# Ground Coupled Redesign of the Medical Office Building

## Architectural Engineering Senior Thesis

## Final Report

## Spring 2015

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**Advisor: Dr. Donghyun Rim**

# Medical Office Building North-East United States

Façade rendering courtesy of Anchor Health Properties

## Building Information

Name: Medical Office Building

Location: North-East United States

Size: 72,706 S.F.

Stories: 2

Occupancy: New healthcare and business

## Architecture

- Façade of building composed of brick and metal with areas of textured glass.
- Building will provide a home to primary and specialty care physician offices, diagnostic imaging, physical therapy and laboratory services.

## Design Team

**Owner**: Anchor Health Properties

**Architect**: Array Healthcare Facilities Solutions

**Civil Engineer**: Nave Newell

**Structural Engineer**: O'Donnell & Naccarato

**MEP Engineer**: The Procz Group, Inc.

**Equipment Planning**: Sockwell & Associates

## Mechanical

- Two 70 ton roof top units feeding multiple VAV boxes
- Five ductless split system units
- Supplemental baseboard heating provided in vestibules, restrooms, stairs, and specialty rooms

## Electrical

- 480/277V 3-phase power source
- 3000A main switchboard, GFI protected
- 600KW emergency generator

## Structural

- Steel framing with composite beam and composite deck for the floors
- Steel joists and deck compose the roof
- Steel stud interior walls
- Structural steel stud exterior walls

**Kale Mullikin | Mechanical | https://www.engr.psu.edu/ae/thesis/portfolios/2015/ktm5125**

**Advisor: Donghyun Rim**

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# Acknowledgements

I would first like to thank the AE faculty for teaching me everything I need to know to complete a massive project like the AE senior thesis. I would like to thank Dr. Donghyun Rim for being my advisor on this project.

I would like to thank Anchor Health Properties for allowing me to use their building as the focus for my thesis. In particular I would like to thank Kurt Hutter for all the help he has provided me in this project. I would also like to thank Randy Cook of The Procz Group Inc. for his help with the mechanical specifications needed for this project.

Finally I would like to thank my family for their help and support all through my college career.

# Chapter 1: Executive Summary

The final report is the result of all of the work that has been put forth in the last year of the architectural engineering program. It aspires to accurately portray the thoughts of the fifth year architectural engineering students and what they have to offer to the industry. The following report details the possibility for implementing a ground coupled system in the Medical Office Building located in the northeast United States and resolutions to the potential impacts this system may have on the rest of the building.

There were two logical ground coupled systems that would be feasible on the site of the Medical Office Building, vertical loop system and a horizontal loop system. After conducting calculations to determine the length of tubing that would be needed to satisfy the load needs of the building, two different layouts were presented with the cost and payback of each detailed. The vertical loop system ultimately had a payback of 28.9 years where the horizontal loop had a payback of 4.9 years. Both of these layout options are feasible for this building, but the horizontal loop would offer a more immediate savings and therefore is more desirable.

As a result of adding a ground coupled system to the building, the original rooftop units could not be used due to the lack of ability to accept an exterior cooling and heating source. Five Trane units were selected to replace the original units. These new units would require a different amount of power and therefore the original panel board and wiring would not suffice. The wires supplying the rooftop units were resized along with the breakers for the units, the ground wire size for the units and the conduit size. A separate panel was used for the units which resulted in the need to size a breaker for the panel, the wires running from the main distribution panel to the subpanel, and the conduit size.

Finally, with the addition of more units to the roof, the roof structure would need to be examined to determine if it was suitable to hold the load of the units. The original structure was suitable but a more cost effective design could have been used for the area of roof that supported the units. After conducting load analysis calculations and selecting an open web steel joist member to replace the original W-shape members, a savings of $32,724 was realized. This savings could potentially help to offset the cost of the ground coupled system.

# Chapter 2: Existing Conditions

## 2.1 Mechanical System Summary

The Medical Office Building is located in North-East United States and is to house many medical offices as well as some examination rooms and a physical therapy area. The building is two stories tall with a total square footage of 72,706.

The main heating and cooling for the Medical Office Building will be provided by two 70 ton rooftop units supplying VAV boxes with reheat coils. The roof top units are self-contained, meaning that there are no hot or cold water lines running to the units. The units utilize a closed loop refrigerant system for cooling and a gas furnace system fueled by propane for heating. The VAV system utilizes electric resistance for the reheat system.

A few additional electric baseboard heating systems are utilized at the entrances to the building. There are also five ductless split system units that supply control rooms for important medical equipment.

## 2.2 Building Load Calculations

The building analysis for technical report two was performed by the computer program Trane TRACE 700. This program is used to calculate load design as well as energy analysis. Pertinent building information was obtained from the construction documents and assumptions that were made came from the ASHRAE standards.

### 2.2.1 Design Conditions

The Medical Office Building is located in the North-East United States. This area is in zone 5A according to ASHREA 90.1 table B-1. This area is very humid in the summers and can be quite cold in the winters. Indoor and outdoor air conditions for the building were obtained from the ASHRAE Handbook of Fundamentals 2009.

The indoor design temperatures were designed to be 72°F for the winter and 75°F for the summer with a maintained relative humidity of 50%.

| | Summer Design Cooling (0.4%) | Winter Design Heating (99.6%) |
|---|---|---|
| Outdoor Air Dry Bulb (°F) | 92.4 | 9.4 |
| Outdoor Air Wet Bulb (°F) | 74.1 | - |
| Indoor Air Design Temp (°F) | 75 | 72 |

**Table 1: Design Conditions**

### 2.2.2 Model Development

The calculations in this report were done under the assumption of a block load procedure. Similar areas were designed and considered to be one block. For example, the offices in the building are all similar so they were considered to be one block. In TRACE, a template was created for each block and then the template was modified to fit the exact conditions for each individual room. In the Medical Office Building there were eight different blocks to be considered. These blocks are:

- Conference
- Corridor
- Lobby
- Office
- Physical Therapy
- Procedure
- Reception
- Storage

The Medical Office Building has 131 different rooms that need to be considered in the analysis of the loads for the building. Each of these rooms was categorized into a different block by their primary function. For orientation of a building on a site, TRACE uses the nomenclature of 0°, 90°, 180°, and 270° to represent North, East, South, and West respectively. The main entrance of the Medical Office Building is located on the North side. Using the main entrance as a reference point, the rooms could then be oriented to in TRACE so the program would know how much solar energy the rooms would obtain and adjust the loads accordingly.

### 2.2.3 Load Assumptions

Pertinent load information for the building was taken from the mechanical drawings and schedules. Information that could not be found in the drawings or schedules was taken from ASHRAE standards 62.1 and 90.1.

### 2.2.4 Occupancy Loads

For the Medical Office Building, occupancy densities were given in the design documents so no assumptions needed to be made. These values also conveniently were the same as the values in the TRACE library since the Medical Office Building is compliant with ASHRAE standards.

| Room Type | Occupancy Density (S.F. / person) |
|---|---|
| Conference | 20 |
| Corridor | 0 |
| Lobby | 33.3 |
| Office | 143 |
| Physical Therapy | 0 |
| Procedure Room | 100 |
| Reception | 16.7 |
| Storage | 0 |

**Table 2: Occupancy Densities**

### 2.2.5 Ventilation Rates

The Medical Office Building was designed to be compliant with AHSRAE standard 62.1. TRACE has a feature where compliancy to ASHRAE 62.1 can be selected and the type of room can also be selected, automatically filling in the correct outdoor air ventilation rates for people based and area based calculations.

| Room Type | People-Based (CFM/Person) | Area-Based (CFM/S.F) |
|---|---|---|
| Conference | 5 | 0.06 |
| Corridor | 0 | 0.06 |
| Lobby | 5 | 0.06 |
| Office | 5 | 0.06 |
| Physical Therapy | 20 | 0.06 |
| Procedure Room | 15 | 0.06 |
| Reception | 5 | 0.06 |
| Storage | 0 | 0.12 |

**Table 3: Ventilation Rates**

### 2.2.6 Lighting and Electric Loads

Lighting and electric loads were not given in the design documents so assumptions had to be made. The assumptions were based off of the ASHRAE standard 90.1 table 9-5. TRACE has the option to add extra load where it may be needed. This was done in the offices and reception areas where there will be extra load associated with printers and computers.

| Room Type | Heat Gain (W/S.F.) |
|---|---|
| Conference | 1.23 |
| Corridor | 0.99 |
| Lobby | 0.9 |
| Office | 1.66 |
| Physical Therapy | 0.91 |
| Procedure Room | 2.48 |
| Reception | 0.71 |
| Storage | 0.74 |

**Table 4: Lighting and Electrical Heat Gain**

### 2.2.7 Calculated Load vs. Designed Load

No load calculation data was provided with the mechanical drawings or the mechanical specifications to compare the TRACE data to. The TRACE data will therefore be checked for logicality based on knowledge of typical AHU sizes for certain building sizes and consulting with design professionals.

