1.6	9.6	1.2	310
2	156 Cafeteria	0	0	122.2	68.5	2956
3	158 LBI	24.4	64.7	115.2	60.1	2627
4	159 Serving	28.1	5.4	14.8	6.6	1764
5	160 Kitchen	6.9	7.2	30.9	13.2	689
6	161 Dishwash	9.4	1.3	5.8	2.8	520
7	163 Office Dry Storage	4.5	0.2	0.9	0.1	195
8	164 Dry Storage	0.5	0.1	0.5	0.1	23
9	168 Corridor 169 Janitor	5.1	1.2	9.2	1.2	281

Table 20: System Zoning and Dedicated Outdoor Air Loads for VWSHP-5

Selection of Heat Pump

- System and Ground Water Temperatures

  Chapter 32 of the ASHRAE 2007 Handbook of Fundamentals prescribes design guidelines for the selection of system and ground water temperatures for the vertical ground source heat pump systems. For determining the approximate groundwater for Haverford, PA, Figure 6 in this standard was applied. As shown in Figure 6 below, Manoa Elementary School is located between the 54 and 56°F contours and a groundwater temperature of 55°F was assumed for this analysis.

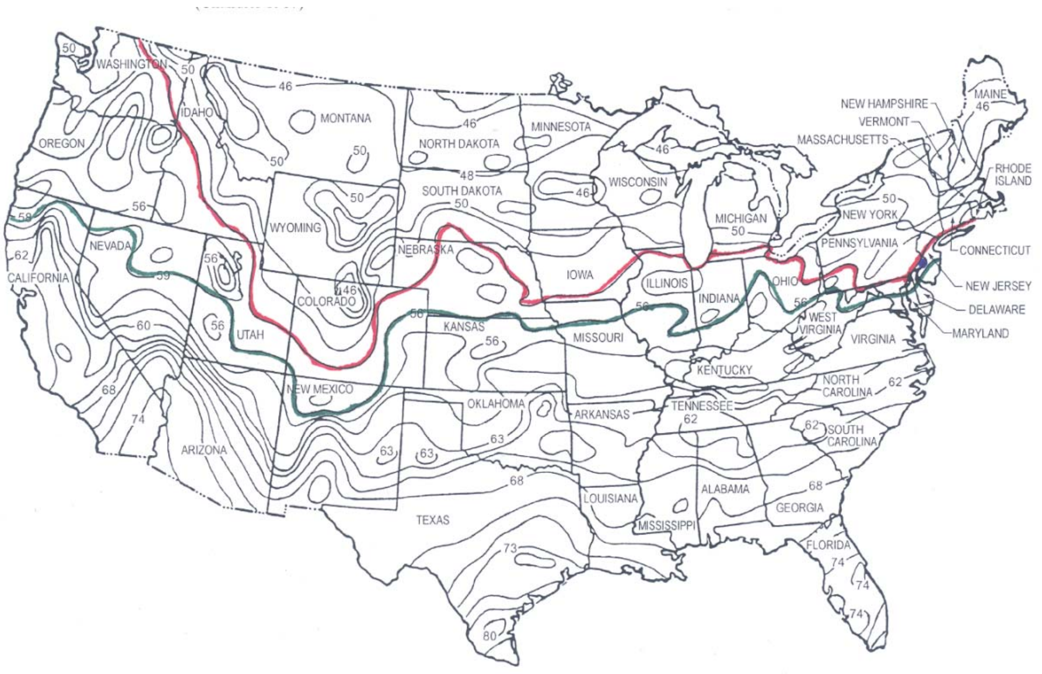


Fig. 17 Approximate Groundwater Temperatures (°F) in the Continental United States

LOCATION OF MANOA ELEMENTARY
54°F CONTOUR
56°F CONTOUR

Figure 6: Approximate Groundwater Temperature for Haverford, PA

According to Chapter 32 of ASHRAE Handbook of Applications, selection of the water temperature entering the unit is a critical part of the design process. If designing the system solely to achieve the highest possible efficiency, selecting a temperature that is very close to the ground temperature is recommended, however this will result in an extremely long and expensive ground loop. If designing the system to minimize installation at the cost of efficiency, an entering water temperature that is much greater will achieve this effect. In order to achieve higher efficiencies and reduce the installation cost of the loop, an entering water temperature of 20°F to 30°F higher than the ground temperature is recommended for cooling and 10°F to 20°F is recommended for heating. Entering water temperatures selected can be seen in the results section below. Also, the heat pumps were selecting using a 10°F ΔT between the entering and leaving water temperatures. These values are also shown in the results section below.

- Heat Pump Information

  The heat pumps selected for design are Carrier Aquazone models to be consistent with the original design's use of the Carrier Corporation. Horizontal units will be used to replace the variable air boxes for all spaces. Large spaces such as the multipurpose room, cafeteria and LGI will utilize multiple heat pumps to serve the load. Heat pump selection and cost is shown in Table 21 below.

  Heat pumps were selected to meet the sensible loads for the individual spaces they serve due to the fact that the dedicated outdoor air unit will be selected to meet the latent loads of the spaces. The primary goal for unit selection was maximizing the total system EER.

Total Cost of Heat Pumps

Model Number	Tons	# of Units	Cost	Average EER
50PSH012	1	29	$100,775	18.1
50PSH018	1.5	18	$126,450	18.5
50PSH024	2	9	$75,600	18.6
50PSH030	3	10	$106,250	17.6
50PSH039	3.5	1	$10,975	17.1
			$420,050	**18.0**

Table 21: Selection and Total Cost of Vertical Ground Source Heat Pump Units

Selection of Dedicated Outdoor Air Unit

Selection of the dedicated outdoor air units was performed using Carrier 100% Outdoor Air Units which were sized to meet the latent heating and cooling loads. These units utilize direct expansion coils, R-410a and energy recovery wheels. The total cost for each of the selected units is given in Table 22 below.

Total Cost of DOAS Units

Symbol	Model #	CFM	Cost
VWSHP-1	62DA38	6,934	$21,329
VWSHP-2	62DA34	8,899	$27,373
VWSHP-3	62DA15	3,607	$11,095
VWSHP-4	62DA12	3,000	$9,228
VWSHP-5	62DA24	4,557	$14,017
			$83,042

Table 22: Selection and Total Cost of Dedicated Outdoor Air Units

Annual Energy Use

The Trane Trace 700 model used when performing the load analysis was used to produce an annual energy usage estimate for Manoa Elementary School. The data used to construct this model was found in the design documents created by the architect and the mechanical and electrical engineers. The energy models used to analyze the vertical ground source heat pumps are described below.

Designs Analyzed

Three systems performances will be analyzed in this section.

- Designed System
  The direct expansion rooftop variable air volume system with series fan boxes and boiler heating will be the first case for energy analysis.
- ASHRAE Baseline Model
  A baseline energy model specified by ASHRAE Standard 90.1 was created for Technical Report 3. Standard 90.1 requires a packaged rooftop variable air volume unit with direct expansion cooling and reheat for cooling and a hot water gas boiler for heating.
- Redesigned System
  The vertical loop ground source heat pump system described above was the final system for the comparison. Modeling this system with the designed and baseline systems will report the amount of energy savings this system creates.

Assumptions

Several assumptions are needed to model all three of the systems mentioned above. The basic assumptions made for this analysis are described below.

- Equipment Efficiencies
  equipment was modeled using the efficiencies and EER's specified in the design documents, ASHRAE Standard 90.1 Appendix G or specified above.
- Supply and Return Fan Types and Energy Use
  Supply and return fans for the designed system were found in the equipment schedules and can be found in Appendix A. Baseline building supply and return fan types and energy use were specified in ASHRAE Standard 90.1 Appendix G and calculated using Trane Trace. The procedure used to calculate the size for the new heat pump system is described in the section Vertical Loop Sizing.
- Electric Rates
  Manoa Elementary School purchases its electricity from PECO Electric Company, which is a subsidiary of the Excelon Company. Rate Schedule 22 was selected for analysis because it is

applicable to churches and schools. This rate structure has no time dependence and the charges are as follows:

- Customer Charge: $0 per month
- Demand Charge: $5.07 per kilowatt per month
- Energy Charge:
    - $0.116 per kilowatt hour per month for the first 300 kilowatt hours
    - $0.084 per kilowatt hour per month for 301 to 1200 kilowatt hours
    - $0.077 per kilowatt hour per month for 1201to 8500 kilowatt hours
    - $0.075 per kilowatt hour per month for remaining kilowatt hours

- Natural Gas Rates

  PECO services the natural gas to the building at the rates defined by the schedule for General Service Commercial and Industrial. This rate schedule is not dependant on time and the charges are as listed below:

    - Fixed Distribution Charge: $25.00 per month
    - Variable Distribution Charge: $3.7785 per Mcf for the first 200 Mcf
      $2.6387 per Mcf for the remaining usage

Annual Energy Cost and Consumption Results

- Cost Results

  Figure 7 shows the energy cost savings of the three systems described above. The ASHRAE Baseline system should be the most expensive system to operate since it is the "worst case scenario" prescribed by ASHRAE to determine relative percent savings for different mechanical systems. The designed scenario falls between the ASHRAE Baseline and the Redesigned system which shows that the system outperforms the baseline scenario but doesn't perform as well as the proposed redesign system.

  ASHRAE Standard 90.1 prescribes a method for calculating the percentage improvement of a designed system over the baseline. Table 23 summarizes these results for the designed system and the proposed system. This table shows that the proposed system outperforms the baseline by almost 25% and saves almost $31,000 annually and outperforms the designed mechanical system by almost 20% and saves almost $19,000 annually. These results are very significant and show the possible benefits of using a more efficient system.

System Energy Savings Comparison				
	Savings Over Baseline		Savings Over Designed	
	%	$	%	$
As Designed	9.56	11,936		
Redesign	24.58	30,680	19.91	18,744

Table 23: Annual Energy Cost Savings

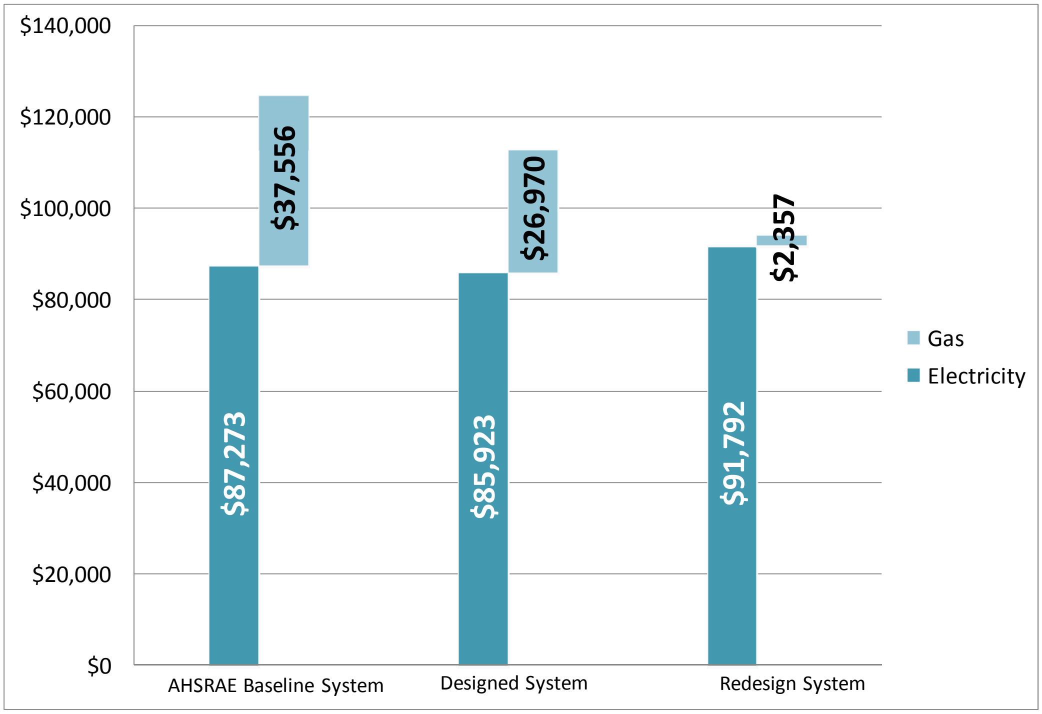


Figure 7: System Annual Energy Costs

- Consumption Results

  Total system consumption follows the same trend as energy savings, but more of the cost savings comes from using less gas than using less electricity. Figure 8 shows the utility consumption of each system. It is clear that all three systems use almost the same amount of electricity, with the proposed design actually consuming more energy than the baseline. Although the system redesign consumes more electricity, the cost of the electricity is less than the other systems. This results from the electric consumption occurring at less on-peak hours which causes a large cost savings. Also, the redesigned system uses almost no gas at all. This is because the redesigned system does not utilize a boiler heating system. The gas consumption seen in the system redesign is due to domestic hot water heaters which are required.

