The *Gaige* Technology and Business Innovation Building
Penn State Berks, Reading PA

Geothermal Redesign of the Gaige Building

Final Report: Architectural Engineering Senior Thesis

THE PENNSYLVANIA STATE UNIVERSITY
SCHREYER HONORS COLLEGE

DEPARTMENT OF ARCHITECTURAL ENGINEERING

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A thesis submitted in partial fulfillment of the requirements for
a baccalaureate degree in Architectural Engineering
with honors in Architectural Engineering

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The *Gaige*

Technology and Business Innovation Building

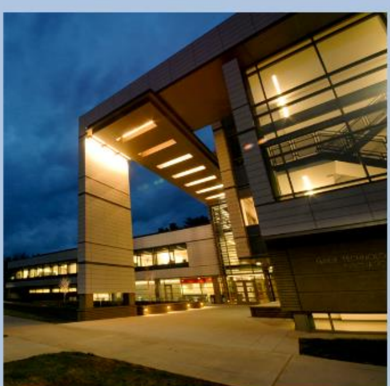
Matthew Neal, Mechanical Option

Penn State Berks Campus, Reading, PA

Penn State Berks, Owner | 64,036 SF (Gross) | Three Stories | $25.7 Million

Night, exterior cafe area

East looking shot of main entrance



Night, exterior canopy lighting

Project Team

Architect:	RMJM / Hillier	MEP:	H.F. Lenz Company
Structural:	Greenman-Pedersen Inc.	Civil:	Gannett Fleming Engineers
Acoustics:	Shen, Milsom, & Wilke	Lighting:	Illumination Arts, LLC
Construction:	Becker and Frondorf	CM:	Allen H. Butz Inc.

Building Systems

Architecture

Function:	Classroom, office, and laboratory building
Facade:	Metal framed curtain wall, terracotta panels
Layout:	Two main wings, with central hallway circulation
Efficiency:	Rainwater harvesting, heat recovery, high performance windows, and advance controls

Mechanical

Ventilation:	Three roof-top units, VAV, occupancy/CO2 sensors
Cooling:	Five air-cooled chillers for data/computer rooms
Heating:	Radiant heat & fin-tube heat exchangers, two 1300 MBH boilers

Lighting/ Electrical

Supply:	Building supply at 480/277 V with 208/120 transformer
Lighting:	Flourescent, some LED, HID, incandescent, and halogen
Controls:	Occupancy sensors and CO2 sensors in larger spaces

Structural

Foundation:	5" slab on grade, grade beams spanning micropiles
Superstructure:	Structural steelm contineous slab-composite decking
Lateral System:	Both X and eccentric braced frames using HSS

Construction

Construction:	From April 2010 through November 2011
Delivery:	Design - Bid - Build

CPEP: http://www.engr.psu.edu/ae/thesis/portfolios/2014/mtn5048/index.html

Abstract

The Gaige Building is located in Reading, PA on the Penn State Berks campus. It has a classroom, office, and lab type occupancy, and is LEED Gold certified. For my senior thesis project, I conducted an extensive analysis of the current design of the Gaige Building, and from that analysis developed several alternatives to potentially improve the current mechanical system in the building. A model of the Gaige Building was constructed in Trace 700, an hourly analysis energy modeling program, and the results from this model were validated against actual energy consumption data from the Gaige Building. Then, a newly designed geothermal system was implemented into the current design of the Gaige Building. Sizing requirements of the geothermal loops were determined for both vertical and horizontal loop designs, and another Trace 700 energy model implemented the new geothermal system. The success of the geothermal system was then evaluated by comparing the emissions from the original and geothermal model, along with a life-cycle costs analysis weighing the increased first costs of the geothermal system against the annual energy savings. Both the horizontal and vertical loop systems decreased annual pollutant emissions by roughly 2.0 %, and the horizontal and vertical loop systems had a discounted payback period of 6.13 and 12.7 years respectively. Another analysis was then performed to determine if implementing a campus wide geothermal system would be feasible. The well field was sized and designed for the campus system, and a block load energy model was created and validated with actual energy consumption data from utility billing information. The campus wide system was found to decrease annual emission by 27 %, but did not offer a reasonable payback period over the life of the system. Finally, an acoustical analysis of the Gaige Building was conducted, showing that the classrooms within the building are in accordance with the classroom acoustics standard, except for some poor transmission loss and standard transmission coefficient ratings for unsealed partitions on the second floor. Heat pump locations were also analyzed to determine a layout that would not negatively impact the background noise levels of the office and classroom spaces within the Gaige Building.

Table of Contents

List of Figures

List of Tables

Acknowledgements

I would first like to thank all of the AE faculty for their help for their interest in us as students and their help over these past five years. For this project specifically, I would like to thanks Professor Moses Ling, Dr. Stephen Treado, Dr. Richard Mistrick, and Dr. Michelle Vigeant. I have appreciate your input and guidance through the process, and the meetings I had with you helped me in the process of developing and writing this thesis. I would also like to personally thank Dr. Michelle Vigeant for coming to Penn State as well, for her advising and mentoring have and are still transforming my educational experience here at Penn State.

For their help on this project, I would like to personally thank Scott Mack, the mechanical engineer from H.F. Lenz who helped me secure this thesis building, and provided me with the information I requested on numerous occasions. Also, I would like to thank Kim Berry from Penn State Berks, for all of the accommodations he made in answering my questions and helping to set up a date to come to the side and take acoustical measurements. A special thanks to Aaron King and Cory Clippinger, who students who assisted me with the onsite acoustic measurements.

I'd also like to thank my family, Mom, Dad, Adam, Jessica, Caleb, Benjamin, and Andrew for always putting up with me. You all inspire me to work hard, not forget to rest, and you all have always been a needed constant in my life. I love you all, and the support you always show to me. Thanks as well to my many AE friends who have helped shape the past five years as well: to Sarah Bednarcik-my sister in AE and in Christ, to Faye Poon-you make every moment I spend with you interesting and unexpected, to Lara Kaiserian-my first AE friend, who I can' believe still puts up with me, Roooooooob Livorio-enough said, to Nick Dastalfo-you are an awesome brother in AE and an even more awesome brother in Christ, and many others I have not listed.

Finally, and most of all, I want to thank Jesus Christ, for the grace you showed me on the cross. You truly have changed my life by giving me life, and although I'm not ready to come yet, I can't wait to spend an eternity with you in heaven. But until then…

> *"Being confident of this, that he who began a good work in you will carry it on to completion until the day of Christ Jesus."* **– Philippians 1:6, NIV**

Final Report

Chapter 1: Executive Summary

This report is focused on analyzing the feasibility of implementing a geothermal system into the current design of the Gaige Building. First, a Trace 700 model of the Gaige Building is validated against actual utility consumption information. From this model and the peak loads that resulted, both a vertical loop and a horizontal loop geothermal system were sized and designed.

Figure 1: The Gaige Building

Once the geothermal loop systems were designed, initial costs for each system were calculated using RS Means costs estimating guides, and annual energy savings were estimated by comparing the previously validated model with a geothermal model of the Gaige Building in Trace 700. From this data, annual emissions were calculated and a life cycle cost estimate was performed. For the new geothermal system, a 2.0% reduction in annual emissions was realized, and for the horizontal and vertical geothermal systems, a discounted payback period of 6.13 and 12.7 years was found, respectively. An additional study was conducted to determine the potential of a campus-wide, centralized geothermal system into the design of the Gaige Building. A block load Trace 700 model was created, and annual energy savings, initial first costs, annual emission, and a payback period were calculated. Overall, the campus wide system caused a 27% decrease in annual emissions, but no feasible payback period was found.

Finally, an acoustic analysis of the performance of the classrooms within the Gaige Building against the classroom acoustics standard was performed. It met all of the standards requirements, except for standard transmission coefficient ratings for a few partitions between classrooms on the second floor. Also, an analysis to determine optimal heat pump placement around noise sensitive spaces such as classrooms and offices was conducted.

Chapter 2: Existing Conditions:

2.1: Building Overview and Background

The Gaige Technology and Business Innovation Building is a 64,000 SF building located in Reading, PA, on the Berks commonwealth campus of Penn State University. The Gaige Building is a host of many functions, but primarily, it is used as classroom, office, and lab space for the college's engineering, business, and hotel and restaurant management programs.

The Gaige Building is three stories tall, and it was constructed between April 2010 and November 2011. It was operated on a design-bid-build project delivery method, and had a full range of consulting services, from cost-estimating to A-V consulting. Functionally, the first floor contains classroom and lab spaces primarily, with a large area for studying and relaxing called the Learning Loft. Once you move to the second floor, you see the same classroom and lab emphasis, but a corridor on the east-west wing of the building provides a large amount of conference and office space.

Once you move to the third floor, the east-west wing of the building is capped off at two stories, but the north-sound wing continues up to three stories to accommodate one more classroom space and ample office and conference space. The exterior of the building consists of weather-resistant terracotta panel, metal framed exterior glazing and curtain wall systems, and precast concrete panels. Together, all of these building elements provide an aesthetically pleasing, but sealed and energy efficient building façade and enclosure. More information on the architecture of the building can be found in the building statistics report performed on the Gaige Building through this same thesis project.

2.2: Existing Mechanical System Overview

The Gaige Building has three main root top units (RTU-1, RTU-2, and RTU-3) that provide ventilation, conditioning, and exhaust for the majority of the spaces within the building's design. The units are sized to 20,500 CFM, 14,000 CFM, and 12,500 CFM respectively. Each of these units serve a variety of spaces within the first, second, and third floors of the building. Air is supplied from the roof top units at a supply temperature of 55 degrees, and it is ducted throughout the building.

At the individual spaces, variable air volume boxes are provided for each zone. The VAV box takes the 55 degree air, and varies the volume of air being supplied to the space to meet the cooling requirement of the space at the current time. The load is monitored by a thermostat located in each of the zones separately. CO2 and occupancy sensors also are coordinated with the VAV boxes to allow for a reduction in outside air required to be supplied to each space. A minimum set point prevents the VAV box from supplying air less than the minimum outside air requirement for the space. A reheat coil prevents from overcooling the space when providing minimum outside air at a time when cooling requirements are reduced.

Two 1300 MBH boilers provide the hot water service for the building and all mechanical heating requirements. Four split system air conditioners are required to provide individual space cooling for the telecom/data rooms in the building, and one computer room air conditioner is required for the IT storage and equipment room, also supplied with an air-cooled chiller. Unit heaters are provided throughout the building as needed in semi-heated spaces, such as the vestibules at the building entrances.

Finally, the heating loads for the building are met by radiant-heating panels and fin-tube heat exchangers placed at exterior walls of spaces that don't experience a year round cooling load. This allows for simultaneous heating and cooling throughout the building in spaces that contain these heating elements. Although it provides poor energy efficiency, the VAV boxes are equipped with reheat coils, so some heating in spaces without panes or fin-tubes could potentially have some heating capacity, but that is not the primary design intent.

2.3: Mechanical System Design Requirements

In this section of this report, an extensive analysis of the mechanical system of the Gaige Building, at Penn State's Berks Commonwealth Campus, is conducted. The design focuses and goals will be initially stated, and then, all aspects of the mechanical system within the Gaige Building will be discussed and analyzed. First, the objectives of the Gaige Building's design will be highlighted, as well as the energy sources that were present at the building's site. Then, the ventilation system of the building will be discussed. Finally, the heating and cooling loads for the building and the heating and cooling systems will be presented.

2.3.1: Design Objectives

One of the main focuses of the Gaige Building was the need for energy performance. As a Penn State Building, it was expected that The Gaige Building would underperform an ASHRAE Standards baseline building by at least 30%. This could be accomplished through the envelope construction of the building as well as the mechanical system used by the building. This need for energy efficiency led to a decision to incorporate very high performance windows and glazing into the façade of the building, a step towards the 30% reduction expectation. As well, the rooftop units for the Gaige Building are each equipped with energy recovery wheels that help to pre-heat outside air in the winter with exhaust air, or pre-cool in the summer.

As well, since the Gaige Building is simply a standalone classroom building, all of the heating and cooling systems are provided from boiler and air-cooled chillers on-site. As a result of the lower loads associated with this type and size of building, a centralized heating boiler plant is used, but all cooling required is provided by separate systems. Each rooftop unit is equipped with internal equipment that provides the necessary cooling, and the individual air-conditioning units are connected to air-cooled chillers that provide the cooling needed for each unit.

The final key design objective was water efficiency throughout the Gaige Building. To accomplish this goal, the Gaige Building incorporates a rainwater harvesting and storage system that provides for nearly 100% of the building's non-potable water usage.

Overall, the Gaige Building is designed to be a building that is a landmark for the Penn State Berks campus. It is a building unlike any other on campus. It acts as a showcase for students, a standard for the building community, and an educational tool for the Reading community. With its energy efficiency, water efficiency, and status in the area, it will be a landmark for much of the future to come. The Gaige Building, as it educates students at the Penn State Berks campus, will be long remembered.

2.3.2: Energy Sources and Rates

For the Gaige Building, the two sources of energy used in the mechanical system are natural gas and electricity. Natural gas is used primarily for the two boilers that provide the hot water for the heating coils in the rooftop units, auxiliary coils in the VAV units, and radiant and fin-tube heaters throughout the building. Electricity is the main utility used by the Gaige Building, and it is used for all internal building operations and cooling. All cooling units (the rooftop units and the air-cooled chillers) use electricity as their energy source. Below table one shows the energy rates that were provided by the mechanical engineers on the project for the energy analysis for the building. These rates were determined before the construction of the Gaige Building, so they do not reflect actual costs.

Energy Rates, Estimated		
Energy Source	Rate	Units
Electricity	0.0964	$/kWh
Natural Gas	15	$/MCF

Table 1: Energy rates used for the cost analysis for the Gaige Building, used in the Trace 700 analysis model and the HAP model from the design engineers

The electricity for the Gaige Building is provided by American Powernet, and PP & L is the company that bills for the distribution of the energy. Since these rates are approximate, energy bills for the Gaige Building's natural gas and electricity were sought out and have been provided by the COO at Penn State Berks. From the data given from Penn State Berks, new rates have been calculated below by averaging the rates on a monthly basis. The data used for the averaging ranges from September of 2011 to June of 2013 and is presented in table two below.

Energy Rates, Actual		
Energy Source	Rate	Units
Electricity	0.0940	$/kWh
Natural Gas	10.44	$/MCF

Table 2: Energy rates that have been calculated using data provided from actual energy bills for the Gaige Building from 2011 to 2013

As you can see, the rate for electricity was a very good approximation, which is to be expected. The natural gas price has shown to be a much lower rate than was expected during the design of the Gaige Building. When the building was originally modeled, prior to 2009, the rates for natural gas were much higher, around the $15/MCF prediction. Since then, the rates have dropped to the new prediction, and even into the $9.00/MCF range. With this new data, updates will be made to the energy model, to further validate the cost data for the Gaige Building, and verify results with the actual energy bills from the Gaige Building.

2.3.3: Design Conditions

In the following two sections, the design conditions associated with the Gaige Building will be discussed. These design conditions reflect both the actual design conditions from the Gaige Building and the values used during the prior and current modeling of the building. First, the indoor design conditions will be presented, and then the outdoor extreme design day data will be given.

2.3.3.1: Indoor Design Conditions

The Gaige Building, being like any modern building, is equipped with individual thermostats to control the space temperatures within the building. Each thermostat logically controls the variable air boxes that adjust the amount of air that is delivered to each space. On the next page, table three summarizes the set points for the different types of spaces within the Gaige Building, depending both on space type and season (cooling/heating values).

Design Set Point for the Gaige Building			
Space Type	Temperature (°F)		Humidity
	Cooling	Heating	
Conditioned Spaces			
Set Point (occupied)	75	70	50%
Drift Point (unoccupied)	85	60	50%
Heating/Ventilation Spaces			
Set Point	110	70	50%
Drift Point	110	60	50%

Table 3: Design set points for the Gaige Building for different spatial types and seasons

2.3.3.2: Outdoor Design Conditions

The Gaige Building is located in Reading, PA, so design values for this site are taken from the ASHRAE 2009 Handbook of Fundamentals. In the model created by the design engineers, which was done only in Carrier HAP, the location of the building was set to Harrisburg, PA. After looking in the ASHRAE Handbook of Fundamentals, it is noted that the Spaatz Field, a local airfield serving Reading PA, has such provided data. Since Spaatz Field is located less than two miles from this project's site, data for it is used in further analysis of the Gaige Building, using the location overrides available in Trace 700. For the final model's analysis of the Gaige Building, Spaatz airfield is used for the weather data instead of Harrisburg, PA.

Weather Inputs-Harrisburg, PA		
Heating	Cooling Data	
DB: 99.6%	DB: 0.4%	WB: 0.4%
8.7 °F	92.4 °F	73.8 °F

Table 4: Data used for the weather design conditions from the design of the Gaige Building, and in previous Technical Assignments

Weather Inputs-Reading, PA-Spaatz Field		
Heating	Cooling Data	
DB: 99.6%	DB: 0.4%	WB: 0.4%
9.4 °F	92.4 °F	74.1 °F

Table 5: Weather data that is used in the final modeling of the Gaige building in this report

2.3.4: Ventilation Requirements

For the Gaige Building, ASHRAE Standard 62.1 was followed to meet ventilation requirements for the building. Not only did Penn State require compliance with this ASHRAE standard, the LEED rating system for new construction also required that the Gaige Building meet ASHRAE requirements to achieve a LEED Gold rating. The Gaige Building is a mix of laboratory, office, and classroom spaces, along with the general required support spaces for any educational building. Previously, in Technical Report One, the Gaige Building's design ventilation values were compared with hand calculations performed using values from ASHRAE Standard 62.1.

One issue identified from the previous analysis was a slight procedural difference between the calculation methods used by H. F. Lenz Company, the mechanical engineers on the project, and my analysis of the ventilation requirements of the building in Technical Report One. H. F. Lenz's calculation used appendix A of Standard 62.1 to calculate all E_v values, and those changes resulted in higher E_v values, and therefore, a lower requirement for indoor air intake. This difference created lower required ventilation values, and resulted in what looks like and underperformance from the building's ventilation system. After further reviewing the Appendix A method of calculating ventilation requirements, a re-evaluation of the Gaige Building's compliance with ASHRAE Standard 62.1 was conducted. For this evaluation, E_v was calculated according to methods laid out in appendix A of ASHRAE standard 62.1, and table six below summarizes this new analysis.

Ventilation Calculation Summary: Appendix A Method			
Unit	Required V_{ot}	Design V_{ot}	Comply?
RTU-1	9367	9020	**No**
RTU-2	5514	5040	**No**
RTU-3	1699	4375	**Yes**

Table 6: Summary of the ventilation calculations performed for the Gaige Building's three RTU's

Although the Gaige Building is still not compliant with the newly calculated requirements, the results are much more reasonable and on much more of a comparable scale than before. The value for E_p, the fraction of primary air to discharge air in the ventilation zone, was assumed to be 1.0 in this calculation, which resulted in F_a, F_b, and F_c to have the value of 1.0 as well. Despite the system's underperformance, the required changes would be very minimal to compensate for the differences. The differences, because of their small relative size, are probably due to different area measurements or some other similar deviation.

2.3.5: Heating and Cooling Loads

Heating and cooling loads were calculated for the Gaige Building using a Trace 700 model, and the results were compared in Technical Report Two with a Carrier HAP model that was created during the design of the Gaige Building. This model was created for design purposes, and it was used to demonstrate that the Gaige Building met requirements set forth in the LEED rating system for new construction. Below, tables seven and eight summarize the calculated heating and cooling loads for the Gaige Building, and then table eight makes a comparison between the Trace 700 model and the Carrier HAP model from the building's design.

Calculated Design Results					
Unit	Service Area (SF)	Cooling (CFM/ton)	Heating (BTU/hr-SF)	Total Supply (CFM/SF)	Ventilation Supply (CFM/SF)
Calculated					
RTU-1	20033	360	46.0	1.4	0.43
RTU-2	13670	361.34	33.7	1.0	0.37
RTU-3	12500	305	31.9	0.8	0.15
AHU-1	102	585.8	23.4	1.1	n/a
AHU-2	75	586	23.4	1.1	n/a
AHU-3	95	508	35.5	1.5	n/a
AHU-4	51	500	24.0	1.1	n/a
CRAC-1	325	523.6	31.6	1.4	n/a
Heat/Vent	4608	n/a	n/a	n/a	n/a
Total	**51459**				**0.30**

Table 7: A summary of the loads calculated from the Trace 700 Model in Technical Report Two

Comparison of Calculated and Design Results					
Unit	Service Area (SF)	Total Supply (CFM/SF)		Ventilation Supply (CFM/SF)	
		Design	Difference (CFM/SF)	Design	Difference (CFM/SF)
RTU-1	20033	1.1	0.3	0.46	-0.03
RTU-2	13670	0.9	0.1	0.38	-0.01
RTU-3	12500	0.8	0.0	0.28	-0.12
AHU-1	102	1.0	0.1	n/a	n/a
AHU-2	75	1.5	-0.4	n/a	n/a
AHU-3	95	1.5	0.0	n/a	n/a
AHU-4	51	1.9	-0.8	n/a	n/a
Total	**51459**			**0.35**	

Table 8: A comparison of the loads calculated from the Trace 700 model and the Carrier HAP model from the design engineers

The heating for the Gaige Building is provided by two gas-fired 1300 MBH boilers. Both boilers are piped in parallel, and two variable speed pumps control the overall supply to the building system. For the cooling of the Gaige Building, each unit provides its own cooling demand with internal cooling equipment or with a separate air-cooled chiller. For the three rooftop units, all were in good agreement with the calculations from the engineers. Only RTU-3 significantly underestimates the ventilation supply of a CFM/SF basis.

2.3.6: Annual Energy Use

To estimate the annual energy use of the Gaige Building, a model was created in Trace 700, an hourly analysis program that simulates building loads and conditions throughout the year. Below, table nine summarizes the results from this analysis. As well, these results are compared to a Carrier HAP model that was created by the mechanical engineers on the project, from H. F. Lenz Company. The Carrier HAP model was used to design the mechanical system and to demonstrate compliance in the LEED certification process. Below, Figure two shows the overall breakdown of energy usage in the Gaige Building.

Building Energy Usage Breakdown			
Type	Load (kBTU/yr)		% Difference
	Designed	Modeled	
Heating	1867073	1017367	-46%
Cooling	236739	465831	97%
Air System Fans	156909	229301	46%
Pumps	44954	28037	-38%
Lights	480901	519662	8%
Electrical Equipment/ Receptacles	1839097	1727367	-6%
Misc. Fuel	113292	272740	141%
Total:	**4738965**	**4260306**	**-10%**

Table 9: A comparison of the annual energy usage calculated from the Trace 700 model and the Carrier HAP Model

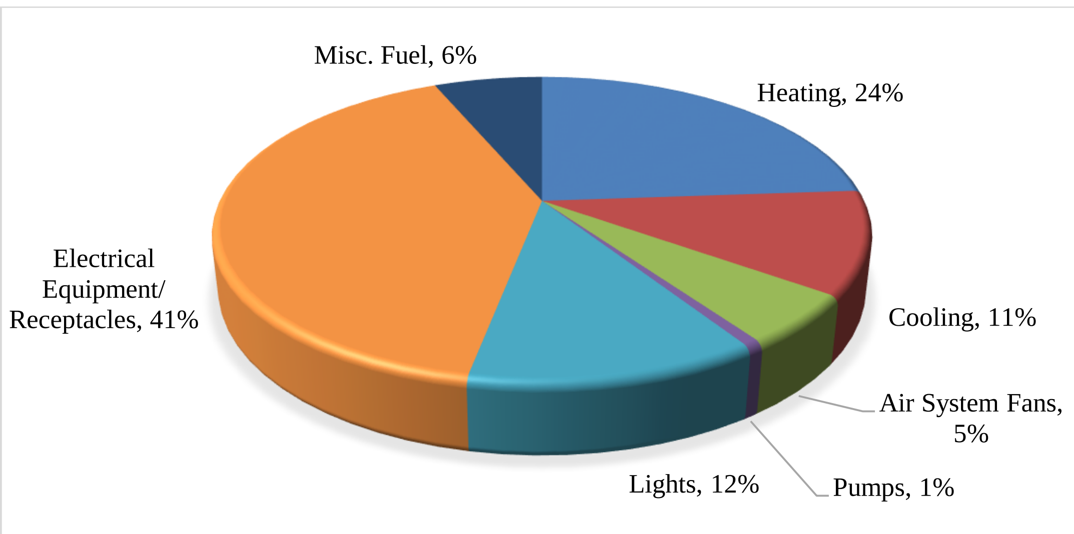


Figure 2: Annual energy distribution as calculated by the Trace 700 model used for the energy estimation of the building

Looking at the results, the overall analysis performed very well, coming in with only a 10% difference between the models. Despite the fact that this difference is a seemingly good result, with further study of the individual differences in the various categories of loads, more difference is found. By analyzing the results, you can see that while the heating of the Gaige Building is under predicted when comparing Trace 700 to Carrier HAP, the cooling is drastically over predicted. These two errors will tend to cancel each other out, and hide some amount of difference between the models.

To further analyze this model, this analysis could be significantly improved by creating a validated model, incorporating actual billing information from the Gaige Building. The COO at Penn State Berks was contacted, and below the energy consumption information is provided for the Gaige Building. First, in Figure three, the overall utility cost for the Gaige Building for the past year is given. Then, both natural gas and electricity are shown separately in the Figures four and five below:

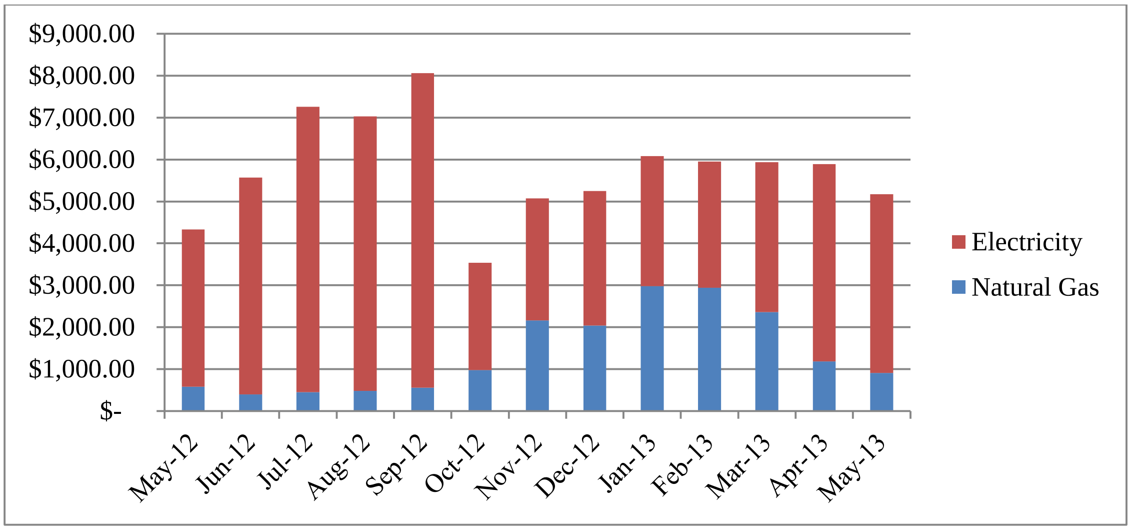


Figure 3: Actual utility costs for the Gaige Building from May 2012 to May 2013

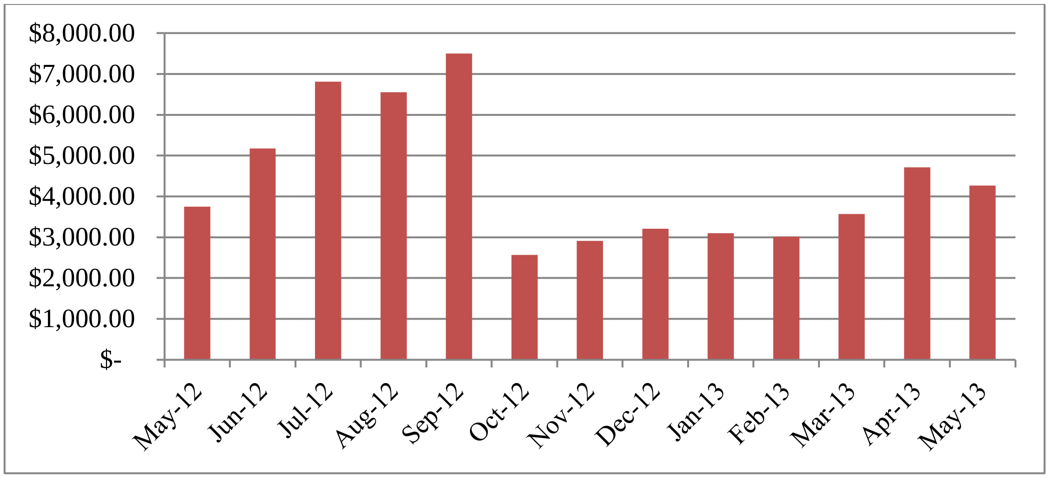


Figure 4: Actual electricity costs for the Gaige Building from May 2012 to May 2013

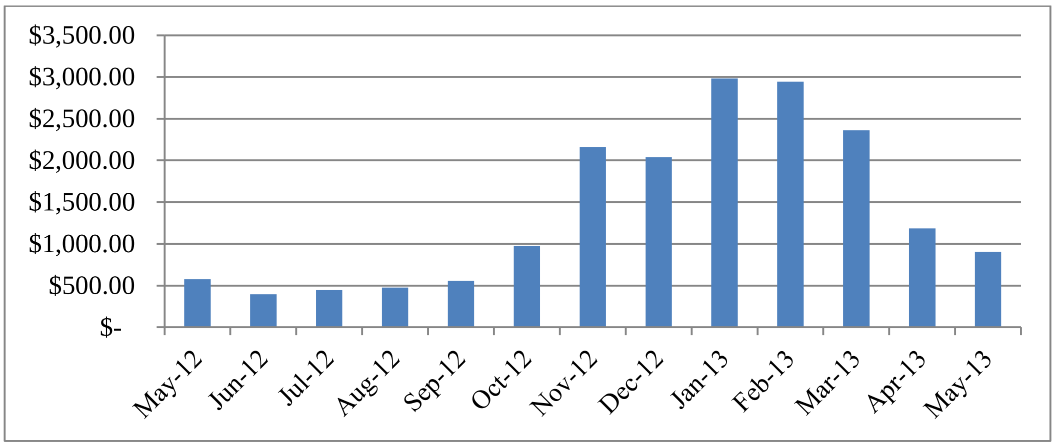


Figure 5: Actual natural gas utility costs for the Gaige Building from May 2012 to May 2013

2.4: Design Load Estimation

The first goal of goal of analysis the Gaige Building's mechanical system was to create a model that accurately estimated the design loads for the Gaige Building. For this report, Trace 700 was selected to perform the design load analysis. H.F. Lenz Company, the MEP firm that worked on the project, used Carrier HAP for the calculation of their design loads. Both programs have subtle differences in their calculation methods, but overall, they both produce accurate and reliable results. Below, the approach to the Trace 700 model will be outlined, as well as all of the assumptions that were used in making the model. These design assumptions outline what data inputs were used to create the model, like schedules, occupancies, ventilation rates, wall constructions, glazing performance, weather information, and lighting and electrical equipment rates. These assumptions will also describe from where the design assumptions were taken. The, with the design assumptions outlined, the two models' results will be compared to check the repeatability of the design results. Finally, the model created was validated to the actual building utility data received from the COO of Penn State Berks.

2.4.1: Model Design Approach

In Trace 700, the model designer is allowed to use various tools to help improve the accuracy and reliability of your results, and to help you decrease the amount of time required to create a reliable model. For the model used in this report, first, templates were created for each space type. The various spaces within the Gaige Building included classroom spaces, laboratory spaces, office spaces, lobby spaces, lounge spaces, one kitchen and dining space, and other basic building support spaces. Templates for each of these room types were made to be applied to individual rooms that controlled the lighting power wattage values, thermostat requirements, occupancy data, and much more.

Once these 'templates' were created, then each individual room was modeled in Trace 700. To do this, each room was created assigned a floor area. Then, all other parameters, outlined below, were added to each room specifically or to each room type from the assigned templates. Once all the rooms were defined, airside equipment was created using the create system function within trace. For the systems, the model for this report contained three roof top units that were assigned the system type "VAV with Baseboard Skin Heating", four air conditioning units assigned the system type "Fan Coil", and one computer room air conditioner assigned to the "Computer Room Unit" system type.

As well, all of the spaces that did not require strict temperature set points were assigned to a system entitled heating/ventilation only, known in Trace 700 as "Ventilation and Heating". Once all of the systems had been created, plants for the energy production were created. For heating, a plant was created with the two gas-fired boilers specified in the design documents. For cooling, each roof top unit was assigned to a separate unitary air side cooling plant, since the cooling equipment is contained in each roof top unit separately. For the four single zone air conditioning units and the computer room air conditioner, each system was assigned to a separate air-cooled chiller. All cooling equipment was assigned to the electric utility and heating was assigned to the gas utility.

2.4.2: System Design Assumptions

The following sections outline how the building was modeled, what data was used for the system inputs as far as internal loads are concerned, and where the data was obtained from. Many of the design assumptions were pulled directly from the model created by H.F. Lenz, for this report aims to recreate accurately the actual model used to design the building. As a starting point, the Trace 700 model was desired to roughly match the Carrier HAP model created by the project engineers. Another analysis will validate the model with actual building utility data, but as a starting point, references from the HPA model are used. It will be discussed where variations between what was designed and what was modeled in Carrier HAP were discovered, and how those variations were addressed.

2.4.2.1: Design Condition Assumptions

For the Gaige Building, standard values were used for space thermostat set points. All occupied spaces were set to values specified in table one below. This space type constitutes the majority of the building, but spaces that only require heating and ventilation were designed at differing thermostat set points. The set points for the Gaige building, and the chosen set points for this model, can be seen previously in table three.

2.4.2.2: Occupancy Assumptions

For the Gaige Building, in order to recreate the best match between the model created by H.F. Lenz Company and the model created for this report, values were chosen based upon the design values found in both the design documentation of the Gaige Building and the model created by H.F. Lenz Company. Although values could be calculated on an occupancy per 1000 SF basis from ASHRAE recommendations, since design occupancies were available, they were used.

2.4.2.3: Ventilation Assumptions

For the ventilation rates in the model, rates were obtained from the design documents from H.F. Lenz Company. Although ventilation rates were calculated from the previous assignment, technical report one, it is the goal of this assignment to best recreate a model for the building, as designed. Because of this, the preloaded ASHRAE standards template values within Trace 700 were not used, and individual ventilation supply rates were input on a space by space basis.

2.4.2.4: Building Infiltration Assumptions

As per recommendation by the mechanical engineer from H.F. Lenz who worked on the project, 0.3 air changes per hour was used as the infiltration to all spaces within in the Gaige Building. This value was selected based upon the fact that the Gaige Building is designed to be positively pressurized, and it is of at least average construction quality. Since the building's façade has been given much thought, shown by its LEED Gold status, the building could probably be considered of a higher quality construction, and a lower value for infiltration could have been used. Since 0.3 air changes per hour was used in H.F. Lenz's model in Carrier HAP, that value was also adopted for the Trace 700 model created for this report.

2.4.2.5: Lighting and Equipment Assumptions

In the Trace 700 model, the constant value of 1.2 Watts/SF is used for the lighting load throughout the building. In the actual design of the building, this is not the value, but this value was the one assumed for the model created by H.F. Lenz in Carrier HAP. For consistency of results and for comparison's sake, 1.2 W/SF was used in the model, but the validation of this model, and for comparison of benefits due to design changes, the building's model will be updated to match actual utility bill information that has been received.

For the equipment loads in the Gaige Building, below, table ten summarizes the assumed loads on a Watt/SF basis, varied by spatial type. These values are generally accepted values for each spatial type, and were used in the previous Carrier HAP model for the building. By using the same values, more consistency can be ensured in the comparison of the results between the

Carrier HAP model and the Trace 700 model. As well, the model provided by H.F. Lenz contained various 'miscellaneous loads' for specific equipment used throughout the building. The type of loads and values for these loads are provided below in table eleven as well.

Electrical Equipment Loads	
Space Type	Load (W/SF)
Server Room	3
Telecom/Data Room	5
Mechanical Room	2
Laboratory	2.5
Shipping/Receiving	1
Office Space	2
Classroom	2
Electrical Room	2
Kitchen Area	500 W
Computer Lab	2.5

Table 10: Electrical equipment loads used in the model on a W/SF basis, with the exception of the kitchen area

Miscellaneous Building Loads		
Space Type	Load	Utility Type
Kitchen Hood Fan	44.8 kW	Electric
Kitchen Refrigeration	8 kW	Electric
Kitchen Hood Heating	515 MBH	Gas
Kitchen Equipment	534 MBH	Gas
Exterior Lighting	4 kW	Electric
Greywater Pumping	6.3 kW	Electric
Shop Compressor	11.6 kW	Electric
Domestic Hot Water	9.2 kW	Electric
Elevator	33 kW	Electric

Table 11: Miscellaneous electrical loads found throughout the building, provided H.F. Lenz Company

2.4.2.6: Construction Type Assumptions

In the Trace 700 model for the Gaige Building for this report, and for the model created by H.F. Lenz in Carrier HAP, average construction values were used for each building element. For the wall construction, all walls are designed to a relatively similar total construction U-value, and an average value was assumed for the energy model. For window and skylight construction, one type of glazing was used throughout the entirety of the building, so the U-value and SHGC value are accurate, and used for all glazing in the model.

For door construction, glass doors are assumed to have the same values as the window construction, and solid doors are provided with another design U-value and solar heat gain coefficient. Other door types with differing U-values, like the shipping/receiving garage door, are altered on an instance by instance basis. Finally, Floors that are slab-on-grade are modeled using an insulation value for perimeter type heat losses, and roofs are assumed to have a constant U-value throughout the Gaige Building's construction. Below, table twelve summarizes the values used for these various construction types in the model of the Gaige Building.

Building Construction Types	
Building Element	Thermal Value(s)
Exterior Wall	U-0.0714
Glazing	U-0.26, SHGC = 0.3
Opaque Door	U-0.167, SHGC = 0.4
Slab on Grade Floor	U-0.0714
Roof	U-0.041

Table 12: Thermal resistance values for different construction types used in the Gaige Building

2.4.2.7: Weather Information Assumptions

For the model created in Carrier HAP, the weather data used was from Harrisburg, PA, for that is the location used in the Carrier HAP model of the building. The location with weather data provided by ASHRAE that is closest to the building site is for the Carl A. Spaatz Airfield, at the Reading Regional Airport. This data is available in the ASHRAE 2009 Handbook of Fundamentals, I-P Edition. After section 14.17 in the Handbook of Fundamentals, the Appendix containing design condition for selected locations contained weather data for this location.

This data is the best possible data available, for the airfield is less than two miles as the bird flies from the Gaige Building. Despite this data being available, since the data was not preloaded into

Carrier HAP, Harrisburg, PA was used for the previous design of the building by H.F. Lenz. For my future models, the design overrides option in Trace 700 will be used to specify the design criterion used for the Gaige Building. The data used in the following mechanical depth analysis incorporated the weather data for Spaatz Airfield, show previously in table three.

2.4.2.8: Schedule Assumptions

When the original model of the Gaige Building was created by H.F. Lenz, various custom schedules were made for use in the Carrier HAP model. Schedules that were assigned are provided in Appendix J. The schedules given for nighttime, compressor, greywater pumping, and kitchen hoods are all used for the miscellaneous loads specified in the Carrier HAP model for the Gaige Building. These are utilization schedules that control the operation of the equipment. Other than that, the "All-Classroom" schedule is the main schedule used for the Gaige Building for the operation of all people, lighting, and ventilation, apart from a separate people and lighting schedule provided for the Office Spaces. As well, and Office miscellaneous load schedule is provided for office equipment operation. Again, all of these schedules can be seen in Appendix J of this report.