The total cooling load for the building was 115.1 tons and the heating load was 1380 MBh. These numbers are very logical due to the building size. It was expected that the cooling load for the building was going to be around 100 tons. The individual split for the cooling loads between the two roof top units also corresponds well with the capacity of the roof top units that were selected to be installed in the building.

When TRACE calculations were conducted, a load profile graph for the heating and cooling coils of the building was also generated. This graph is shown in the figure below. The graph depicts the amount of heating energy and cooling energy that will be utilized for each month. During the winter months, December through March, there will only be a heating load present because the building is located in the Northeast area of the country where the temperature during the winter gets very low. During the spring and fall months, April, May, September, October, and November, there will be a mix of heating and cooling because of the varying change in temperature and humidity during these months. The overall energy usage of these months will also be low due to the fact that the two roof top units are equipped with economizers and these months offer the best temperatures for economizers to be used effectively. During the summer months, June, July, and August, there will be a large amount of cooling load present due to the large amount of humidity the Northeast experiences during the summer. There will also be some heating load from the electric coil in the VAV boxes from the occupants of the building fine-tuning the temperature to what they desire.

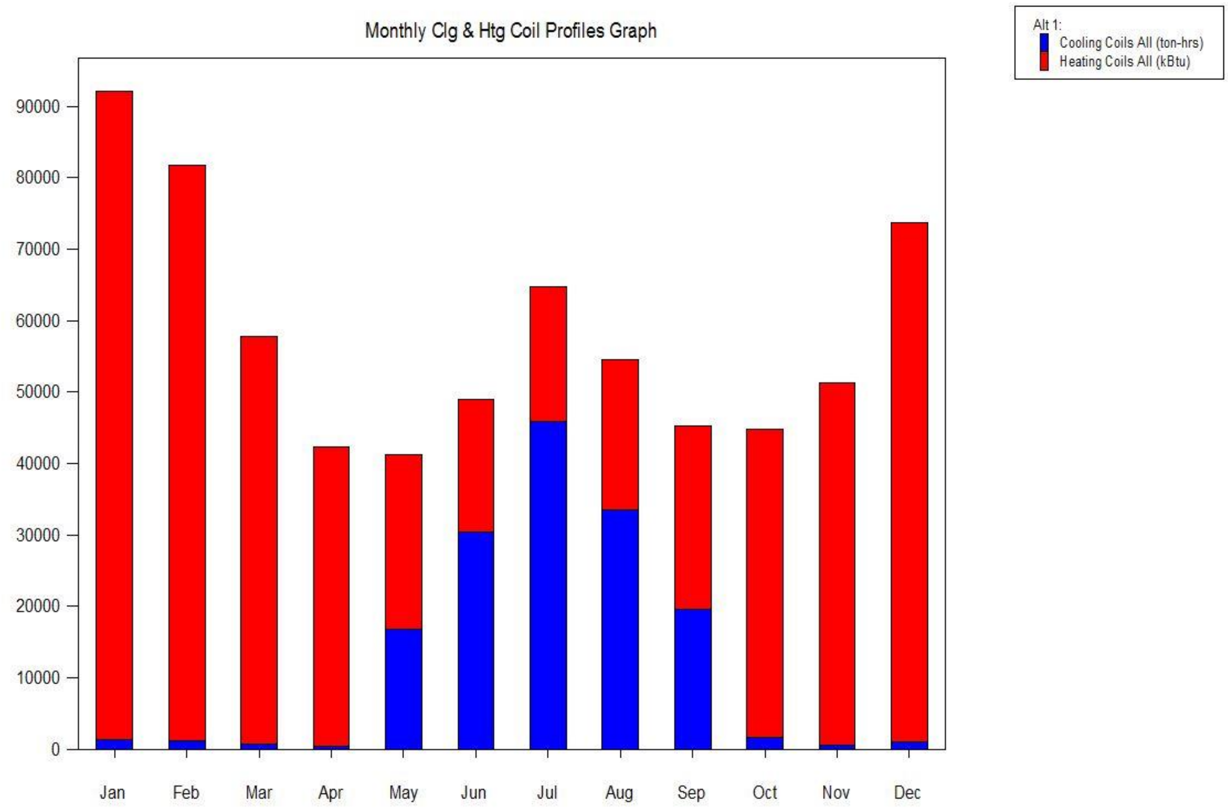


**Figure 1: Monthly Heating and Cooling Profiles**

The engineers at The Procz Group, Inc. most likely used Trane TRACE or a similar software to analyze the loads of the building and come up with an accurate model to select the units to serve the building. They would have, although, used much more detail to develop a much more accurate model to present to the owner compared to the model that was developed for this report. This level of accuracy could not be achieved for this report, however, because there was certain information that was unknown that could have only been answered by being a part of the design team and by having much more time to work on the model. A full list of the TRACE outputs can be seen in the appendix sections of Technical Report 2, available on the CPEP website.

## 2.3 Building Energy and Cost Analysis

### 2.3.1 Energy Consumption

The Trane TRACE program was also used to do an energy analysis on the Medical Office Building. From this analysis, it was determined that the Medical Office Building would use an estimated 3.6 million kBtu per year with a breakdown of the energy utilized shown in the figure below. Detailed information was not able to be obtained from the design documents regarding fuel costs, water and air flow rates and equipment performance characteristics so the default information provided by TRACE was utilized.

| | Electric (kWh) | Gas (kBtu) | Total Building Energy (kBtu/yr) |
|---|---|---|---|
| Heating | - | 709,240 | 709,240 |
| Cooling | 204,744 | - | 698,791 |
| Lighting | 529,746 | - | 1,808,024 |
| Receptacles | 115,781 | - | 395,161 |
| | | | 3,611,216 |

**Table 5: Energy Use per Year**

It is unknown if an energy analysis was performed by the designing engineers. If one was not performed, it would be most likely because this building was designed to be compliant with ASHRAE. ASHRAE standards are already designed to be energy efficient; therefore performing an analysis could potentially be an inefficient use of time and money. If one was performed though, the designers would have most likely used software similar to TRACE.

### 2.3.2 Annual Cost Summary

The total cost per year for electricity is $42,514 and the total cost per year for gas is $3,546. This brings the total cost for utilities per year to $46,060 with an average cost per square foot of $1.02. The figure below shows a breakdown of the monthly cost for gas, electricity, and the total monthly utility cost.