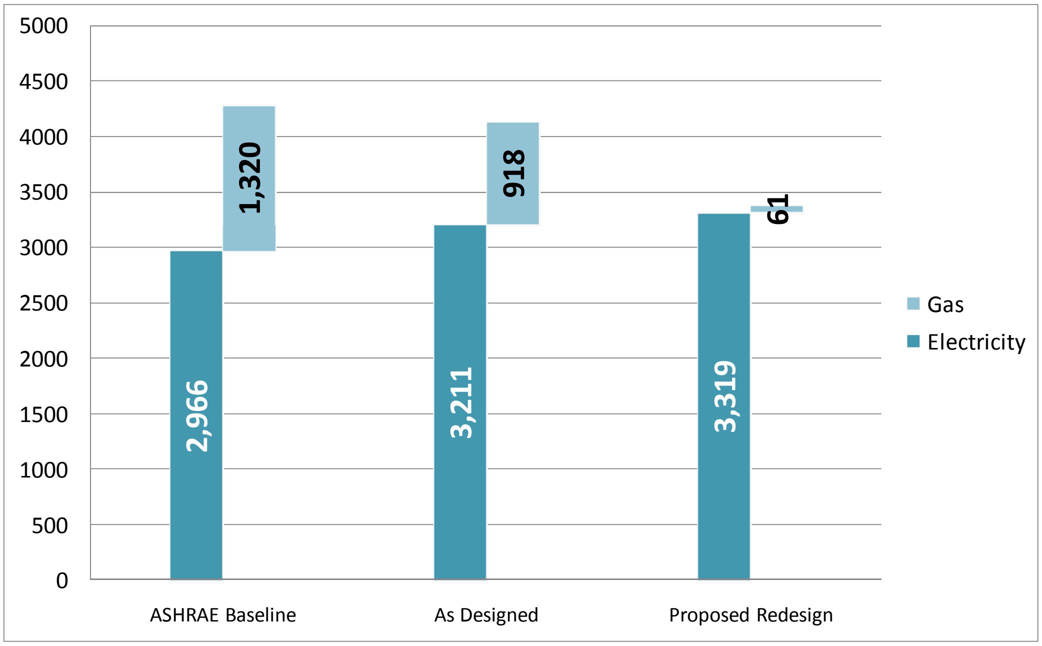


Figure 8: Annual Energy Consumption (MBH)

LEED Implications

Although Manoa Elementary School was never designed to achieve LEED Certification, an analysis of the proposed mechanical system's performance using LEED NC 3.0 Credit 1 of Energy and Atmosphere is useful for comparison. This credit relates the percent cost savings of a mechanical system relative to a baseline system into a number of points. According to this method, the rooftop variable air volume air handling unit with series fan powered boxes results in a 10% improvement over the baseline and therefore doesn't meet the prerequisite for this method and is not eligible for LEED Certification. The redesigned system, however, with a percent savings of 25% would be awarded 7 points out of a possible 19. This is a significant amount of points considering a total of 40 points will earn LEED Certification.

Greenhouse Gas Emissions

The ground source heat pump system consumes less gas and electricity than the designed mechanical system and will therefore have lower greenhouse gas emissions. Emissions for all three systems are summarized in Table 24 below. The results of this greenhouse gas study show that the proposed system will emit 15,600 pounds per year less greenhouse gas emissions than the baseline and 10,800 pounds per year less than the designed system. This reduction will have a huge positive impact on the environment. Since Manoa Elementary School is located in a suburban neighborhood the reduction will also benefit the residents.

Greenhouse Gas Emission Data				
	CO2 (lbm/year)	NOX (lbm/year)	SOX (lbm/year)	Total Redesign Savings (lbm/year)
ASHRAE Baseline	2.02E+04	3.05E+01	1.64E+03	1.56E+04
As Designed	1.59E+04	2.47E+01	1.15E+03	1.08E+04
Redesign	6.15E+03	1.10E+01	1.03E+02	

Table 24: Greenhouse Gas Emission Comparison

Ground Source Heat Pump: Horizontal Loop

Load Analysis

Assumptions

All assumptions for this system are identical to the ones listed above.

Results

For this analysis, the rooftop variable air volume units were replaced with ground source heat pumps in conjunction with a rooftop dedicated outdoor air unit. Because a new mechanical system was implemented to replace the designed system, the rooftop air handling units designated as AHU have been renamed for this analysis to HWSHP. Zoning of this system, as well as the cooling, heating and ventilation load for each heat pump unit is modeled to be identical to the vertical ground source heat pump system, with the exception of the pumping energy, zoning and outdoor air loads are identical to the values in Tables 17 through 21.

Selection of Heat Pump

The selection for horizontal heat pumps is identical to the vertical heat pump selection since the loads are identical.

Selection of Dedicated Outdoor Air Unit

The selection for dedicated outdoor air units is identical to the units serving the vertical heat pump selection since the loads are identical.

Annual Energy Use

Designs Analyzed

Three systems performances will be analyzed in this section.

- Designed System
  The same direct expansion rooftop variable air volume system with series fan boxes and boiler heating will be the first case for energy analysis was used for this analysis.
- ASHRAE Baseline Model
  Same energy model as before was used for this analysis.
- Redesigned System
  The horizontal loop ground source heat pump system described above was the final system for the comparison. Modeling this system with the designed and baseline systems will report the amount of energy savings this system creates.

Assumptions

All assumptions stated for vertical loop ground source heat pumps also apply to horizontal system.

Annual Energy Cost and Consumption Results

- Cost Results
  Figure 9 shows the energy cost savings of the three systems described above. These results are similar to those seen above, with the ASHRAE Baseline system should be the most expensive system to operate. The designed scenario again falls between the ASHRAE Baseline and the Redesigned system which shows that the system outperforms the baseline scenario but doesn’t perform as well as the proposed redesign system.

ASHRAE Standard 90.1 prescribes a method for calculating the percentage improvement of a designed system over the baseline. Table 25 summarizes these results for the designed system and the proposed system. This table shows that the proposed system outperforms the baseline by 12% and saves $15,000 annually and outperforms the designed mechanical system by almost 3% and saves just over $3,000 annually. These results are less significant but still show the possible benefits of using a more efficient system.

System Energy Savings Comparison				
	Savings Over Baseline		Savings Over Designed	
	%	$	%	$
As Designed	9.56	11,936		
Redesign	12.07	15,065	2.85	3,129

Table 25: Annual Energy Cost Savings

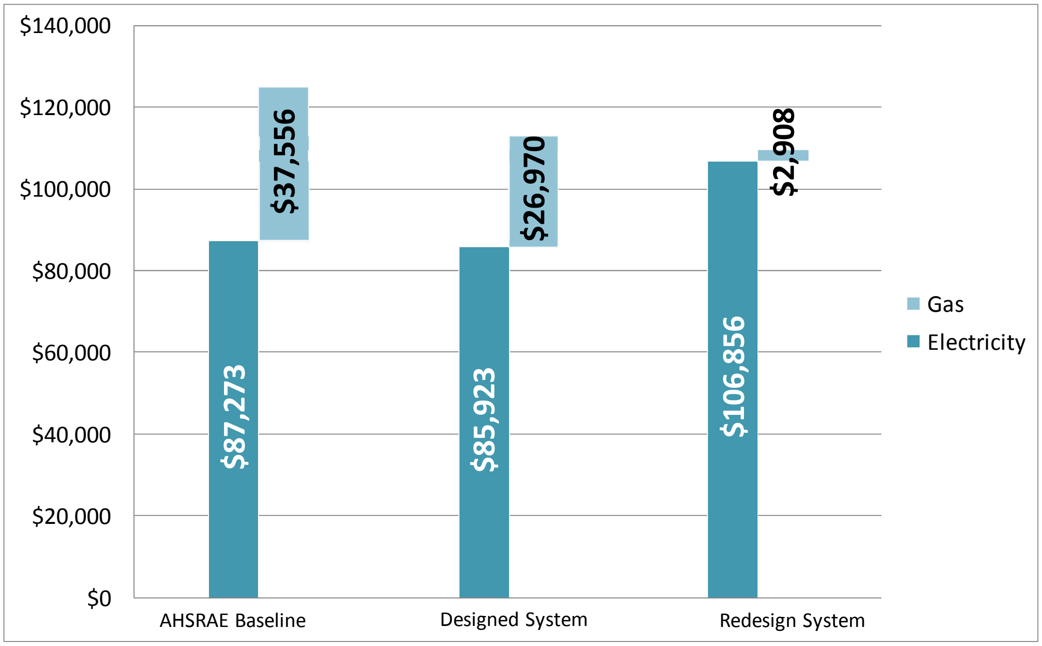


Figure 9: System Annual Energy Costs

- Consumption Results

  Total system consumption follows the same trend as energy savings, but more of the cost savings comes from using less gas than using less electricity. Figure 10 shows the utility consumption of each system. It is clear that all three systems use almost the same amount of electricity, with the proposed design actually consuming more energy than the baseline. Although the system redesign consumes more electricity, the cost of the electricity is less than the other systems. This results from the electric consumption occurring at less on-peak hours which causes a large cost savings. Also, the redesigned system uses almost no gas at all. This is because the redesigned system does not utilize a boiler heating system. The gas consumption seen in the system redesign is due to domestic hot water heaters which are required.

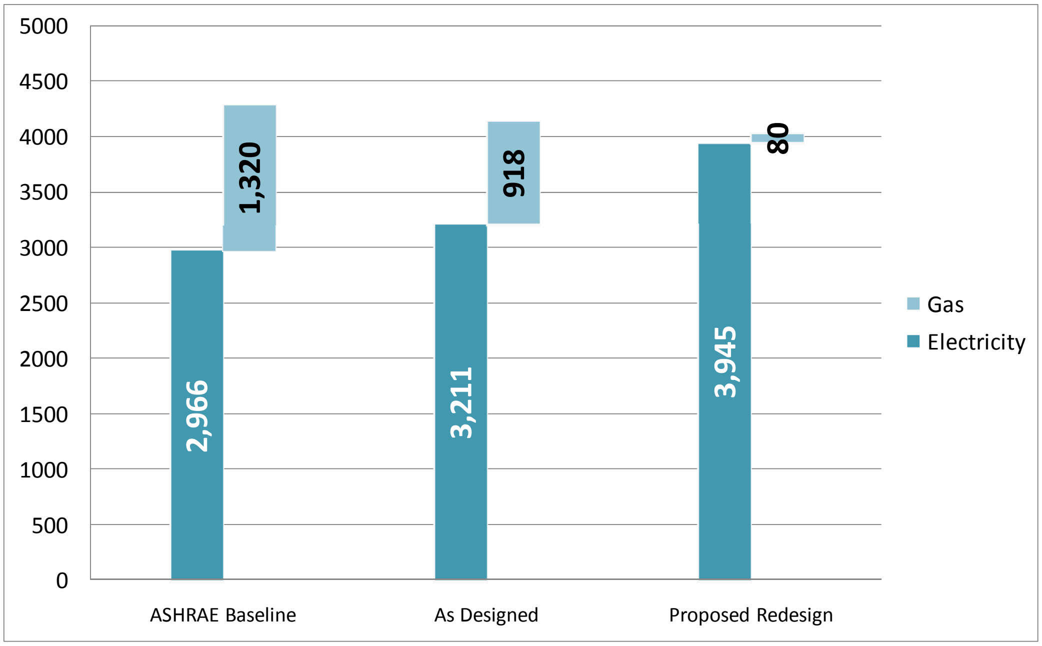


Figure 10: Annual Energy Consumption (MBH)

LEED Implications

The redesigned system with a percent savings of 12% is the minimum certifiable and would be awarded only 1 point out of a possible 19. This is not a significant amount of points considering it takes a total of 40 points will earn LEED Certification.

Greenhouse Gas Emissions

The ground source heat pump system consumes less gas and electricity than the designed mechanical system and will therefore have lower greenhouse gas emissions. Emissions for all three systems are summarized in Table 26 below. The results of this greenhouse gas study show that the proposed system will emit 14,300 pounds per year less greenhouse gas emissions than the baseline and 9,550 pounds per year less than the designed system. This reduction will have a huge positive impact on the environment. Since Manoa Elementary School is located in a suburban neighborhood the reduction will also benefit the residents.