2.4.3: Model Comparison with Utility Data

Once this new data was obtained, first, new cost factors were input into the previous Trace 700 model. The new natural gas and electricity costs were taken to be the average of the costs from the past year of data, and then the annual energy costs were estimated. Below, in table 13, the modeled results with the updated utility costs are compared to the actual charges from the Gaige building bills from June 2012 to May 2013.

Annual Energy Cost Information		
Modeled (Trace 700)		
Natural Gas	$	23,396.00
Electricity	$	85,404.00
Actual Cost from Billing		
Natural Gas	$	17,431.31
Electricity	$	53,390.19

Table 13: Annual energy costs for both the Trace 700 model and actual data from the Gaige Building

As it can be seen in table 13 above, the natural gas ends up being a very reasonable approximation, but the electricity consumption is over predicted. Knowing that the major electrical loads are due to cooling equipment and receptacle loads, a plot showing the electrical demand per month was made to determine where the shortcoming occurred. By showing both modeled and actual demand on a monthly basis, it can be seen whether this short coming is seen in the summer months, when cooling is needed, or if it is a consistent year round under prediction, which would be due to an error in receptacle loads most likely. This evaluation is shown below in Figure six. Also, the same comparison is given for natural gas consumption in Figure seven.

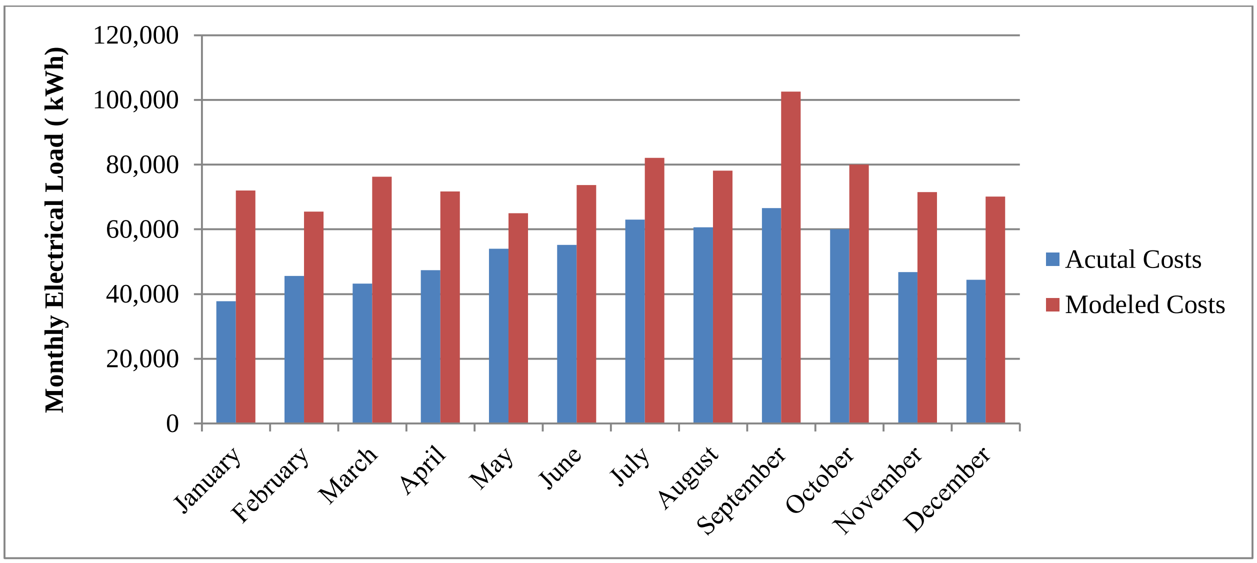


Figure 6: Actual vs. Modeled electricity consumption on a monthly basis

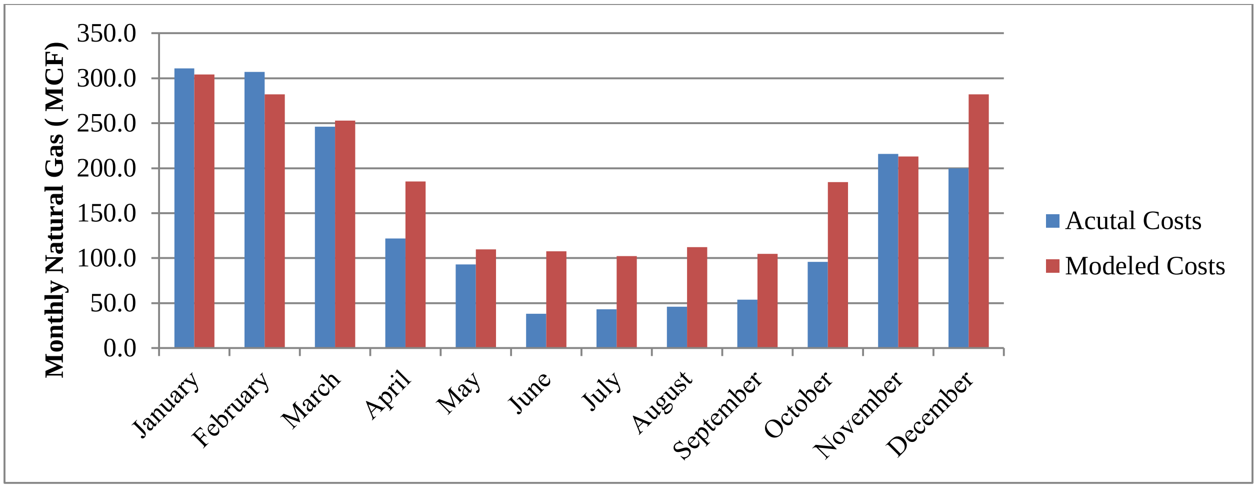


Figure 7: Actual vs. Modeled natural gas consumption on a monthly basis

After this comparison, it is clear that some of the over prediction of the natural gas consumption is probably due to a load that is present during the summer months of June, July, and August that should not be present. The main take away from this analysis is the difference in the electrical loads. It seems that the electrical load overestimation is mainly due to an overestimation of receptacle like loads. It can be seen that the most difference is found during the months from November through March, where the receptacle loads will dominate the electricity consumption since cooling is not as high during the summer months.

2.4.4: Model Validation

Now since the major points of deviation between the model of the Gaige Building and the actual utility data from the Gaige Building have been identified, the model can be adjusted and validated to physically relevant data. To adjust to model and validate it to match the results taken from the utility data received for the Gaige Building, first the electrical loads in the building were considered. Analyzing the difference between the modeled results and the utility information shown previously in Figure six, it can be seen that the overestimation of the electrical loads in the Gaige Building occurs year round. This points to the fact that the overestimation should mainly be from year round electrical load, such as the modeled receptacle and miscellaneous loads, as opposed to a seasonal loads, such as electrical costs from cooling.

To adjust for these load differences, the main building receptacle loads were reduced by reducing the overall electrical loads on a Watts per square foot basis, consistently throughout the building. The reduction in the internal electrical loads for the building was adjusted so that the electricity consumption data in the fall, spring, and winter months roughly matched the Gaige Building's consumption. Once the electricity was validated to the non-summer months, an overestimation of the electrical loads still remained in only the summer months of May, June, July, and August. This overestimation pointed to an overestimation of the cooling load, which would cause this increase in the summer months. To account for this change, the internal lighting loads were also adjusted on a Watts per square foot basis to validate the cooling loads in the building to the actual building utility data for the summer months. Once these adjustments had been made, the results of the comparison between the utility data and the model only deviated by 2.05 % annually. Below, shown in Figure eight is a comparison of the actual consumption of electricity for the Gaige Building with the validated model electricity consumption data.

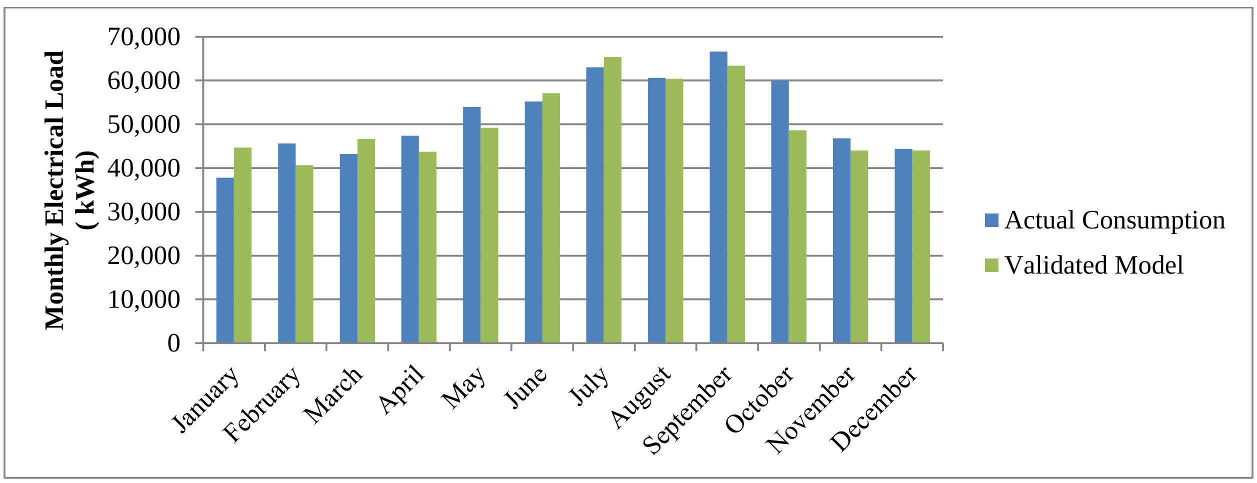


Figure 8: Comparison of actual monthly electricity consumption with results from the validated Trace 700 model

Once the electrical loads for the Gaige Building had been validated, the same process was done using the modeled and actual natural gas consumption data. As previously shown in Figure seven, the natural gas consumption data seemed to be fairly accurate in the winter months, when peak usage occurred, but during the summer months, there was a severe overestimation. Since this overestimation occurred outside of the heating season for the building, some of the year round natural gas loads, such as consumption loads from the kitchen, were adjusted to validate the summer usage predicted in the model with the actual usage data. Once this was done, the heating loads then demonstrated a slight underestimation of usage, so building heating sources were adjusted to validate the model as well with the utility data. Once this analysis was complete, the natural gas consumption data was found to differ with the utility data by only 0.65% annually. A comparison of monthly natural gas usage between the validated model and the utility data can be seen below in Figure nine. Also, the results we compared on a cost basis, using the monthly and annual costs with natural gas and electricity combined into one bill. The energy rates that were presented in table two were used in this model to predict monthly and annual utility costs, which are based upon an annual average from the utility bills. Once compared, only a 1.2% difference was found in annual natural gas costs and a 3.7% difference was found in annual electricity costs.

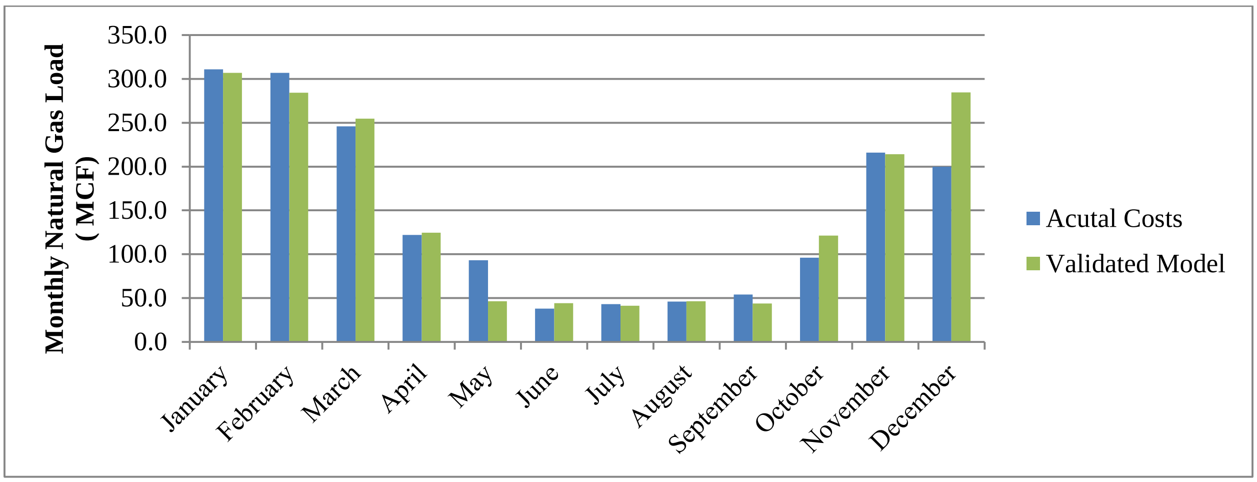


Figure 9: A comparison between the utility data for natural gas usage in the Gaige Building and the validated building model.

2.5: Existing Annual Costs, Energy Consumption, and Emissions

With a validated model of the Gaige Building, now a baseline can be set to which we can compare other design options that will be explored in the mechanical depth for the Gaige Building. To do so, we must consider the various impacts of the Gaige Building's energy use beyond annual energy costs. We can also consider how much energy would have been required to produce the energy and transport it to the Gaige Building from the energy's source. This is done below by considered site energy versus source energy consumption. Finally, we can also consider the environmental impact of our building by calculating the total annual emission rates that will be a result of the energy consumption of the building.

2.5.1: Annual Energy Costs

From the validated model of the Gaige Building, we can calculate the annual energy costs for the Gaige Building for both its electricity and natural gas sources. Using the validated Trace 700 model of the Gaige Building, with the energy rate structures from table two, the following Figures show the annual costs for the Gaige Building. Figure ten shows both the monthly electricity and natural gas costs below. These will be the values used to help evaluate annual cost savings for other design alternatives proposed in the mechanical depth. Also, table fourteen below summarizes the totals for the annual electricity and natural gas costs to be used in calculating annual energy savings in comparative analyses. For simplicity, the year-round, constant miscellaneous electrical and natural gas loads have now been removed from the analysis model. Since all of the alternative comparisons will be done using differences in annual costs, or annual energy savings, the removal of these constant loads will have no effect on overall results.

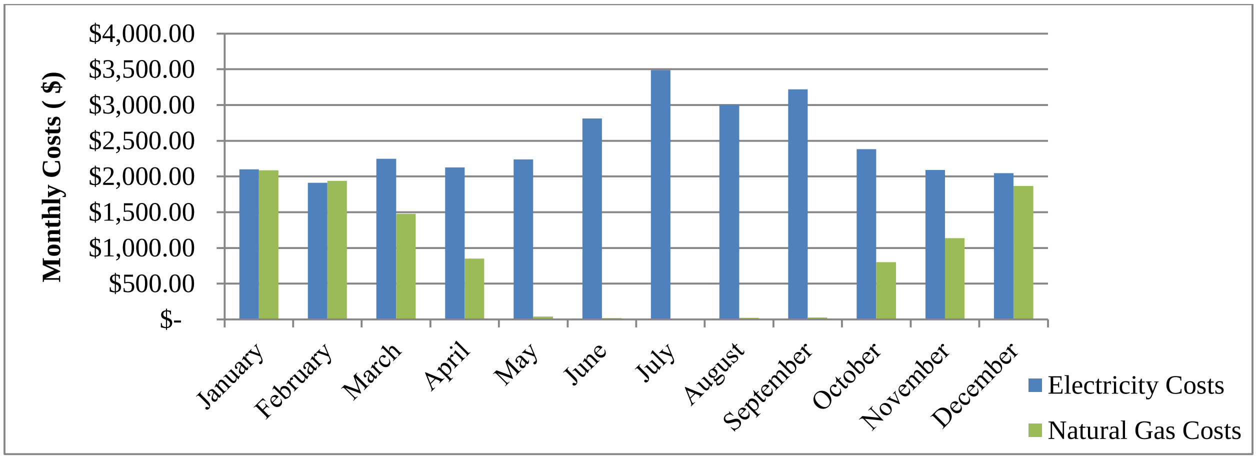


Figure 10: The monthly energy costs for the Gaige Building for electricity and natural gas. Calculated from the validated model of the building in Trace 700

Also, below table fourteen summarizes the annual energy cost values that will be used for future comparative analyses proposed in the mechanical depth assessment.

Annual Energy Costs	
Natural Gas ($)	Electricity ($)
$ 10,282.00	$ 29,673.00

Table 14: A summary of the annual energy costs in the validated model of the Gaige Building, to be compared with other analyses in the mechanical depth

2.5.2: Site versus Source Energy Comparison

Another issue that should be noted is the difference between site and source energy. Although the Gaige Building will use a certain amount of energy which is supplied to the building on an annual basis, the environmental impact of that energy usage is still not clear. Even though energy sources can be equated on a consumption basis, you must consider how much energy is lost in the processes of production and transportation of that energy to the building site. In the Gaige Building, although natural gas does not have significant losses associated with transportation to the site, electricity does have such losses. Much electricity is lost due to its transportation over many miles before it reaches the building. To account for this, from requirements given from the mechanical engineer on the project, a 28% factor was applied to account for the total amount of energy it took at the source of production to deliver the required site energy to the building.

To compare the heating and cooling building energy requirements from both a site and source perspective, Figures 11 and 12 are provided below. First, Figure 11 shows that when considering natural gas consumption, it accounts for 47.4% of the building's annual HVAC energy consumption, but when considering these fuels from a source perspective as shown in Figure 12, natural gas reduces to only accounting for 20.1% of the annual HVAC energy consumption. Although we typically look at annual cost savings when comparing alternatives, site energy must also be a comparative tool between design options. This is a strong consideration when determining the overall impact of your building on the environment as well, as opposed to simply the impact of your building from an annual cost perspective to the owner.

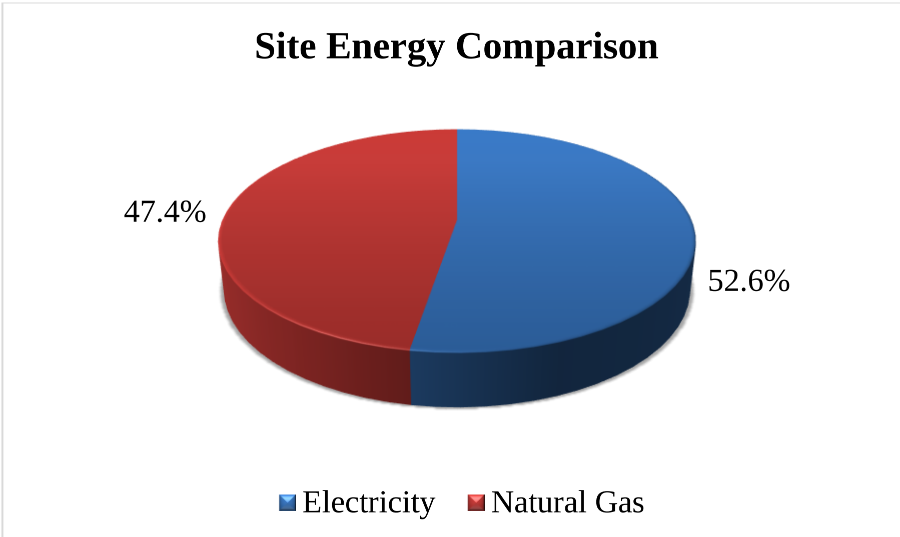


Figure 11: A Figure showing the comparison of heating energy (natural gas) to other building energy (electricity) from a site energy perspective

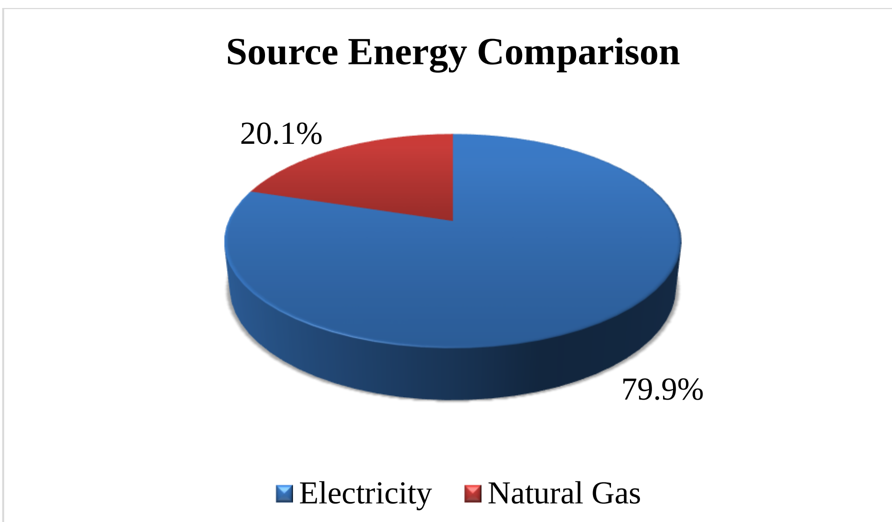


Figure 12: A Figure showing the comparison of heating energy (natural gas) to other building energy (electricity) from a source energy perspective

2.5.3: Total Annual Emission Rates

The annual emissions that are associated with the Gaige Building from its daily operation and energy use are shown in table 15 below. By factoring out the electrical consumption and the natural gas consumption of the Gaige Building on an annual basis, and multiplying by a factor of emissions per unit of energy consumed (source), the total emission of the Gaige Building can be estimated. For electricity, a division factor of 28% was required to calculate the amount of source energy consumed. Factors were taken from the *Source Energy and Emission Factors for Energy Use in Buildings* report from the National Renewable Energy Laboratory. The tables from which the factors were taken can be found in Appendix C, which shows tables three and eight from the report put out by the NREL, revised in 2007. Below, table fourteen summarizes the amount of pollutants put out annually by the Gaige Building. As well, Figure 13 shows a breakdown of the pollutants produced by the Gaige Building on an annual basis.

Annual Emissions Summary					
Pollutant	Electricity Rate (lb/kWh)	Natural Gas Rate (lb/MCF)	Source Electricity (kWh/yr)	Natural Gas (MCF/yr)	Total Emissions (lb/yr)
CO2e	1.74E+00	1.23E+02	2171507	1812	4001309.7
CO_2	1.64E+00	1.22E+02	2171507	1812	3782346.9
CH4	3.59E-03	2.50E-03	2171507	1812	7800.2
N_2O	3.87E-05	2.50E-03	2171507	1812	88.6
NOx	3.00E-03	1.11E-01	2171507	1812	6715.7
SO_x	8.57E-03	6.32E-04	2171507	1812	18611.0
CO	8.54E-04	9.33E-02	2171507	1812	2023.5
TNMOC	7.26E-05	6.13E-03	2171507	1812	168.8
Lead	1.39E-07	5.00E-07	2171507	1812	0.3
Mercury	3.36E-08	2.60E-07	2171507	1812	0.1
PM10	9.26E-05	8.40E-03	2171507	1812	216.3
Solid Waste	2.05E-01	0.00E+00	2171507	1812	445159.0

Table 15: Table summarizing the total annual emissions of the Gaige Building

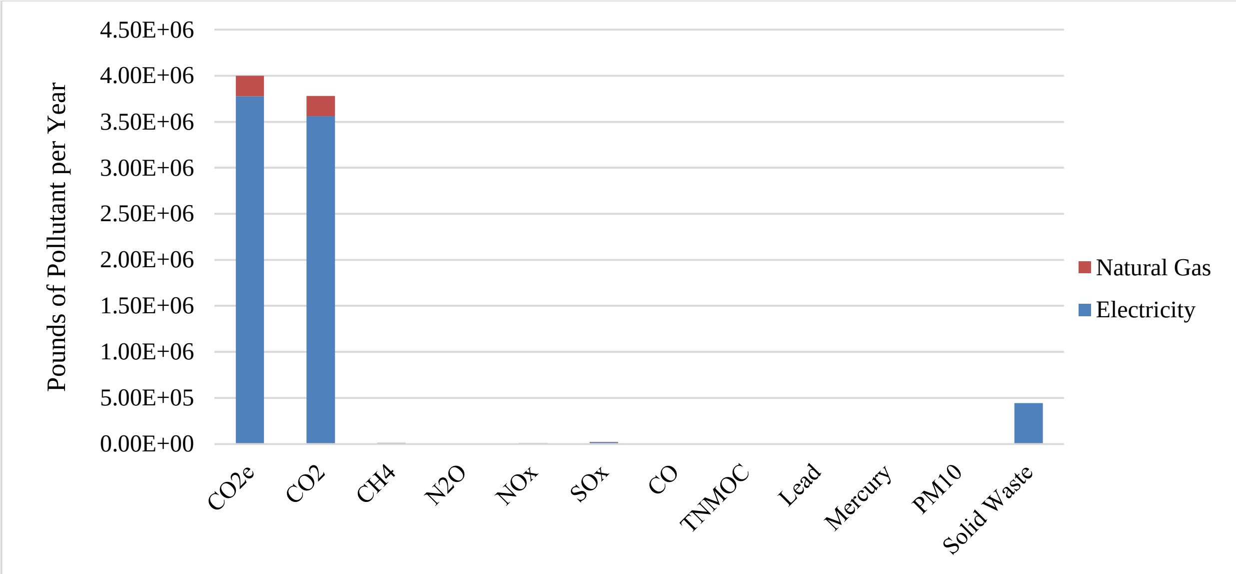


Figure 13: A graph showing the annual emission of each pollutant the Gaige Building by energy source

Chapter 3: Mechanical Depth: Geothermal Analysis

After the initial analysis of the Gaige Building, it was clear that geothermal energy would be a good consideration for the Gaige Building. First, the ground temperatures in south-eastern Pennsylvania were favorable for year-round geothermal operation, both in heating and cooling. Also, when looking at the site surrounding the Gaige Building, there is a large amount of open, undisturbed and unused space adjacent to the building. Below, in Figure 14, is a campus map of the Penn State Berks campus, highlighting the Gaige Building's location and the open space surrounding it.

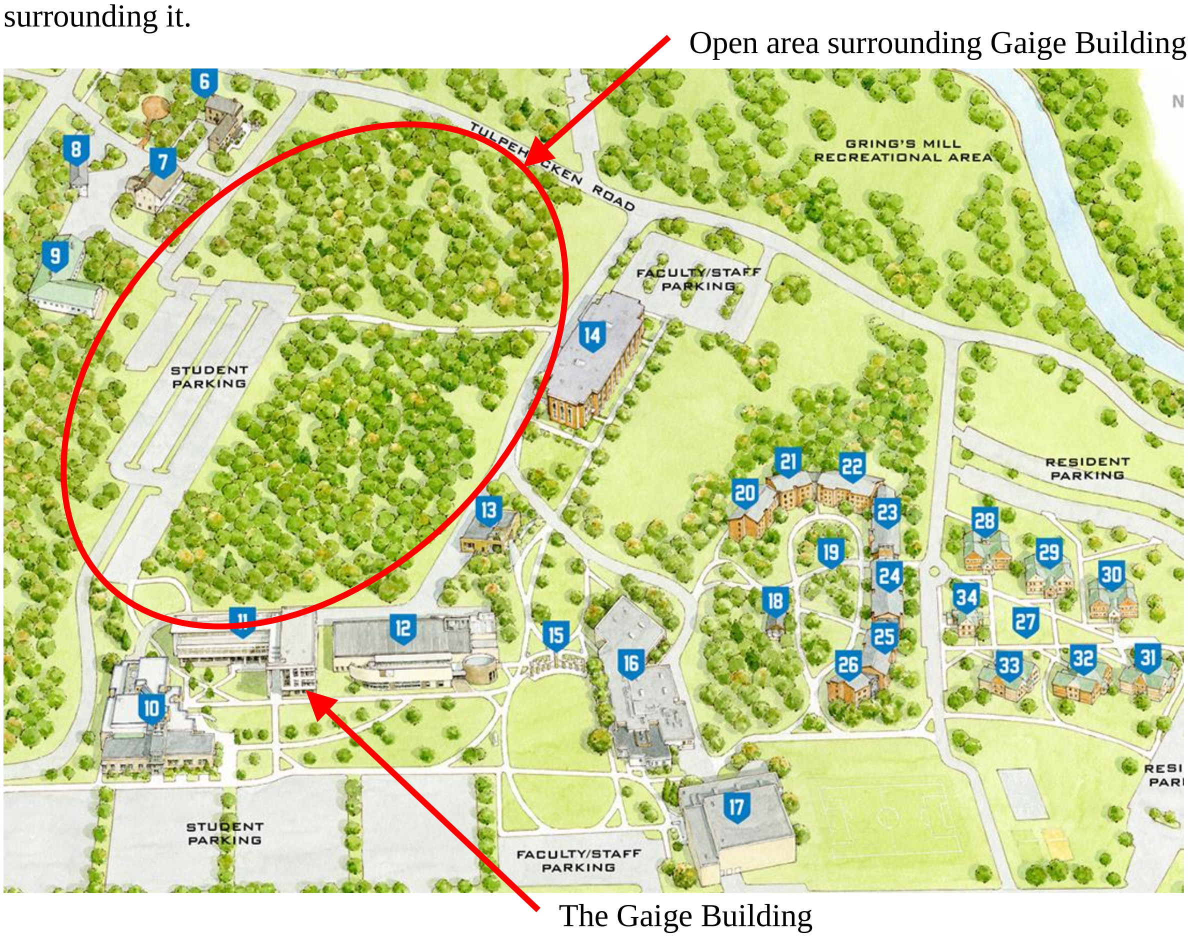


Figure 14: Penn State Berks campus map showing the Gaige Building and surrounding open area for potential geothermal well field

With this large amount of open area located right next to the Gaige Building, the ability to harvest 'free' cooling and heating was an option that seemed like it must be considered. This motivation inspired an analysis of whether or not utilizing a geothermal well field ground loop as an energy source for the Gaige Building would decrease the annual energy costs enough to justify the initial increase in first costs required for the well field.

Out of this study, it was also realized that the open space available was much larger than was needed for a geothermal well field for just the Gaige Building. With this, a second mechanical study was conducted, to determine if it would be feasible to construct a centralized geothermal well field to serve the majority of the campus buildings. With the large amount of space available, and with a large collections of building near each other, all under the same owner, much more annual savings could be realized when considering the larger campus that the Gaige Building was located in. To study this option, models of the campus as a whole were created, and initial first cost increases were compared against annual savings to help determine if the large first costs of a campus wide geothermal system would pay off over the life of the system.

3.1 Geothermal Analysis of the Gaige Building

First, an analysis of the Gaige Building's potential for a geothermal well-field system was analyzed. In the sections below, an overview will be given of the design objectives for this system, the overall configuration of the system, and the layout and setup of the geothermal well field. Then, alterations in the Gaige Building's internal system layout will be discussed. Finally, annual savings from the geothermal system will be modeled and calculated, and the performance of the new system will be evaluated based upon its overall emissions reductions and the payback period for the system using a discounted payback life-cycle cost analysis.

3.1.1: Design Objectives

For the Gaige Building the system design objects were straightforward: reduce annual emissions and utility costs by utilizing the thermal energy located onsite. In a geothermal system, the fundamental reason it works is due to the relatively constant ground temperatures that can be found when you are only 10 to 20 feet below ground level. Despite the large temperature fluctuations that we experience above ground, ranging from 0° up to 90° during normal yearly conditions, the ground temperature remains relatively constant. With this, during the summer months, when cooling is needed, the ground can act as a heat sink. Water source heat pumps can extract heat from the building, meeting the building's cooling load conditions, and transferring that heat to the ground through the geothermal ground loop. As you can see in Figure 15 below, a large portion of the Gaige Building's energy consumption goes toward the heating and cooling loads of the building, shown at the base of the bars in blue and red. This energy is energy that can be recovered from the ground using a ground coupled heat pump system.

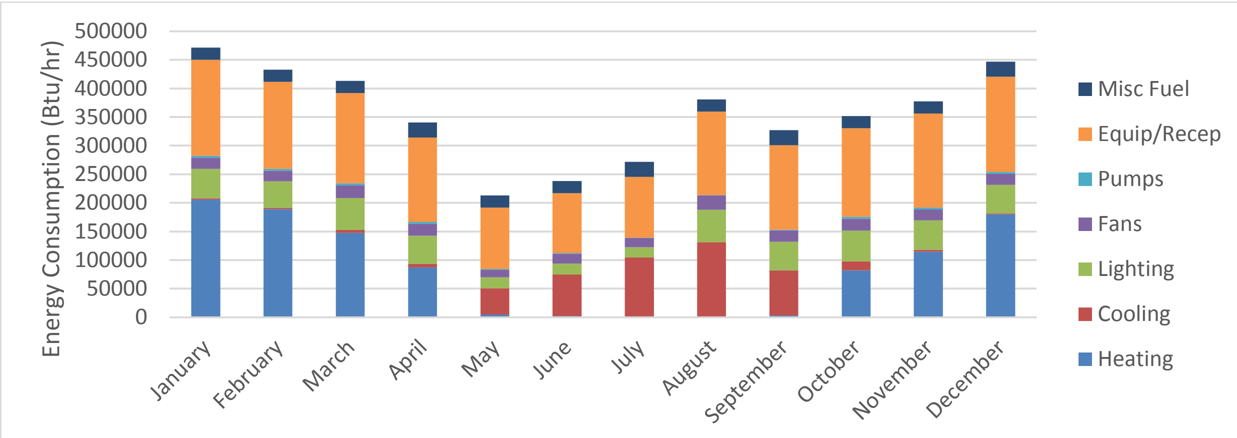


Figure 15: A graph breaking down the monthly energy consumption of the Gaige Building into the various energy consumption categories

In the reverse sense, during the winter months, the ground can act as a heat source. When air temperatures are much lower than ground temperatures, and the building spaces call for heating, the ground loop can transfer heat from the ground to the spaces using the water source heat pumps again. With this system design, you are now getting 'free' cooling and heating throughout the year, and the ground's constant temperature helps it to perform favorable in both the heating and cooling season. Despite this seemingly 'perfect' scenario, it must be determined exactly how 'free' the energy is. To determine the feasibility of implementing one of these systems, you must consider various factors.

First, the large increase in initial first costs of the building must be considered. This comes from mainly the drilling, pouring, and casting of the geothermal well field, and the large cost of installing many water source heat pumps throughout the building, serving individual or small groups of spaces. Also, the operating costs of the system must be included in the building's calculations as well. Although thermal energy is being harvested from the ground, the heat pumps must still be run throughout the building, energy must be used to pump the ground water throughout the building and the well field, and electricity costs to run the other mechanical equipment in the building will still be present. These initial costs must be considered, and weighed against the annual savings in energy costs to see if the system will 'pay itself off' over the life of the system. All of these factors are determined and evaluated in the following sections.

3.1.2: Geothermal System Sizing and Calculations

To size the geothermal well field, the required lengths were calculated from the Gaige Building's peak annual heating and cooling loads using equations provided in chapter 34 of the ASHRAE Handbook-HVAC Applications. The methods and equations provided in chapter 34, entitled *Geothermal Energy*, are outlined and shown below. First, below are the two equation listed that are used to calculate the overall required lengths for cooling and heating, based upon many different site factors, ground conditions, and the design of the individual geothermal bores. These equations are outlined below, and each variable is shown and described. Finally, information is provided as to how each variable was calculated for the specific application shown for the Gaige Building.

$$L_c = \frac{q_a R_{ga} + (q_{lc} - 3.41W_c)(R_b + PLF_m R_{gm} + R_{gd} F_{sc})}{t_g - \frac{t_{wi} + t_{wo}}{2} - t_p}$$

$$L_h = \frac{q_a R_{ga} + (q_{lh} - 3.41W_h)(R_b + PLF_m R_{gm} + R_{gd} F_{sc})}{t_g - \frac{t_{wi} + t_{wo}}{2} - t_p}$$

$F_{sc} - short - circuit\ heat\ loss\ factor$
$L_c - required\ bore\ length\ for\ cooling, ft$
$L_h - reuqired\ bore\ length\ for\ heating, ft$
$PLF_m - part - load\ factor\ during\ design\ month$
$q_a - net\ annual\ average\ heat\ transfer\ to\ ground, Btu/h$
$q_{lc} - building\ design\ cooling\ block\ load, Btu/h$
$q_{lh} - buildling\ design\ heating\ block\ load, Btu/h$

$R_{ga} - effective\ thermal\ resistance\ of\ ground\ (annual\ pulse), (ft*h*°F)/Btu$
$R_{gd} - effective\ thermal\ resistance\ of\ ground\ (peak\ daily\ pulse), (ft*h*°F)/Btu$
$R_{gm} - effective\ thermal\ resistance\ of\ ground\ (monthly\ pulse), (ft*h*°F)/Btu$
$R_b - thermal\ resistance\ of\ bore, (ft*h*°F)/Btu$
$t_g - undistured\ ground\ temperature, °F$
$t_p - temperature\ penalty\ for\ interference\ of\ adjacent\ bores, °F$
$t_{wi} - liquid\ temperature\ at\ heat\ pump\ inlet, °F$
$t_{wo} - liquid\ temperature\ at\ heat\ pump\ outlet, °F$
$W_c - system\ power\ input\ at\ design\ cooling\ load, W$
$W_h - system\ power\ input\ at\ design\ heating\ load, W$

Short-Circuit Heat Loss Factor (F_{sc})

For the well field design of the Gaige Building, the bores are piped in parallel and a flow rate of 3 gpm is assumed per bore. Using a chart from page 30, chapter 34 of the ASHRAE handbook of HVAC Applications, the short circuit heat loss factor was found to be 1.04. The table is shown below as table 16.

	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

Table 16: From ASHRAE HVAC Application, chapter 34, used to find short circuit heat loss factor

Part Load Factor (PLF_m)

Since the part-load factor is unknown, a worst case value is chosen for PLF_m. In this case, the worst case chosen is for $PLF_m = 1.0$.

Net Annual Average Heat Transfer to Ground (q_a)

This value is chosen to be the difference between the heating and cooling block loads, which will estimate the annual heat transfer to the ground. For the Gaige Building, this value was found to be 387,000 Btu/hr.

Building Design Cooling Block Load (q_{lc})

This value was found using the Trace 700 model that was created and validated to the Gaige Building's utility cost information. Using the model, the peak, or design, cooling load for the Gaige Building is 1,066,400 Btu/hr. This is the value to which the bore lengths should be calculated.

Building Design Heating Block Load (q_{lh})

The well field also needs to be calculated using the design heating load for the Gaige Building, for the same Trace 700 model mentioned in the previous section, this value was found to be 679,400 Btu/hr.

Effective Thermal Resistance of Ground—Annual Pulse (R_{ga})

This ground thermal annual pulse was calculated with a bore diameter of 6 inches, and the soil type determined as follows. The Berks campus in the geologic region termed the great valley in Eastern Pennsylvania. From a county geology map, the location of the building site is set on Trenton limestone and calciferous sandstone. With these two values from table five of ASHRAE Applications chapter 34, the thermal conductivity can be used on average as 1.7 and a diffusivity of 1.05. The results with these values calculated the effective thermal resistance of the ground for an annual pulse to be 0.215. These calculations are laid out below in the ground thermal resistance calculations section.

Effective Thermal Resistance of Ground—Peak Daily Pulse (R_{gd})

Using the equations from the ASHRAE chapter 34, the effective thermal resistance of the ground for a peak daily pulse was found to be 0.129. The notes for this calculation are similar to above under R_{ga}, and the calculations are laid out in the ground thermal resistance calculations section.

Effective Thermal Resistance of Ground—Monthly Pulse (R_{gm})

For a monthly pulse, the effective thermal resistance of the ground was found to be 0.207. The notes for this calculation are similar to above under R_{ga}, and the calculations are laid out below in the ground thermal resistance calculations section.