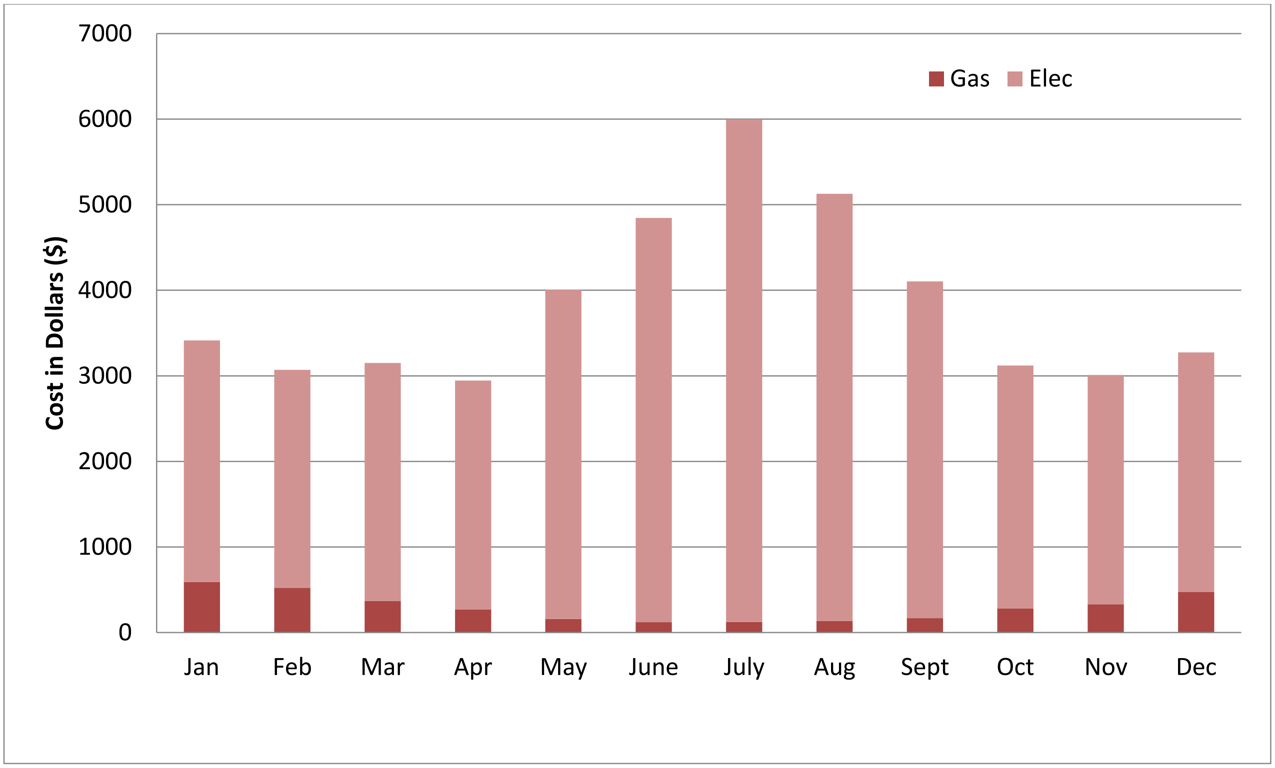


**Figure 2: Monthly Utility Cost**

### 2.3.3 Environmental Impact

TRACE also has the ability to calculate the emissions that a building will produce in a year. This feature is useful when comparing different systems based on the amount of emissions they produce. The table below is a summary of the emissions per year produced by the Medical Office Building.

| Contributor | Amount |
|---|---|
| CO2 | 1,027,144 lbm/year |
| SO2 | 7,991 gm/year |
| NOX | 1,536 gm/year |

**Table 6: Yearly Emissions**

# Chapter 3: Mechanical Proposal

## 3.1 Ground coupled System

After reviewing potential alternatives for energy savings in the Medical Office Building, it was determined that the addition of a ground coupled system would provide the best potential to decrease the energy usage in the building, primarily by the elimination of the use of propane fuel. Ground coupled systems are desirable because of the constant and steady temperature of the earth’s crust, which is about 50 °F. This steady temperature allows for the extraction of heat from the ground in the winter and the return of heat to the ground in the summer. During the winter, the working fluid is circulated through the wells where it extracts heat from the surrounding soil. This fluid is then pumped to the air handling unit where it passes through a heat exchanger to heat the air. In the summer, heat is extracted from the air at the air handling unit and transferred into the working fluid. The warm fluid then travels down into the wells where it transfers the heat into the ground. The Medical Office Building sits on a reasonably sized site which allows for enough space to place a ground coupled well system on the site. This can be seen in the figure below where the red indicates the building location and the green indicates the areas of the site in which ground coupled wells could be placed. 4

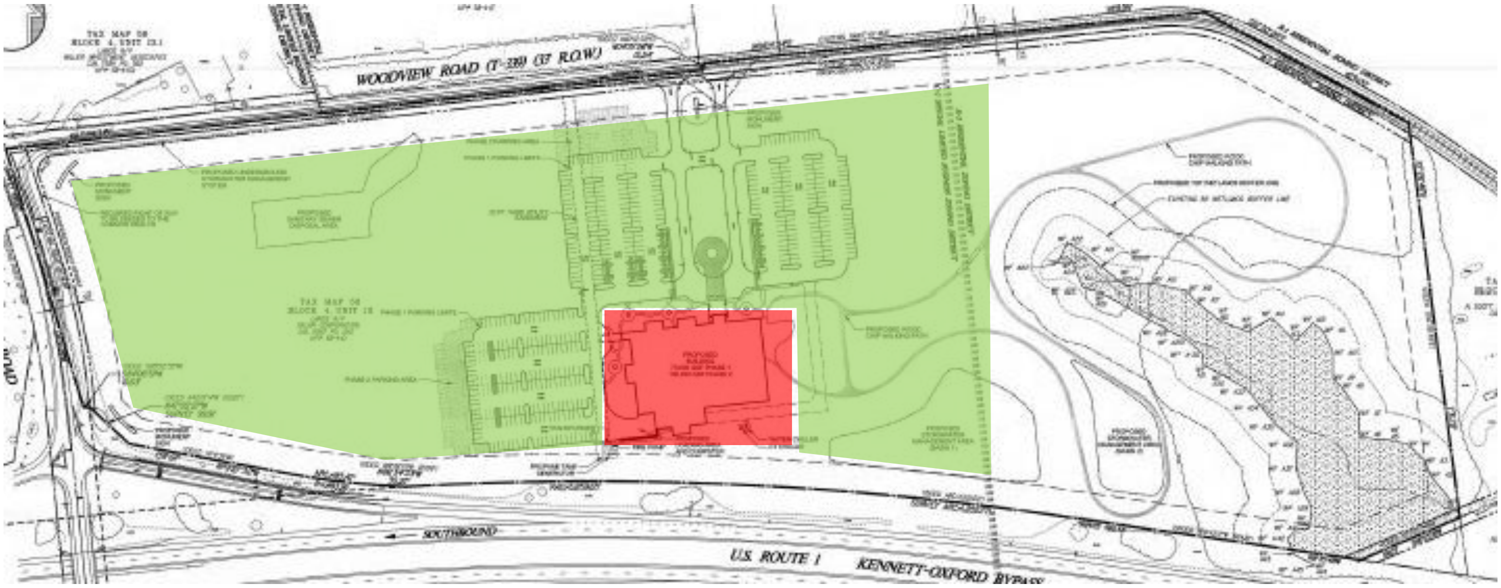


Figure 3: Possible Ground Coupled Loop Locations

# 3.2 Ground coupled Sizing and Calculations

To determine the number of wells needed to heat and cool the Medical Office Building, the required bore length for heating and cooling must be calculated. These equations are found in the ASHRAE Applications Handbook, Chapter 32, Ground coupled Energy. Once this length is found, well depth can then be determined as well as the number of wells required for the site. The required length for cooling can be found as follows:

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

The required length for heating can be found as follows:

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

Where:

$F_{sc}$ = short circuit heat loss factor

$L_c$ = required bore length for cooling, ft

$L_h$ = required bore length for heating, ft

$PLF_m$ = part load factor during design month

$q_a$ = net annual average heat transfer to the ground, Btu/h

$q_{lc}$ = building design cooling block load, Btu/h

$q_{lh}$ = building design heating block load, Btu/h

$R_{ga}$ = effective thermal resistance of ground (annual pulse), h*ft*°F/Btu

$R_{gd}$ = effective thermal resistance of ground (daily pulse), h*ft*°F/Btu

$R_{gm}$ = effective thermal resistance of ground (monthly pulse), h*ft*°F/Btu

$R_b$ = thermal resistance of pipe, h*ft*°F/Btu

$t_g$ = undisturbed ground temperature, °F

$t_p$ = temperature penalty for interference of adjacent bores, °F

$t_{wi}$ = liquid temperature at heat pump inlet, °F

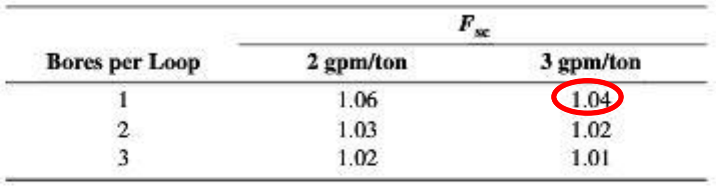
$t_{wo}$ = liquid temperature at heat pump outlet, °F

$W_c$ = power input at design cooling load, W

$W_h$ = power input at design heating load, W

## Short Circuit Heat Loss Factor ($F_{sc}$)

The short circuit heat loss factor is the reduction in performance in a ground coupled well system due to the upward and downward flowing legs of a typical U-tube found in a ground coupled well. This factor was determined from a table the ASHRAE applications handbook, which can be seen below. Values of one bore per loop and 3 gpm/ton were used in determining the values of the short circuit heat loss factor. This resulted in an $F_{sc}$ of 1.04.