Greenhouse Gas Emission Data				
	CO2 (lbm/year)	NOX (lbm/year)	SOX (lbm/year)	Total Redesign Savings (lbm/year)
ASHRAE Baseline	2.02E+04	3.05E+01	1.64E+03	1.43E+04
As Designed	1.59E+04	2.47E+01	1.15E+03	9.55E+03
Redesign	7.40E+03	1.31E+01	1.31E+02	

Table 26: Greenhouse Gas Emission Comparison

Air Source Heat Pump

Load Analysis

Designs Analyzed

Three systems performances will be analyzed in this section.

- Designed System
  The same direct expansion rooftop variable air volume system with series fan boxes and boiler heating will be the first case for energy analysis was used for this analysis.
- ASHRAE Baseline Model
  Same energy model as before was used for this analysis.
- Redesigned System
  The air source heat pump system described above was the final system for the comparison. Modeling this system with the designed and baseline systems will report the amount of energy savings this system creates.

Assumptions

All assumptions for this system are identical to the ones listed for ground source heat pump- vertical loop.

Results

Results for the following air source heat pump systems are shown in Tables 27 through 31 below.

ASHP-1 Zoning

Zone	Rooms	Sensible Load (MBH)	Latent Load (MBH)	Heating Load (MBH)	Heating Ventilation Load (MBH)	CFM
1	101 SEM Classroom	21.3	18	35	17.5	902
2	102 SEM 2 Classroom	16.9	8.6	34.5	17.5	779
3	105 SE 6 Resource Classroom	15.8	6.6	27.8	13.3	736
4	106 Kindergarten Classroom 1 111 Corridor 124 Faculty Workroom 126 Vestibule	28.4	14	56.20	22.5	1523
5	301 SE 4	23.8	7.2	32.4	15.4	777
6	302 Fourth Grade Classroom 2 304 Storage	26	8.2	35.1	15.9	800
7	305 Fifth Grade Classroom 1	19.8	4.5	34.6	17.5	779
8	306 Restroom	10.1	1.3	6.1	0	286
9	307 Corridor	36.2	6.1	32.3	7.9	645
10	309 Fifth Grade Classroom 3	18	3.4	27.4	13.3	673
11	310 Fifth Grade Classroom 4	17.7	10.3	34.4	17.5	777
12	314 Fourth Grade Classroom 1	17.3	10.2	34.1	17.5	772
13	315 Reading Seminar	18.6	4.4	31.6	15.9	712
14	316 SE Classroom	14.8	10	31.6	15.9	712
15	318 Corridor 322 Faculty Meeting	20.3	4.6	19.4	7.5	570
16	326 Storage 323 Faculty Planning	11.3	3.2	14.5	5.8	405
17	324 Fourth Grade Classroom 2	15.9	10.5	34	17.5	770
18	325 Fourth Grade Classroom 1	19.3	4.7	34	15.5	770
19	327 SE 5 Classroom	22	4.3	36	17.5	804
20	Fourth Grade	19.7	4.7	34.2	17.5	773

Table 27: System Zoning and Dedicated Outdoor Air Loads for ASHP-1

ASHP-2 Zoning						
Zone	Rooms	Sensible Load (MBH)	Latent Load (MBH)	Heating Load (MBH)	Heating Ventilation Load (MBH)	CFM
1	107 First Grade Classroom 1	9.9	13.8	31	16.4	755
2	109 First Grade Classroom 2	9.9	13.8	31.1	16.4	756
3	112 Kindergarten Classroom 2 113 Conference 115 Storage	18.1	12.2	36.4	18.4	963
4	117 First Grade Classroom 3	9.8	14.3	31.00	16.4	754
5	118 Kindergarten Classroom 3	1.4	24.3	31.4	14.9	743
6	119 First Grade Classroom 1 120 Faculty Workroom 121 Corridor	17.7	12.9	39.6	18.5	1024
7	201 SE 3	10.7	10.1	28.7	14.4	690
8	202 Second Grade Classroom 2 204 Storage	13.5	9.9	29.5	14.8	728
9	205 Second Grade Classroom 1 206 Restroom 207 Corridor	22.8	14.6	42.2	18.3	1268
10	209 Second Grade Classroom 3	9.7	16.1	30.8	16.4	751
11	210 Second Grade Classroom 4	13.9	10.8	31.2	16.4	758
12	213 Third Grade Classroom 3	9.9	13.7	31.1	16.4	756
13	214 Third Grade Classroom 4	14.5	10.6	31	16.4	755
14	215 SEM	9.6	10.5	28.7	14.9	705
15	216 Seminar Learning Support 222 Faculty Meeting 223 Faculty Planning	19.9	14.3	44.3	24.1	1085
16	224 Third Grade Classroom 2	12.2	22.1	27.8	14.4	673
17	225 Third Grade Classroom 1 226 Storage	14.8	10.1	32.6	15.2	920
18	227 SE 2 Classroom	19.1	13.5	41	18.8	1081

Table 28: System Zoning and Dedicated Outdoor Air Loads for ASHP-2

ASHP-3 Zoning

Zone	Rooms	Sensible Load (MBH)	Latent Load (MBH)	Heating Load (MBH)	Heating Ventilation Load (MBH)	CFM
1	129 Administration	4.6	0.9	2.5	0.7	190
2	130 Reception 131 Hallway	5.7	2.5	7.4	3	289
3	132 Nurse 132.2 Exam	5.2	2.4	8	3.5	290
4	133 Hallway 134 Conference 135 Conference	12.4	10	25.4	12.8	661
5	136 Guidance	2.6	0.4	9.2	4.8	245
6	139 IST	3.8	2.1	7	3.4	232
7	140 Principal 141 Corridor	11.1	1.5	10.2	2	494
8	142 Library High	39.1	16.3	49.7	16.3	2004
9	142 Library Low 142.2 Storage	19.1	13.3	33.7	14.6	1047
10	143 Office 144 Workroom	5.7	1.9	5	2.1	271
11	145 Music Room 145.1 Storage 146 Faculty Dining	24.9	13.5	44.9	21.9	1261
12	147 Music Room 147.1 Storage	21.7	13	39.1	15.2	929
13	139 Art Room 149.1 Art Storage	18.6	6.4	62.2	30.4	1211
14	150 Corridor	18.4	2.7	16	3	786
15	151 Corridor	14.5	1	10.7	1.3	594
16	152.1 Gym Office	4.3	0.8	1.9	0.7	189

Table 29: System Zoning and Dedicated Outdoor Air Loads for ASHP-3

ASHP-4 Zoning

Zone	Rooms	Sensible Load (MBH)	Latent Load (MBH)	Heating Load (MBH)	Heating Ventilation Load (MBH)	CFM
1	Multipurpose Room	30.65	31.75	64.3	24.7	1460.25
2	Multipurpose Room	30.65	31.75	64.3	24.7	1460.25
3	Multipurpose Room	30.65	31.75	64.3	24.7	1460.25
4	Multipurpose Room	30.65	31.75	64.3	24.7	1460.25

Table 30: System Zoning and Dedicated Outdoor Air Loads for ASHP-4

ASHP-5 Zoning						
Zone	Rooms	Sensible Load (MBH)	Latent Load (MBH)	Heating Load (MBH)	Heating Ventilation Load (MBH)	CFM
1	155 Ramp	6.6	8.6	9.6	1.2	305
2	156 Cafeteria	24.4	4.8	122.2	68.5	3043
3	158 LBI	26.3	8.5	118.4	61.3	2725
4	159 Serving	30.2	8	14.8	6.6	1283
5	160 Kitchen	15.8	16.1	30.9	13.2	718
6	161 Dishwash	10.1	1.8	5.8	2.8	445
7	163 Office Dry Storage	4.8	0.3	0.9	0.1	203
8	164 Dry Storage	0.9	0.2	0.7	0	35
9	168 Corridor 169 Janitor	5.5	1.6	9.8	1.2	262

Table 31: System Zoning and Dedicated Outdoor Air Loads for ASHP-5

Selection of Heat Pump

The heat pumps selected for design are Carrier Infinity models to be consistent with the original design's use of the Carrier Corporation. These units will be used to replace the variable air boxes for all spaces. Large spaces such as the multipurpose room, cafeteria and LGI will utilize multiple heat pumps to serve the load. Heat pump selection and cost is shown in Table 32 below.

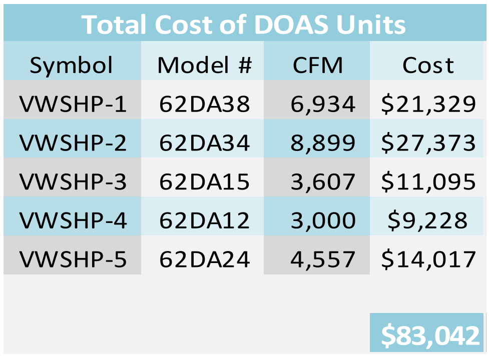
Heat pumps were selected to meet the sensible loads for the individual spaces they serve due to the fact that the dedicated outdoor air unit will be selected to meet the latent loads of the spaces. The primary goal for unit selection was maximizing the total system EER.

Total Cost of Heat Pumps				
Model Number	Tons	# of Units	Cost	Average EER
25HNA012	1	29	$72,268	14.0
25HNA018	1.5	18	$60,120	14.3
25HNA024	2	9	$31,815	14.9
25HNA36	3	10	$42,400	13.1
25HNA39	3.5	1	$4,800	13.7
			$211,403	**14.0**

Table 32: Selection and Total Cost of Vertical Ground Source Heat Pump Units

Selection of Dedicated Outdoor Air Unit

Selection of the dedicated outdoor air units was performed using Carrier 100% Outdoor Air Units which were sized to meet the latent heating and cooling loads. These units utilize direct expansion coils, R-410a and energy recovery wheels. The total cost for each of the selected units is given in Table 33 below.



Total Cost of DOAS Units			
Symbol	Model #	CFM	Cost
VWSHP-1	62DA38	6,934	$21,329
VWSHP-2	62DA34	8,899	$27,373
VWSHP-3	62DA15	3,607	$11,095
VWSHP-4	62DA12	3,000	$9,228
VWSHP-5	62DA24	4,557	$14,017
			$83,042

Table 33: Selection and Total Cost of Dedicated Outdoor Air Units

Annual Energy Use

Designs Analyzed

Three systems performances will be analyzed in this section.

- Designed System
  The designed system is the same as the one used to analyze both vertical and horizontal heat pumps.
- ASHRAE Baseline Model
  The same baseline model as the other two comparisons was used in this study.
- Redesigned System
  The air source heat pump system described above was the final system for the comparison. Modeling this system with the designed and baseline systems will report the amount of energy savings this system creates.

Assumptions

The assumptions made for modeling vertical and horizontal ground source heat pumps also apply to this analysis.

Annual Energy Cost and Consumption Results

- Cost Results
  Figure 11 shows the energy cost savings of the three systems described above. These results are similar to those seen above, with the ASHRAE Baseline system should be the most expensive system to operate. The designed scenario again falls between the ASHRAE Baseline and the Redesigned system which shows that the system outperforms the baseline scenario but doesn't perform as well as the proposed redesign system.

  ASHRAE Standard 90.1 prescribes a method for calculating the percentage improvement of a designed system over the baseline. Table 34 summarizes these results for the designed system and the proposed system. This table shows that the proposed system outperforms the baseline by almost 18% and saves almost $21,500 annually and outperforms the designed mechanical system by 9% and saves $9,500 annually. These results show the possible benefits of using a more efficient system.