Ground Thermal Resistance Calculations

For the three effective thermal resistances of the ground listed in the previous three sections, the following equations were used to calculate the resistances.

$$R_{ga} = \frac{G_f - G_1}{k_g} \qquad R_{gm} = \frac{G_1 - G_2}{k_g} \qquad R_{gd} = \frac{G_2}{k_g}$$

Where the G-factors are found using Figure 15, and also using the following Fourier Numbers

$$\tau_1 = 3650\ days$$

$$\tau_2 = 3650 + 30 = 3680\ days$$

$$\tau_f = 3650 + 30 + 0.25 = 3680.25\ days$$

$$Fo_f = \frac{4 * 1.05 * 3680.25}{0.5^2} = 61828.2 \qquad Fo_1 = \frac{4 * 1.05 * (3680.25 - 3650)}{0.5^2} = 508.2$$

$$Fo_2 = \frac{4 * 1.05 * (3680.25 - 3680)}{0.5^2} = 4.2$$

From Figure 15 in chapter 34 of the ASHRAE Applications:

$$G_f = 0.938 \quad and \quad G_1 = 0.572 \quad and \quad G_2 = 0.220$$

So with these G values,

$$R_{ga} = \frac{0.938 - 0.572}{1.7} = 0.215 \qquad R_{gm} = \frac{0.572 - 0.220}{1.7} = 0.207 \qquad R_{gd} = \frac{0.220}{1.7} = 0.129$$

Below, the Figure 15 from chapter 34 of the ASHRAE Applications is provided, labeled Figure 16 in this report.

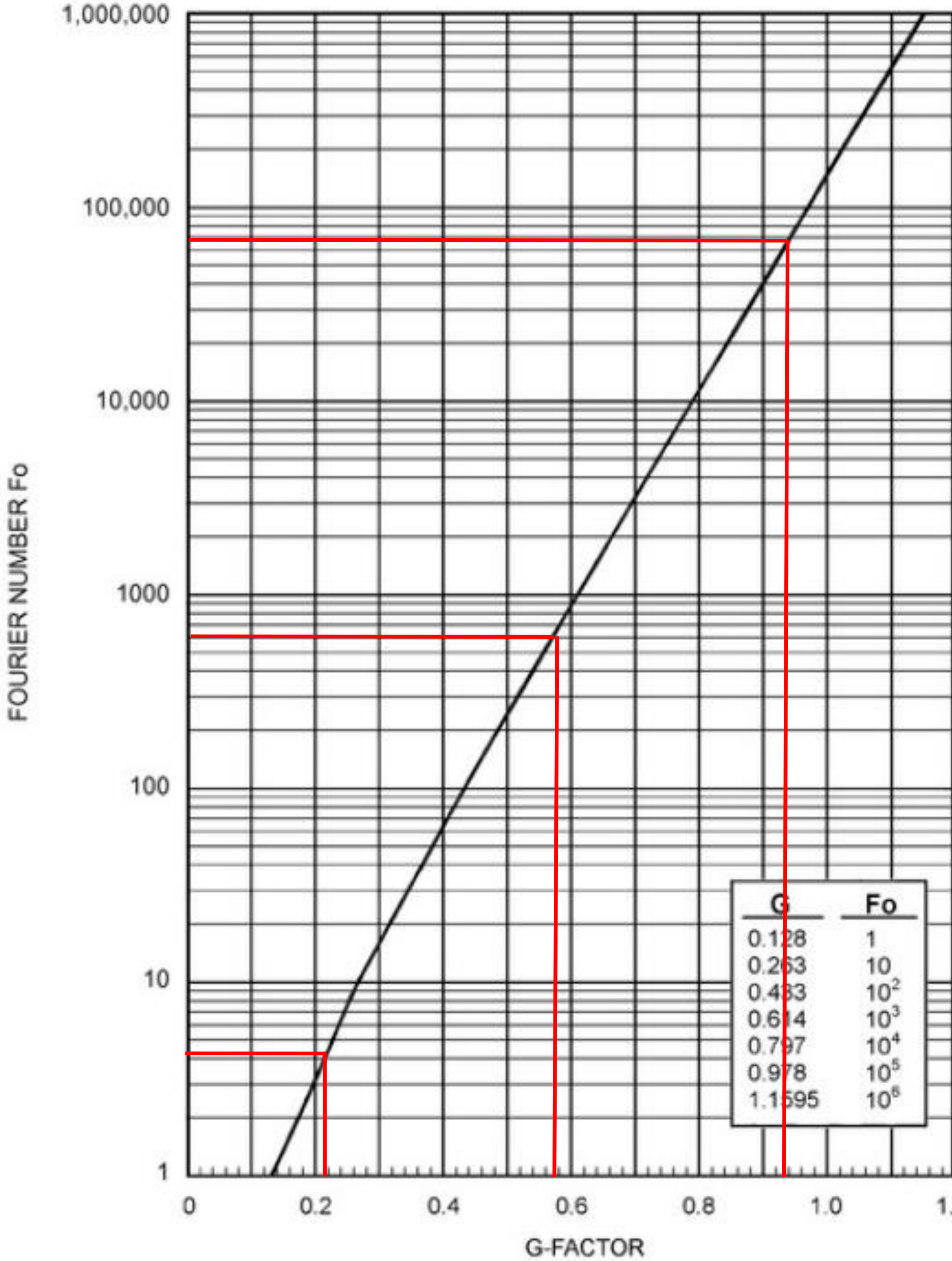


Figure 16: Graph from chapter 34 of ASHRAE Applications to help calculate G factors

Thermal Resistance of Bore (R_b)

For this, a 1.25" diameter U-tube was selected with a 6 inch bore diameter and a bore fill with 1.0 Btu/(hr*ft*F) conductivity. High-Density polyethylene U-Tube is assumed. This makes the thermal resistance of the bore to be equal to 0.09. Figure 17 below shows the table used to help find a value for the thermal resistance of the bore.

Table 6. Thermal Resistance of Bores R_b for High-Density Polyethylene U-Tube Vertical Ground Heat Exchangers

	Bore Fill Conductivity,* Btu/h·ft·°F					
	4 in. Diameter Bore			6 in. Diameter Bore		
U-Tube Diameter, in.	0.5	1.0	1.5	0.5	1.0	1.5
3/4	0.19	0.09	0.06	0.23	0.11	0.08
1	0.17	0.08	0.06	0.20	0.10	0.07
1 1/4	0.15	0.08	0.05	0.18	0.09	0.06

* Based on DR 11, HDPE tubing with turbulent flow

Corrections for Other Tubes and Flows

DR 9 Tubing	Re = 4000	Re = 1500
+0.02 Btu/h·ft·°F	+0.008 Btu/h·ft·°F	+0.025 Btu/h·ft·°F

Sources: Kavanaugh (2001) and Remund and Paul (2000).

Figure 17: Table six from chapter 34 of ASHRAE Applications used to calculated bore thermal resistance

Undisturbed Ground Temperature (t_g)

The undisturbed ground temperature was chosen to be 53 degrees F according to Figure 17 from ASHRAE applications chapter 34. This was taken from Figure eighteen shown below for Reading, PA. Graph lines are in 2 degree increments.

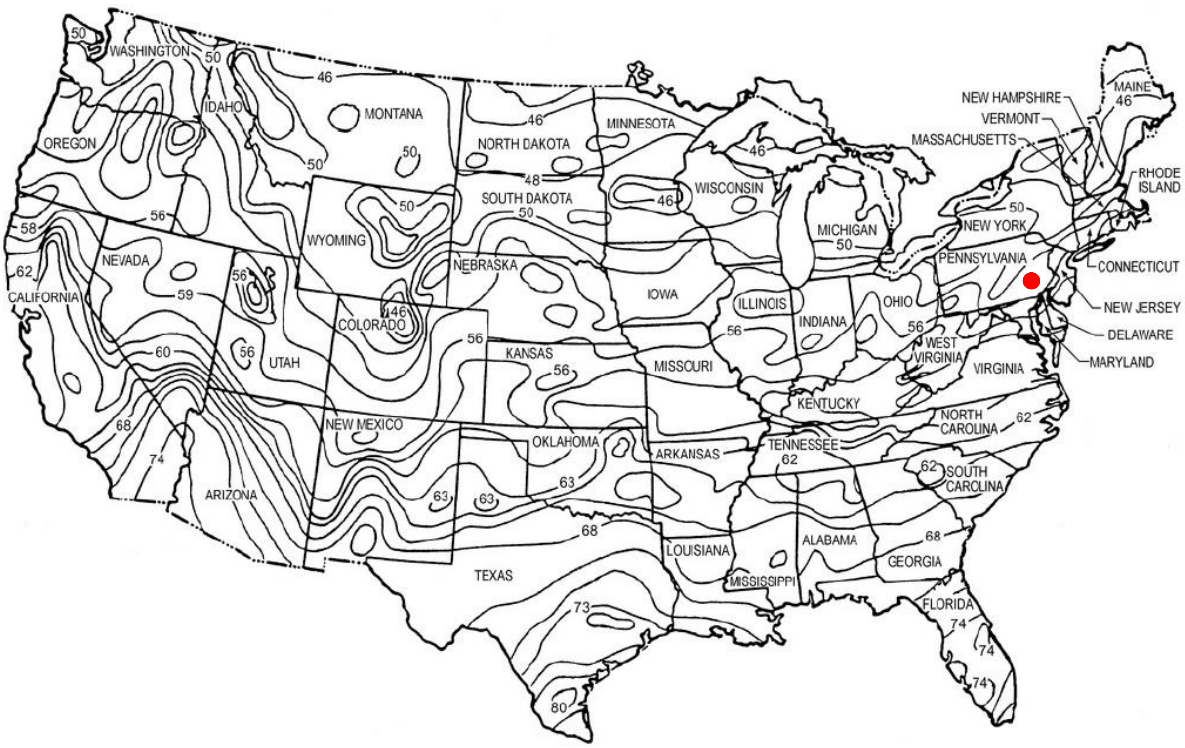


Figure 18: Undisturbed ground temperatures for the United States, Reading, PA shown at red dot

Temporary Penalty for Interference of Adjacent Bores (t_p)

With the ground temperature determined to be 53 °F, and values of 750 equivalent full load hours during heating and 750 equivalent full load hours during cooling assumed, we can calculate the estimated temperature penalty for adjacent bores spacing. With these values, using table 7 from ASHRAE Applications, chapter 34, the long-term temperature penalty was found to be 1.8 °F. This is used as a long term temperature penalty.

Liquid Temperature at Heat Pump Inlet (t_{wi})

The water temperature at the inlet to the geothermal bores is chosen relative to the ground temperature, of 53 °F. For cooling, the temperature is typically chosen to be 20 °F to 30 °F higher than undisturbed ground temperature for cooling and 10 °F to 20 °F lower for heating. For this test, 78 °F is used for cooling and 38 °F is used for heating.

Liquid Temperature at Heat Pump Outlet (t_{wo})

These values were chosen to be roughly five to seven degrees different from the entering temperature to the heat pumps. The value increases for cooling mode, and decreases for heating mode. To ensure that freezing would not be an issue, this system design was chose to use a heating outlet temperature of 33 degrees and a cooling outlet temperature of 85 degrees.

System Power Input at Design Cooling Load (W_c)

For the geothermal well field, once the overall well field was designed, the pump head for the system and flow rate was used to help select a pump for the geothermal well field. Once the initial pump was found, which will be provided in the equipment selection section 3.1.6 below, the input power to the system was found to be 3728.5 W, calculated from the pumps horse power.

System Power Input at Design Heating Load (W_h)

The pump chosen for the system for cooling will be the same pump chosen for heating. Thus, the input power to the system during heating will also be 3728.5 W.

Final Geothermal Length Calculations

Below, table 17 summarizes the previously listed values and provides the calculations for L_c and L_h from the equations at the beginning of this section.

Geothermal Design		
Parameter	Heating	Cooling
Short-Circuit Factor (F_{sc})	1.04	1.04
Part-Load Factor (PLF_m)	1	1
Average Heat Transfer to Ground (q_a)	387000	387000
Block Loads (q_{lc} and q_{lh})	679400	1066400
Resistance of Ground, Annual pulse (R_{ga})	0.215	0.215
Resistance of Ground, Daily pulse (R_{gd})	0.129	0.129
Resistance of Ground, Monthly pulse (R_{gm})	0.207	0.207
Resistance of Bore (R_b)	0.09	0.09
Undisturbed Ground Temperature (tg)	53	53
Temperature Penalty for Bore Spacing (t_p)	1.8	1.8
Heat Pump Inlet Temperature (t_{wi})	38	78
Heat Pump Outlet Temperature (t_{wo})	33	85
System Power Input (W_c and W_h)	3728.5	3728.5
Required Bore Length (L_c and L_h)	23636.4	17760.4

Table 17: A table summarizing the geothermal length calculations for the Gaige Building

Looking at the results, it is clear that the heating design length will constrain the required length for the Gaige Building. This is the total length of all of the bores that will be required to meet the system design requirements.

3.1.3: Geothermal System Layout—Vertical Bore Option

The first option to consider for the layout of the geothermal system was a vertical bore well field. The vertical well field is arguably the most popular layout, for it provides the most cooling potential for the building compared to the amount of land it occupies. For the vertical well field, in order to minimize interaction effects between adjacent bores, wells are placed with a minimum of 20 feet apart. This means that each well drilled roughly occupies 400 square feet. Well depths can range anywhere from 50 feet to 400 feet, but typically, they fall in the range of

200 to 300 feet. The well field depth choice is a balance of cost, space, and the geological conditions of your particular well field location.

For the Gaige Building, the vertical bores that were designed are six inches in diameter, with one inch high density polyethylene (HDPE) piping. To balance the constraints of creating a well field that is smaller in size, well depth was compared with required number of bores. Below, table 18 summaries the number of wells that would be required based upon vertical depth.

Required Number of Vertical Bores			
Well Depth	**Required Bore Length**	**# of Wells**	**# of Wells, 20% Safety**
100	23636.4	237	284
200	23636.4	119	142
300	23636.4	79	95
400	23636.4	60	71

Table 18: A table showing the required number of bores to serve the Gaige Building, depending upon bore depth

For this building, a total of 100 wells were selected for the well field design, with a depth of 300 feet. This was chosen as a balance between total number of wells and the space it would occupy. Also, since the Gaige Building's new proposed energy source will be heavily reliant on geothermal energy, it was desired to have a 20% increase in the number of wells required, in case some of the wells would develop a flaw and need to be shut off from the rest of the well field. Each of the wells were designed with a bentonite backfill, and the wells would be drilled, piping installed, and backfilled one at a time. Some phasing in the construction process might be possible, but the overall schedule of the project should be considered for this purpose. Below, in Figure 19, a summary of the design of a single bore is given.

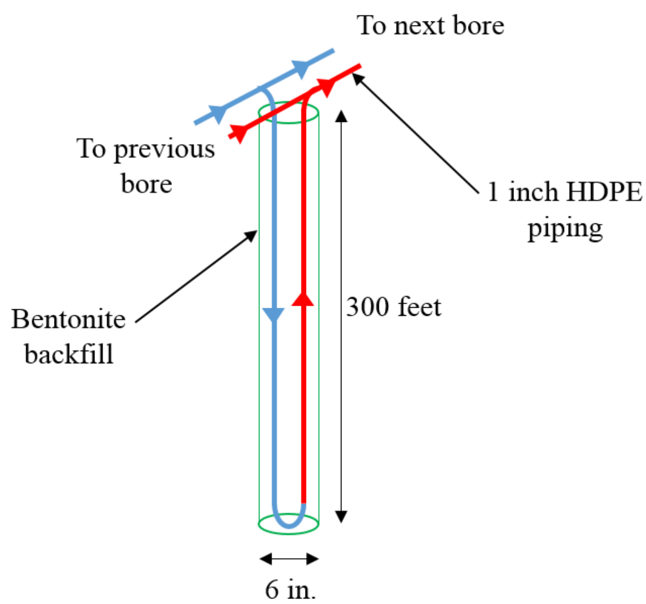


Figure 19: Specifications of a vertical well designed for the Gaige Building

Also, below in Figure 20, a site plan is provided showing the overall layout of the geothermal wells near the Gaige Building. The blue piping is the return and the red piping is the supply. Along with this picture, Figure 21 shows the location of the geothermal well field site plan with respect to the rest of the campus as a whole. As can be seen, the geothermal well field has been piped in a reverse-return pattern, to allow for self-balancing of all of the total flow to each of the bores, ensuring the proposed 3 gpm flow rate in each bore. This will help to ensure the best possible heat transfer between the ground and the well field.

Figure 20: Site layout of the vertical geothermal well field

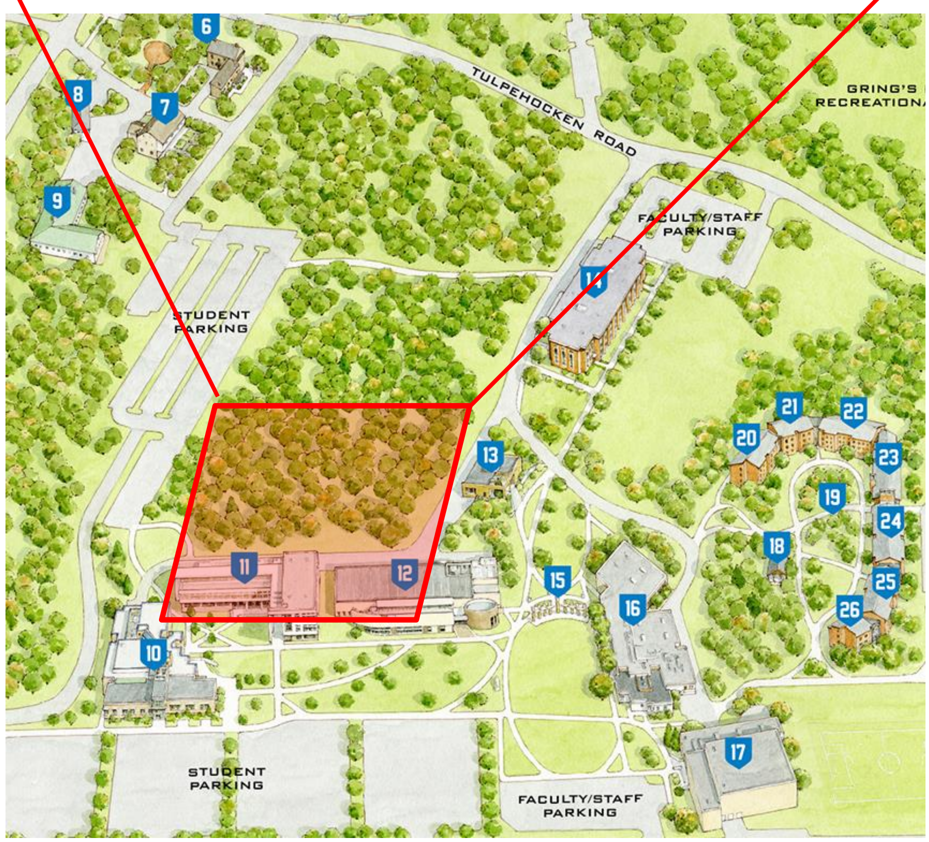


Figure 21: Location of the geothermal well field with respect to the rest of campus

3.1.4: Geothermal System Layout—Horizontal Bore Option

Along with the large amount of space, a horizontal piping layout should also be considered. Typically, for a larger building like the Gaige Building, a horizontal bore option would not even be a consideration. This is due to the fact that a large length of piping is required to design and meet the loading requirements of the building. This leaves horizontal geothermal loops mainly to be implemented in smaller scale applications, commonly in small buildings or residential applications. For the Gaige Building, as seen above in Figure 21, there is still much open space that could be utilized, and is not being occupied by the more spatially efficient vertical bore hole arrangement. The design for the horizontal field was done in a similar fashion to the vertical well field. Bore thermal characteristics and properties are chosen to be similar to the vertical bore options, so the same total length of 23,636 feet is required for the horizontal loop. To be sure load requirements are met, and to allow for extra sizing of the well field in case of the need to shut off one loop due to a failure of some sort, again a 20% factor of safety is applied, making the design required length 28,364 feet. Below, Figure 22 shows of a cross section of a horizontal trench containing a geothermal pipe, from chapter 34 of ASHRAE applications.

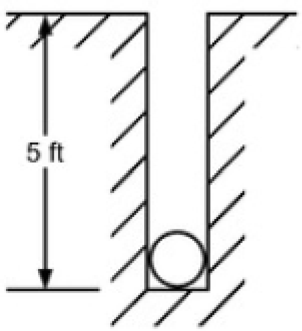


Figure 22: A horizontal loop geothermal pipe, typical section for one loop per pipe, *ASHRAE Application, Ch 34*

One pipe per loop was chosen to minimize the thermal effects between loops and to allow for easier construction and backfilling of the loops. Below, table 19 summarizes the lengths of the horizontal loops, and Figure 23 shows the layout and design of the horizontal loop system for the Gaige Building. As you can see, the total length of the piping comes out to 28,550 feet, meeting the design requirement of 28,364 feet, which includes the 20% safety factor.

Required Number of Horizontal Loops		
Loop Length	**Number of Loops**	**Total Length**
800	20	16000
775	1	775
750	4	3000
700	5	3500
675	1	675
650	4	2600
400	5	2000
	Total Length	**28550**

Table 19: A summary of how differing loop lengths are used to meet the horizontal loop length requirements

Figure 23: Proposed configuration of the Gaige Building's horizontal loop geothermal system

3.1.5: Proposed System Configuration

For the proposed geothermal system, various factors were key in the design of the system operation. The main components of the system include the geothermal well field itself, the pumps servicing the geothermal well field, the many individual water source heat pumps distributed through the building, the piping serving the building, and the pumps supplying the ground water to the water source heat pumps. First, it was desired to decouple the geothermal well field from the rest of the building. This would allow the geothermal system to operate or adjust flow independently of the flow going to the building pumps servicing the heat pumps. This way, even when the building's load is adjusted to current demand conditions, the geothermal well field can still operate independently of the building. This also helps to isolate systems so that not all systems need to be shut off to perform maintenance on the building.

Below, in Figure 24, you can see the overall schematic of the system and how the geothermal well field is connected to the building loads. The system contains various common pipes that help to decouple the various aspects of the building's piping design as previously discussed.

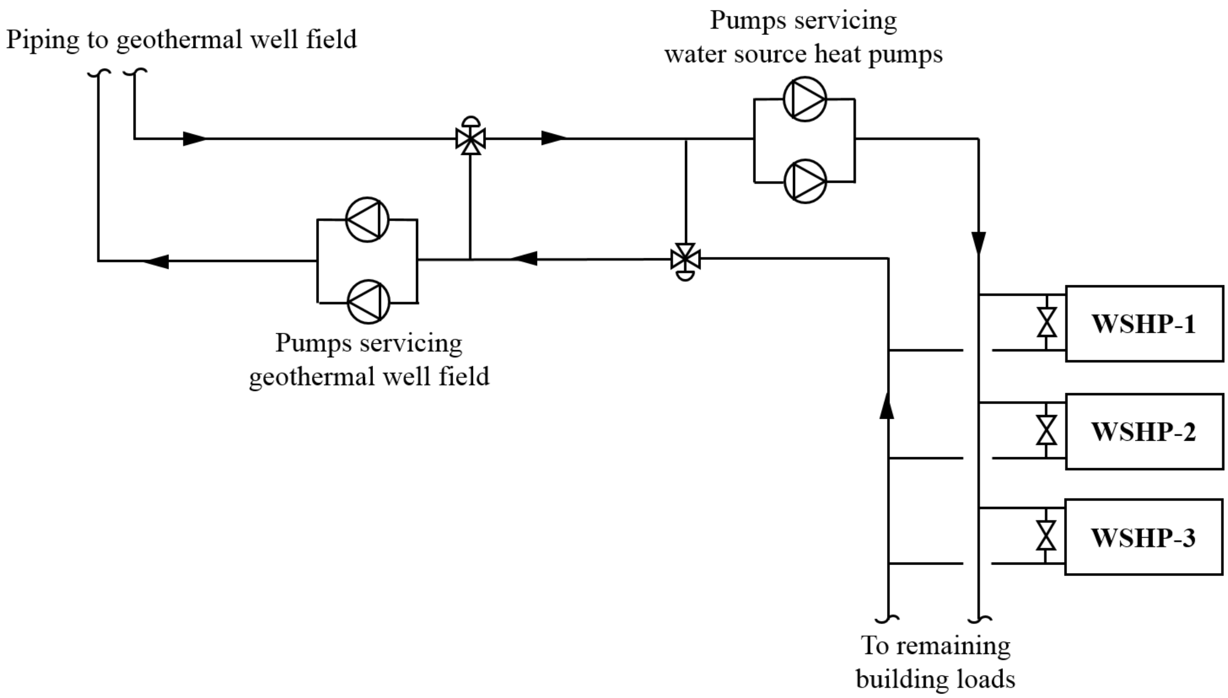


Figure 24: A schematic of the piping arrangement in the Gaige Building's proposed geothermal design

Along with servicing heat pumps placed in each of the building spaces, the geothermal loop will also serve a larger capacity water source heat pump that will service the heating / cooling coil for the dedicated outdoor air unit. Also, with hot water demand for the building, a boiler will be provided to supply the hot water to the building. The boiler will also be sized to provide supplemental hot water to the heating coils, in case the geothermal system cannot fully meet the heating load. This design of having a backup boiler in the system was included in the energy model for the space, so it will also potentially supplement the water system as well during heating season.

3.1.6: Building Piping Layout

In order to implement a new ground loop into the Gaige Building, not only must the pumps be sized and placed in the mechanical room, but a piping distribution plan must be laid out within the building, and space considerations must be made. The ground loop will enter into the building on the first floor, coming into the mechanical room in the upper left corner of the building. There is currently a large amount of space in that mechanical room, so space concerns will not be an issue when placing the additional pumps required in the Gaige Building's design. It is proposed that the ground water loop be piped throughout the building through a central pipe run that passes through the main circulation corridor of the building. This piping will be exposed in the main corridor, for it has an open atrium style plan, and then it will run above the drop acoustical ceiling tile when it circulates through the office spaces. Below, main piing runs are shown for the first, second, and third floor, in Figures 25, 26, and 27 respectively.

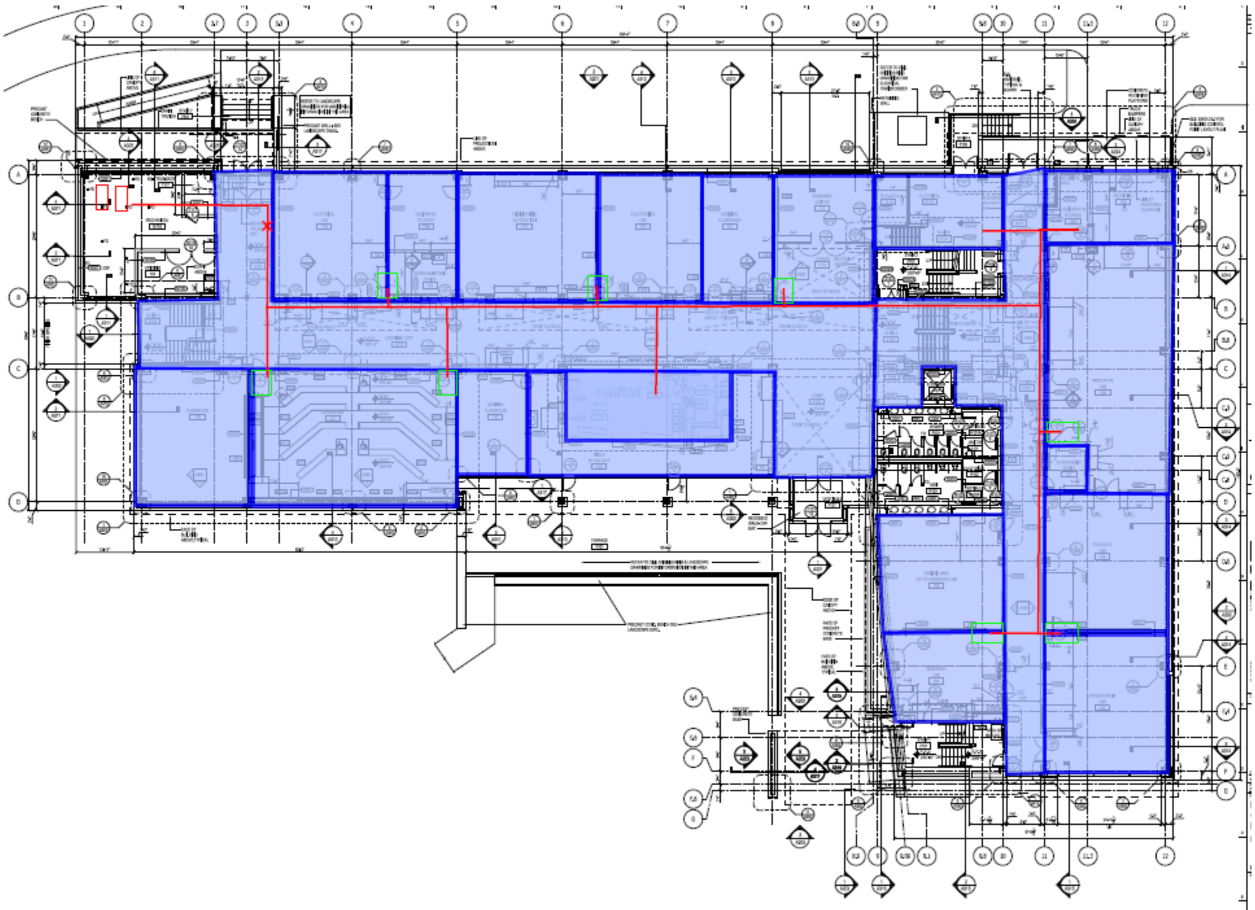


Figure 25: A diagram of the first floor HVAC zoning and piping distribution

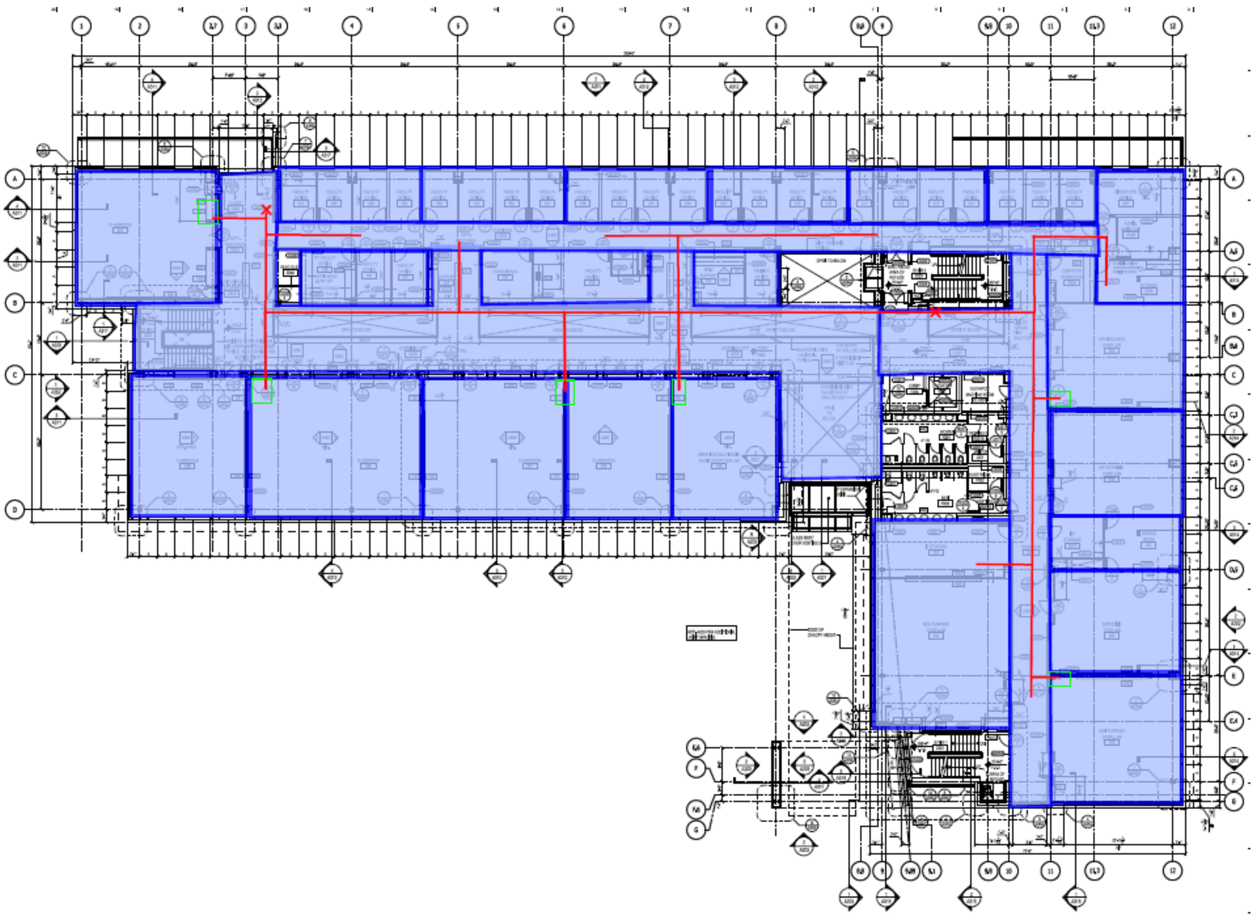


Figure 26: A diagram of the second floor HVAC zoning and piping distribution

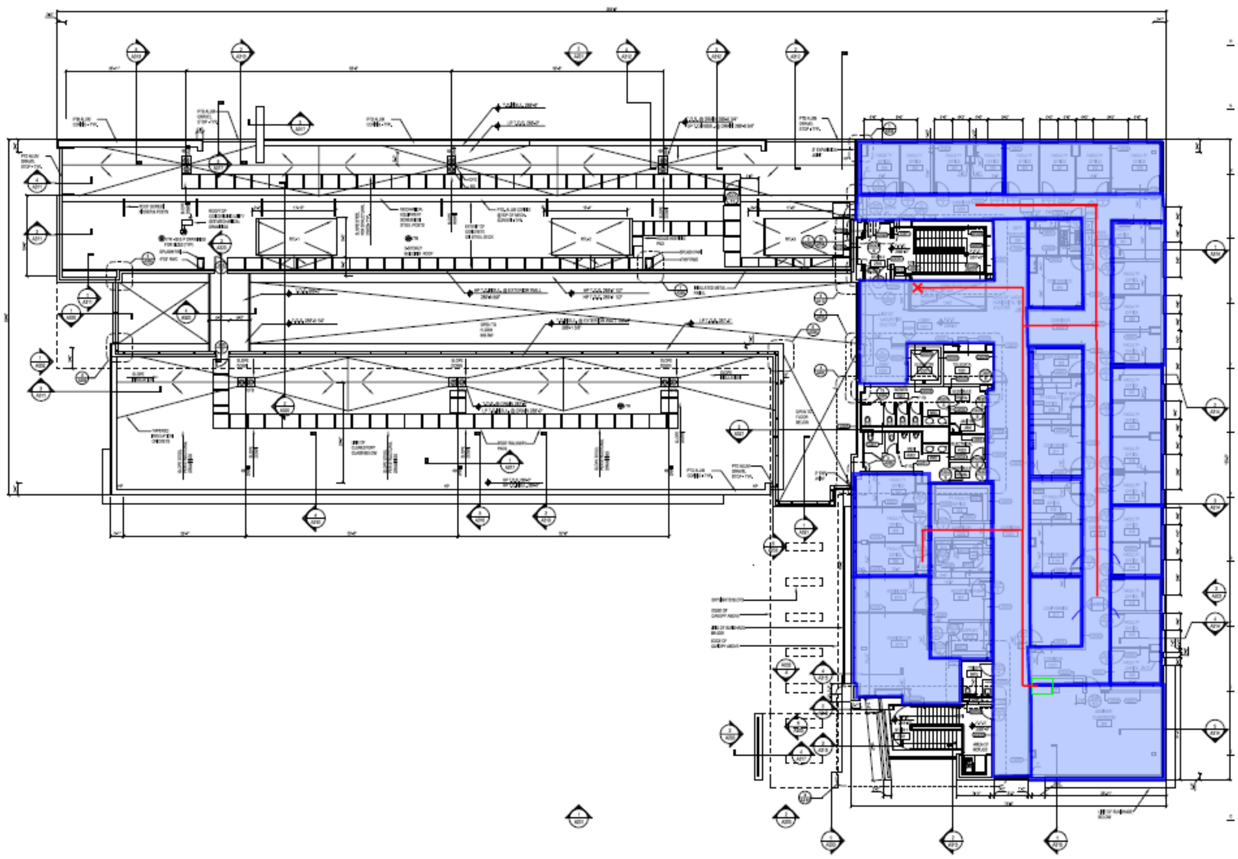


Figure 27: A diagram of the third floor HVAC zoning and piping distribution

As you can see in the Figures above, the slue boxes with the light blue shading represent the different HVAC zones that were developed for the Gaige Building. Each blue box is one space or a group of rooms that will all be served by one water source heat pump, sized to the appropriate capacity based upon the peak loads. The red lines represent main distribution piping runs, which will run a supply and return pipe to and from each of the water source heat pumps. Where a light green boxes exist, there will be a small maintenance room constructed to house the heat pumps next to larger spaces. These rooms will allow for easy access for mechanical maintenance and testing. Also, they will allow for acoustic isolation between noise sensitive spaces, such as classroom, and the noise coming from the casing of the heat pumps. This analysis will be further discussed in the acoustics breadth of the thesis, chapter four.

3.1.7: Geothermal Equipment Selection

For the geothermal system, similar building piping and pumps will be used as in the original design for the Gaige Building. The new additional costs for the Gaige Building will include new pumps to service the geothermal well field. In order to size the pump, the maximum flow rate for the pump was based upon the 3 gpm flow rate per bore, and the total head loss to the furthest bore was calculated to size the head loss for the pump. Since a reverse-return piping arrangement was used, the head loss can be calculated using any bore for the analysis. Table 20 below summaries the heat loss calculation for the geothermal well field pumps.

Head Loss for Vertical Geothermal Well Field Pumps								
Segment	Length (ft)	Flow Rate (gpm)	Pipe size (in)	# of Fittings		Equivalent Length	Head Loss ft/100 ft	Total Head Loss
				Elbows	Tees			
Header 1	208.5	300	5	2	0	60	1.72	4.6
Header 2	20	270	5	0	1	20	1.41	0.6
Header 3	20	240	5	0	1	20	1.14	0.5
Header 4	20	210	5	0	1	20	0.89	0.4
Header 5	20	180	5	0	1	20	0.67	0.3
Header 6	20	150	4	0	1	20	1.41	0.6
Header 7	20	120	4	0	1	20	0.93	0.4
Header 8	20	90	3	0	1	20	2.22	0.9
Header 9	20	60	2.5	0	1	20	2.54	1.0
Header 10	30	30	2	1	1	50	2.08	1.7
Bore 1	20	27	2	0	1	20	1.72	0.7
Bore 2	20	24	2	0	1	20	1.38	0.6
Bore 3	20	21	2	0	1	20	1.08	0.4
Bore 4	20	18	1.5	0	1	20	3.28	1.3
Bore 5	20	15	1.5	0	1	20	2.34	0.9
Bore 6	20	12	1.5	0	1	20	1.55	0.6
Bore 7	20	9	1.5	0	1	20	0.91	0.4
Bore 8	20	6	1	0	1	20	3.08	1.2
Bore 9	20	3	1	0	1	20	0.85	0.3
Bore 10	610	3	1	0	6	120	0.85	6.2
Header 10	10	30	2	1	0	30	2.08	0.8
Header 11	616.5	300	5	4	0	120	1.72	12.6
							Total head for Pump	**37.0**

Table 20: Head loss calculation summary table for the geothermal pump in the Gaige Building

The calculations for the head loss per 100 feet of piping were done using the Hazens-Willams equation, with a constant for HDPE piping of c = 140. From this table, we need to select a pump for the geothermal well field that can operate efficiently with a total head of 37 feet H_2O and with a flow rate of 300 gpm. A base mounted, centrifugal Bell and Gossett series e-1510 3AD pump was selected. A picture of the pump is provided below in Figure 28.