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

**Figure 4: $F_{sc}$ Table from ASHRAE Applications Chapter 32**

## Required Bore Length for Cooling/Heating ($L_c/L_h$)

The equation for the length of cooling and heating is derived from the steady-state heat transfer equation which is as follows:

$$q = \frac{L(t_g - t_w)}{R}$$

The equation for the required bore length for cooling and heating tells us the number of feet of tubing that needs to be present in the ground to satisfy the load of the building. Since the lengths will not be identical, the larger of the lengths needs to be selected. This will result in an oversizing of the other which will be beneficial.

## Part Load Factor During the Design Month ($PLF_m$)

Due to the fact that the part load factor is unknown for the building, the worst case scenario was assumed. This means that the part load factor will have a value of 1.0.

### Building Design Cooling Block Load ($q_{lc}$)

The building design cooling block load is the maximum amount of cooling that the building will need during its peak condition. For the Medical Office Building this will occur sometime during the summer months of June, July, and August. This value was obtained from the Trane TRACE calculations that were conducted. The value of the design cooling block load is 917,038 BTU/h.

### Building Design Heating Block Load ($q_{lh}$)

The building design heating block load is the maximum amount of heating that the building will require during its peak condition. This will occur sometime during the December, January, and February months for the Medical Office Building. This value was also obtained from the Trane TRACE calculations that were conducted. The value of the design heating block load is 853,865 BTU/h.

### Net Annual Average Heat Transfer to the Ground ($q_a$)

The net annual average heat transfer to the ground is calculated by the difference of heat being added to the ground by cooling in the summer and the heat that is removed from the ground in the winter. For the Medical Office Building to use ground coupled to replace its current system, it will add 63,173 BTU/h of heat to the ground per year.

### Effective Thermal Resistance of Ground (annual, daily, and monthly pulse)

To determine the effective thermal resistance of the ground, it is required to use the Fourier number (Fo) which is as follows:

$$Fo = \frac{4 * \alpha_g * \tau}{d_b^2}$$

$\alpha_g$ is the thermal diffusivity of the ground. From a geological survey of the ground it was determined that the Medical Office Building sits on an area that is composed of silt loam which is about the same as light sand. The thermal diffusivity of this material is 0.9. (need note of website in appendix) The outside diameter of the pipe in the bore is also needed which was decided to be 1.25 inches. This variable is denoted by $d_b$. The last variable needed is $\tau$, which is the time of operation. There are three different types of pulses that can be used to model a typical system: 10 years (3650 days), one month (30 days), and 6 hours (0.25 days). These pulses are then used to calculate three different τ which is shown below.

$\tau_1$ = 3650 days

$\tau_2$ = 3650 + 30 = 3680 days

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

Three different Fourier numbers can then be computed as follows:

$$F_f = \frac{4 * \alpha_g * \tau_f}{d_b^2} = 8479$$

$$F_1 = \frac{4 * \alpha_g * (\tau_f - \tau_1)}{d_b^2} = 69.6$$

$$F_2 = \frac{4 * \alpha_g * (\tau_f - \tau_2)}{d_b^2} = 0.576$$

These Fourier numbers are then used to determine a G-factor for each of the Fourier numbers. The G-factor is determined by using the following graph.

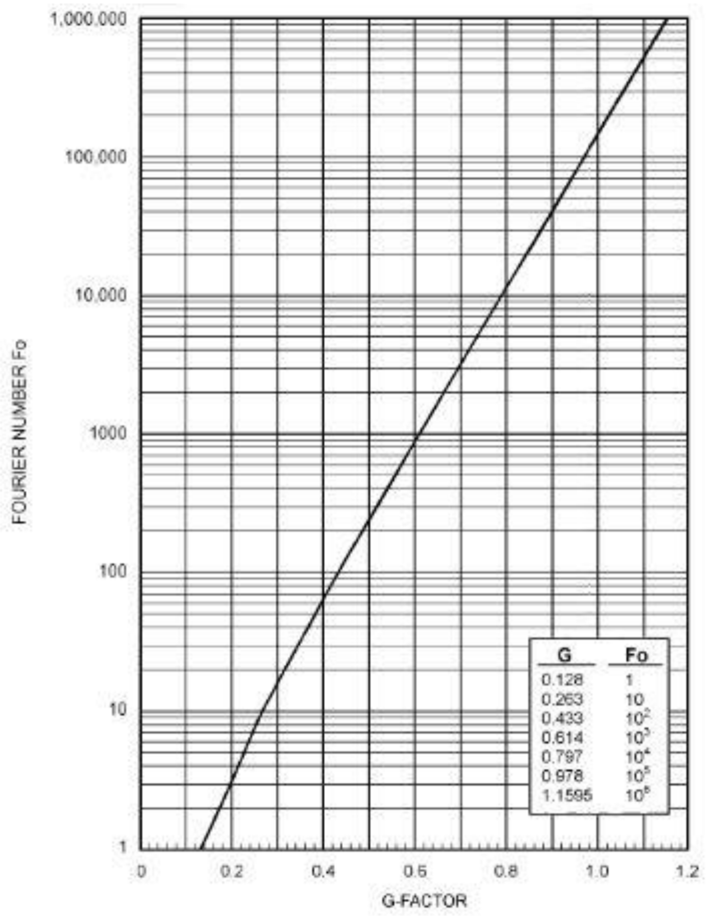


**Figure 5: Fourier/G-Factor Graph for Ground Thermal Resistance from ASHRAE Applications Chapter 32**

The G-factors were determined to be as follows:

$$G_f = 0.7699$$

$$G_1 = 0.4032$$

$$G_2 = 0.1271$$

The G-factors are then used to determine the effective thermal resistance of the ground for the annual pulse, the daily pulse, and the monthly pulse. These equations are as follows with $k_g$ being the thermal conductivity of the ground determined from geological surveys and being a value of 0.9.

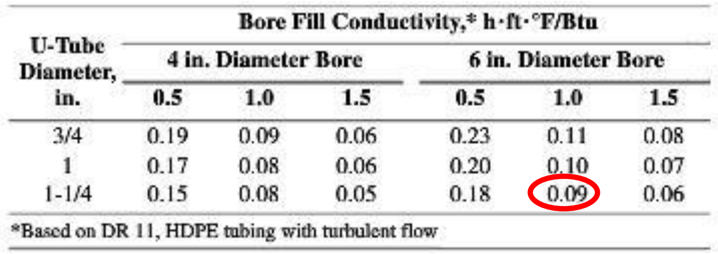
$$R_{ga} = \frac{G_f - G_1}{k_g} = 0.4074$$

$$R_{gm} = \frac{G_1 - G_2}{k_g} = 0.3067$$

$$R_{gd} = \frac{G_2}{k_g} = 0.1412$$

## Thermal Resistance of Pipe ($R_b$)

The thermal resistance of the pipe was determined using a table from the ASHRAE applications handbook and is provided below. A tube diameter of 1.25 inches was used as well as a 6 inch bore diameter. The value of $R_b$ was found to be 0.09.



| U-Tube Diameter, in. | Bore Fill Conductivity,* h·ft·°F/Btu | | | | | |
|---|---|---|---|---|---|---|
| | 4 in. Diameter Bore | | | 6 in. Diameter Bore | | |
| | 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

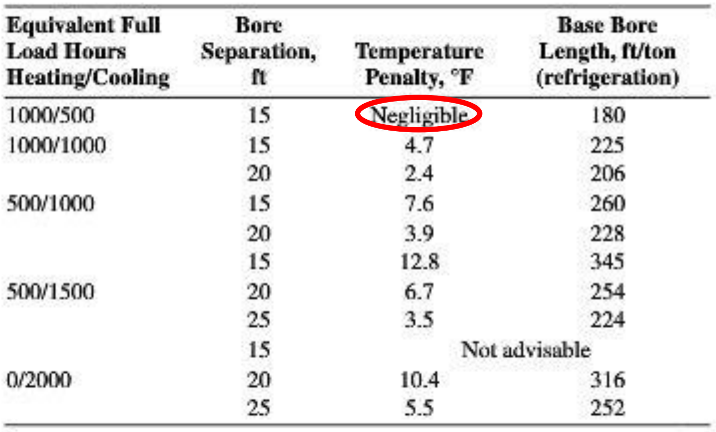
**Figure 6: Thermal Resistance of Bores for High-Density Polyethylene U-Tube from ASHRAE Applications Chapter 32**

## Undisturbed Ground Temperature ($T_g$)

The undisturbed ground temperature is the uniform temperature of the ground that has not been previously excavated or disturbed. This temperature was determined using the contour map found in the ASHRAE applications handbook. For the area where the Medical Office Building is located, the undisturbed ground temperature was found to be 53°F.