System Energy Savings Comparison				
	Savings Over Baseline		Savings Over Designed	
	%	$	%	$
As Designed	9.56	11,936		
Redesign	17.18	21,445	9.20	9,509

Table 34: Annual Energy Cost Savings

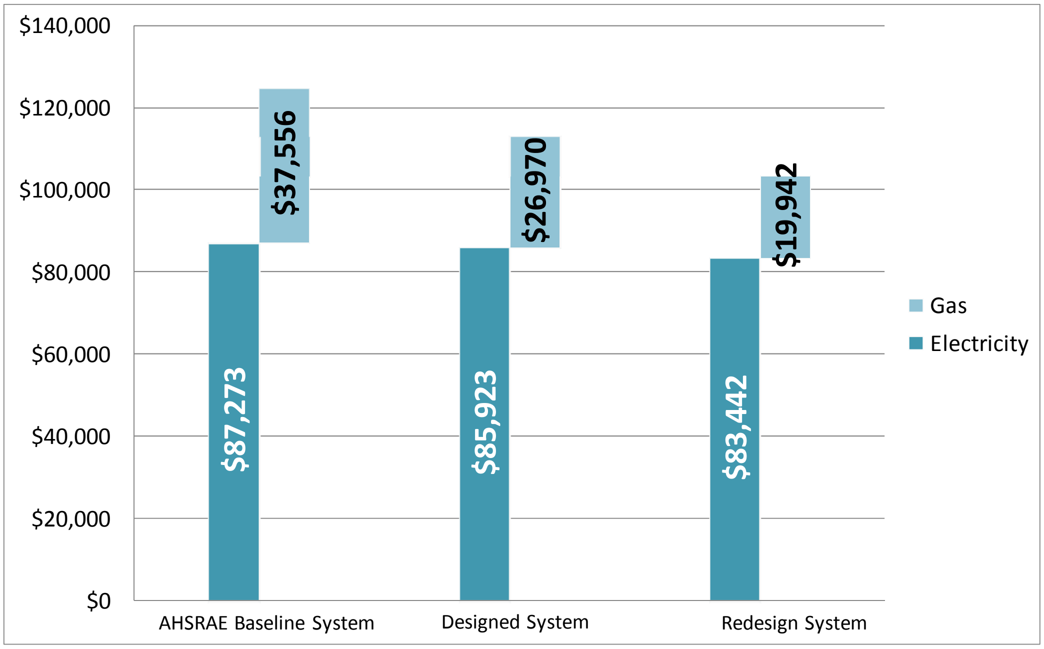


Figure 11: System Annual Energy Costs

- Consumption Results

  Total system consumption follows the same trend as energy savings, but more of the cost savings comes from using less gas than using less electricity. Figure 12 shows the utility consumption of each system. In this scenario there is a great deal of variation in electricity consumption with the designed system using the most and the proposed system using the least. This reduced consumption results in a large cost savings. Also, the redesigned system uses less gas than the other two systems. This is because the redesigned system does not utilize a boiler heating system. The gas consumption seen in the system redesign is due to domestic hot water heaters which are required.

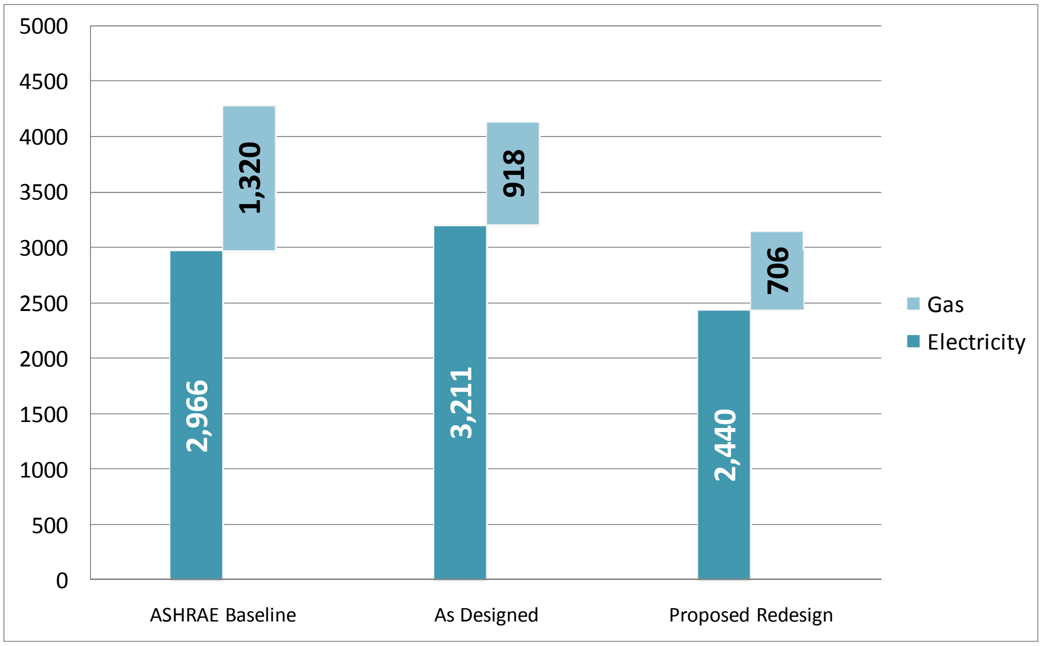


Figure 12: Annual Energy Consumption (MBH)

LEED Implications

The redesigned system with a percent savings of 17% and would be awarded 3 points out of a possible 19. This is not a significant amount of points considering it takes a total of 40 points will earn LEED Certification.

Greenhouse Gas Emissions

The ground source heat pump system consumes less gas and electricity than the designed mechanical system and will therefore have lower greenhouse gas emissions. Emissions for all three systems are summarized in Table 35 below. The results of this greenhouse gas study show that the proposed system will emit 8,750 pounds per year less greenhouse gas emissions than the baseline and 4,000 pounds per year less than the designed system. This reduction will have a huge positive impact on the environment. Since Manoa Elementary School is located in a suburban neighborhood the reduction will also benefit the residents.

Greenhouse Gas Emission Data				
	CO2 (lbm/year)	NOX (lbm/year)	SOX (lbm/year)	Total Redesign Savings (lbm/year)
ASHRAE Baseline	2.02E+04	3.05E+01	1.64E+03	8.75E+03
As Designed	1.59E+04	2.47E+01	1.15E+03	4.00E+03
Redesign	1.22E+04	1.89E+01	8.82E+02	

Table 35: Greenhouse Gas Emission Comparison

System Cost Comparison

Figure 13 below combines all three proposals with the baseline and designed energy cost in order to gain perspective on the results. This figure shows that the proposed redesign systems, although being all heat pumps, perform drastically different when applied to the same building. This figure shows that the vertical loop ground source heat pump results in the most energy savings whereas the horizontal loop results in the least. This is because the pumping power for these two systems is so different. The pumping energy required for the horizontal loop adds $15,064 in electricity, which is very significant.

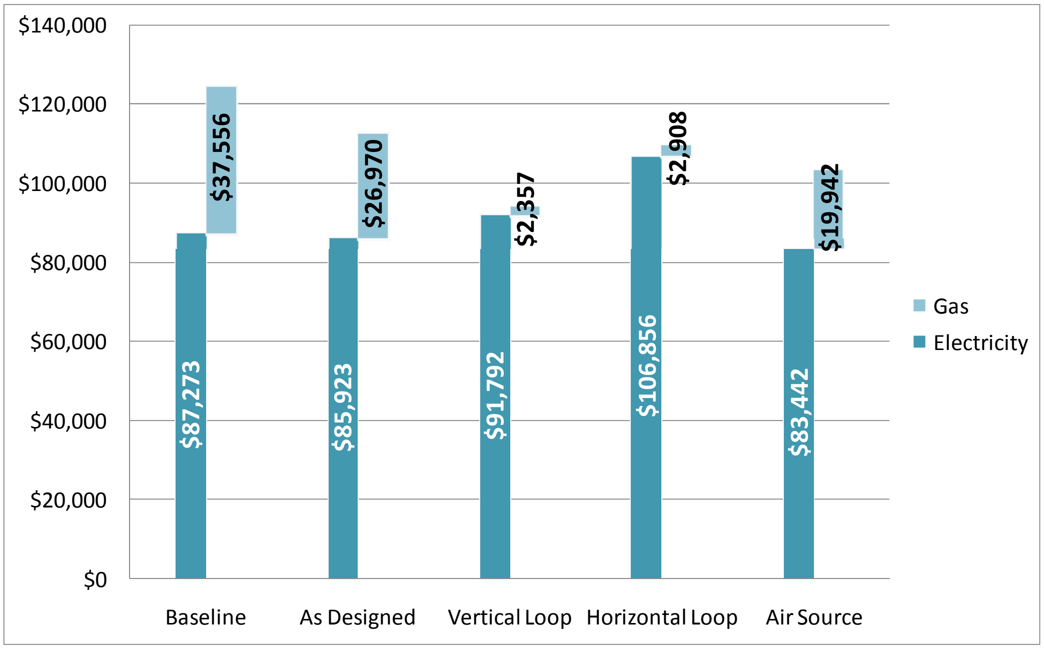


Figure 13: Combined System Energy Cost

Total utility consumption is also important for analysis. Figure 14 combines the energy use of all three proposed systems with the baseline and the designed systems. These results are different than the cost comparison. The system which consumes the least total energy is the air source heat pump, which consumes 234 MBH less than the vertical loop heat pump system. Although this system consumes less total energy than the rest, it is the most expensive in energy cost out of the three alternatives because it consumes a significantly larger amount of natural gas than the other two systems. It is reasonable to say that both ground source heat pump systems are a better selection than the air source because of the significant cost decrease that results from using less gas. Less gas consumption also leads to reduced greenhouse gas emissions which are summarized in Table 36 below.

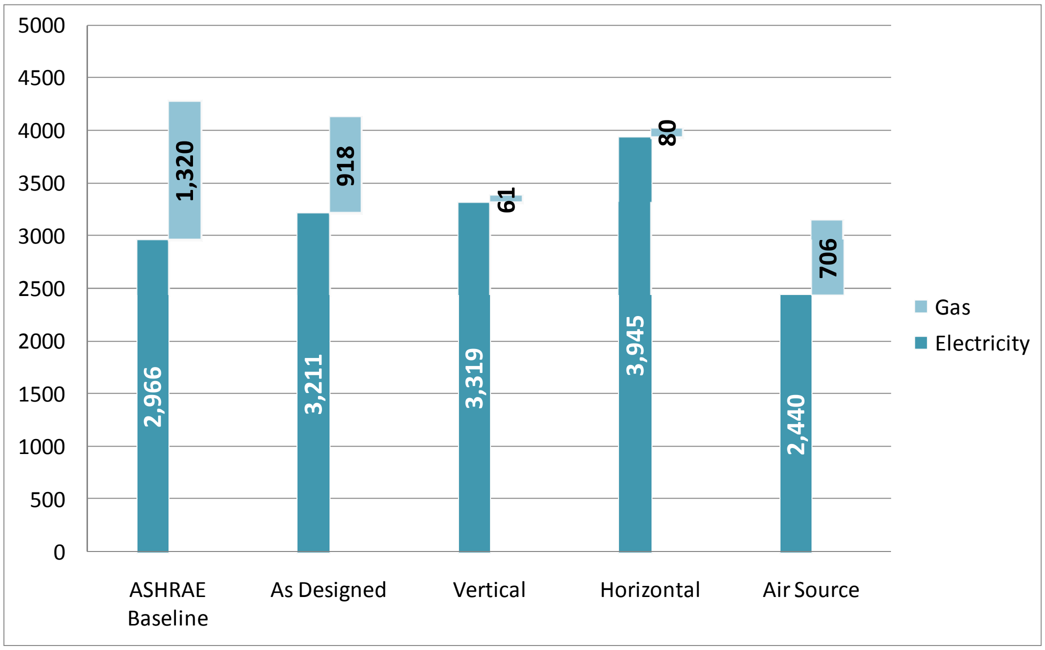


Figure 14: Combined Energy Consumption Analysis

Greenhouse Gas Emission Data				
	CO2 (lbm/year)	NOX (lbm/year)	SOX (lbm/year)	Total Emissions (lbm/year)
ASHRAE Baseline	2.02E+04	3.05E+01	1.64E+03	2.18E+04
As Designed	1.59E+04	2.47E+01	1.15E+03	1.71E+04
Vertical Loop	6.15E+03	1.10E+01	1.03E+02	6.26E+03
Horizontal Loop	7.40E+03	1.31E+01	1.31E+02	7.54E+03
Air Source	1.22E+04	1.89E+01	8.82E+02	1.31E+04

Table 36: Combined Greenhouse Gas Emissions

Ground Loop Sizing

Vertical Loop

Sizing Method

Chapter 32 of the 2007 ASHRAE Handbook of Applications prescribes a method for sizing the system's vertical loop. This method allows you to calculate the total length of ground loop required necessary to meet the heating and cooling loads. Because the heating and cooling loads are not the same, the required loop length for each case needs to be found and the larger of the two will be the final design length. These equations take into account the daily, monthly and annual pulse of the ground loop. The equations are as follows.