Figure 28: A picture of a Bell and Gossett, base mounted centrifugal pump, series e-1510

Shown below, in Figure 29, is a chart provided by Bell and Gossett that helps to select an appropriate pump to meet your flow and head loss requirements. Then, Figure 30 shows the specific pump curves for the 3AD centrifugal pump, with red lines highlighting our operating point for this pump. As you can see, we are operating at a very efficient point on the pump curves, at roughly 84%. Thus, this pump is a good selection for the geothermal well field. Also, there will be two pumps, piped in parallel installed in the building, so that if maintenance is required, one pump can run while the other is being worked upon. A pump was also selected for the horizontal geothermal well field, needing a flow rate of 120 gpm and a head of 45 ft H_2O. The pump selected is shown in green in Figure 29 and its operation condition is shown in Figure 31. A 1.5AD centrifugal, base mounted pump was chosen for the horizontal well field, also operating at efficient conditions for the pump. For a calculation summary of the head loss for the horizontal geothermal loop, please refer to Appendix B.

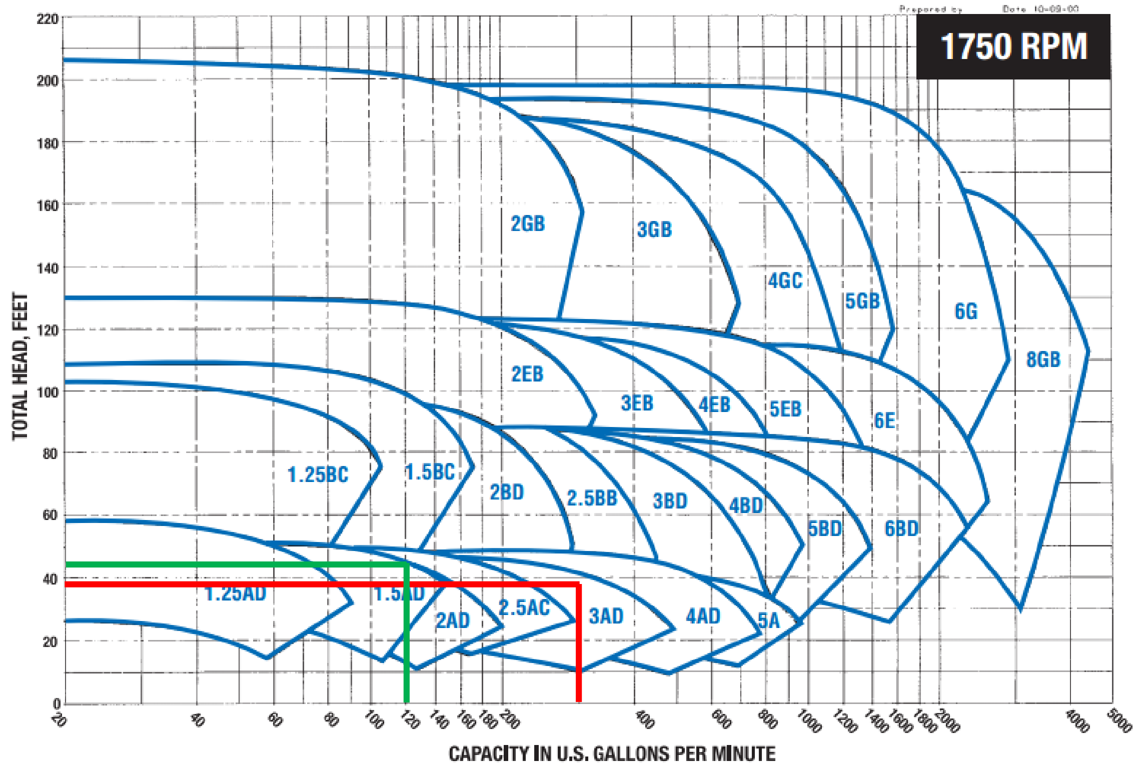


Figure 29: Pump selection diagram provided by Bell and Gossett to assist in pump sizing. Vertical geothermal pump is shown in red and horizontal geothermal loop pump is shown in green

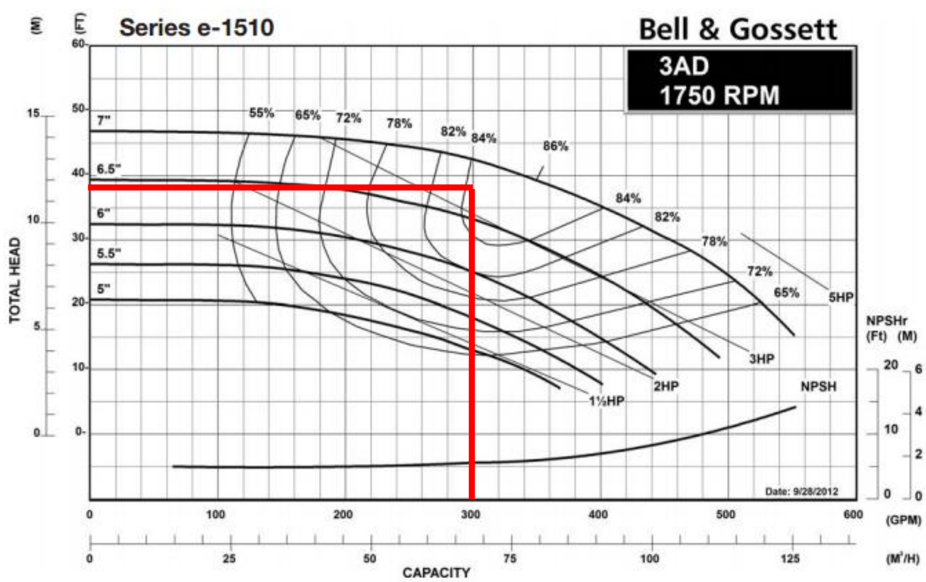


Figure 30: Pump curve for the selected vertical bore geothermal pump shown at operating conditions in red

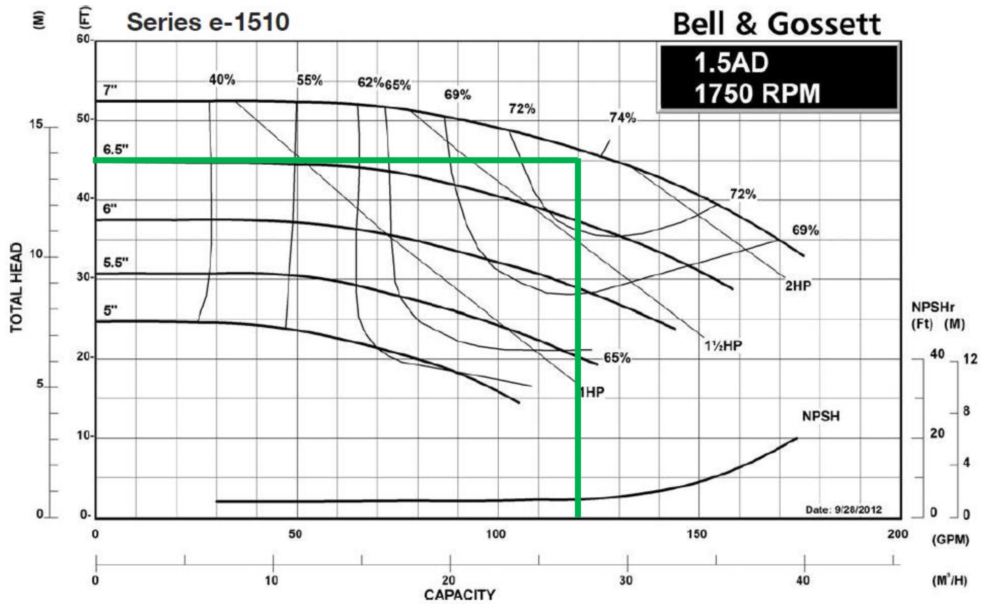


Figure 31: The pump curves shown for the horizontal loop geothermal field pump, operating conditions shown

As well, the head loss and flow rate for the building pumps serving the water source heat pumps were sized and calculated based upon the main distribution piping line and runs provided in section 3.1.6. The head loss required for the pumps was found to be 40.5 ft H_2O, operating at a flow rate of 413 gpm. Again, two pumps will be piped in parallel, but each pump will be capable of individually serving the building. Shown below, in Figures 32 and 33 respectively, are the pump selection diagram again for the Bell and Gossett pumps, along with the pump operating curves for the selected pump for building operation. The pump selected for the building distribution is a Bell and Gossett base mounted centrifugal pump, series e-1510, type 4AD. Calculation for this pump's head loss requirements can be found in Appendix A.

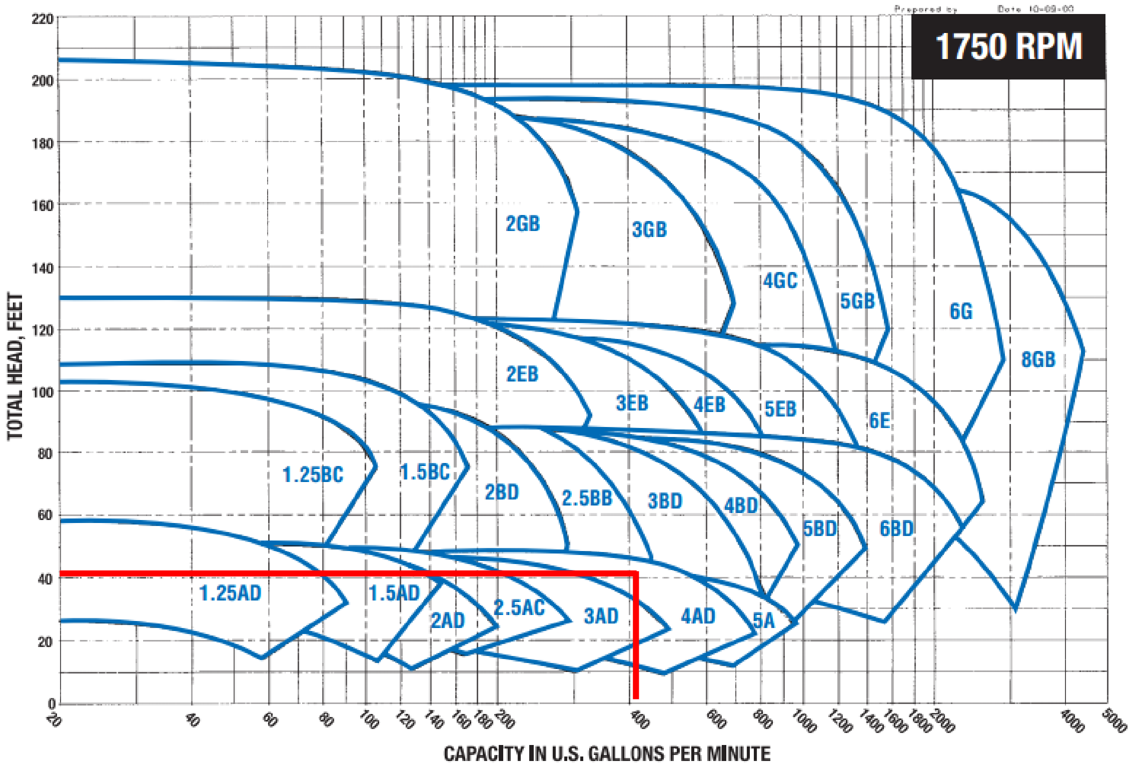


Figure 32: Pump selection diagram provided by Bell and Gossett

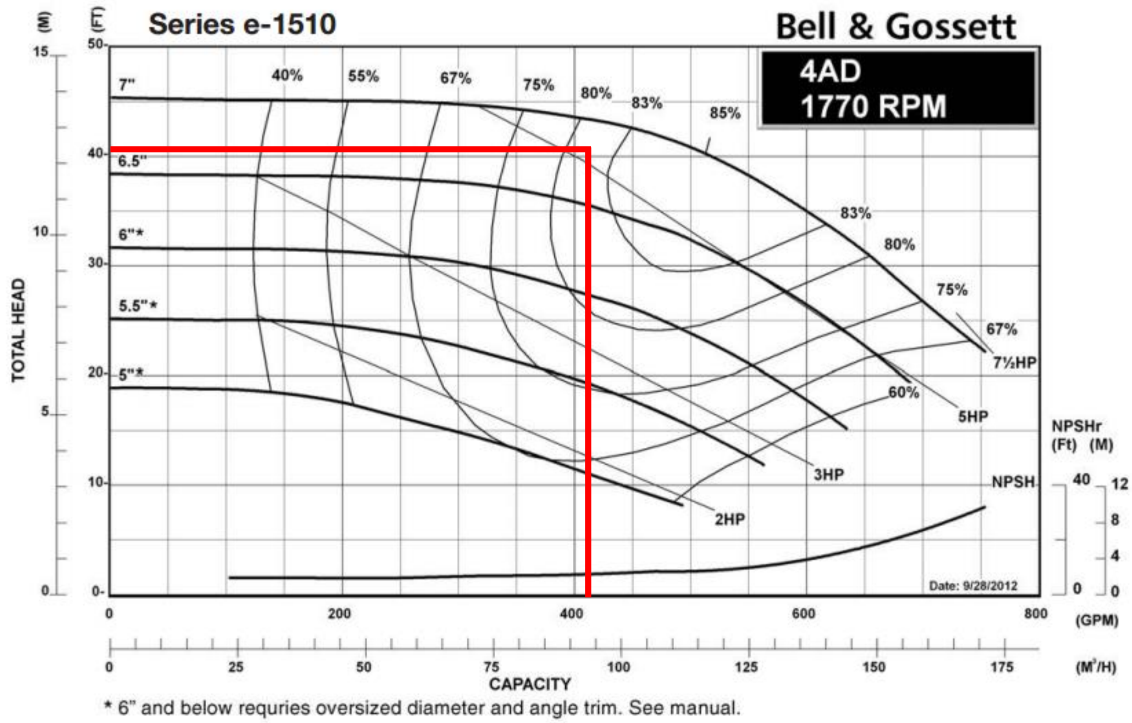


Figure 33: Pump operating curves for the building pumps, shown at operating conditions in red

Along with pumps, water source heat pumps must be selected. For the Gaige Building, Carrier compact water source heat pumps were selected. These were selected because they came in a variety of smaller capacity sizes, and offered high efficiency, helping to reduce the operating costs of the heat pumps and create more annual savings from the geothermal system over its lifetime. As well, these heat pumps provided a substantial amount of acoustical data from a similar model, so extensive acoustic analysis was able to be done on the heat pumps. A sketch of these units, both horizontal and vertical, is given on the next page in Figure 34.

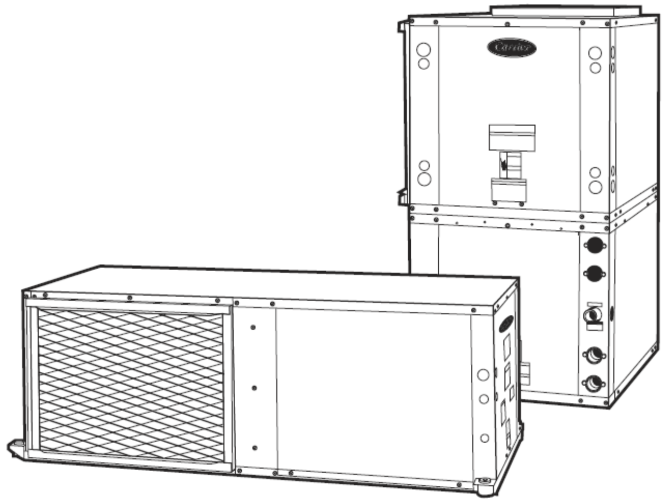


Figure 34: A sketch of the water source heat pumps selected from Carrier, both horizontal and vertical unit shown

3.1.8: Dedicated Outdoor Air System

To make the installation of the ground loop serving heat pumps possible within the Gaige Building, a dedicated outdoor air system (DOAS) must be utilized. While the heat pumps will monitor space load through the use of thermostats, the heat pumps will simply pull 100% return air from the space, condition it to meet current load conditions, and put that air back into the space. This will not accomplish the ventilation requirements for the space, so a separate dedicated outdoor air system will be installed within the Gaige Building. Since the previous design of the Gaige Building included multiple packaged rooftop units, a well-designed and heavy infrastructure of ductwork is already laid out, throughout the building's design. Instead of having three separate rooftop units, now, since this unit will only be servicing the ventilation air for the building, one smaller unit will be able to serve the entire building. A 15 ton dedicated outdoor air unit, with a maximum airflow of 20,000 CFM, was selected for the Gaige Building.

As well, a total energy recovery unit will be incorporated into the outdoor air intake and exhaust for the DOAS, recovering energy that would be lost in the exhaust air otherwise. This will provide preconditioning of the outdoor air. The main ductwork systems will operate under a similar layout, but the amount of ductwork will be drastically reduced, since the airflow for only ventilation air will be much lower than the airflow required for the previous building design. Ventilation air will be supplied at a neutral temperature to the space, separating out the job of space conditioning and ventilation between the water source heat pumps and the DOAS. The dedicated outdoor air unit will be served by a large capacity water source heat pump through the ground loop within the building. The ventilation air will use variable air volume boxes with CO_2 and occupancy sensors to save energy by not requiring a consistent 100% OA supply throughout the buildings operation schedule.

3.1.9: Annual Energy and Cost Analysis

To determine the annual energy usage and costs saving from implementing a geothermal system, the validated model of the Gaige Building was used to determine the annual savings from the geothermal system due to reduced energy use. First, the validated model's energy costs per month and energy use per month, by energy source, were calculated for the existing building's design. Then, the system in the trace model was adjusted to a ground source heat pump system. Water source heat pumps were added to the model, to replace the existing system, and the energy sources were adjusted to a ground source heat pump. Finally, a DOAS was added to the model, since now the outdoor air would be separated from the space conditioning. Below, in Figures 35, 36, and 37 is a comparison of the monthly energy consumption and the monthly energy costs of the old Gaige Building design and the new design of the Gaige Building with a geothermal system. They are split into electricity, natural gas, and total monthly costs.

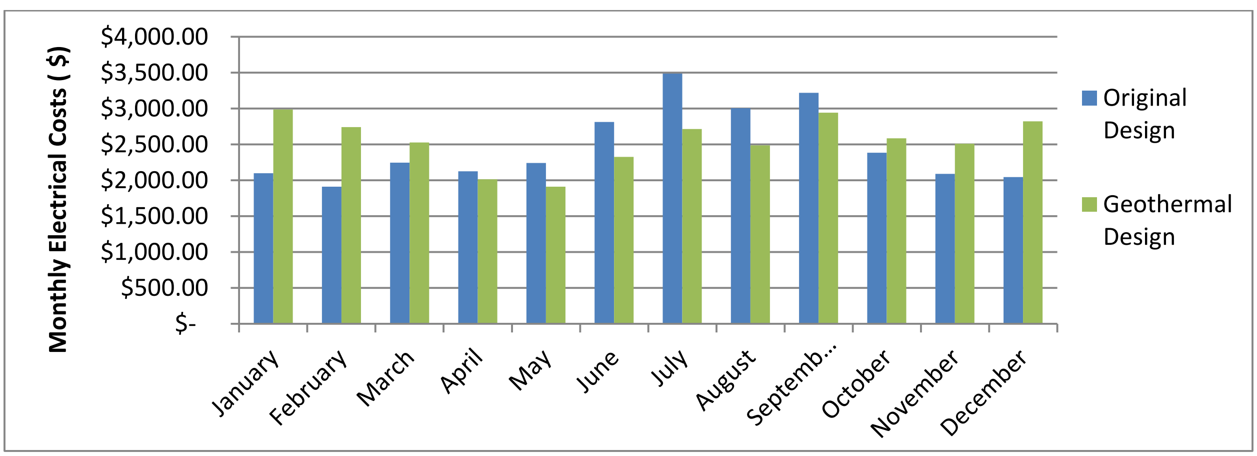


Figure 35: Monthly electricity costs for the original and geothermal redesign of the Gaige Building

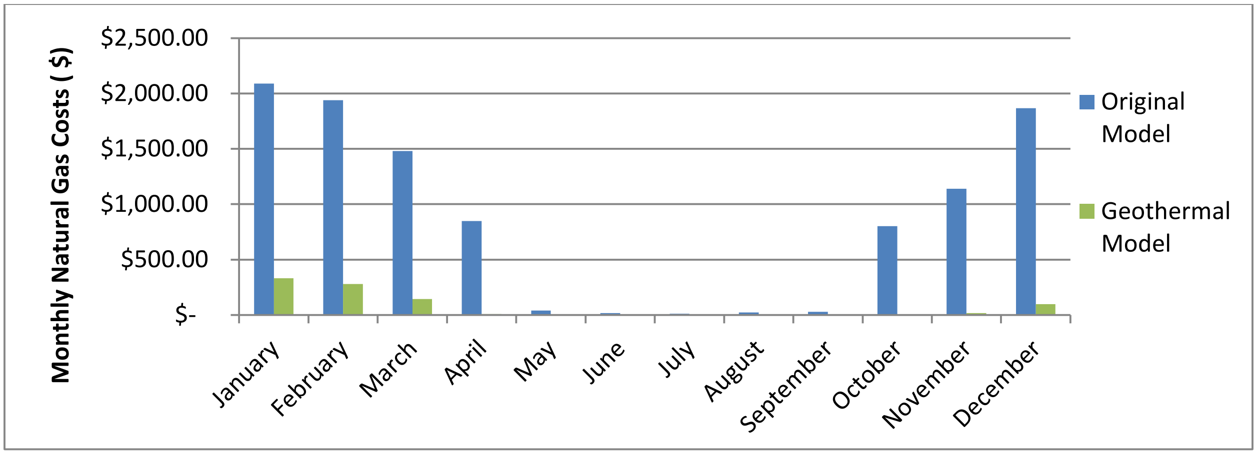


Figure 36: Monthly natural gas costs for the original and geothermal redesign of the Gaige Building

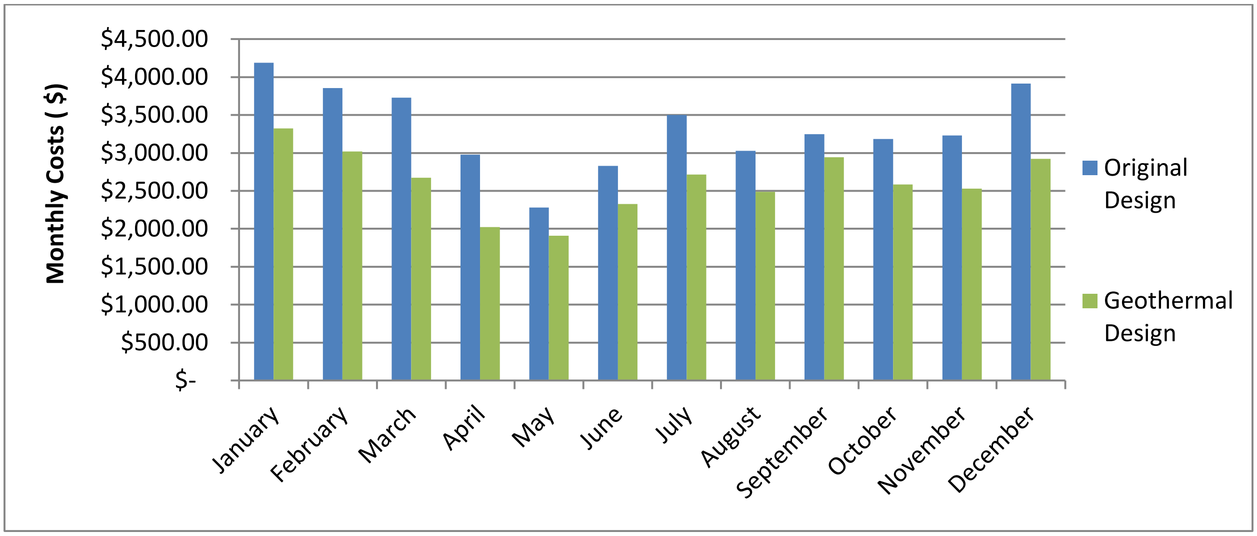


Figure 37: Monthly energy costs for the original and geothermal redesign of the Gaige Building

When it is calculated, by changing the Gaige Building to a geothermal system, an $8,494.00 energy savings can be realized. Although the electricity consumption costs are actually higher on an annual basis, there is a drastic decrease in natural gas consumption costs, which create the annual savings. The electricity costs are higher in the summer, due to the heat pump costs of operation year round, but they are lower in the summer, due to the more efficient cooling mechanism from implementing the geothermal system. Also, we can look at the annual energy consumption and savings on a monthly basis as well. Below, Figures 38 and 39 show the monthly energy consumption for natural gas and electricity for the original and geothermal redesign of the Gaige Building.

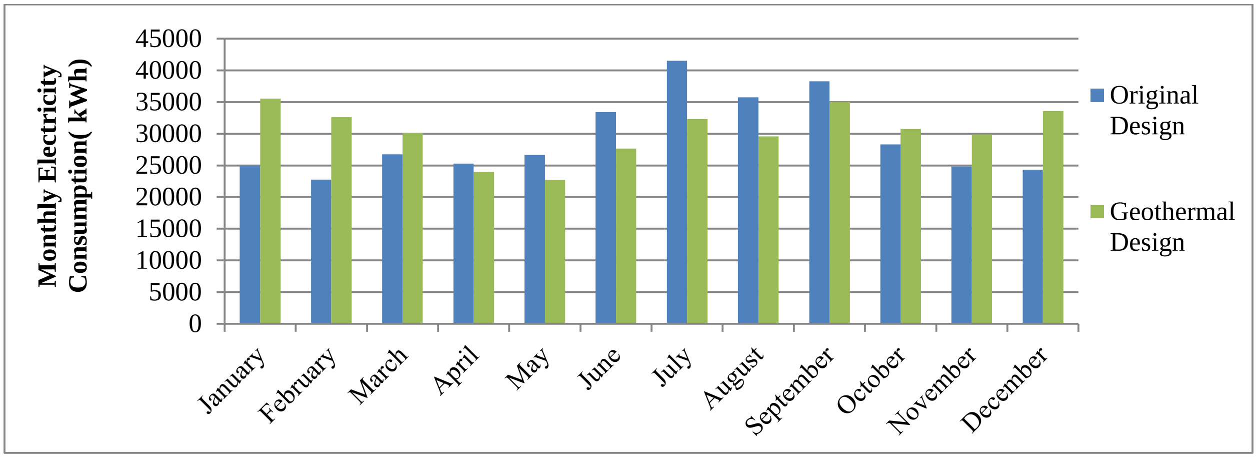


Figure 38: Monthly electricity consumption of the Gaige Building with the original and geothermal redesign

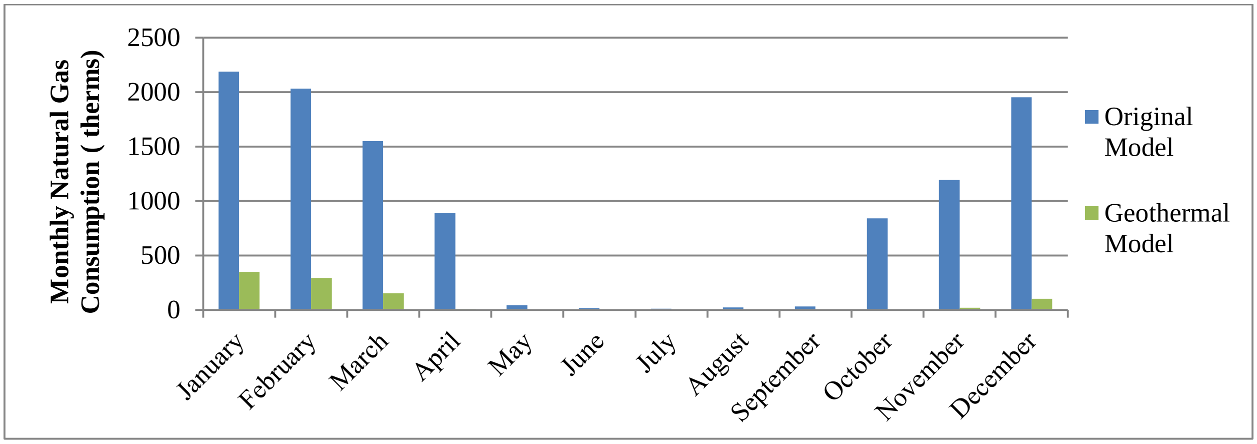


Figure 39: Monthly natural gas consumption of the Gaige Building with the original and geothermal redesign

The energy consumption roughly follows the same trends that can be seen in the energy cost graphs. As can be seen, new design of the Gaige Building is successful at reducing both energy consumption and cost. It must be further determined whether or not these energy savings will justify the increased initial costs of the geothermal system.

3.1.10: Source Energy Consumption and Emissions

When considering the success or failure of a mechanical system in a building, cost is not the only consideration. As well, it is important to look into the amount of pollutants that each particular option will put into the environment. Although this is not something that will 'pay off' for the building owner in the long run, it is an important decision that impacts the world around us and everyone that lives in it. For the Gaige Building, a previous analysis of the emissions for the original design was already provided in section 2.5.3. For the analysis and validation of the Gaige Building and for the geothermal model of the Gaige Building, some of the miscellaneous loads, such as receptacle loads and natural gas loads for kitchen equipment were removed from the model, for simplicity. The results below will show only the emissions from the Gaige Building due to the mechanical system's energy consumption. This is why the numbers are lower than what was seen in the previous analysis from chapter two. Below, Figures 40 and 41 show the emissions for the original HVAC system within the Gaige Building and the geothermal system respectively. Then, in table 21, the change in major pollutants for the Gaige Building is provided.

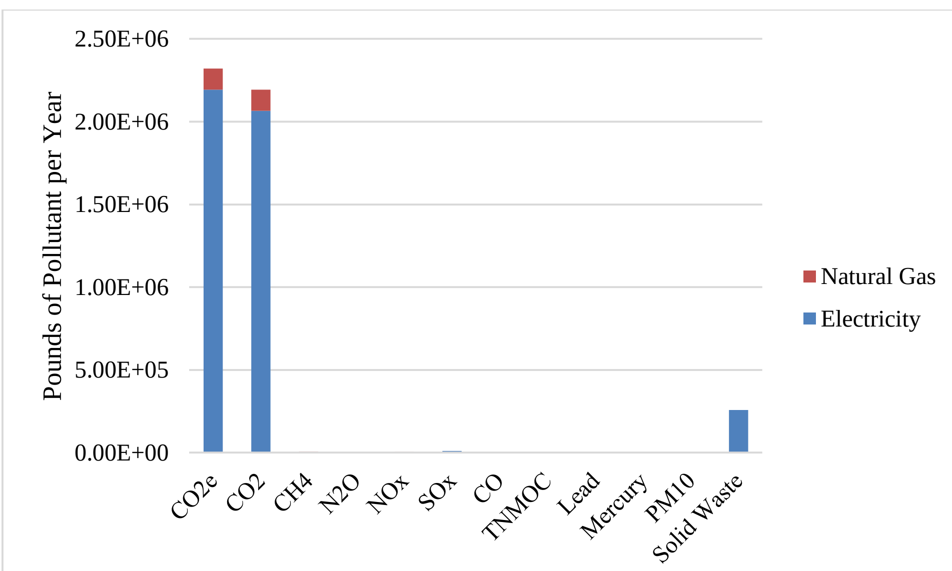


Figure 40: A graph showing the annual pollutants from the of the original Gaige Building's mechanical system

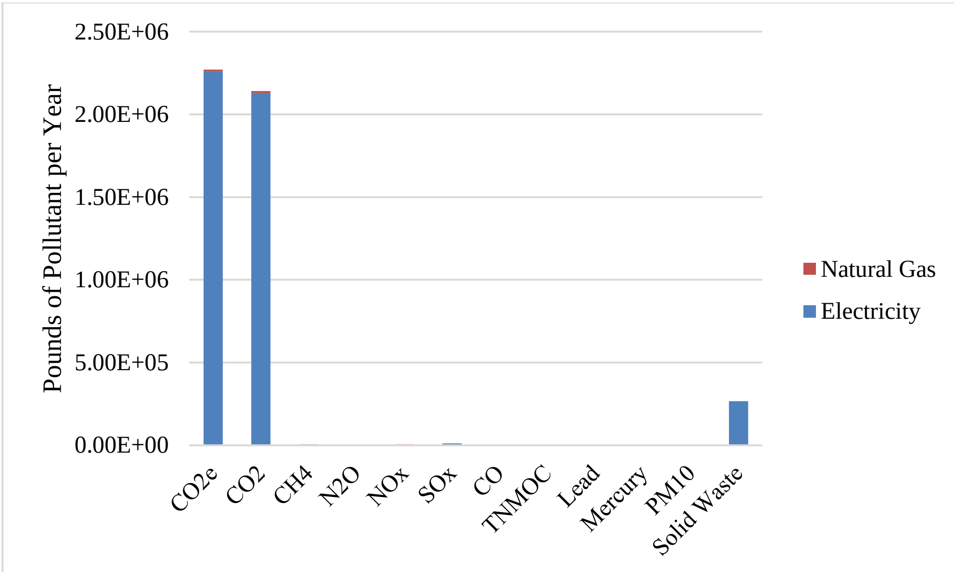


Figure 41: A graph showing the annual pollutants from the geothermal system for the Gaige Building

Difference in Total Annual Emissions			
Pollutant	Original Design Total Emissions (lb/yr)	Geothermal Design Total Emissions (lb/yr)	Percent Decrease %
CO2e	2321124.8	2270409.1	2.18%
CO_2	2194071.2	2140470.1	2.44%
CH4	4526.3	4661.8	-2.99%
NOx	3896.3	3905.4	-0.23%
SOx	10799.6	11128.1	-3.04%
CO	1173.6	1117.3	4.80%
Solid Waste	258316.8	266191.0	-3.05%

Table 21: A table showing the percent decrease in emissions from switching to a geothermal system

As you can see, there is very little change in the pounds of pollutant produced each year between swapping designs. The most prominent pollutants, CO_{2e} and Co_2 are both reduced by using the geothermal alternative system, although the reduction is only on the order of two percent. As well, CO is reduced, but it is a much less prevalent pollutant. Despite the large decrease in natural gas consumption, since it is a pretty clean fuel to burn, not much change is seen in the emissions of the Gaige Building. Finally, we can also look at a site versus source energy comparison for the new building. Below, Figures 42 and 43 show site energy consumption breakdown and source energy consumption breakdown for the Gaige Building. Although the energy consumption overall for source energy did not change much, the distribution between electricity and natural gas did change significantly.

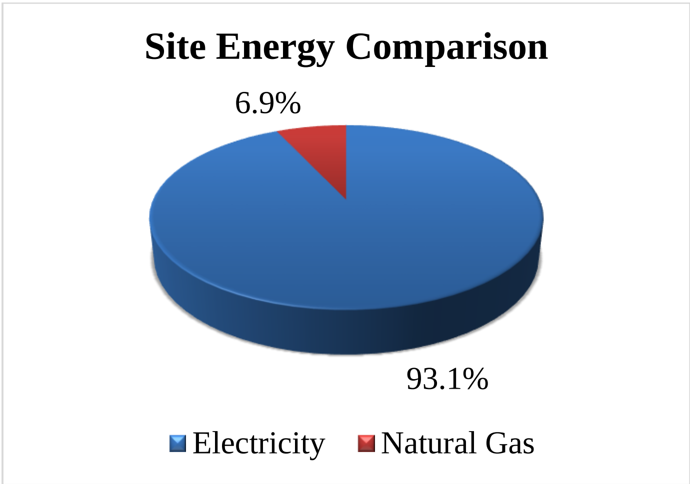


Figure 42: Site energy consumption for the Gaige Building with a geothermal system

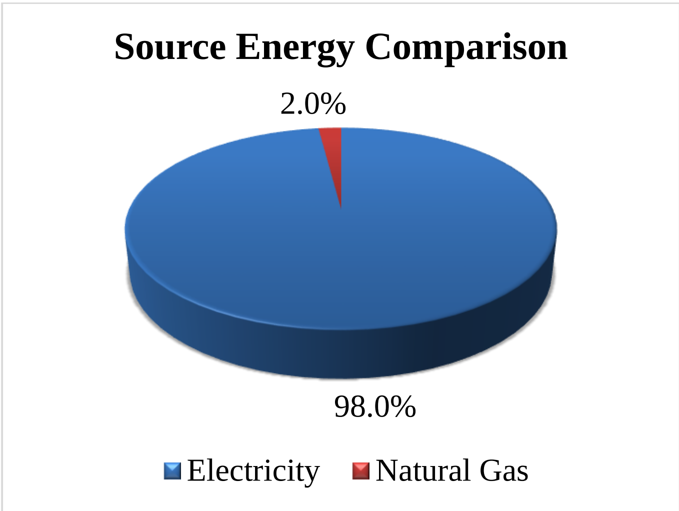


Figure 43: Source energy consumption for the Gaige Building with a geothermal system

3.1.11: Life Cycle Cost Analysis

Finally, we must determine whether or not the increased first costs for the Gaige Building will pay off over the life of the system, verifying whether or not a geothermal system can be successfully implemented. To do so, a life cycle cost analysis must be performed taking into account various factors. First, the analysis must take into account the increase in initial first costs for the implementation of a new system design. Then, you must also make judgments as to what the different systems' yearly maintenance costs and repairs will be. Finally, you must determine the annual savings, or the costs you will save each year due to decreased operating costs. A discounted payback analysis can be run to see how many years it will take the system to pay itself off. Once a system pays itself off, you could analyze how much money you might save over the life of the system, and put that savings towards the next required system overhaul. When a system reaches the end of its life, if it can pay for itself, and save enough money to replace the mechanical system in the building, then it is a successful project.

For the costs estimates, a thorough analysis of the increased costs associated with the materials, labor, and equipment required to install and maintain a geothermal system was performed. Only added costs were considered, such as the increased costs for heat pumps, geothermal well boring, laying pipe, etc. A detailed report of this cost estimating can be found in chapter five, or the construction breadth assignment of this thesis. Also, in this first costs estimate, some savings were realized from the initial system. Since the rooftop units and baseboard heaters were no longer required for the geothermal design, those numbers were taken to be savings from the original design, and helped to offset the increased initial first costs. Once the total first costs of the geothermal system was calculated, the savings were used to offset the pricing and the following were the final values for the increase in initial first costs. Table 22 below shows the increased first costs for the vertical geothermal piping system, and table 23 below shows the increased first costs of the horizontal geothermal system.

Vertical - Increased First-Costs	
Cost Item	**Amount**
Increased First Cost - General	$ 655,736.06
Location Multiplier - Reading PA	0.988
Increased First Cost - Reading	$ 647,867.23
Savings from Original Design - 2009	$ 484,710.00
Time Multiplier - 2014 to 2009	0.889
Savings from Original Design - 2014	$ 545,230.60
Overall First Cost Increase:	**$ 102,636.63**

Table 22: Increased first costs for the vertical well geothermal layout

Horizontal - Increased First-Costs	
Cost Item	**Amount**
Increased First Cost - General	$ 601,959.52
Location Multiplier - Reading PA	0.988
Increased First Cost - Reading	$ 594,736.01
Savings from Original Design - 2009	$ 484,710.00
Time Multiplier - 2014 to 2009	0.889
Savings from Original Design - 2014	$ 545,230.60
Overall First Cost Increase:	**$ 49,505.41**

Table 23: Increased first costs for the horizontal loop geothermal system

Above, you can see that the savings that were calculated in 2009 have been adjusted to their worth in 2014, and the estimates made using RS Means were adjusted using a location multiplier to Reading, PA. With these increased first costs, now a life cycle cost analysis can be run to determine what the payback period will be for both the vertical and horizontal geothermal systems. For both analysis, average estimates of maintenance costs are used for the building. For the original design, an average for university building annual maintenances costs of $0.12 per square foot is used, and then, a number for a building that has a lower maintenance cost per square foot was used for the geothermal options. That value was chosen to be $0.063 per square foot. These values were taken from an ASHRAE database, with a link provided below.

http://xp20.ashrae.org/publicdatabase/all_maintenance.asp?specific_selected=6

Now, with the maintenance costs set and the increase in initial first costs for the building determined, we can run life cycle cost analyses for both the horizontal well and vertical well cases. For the analyses, table 24 below summarizes the rates used for the escalation factors and the discount rate applied to the discounted payback analysis.