## Temperature Penalty for Interference of Adjacent Bores ($t_p$)

The temperature penalty comes from the thermal interference of adjacent bores. This penalty number is selected using the number of equivalent full-load hours for heating and cooling for the location of the building. These numbers are selected from table 8 in chapter 32 of the ASHRAE applications handbook. The medical office building the equivalent full-load hours for heating is 930 and the equivalent full-load hours for cooling are 680. Using these numbers and a bore spacing of 15 feet, the temperature penalty was selected as negligible from the table show below from the ASHRAE applications handbook. These penalty numbers are a worse-case scenario due to the fact that groundwater movement will mitigate the amount of interference seen by each well.



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

**Figure 7: Long Term Change in Ground Field Temperature from ASHRAE Applications Chapter 32**

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

The temperature of the liquid coming into the heat pumps is very important because it drives the cost of the ground coil and the efficiency of the heat pump. Choosing an inlet temperature close to the ground temperature will cause a higher efficiency of the heat pump but will cause to ground coil to be very long. The opposite is true for an inlet temperature far from the ground temperature. The ground coil will be very short, but this will cause the efficiency of the heat pump to go down. ASHRAE applications recommends $t_{wi}$ to be 20 to 30°F above $t_g$ for cooling and 10 to 20°F below $t_g$ for heating. For the Medical Office Building, $t_{wi}$ for cooling will be 78°F for cooling and 38°F for heating.

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

Temperature values for the heat pump outlet were chosen to be 5-7°F different from the liquid temperatures coming in. The addition of heat in the summer will cause the temperature of the fluid to rise and the removal of heat in the winter will cause the temperature to fall. This will result in a $t_{wo}$ of 85°F for cooling and a $t_{wo}$ of 33°F for heating.

## Power Input at Design Heating/Cooling Load ($W_c$, $W_h$)

These values are determined from the amount of energy the pump will use to move the fluid from the building to the well and back at the peak load. Using average values from ASHRAE of 0.125 hp/ton and a building load of 115.5 tons, it was determined that the power used would be 14.4 hp which equates to 10.7KW.

### Equivalent Lengths and Number of Wells

After all of the calculations were performed, the number of feet needed to cool the Medical Office Building was 8925.3 and the number of feet to heat was 9305.8. Since heating the Medical Office Building with ground coupled will require the most length, it will be the driving factor in determining the number of wells that will be needed to serve the building.

## 3.3 Well Type

### 3.3.1 Vertical Loop

The vertical well is the most common well used for ground coupled applications. Although it comes at a higher initial cost, the vertical well takes up very little space and offers the maximum opportunity for heat transfer to the soil. The vertical well consists of a continuous U-tube that is placed down in the well and is connected to a supply and return header at the top of the well. The well is then filled with a grout to increase the heat transfer potential. Since the ground coupled system will be the primary source of heating and cooling in the building, it is highly recommended that a factor of safety be applied to the required length. It was decided to go with a factor of safety of 15% for this building. This now takes the required length from 9305.8 feet to 10702 feet. The number of wells required for different depths is shown below in table 7.

| Well Depth (ft) | Required Length | Number of Wells |
|---|---|---|
| 100 | 10702 | 108 |
| 200 | 10702 | 54 |
| 300 | 10702 | 36 |

**Table 7: Required number of bores depending on bore depth**

The decision was made to use the 300’ wells due to the smaller footprint and the fewer number of connections that would have to be made, therefore reducing the possibility for failures.

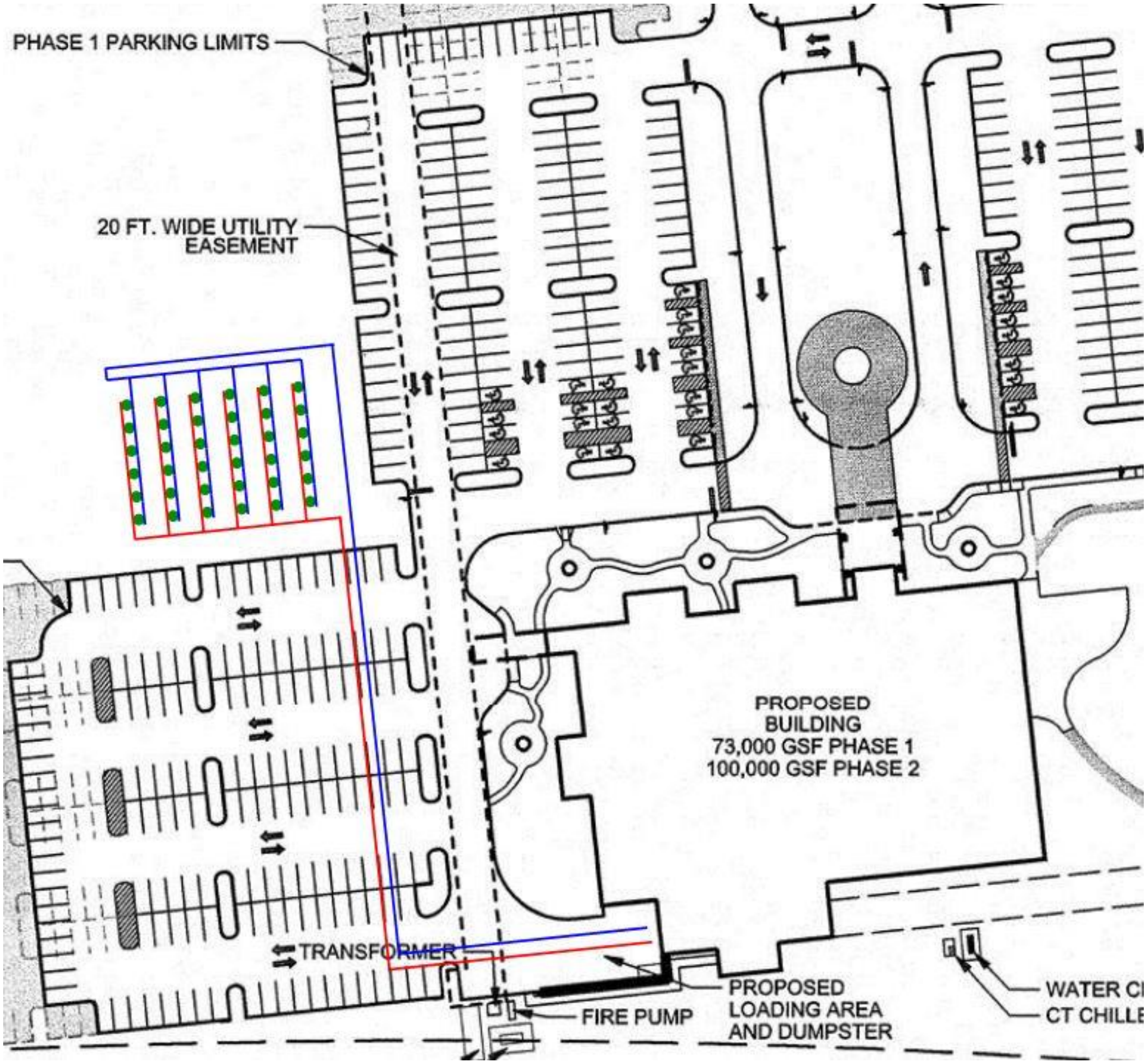


**Figure 8: Vertical loop well and piping layout**

### 3.3.2 Horizontal Loop

The horizontal loop option is less common because of the large amount of ground that it takes up. This loop system is much cheaper than the vertical loop option due to the fact that there is not the need to dig very deep into the ground. Most horizontal loops only sit about 5’ below the surface which greatly reduces the amount of excavation needed. As with the vertical bore option, the horizontal loop will also have a safety factor of 15% applied to it which will make the required length also 10702 feet. The site of the Medical Office Building will be able easily accommodate the required length by having 13 800’ long loops and one 400’ long loop. This will bring the total length to 10800 feet which will satisfy the required length. The layout of the horizontal loop can be seen in the figure below.