- Cooling Length

$$L_C = \frac{q_c R_a + (q_{lc} - 3.41 W_c)(R_b + PLF_m R_m + R_{gm} + R_{gd} F_{sc}}{t_g - \frac{t_{wi} - t_{wo}}{2} - t_p}$$

- Heating Length

$$L_C = \frac{q_c R_a + (q_{lc} - 3.41 W_c)(R_b + PLF_m R_m + R_{gm} + R_{gd} F_{sc}}{t_g - \frac{t_{wi} - t_{wo}}{2} - t_p}$$

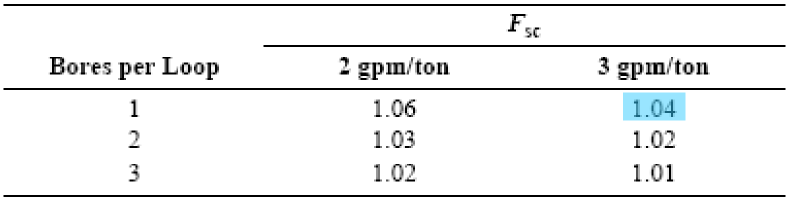
- Variables
  - **F_{sc}** is the short circuit heat loss factor
  - **L_c** is the required bore length for cooling, in feet
  - **L_h** is the required bore length for heating, in feet
  - **PLF_m** is the part load factor during the design month
  - **q_a** is the net annual average heat transfer to the ground, in Btu/h
  - **q_{lc}** is the building design cooling block load, in Btu/h
  - **q_{lh}** is the building design heating block load, in Btu/h
  - **R_{ga}** is the effective thermal resistance of the ground (annual pulse), in h·ft·°F/Btu
  - **R_{gd}** is the effective thermal resistance of the ground (daily pulse), in h·ft·°F/Btu
  - **R_{gm}** is the effective thermal resistance of the ground (monthly pulse), in h·ft·°F/Btu
  - **R_b** is the thermal resistance of the pipe, in h·ft·°F/Btu
  - **t_g** is the undisturbed ground temperature, in °F
  - **t_p** is the temperature penalty for interference of the adjacent bores, in °F
  - **t_{wi}** is the liquid temperature at a heat pump inlet, in °F
  - **t_{wo}** is the liquid temperature at the heat pump outlet, in °F
  - **W_c** is the power input at the design cooling load, in W
  - **W_h** is the power input at the design heating load, in W

Assumptions

Several variable definitions need to be assumed in order to calculate the required length. The assumptions made to perform this analysis are as follows.

- Short Circuit Heat Loss Factor

The following table in Chapter 32 of ASHRAE Handbook of Fundamentals 2007 was used to determine this value. The system was designed under the assumptions of 1 bore per loop and 3 gpm per ton. This resulted in a short circuit heat loss factor of 1.04.



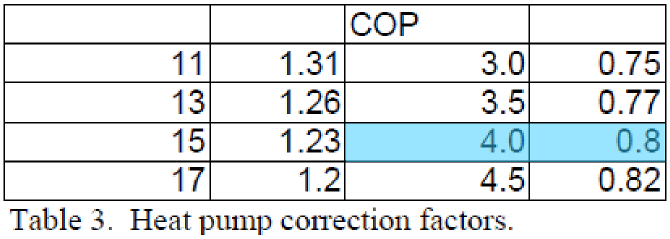
	F_{sc}	
Bores per Loop	**2 gpm/ton**	**3 gpm/ton**
1	1.06	1.04
2	1.03	1.02
3	1.02	1.01

Figure 15: ASHRAE Short Circuit Heat Loss Factor

- Part Load Factor
  Actual building performance data was not available for this analysis therefore a part load factor of 1.0, which is the worst case scenario, was assumed for PLF_m.
- Net Annual Average Heat Transfer to the Ground
  The method for calculating this variable is outlined in detail in the paper entitled Updating and Debugging the Federal Renewable Energy Screening Assistant: Ground Coupled Heat Pump Algorithm published by the National Renewable Energy Laboratory. The equation is as follows:

$$q_a = \frac{C_{fc} q_{lc} EFLhours_c + C_{fh} q_{lh} EFLhours_h}{8760}$$

Where C_{fc} and C_{fh} are the heat pump correction factors found using a table in the article, q_{lc} and q_{lh} are the heating and cooling loads determined from Trane Trace, and the EFLhours are the equivalent full load hours which were found in Appendix 4 of McQuay's Geothermal Heat Pump Design Manual. The largest of the EFLhours were selected for both heating and cooling. Tables for C and EFLhours are shown in Figures 16 and 17 respectively.

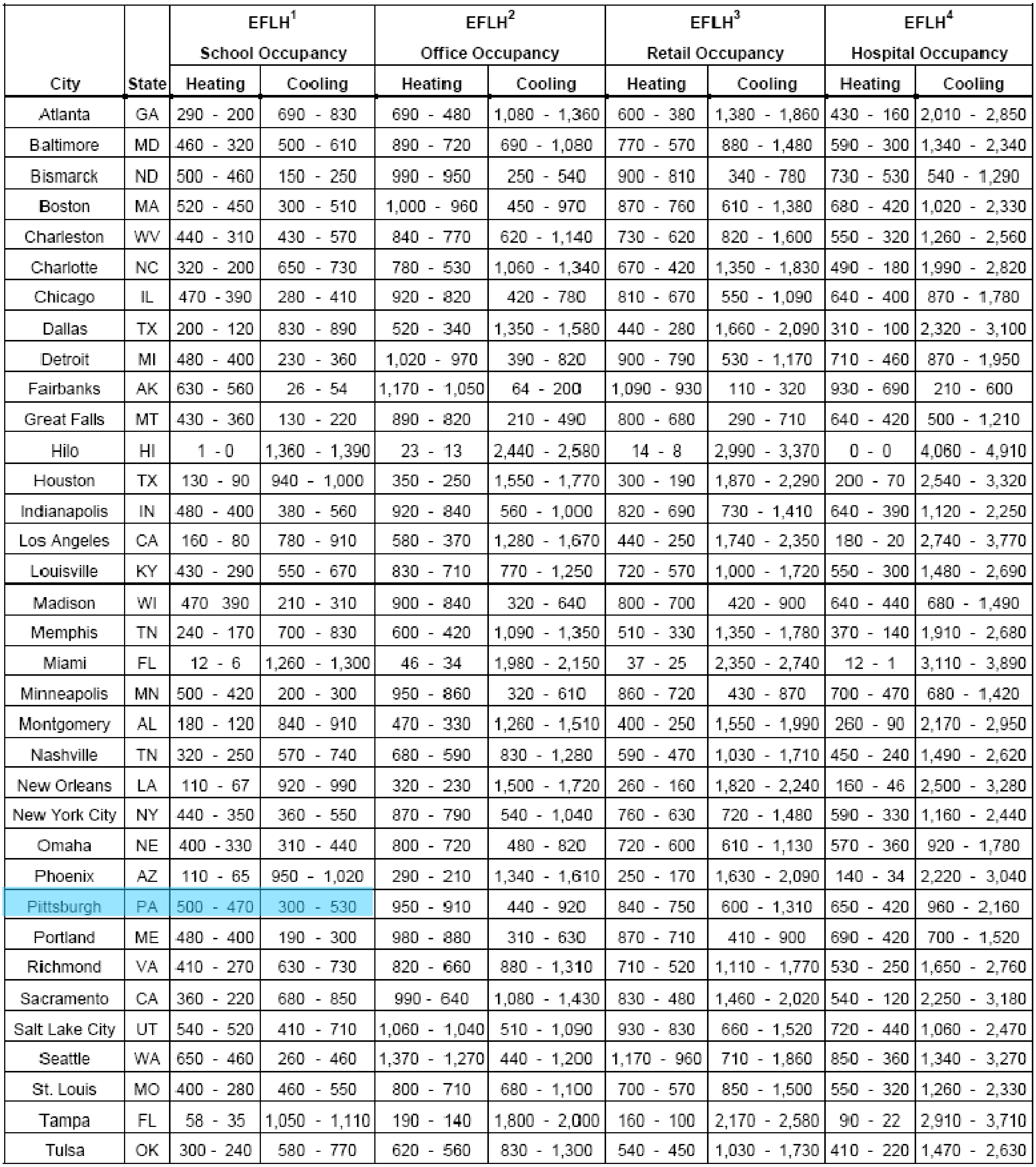


		COP	
11	1.31	3.0	0.75
13	1.26	3.5	0.77
15	1.23	4.0	0.8
17	1.2	4.5	0.82

Table 3. Heat pump correction factors.

Figure 16: COP Correction Factors

Appendix 4 – Equivalent Full Load Hours[25]



City	State	EFLH[1] School Occupancy		EFLH[2] Office Occupancy		EFLH[3] Retail Occupancy		EFLH[4] Hospital Occupancy	
		Heating	Cooling	Heating	Cooling	Heating	Cooling	Heating	Cooling
Atlanta	GA	290 - 200	690 - 830	690 - 480	1,080 - 1,360	600 - 380	1,380 - 1,860	430 - 160	2,010 - 2,850
Baltimore	MD	460 - 320	500 - 610	890 - 720	690 - 1,080	770 - 570	880 - 1,480	590 - 300	1,340 - 2,340
Bismarck	ND	500 - 460	150 - 250	990 - 950	250 - 540	900 - 810	340 - 780	730 - 530	540 - 1,290
Boston	MA	520 - 450	300 - 510	1,000 - 960	450 - 970	870 - 760	610 - 1,380	680 - 420	1,020 - 2,330
Charleston	WV	440 - 310	430 - 570	840 - 770	620 - 1,140	730 - 620	820 - 1,600	550 - 320	1,260 - 2,560
Charlotte	NC	320 - 200	650 - 730	780 - 530	1,060 - 1,340	670 - 420	1,350 - 1,830	490 - 180	1,990 - 2,820
Chicago	IL	470 - 390	280 - 410	920 - 820	420 - 780	810 - 670	550 - 1,090	640 - 400	870 - 1,780
Dallas	TX	200 - 120	830 - 890	520 - 340	1,350 - 1,580	440 - 280	1,660 - 2,090	310 - 100	2,320 - 3,100
Detroit	MI	480 - 400	230 - 360	1,020 - 970	390 - 820	900 - 790	530 - 1,170	710 - 460	870 - 1,950
Fairbanks	AK	630 - 560	26 - 54	1,170 - 1,050	64 - 200	1,090 - 930	110 - 320	930 - 690	210 - 600
Great Falls	MT	430 - 360	130 - 220	890 - 820	210 - 490	800 - 680	290 - 710	640 - 420	500 - 1,210
Hilo	HI	1 - 0	1,360 - 1,390	23 - 13	2,440 - 2,580	14 - 8	2,990 - 3,370	0 - 0	4,060 - 4,910
Houston	TX	130 - 90	940 - 1,000	350 - 250	1,550 - 1,770	300 - 190	1,870 - 2,290	200 - 70	2,540 - 3,320
Indianapolis	IN	480 - 400	380 - 560	920 - 840	560 - 1,000	820 - 690	730 - 1,410	640 - 390	1,120 - 2,250
Los Angeles	CA	160 - 80	780 - 910	580 - 370	1,280 - 1,670	440 - 250	1,740 - 2,350	180 - 20	2,740 - 3,770
Louisville	KY	430 - 290	550 - 670	830 - 710	770 - 1,250	720 - 570	1,000 - 1,720	550 - 300	1,480 - 2,690
Madison	WI	470 390	210 - 310	900 - 840	320 - 640	800 - 700	420 - 900	640 - 440	680 - 1,490
Memphis	TN	240 - 170	700 - 830	600 - 420	1,090 - 1,350	510 - 330	1,350 - 1,780	370 - 140	1,910 - 2,680
Miami	FL	12 - 6	1,260 - 1,300	46 - 34	1,980 - 2,150	37 - 25	2,350 - 2,740	12 - 1	3,110 - 3,890
Minneapolis	MN	500 - 420	200 - 300	950 - 860	320 - 610	860 - 720	430 - 870	700 - 470	680 - 1,420
Montgomery	AL	180 - 120	840 - 910	470 - 330	1,260 - 1,510	400 - 250	1,550 - 1,990	260 - 90	2,170 - 2,950
Nashville	TN	320 - 250	570 - 740	680 - 590	830 - 1,280	590 - 470	1,030 - 1,710	450 - 240	1,490 - 2,620
New Orleans	LA	110 - 67	920 - 990	320 - 230	1,500 - 1,720	260 - 160	1,820 - 2,240	160 - 46	2,500 - 3,280
New York City	NY	440 - 350	360 - 550	870 - 790	540 - 1,040	760 - 630	720 - 1,480	590 - 330	1,160 - 2,440
Omaha	NE	400 - 330	310 - 440	800 - 720	480 - 820	720 - 600	610 - 1,130	570 - 360	920 - 1,780
Phoenix	AZ	110 - 65	950 - 1,020	290 - 210	1,340 - 1,610	250 - 170	1,630 - 2,090	140 - 34	2,220 - 3,040
Pittsburgh	PA	500 - 470	300 - 530	950 - 910	440 - 920	840 - 750	600 - 1,310	650 - 420	960 - 2,160
Portland	ME	480 - 400	190 - 300	980 - 880	310 - 630	870 - 710	410 - 900	690 - 420	700 - 1,520
Richmond	VA	410 - 270	630 - 730	820 - 660	880 - 1,310	710 - 520	1,110 - 1,770	530 - 250	1,650 - 2,760
Sacramento	CA	360 - 220	680 - 850	990 - 640	1,080 - 1,430	830 - 480	1,460 - 2,020	540 - 120	2,250 - 3,180
Salt Lake City	UT	540 - 520	410 - 710	1,060 - 1,040	510 - 1,090	930 - 830	660 - 1,520	720 - 440	1,060 - 2,470
Seattle	WA	650 - 460	260 - 460	1,370 - 1,270	440 - 1,200	1,170 - 960	710 - 1,860	850 - 360	1,340 - 3,270
St. Louis	MO	400 - 280	460 - 550	800 - 710	680 - 1,100	700 - 570	850 - 1,500	550 - 320	1,260 - 2,330
Tampa	FL	58 - 35	1,050 - 1,110	190 - 140	1,800 - 2,000	160 - 100	2,170 - 2,580	90 - 22	2,910 - 3,710
Tulsa	OK	300 - 240	580 - 770	620 - 560	830 - 1,300	540 - 450	1,030 - 1,730	410 - 220	1,470 - 2,630