Life Cycle Rate Assumptions	
Discount Rate	8.00%
Escalation Rates	
Electricity	3.75%
Natural Gas	5.00%
Materials	1.73%
Main. & Labor	1.73%
Study Period	20 years

Table 24: Rates using in the life cycle costs analyses for the Gaige Building

After the analyses were run, the vertical geothermal well field option was found to have a simple payback period of about 12.1 years. When the discounted life cycle cost analysis was performed, taking into account maintenance costs, escalation factors, and a discount rate, the discounted payback period was found to be 12.7 years. The life cycle cost present value of savings graph is shown below in Figure 44.

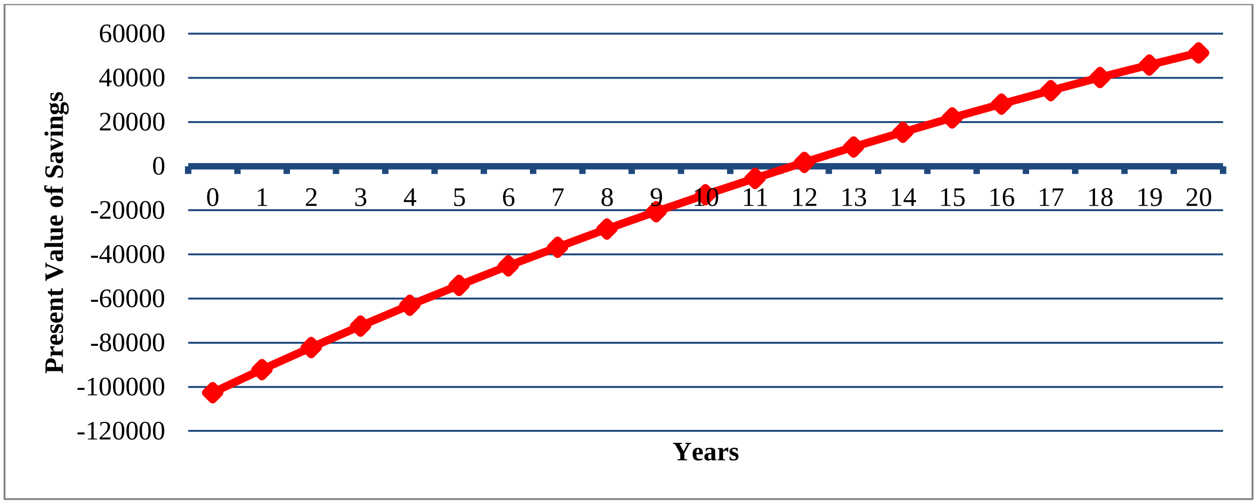


Figure 44: Life cycle cost analysis of the vertical well system for the Gaige Building

For the horizontal geothermal design, the same analysis was run, using the appropriate initial increase in first costs for the building. The simple payback for this analysis was found to be 5.83 years, and the discounted payback analysis showed a payback period of 6.13 years. The present value of savings for this design option is also shown below in Figure 45.

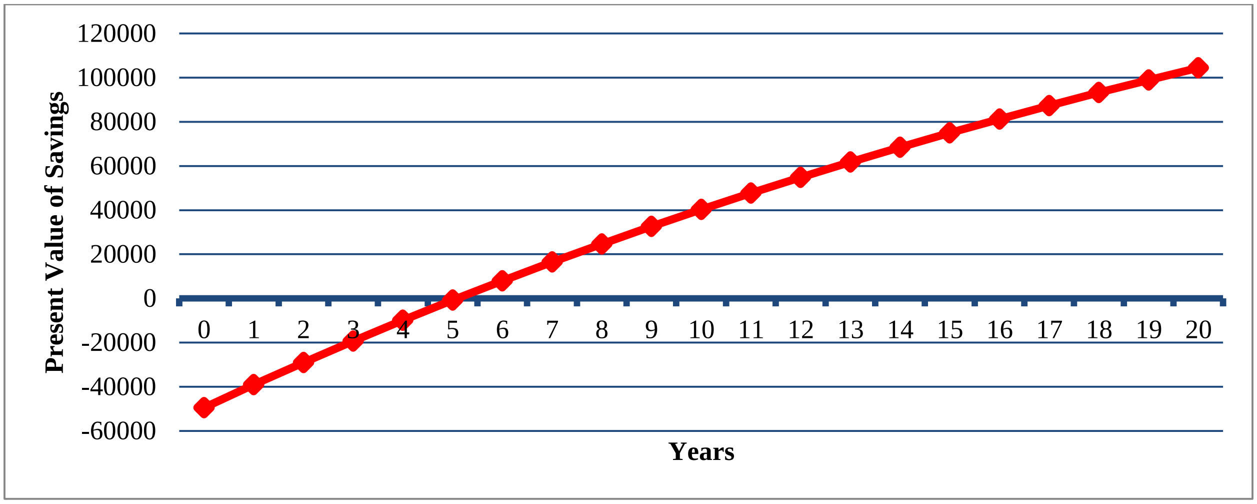


Figure 45: The life cycle cost analysis for the horizontal loop option for the Gaige Building

As can be seen from the present analysis, both of these options, when considering the increased initial investment, as compared to the original design of the building, will pay off within 13 years of the construction of the building. Considering the life of this building is most likely at least 50 years, and estimating the life of a geothermal system to be around 30 years or more, either system will pay back its initial investment and be a viable option for the Gaige Building. That being said, the horizontal loop option has a much better payback period. This is due to its reduced first costs, for it is not required to rent and bring in a rig to drill deep wells for the geothermal well field. Since the space is available, it is recommended that the horizontal loop system be selected for the building's design. If less space is desired to be used, options of placing multiple horizontal pipes in one trench could be considered.

If it is desired to use and disturb less space during the building's construction, the vertical well field is also a great option. It can be located right next to the building, allowing for much less disturbance of existing parking lots and some access roads. This might be a better option, depending upon whether or not the construction would take place during the school year when classes are in session. Both design options are fine choices, and the decision would be left to the owners to weigh out the pros and cons relating to the increased payback.

3.2: Campus-wide Geothermal System Analysis

After realizing the geothermal potential of the Reading, PA area, the idea of implementing a geothermal system for the entire Berks campus was also an option that could be analyzed. Toward the beginning of the project, I was provided with monthly billing data for all of the campus buildings on the Penn State Berks campus. With this data available, a rough estimate of how all of these building could work together, in one centralized system needed to be observed. With the rare opportunity of having many buildings with the same owner so close to each other, a centralized system needed to be analyzed.

3.2.1: Campus-wide Geothermal Motivation

Various factors influenced the motivation behind this analysis. First, it is known that whenever you can produce energy at a centralized plant, you can do so much more efficiently than if you are producing energy separately at many different sites with less efficient equipment. Also, for a geothermal system, since it is already extremely energy efficient, allowing many different load sources to take advantage of this efficiency would have great potential benefits. Also, the potential load diversity that could be present on the campus seemed like a good option as well. If all of the buildings were to be run off a centralized system, and if certain buildings have very difference schedules of loading, one building might experience maximum load a different time than other buildings. Instead of having to size multiple systems separately at the separate maximum loads, the two buildings energy sources could be combined, and great load diversity benefits could be realized.

On the Penn State Berks campus, many different types of building exist: public assembly spaces, classrooms, offices, dorm buildings, athletic facilities, and others. Along with all of these buildings being located relatively close to each other, there is still a large amount of open space available on the campus, which gives good potential to install geothermal well fields. If a certain amount of load diversity could be realized, it would also decrease the number of wells that would be required to serve the entire campus. This would be because loads peaking in the dormitories would happen later in the evening and at night, although loads for the classrooms and offices would peak before lunch and in the afternoon. These different types of loads being offset in schedule would allow for a smaller well field to serve the entire campus, operating at a more constant rate. The following section details how an approximate analysis of the feasibility of such a system was analyzed.

3.2.2: Campus Wide Load Analysis

First, a campus wide load study was conducted to determine the initial feasibility of the system. To do so, the monthly cost data for the Berks Campus was broken down into costs on a building by building basis, for total energy costs, electricity costs, and natural gas costs. Below, in Figures 46, 47, and 48 are the energy costs for the entire Penn State Berks Campus.

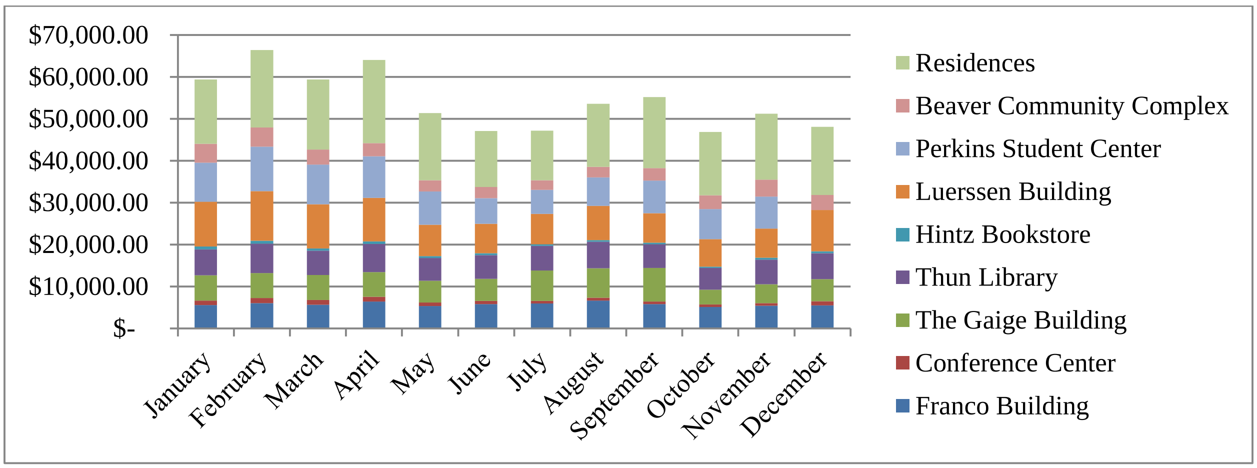


Figure 46: Total monthly energy costs for the Penn State Berks campus by specific building

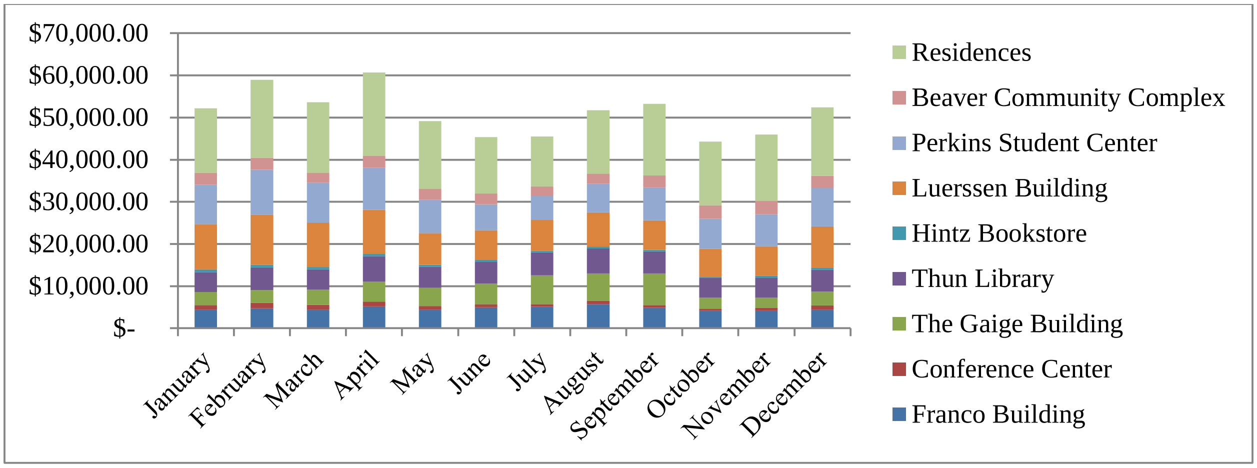


Figure 47: Total monthly electricity costs for the Penn State Berks campus by specific building

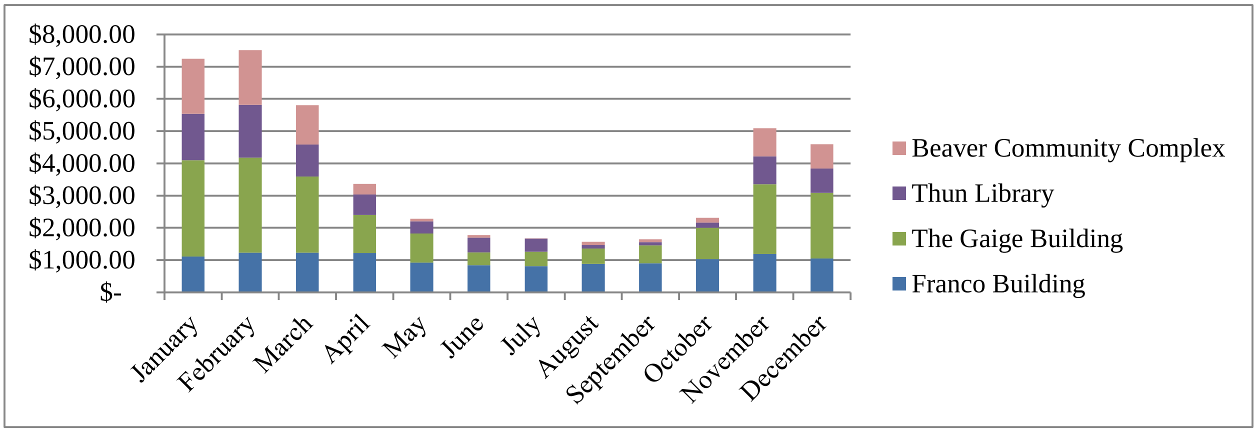


Figure 48: Total monthly natural gas costs for the Penn State Berks campus by specific building

Notice the significant amount of electrical energy costs used by the residences in comparison to the rest of the campus. Since the rest of the campus is mainly office/classroom type buildings, hopefully a large amount of load diversity can be realized by placing these different building occupancy types on a similar system.

3.2.3: Energy Analysis of Campus Buildings

To determine how much potential savings on energy from the Berks campus could be realized, the heating, cooling, and ventilation load must somehow be extracted from the monthly energy bills for the campus buildings. Since very limited knowledge was known on each building's size, location, and specifics, somehow average building energy usage data that was broken down by building type and percentages of total energy use needed to be utilized. This way, as long as a total energy use was known for the building and what type of building it was, we could roughly extract the heating, cooling, and ventilation energy loads from the monthly bills, using percentage estimates. This energy would be the amount of the bills that could be serviced by a geothermal system and realized into energy savings, instead of the current design situation.

To do this analysis, a study conducted by the Energy Information Administration (EIA) from 2003 and 2008 was utilized. This survey recorded the individual end use of each particular fuel type servicing a building, including natural gas and electricity. Overall, it provides detailed annual costs for these building by end use of the fuel. Building information on year of construction, occupancy type, location, and much more is also provided in the data from the survey. To determine the energy breakdowns of the Penn State Berks campus buildings, building information from this survey was taken and averaged over many different building that had similar characteristics to the specific campus buildings. First, table 25 below summarizes the different building on the Penn State Berks campus, and what type of occupancy they serve.

Penn State Berks Campus Buildings	
Building Name	**Occupancy**
The Franco Building	Office/Classroom
Janssen Office Building	Office
Janssen Conference Center	Public Assembly
The Gaige Building	Classroom/Office
Thun Library	Public Assembly/Office/Classroom
Hintz Bookstore	Retail
Luerssen Building	Classroom
Perkins Student Center	Office/Food Service/Public Assembly
Beaver Community Center	Public Assembly/Office
Woods Residence Complex	Lodging
Amber House	Lodging
Poplar House	Lodging
Willow House	Lodging
Ivy House	Lodging
Juniper House	Lodging
Evergreen House	Lodging
Pepperwood House	Lodging
Village Residence Complex	Lodging
Laurel Hall	Lodging
Bowman Hall	Lodging
Sweetwood Hall	Lodging
Oakmoss Hall	Lodging
Greenbrier Hall	Lodging
Sage Hall	Lodging
Cedar Hall	Lodging

Table 25: A list of the Berks campus building and their occupancy types

To determine what portions of the load of the building were devoted to heating, cooling, and ventilation, EIA data was taken for the educational, office, public assembly, lodging, retail, and food service type buildings. To get the best averages, most relating to the Penn State Berks, the building data was filtered so only buildings in the Mid-Atlantic region, around Pennsylvania and New York, that were built after 1970 and were of the desired occupancy type were included. So, for each type of building, the buildings that met the listed criteria were grouped, and percentages were developed of what amount of total energy, for electricity and natural gas, was devoted to heating, cooling, and ventilation.

The only other specific in the analysis was that for some of the campus building, they were not supplied with natural gas, and only received electricity. For these building, instead of determining percentages for electricity and natural gas separately, the EIA data that provided overall energy costs in a building by end use was used. This was used for it did not assume any particular type of fuel use in the building, and is more generalizable across different buildings and system configurations. Below, in tables 26 and 27, a summary of the percentages estimates for each building type is given.

Energy Multipliers for Electric - Natural Gas Energy Source Buildings

Building Type	Heating		Cooling		Ventilation
	Electricity	Natural Gas	Electricity	Natural Gas	
Office - Mid Atlantic	5.88%	54.94%	9.52%	4.01%	9.83%
Classroom - Mid Atlantic	4.93%	68.61%	11.20%	0.00%	30.28%
Public Assembly - Mid Atlantic	1.63%	54.90%	4.96%	38.78%	51.11%
Classroom / Office Averaged	5.40%	61.77%	10.36%	2.00%	20.05%
Public Assembly/Classroom/Office	4.15%	59.48%	8.56%	14.26%	30.40%
Public Assembly/Office	3.75%	54.92%	7.24%	21.39%	30.47%

Table 26: Summary of the percentage of overall fuel use for the heating, cooling, and ventilation of building that use both natural gas and electricity as an energy source

Energy Multipliers for Electric only Buildings

Building Type	Heating	Cooling	Ventilation
Office - Mid Atlantic	27.99%	7.21%	6.18%
Public Assembly - Mid Atlantic	39.95%	19.08%	20.98%
Classroom - Mid Atlantic	50.72%	4.91%	13.26%
Lodging - Mid Atlantic	12.46%	5.43%	2.18%
Food Service - Mid Atlantic	17.51%	2.98%	3.69%
Retail - Mid Atlantic	31.24%	6.24%	8.06%
Classroom / Office Averaged	39.36%	6.06%	9.72%
Office/Food Service/Public Assembly	28.48%	9.76%	10.28%

Table 27: A summary of the percentage of electricity used for heating, cooling, and ventilation for the electric only service building on the Penn State Berks campus

After developing these percentage estimates from the EIA database, the annual total heating and cooling loads for each building was estimated. For the ventilation load, since it was not separated into heating and cooling data separately in the EIA building survey, the ratio of heating ventilation energy to cooling ventilation energy from the previous in depth analysis of the Gaige Building was applied to each building's ventilation type load. Although this is an approximation, since all of the buildings are located on the same campus, in the same region, they should have similar comparisons between heating and cooling ventilation air energy consumption, despite differences in amount of ventilation energy required. Once this data was calculated, table 28 below summarizes the total annual heating and cooling energy that was determined for each campus building. With this data, a model can be made to estimate the annual savings from implementing a geothermal system for the entire Penn State Berks Campus.

Annual HVAC Energy Usage Estimates		
Building Name	Totals	
	Electricity (kWh)	Natural Gas (therms)
The Franco Building	163007	7525
The Gaige Building	223701	11643
Thun Library	330557	7041
Luerssen Building	800746	0
Janssen Conference Center	101072	0
Perkins Student Center	593073	0
Beaver Community Center	176622	5607
Hintz Bookstore	31168	0
All Campus Residences	455342	0

Table 28: Overall annual energy use estimates for each campus building

3.2.4: Modeling Validation of Overall Campus Energy Consumption

Next, a block load model for the entire Penn State Berks campus was made using Trace 700. First, gross square-footage estimates were taken for each building, and rough building heights were estimated for each building as well. Then, in a Trace 700, each campus building was modeled separately. The building was modeled as one space, and ventilation loads, internal loads, and other general specifics were all based upon typical values for a particular building type. Building envelope construction values were assumed to be ASHRAE baseline standards, and each building was assumed to have 35 % windows on all walls. Each building was given an ASHRAE baseline standard system type, with either an electric or natural gas boiler, depending upon the building. With each building modeled separately, an annual energy consumption was estimated. The results of the trace model were compared against target values in table 28, and internal loads were adjusted until the annual energy consumption matched the target value set from the analysis with the EIA data. Below, table 29 summarizes the comparison of the EIA target energy consumption values with the model outputs for each building separately in Trace 700.

Model Validation Performance						
Building Name	EIA Targets		Model Results		Percentage Deviations	
	Electricity (kWh)	Natural Gas (therms)	Electricity (kWh)	Natural Gas (therms)	Electricity (kWh)	Natural Gas (therms)
The Franco Building	163007	7525	164693	7905	1.03%	5.04%
The Gaige Building	223701	11643	226577	11816	1.29%	1.49%
Thun Library	330557	7041	331394	7089	0.25%	0.69%
Luerssen Building	800746	0	800627	0	0.01%	n/a
Janssen Conference Center	101072	0	100504	0	0.56%	n/a
Perkins Student Center	593073	0	592461	0	0.10%	n/a
Beaver Community Center	176622	5607	177305	5338	0.39%	4.79%
Hintz Bookstore	31168	0	31800	0	2.03%	n/a
All Campus Residences	455342	0	458615	0	0.72%	n/a

Table 29: Percentage deviations between EIA data targets for annual energy consumption and Trace 700 results

As you can see, the individual building spaces are now extremely well matched to the targets set using the EIA data estimation. The validation and adjustments of the internal loads now have accurately modeled each building's energy usage on an annual basis. The errors are all less than about 5.0%, which is an acceptable range of error, and this maximum error only occurs for two quantities in table 29 above. Other errors are all around 2.0% or less.

3.2.5: Geothermal Modeling of Overall Campus

Now that a model of each campus building has been created and validated, a Trace model of the entire campus needs to be created. For this model, all of the buildings that were modeled separately in the prior analysis were all combined into one Trace 700 model. For the purposes of this analysis, each building is treated as a 'room' and the buildings are then all able to be connected into the same central system. Again, the trace models for the buildings only contain HVAC loads and energy uses. All other loads, such as receptacle and other miscellaneous loads have been removed from the model for simplicity in model comparison and validation. First, all of the buildings were added together, and two systems were created for the model. One was packaged rooftop unit system with a gas fired boiler, and the other was a packaged rooftop unit system with electric resistance heating. The buildings were then assigned to the system that was representative of their current design. From this, energy rates were given, and total annual energy cost and consumption estimates were extracted.

After this new 'baseline' model was created, the model was copied, and the system servicing the campus was changed. The system was altered to a ground loop source that was serviced by water source heat pumps. The number of water source heat pump assigned to each building was determined using data from the Gaige Building's analysis. The total number of heat pumps in the Gaige Building was divided by the cooling load of the Gaige Building, provided a heat pumps per ton of cooling fraction. Then, this fraction was simply multiplied by each buildings' peak cooling load to determine the number of heat pumps that should be placed designed into the model. Finally, the model of the entire campus, now on a solely geothermal system was run. Below, Figure 49 summaries the comparison between monthly costs of the entire campus using its current system and using a potentially full geothermal system. Overall, an annual energy savings of $58,166.00, which will go toward paying off the initial increased costs of the system.

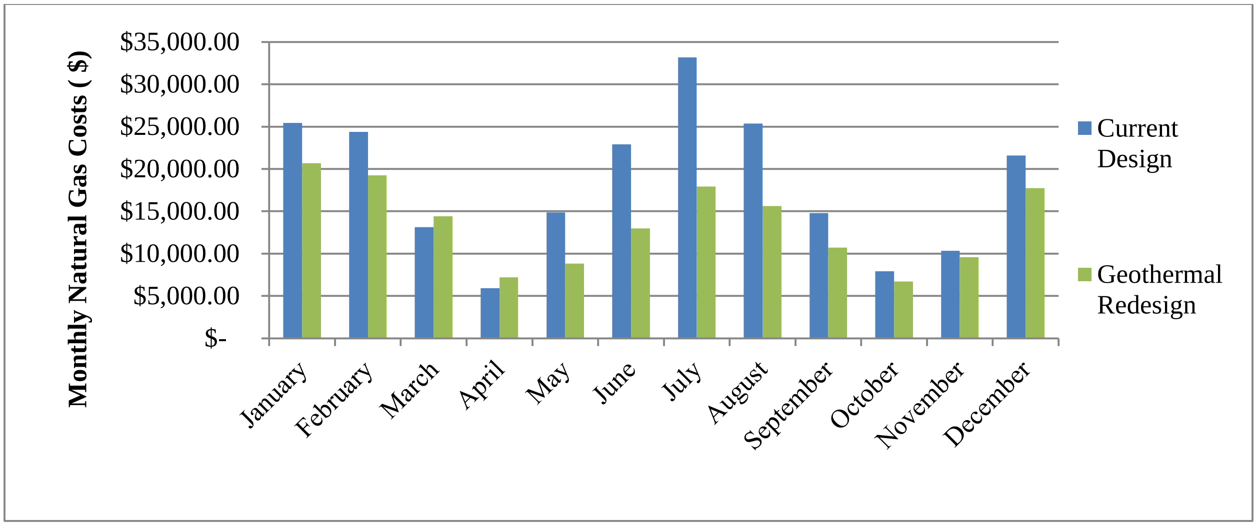


Figure 49: Annual energy cost comparison between the original campus and the geothermal redesign of the campus

3.2.6: Campus Wide Geothermal Sizing and Layout

Another goals of the campus-wide geothermal system for the Berks Campus was reducing the total number of well required by taking advantage of the load diversity among the campus. Since geothermal well fields are designed to peak loading conditions, the diversity among campus buildings will cause the overall peak for the campus to be less than the sum of all the building peak cooling and heating loads. Below, table 30 summarizes the calculation for the required length of the geothermal sizing for the entire campus. All design assumptions are the same as in the design of the Gaige Building's geothermal length requirements, but the amount of pumping energy required has increased since larger volume of water will now flow through the loops and the pumps that supply water to the building will be larger.

Campus-wide Geothermal Design		
Parameter	Heating	Cooling
Short-Circuit Factor (F_{sc})	1.04	1.04
Part-Load Factor (PLF_m)	1	1
Average Heat Transfer to Ground (q_a)	-1390309	-1390309
Block Loads (q_{lc} and q_{lh})	17939009	16548700
Resistance of Ground, Annual pulse (R_{ga})	0.215	0.215
Resistance of Ground, Daily pulse (R_{gd})	0.129	0.129
Resistance of Ground, Monthly pulse (R_{gm})	0.207	0.207
Resistance of Bore (R_b)	0.09	0.09
Undisturbed Ground Temperature (t_g)	53	53
Temperature Penalty for Bore Spacing (t_p)	1.8	1.8
Heat Pump Inlet Temperature (t_{wi})	38	78
Heat Pump Outlet Temperature (t_{wo})	33	85
System Power Input (W_c and W_h)	111855	111855
Required Bore Length (L_c and L_h)	463653.1	220436.7

Table 30: Required geothermal total well lengths for the campus-wide geothermal system

With the total of 463,653 required feet of geothermal wells, it is clear from the previous geothermal layouts for the Gaige Building that a deep vertical well design must be used. This is the only way the geothermal wells could be placed in the open area available and meet the given loading requirements. For the wells, 500' deep well were chosen as a balance between space requirements and drilling depth requirements. For the total length, the number of bores is calculated below, with a safety factor of 1.1 applied.

$$\#\ of\ Bores = 1.1 * \frac{463653.1}{500} = 1020\ wells$$

To air on the side of caution, since this will be the main energy source for the campus, the total number of wells was then rounded up to the nearest 50, to 1050 wells, which is more on the order of a safety factor of 1.13. This extra 'oversizing' of the campus system will allow for sections of the well field to be shut off if some sort of break occurs. Since the pipes are bored into the ground, maintenance of existing bores is seemingly impossible, for new bores would probably just be drilled as a replacement. Below, Figure 50 shows the potential vertical well field layout and distribution piping plan for the campus. The wells are shown in green and the orange boxes are pump locations.

Figure 50: A layout of the overall geothermal system to serve the campus. Well field piping is shown in blue and red, and orange piping is part of the campus distribution piping. Pumps are shown as orange boxes

Another goal of this system was to take advantage of the diverse loads on the campus. To demonstrate what gains were found from building load diversity, the maximum geothermal length calculations were performed for each building separately, and then these lengths were all added together. This value, of geothermal bore requirements with separate building compared to geothermal bore requirements for a centralized geothermal plan will help to demonstrate the diversity. Below, table 31 first shows what the total bore requirement would be if all of the campus buildings are considered to be separate, using 500' vertical geothermal wells. As can be seen, from the campus system, the geothermal wells were able to realize an 89% diversity factor.

Building	Required 500' Bores
The Gaige Building	48
The Franco Building	109
The Thun Library	173
The Hintz Bookstore	4
The Beaver Community Commons	122
The Perkins Student Center	202
The Janneson Conference Center	37
The Luerssen Building	284
All Campus Residences	58
Total Bores for Campus, separate	**1038**
Total Bores for Campus, together	**928**
Diversity Realized	**89.4%**

Table 31: A comparison between the required geothermal lengths for separate and centralized geothermal systems

3.2.7: Cost and Energy Analysis

Now, the campus-wide geothermal system option must be considered as to whether or not will be a successful implementation into the Penn State Berks Campus. First, the success of the system can be determined by the emissions reductions that occur as a result of the system. Below, a similar analysis is done, comparing the non-geothermal system for the Berks Campus with the geothermal system retrofit for the campus. Figure 51 shows the annual emission for the original campus, at its current state, and then Figure 52 shows the annual emission for the geothermal redesign of the campus.

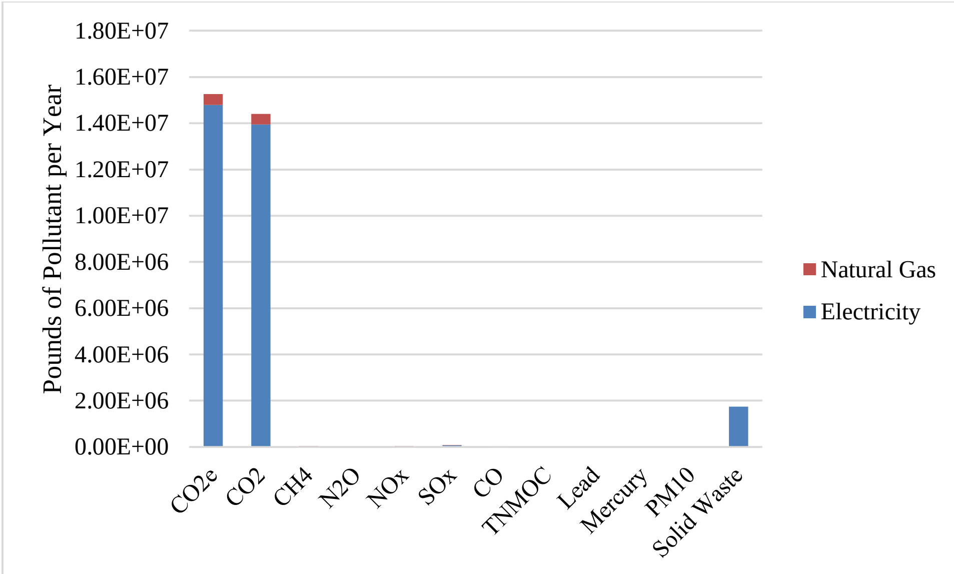


Figure 51: Estimated annual emissions from the current campus system for Penn State Berks

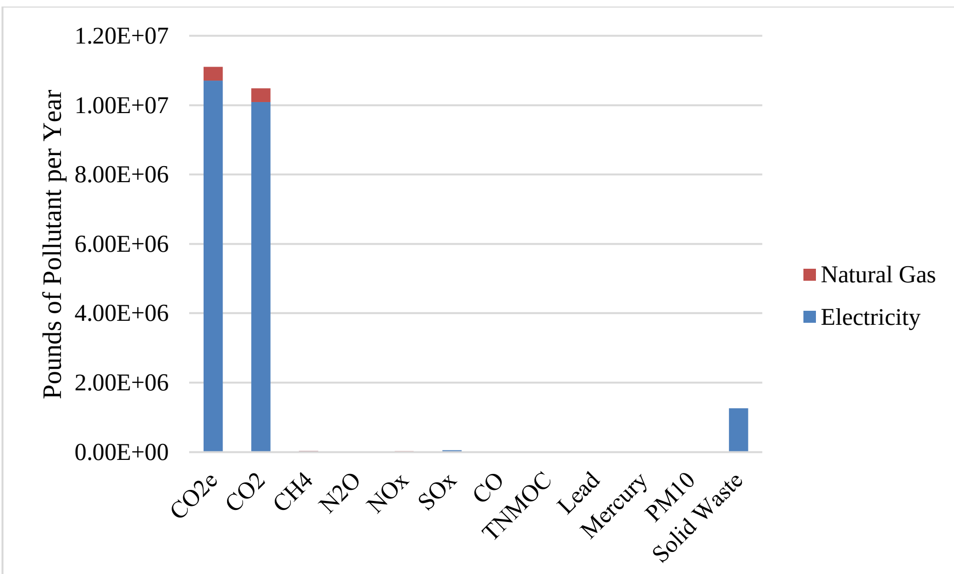


Figure 52: Estimated annual emissions from the geothermal redesign of the Penn State Berks campus

As can be seen in the Figures above, there is a drastic reduction in total emissions from the geothermal redesign of the Gaige Building. Table 32 below summarizes the reduction in emission for each pollutant included in Figure 51 and 52. When looking at these results, a total emissions reduction around 27.0% to 27.5% can be found for all of the pollutants in the Berks Campus.

Where the main energy savings for the Gaige Building came from natural gas expenses, some of the campus buildings use electricity as their sole heating and cooling source. The reduction in electricity use has an extremely large impact upon source energy consumption, for electricity has a much higher source energy consumption penalty due to its large losses during transportation and production, as opposed to the negligible losses for natural gas. As a way of reducing the annual emission of pollutant to the environment, the geothermal redesign for the campus is extremely successful option.

Difference in Total Annual Emissions			
Pollutant	**Original Design Total Emissions (lb/yr)**	**Geothermal Design Total Emissions (lb/yr)**	**Percent Decrease %**
CO2e	15258985.5	11108037.4	27.20%
CO_2	14405155.4	10489303.8	27.18%
CH4	30525.2	22104.3	27.59%
N_2O	338.5	246.3	27.24%
NO_x	25923.5	18824.4	27.38%
SO_x	72849.1	52749.9	27.59%
CO	7614.6	5558.6	27.00%
TNMOC	640.5	466.7	27.13%
Lead	1.2	0.9	27.57%
Mercury	0.3	0.2	27.55%
PM10	819.1	597.2	27.10%
Solid Waste	1742541.0	1261763.3	27.59%

Table 32: Annual pollutant emissions for each design, and the percentage reduction from the geothermal redesign

Finally, the other relevant factor in weighing the success of the campus-wide geothermal redesign for the Berks campus is the life cycle cost analysis of the implementation of the new system. To do this, an annual savings of $58,166.00 from section 3.2.5 has already been shown. For the rest of the life cycle cost analysis, the other considerations that must be made are the increased first costs due to heat pumps, dedicated outdoor air units, geothermal well field and piping materials, labor, and equipment costs, building piping costs, etc. Since the entire well field for the campus system has been designed, costs associated with the well field can be accurately estimated based upon design calculations and cost estimating. A summary of the campus-wide geothermal well field costs can be found in Appendix E. The total costs for the campus geothermal well field, from appendix E, comes out to $5,234,544.88.

To estimate the increased first costs that would be required for the installation of heat pumps, outdoor air units, pumps, and maintenance of each building, values from the Gaige Building analysis were used. For each of these categories, the total costs for each area was divided by the Gaige Building's design cooling load, providing an estimate of cost in $/Btu/hr. then, these estimates were multiplied by the cooling loads for each of the campus buildings, and rough estimates of the increased first costs could be calculated. Values are calculated for each building, and then it is broken down into a total increased first cost for all of these system for the overall campus. Below, tables 33 and 34 summarize these calculations and estimates.

Building Name	**Peak Cooling**	**Costs of System for Each Building**			
		# Heat Pumps	**Heat Pumps**	**Heat Pump Piping**	**Building Pumps**
Costs of System, &/Btu/hr cooling		2.12E-05	5.45E-02	4.65E-03	1.07E-02
The Franco Building	1921100	41	$ 104,758.71	$ 8,934.18	$ 20,584.45
The Gaige Building	2782100	59	$ 151,709.54	$ 12,938.30	$ 29,810.00
Thun Library	3225500	68	$ 175,888.40	$ 15,000.36	$ 34,561.00
Luerssen Building	2878300	61	$ 156,955.38	$ 13,385.69	$ 30,840.78
Janssen Conference Center	462700	10	$ 25,231.30	$ 2,151.81	$ 4,957.80
Perkins Student Center	2431400	52	$ 132,585.66	$ 11,307.36	$ 26,052.27
Beaver Community Center	1650600	35	$ 90,008.18	$ 7,676.20	$ 17,686.06
Hintz Bookstore	67300	1	$ 3,669.91	$ 312.98	$ 721.11
All Campus Residences	970500	21	$ 52,921.93	$ 4,513.36	$ 10,398.84
	Totals:	**348**	**$ 893,729.02**	**$ 76,220.24**	**$ 175,612.31**

Table 33: Estimate of initial costs for heat pumps, heat pump piping, and building water pumps for the campus

Building Name	Peak Cooling	Costs of System for Each Building		
		DOAS Cost	Maintenance	
			Original	Geothermal
Costs of System, &/Btu/hr cooling		3.11E+00	1.00E+00	6.89E-01
The Franco Building	1921100	$ 12,567.49	$ 4,045.97	$ 2,785.75
The Gaige Building	2782100	$ 18,200.00	$ 5,859.29	$ 4,034.27
Thun Library	3225500	$ 21,100.64	$ 6,793.12	$ 4,677.23
Luerssen Building	2878300	$ 18,829.32	$ 6,061.90	$ 4,173.77
Janssen Conference Center	462700	$ 3,026.90	$ 974.48	$ 670.95
Perkins Student Center	2431400	$ 15,905.78	$ 5,120.70	$ 3,525.72
Beaver Community Center	1650600	$ 10,797.93	$ 3,476.28	$ 2,393.50
Hintz Bookstore	67300	$ 440.26	$ 141.74	$ 97.59
All Campus Residences	970500	$ 6,348.84	$ 2,043.94	$ 1,407.30
	Totals:	**$ 107,217.17**	**$ 34,517.41**	**$ 23,766.09**

Table 34: Estimates for the initial costs of DOAS units and building maintenance for the campus

Overall, these totals come out to an increase in initial first costs for the campus of $1,252,778.74 for building costs, and a maintenance cost of $34,517.41 per year for the original campus, with a decreased maintenance cost per year of $23,766.09 for the geothermal system. Now that the cost estimates have been made for building expenses, maintenance costs, and well field costs, we can calculate the final increase in first costs for the campus-wide geothermal system. For this analysis, the savings from the Gaige Building's original design are still included, assuming that this system had not been constructed yet, but all other buildings are assumed to be built, so no savings are realized from their current system design. Below, table 35 shows the increase in first costs for the previously discussed estimates for a geothermal well field of 1050 vertical bores.