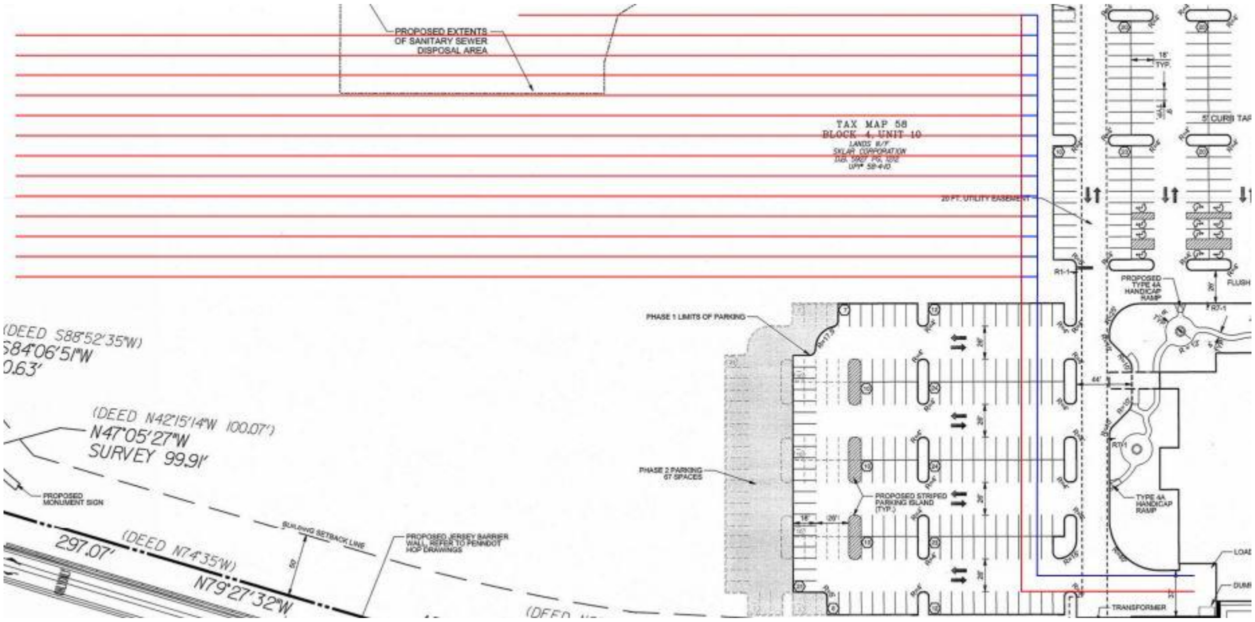


Figure 9: Horizontal loop piping layout

# 3.4 Cost Analysis

## 3.4.1 Rooftop Units

Due to the fact that the current rooftop units are unable to accommodate a ground coupled system, new units needed to be selected. After performing research, it was discovered that units of the original size are not manufactured for ground coupled purposes, therefore smaller units needed to be selected and there would be a need for more units on the roof. For the purpose of analysis, Trane Axiom high efficiency rooftop units were selected. The model that was selected was a Gere 300 and has a capacity of 25 tons. Since exact pricing information was not available, RS Means was consulted to determine a price per unit. The price for the installation of one new 25 ton unit including labor is $24,975. The Medical Office Building will require five of these units which brings the total cost for all of the new units to $124,875. Since the originally designed units will not be used, the cost of the units in the original design will be considered a savings. From a detailed pricing list done by Trane for Ohio State, it was found that the price per ton for a 70 ton packaged rooftop unit was $895. This calculated savings from the original design is then $125,300. Since the cost for the new units and the savings from the originally designed units are within $500, the cost for the units will be omitted when calculating the simple and discounted payback.

### 3.4.2 Vertical Loop

RS Means has not yet included the cost to drill and install a ground coupled system so other means had to be used. Upon reviewing the ASHRAE Applications handbook, it was found that in the ground coupled section (chapter 32) there was an example depicting the cost for a ground coupled well system on a four story office building. The Medical Office Building is relatively similar to the one in the example so the cost per foot provided was used. The ASHRAE cost per foot for a vertical bore is $10.57. Using this value the cost for the Medical Office Building to install 36 300’ deep vertical ground coupled wells is $114,156.

### 3.4.3 Horizontal Loop

Again, RS Means does not provide information on the cost to install a horizontal ground coupled loop, but it does have cost for trenching which can be slightly adjusted for a ground coupled design. To use a chain trencher to dig and backfill a trench 6” wide and 60” deep, RS Means recommends a cost of $1.12 per linear foot. This would bring the cost to trench a horizontal ground coupled system on the site of the Medical Office Building to $12,096. To account for the cost of pipe and fittings, an extra 50% was added which brings the total cost to $18,144.

## 3.5 Life Cycle Cost Analysis

To determine if this new system would be worthwhile to install, a life cycle cost analysis must be performed. The purpose of this analysis is to determine if the system will save money through energy conservation and if it is enough money to offset the increase in initial cost to install the system. Using the Trane TRACE program, an analysis was performed using a ground coupled system to determine how much energy the new system would save compared to the old system. It was found that the new system’s yearly cost for utilities was $42,115 with an average cost per square foot of $0.94. This is a savings of $3,945 in utilities compared to the original design. The following figure below shows a comparison in monthly utility cost.

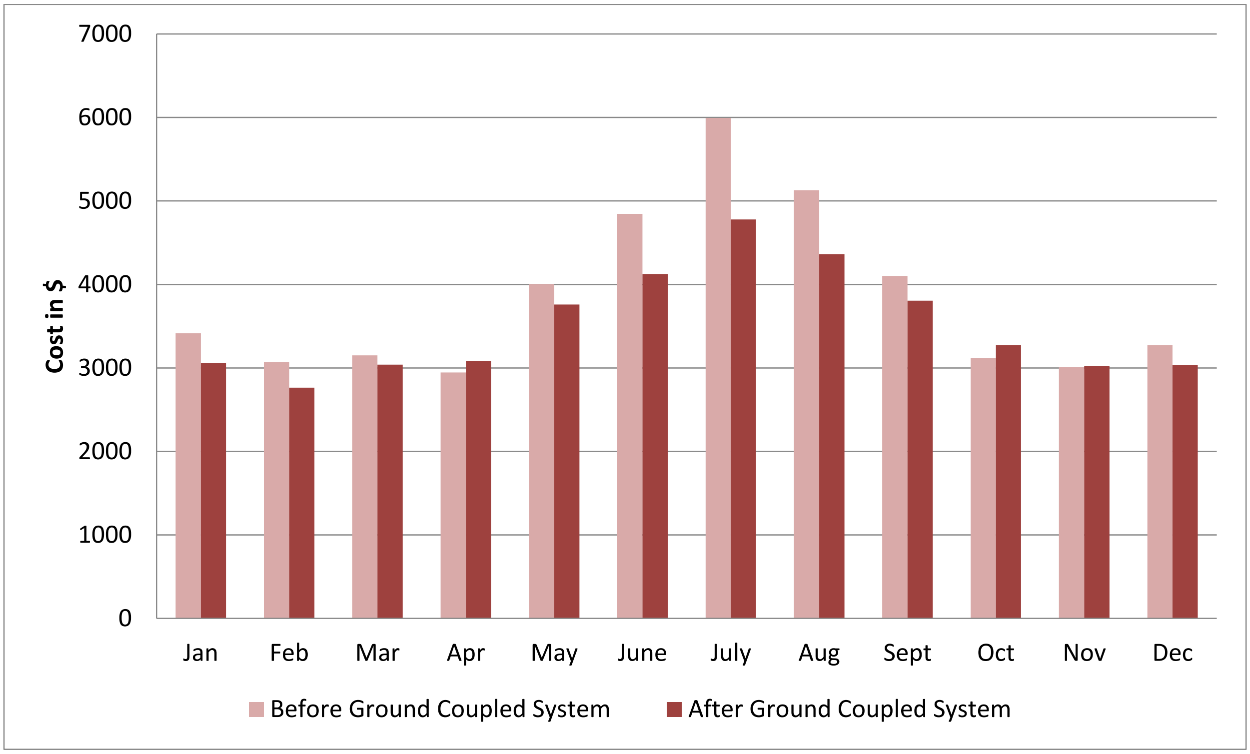


**Figure 10: Utility cost before and after a ground coupled system is installed**

The most common way to determine if the high initial cost of a system will save money in the long run is to find the payback period. The payback period is the amount of time for a system to pay for itself in the amount of money it saves. There are two types of payback that were used in the analysis of the ground coupled system in the Medical Office Building, simple payback and discounted payback. Simple payback is the investment divided by the amount it saves per year to determine how many years it will take for the savings to offset the cost of the investment. Discounted payback is more complicated because it takes into account the changing value of the dollar. Discounted payback is typically a longer period than the simple payback but it yields a more accurate result.