Figure 17: Equivalent Full Load Hours

- Building Design Block Loads
  The building design cooling and heating loads were determined by modeling the building and the ground source heat pump system in Trane Trace, which is described in the Load Analysis section.
- Effective Thermal Ground Resistances
  The method for calculating the value of these variables was found in Chapter 32 of the ASHRAE Handbook of Applications. In order to solve the equations listed in this chapter, the pulse time, Fourier number and the G-Factor must first be found. The thermal diffusity must also be found using Table 5 of the handbook. Since the most difficult parameters to evaluate when calculating the required borehole length are the equivalent thermal resistances of the ground, a worst-case scenario was assumed for this variable, as seen in Figure 18. Sizing the loop to meet a worst case scenario has the possibility to be beneficial during the heating season.

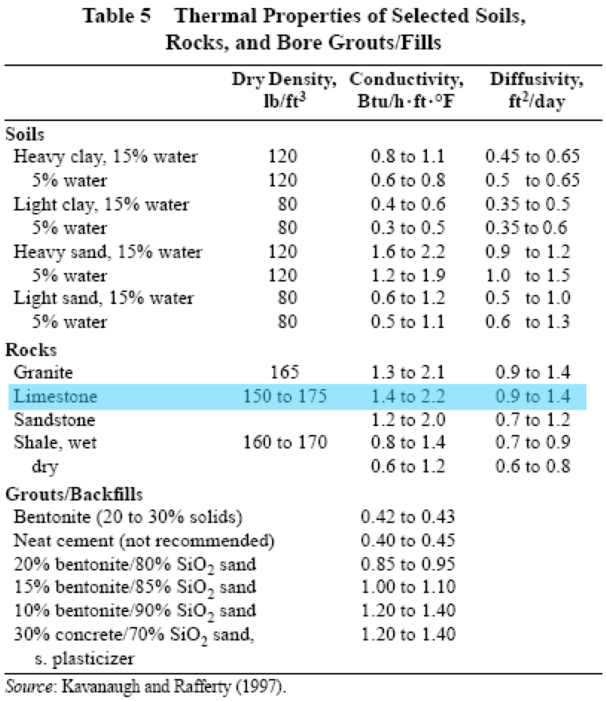


Table 5 Thermal Properties of Selected Soils, Rocks, and Bore Grouts/Fills

	Dry Density, lb/ft^3	Conductivity, Btu/h·ft·°F	Diffusivity, ft^2/day
Soils			
Heavy clay, 15% water	120	0.8 to 1.1	0.45 to 0.65
5% water	120	0.6 to 0.8	0.5 to 0.65
Light clay, 15% water	80	0.4 to 0.6	0.35 to 0.5
5% water	80	0.3 to 0.5	0.35 to 0.6
Heavy sand, 15% water	120	1.6 to 2.2	0.9 to 1.2
5% water	120	1.2 to 1.9	1.0 to 1.5
Light sand, 15% water	80	0.6 to 1.2	0.5 to 1.0
5% water	80	0.5 to 1.1	0.6 to 1.3
Rocks			
Granite	165	1.3 to 2.1	0.9 to 1.4
Limestone	150 to 175	1.4 to 2.2	0.9 to 1.4
Sandstone		1.2 to 2.0	0.7 to 1.2
Shale, wet	160 to 170	0.8 to 1.4	0.7 to 0.9
dry		0.6 to 1.2	0.6 to 0.8
Grouts/Backfills			
Bentonite (20 to 30% solids)		0.42 to 0.43	
Neat cement (not recommended)		0.40 to 0.45	
20% bentonite/80% SiO$_2$ sand		0.85 to 0.95	
15% bentonite/85% SiO$_2$ sand		1.00 to 1.10	
10% bentonite/90% SiO$_2$ sand		1.20 to 1.40	
30% concrete/70% SiO$_2$ sand, s. plasticizer		1.20 to 1.40	

Source: Kavanaugh and Rafferty (1997).

Figure 18: ASHRAE Table for Determining Soil Diffusivity

- Thermal Resistance of the Pipe
  Several assumptions had to be made in order to calculate this value. Table 6 in the ASHRAE Applications requires the tube material, the tube diameter and the borehole diameter need to be known in order to determine the thermal resistance of the pipe. For the purpose of this calculation, a 1" diameter polyethylene U-tube in a 4 inch diameter bore hole with a thermal conductivity of 1.0 Btu/h·ft·°F is assumed. These assumptions result in a pipe thermal resistance of 0.08 Btu/ h·ft·°F.
- Undisturbed Ground Temperature
  This value was determined using Appendix 1 in McQuay's Geothermal Heat Pump Design Manual which listed the ground temperature for Philadelphia, PA as 55°F.
- Temperature Penalty for Interference of Adjacent Bores
  Chapter 32 of ASHRAE Handbook of Applications includes a table to be utilized when determining this variable. This table can be seen in Figure 19 below, including the worst-cast scenario assumption.

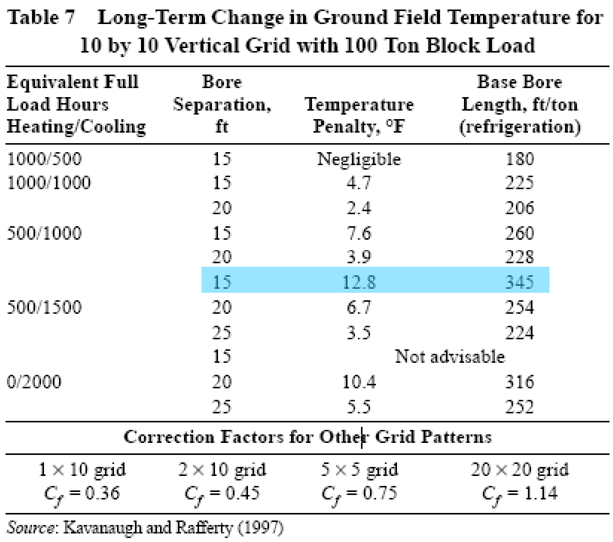


Table 7 Long-Term Change in Ground Field Temperature for 10 by 10 Vertical Grid with 100 Ton Block Load

Equivalent Full Load Hours Heating/Cooling	Bore Separation, ft	Temperature Penalty, °F	Base Bore Length, ft/ton (refrigeration)
1000/500	15	Negligible	180
1000/1000	15	4.7	225
	20	2.4	206
500/1000	15	7.6	260
	20	3.9	228
500/1500	15	12.8	345
	20	6.7	254
	25	3.5	224
0/2000	15	Not advisable	
	20	10.4	316
	25	5.5	252

Correction Factors for Other Grid Patterns

1 × 10 grid	2 × 10 grid	5 × 5 grid	20 × 20 grid
$C_f = 0.36$	$C_f = 0.45$	$C_f = 0.75$	$C_f = 1.14$

Source: Kavanaugh and Rafferty (1997)

Figure 19: ASHRAE Long-Term Change in Ground Field Temperature

- Heat Pump Water Temperatures
  Selection of the entering and leaving water temperatures was based off of information found in the 2007 ASHRAE Handbook of Fundamentals Chapter 32 and is described in more detail in the Vertical Loop Heat Pump Selection.
- Power Input at Design
  Chapter 32 in the 2007 ASHRAE Handbook of Fundamentals states that installed pumping power for a ground source heat pump system varies from 0.04 to 0.21 horsepower per ton. Assuming a worst case scenario, the total power input for cooling and heating is 18,650W and 14,920W, respectively.

Results

After entering all of the values of the variables discussed above into the equation, the calculated loop lengths to meet the cooling and heating loads are shown in Tables 37 and 38 respectively.

Cooling Design Information			
Entering Water Temperature (°F)	Leaving Water Temperature (°F)	Cooling Load (MBH)	Total Borehole Length (feet)
75	85	1,434	23,959

Table 37: Cooling Design Ground Loop Length

Heating Design Information			
Entering Water Temperature (°F)	Leaving Water Temperature (°F)	Heating Load (MBH)	Total Borehole Length (feet)
45	35	1,153	25,052

Table 38: Heating Design Ground Loop Length

In order to meet the cooling and the heating loads, the larger of these two loads, the larger of the two lengths, in this case the heating load, controls. The construction management breadth of this report further researches the loop design. The optimization study focused on finding the number of boreholes at a specified depth which produced the lowest construction cost. This study found the most economical loop design to be 115 boreholes at a depth of 218 feet.

The layout of the loop on the site was designed trying to minimize the diameter of the pipe and pumping power. In McQuay's Geothermal Heat Pump Design Manual utilization of a header system with smaller branch loops is suggested to accomplish these design factors. The horizontal spacing distance between loops is ideally recommended to be 25 feet center to center, however 15 to 20 feet is acceptable because most sites aren't large enough to allow this spacing. Figure 20 below shows the vertical loop design with respect to the building. The system was divided into a header system with 23 branches each with five vertical loops, totaling 115 loops, and evenly spaced 25 feet in every direction.

Figure 20: Vertical Borefield Layout

Horizontal Loop

Sizing Method

Table 11in Chapter 32 of ASHRAE's Handbook of Applications recommends the length per ton for sizing the horizontal loop.

Assumptions

- Table 11 mentioned above is designed for use on residential ground source heat pump systems. For the sake of this analysis, it is assumed that these recommendations can also be applied to Manoa Elementary School.
- A horizontal 6-Pipe coil will be assumed for design purposes.
- Ground temperature is the same as what was determined for the heat pump selection process.

Results

Applying the assumptions to Table 11, a 150 foot per ton loop is recommended to serve the heating and cooling loads. The total system load which utilizes the ground for heat transfer is when cooling and totals 119.5 tons which requires a total horizontal loop length of 17,925 feet. Vertical spacing of the loop is also recommended in this chapter. Figure 21 below details the trench layout.

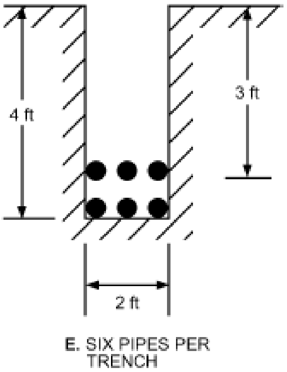


Figure 21: 6-Pipe Horizontal Trench Layout

Construction Management Breadth

Construction Goals

The use of vertical ground source heat pumps as the building mechanical system results in expensive excavation and can potentially add a significant amount of time to the construction schedule. Because of these factors, research into optimizing the impact of vertical ground source heat pumps is vital for the construction and economics of the project. The goal of this study is to determine the number and depth of boreholes which meet the mechanical load requirements of the building and minimize the construction cost and schedule impact.

Material and Equipment Assumptions

- Piping

  The calculation procedure for determining the required loop length involved assuming the size and material of the pipe to be 1" High Density Polyethylene (HDPE). R.S. Means 2009 prices this pipe at $0.53 per linear foot and comes in 40 foot lengths.

  A welding machine and crew are also required to attach the elbows and fuse the pipe lengths together. Each weld costs $4.79 and the welding machine costs $40.25 to rent per day.
- Borehole Driller

  The depth of the borehole greatly affects the cost and production rate during construction. Three earth augers with varying depths and rents will be analyzed. The rig performance data is shown in Table 38.