Horizontal - Increased First-Costs	
Cost Item	**Amount**
Increased First Cost - Building Costs	$ 1,252,778.74
Increased First Cost – Well Field Costs	$ 5,734,520.38
Location Multiplier - Reading PA	0.988
Increased First Cost - Reading	$ 6,903,451.53
Savings from Original Design - 2009	$ 484,710.00
Time Multiplier - 2014 to 2009	0.889
Savings from Original Design - 2014	$ 545,230.60
Overall First Cost Increase:	**$ 6,358,220.94**

Table 35: Overall increase in first costs for the campus geothermal system

Once this increase in first costs is applied, and a discounted payback life-cycle cost analysis is run with the previously discussed maintenance costs, it is found that the simple payback for the campus-wide geothermal system was around 70 years, which will not produce a favorable payback period. To determine in any increase in load diversity would help decrease the payback period substantially, an analysis was run, changing the number of bores required by increasing a load diversity percent reduction factor. Below, table 36 summarizes the simple payback period results for the different percent diversity factors.

Simple Payback with 10% Safety Factor			
Load Diversity % Reduction	**Bores with 10% Safety**	**First Cost Increase**	**Simple Payback**
100%	1142	$ 6,185,478.68	82.64
95%	1085	$ 5,906,080.61	78.90
90%	1028	$ 5,626,682.53	75.17
85%	971	$ 5,347,284.45	71.44
80%	914	$ 5,067,886.37	67.70
75%	857	$ 4,788,488.30	63.97
70%	800	$ 4,509,090.22	60.24
65%	743	$ 4,229,692.14	56.51
60%	686	$ 3,950,294.06	52.77
55%	628	$ 3,665,994.26	48.98
50%	571	$ 3,386,596.19	45.24
Actual Building	1050	$ 5,734,520.38	76.61

Table 36: A table summarizing the simple payback period as the number of bores is adjusted with load diversity

As can be seen, even if a 50% diversity factor is found, meaning the peak building loads for half of the campus load occurs at a time when the other has experiences no load, the payback period is still on the order of 50 years, which is approaching the potential life of the system. Also, these estimates are assuming no discount rate, which is not an extremely realistic assumption. Otherwise, the payback period would be seemingly infinite for most of these cases.

With the current analysis, no initial savings from other design options is being realized, for it is assumed that this would be a retrofit project, and not a design alternative, as is assumed with the Gaige Building. To determine what type of initial savings would justify this system installation, various levels of savings were analyzed to determine what type of initial first costs could be justified with the current annual energy savings. Below, table 37 summarizes an added savings that could justify the construction of the campus wide geothermal system. These savings could be the result of a dormitory renovation, a construction of a new building, or even a goal of future campus expansion. Then, it compares the added savings with a new increased first cost estimate, along with a simple and discounted payback criterion.

Savings Comparison – With Current Safety Factor			
Increased Initial Savings ($)	**New Initial First Cost**	**Simple Payback Period**	**Discounted Payback Period**
Current Design	$ 5,734,520.38	76.61	> 40 years
$ 1,000,000.00	$ 4,734,520.38	63.25	> 40 years
$ 2,000,000.00	$ 3,734,520.38	49.89	> 40 years
$ 3,000,000.00	$ 2,734,520.38	36.53	> 40 years
$ 4,000,000.00	$ 1,734,520.38	23.17	> 40 years
$ 4,250,000.00	$ 1,484,520.38	19.83	> 40 years
$ 4,400,000.00	$ 1,334,520.38	17.83	30.11
$ 4,500,000.00	$ 1,234,520.38	16.49	25.02
$ 4,600,000.00	$ 1,134,520.38	15.16	21.56
$ 4,700,000.00	$ 1,034,520.38	13.82	18.76
$ 4,800,000.00	$ 934,520.38	12.48	16.34
$ 4,900,000.00	$ 834,520.38	11.15	14.18
$ 5,000,000.00	$ 734,520.38	9.81	12.21
$ 5,100,000.00	$ 634,520.38	8.48	10.39
$ 5,200,000.00	$ 534,520.38	7.14	8.68
$ 5,300,000.00	$ 434,520.38	5.80	7.08
$ 5,400,000.00	$ 334,520.38	4.47	5.56
$ 5,500,000.00	$ 234,520.38	3.13	4.10

Table 37: A table showing how an added first cost savings can impact the campus-wide system's payback period

As you can see, the simple payback estimate doesn't start to produce a realistic payback period until an initial savings on investing of around $3,000,000.00 is found, and the discounted payback period does not become feasible until around a $4,400,000.00 initial savings on investment is shown. For the Penn State Berks campus, this is probably not a realizable goal, but for a campus that is undergoing substantial renovations, large amounts of growth, or simply an overhaul on many of the building's mechanical systems, savings could be realized by removing the need for expensive air handling units, reducing the amount of ductwork required to be installed, and heating or cooling distribution systems, like fin tube or radiant heaters. Overall, a more campus oriented system might pay off, but it would be heavily dependent upon the campus's future building goals, plans, and direction.

Chapter 4: Acoustical Breadth

In order to consider how the new geothermal system would impact the acoustic performance of the Gaige Building, an acoustical analysis was performed. In this analysis, heat pump locations were modeled in Odeon, a room acoustics program. This program allows a user to model room geometries, assign material properties to surfaces, specify transmission loss values to room partitions, place sound sources within rooms, and place receivers, or measurement locations, within the rooms as well. ODEON was used to determine how specific heat pump placements impacted the background noise within the classroom spaces they were serving. The scope of the breadth included taking onsite measurements for reverberation time, background noise level, and transmission loss in various classrooms and conference rooms.

4.1: Honors Work: Acoustics Performance of the Gaige Building

The main goal of taking these measurements was to determine the overall acoustic performance of the Gaige Building, with respect to the classroom acoustics standard, ANSI S12.60, put forth through the American National Standards Institute in conjunction with the Acoustical Society of America. An additional purpose of taking these measurements was to give myself exposure to these types of measurements. As well, two students from the third year architectural acoustics class, AE 309, had the opportunity to help with the measurements, gaining exposure to architectural acoustics measurement techniques, applying their outside of the classroom,. ANSI S12.60 is a standard set forth that specifies acoustical design requirements for K-12 classrooms. The standard specifies recommended maximum reverberation times (RT) and minimum background noise level (BNL) requirements. Although the Gaige Building is not a K-12 classroom space, these values still provide suitable design targets for the classrooms in this building.

4.1.1: Reverberation Time Measurement and Results

RT measurements were taken in six of the classroom spaces. For the RT measurements, the interrupted noise source method was used. This method involves playing pink noise through loudspeakers for a few seconds, bringing the room to an excited state. Then, the pink noise is stopped, 'interrupting' the noise signal, and the microphone measures the decay of sound within the room. Measurements were taken at two different locations within each space, and these results were averaged to calculate the reverberation time for each classroom. Figure 53 below shows a measurement for RT using the B&K sound level analyzer.

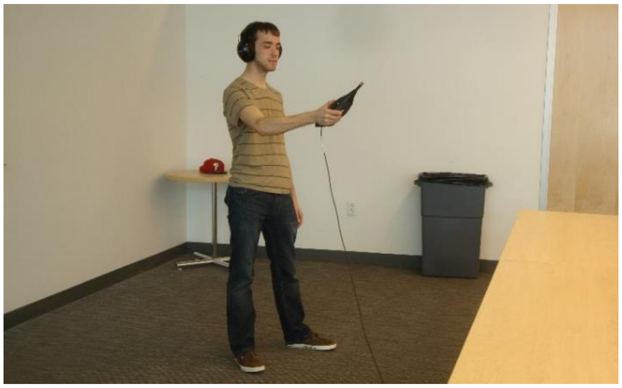


Figure 53: Reverberation time measurement using a B&K 2250 sound level analyzer (thesis author: Matthew Neal)

ANSI S12.60 specifies that the maximum RT for a classroom less than 10,000 cubic feet should be 0.6 seconds, and for classrooms that are greater than 10,000 cubic feet, 0.7 seconds is the maximum target. Measurements were taken in six of the classrooms within the Gaige Building. Three of these classrooms were less than 10,000 cubic feet, and the other three had a volume that was greater than 10,000 cubic feet. Figure 54 below shows the results for the RT measurements of classroom less than 10,000 cubic feet.

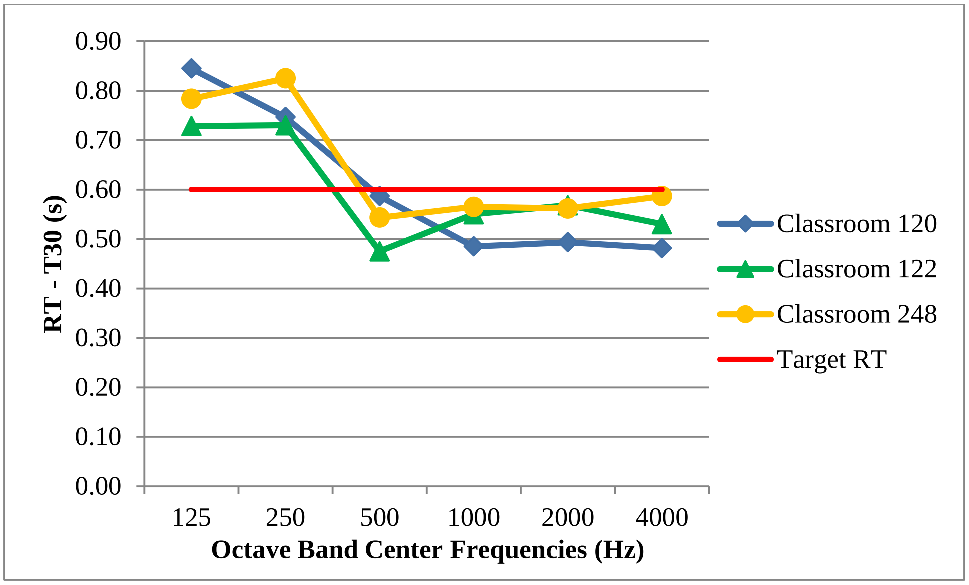


Figure 54: RT measurements of classrooms in the Gaige Building that are less than 10,000 cubic feet

As shown in Figure 54, the classrooms with volumes less than 10,000 ft^3 meet the design target for the 500-4000 Hz octave bands, but not for the two lowest bands at 125 and 250 Hz. These results are not unexpected due to the poor low frequency performance of most standard building materials, which behave as porous absorbers. Although these measured RTs are not ideal, these values are not excessively long, and should not negatively impact the overall speech intelligibility within the space.

For the classroom spaces that are greater than 10,000 cubic feet, the same trend is observed (see Figure 55). At lower frequencies, worse performance is seen, but that is expected. Classroom 121 has a slightly high RT in the 2000 Hz octave band, but in terms of a perceptual difference from the design target of 0.7 seconds, a deviation in RT of 0.06s is negligible. Another note that should be made is the basis of the standard. Since this standard is designed for K-12 classrooms, the set points are targeted towards a much lower level of student, even students who have very minimal education at a young age. Since the students using the Gaige Building classrooms will be primarily of college age or older, they will have much less trouble comprehending a speaker in a non-ideal listening environment. Thus, some of the octave bands that do not meet the design targets for RT perform well for their desired application. Overall, the classrooms in the Gaige Building substantially meet the requirements set forth in the classroom acoustics standard.

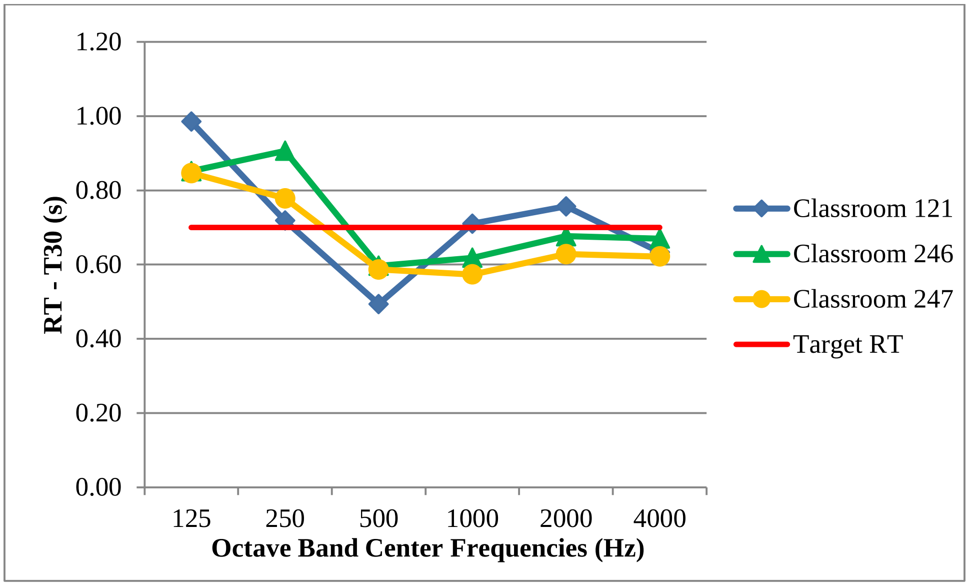


Figure 55: RT measurements of classrooms in the Gaige Building that are greater than 10,000 cubic feet

4.1.2: Background Noise Level

Background noise levels were also measured in the Gaige Building classrooms. ANSI S12.60 specifies a maximum background noise level 35 dBA for a one hour averaged measurement, which roughly translates to NC – 30. For these measurements, the sound level analyzer was used to take a 20 second average of the background noise level in each space at two different locations.

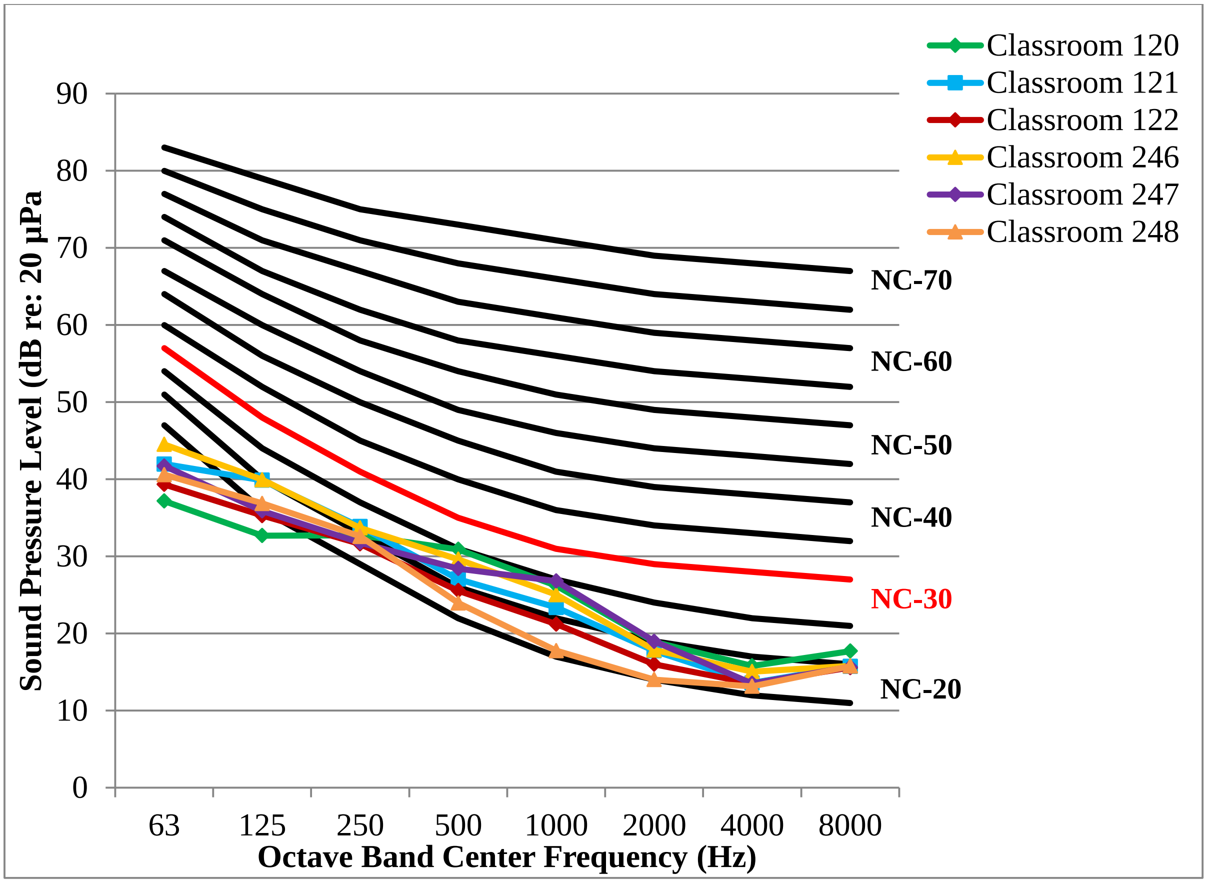


Figure 56: Background noise levels in the six classroom spaces. The target NC-35 is shown in red

All of the classroom spaces meet or exceed this minimum requirement for background noise level in a room, as shown in Figure 56. All rooms measured were at or below NC-25, which meets requirements for a classroom space. Although, it should be noted that the measurements were taken on a Sunday, when there was little to no occupancy in the spaces. As a result, the HVAC system was most likely not operating at full capacity in most cases, which would increase the measured background noise levels.

4.1.3: Apparent Transmission Loss and Sound Transmission Coefficient

Sound isolation criterion should also be considered when designing a classroom. Transmission Loss (TL) is the measure of how many decibels of reduction are measured when a sound is transmitted through a partition into an adjacent space. TL is measured in one-third octave bands, and behaves quite differently depending upon frequency. The sound transmission coefficient

(STC) rating is a one number representation of how a partition performs acoustically across all frequencies. For classrooms located next to adjacent occupied spaces, a minimum STC rating of 50 is required for partitions. For the measurement trip, transmission loss measurements were taken, to determine if the current partitions in the Gaige Building met this standard for transmission loss.

The apparent transmission loss (ATL) for a number of partitions was measured in accordance with ASTM E366-11, the *Standard Test Method for Measurement of Airborne Sound Attenuation between Rooms in Buildings* [6]. Since TL is the performance of a particular partition when measured under laboratory conditions, the ATL will always be lower than the TL values for a particular partition due to flanking paths, which typically occur in constructed partitions in buildings. Flanking paths act as 'short-circuits' for sound to travel in a path around a partition, and they decrease the overall performance of a particular partition. Examples of flanking paths include closely spaces exterior windows, doors, ductwork above or through a particular partition and even sound that travels through the ceiling plenum or a floor construction. Since ATL measurements are taken on site, the measurements include the noise that travels through both the partition in question along with the flanking paths in the building's design. This is why the measurement is classified as apparent, or ATL, and not simply TL.

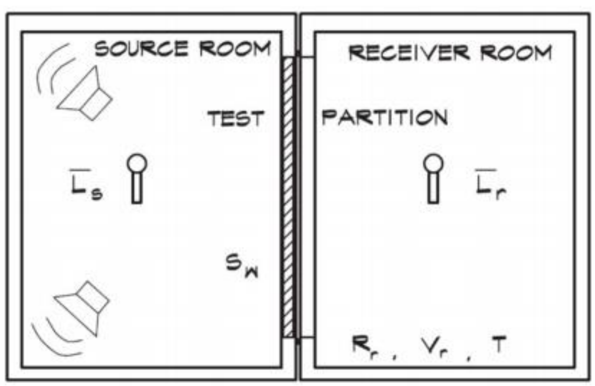


Figure 57: Typical measurement setup to take transmission loss measurement of a partition between rooms (Graphic from *Architectural Acoustics* by Marshall Long, with modification Michelle Vigeant)

For the measurements, pink noise was played using two speakers placed in the corners of the room opposite the partition being measured, as shown in Figure 57. The placement of the speakers during measurement is shown below in Figure 58.

Figure 58: Setting up JBL speakers in the 'source' room for the transmission loss measurements (AE 309 Students: Aaron King and Cory Clippinger)

First, the sound pressure level with the noise sources on was measured in the receiving room. The sound sources were then increased in level until the measured levels in the receiving room were at least 10 dB above the background noise levels in all measured third octave bands. Once the level was confirmed to be sufficiently above the background noise level, then measurements of the source room levels were taken, as seen in Figure 59 below.

Figure 59: Sound pressure level (SPL) measurements in the 'source' room for transmission loss measurements using a B&K 2250 sound level analyzer. (AE 309 students: Aaron King and Cory Clippinger)

To calculate the apparent transmission loss for a particular partition, the formula below is used:

$$ATL = L_{P,source} - L_{P,receiving} + 10\log\left(\frac{S}{A}\right)$$

In the equation above, $L_{P,source}$ is the measured level in the source room, $L_{P,receiving}$ is the measured level in the receiving room, S is the surface area of the partition, and A is the total absorption in the receiving room. The total absorption in the receiving room can be determined by taking the measured reverberation time in the receiving room, in third octave bands, and using Sabine's RT equation to extract the total absorption term that is in the denominator of the equation. The above equation for ATL is then calculation for each third octave band, determining the overall performance of the partition. An apparent STC rating, or ASTC rating, can then be calculated, and the performance of a particular partition can be determined.

ATL measurements were taken for four different partitions. The partitions were between classrooms 120 and 121, 121 and 122, 246 and 247 as well as 247 and 248. Measurements were taken using the previously described methodology, and once ATL data was calculated, ASTC ratings were assigned to each partition. All walls are a metal stud construction with insulation, and one layer of gypsum wall board on each side of the wall. As well, all walls are built to structure. ATL calculations for all of the partitions can be found in Appendix H.

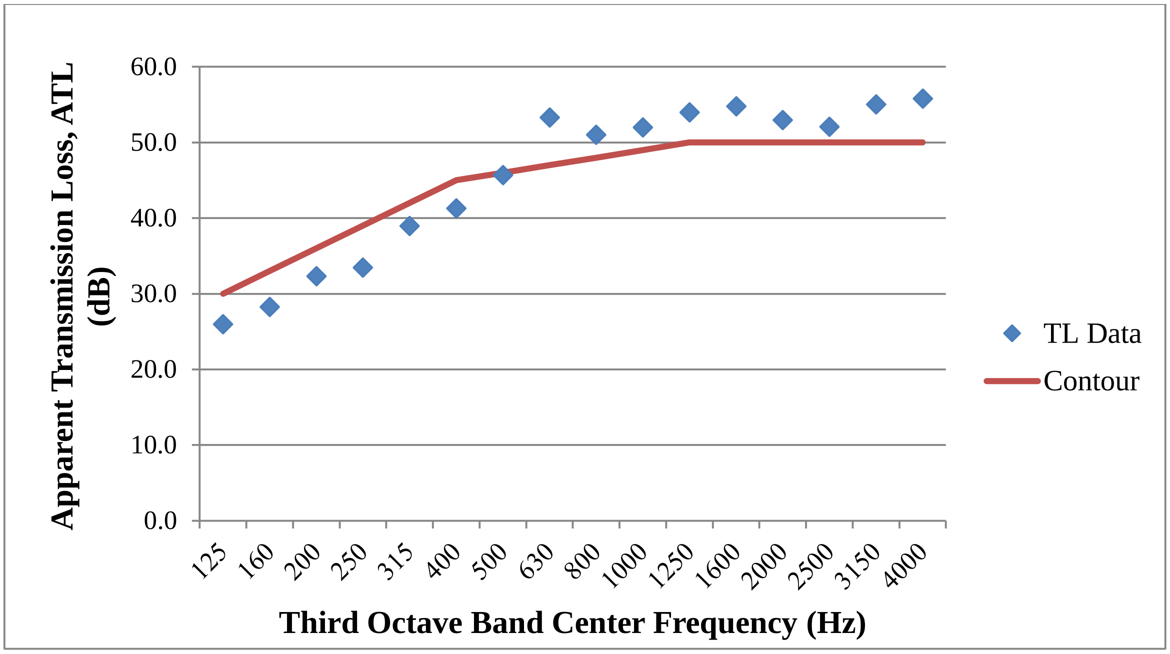


Figure 60: ATL measurement results for the partition between classrooms 120 and 121, with an ASTC of 46

Above, Figure 60 shows the ATL results that were measured for the partition between classrooms 102 and 121. The measured ASTC was determined to be 46, for a partitions with a specified STC of 50. The measurements appear to be very realistic, for they follow the shape of the TL curve used to calculate STC. Reference STC values are obtained from measurements in laboratories, under ideal conditions. Since partitions constructed in the field are not in ideal conditions, on average, ASTC values are typically 5 to 8 points lower than STC values. Since the ASTC measurements is within this range, an ASTC measurement of 46 is acceptable for a partition with an STC rating of 50.

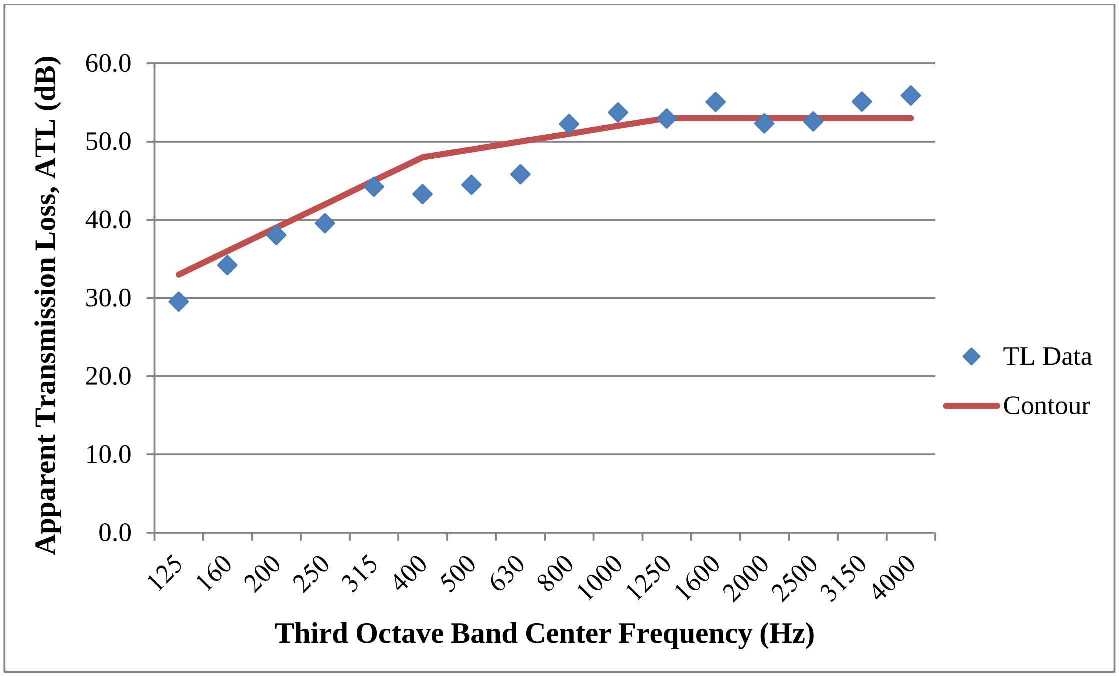


Figure 61: ATL measurement results for the partition between classrooms 121 and 122, with an ASTC of 49

Figure 61 above shows the ATL measurement results for the partitions between classroom 121 and 122 on the first floor. The ASTC of this partition was measured to be 49, for a design STC of 50. As said in the previous analysis, ASTC measurements are typically lower than STC values, so this partition is adequately isolating noise, meeting its design specifications. Although favorable results were found for the partitions on the first floor, the partitions on the second floor were not found to meet desired design targets.

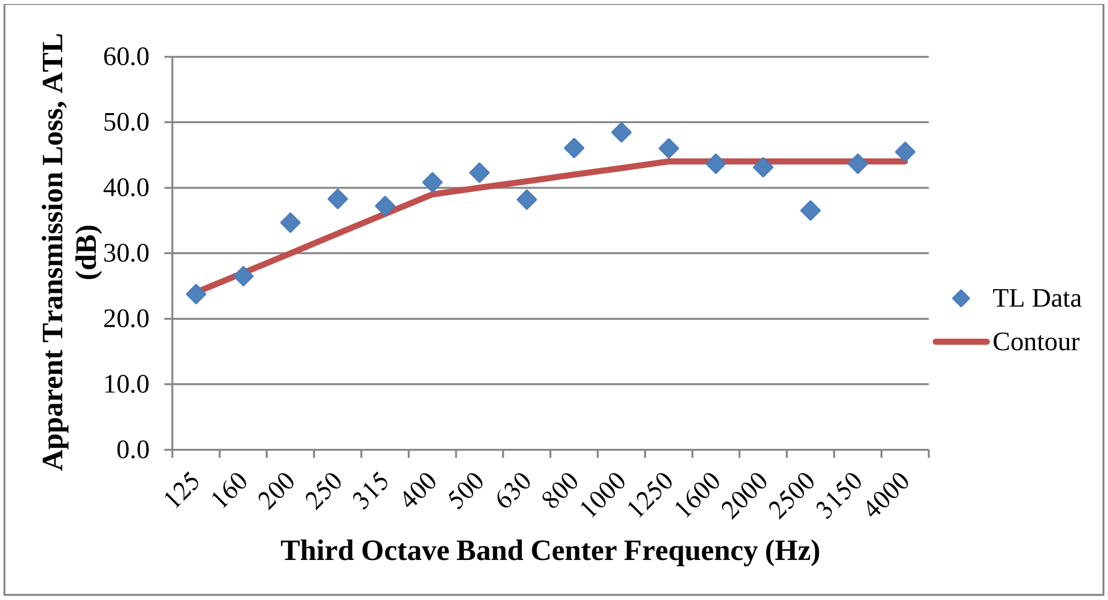


Figure 62: ATL measurement results for the partition between classrooms 246 and 247, with an ASTC of 40

The ATL measurements for the partition between classroom 246 and 247, seen in Figure 62, produced an overall ASTC of 40. This measurement is not within the level of tolerance previously described between design STC and ASTC. Details of this underperformance will be discussed with the other partition of the second floor.

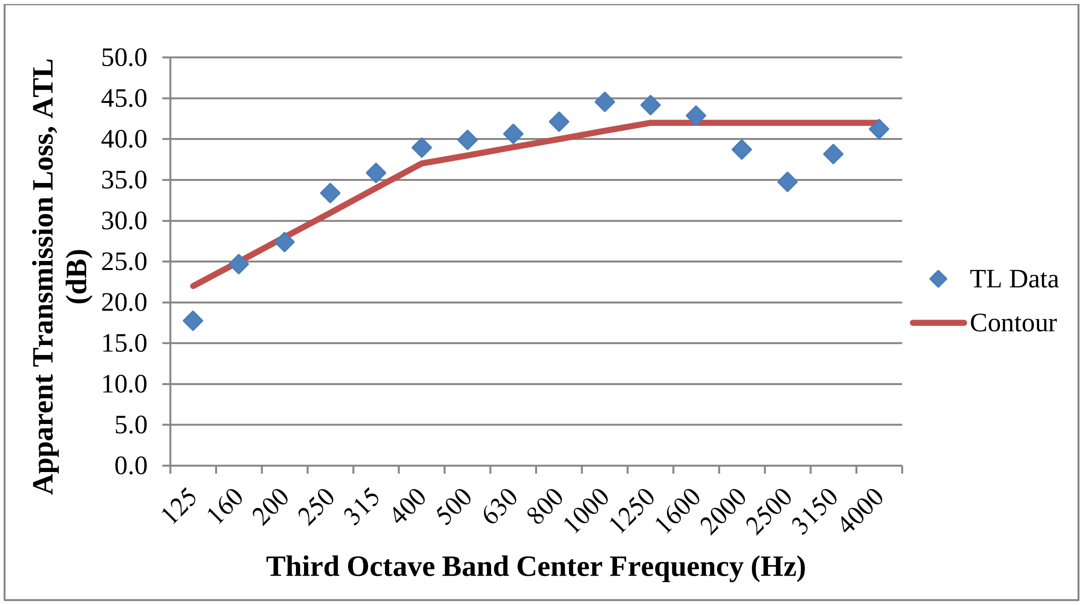


Figure 63: ATL measurement results for the partition between classrooms 247 and 248, with an ASTC of 38

The other partition on the second floor between classroom 247 and 248, does not meet the standards set out in ANSI S12.60 as well, shown in Figure 63. At an ASTC of 38, this partition is well outside the acceptable range for ASTC, compared to an STC of 50. At an ASTC of 38 and 40, these partitions are not behaving as designed.

Figure 64: One of the low performing walls, shown where it is built into a window glazing system

Figure 65: The gap in the same wall shown in Figure 64, where the wall meets the window

While taking these measurements, it was audibly clear that the problem was coming from the exterior side of the partition. The walls were built into a continuous glazing system, shown in Figure 64 above, which ran along the exterior of all of the classroom. The walls were built very close to the windows, but they were not properly sealed, causing a huge decrease in acoustic performance. The gap in the wall can be seen in Figure 65 above. As well, a large dip is present in the TL measurements around the 2500 Hz third octave band. This could be some sort of coincidence dip in the partition, or it could also be some sort of resonance that is happening due to the sizing and spacing of the gap between the windows and the wall.

Anytime a hole exists in a building structure, it will behave like a 'short-circuit', just like a flanking path, and significantly reduce the STC rating of any construction. Even if the opening is small, it will still have a large effect on the performance of the partition. It is important to not only specify acoustical caulking and sealant on a project, but also to be sure the installers know that all openings and joints need to be well sealed, without any gaps or openings.

As well, aural simulations, or auralizations were created in ODEON showing what it would sound to sit in the back of a classroom with a speaker talking on the other side of the wall in an adjacent classroom. Auralizations were created in ODEON. These auralizations were made using the measured ATL data for the ASTC 38 wall and the ASTC 49 wall, to help demonstrate the difference in performance. To listen to these auralizations, please visit the acoustics page on my senior thesis CPEP website.

4.2: Heat Pump Noise Control and Isolation

Since the mechanical system of the Gaige Building is proposed to change to geothermal system, as opposed to the standard rooftop unit system, various acoustical considerations must be made. In a geothermal system that utilizes water source heat pumps, water from the group loop is piped throughout the building using large capacity centrifugal pumps located in a mechanical room where the ground loop enters the building. Then, that group loop is piped to each individual water source heat pump. Each water source heat pump serves one room, or multiple smaller rooms. Due to this change, the mechanical equipment must now be located within close proximity to noise sensitive spaces, such as classroom and offices. The following section determines appropriate heat pumps locations servicing classroom and office type spaces.

4.2.1: Heat Pump Location Options

The first goal of this analysis was to determine what would be an acceptable placement for the heat pump units from an acoustical perspective. Odeon was used to predict the effects of particular placements of heat pumps within the Gaige Building. The geometries of the classrooms were modeled in Google SketchUp, and then imported into ODEON. The acoustic properties of the classroom's surface finishes were assigned in Odeon, and sources and receivers were placed in the classroom (see Figure 66). One source was placed in the front center of the room roughly where an instructor would be standing and talking. The speaker source was assigned to output a 10 second passage of speech, and it was set to a standard talking level with a sound power of 71.0 dB. Two receiver locations on either side of the room were placed, approximating multiple locations where a student might sit.

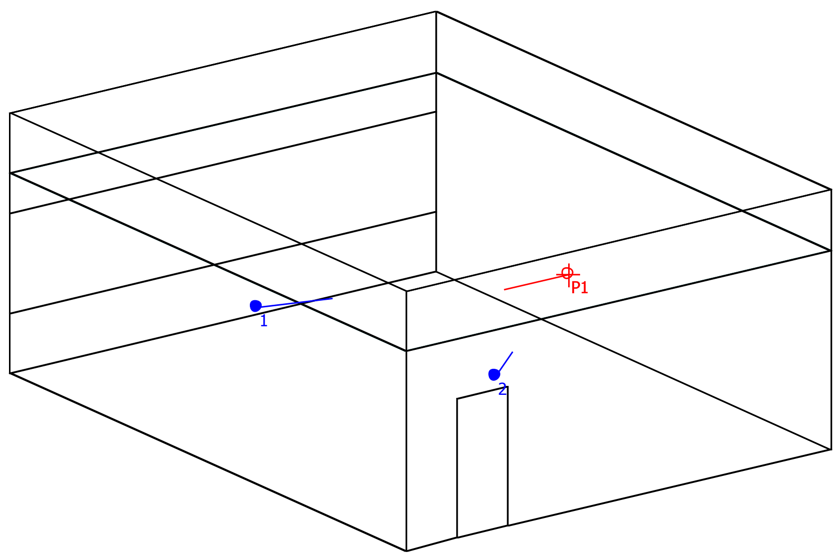


Figure 66: Source location of instructor shown in red, and receiver locations shown in blue, typical classroom

The model was used to predict BNL due to changes in heat pump placement. A-weighted sound pressure levels were calculated, and it was shown whether or not the BNL limit of 35 dBA was exceeded or not. The two options considered were placing the heat pump in the plenum space above the classroom ceiling and placing the heat pumps in a small service cabinet that could be created between the two classrooms.

4.2.2: Heat Pump within Plenum Space

First, a plenum space was added to the model described above. Six sources, positioned in a rectangle of the approximate size of a water source heat pump unit, were placed horizontally within the ceiling plenum. For the transmission loss of the ceiling tile, the mass law was used to approximate the transmission loss of the acoustic ceiling tile since ceiling tiles are a homogeneous material. The tiles were assumed to a surface mass density of 0.55 lb/ft^2. The heat pump sound sources were each given sound power levels that added up to levels provided from the Carrier water source heat pump datasheets for sound power levels of casing radiated noise (see Appendix H). The levels of the six sources were identical, and they were made so that the sum of all six sources would add up to the sound power levels provided in the units data sheet. A grid response analysis of the space revealed that the A-weighted sound pressure levels from the heat pump in the ceiling plenum above the room varied between 50 dBA and 55 dBA (Figure 67). The grid response was created in Odeon using a ray racing algorithm to study the sound propagation in both rooms and through the ceiling partition.

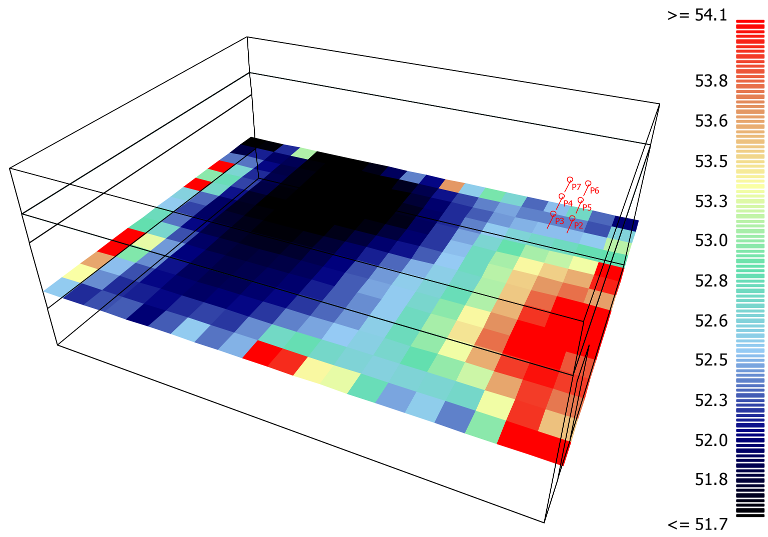


Figure 67: A grid response showing the A-weighted sound pressure levels when heat pump is running in the plenum space above the classroom

The A-weighted sound pressure levels in this classroom far exceed the 35 dBA limit set in ANSI S12.60, so this option of heat pump placement would not be acceptable. Auralizations for what it would sound like to listen to a speaker in the front of the room, from receiver location one or two, with the heat pump operating in the background have been made, and are provided online on my CPEP website on the Acoustics page.

4.2.3: Heat Pumps in Small Service Room

Since the first option was unsuccessful, a second consideration was made to place heat pumps in small mechanical room located between the two classrooms. Two heat pumps could be placed inside this room, one for each classroom, which would ensure better sound isolation between the units and the classrooms, as well as allow for easy access for equipment maintenance.