### 3.5.1 Vertical Loop

The vertical ground coupled loop had an initial cost of $114,156. The simple payback for this system was calculated to be 28.9 years. Discounted payback was attempted to be calculated but due to the NIST Manual 135 supplement only having escalation rates up to 30 years out, it was not possible to determine an accurate discounted payback period.

### 3.5.2 Horizontal Loop

The process used in calculating the simple and discounted payback for the vertical loop system was also used for the horizontal loop system. The horizontal ground coupled loop had an initial cost of $18,144. The simple payback for this system was calculated to be 4.6 years and the discounted payback was calculated to be 4.9 years.

## 3.6 Conclusions

After performing calculations to determine the length of the piping needed for a ground coupled system, this length was then used to determine the cost to install a horizontal and vertical loop system on the site. This cost was then analyzed against the savings that would be produced by the ground coupled system to determine the payback period for each system. The vertical loop has a payback of 28.9 years and the horizontal loop has a payback of 4.9 years. Both of these payback periods are reasonable for the life of the building and the system, but the horizontal loop has a more desirable payback period for an owner, even though it does take up a considerably larger amount of area compared to the vertical loop system.

# Chapter 4: Electrical Breadth

When installing new systems in a building different from the original design, it is important to consider what other systems will be impacted by the change in the design. In the case of the Medical Office Building, the new ground coupled system will cause major problems with the electrical system. To be able to accommodate the new ground coupled system, the current electrical system will need to be modified.

## 4.1 Original Electrical Design

The Medical Office Building has an incoming service of 10,000A that passes through a stepdown transformer to bring the amperage down to 3000A. The service then goes to the main panel where it is distributed to different sub panels. On the same panel as the rooftop units are two motors, the elevator controls, and a chiller for the MRI magnet cooling. The size of this panel is 800A. The whole building is run on 480/277V three phase power.

## 4.2 Electrical Redesign

### 4.2.1 Breaker Size

The new rooftop units will be able to run on the current electrical system without needing modification. They are specified to run on a three phase system of 460 volts with amplitude of 60 hertz. From the online design information, the nameplate rated-load current for the new rooftop units is 52.9A. According to article 440.12(A)(1) of the NFPA National Electric Code, the ampere rating of the disconnecting device must be 115 percent of the nameplate rated-load current. For the units that were selected, this would be 60.8A. The protection device that must be selected must be the next available size up from the new calculated ampere rating. According to article 240.6(A) of the NEC, the next standard size for the protection device is 70A.

### 4.2.2 Wire Size

Since these new rooftop units have a different need for amperage, they will require a different size to wire running from the panel to the unit itself. The new sizes of the wires were chosen using table 310.15(B)(16) of the NEC which is shown below. Since the ampere requirement for the units is relatively small, copper wire was used instead of aluminum. The temperature rating that was used was 75°C, which is the middle column of the copper section in the table. Going down the table, there are two sizes of wire to be considered, 6AWG and 4 AWG. The 6 AWG wire has an ampere rating of 65A which will work in supplying the units but this size of wire is not protected by the breaker, meaning the wire could be damaged in an overcurrent situation. The ampere rating of the 4 AWG wire is 85A which is plenty capable of handling the current to the units and it is also protected by the circuit breaker in an overcurrent situation.

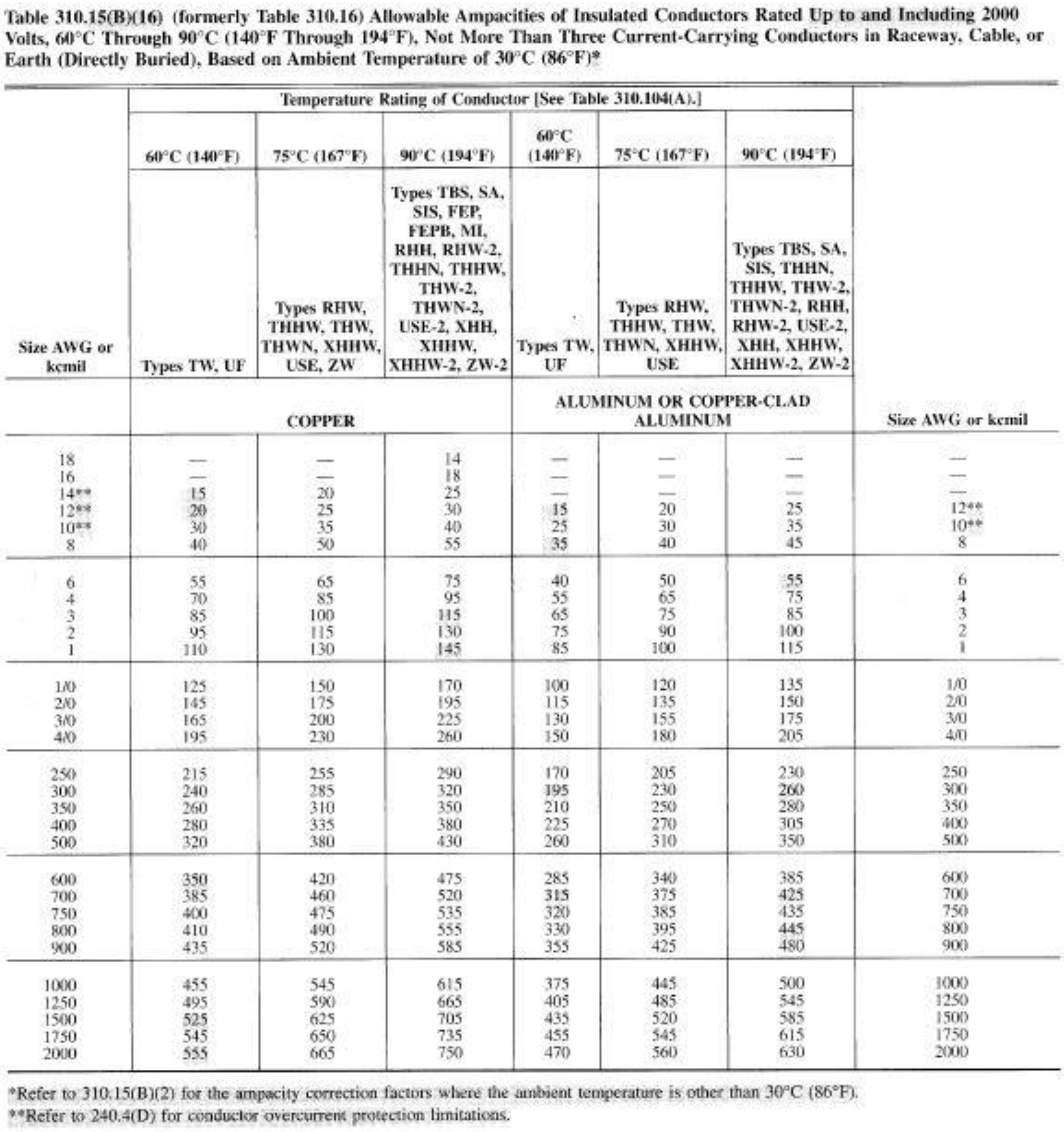


**Table 310.15(B)(16) (formerly Table 310.16) Allowable Ampacities of Insulated Conductors Rated Up to and Including 2000 Volts, 60°C Through 90°C (140°F Through 194°F), Not More Than Three Current-Carrying Conductors in Raceway, Cable, or Earth (Directly Buried), Based on Ambient Temperature of 30°C (86°F)***