Earth Auger Data		
Bore Length (feet)	Rent ($/day)	Output (feet/day)
< 225	12190	1800
225 ≤ Lbore ≤ 325	14840	1200
> 325	12190	900

Table 38: Earth Auger Performance Data

- Grout

  The cost of grouting boreholes is constant regardless of the number and length of holes. The total cost of grouting is $5,937.
- Miscellaneous Site Costs

  The purge and testing of the system and unforeseen conditions add additional cost to the system. These costs are specified to numbers of boreholes and increases linearly.

Borehole Optimization Study

The assumptions above were used in conjunction with Microsoft Excel to determine the optimum configuration of length and number of boreholes to produce the lowest cost. Several things were assumed when programming the spreadsheet. These assumptions are as follows.

- All lengths of time for equipment rental were rounded up to a whole period. Since equipment is rented either daily or weekly there would be no cost savings for ending use before the rental period is over.
- Total loop length changes to equal the number of bores times the length per bore. On site everything would be installed to be uniform, not meet a specific designed length.
- All lengths were rounded up to exclude any decimal places. Again in the field they would not measure absolutely accurate.

Results of the spreadsheet programming are shown in Figure 22 and Tables 39, 40 and 41.

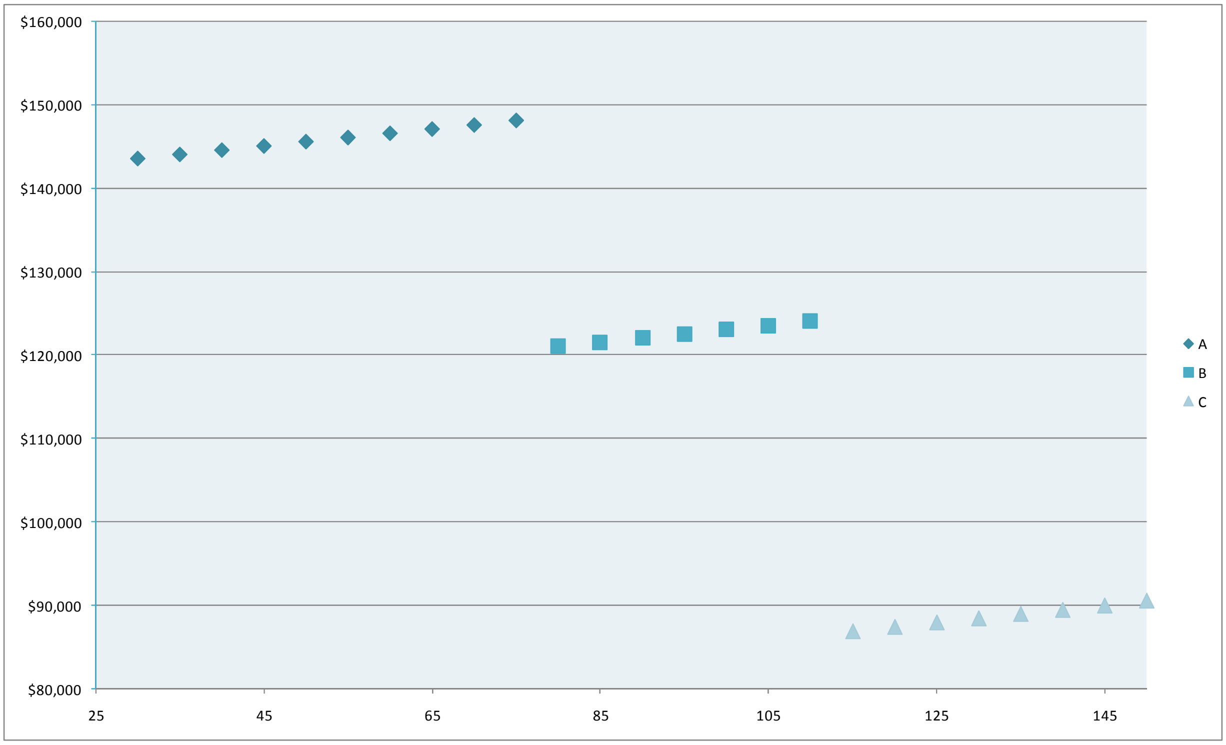


Figure 22: Number of Boreholes vs. Cost

Drill A: Depths Greater Than 325'

Calculated Length	# Boreholes	Length per bore	Actual Length	Drilling			Pipe Cost	Welding			Grouting Cost	Miscellaneous Cost	Total Cost
				Days	Rental Weeks	Cost		Number	Rental Days	Cost			
25,052	30	836	25,080	28	6	$101,760	$13,292	627	2	$3,096	$5,937	$19,500	$143,585
25,052	35	716	25,060	28	6	$101,760	$13,282	627	2	$3,093	$5,937	$20,000	$144,072
25,052	40	627	25,080	28	6	$101,760	$13,292	627	2	$3,096	$5,937	$20,500	$144,585
25,052	45	557	25,065	28	6	$101,760	$13,284	627	2	$3,094	$5,937	$21,000	$145,075
25,052	50	502	25,100	28	6	$101,760	$13,303	628	2	$3,098	$5,937	$21,500	$145,598
25,052	55	456	25,080	28	6	$101,760	$13,292	627	2	$3,096	$5,937	$22,000	$146,085
25,052	60	418	25,080	28	6	$101,760	$13,292	627	2	$3,096	$5,937	$22,500	$146,585
25,052	65	386	25,090	28	6	$101,760	$13,298	627	2	$3,097	$5,937	$23,000	$147,092
25,052	70	358	25,060	28	6	$101,760	$13,282	627	2	$3,093	$5,937	$23,500	$147,572
25,052	75	335	25,125	28	6	$101,760	$13,316	628	2	$3,101	$5,937	$24,000	$148,115

Table 39: Total Cost Data for Drilling Greater than 325 feet

Drill B: Depths Greater Between 225 and 325 feet

Calculated Length	# Boreholes	Length per bore	Actual Length	Drilling			Pipe Cost	Welding			Grouting Cost	Miscellaneous Cost	Total Cost
				Days	Rental Weeks	Cost		Number	Rental Days	Cost			
25,052	80	314	25,120	21	5	$74,200	$13,314	628	2	$3,101	$5,937	$24,500	$121,051
25,052	85	295	25,075	21	5	$74,200	$13,290	627	2	$3,095	$5,937	$25,000	$121,522
25,052	90	279	25,110	21	5	$74,200	$13,308	628	2	$3,099	$5,937	$25,500	$122,045
25,052	95	264	25,080	21	5	$74,200	$13,292	627	2	$3,096	$5,937	$26,000	$122,525
25,052	100	251	25,100	21	5	$74,200	$13,303	628	2	$3,098	$5,937	$26,500	$123,038
25,052	105	239	25,095	21	5	$74,200	$13,300	627	2	$3,098	$5,937	$27,000	$123,535
25,052	110	228	25,080	21	5	$74,200	$13,292	627	2	$3,096	$5,937	$27,500	$124,025

Table 40: Total Cost Data for Drilling Between 225 and 325 feet

Drill C: Depths Less than 225 feet

Calculated Length	# Boreholes	Length per bore	Actual Length	Drilling			Pipe Cost	Welding			Grouting Cost	Miscellaneous Cost	Total Cost
				Days	Rental Weeks	Cost		Number	Rental Days	Cost			
25,052	115	218	25,070	14	3	$36,570	$13,287	627	2	$3,095	$5,937	$28,000	$86,889
25,052	120	209	25,080	14	3	$36,570	$13,292	627	2	$3,096	$5,937	$28,500	$87,395
25,052	125	201	25,125	14	3	$36,570	$13,316	628	2	$3,101	$5,937	$29,000	$87,925
25,052	130	193	25,090	14	3	$36,570	$13,298	627	2	$3,097	$5,937	$29,500	$88,402
25,052	135	186	25,110	14	3	$36,570	$13,308	628	2	$3,099	$5,937	$30,000	$88,915
25,052	140	179	25,060	14	3	$36,570	$13,282	627	2	$3,093	$5,937	$30,500	$89,382
25,052	145	173	25,085	14	3	$36,570	$13,295	627	2	$3,096	$5,937	$31,000	$89,898
25,052	150	168	25,200	14	3	$36,570	$13,356	630	2	$3,111	$5,937	$31,500	$90,474
25,052	155	162	25,110	14	3	$36,570	$13,308	628	2	$3,099	$5,937	$32,000	$90,915
25,052	160	157	25,120	14	3	$36,570	$13,314	628	2	$3,101	$5,937	$32,500	$91,421
25,052	165	152	25,080	14	3	$36,570	$13,292	627	2	$3,096	$5,937	$33,000	$91,895
25,052	170	148	25,160	14	3	$36,570	$13,335	629	2	$3,106	$5,937	$33,500	$92,447
25,052	175	144	25,200	14	3	$36,570	$13,356	630	2	$3,111	$5,937	$34,000	$92,974
25,052	180	140	25,200	14	3	$36,570	$13,356	630	2	$3,111	$5,937	$34,500	$93,474
25,052	185	136	25,160	14	3	$36,570	$13,335	629	2	$3,106	$5,937	$35,000	$93,947
25,052	190	132	25,080	14	3	$36,570	$13,292	627	2	$3,096	$5,937	$35,500	$94,395
25,052	195	129	25,155	14	3	$36,570	$13,332	629	2	$3,105	$5,937	$36,000	$94,944
25,052	200	126	25,200	14	3	$36,570	$13,356	630	2	$3,111	$5,937	$36,500	$95,474
25,052	205	123	25,215	14	3	$36,570	$13,364	630	2	$3,112	$5,937	$37,000	$95,983
25,052	210	120	25,200	14	3	$36,570	$13,356	630	2	$3,111	$5,937	$37,500	$96,474
25,052	215	117	25,155	14	3	$36,570	$13,332	629	2	$3,105	$5,937	$38,000	$96,944
25,052	220	114	25,080	14	3	$36,570	$13,292	627	2	$3,096	$5,937	$38,500	$97,395
25,052	225	112	25,200	14	3	$36,570	$13,356	630	2	$3,111	$5,937	$39,000	$97,974
25,052	230	109	25,070	14	3	$36,570	$13,287	627	2	$3,095	$5,937	$39,500	$98,389
25,052	235	107	25,145	14	3	$36,570	$13,327	629	2	$3,104	$5,937	$40,000	$98,938
25,052	240	105	25,200	14	3	$36,570	$13,356	630	2	$3,111	$5,937	$40,500	$99,474
25,052	245	103	25,235	14	3	$36,570	$13,375	631	2	$3,115	$5,937	$41,000	$99,996
25,052	250	101	25,250	14	3	$36,570	$13,383	631	2	$3,117	$5,937	$41,500	$100,506
25,052	255	99	25,245	14	3	$36,570	$13,380	631	2	$3,116	$5,937	$42,000	$101,003
25,052	260	97	25,220	14	3	$36,570	$13,367	631	2	$3,113	$5,937	$42,500	$101,487

Table 41: Total Cost Data for Drilling Less Than 225 feet

The graph in Figure 22 shows that the optimum design condition occurs at 115 bores 218 feet each. There are many benefits to this result. First of all it is the least expensive combination to install. This combination also maximizes the daily output of that rig, which minimizes the impact of installation on the construction schedule.

Architecture Breadth

Architectural Goals

The goal for the redesign of the architecture is to reduce the amount of solar heat gain the building receives by exploring the use of solar shading devices.

Solar Shading Redesign

The orientation of the building results in higher solar heat gains in some spaces and lower gains in others. The Trane Trace room checksums page was used to analyze the orientations where solar shading would be most beneficial. The most critical solar heat gains occur in the classroom wing and are as 21% of the total cooling load. The orientation of interest is highlighted in Figure 23.

Figure 23: Focus of Solar Shading Design

A comparison of the effect of using a horizontal versus a vertical shading system will be the purpose of the analysis. Shading devices were programmed into Trane Trace to determine the energy savings each system produced for the three proposed systems. Several assumptions were made when programming the shades into Trace. These assumptions are listed below.

- Horizontal Shades
  The horizontal shading system was designed by expanding the entryway shading to cover the front façade of the building. A rendering of what this system might look like is included in Appendix B. The dimensions for the shading device are the same as what was designed and they extend 10 feet past the window.
- Vertical Shades
  The vertical fins took inspiration from the brick fin that separates the entryway from the classroom wing of the building. As seen in the rendering in Appendix B, the vertical shading system repeated this element along the length of the façade, protruding out 5 feet for exaggeration and shading. This system also produced a large energy savings, however since it doesn't protrude out so far would not have the same visual effect as the horizontal system.

Solar Shading Effect

- Horizontal Shades
  Figure 24 shows the energy cost savings for the implementation on this system. From the results it appears that shading the façade results in a significant energy savings. However, this system might be too visually obstructive. The shaded façade is along the main entrance of the building and the use of shades here would darken the façade and make it less appealing.