The previous model was expanded to include another classroom adjacent to the existing room, along with the mechanical room. Figure 68 below shows the new model with receiver locations, a speaking source location, and the sources for the two heat pumps. Again, since there are to be two heat pumps in the mechanical room, the room is modeled with six sources per heat pump, which combined to produce the overall radiated sound power levels.

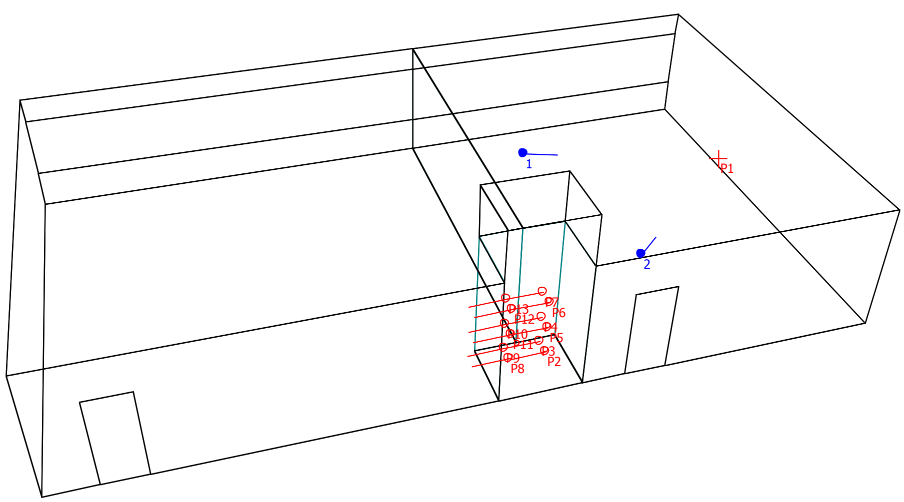


Figure 68: The geometrical model of the two classroom spaces with sources and receivers shown

For the partitions between classrooms and the small mechanical access room, the transmission loss data from the onsite measurements of the Gaige Building was used in the model. For this new wall construction, the same partition, with a target STC of 50, was used. This partition is a metal stud wall, with insulation and one layer on gypsum wall board on either side. The data input into the model was for the best performing wall, of ASTC 49. It is assumed that the walls between the mechanical room and classroom will be built to structure and no gaps will be left during construction. If the walls did not achieve this ATL or ASTC targets, the performance shown below will not be achieved. Figure 69 shows a grid response of the background noise levels (dBA) that would be present if the heat pumps were operating.

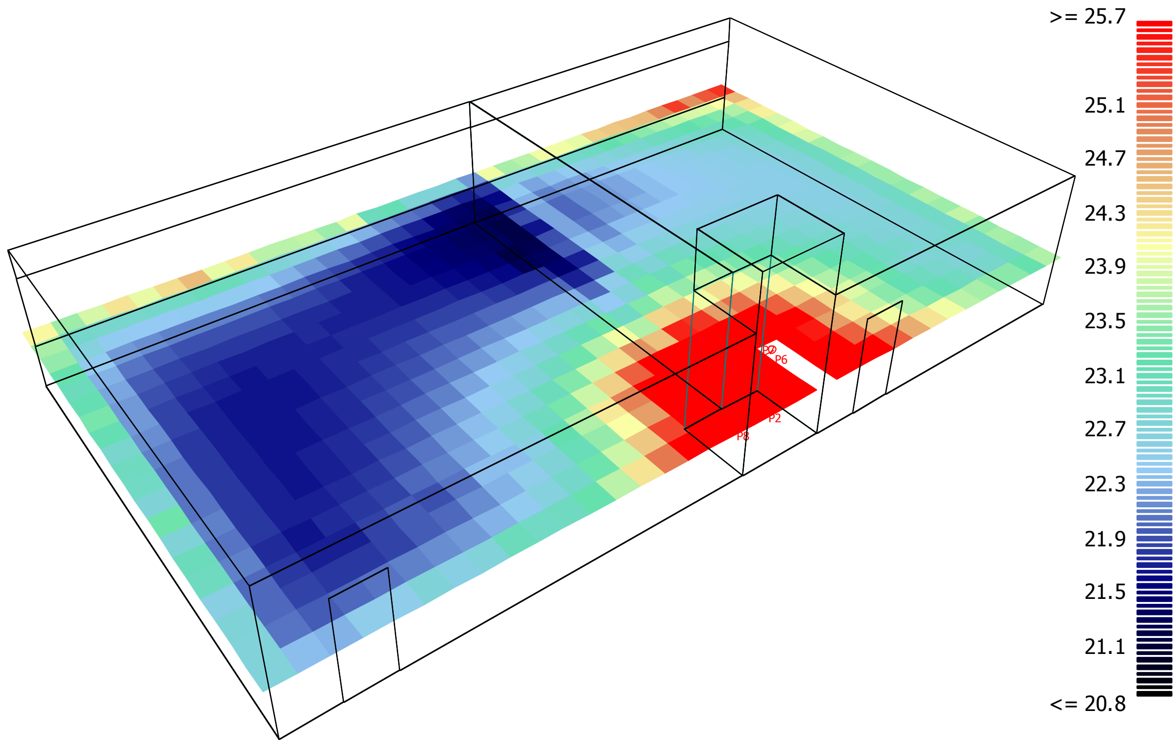


Figure 69: A grid response showing the resulting A-weighted sound pressure levels in both classrooms if two heat pumps were operating within the small mechanical room

In the grid response shown above, the A-weighted sound pressure levels in the classroom range from around 21 dBA to around 25 dBA. Although the squares within the mechanical room are shown in red, they fall in the greater than 26 dBA category and are around a level of 75 dBA. In the classrooms, right next to the mechanical room, a simulated level of around 29 dBA is observed. All of these A-weighted sound pressure level values are well below the limit of 35 dBA specified in the standard. From this analysis, the placement of heat pump is a small mechanical access room a viable option for the location of the heat pumps. Just like in the heat pump within the ceiling ODEON model, auralizations were created to demonstrate what it would sound like to listen to a talker in front of the room with the heat pumps operating from the adjacent room. (Please visit the acoustics page of my CPEP website to listen to conduct a personal evaluation of the performance of these heat pump placements on your own.)

4.2.2: Analysis of Sound Isolation through Partitions

Overall, with the addition of the heat pumps within the Gaige Building, it is suggested that for large spaces, such as classrooms or laboratory spaces, small mechanical access rooms be added throughout the architectural design. This design modification would allow for easy maintenance access to the water source heat pumps, as shown in the previous analysis. The heat pumps are too loud to place in the plenum space above the ceiling, so this method is a good option.

For smaller spaces, such as the offices, it is recommended that the walls between the corridors and the offices be built to structure, and the heat pumps placed above the plenum space in the hallway. This would allow the noise sources to be located in a less noise sensitive space, such as a corridor. The designer should now specify similar performing STC 50 walls between the corridors and the offices, otherwise, the performance modeled with the heat pump in the small room adjacent to the classroom will not be reached. A poor performing partition will not adequately isolate the heat pumps in the corridor plenum space from the office space. Currently, the walls between the hallway and the offices are not built to structure, so this would need to be specified in the new design.

4.2.3: Analysis of Air Noise through Diffusers

Finally, another source of noise from the heat pumps would be noise traveling through the ductwork into the space. To ensure that airside noise would not be an issue, a duct noise modeling program, AIM by Dynasonics, was used to model the ductwork extending from the heat pumps for a classroom and a private office space. The sound power levels of noise for the water source heat pumps from the ducted supply were entered into the program, and return and supply paths were added to both the classroom and the office ductwork models.

To the classroom, the path was modeled with a return path containing two elbows, one takeoff, 15 feet of rectangular duct, flex duct that connected into the supply diffuser, end reflection loss, and a room correction factor. For the supply path, the ductwork was modeled with one elbow, one takeoff, 11 feet of rectangular ductwork, flex duct connection to the diffuser, end reflection loss, and a room correction factor. After combining the effects of these two path into the room together, the NC levels for the room were found to be too high, but only in the upper frequency ranges. To reduce the levels entering into the room at these upper frequencies, 5 feet of one inch duct liner was added to the return path, and 3 feet of one inch duct liner was added to the supply path. With these changes made, the background noise level in the classroom was then estimated at NC-29 with a background noise level of 35 dBA, both satisfactory for a classroom space. It is recommended that in the design of the heat pump system, at least five feet of duct lining be placed in the return path and three feet of duct lining be placed in the supply path. Below, Figure 70 shows a plot of the background noise level calculated for this classroom. Specifics for this calculation can be found in Appendix I.

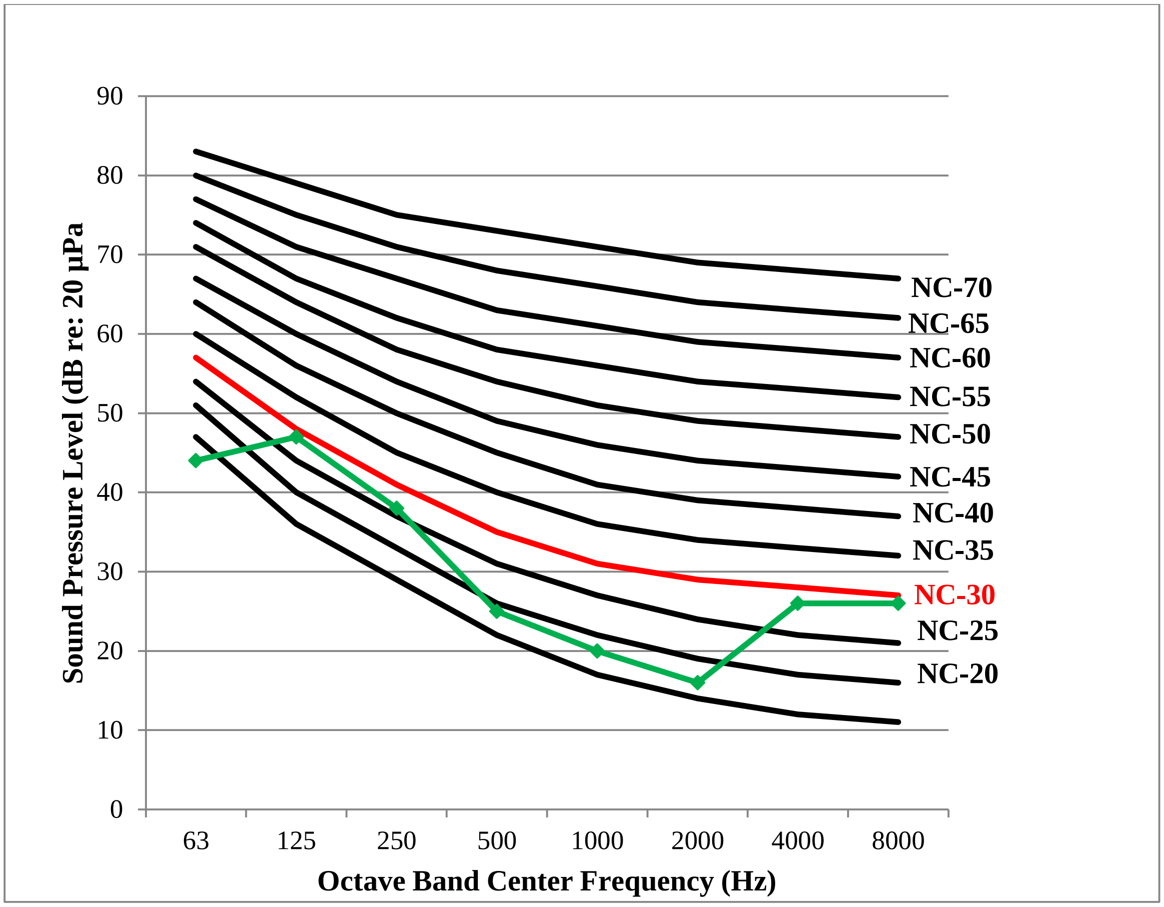


Figure 70: NC plot of background noise level from heat pump duct work for a typical classroom

Again, a similar analysis was done for a typical office space. For the supply path, the ductwork was modeled with one takeoff, seven feet of rectangular ductwork, flex duct connecting to the diffuser, end reflection loss, and a room correction factor. The return path was modeled with one takeoff, seven feet of rectangular ductwork, flex duct connecting to the diffuser, end reflection loss, and also a room correction factor. With both of these paths added together, there was again some noise control issues in the higher frequencies, so three feet of one inch duct liner was added to the supply path and two feet of one inch duct liner was added to the supply path.

With this addition, the office was then calculated to be at NC-27 with a background noise level of 34 dBA, meeting the NC-30 design target for a private office of NC-30. Since this analysis was proven successful, the following design guidelines were setup to ensure proper HVAC noise control in the new heat pump design. For an office spaces close to a heat pump, at least three feet of duct lining should be placed in the supply path, and at least two feet of duct lining should be placed in the return path. Below, in Figure 71, an NC plot shows the calculated background noise levels for this typical office space.

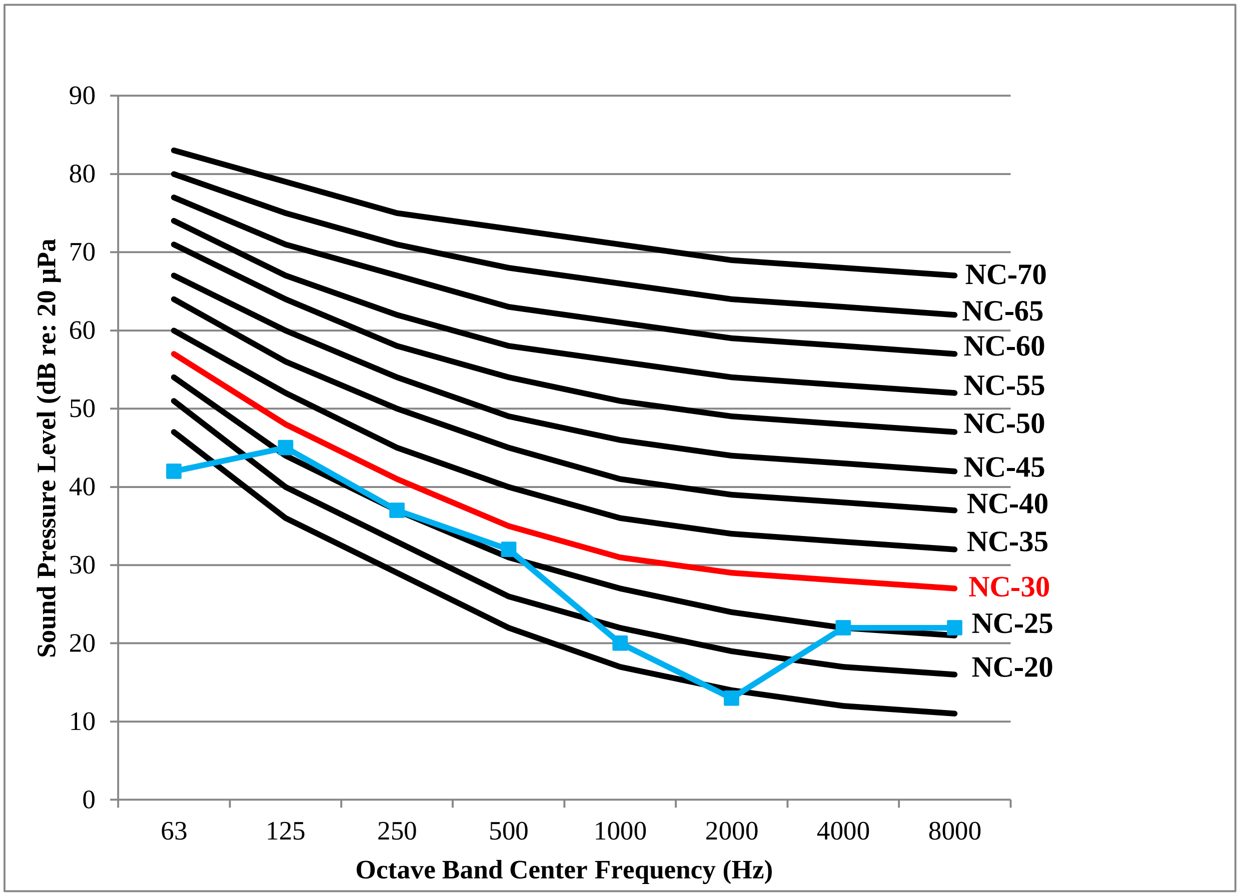


Figure 71: NC plot of background noise level from heat pump duct work for a typical office

Chapter 5: Construction Breadth

When considering whether or not a geothermal system will be a favorable option for a building, the most important, and normally the make or break decision is centered around cost. The justification behind a geothermal system is that the increased initial costs of the building will be justified, and ultimately paid off from the annual energy savings in the long run. You want to be able to show that a system will pay itself off within a reasonable amount of time, typically within the lifetime of a system. To do so, information on what increased costs will result from the addition of various system parts must be determined, estimated, and included in any life cycle cost analysis. For the construction breadth of this thesis, costs estimations are made for the Gaige Building, estimating the increase in initial costs due to the addition of water source heat pumps, outdoor air units, piping, and large costs associated with the installation of a horizontal well field. RS Means Building and Mechanical cost reference data was used for this analysis. Below, each section summarizes the main considerations made in this design and presents the overall cost analysis results. The results of these estimations were used the analyses in section 3.1, for the life cycle cost analysis of the Gaige Building geothermal system. These values were used to help determine the initial increase in first costs.

4.1: Geothermal Bore Cost Evaluation

The major costs associated with any geothermal installation is in the materials, labor, and equipment used in the installation of the geothermal well field. For the Gaige Building, two different types of well field arrangements are being considered: a horizontal loop system and a vertical loops system. Both system have their pros and cons, but the main considerations are space and costs. The vertical loop system takes up much less space than the horizontal loop system, but it typically costs more to install and construct per unit length of well. In the next two sections, 4.1.1 and 4.1.2, costs are estimated for the construction of a vertical and a horizontal geothermal loop system. Then, to help determine which loop is a better cost, they are compared, both using a constant length of cooling.

4.1.1: Vertical Bore Cost Estimation

For the vertical bore design, the main costs for the construction comes from drilling and boring the well, installing the pipework, and casting the grout or fill around the pipe. In the costs estimation for a vertical bore, the vertical bore was designed to be 300 feet deep, and a unit price per bore was estimated. For most specifics on the design of the geothermal well, refer back to Figure 19 in section 3.1.3. This way, in the overall cost analysis, the costs could be estimated easily on a per bore basis. Below, table 38 summarizes the cost estimation for a vertical geothermal well.

Geothermal Additional First Costs-Cost Per Pile							
Item	Unit Cost				Amount	Units	Expense
	Materials	Labor	Equipment	Total			
Pile Boring and Filling	$ 1.09	$ 5.28	$ 3.92	$ 10.29	300	VLF	$ 3,088.41
1" HDP Pipe	$ 0.79	$ -	$ -	$ 0.79	600	LF	$ 474.00
1" HDP Elbow	$ 5.60	$ -	$ -	$ 5.60	4	Each	$ 22.40
1" HDP Joints	$ -	$ 5.55	$ -	$ 5.55	10	Each	$ 55.50
1" HDP Tee	$ 7.30	$ -	$ -	$ 7.30	2	Each	$ 14.60
Welding Machine	$ -	$ -	$ 40.50	$ 40.50	1.47	Each	$ 59.34
						Total	**$ 3,714.25**

Table 38: Costs estimate for a vertical geothermal well, based upon a 300' deep well

All estimated were taken from RS Means cost estimation data. The only assumption that was made was in the pile boring and filing for the vertical well. Since RS Means does not provide cost estimations for vertical geothermal wells specifically, data for the boring and filling of a bored pile caisson were used. RS Means had extensive data for this type of cost, and it was seen to be a reasonable alternative that worked well for this estimation. Data were not provided for a 6" bore though, for that is not a standard size of caisson, so extrapolation was used to determine cost estimates for a 6" bore from other diameters of bores listed. Below Figure 72 shows the total cost per vertical linear foot of pile, with the x axis being diameter of bore. From this data, a second order polynomial was fit to the data, and approximations for the units costs were made for a 6" pile.

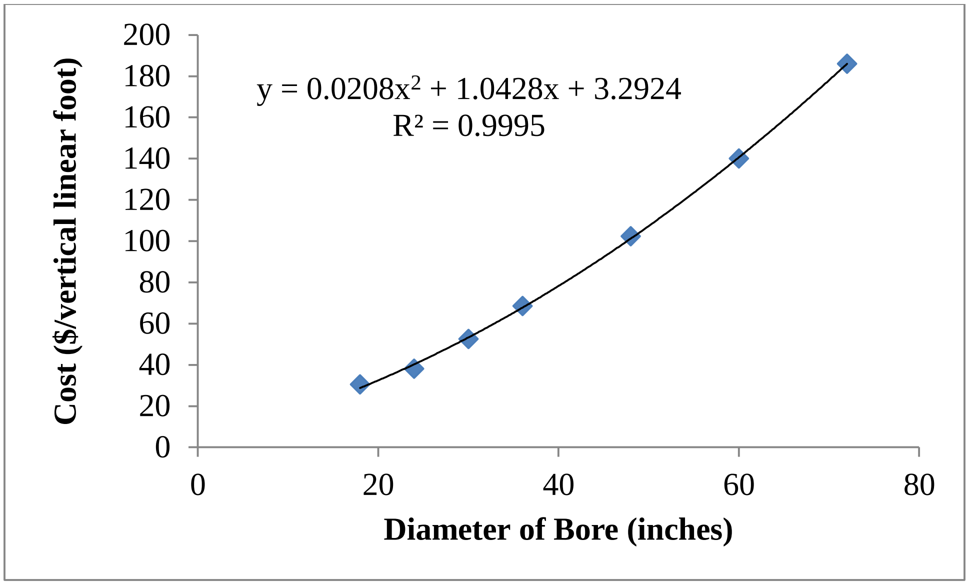


Figure 72: A graph showing RS Means data for pile boring costs as bore diameter changes

Using the trend line that was fit for the data, the total cost per vertical linear foot for the pile boring, drilling, and casting was estimated to be $10.29 for a 6" diameter well. Using the data for the cost estimates for the vertical well, below, Figure 73 shows the percentage distribution between boring costs and piping costs.

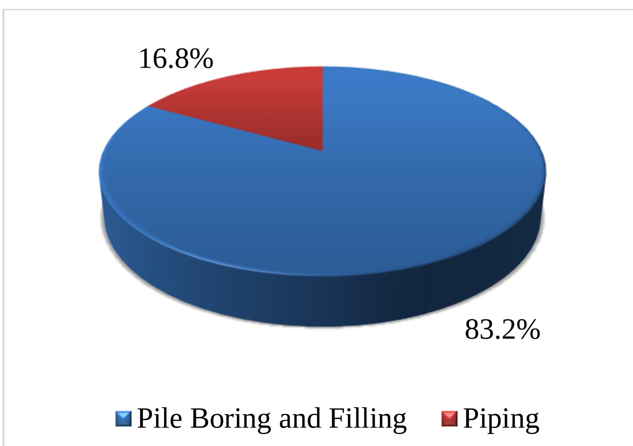


Figure 73: A pie chart showing the percentage breakdown of costs for a vertical geothermal well that is 300' deep

4.1.2: Horizontal Bore Cost Estimation

As well, the costs need to be estimated for a horizontal loop geothermal system. A similar analysis was done, again using RS Means data, as compared to the analysis for the vertical bore. The difference between the two options is that instead of boring, the horizontal loop option only uses long trenches that are then partially backfilled with bentonite, and then backfilled with soil. Below, table 39 shows the overall cost estimation for a horizontal loop that is 800 feet long (the most typical length for a horizontal loop in our given design). Also, the costs are broken down between trenching costs and piping costs in Figure 74, similarly to what was done for the vertical bore costs.

Geothermal Additional First Costs-Cost Per Pile							
Item	Unit Cost				Amount	Units	Expense
	Materials	Labor	Equipment	Total			
Trenching for piles	$ -	$ 0.59	$ 0.75	$ 1.34	800	LF	$ 1,073.24
Fill for Trenches	$ 4.85	$ 1.09	$ 0.41	$ 6.35	800	LF	$ 5,079.17
Backfill for Trenches	$ -	$ 0.61	$ 0.21	$ 0.82	800	LF	$ 655.64
Hauling Dirt	$ -	$ 0.27	$ 0.37	$ 0.63	800	LF	$ 507.37
1" HDP Pipe	$ 0.79	$ -	$ -	$ 0.79	1600	LF	$ 1,264.00
1" HDP Elbow	$ 5.60	$ -	$ -	$ 5.60	2	Each	$ 11.20
1" HDP Joints	$ -	$ 5.55	$ -	$ 5.55	49	Each	$ 271.95
1" HDP Tee	$ 7.30	$ -	$ -	$ 7.30	2	Each	$ 14.60
Welding Machine	$ -	$ -	$ 40.50	$ 40.50	1.47	Days	$ 59.34
						Total	**$ 8,936.51**

Table 39: Cost estimates for a horizontal geothermal loop that is 800 feet long

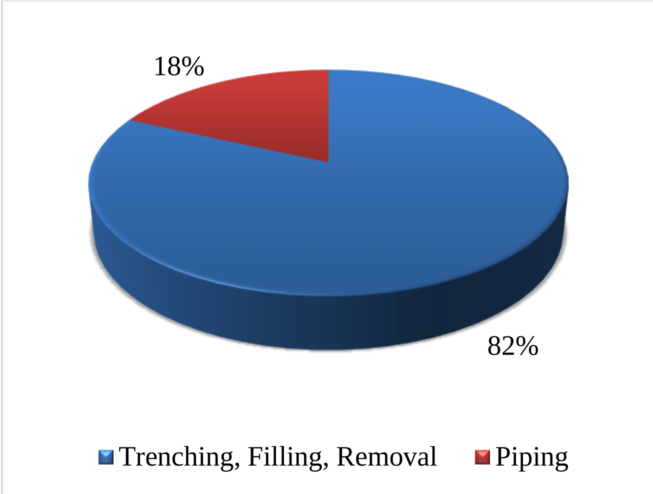


Figure 74: A pie chart showing the breakdowns between trenching and piping costs for a 800' horizontal loop

A similar analysis was performed for each length of horizontal loop, since not all of the horizontal geothermal loops are the same size. For the vertical design, it was possible to design each well to a depth of 300 feet, but due to site constraints, the lengths of the horizontal loops had to be adjusted to fit the given land area. Below, table 40 summarizes the costs for each total length of horizontal loop. Costs provided are costs per loop installed. The 300 feet long loop is not a standard loop in the system design, but is provided for comparison with the vertical wells in the next section.

Horizontal Loop Length (ft)	Cost Per Loop	Number in Design
800	$ 8,936.51	20
775	$ 8,662.85	1
750	$ 8,389.20	4
700	$ 7,836.33	5
675	$ 7,562.68	1
750	$ 7,289.02	4
400	$ 4,535.80	5
300	$ 3,435.62	n/a

Table 40: A summary of the cost per horizontal loop, as loop length is adjusted

4.1.3: Comparison of Vertical Bore to Horizontal Bore Costs

When comparing the two options of a vertical or horizontal well, it is clear that the horizontal well pricing is much cheaper. For a 300 foot bore vertical well, the cost comes out to $3,714.25, but for a 300 foot horizontal loop, the cost comes out to only $3,435.62. With roughly a $300.00 difference per bore, this would amount to a very significant savings on a project, especially when considering life-cycle cost analysis. Also, when projects become larger and larger, with more required bores, this cost will become even more important. For the Gaige Building, since space is available, the horizontal loop would be the recommended choice, unless it was not desired to disrupt more campus land than was needed for the geothermal well system.

4.2: Gaige Building Geothermal—Initial Costs

The next step in this cost analysis was to analyze the change in initial costs between the current design of the Gaige Building's mechanical system and the potential geothermal design of the Gaige Building. For this analysis, the total costs, including bore costs, well field piping and trenching costs, savings from the original mechanical system design, and factors such as location and time cost indexes were included in the analysis.

4.2.1: Savings from Original Design

The first consideration in analyzing the difference in costs between the original design of the Gaige Building and the newly proposed geothermal system. Such savings were found in the costs for the packaged rooftop units and in the radiant and fin tube heaters in the current building design. Appendix D contains the budget estimates from the original mechanical design, from which these savings estimated were taken. Below, table 41 summarizes the savings that can be realized from the original design of the Gaige Building.

Geothermal Cost Savings				
Item	**Unit Cost**	**Amount**	**Units**	**Savings**
RTU's - Quote (20,500, 14,000, 10,725 CFM's)	$ 300,000.00	1	All	$ 300,000.00
RTU Installation	$ 2.00	45,230	CFM	$ 90,460.00
Fin Tubes	$ 75.00	1150	LF	$ 86,250.00
Radiant Heat Panels	$ 100.00	80	Each	$ 8,000.00
				$ 484,710.00

Table 41: Summary of cost savings that can be realized from the original Gaige Building's design

4.2.2: Initial Costs for Vertical Bore Design

For the vertical well field, costs were estimated to determine the increase in initial costs due to the addition of the new equipment, piping, and labor that would need to be done to estimate the costs for the new geothermal design. In this cost analysis, considerations for heat pumps costs in the building, heat pump piping costs, building centrifugal pumps, geothermal pumps, geothermal piping, well field costs, and DOAS costs were all considered in the analysis. For the details of the specific analysis for the proposed vertical well field design, see Appendix F. Overall, the total increase in cost due to the building and well field construction costs came out to be $655,736.06. Now, to determine the overall additional first costs for the life-cycle cost analysis, the savings must be incorporated into this analysis. First, the savings estimate is adjusted from its estimation year of 2009 to the present year of 2014. Then, the cost estimate for the building and well field increased costs are adjusted using a location multiplier of 0.988, which is the overall location based multiplier for Reading, PA as provided by RS Means data. Table 42 below summarizes this analysis, and presents a total increase in initial first costs for the vertical geothermal well field of $102,636.63

Vertical - Increased First-Costs	
Cost Item	**Amount**
Increased First Cost - General	$ 655,736.06
Location Multiplier - Reading PA	0.988
Increased First Cost - Reading	$ 647,867.23
Savings from Original Design - 2009	$ 484,710.00
Time Multiplier - 2014 to 2009	0.889
Savings from Original Design - 2014	$ 545,230.60
Overall First Cost Increase:	**$ 102,636.63**

Table 42: A summary of the initial first costs increase for the vertical geothermal system

4.2.3: Initial Costs for Horizontal Bore Design

An identical analysis was run for the horizontal loop geothermal system as was described in the previous section for the vertical well field. For details on the overall calculation of additional building and loop field costs, please see Appendix G. Overall, the increase for the total costs from the building and the geothermal loop came out to be $601,959.52. This increase was then combined with the savings, and table 43 below summarizes the final increase in first costs for the Gaige Building with a horizontal geothermal loop design. The increase in cost came out to be $49,505.41.

Horizontal - Increased First-Costs	
Cost Item	**Amount**
Increased First Cost - General	$ 601,959.52
Location Multiplier - Reading PA	0.988
Increased First Cost - Reading	$ 594,736.01
Savings from Original Design - 2009	$ 484,710.00
Time Multiplier - 2014 to 2009	0.889
Savings from Original Design - 2014	$ 545,230.60
Overall First Cost Increase:	**$ 49,505.41**

Table 43: A summary of the overall increased first costs for the horizontal loop geothermal design

Chapter 6: Conclusions

Overall, the geothermal redesign of the Gaige Building was a success. When considering the horizontal versus the vertical loop design of the geothermal system, either option would be a fine choice. For the horizontal loop system, you still get the same design heating and cooling lengths, but you have a payback period of 6.13 years, meaning further energy savings after about year six could go towards other campus renovations or a future system overhaul for the building. For the vertical loop design, a payback period of 12.7 years is found. There is an increased first cost, due to the increased cost of boring and drilling associated with the mechanical system. Despite the fact that this system would take twice as long to pay back as compared to the horizontal loop system, it could still be the better choice. With the vertical loop system, much less earth is disrupted, and much less work would be done on tree removal and ripping up and replacing the exiting parking lots that are present where the well field would need to be placed in the horizontal design. Depending upon how the owner values cost savings versus space requirements, either option could be the better choice.

When the campus-wide geothermal system is considered, at first, it looks like a very unfeasible option, with tremendously long payback periods. The main difference though in this analysis and the Gaige Building's analysis is the inability to justify initial costs savings through the comparison with other building mechanical system options. When we just consider the campus-wide system a retrofit, and we 'throw away' all of the existing mechanical infrastructure in the buildings, we lose those potential savings. If the campus is considering any major mechanical renovations, or major renovations of their dormitory buildings, they could potentially weigh this design against other design options. This would allow for an increased amount of costs savings for the design, and potentially justify the campus wide redesign. With a campus wide redesign, it would also be easy to add new buildings into the system, for additional added cost savings.

On the emissions side of the analysis, the Gaige Building alone did not have a drastic reduction in total annual emissions. This is due to the fact that the source energy consumption is heavily dominated by electricity consumption. If the Gaige Building were to use a geothermal system, its savings were really found by reducing the natural gas loads. The cooling load electrical savings were covered up by the increase in electricity consumption due to the operation of many different heat pumps throughout the building, throughout the year. On the other hand, when a campus wide geothermal system was considered, it had a 27% reduction in annual emissions, a drastic impact upon the campus total emissions. This was mainly influenced by the buildings that ran solely off of electricity as their cooling and heating source. Since electricity has a large impact upon source energy consumption, and the fact that all of the savings from these types of buildings were on the electrical utility bill, it had a large impact upon annual emissions. With these savings realized, this is another arguments that is strong in the favor of a high capacity, campus-wide geothermal system, ignoring the life-cycle cost feasibility questions.

Finally, a thorough acoustic analysis of the Gaige Building was conducted. As compared to ANSI S12.60, the classroom acoustics standard, the Gaige Building did a great job of meeting requirements. All six of the measured classrooms exhibited adequate reverberation times, and adequate background noise levels. There were some low frequency reverberation issues, but this is understandable due to the low frequency absorption limitation of porous absorbers. Two out of four of the tested partitions performed well, with an ASTC measuring at least 46 for a specified design STC of 50. On the other hand, both of the partitions tested on the second floor did not perform well, having ASTC ratings of 38 and 40, for a wall with a design STC of 50. This severe underperformance was due to poor sealing between the edge of the partition and the continuous window glazing. This poor sealing left visible gaps between the wall and window construction, short-circuiting the sound transmission performance of the wall, and thus, drastically decreasing the STC of the wall.

Finally, it was found that the best placement for the geothermal water source heat pumps would be in the hallway ceiling plenum for the offices, with the wall between the hallway and the offices being built to structure. Also, to properly isolate the heat pumps from the classroom spaces, additional mechanical access rooms should be placed near existing classrooms and labs. This allows for proper sound isolation, with easy access to the heat pumps for maintenance purposes. Finally, guidelines for controlling duct noise from the heat pumps was provided to ensure that adequate NC-levels in the offices and classrooms are met.