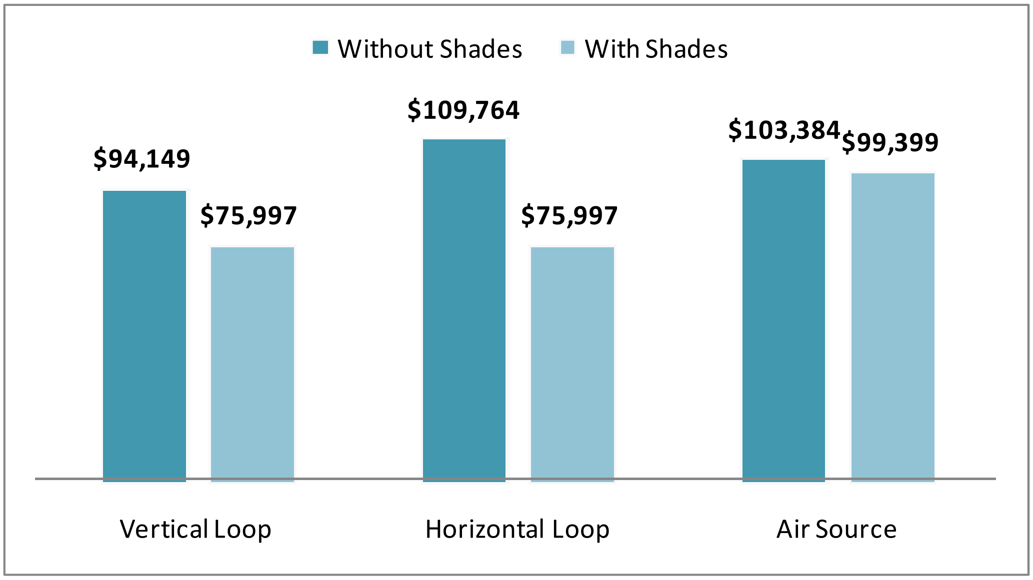


Figure 24: Energy Cost Savings with the use of Horizontal Shades.

- Vertical Shades

  Figure 25 shows the energy cost savings for the implementation on this system. From the results it appears that shading the façade results in a significant energy savings. This system also produced a large energy savings; however since it doesn't protrude out so far would not have the same visual effect as the horizontal system.

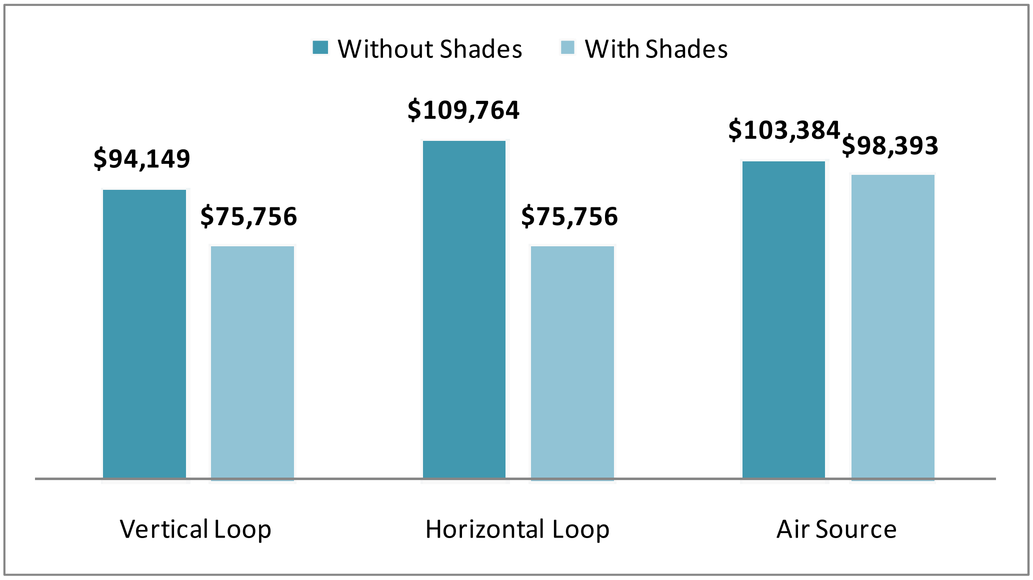


Figure 25: Energy Cost Savings with the use of Vertical Shades.

Vertical Ground Source Heat Pump

The total cost for this system includes the total cost of the heat pumps, the dedicated outdoor air units and the loop construction costs. The mechanical system designed by H.F. Lenz Company utilizes 5 rooftop air handling units with a total cost of $280,000 and 5 air cooled condensing units that cost a total of $12,000 resulting in a total system cost of $292,000 in equipment costs. The electricity and gas costs for this system total $112,893. The proposed system design is composed of 67 heat pumps which cost $420,050 total, 5 dedicated outdoor air units which cost $82,042 and the vertical loop which costs $86,889. The total system cost for the vertical loop ground source heat pump system is $588,981 and costs and additional $94,149 in utilities per year. The payback period for this system can be found by subtracting the designed system cost from the proposed system cost and dividing the result by the difference in operational cost. The payback period for the proposed system is 10.76 years.

This estimate is not entirely accurate since the decentralized heat pump system will use far less duct to distribute the air. Using R.S. Means, the decentralized heat pump system will require 108 pounds of sheet metal to distribute the air. At a cost of $10.30 per pound, the total cost of ductwork for the 67 heat pumps comes to $74,531. The total designed ductwork and insulation cost totaled $319,850. Incorporating these costs into the analysis, the system payback period becomes 1.2 years. This is an extremely good payback period.

Summary and Recommendations

The rooftop variable air volume system currently designed for Manoa Elementary School may at first seem like the most beneficial option for design, however further analysis has to be done to determine the performance of the system as well as the impact it has on the environment. Factors which sway most building owners to implement this type of system are its low first cost, minimal system maintenance and the limited amount of building floor area required to house the mechanical equipment. However, as shown in the analysis, this type of system consumes a significant amount of energy per year which not only cost the owner more capital but also releases more greenhouse gasses into the atmosphere facilitating global warming.

The designed system is in no way inadequate or fails to service the buildings needs, in fact, the designed system shows a 10% energy cost savings compared to the baseline system. The design engineers for this system were faced with a difficult challenge in designing a system that provided a comfortable environment to the occupants yet staying within the small budget.

This report researched and analyzed the performance of three different types of heat pump systems to determine the resulting energy savings of each system as well as analyzing what system components differ one type from the next.

Two different types of ground source heat pumps were analyzed: one that utilized a vertical loop for exchange with the ground and the other that utilized a horizontal loop. The purpose of researching these two systems were to determine how much energy savings they would have compared to the designed system and also to research the effect the type of loop has on the performance and cost of the building.

In conjunction with the two ground source heat pumps analyzed, an air source heat pump was also studied to determine what effect it has on a building as well as directly comparing the performance of this to the performance of the ground loop.

Results of this analysis demonstrated that although a vertical loop geothermal system has a higher first cost it significantly reduces the yearly operating cost and the greenhouse gas emissions. This is beneficial for the district for allocating tax dollars to help improve the district instead of maintaining their mechanical system. Therefore, it is my recommendation that the Haverford Township School Board meet with the residents of the neighborhood and discuss the possibility spending more money up front on the mechanical system would save them all money in the long run.

Credits and Acknowledgements

I would like to express my gratitude to all those who have aided me in my year-long research and development of Manoa Elementary School. The following people were extremely helpful:

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My fellow AE students who have helped keep my sanity this year

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Appendix A: Mechanical Equipment Schedules

Roof Top Air Handling Units

Symbol	Connected System CFM	OA CFM	CFM	Supply Fan Data				Return Fan Data				Exhaust Fan Data						Chilled Water Coil	Pre-Heat Hot Water Coil	Heat Hot Water Coil	Pre-Filter Data		Cartridge Filter Data	
				Drive	RPM	HP	VFD	Drive	RPM	HP	VFD	Symbol	CFM	Drive	RPM	HP	VFD	Total MBH	Total MBH	Total MBH	Efficiency %	MERV	Efficiency %	MERV
AHU-1	17,030	7,000	17,500	Belt	1,215	25	Yes	Belt	883	10	Yes	EF-6	1,500	Belt	1,339	0.5	No	859	633	N/A	30	8	85	13
AHU-2	21,175	8,000	20,500	Belt	1,033	30	Yes	Belt	590	10	Yes	EF-7 EF-13	2,200 1,000	Belt Belt	1,294 1,689	1 0.5	No No	978	725	N/A	30	8	85	13
AHU-3	13,020	5,300	13,500	Belt	1,280	25	Yes	Belt	881	7.5	Yes	EF-10 EF-11	1,850 310	Belt Belt	1,540 1,370	0.8 0.2	No No	662	525	N/A	30	8	85	13
AHU-4	8,000	3,000	8,000	Belt	1,860	20	No	N/a	N/A	N/A	N/A	EF-12	150	Belt	1,623	0.3	No	378	417	N/A	30	8	85	13
AHU-5	8,200	4,500	8,500	Belt	1,966	20	No	Belt	1,397	7.5	Yes	EF-8 EF-9	1,750 815	Belt Belt	1,510 2,350	1 0.5	No No	470	622	266	30	8	85	13

Air-Cooled Ductless Split Systm Units

ACCU Symbol	SSAHU Symbol	Supply @ High CFM	OA CFM	Net Cooling BTUh	ACCU Condenser Fan CFM		ACCU Compressor		System SEER	System EER
					High	Low	Type	LRA		
ACCU-1	SSAHU-1	726	0	18,600	1,000	830	Recip	48	10	9.6
ACCU-2	SSAHU-2	726	0	18,600	1,000	830	Recip	48	10	9.6
ACCU-3	SSAHU-3	726	0	18,600	1,000	830	Recip	48	10	9.6
ACCU-4	SSAHU-4	726	0	18,600	1,000	830	Recip	48	10	9.6
ACCU-5	SSAHU-5	726	0	18,600	1,000	830	Recip	48	10	9.6

Boilers

Symbol	Input MBH	Gross Output MBH	EWT ˚F	LWT ˚F	Boiler HP
BLR-1	2,668	2,103	150	180	62.8
BLR-2	2,668	2,103	150	180	62.8

Pumps

Pump No	Type	System	Operation	Max BHP	Motor HP	RPM	VFD	Operating Conditions		Impeller Diameter
P-1	Floor Mounted	HWS/R	Duty	13.6	15	1750	Yes	GPM	320	10.0"
								Feet Head	90	
								Efficiency	75	
P-2	Floor Mounted	HWS/R	Standby	13.6	15	1750	Yes	GPM	320	10.0"
								Feet Head	90	
								Efficiency	75	
P-3	In-Line	BLR-1	Duty	2.46	3	1750	No	GPM	210	6.5"
								Feet Head	30	
								Efficiency	71	
P-4	In-Line	BLR-2	Duty	2.46	3	1750	No	GPM	210	6.5"
								Feet Head	30	
								Efficiency	71	
P-5	Floor Mounted	CHS/R	Duty	18.2	20	1750	No	GPM	545	10.375"
								Feet Head	90	
								Efficiency	80	
P-6	Floor Mounted	CHS/R	Standby	18.2	20	1750	No	GPM	545	10.375"
								Feet Head	90	
								Efficiency	80	
P-7	In-Line	Domestic Hot Water Heater	Duty	0.98	1	1750	No	GPM	100	5.375"
								Feet Head	20	
								Efficiency	57	
P-8	In-Line	Domestic Hot Water Heater	Standby	0.98	1	1750	No	GPM	100	5.375"
								Feet Head	20	
								Efficiency	57	
P-9	In-Line	AHU-1 HWS/R	Duty	0.24	0.25	1725	No	GPM	35	4"
								Feet Head	12	
								Efficiency	51	
P-10	In-Line	AHU-2 HWS/R	Duty	0.2	0.25	1725	No	GPM	29	4.625"
								Feet Head	12	
								Efficiency	45	
P-11	In-Line	AHU-3 HWS/R	Duty	0.3	0.33	1725	No	GPM	35	4.375"
								Feet Head	15	
								Efficiency	52	
P-12	In-Line	AHU-4 HWS/R	Duty	0.19	0.25	1725	No	GPM	28	4.5"
								Feet Head	12	
								Efficiency	45	
P-13	In-Line	AHU-5 HWS/R	Duty	0.33	0.33	1725	No	GPM	42	5.25"
								Feet Head	15	
								Efficiency	54	

Appendix B: Architectural Renderings

Building: Architect's Rendering

Building: As Designed

Building: Horizontal Shading Design

Building: Vertical Shading Design