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Appendix A: Building Pump Head Loss Calculations

Segment	Length	Flow Rate	Pipe size	# of Fittings		Equivalent Length	Loss ft/100 ft	Total Head Loss
				Elbows	Tees			
Supply 1	37.5	413	6	1	1	50	2.4	2.09
Supply 2	14	266	5	1	1	50	2.6	1.64
Supply 3	5	259	5	0	1	20	2.4	0.61
Supply 4	18.5	238	5	1	0	30	2.1	1.01
Supply 5	46.2	224	5	0	1	20	1.9	1.23
Supply 6	25	203	5	0	1	20	1.6	0.70
Supply 7	27	189	5	0	1	20	1.4	0.64
Supply 8	61	140	4	0	1	20	2.3	1.87
Supply 9	49	77	3	2	1	80	3.1	4.00
Supply 10	18	56	3	1	0	30	1.7	0.82
Supply 11	15	21	2	0	1	20	2.0	0.70
Supply 12	39	14	1.5	0	1	20	3.8	2.27
Supply 13	10	7	1.5	0	0	0	1.1	0.11
Return 1	10	7	1.5	0	0	0	1.1	0.11
Return 2	39	14	1.5	0	1	20	3.8	2.27
Return 3	15	21	2	0	1	20	2.0	0.70
Return 4	18	56	2	1	0	30	12.4	5.93
Return 5	49	77	3	2	1	80	3.1	4.00
Return 6	61	140	4	0	1	20	2.3	1.87
Return 7	27	189	5	0	1	20	1.4	0.64
Return 8	25	203	5	0	1	20	1.6	0.70
Return 9	46.2	224	5	0	1	20	1.9	1.23
Return 10	18.5	238	5	1	0	30	2.1	1.01
Return 11	5	259	5	0	1	20	2.4	0.61
Return 12	14	266	5	1	1	50	2.6	1.64
Return 13	37.5	413	6	1	1	50	2.4	2.09
							Total Head	40.48

Appendix B: Horizontal Geothermal Pump Head Calculations

Head Loss for Geothermal Well Field Pumps								
Segment	Length (ft)	Flow Rate (gpm)	Pipe size (in)	# of Fittings		Equivalent Length	Head Loss ft/100 ft	Total Head Loss
				Elbows	Tees			
Header 1	446	120	4	3	0	90	0.93	5.0
Header 2	20	117	4	0	1	20	0.89	0.4
Header 3	20	114	4	0	1	20	0.85	0.3
Header 4	20	111	4	0	1	20	0.81	0.3
Header 5	20	108	4	0	1	20	0.77	0.3
Bore 1	1600	3	1	2	1	80	0.85	14.4
Header 7	30	21	2	0	1	20	1.08	0.5
Header 8	20	24	2	0	1	20	1.38	0.6
Header 9	20	27	2	0	1	20	1.72	0.7
Header 10	20	30	2	0	1	20	2.08	0.8
Header 11	20	33	2	0	1	20	2.49	1.0
Header 12	20	36	2.5	0	1	20	0.99	0.4
Header 13	20	39	2.5	0	1	20	1.14	0.5
Header 14	20	42	2.5	0	1	20	1.31	0.5
Header 15	20	45	2.5	0	1	20	1.49	0.6
Header 16	20	48	2.5	0	1	20	1.68	0.7
Header 17	20	51	2.5	0	1	20	1.88	0.8
Header 18	20	54	2.5	0	1	20	2.09	0.8
Header 19	20	57	2.5	0	1	20	2.31	0.9
Header 20	20	60	2.5	0	1	20	2.54	1.0
Header 21	20	63	3	0	1	20	1.15	0.5
Header 22	20	66	3	0	1	20	1.25	0.5
Header 23	20	69	3	0	1	20	1.36	0.5
Header 24	20	72	3	0	1	20	1.47	0.6
Header 25	20	75	3	0	1	20	1.58	0.6
Header 26	20	78	3	0	1	20	1.70	0.7
Header 27	20	81	3	0	1	20	1.82	0.7
Header 28	20	84	3	0	1	20	1.95	0.8
Header 29	20	87	3	0	1	20	2.08	0.8
Header 30	20	90	3	0	1	20	2.22	0.9
Header 31	20	93	3	0	1	20	2.36	0.9
Header 32	20	96	3	0	1	20	2.50	1.0
Header 33	20	99	4	0	1	20	0.65	0.3

Header 34	20	102	4	0	1	20	0.69	0.3
Header 35	20	105	4	0	1	20	0.73	0.3
Header 36	20	108	4	0	1	20	0.77	0.3
Header 37	20	111	4	0	1	20	0.81	0.3
Header 38	20	114	4	0	1	20	0.85	0.3
Header 39	20	117	4	0	1	20	0.89	0.4
Header 40	401	120	4	2	1	80	0.93	4.5
							Total head for Pump	**45.7**

Appendix C: Emissions Factors

Table 8 Emission Factors for On-Site Combustion in a Commercial Boiler (lb of pollutant per unit of fuel)

Pollutant (lb)	Commercial Boiler					
	Bituminous Coal *	Lignite Coal **	Natural Gas	Residual Fuel Oil	Distillate Fuel Oil	LPG
	1000 lb	1000 lb	1000 ft^3 ***	1000 gal	1000 gal	1000 gal
CO_{2e}	2.74E+03	2.30E+03	1.23E+02	2.56E+04	2.28E+04	1.35E+04
CO_2	2.63E+03	2.30E+03	1.22E+02	2.55E+04	2.28E+04	1.32E+04
CH_4	1.15E-01	2.00E-02	2.50E-03	2.31E-01	2.32E-01	2.17E-01
N_2O	3.68E-01	ND †	2.50E-03	1.18E-01	1.19E-01	9.77E-01
NO_X	5.75E+00	5.97E+00	1.11E-01	6.41E+00	2.15E+01	1.57E+01
SO_X	1.66E+00	1.29E+01	6.32E-04	4.00E+01	3.41E+01	0.00E+00
CO	2.89E+00	4.05E-03	9.33E-02	5.34E+00	5.41E+00	2.17E+00
VOC	ND †	ND †	6.13E-03	3.63E-01	2.17E-01	3.80E-01
Lead	1.79E-03	6.86E-02	5.00E-07	1.51E-06	ND †	ND †
Mercury	6.54E-04	6.54E-04	2.60E-07	1.13E-07	ND †	ND †
PM10	2.00E+00	ND †	8.40E-03	4.64E+00	1.88E+00	4.89E-01

* from the U.S. LCI data module: Bituminous Coal Combustion in an Industrial Boiler (NREL 2005)
** from the U.S. LCI data module: Lignite Coal Combustion in an Industrial Boiler (NREL 2005)
*** Gas volume at 60°F and 14.70 psia.
† no data available

Table 3 Total Emission Factors for Delivered Electricity (lb of pollutant per kWh of electricity)

Pollutant (lb)	National	Eastern	Western	ERCOT	Alaska	Hawaii
CO_{2e}	1.67E+00	1.74E+00	1.31E+00	1.84E+00	1.71E+00	1.91E+00
CO_2	1.57E+00	1.64E+00	1.22E+00	1.71E+00	1.55E+00	1.83E+00
CH_4	3.71E-03	3.59E-03	3.51E-03	5.30E-03	6.28E-03	2.96E-03
N_2O	3.73E-05	3.87E-05	2.97E-05	4.02E-05	3.05E-05	2.00E-05
NO_X	2.76E-03	3.00E-03	1.95E-03	2.20E-03	1.95E-03	4.32E-03
SO_X	8.36E-03	8.57E-03	6.82E-03	9.70E-03	1.12E-02	8.36E-03
CO	8.05E-04	8.54E-04	5.46E-04	9.07E-04	2.05E-03	7.43E-03
TNMOC	7.13E-05	7.26E-05	6.45E-05	7.44E-05	8.40E-05	1.15E-04
Lead	1.31E-07	1.39E-07	8.95E-08	1.42E-07	6.30E-08	1.32E-07
Mercury	3.05E-08	3.36E-08	1.86E-08	2.79E-08	3.80E-08	1.72E-07
PM10	9.16E-05	9.26E-05	6.99E-05	1.30E-04	1.09E-04	1.79E-04
Solid Waste	1.90E-01	2.05E-01	1.39E-01	1.66E-01	7.89E-02	7.44E-02

Appendix D: Original Mechanical System Costs

CODE	DESCRIPTION	QUANTITY	UNIT	UNIT COST	COST
23000	Heating, Ventilation & Air Conditioning				
1	RTU's - Quote (20,500, 14,000, 10,725 CFM's)	1	LS	300,000.00	300,000
2	- Installation	45,230	CFM	2.00	90,460
3	Exhaust Fans	7,590	CFM	1.50	11,390
4	MAU - 4,000 CFM	1	EA	12,000.00	12,000
5	- 3,300 CFM	1	EA	9,900.00	9,900
6	Kitchen Hood Exhaust	2	EA	5,000.00	10,000
7	Split System- Mr. Slim 1.5 Ton/Ductless	4	EA	5,000.00	20,000
8	Computer Room AC	1	EA	7,200.00	7,200
9	Boilers - 850 MBH	2	EA	24,000.00	48,000
10	Pumps - 85 GPM	3	EA	2,000.00	6,000
11	- 170 GPM	2	EA	4,000.00	8,000
12	Piping- HW Heating - 4"	30	LF	100.00	3,000
13	- 3"	680	LF	74.00	50,320
14	- 2"	370	LF	48.00	17,760
15	- 1 1/2"	340	LF	32.00	10,880
16	- 1 1/4"	1,380	LF	29.00	40,020
17	- 1"	2,120	LF	25.00	53,000
18	- 3/4"	640	LF	20.00	12,800
19	- Refrigerant Piping/Not Sized	390	LF	50.00	19,500
20	Hydronic Specialties - Misc./Etc	1	EA	5,000.00	5,000
21	- Chemical Feeder Tank	1	EA	7,500.00	7,500
22	- Expansion Tank/Not Sized	1	EA	2,000.00	2,000
23	- Fin Tube	1,150	LF	75.00	86,250

24	- Cabinet Unit Heater	5	EA	1,250.00	6,250
25	- Unit Heater	3	EA	900.00	2,700
26	- Radiant Heat Panels	80	LF	100.00	8,000
27	VAVs w/ Reheat	85	EA	1,250.00	106,250
28	Ductwork - Sheet metal	52,200	LB	7.00	365,400
29	- 16 Gauge Sheet metal	11,000	LB	7.00	77,000
30	- Insulation	42,270	SF	3.00	126,810
31	- Telescoping Source Capture Arm	1	EA	7,500.00	7,500
32	Dampers- Volume	232	EA	200.00	46,400
33	- Fire	3	EA	1,000.00	3,000
34	GRD	60	EA	300.00	18,000
35	- Linear Diffuser	1,230	LF	100.00	123,000
36	- Jet Flow Diffuser	11	EA	500.00	5,500
37	Sound Dampers	3	EA	1,000.00	3,000
38	Controls Allowance	59,750	SF	6.00	358,500
39	CO2 Sensors	29	EA	500.00	14,500
40	Testing and Balancing	59,750	SF	0.75	44,810
41	Commissioning	1	LS	-	NIC
42	Louver- 30x18"	30	SF	60.00	1,800
43					0
44					0
45					0
46					0
	Subtotal				2,149,400

Appendix E: Campus Geothermal Well Field Costs

Geothermal Additional First Costs				
Item	Total	Amount	Units	Expense
Well Field Piping Costs-High Density Polyethylene				
1" Diameter	$ 0.79	1700	Per 40'	$ 1,343.00
1.5" Diameter	$ 1.00	2720	Per 40'	$ 2,720.00
2" Diameter	$ 1.67	4684	Per 40'	$ 7,822.28
3" Diameter	$ 2.01	14428	Per 40'	$ 29,000.28
4" Diameter	$ 3.36	1080	Per 40'	$ 3,628.80
6" Diameter	$ 5.55	2916	Per 40'	$ 16,183.80
8" Diameter	$ 6.50	609	Per 40'	$ 3,958.50
10" Diameter	$ 10.05	220	Per 40'	$ 2,211.00
12" Diameter	$ 10.05	1590	Per 40'	$ 15,979.50
1" Elbow	$ 5.60	170	Each	$ 952.00
1.5" Elbow	$ 7.00	0	Each	$ -
2" Elbow	$ 7.00	2	Each	$ 14.00
3" Elbow	$ 14.00	18	Each	$ 252.00
4" Elbow	$ 19.60	6	Each	$ 117.60
6" Elbow	$ 45.00	34	Each	$ 1,530.00
8" Elbow	$ 98.00	0	Each	$ -
10" Elbow	$ 380.00	0	Each	$ -
12" Elbow	$ 380.00	4	Each	$ 1,520.00
1" Tee	$ 7.30	34	Each	$ 248.20
1.5" Tee	$ 10.25	136	Each	$ 1,394.00
2" Tee	$ 8.80	170	Each	$ 1,496.00
3" Tee	$ 16.10	676	Each	$ 10,883.60
4" Tee	$ 23.50	6	Each	$ 141.00
6" Tee	$ 58.50	64	Each	$ 3,744.00
8" Tee	$ 145.00	13	Each	$ 1,885.00
10" Tee	$ 430.00	11	Each	$ 4,730.00
12" Tee	$ 430.00	20	Each	$ 8,600.00
1" Joints	$ 5.55	483	Each	$ 2,680.65
1.5" Joints	$ 8.65	472	Each	$ 4,082.80
2" Joints	$ 11.85	620	Each	$ 7,347.00
3" Joints	$ 15.15	2403	Each	$ 36,405.45
4" Joints	$ 19.65	56	Each	$ 1,100.40

	6" Joints	$ 30.00	324	Each	$ 9,720.00
	8" Joints	$ 39.50	50	Each	$ 1,975.00
	10" Joints	$ 47.50	33	Each	$ 1,567.50
	12" Joints	$ 47.50	103	Each	$ 4,892.50
Welding Machine Costs					
	1" to 2" Machine	$ 40.50	9	Days	$ 364.50
	3" to 4" Machine	$ 46.00	25	Days	$ 1,150.00
	6" to 8" Machine	$ 103.00	6	Days	$ 618.00
	10" to 14" Machine	$ 178.00	4	Days	$ 712.00
Geothermal Well, total expense		$ 4,901.72	1050	Bore	$ 5,146,806.69
Trenching for Pipes		$ 2.39	29947	LF	$ 71,573.33
Pumps					
	Well Field Pumps-70 head 186 gpm, 5 HP	$ 9,505.00	34	Each	$ 323,170.00

$ 5,734,520.38

Appendix F: Costs of Vertical Geothermal System

Geothermal Additional First Costs				
Item	**Unit Cost**	**Amount**	**Units**	**Expense**
DOAS Water Source HP	$ 18,200.00	1	Each	$ 18,200.00
Energy Recovery Unit	$ 26,925.00	1	Each	$ 26,925.00
Backup Boiler - 240 MBH	$ 5,825.00	1	Each	$ 5,825.00
Pumps				
Well field Pumps	$ 9,505.00	2	Each	$ 19,010.00
Building Pumps	$ 14,905.00	2	Each	$ 29,810.00
Well field Piping Costs-High Density Polyethylene				
1" Diameter	$ 0.79	400	Per 40'	$ 316.00
1.5" Diameter	$ 1.00	800	Per 40'	$ 800.00
2" Diameter	$ 1.67	760	Per 40'	$ 1,269.20
3" Diameter	$ 2.01	80	Per 40'	$ 160.80
4" Diameter	$ 3.36	80	Per 40'	$ 268.80
6" Diameter	$ 5.55	985	Per 40'	$ 5,466.75
8" Diameter	$ 6.50	-	Per 40'	$ -
10" Diameter	$ 10.05	-	Per 40'	$ -
1" Elbow	$ 5.60	-	Each	$ -
1.5" Elbow	$ 7.00	-	Each	$ -
2" Elbow	$ 7.00	12	Each	$ 84.00
3" Elbow	$ 14.00	-	Each	$ -
4" Elbow	$ 19.60	-	Each	$ -
6" Elbow	$ 45.00	6	Each	$ 270.00
8" Elbow	$ 98.00	-	Each	$ -
10" Elbow	$ 380.00	-	Each	$ -
1" Tee	$ 7.30	-	Each	$ -
1.5" Tee	$ 10.25	-	Each	$ -
2" Tee	$ 8.80	2	Each	$ 17.60
3" Tee	$ 16.10	4	Each	$ 64.40
4" Tee	$ 23.50	4	Each	$ 94.00
6" Tee	$ 58.50	8	Each	$ 468.00
8" Tee	$ 145.00	-	Each	$ -
10" Tee	$ 430.00	-	Each	$ -
1" Joints	$ 5.55	8	Each	$ 44.40
1.5" Joints	$ 8.65	16	Each	$ 138.40

2" Joints	$	11.85	45	Each	$	533.25
3" Joints	$	15.15	12	Each	$	181.80
4" Joints	$	19.65	12	Each	$	235.80
6" Joints	$	30.00	56	Each	$	1,680.00
8" Joints	$	39.50	-	Each	$	-
10" Joints	$	47.50	-	Each	$	-
Welding Machine Costs						
1" to 2" Machine	$	40.50	2	Days	$	81.00
3" to 4" Machine	$	46.00	2	Days	$	92.00
6" to 8" Machine	$	103.00	2	Days	$	206.00
Geothermal Well, total expense	$	3,714.25	100	Bore	$	371,425.07
Trenching for Pipes	$	2.39	3,105	LF	$	7,420.95
Heat Pumps						
1/2 ton - 006	$	2,152.39	14	Each	$	30,133.40
3/4 ton - 009	$	2,196.23	5	Each	$	10,981.17
1 ton - 012	$	2,245.00	4	Each	$	8,980.00
1.25 ton - 015	$	2,304.16	6	Each	$	13,824.97
1.5 ton - 018	$	2,370.00	6	Each	$	14,220.00
2 ton - 024	$	2,545.00	4	Each	$	10,180.00
2.5 ton - 030	$	2,675.00	6	Each	$	16,050.00
3 ton - 036	$	2,825.00	2	Each	$	5,650.00
3.5 ton - 042	$	3,175.00	6	Each	$	19,050.00
4 ton - 048	$	3,400.00	2	Each	$	6,800.00
5 ton - 060	$	3,960.00	4	Each	$	15,840.00
Building Heat Pump Piping Costs-High Density Polyethylene						
1" Diameter	$	0.79	-	Per 40'	$	-
1.5" Diameter	$	1.00	1,177	Per 40'	$	1,176.60
2" Diameter	$	1.67	385	Per 40'	$	643.28
3" Diameter	$	2.01	417	Per 40'	$	838.17
4" Diameter	$	3.36	318	Per 40'	$	1,068.48
6" Diameter	$	5.55	346	Per 40'	$	1,922.52
8" Diameter	$	6.50	-	Per 40'	$	-
10" Diameter	$	10.05	-	Per 40'	$	-
1" Elbow	$	5.60	-	Each	$	-
1.5" Elbow	$	7.00	10	Each	$	70.00
2" Elbow	$	7.00	2	Each	$	14.00
3" Elbow	$	14.00	4	Each	$	56.00

4" Elbow	$	19.60	2	Each	$	39.20
6" Elbow	$	45.00	6	Each	$	270.00
8" Elbow	$	98.00	-	Each	$	-
10" Elbow	$	380.00	-	Each	$	-
1" Tee	$	7.30	-	Each	$	-
1.5" Tee	$	10.25	30	Each	$	307.50
2" Tee	$	8.80	14	Each	$	123.20
3" Tee	$	16.10	12	Each	$	193.20
4" Tee	$	23.50	8	Each	$	188.00
6" Tee	$	58.50	12	Each	$	702.00
8" Tee	$	145.00	-	Each	$	-
10" Tee	$	430.00	-	Each	$	-
1" Joints	$	5.55	-	Each	$	-
1.5" Joints	$	8.65	124	Each	$	1,072.60
2" Joints	$	11.85	51	Each	$	604.35
3" Joints	$	15.15	53	Each	$	802.95
4" Joints	$	19.65	35	Each	$	687.75
6" Joints	$	30.00	53	Each	$	1,590.00
8" Joints	$	39.50	-	Each	$	-
10" Joints	$	47.50	-	Each	$	-
Welding Machine Costs						
1" to 2" Machine	$	40.50	3	Days	$	121.50
3" to 4" Machine	$	46.00	3	Days	$	138.00
6" to 8" Machine	$	103.00	3	Days	$	309.00

Total	**$ 655,736.06**

Appendix G: Costs of Horizontal Geothermal System

Geothermal Additional First Costs				
Item	Total Unit Cost	Amount	Units	Expense
DOAS Water Source HP	$ 18,200.00	1	Each	$ 18,200.00
Energy Recovery Unit	$ 26,925.00	1	Each	$ 26,925.00
Backup Boiler - 240 MBH	$ 5,825.00	1	Each	$ 5,825.00
Pumps				
Well Field Pumps	$ 9,505.00	2	Each	$ 19,010.00
Building Pumps	$ 14,905.00	2	Each	$ 29,810.00
Well field Piping Costs-High Density Polyethylene				
1" Diameter	$ 0.79	0	Per 40'	$ -
1.5" Diameter	$ 1.00	0	Per 40'	$ -
2" Diameter	$ 1.67	220	Per 40'	$ 367.40
3" Diameter	$ 2.01	840	Per 40'	$ 1,688.40
4" Diameter	$ 3.36	1287	Per 40'	$ 4,324.32
6" Diameter	$ 5.55	0	Per 40'	$ -
8" Diameter	$ 6.50	0	Per 40'	$ -
10" Diameter	$ 10.05	0	Per 40'	$ -
1" Elbow	$ 5.60	0	Each	$ -
1.5" Elbow	$ 7.00	0	Each	$ -
2" Elbow	$ 7.00	0	Each	$ -
3" Elbow	$ 14.00	0	Each	$ -
4" Elbow	$ 19.60	5	Each	$ 98.00
6" Elbow	$ 45.00	0	Each	$ -
8" Elbow	$ 98.00	0	Each	$ -
10" Elbow	$ 380.00	0	Each	$ -
1" Tee	$ 7.30	0	Each	$ -
1.5" Tee	$ 10.25	0	Each	$ -
2" Tee	$ 8.80	10	Each	$ 88.00
3" Tee	$ 16.10	42	Each	$ 676.20
4" Tee	$ 23.50	23	Each	$ 540.50
6" Tee	$ 58.50	0	Each	$ -
8" Tee	$ 145.00	0	Each	$ -
10" Tee	$ 430.00	0	Each	$ -
1" Joints	$ 5.55	0	Each	$ -

	1.5" Joints	$ 8.65	0	Each	$ -
	2" Joints	$ 11.85	31	Each	$ 367.35
	3" Joints	$ 15.15	126	Each	$ 1,908.90
	4" Joints	$ 19.65	100	Each	$ 1,965.00
	6" Joints	$ 30.00	0	Each	$ -
	8" Joints	$ 39.50	0	Each	$ -
	10" Joints	$ 47.50	0	Each	$ -
Welding Machine Costs					
	1" to 2" Machine	$ 40.50	2	Days	$ 81.00
	3" to 4" Machine	$ 46.00	2	Days	$ 92.00
	6" to 8" Machine	$ 103.00	2	Days	$ 206.00
Geothermal Well, total expense					
	800' Bore	$ 8,936.51	20	Bore	$ 178,730.21
	775' Bore	$ 8,662.85	1	Bore	$ 8,662.85
	750' Bore	$ 8,389.20	4	Bore	$ 33,556.79
	700' Bore	$ 7,836.33	5	Bore	$ 39,181.67
	675' Bore	$ 7,562.68	1	Bore	$ 7,562.68
	650' Bore	$ 7,289.02	4	Bore	$ 29,156.08
	400' Bore	$ 4,535.80	5	Bore	$ 22,679.00
Trenching for Pipes		$ 2.39	2,347	LF	$ 5,609.33
Heat Pumps					
	1/2 ton - 006	$ 2,152.39	14	Each	$ 30,133.40
	3/4 ton - 009	$ 2,196.23	5	Each	$ 10,981.17
	1 ton - 012	$ 2,245.00	4	Each	$ 8,980.00
	1.25 ton - 015	$ 2,304.16	6	Each	$ 13,824.97
	1.5 ton - 018	$ 2,370.00	6	Each	$ 14,220.00
	2 ton - 024	$ 2,545.00	4	Each	$ 10,180.00
	2.5 ton - 030	$ 2,675.00	6	Each	$ 16,050.00
	3 ton - 036	$ 2,825.00	2	Each	$ 5,650.00
	3.5 ton - 042	$ 3,175.00	6	Each	$ 19,050.00
	4 ton - 048	$ 3,400.00	2	Each	$ 6,800.00
	5 ton - 060	$ 3,960.00	4	Each	$ 15,840.00
Building Heat Pump Piping Costs-High Density Polyethylene					
	1" Diameter	$ 0.79	-	Per 40'	$ -
	1.5" Diameter	$ 1.00	1,177	Per 40'	$ 1,176.60
	2" Diameter	$ 1.67	385	Per 40'	$ 643.28
	3" Diameter	$ 2.01	417	Per 40'	$ 838.17
	4" Diameter	$ 3.36	318	Per 40'	$ 1,068.48

	6" Diameter	$ 5.55	346	Per 40'	$ 1,922.52
	8" Diameter	$ 6.50	-	Per 40'	$ -
	10" Diameter	$ 10.05	-	Per 40'	$ -
	1" Elbow	$ 5.60	-	Each	$ -
	1.5" Elbow	$ 7.00	10	Each	$ 70.00
	2" Elbow	$ 7.00	2	Each	$ 14.00
	3" Elbow	$ 14.00	4	Each	$ 56.00
	4" Elbow	$ 19.60	2	Each	$ 39.20
	6" Elbow	$ 45.00	6	Each	$ 270.00
	8" Elbow	$ 98.00	-	Each	$ -
	10" Elbow	$ 380.00	-	Each	$ -
	1" Tee	$ 7.30	-	Each	$ -
	1.5" Tee	$ 10.25	30	Each	$ 307.50
	2" Tee	$ 8.80	14	Each	$ 123.20
	3" Tee	$ 16.10	12	Each	$ 193.20
	4" Tee	$ 23.50	8	Each	$ 188.00
	6" Tee	$ 58.50	12	Each	$ 702.00
	8" Tee	$ 145.00	-	Each	$ -
	10" Tee	$ 430.00	-	Each	$ -
	1" Joints	$ 5.55	-	Each	$ -
	1.5" Joints	$ 8.65	124	Each	$ 1,072.60
	2" Joints	$ 11.85	51	Each	$ 604.35
	3" Joints	$ 15.15	53	Each	$ 802.95
	4" Joints	$ 19.65	35	Each	$ 687.75
	6" Joints	$ 30.00	53	Each	$ 1,590.00
	8" Joints	$ 39.50	-	Each	$ -
	10" Joints	$ 47.50	-	Each	$ -
Welding Machine Costs					
	1" to 2" Machine	$ 40.50	3	Days	$ 121.50
	3" to 4" Machine	$ 46.00	3	Days	$ 138.00
	6" to 8" Machine	$ 103.00	3	Days	$ 309.00

Total	**$ 601,959.52**

Appendix H: Acoustics Reference Data

Measured T30 Data By Classroom

T30 (s)	Octave Bands (Hz)								Volume
	63	**125**	**250**	**500**	**1000**	**2000**	**4000**	**8000**	
Classroom 120	1.06	0.88	0.79	0.62	0.47	0.49	0.47	0.40	
	2.11	0.81	0.70	0.55	0.50	0.50	0.49	0.40	
Average	1.58	0.85	0.75	0.59	0.49	0.49	0.48	0.40	8,000
Classroom 121	1.04	0.94	0.71	0.50	0.74	0.77	0.66	0.46	
	1.45	1.03	0.73	0.49	0.68	0.74	0.61	0.45	
Average	1.24	0.99	0.72	0.49	0.71	0.76	0.63	0.45	16985
Classroom 122	0.70	0.73	0.68	0.48	0.58	0.58	0.54	0.44	
	0.57	0.73	0.78	0.47	0.52	0.56	0.52	0.43	
Average	0.63	0.73	0.73	0.48	0.55	0.57	0.53	0.43	4220
Classroom 246	1.50	0.84	0.93	0.61	0.63	0.68	0.68	0.51	
	1.79	0.86	0.89	0.59	0.60	0.67	0.66	0.52	
Average	1.64	0.85	0.91	0.60	0.62	0.68	0.67	0.51	13850
Classroom 247	0.83	0.91	0.85	0.56	0.58	0.61	0.62	0.50	
	0.86	0.78	0.71	0.61	0.57	0.65	0.63	0.50	
Average	0.84	0.85	0.78	0.59	0.57	0.63	0.62	0.50	11100
Classroom 248	0.81	0.74	0.86	0.56	0.57	0.56	0.60	0.47	
	0.88	0.82	0.79	0.52	0.56	0.56	0.57	0.46	
Average	0.84	0.78	0.83	0.54	0.57	0.56	0.59	0.47	8430

Background Noise Levels

Room	Level (dB)							
	Octave Bands (Hz)							
	63	125	250	500	1000	2000	4000	8000
Classroom 120	37.3	32.0	33.1	31.6	27.7	20.2	16.8	19.0
	37.1	33.4	32.4	30.3	24.8	17.6	14.8	16.5
Average	37.2	32.7	32.7	30.9	26.2	18.9	15.8	17.7
Classroom 121	42.5	39.8	33.9	26.6	22.0	17.0	13.8	15.9
	41.5	39.9	33.8	27.5	24.7	18.5	13.4	15.6
Average	42.0	39.9	33.9	27.1	23.4	17.8	13.6	15.8
Classroom 122	39.5	35.1	31.9	26.1	22.1	17.2	14.1	15.7
	39.1	35.5	31.3	25.0	20.3	14.8	12.9	15.5
Average	39.3	35.3	31.6	25.6	21.2	16.0	13.5	15.6
Classroom 246	44.8	40.2	32.8	29.7	24.4	17.0	14.4	15.8
	44.2	39.7	34.6	29.6	25.6	18.7	15.7	15.9
Average	44.5	39.9	33.7	29.6	25.0	17.9	15.1	15.8
Classroom 247	42.5	35.8	32.5	28.8	27.7	20.6	13.9	15.7
	41.0	35.9	31.1	28.0	25.9	17.4	13.2	15.6
Average	41.7	35.9	31.8	28.4	26.8	19.0	13.5	15.7
Classroom 248	39.6	37.5	31.9	23.5	17.8	14.1	13.1	15.7
	41.7	36.2	33.3	24.4	17.8	13.9	13.2	15.8
Average	40.6	36.9	32.6	24.0	17.8	14.0	13.1	15.8

ATL Data Measurements

Rooms	**Value of ATL (dB) for Third Octave Band (Hz)**						
	125	**160**	**200**	**250**	**315**	**400**	**500**
120-121	25.95	28.25	32.31	33.46	38.97	41.27	45.68
121-122	29.52	34.21	38.04	39.56	44.22	43.29	44.45
246-247	23.76	26.49	34.67	38.29	37.22	40.82	42.3
247-248	17.76	24.68	27.41	33.4	35.86	38.94	39.9

ATL Data Measurements - Continued									
Rooms	Value of ATL (dB) for Third Octave Band (Hz)								
	630	800	1000	1250	1600	2000	2500	3150	4000
120-121	53.3	51	52	53.95	54.79	52.97	52.07	55.02	55.79
121-122	45.8	52.25	53.73	52.93	55.06	52.32	52.58	55.1	55.9
246-247	38.19	46.07	48.44	46.01	43.65	43.12	36.49	43.66	45.47
247-248	40.64	42.14	44.58	44.19	42.89	38.74	34.78	38.16	41.23

Heat Pump Acoustic Data:

Performance data (cont)

Carrier

OCTAVE BAND SOUND POWER LEVEL (dB re 1PW)
STANDARD UNIT — TESTED IN ACCORDANCE WITH ARI 260

50PTH, PTV,PTD UNITS	MODE	DUCTED DISCHARGE OCTAVE BAND FREQUENCY, Hz							FREE AIR INLET COMBINED WITH CASING (CABINET) RADIATED OCTAVE BAND FREQUENCY, Hz						
		125	250	500	1000	2000	4000	8000	125	250	500	1000	2000	4000	8000
026	Fan Only	49	49	48	44	37	36	35	56	52	53	45	42	37	32
	Cooling: Part Load	49	51	51	48	44	43	36	61	55	56	50	48	43	36
	Cooling: Full Load	45	46	53	46	43	42	34	54	48	55	49	44	39	34
	Heating: Part Load	55	53	54	50	46	45	35	67	58	60	52	47	45	38
	Heating: Full Load	49	49	55	48	46	56	39	62	51	58	53	47	43	40
038	Fan Only	54	51	50	46	39	35	33	58	53	48	42	40	34	30
	Cooling: Part Load	57	53	53	51	46	43	36	61	55	52	48	44	40	35
	Cooling: Full Load	60	56	57	55	51	50	41	63	57	55	50	45	43	37
	Heating: Part Load	60	55	55	52	48	44	36	65	58	57	50	44	42	39
	Heating: Full Load	64	58	59	57	53	61	43	68	59	57	53	48	46	42
049	Fan Only	62	55	54	50	43	41	40	62	58	53	46	43	39	35
	Cooling: Part Load	60	57	57	54	50	49	43	72	63	61	53	50	46	43
	Cooling: Full Load	60	58	59	57	53	53	45	63	57	57	52	47	45	41
	Heating: Part Load	64	59	57	55	51	50	38	71	64	63	53	48	47	45
	Heating: Full Load	64	60	61	59	55	65	49	68	60	60	54	49	47	45
064	Fan Only	56	53	52	50	44	41	33	62	56	51	46	42	39	31
	Cooling: Part Load	62	59	59	56	52	51	44	66	60	64	53	50	48	41
	Cooling: Full Load	65	60	60	58	54	53	46	68	64	65	55	52	50	44
	Heating: Part Load	66	64	62	60	57	55	49	68	64	62	56	54	52	46
	Heating: Full Load	70	68	66	65	62	60	54	72	68	66	61	59	58	52

NOTES:
1. All sound power level performance is expressed in dB with reference to 1 picoWatt.
2. Data based on sound measurements made in a reverberant room on representative units from each cabinet size in accordance with ARI 260.
3. All data is third party tested and verified.

Ceiling Transmission Loss Estimates – Mass Law

Ceiling TL Estimates	Frequency (Hz)											
	50	63	80	100	125	160	200	250	315	400	500	630
TL (dB)	0.00	0.00	0.00	1.60	3.54	5.68	7.62	9.56	11.56	13.64	15.58	17.59

Ceiling TL Estimates Cont.	Frequency (Hz)											
	800	1000	1250	1500	2000	2500	3150	4000	5000	6300	8000	10000
TL (dB)	19.66	21.60	23.54	25.12	27.62	29.56	31.56	33.64	35.58	37.59	39.66	41.60

Appendix I: Ductwork Noise Outputs from Dynasonics

Classroom

Calculation Summary

	Element	Properties	NC	63	125	250	500	1K	2K	4K	dB(A)
				Octave Midband Frequency, Hz							
1	**Classroom**	**Criteria: NC-30**	**29**	**44**	**47**	**38**	**25**	**20**	**16**	**26**	**35**
2	**Return Path (1 (1))**	**Criteria: NC-30**									
3	Water Source Heat Pump 064			72	72	68	66	61	59	58	
4	Rectangular Elbow Miter	20"x14" (0")		0	-1	-5	-8	-4	-3	-3	
				44	39	33	25	17	8	0	
5	Rectangular Duct	20"x14"x5' (1")		-2	-1	-3	-8	-17	-15	-11	
6	Rectangular Elbow Miter	10"x14" (0")		0	0	-1	-5	-8	-4	-3	
				66	62	57	51	44	36	28	
7	Rectangular Duct	10"x14"x5' (0")		-2	-1	-1	0	0	0	0	
8	Takeoff (Branch Power Split)	20"x20" / 12"x10"		-3	-3	-3	-3	-3	-3	-3	
				43	37	31	23	14	4	0	
9	Rectangular Duct	12"x10"x5' (0")		-2	-1	-1	0	0	0	0	
10	Flexible Duct	9"x5'		-4	-6	-11	-18	-19	-19	-10	
11	End Reflection Loss	9" (Flush)		-15	-9	-4	-2	0	0	0	
12	Room Correction (Normally Furnished)	15'x30'x10'		-5	-6	-6	-7	-8	-9	-10	
13	**SUM**		**26**	**42**	**44**	**35**	**21**	**13**	**7**	**17**	**31**
14	**Supply Path (1)**	**Criteria: NC-30**									
15	Water Source Heat Pump 064			70	70	68	66	65	62	60	
16	Rectangular Duct	17.5"x19"x5' (0")		-2	-1	-1	0	0	0	0	
17	Rectangular Elbow Miter	17.5"x19" (0")		0	-1	-5	-8	-4	-3	-3	
				39	33	26	19	10	1	0	
18	Rectangular Duct	17.5"x19"x3' (0")		-1	-1	0	0	0	0	0	
19	Takeoff (Branch Power Split)	17.5"x19" / 12"x8"		-3	-3	-3	-3	-3	-3	-3	
				50	45	38	31	22	13	2	
20	Rectangular Duct	12"x8"x3' (1")		-1	-1	-3	-6	-14	-15	-10	
21	Flexible Duct	9"x4'		-3	-5	-9	-16	-16	-17	-9	
22	End Reflection Loss	9" (Flush)		-15	-9	-4	-2	0	0	0	
23	Room Correction (Normally Furnished)	30'x15'x10'		-5	-6	-6	-7	-8	-9	-10	
24	**SUM**		**28**	**41**	**43**	**36**	**23**	**19**	**15**	**25**	**32**

Office
Calculation Summary

Element		Properties	NC	63	125	250	500	1K	2K	4K	dB(A)
				Octave Midband Frequency, Hz							
25	**Office**	**Criteria: NC-30**	**27**	**42**	**45**	**37**	**32**	**20**	**13**	**22**	**34**
26	**Return Path (2)**	**Criteria: NC-30**									
27	Water Source Heat Pump 026			67	67	58	60	52	47	45	
28	Rectangular Duct	20"x12"x5' (0")		-2	-1	-1	0	0	0	0	
29	Takeoff (Branch Power Split)	20"x12" / 10"x8"		-3	-3	-3	-3	-3	-3	-3	
				14	7	0	0	0	0	0	
30	Rectangular Duct	10"x8"x2' (1")		-1	-1	-2	-4	-9	-11	-7	
31	Flexible Duct	10"x3'		-2	-4	-7	-14	-12	-13	-6	
32	End Reflection Loss	10" (Flush)		-14	-8	-4	-1	0	0	0	
33	Room Correction (Normally Furnished)	8'6"x12'x10'		-4	-5	-6	-7	-7	-8	-9	
34	**SUM**		**26**	**42**	**45**	**35**	**31**	**19**	**12**	**20**	**33**
35	**Supply Path (1)**	**Criteria: NC-30**									
36	Water Source Heat Pump 026			55	55	53	54	50	46	45	
37	Rectangular Duct	20"x12"x4' (0")		-2	-1	0	0	0	0	0	
38	Takeoff (Branch Power Split)	20"x12" / 10"x8"		-3	-3	-3	-3	-3	-3	-3	
				14	7	0	0	0	0	0	
39	Rectangular Duct	10"x8"x3' (1")		-1	-1	-3	-7	-14	-16	-10	
40	Flexible Duct	10"x2'		-1	-3	-6	-11	-10	-11	-4	
41	End Reflection Loss	10" (Flush)		-14	-8	-4	-1	0	0	0	
42	Room Correction (Normally Furnished)	8'6"x12'x10'		-4	-5	-6	-7	-7	-8	-9	
43	**SUM**		**22**	**30**	**33**	**31**	**25**	**15**	**8**	**18**	**27**

Appendix J: Schedules Used in the Trace 700 Model

Classroom Schedule:

Hourly Profiles:

1:Design Day

Hour	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Value	0	0	0	0	0	0	0	20	100	100	100	100	100	100	100	100	100	100	100	100	100	100	20	0

2:M-F Fall & Spring

Hour	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Value	0	0	0	0	0	0	0	20	80	100	100	100	100	100	100	100	81	80	80	80	80	50	0	0

3:Summer

Hour	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Value	0	0	0	0	0	0	0	0	20	20	20	20	20	20	20	20	20	60	60	60	60	0	0	0

4:Weekend

Hour	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Value	0	0	0	0	0	0	0	0	0	20	20	20	20	20	20	0	0	0	0	0	0	0	0	0

5:Holiday

Hour	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Value	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Compressor Schedule (for all times and days)

Hourly Profiles:

1:Profile One

Hour	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Value	20	20	20	20	20	20	20	20	20	50	20	20	50	20	20	50	20	20	20	20	20	20	20	20

Greywater Pumps Schedule (for all times and days)

Hourly Profiles:

1:Profile One

Hour	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Value	11	11	11	11	11	11	11	30	30	30	30	30	30	30	30	30	30	30	30	11	11	11	11	11

Kitchen Hoods Schedule (profile one for all days, except profile two for Thursdays)

Hourly Profiles:

1:Profile One

Hour	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Value	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	100	100	100	100	0	0	0

2:Profile Two

Hour	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Value	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Mechanical Schedule (for all times and days)

Hourly Profiles:

1:Profile One

Hour	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Value	50	50	50	50	50	50	50	100	100	100	100	100	100	100	100	100	100	100	100	100	50	50	50	50

Nighttime Schedule

Hourly Profiles:

1:Winter

Hour	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Value	100	100	100	100	100	100	100	100	0	0	0	0	0	0	0	0	100	100	100	100	100	100	100	100

2:Spring/Fall

Hour	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Value	100	100	100	100	100	100	100	0	0	0	0	0	0	0	0	0	0	0	0	100	100	100	100	100

3:Summer

Hour	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Value	100	100	100	100	100	100	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	100	100	100

Office Electrical Schedule

Hourly Profiles:

1:Design Day

Hour	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Value	25	25	25	25	25	25	25	100	100	100	100	100	100	100	100	100	100	100	100	25	25	25	25	25

2:M-F Fall & Spring

Hour	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Value	25	25	25	25	25	25	25	50	50	90	90	90	50	90	90	90	50	50	25	25	25	25	25	25

3:Weekend or Summer

Hour	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Value	0	0	0	0	0	0	0	25	50	50	50	50	50	50	50	50	25	0	0	0	0	0	0	0

4:Holiday

Hour	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Value	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Office People and Lighting Schedule

Hourly Profiles:

1:Design Day

Hour	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Value	0	0	0	0	0	0	0	70	100	100	100	100	70	100	100	100	100	40	20	0	0	0	0	0

2:M-F Fall & Spring

Hour	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Value	0	0	0	0	0	0	0	20	50	80	80	80	50	80	80	80	50	20	5	0	0	0	0	0

3:Weekend or Summer

Hour	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Value	0	0	0	0	0	0	0	0	10	10	10	10	10	10	10	10	10	0	0	0	0	0	0	0

4:Holiday

Hour	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Value	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Academic Vita Matthew T. Neal

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Education

Combined Masters of Science and Bachelor of Architectural Engineering
Mechanical Option
The Pennsylvania State University, Schreyer Honors College
Graduating Class of 2014 (BAE) and 2015 (MS)

Relevant Coursework

Advanced Architectural Acoustics, Fundamentals of Acoustics, Acoustics in a Fluid Media, 2012 Rome Study Abroad Program, Advanced HVAC, Thermodynamics, Structural Analysis, Fundamentals of HVAC, Fundamentals of Electrical Systems, Architectural Design Studio coursework

Work Experience

Research Experience for Undergraduates — May 2013 to Sept. 2013
The Applied Research Lab, Penn State — University Park, PA
- Performed a literature review of background research
- Created and validated a computer model of a 2000 seat concert hall
- Conducted subjective studies on concert hall acoustics

Student Researcher — July 2012 to August 2012
The Applied Research Lab, Penn State — University Park, PA
- Gathered, processed, analyzed, and presented acoustical data
- Measured acoustical properties of thermo-acoustic speakers

Mechanical / HVAC Intern — May 2011 to August 2011
H. F. Lenz Company — Johnstown, PA
- Developed mechanical equipment within Revit MEP
- Calculated ventilation requirements and heating loads

Presentations

"The effect of using matched, but not individualized, head related transfer functions on the subjective evaluation of auralizations" Neal & Vigeant
Acoustical Society of America Meeting, San Francisco – December 2nd, 2013

Activities

Essence of Joy, Treasurer	Fall 2009 to Present
The Navigators, Bible Study Leader	Fall 2009 to Present
Acoustical Society of America	Fall 2013 to Present

Awards & Honors

AE Alumni Association Scholarship	Spring 2011
Dean's List	Fall 2009 to Fall 2012
AE General Scholarship	Spring 2012
Tau Beta Pi Engineering Honor Society	Fall 2011 to Present**0**