| | Temperature Rating of Conductor [See Table 310.104(A).] | | | | | | |
|---|---|---|---|---|---|---|---|
| | 60°C (140°F) | 75°C (167°F) | 90°C (194°F) | 60°C (140°F) | 75°C (167°F) | 90°C (194°F) | |
| Size AWG or kcmil | Types TW, UF | Types RHW, THHW, THW, THWN, XHHW, USE, ZW | Types TBS, SA, SIS, FEP, FEPB, MI, RHH, RHW-2, THHN, THHW, THW-2, THWN-2, USE-2, XHH, XHHW, XHHW-2, ZW-2 | Types TW, UF | Types RHW, THHW, THW, THWN, XHHW, USE | Types TBS, SA, SIS, THHN, THHW, THW-2, THWN-2, RHH, RHW-2, USE-2, XHH, XHHW, XHHW-2, ZW-2 | |
| | COPPER | | | ALUMINUM OR COPPER-CLAD ALUMINUM | | | Size AWG or kcmil |
| 18 | — | — | 14 | — | — | — | — |
| 16 | — | — | 18 | — | — | — | — |
| 14** | 15 | 20 | 25 | — | — | — | — |
| 12** | 20 | 25 | 30 | 15 | 20 | 25 | 12** |
| 10** | 30 | 35 | 40 | 25 | 30 | 35 | 10** |
| 8 | 40 | 50 | 55 | 35 | 40 | 45 | 8 |
| 6 | 55 | 65 | 75 | 40 | 50 | 55 | 6 |
| 4 | 70 | 85 | 95 | 55 | 65 | 75 | 4 |
| 3 | 85 | 100 | 115 | 65 | 75 | 85 | 3 |
| 2 | 95 | 115 | 130 | 75 | 90 | 100 | 2 |
| 1 | 110 | 130 | 145 | 85 | 100 | 115 | 1 |
| 1/0 | 125 | 150 | 170 | 100 | 120 | 135 | 1/0 |
| 2/0 | 145 | 175 | 195 | 115 | 135 | 150 | 2/0 |
| 3/0 | 165 | 200 | 225 | 130 | 155 | 175 | 3/0 |
| 4/0 | 195 | 230 | 260 | 150 | 180 | 205 | 4/0 |
| 250 | 215 | 255 | 290 | 170 | 205 | 230 | 250 |
| 300 | 240 | 285 | 320 | 195 | 230 | 260 | 300 |
| 350 | 260 | 310 | 350 | 210 | 250 | 280 | 350 |
| 400 | 280 | 335 | 380 | 225 | 270 | 305 | 400 |
| 500 | 320 | 380 | 430 | 260 | 310 | 350 | 500 |
| 600 | 350 | 420 | 475 | 285 | 340 | 385 | 600 |
| 700 | 385 | 460 | 520 | 315 | 375 | 425 | 700 |
| 750 | 400 | 475 | 535 | 320 | 385 | 435 | 750 |
| 800 | 410 | 490 | 555 | 330 | 395 | 445 | 800 |
| 900 | 435 | 520 | 585 | 355 | 425 | 480 | 900 |
| 1000 | 455 | 545 | 615 | 375 | 445 | 500 | 1000 |
| 1250 | 495 | 590 | 665 | 405 | 485 | 545 | 1250 |
| 1500 | 525 | 625 | 705 | 435 | 520 | 585 | 1500 |
| 1750 | 545 | 650 | 735 | 455 | 545 | 615 | 1750 |
| 2000 | 555 | 665 | 750 | 470 | 560 | 630 | 2000 |

*Refer to 310.15(B)(2) for the ampacity correction factors where the ambient temperature is other than 30°C (86°F).

**Refer to 240.4(D) for conductor overcurrent protection limitations.

**Figure 11: Allowable Ampacities of Insulated Conductors**

### 4.2.3 Grounding

According to the NEC, all equipment must be grounded with a few exceptions that are specified in article 250.20. The rooftop units of the Medical Office Building do not fall under these exceptions so they are required to be grounded. The size of a grounding wire is determined by the size of the overcurrent device protecting the equipment. To determine the size, table 250.122 of the NEC is utilized which is shown below. According to the table, the ampere rating of the overcurrent device must not exceed the value of the table for the certain gauge of wire. For the Medical Office Building, 8 AWG copper wire was selected which has a maximum rating of 100A which is larger than the overcurrent device protecting the units.

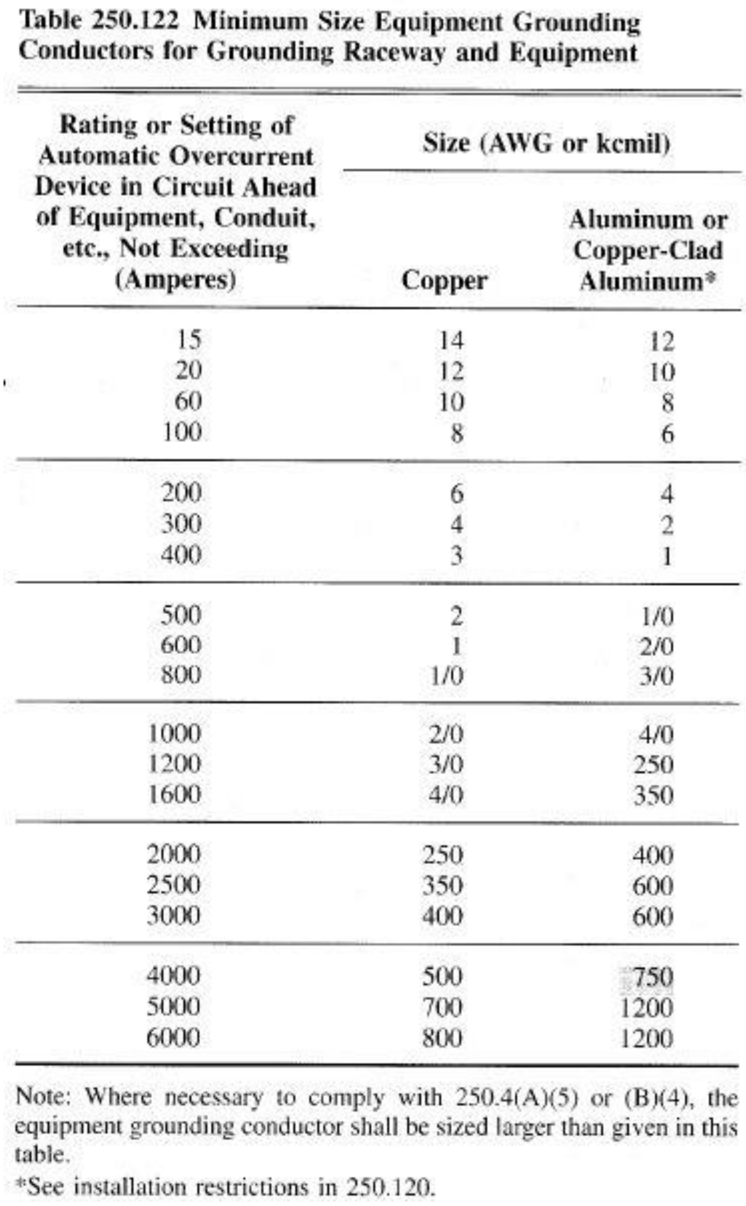


**Table 250.122 Minimum Size Equipment Grounding Conductors for Grounding Raceway and Equipment**

| Rating or Setting of Automatic Overcurrent Device in Circuit Ahead of Equipment, Conduit, etc., Not Exceeding (Amperes) | Size (AWG or kcmil) | |
|---|---|---|
| | Copper | Aluminum or Copper-Clad Aluminum* |
| 15 | 14 | 12 |
| 20 | 12 | 10 |
| 60 | 10 | 8 |
| 100 | 8 | 6 |
| 200 | 6 | 4 |
| 300 | 4 | 2 |
| 400 | 3 | 1 |
| 500 | 2 | 1/0 |
| 600 | 1 | 2/0 |
| 800 | 1/0 | 3/0 |
| 1000 | 2/0 | 4/0 |
| 1200 | 3/0 | 250 |
| 1600 | 4/0 | 350 |
| 2000 | 250 | 400 |
| 2500 | 350 | 600 |
| 3000 | 400 | 600 |
| 4000 | 500 | 750 |
| 5000 | 700 | 1200 |
| 6000 | 800 | 1200 |

Note: Where necessary to comply with 250.4(A)(5) or (B)(4), the equipment grounding conductor shall be sized larger than given in this table.

*See installation restrictions in 250.120.

**Figure 12: Minimum size for equipment grounding**

### 4.2.4 Conduit Size

Since the rooftop units will require a smaller wire size, this may also cause them to require a smaller conduit size. Conduit size is determined by how many wires will be running in the conduit and what type of wire will be running in the conduit. These sizes are determined by using table C.1 in the Annex section of the NEC which is shown below. The type of conduit that will be used is electrical metallic tubing (EMT) and the type of wire that was selected was RHH, RHW, and RHW-2. There will be four wires running in each conduit to supply the rooftop units, three 4AWG wires and one 8AWG wire. After examining the table the first size that will accommodate three 4 AWG wires is 1 ¼ inch conduit. This size conduit is rated for four 4 AWG wires and since the grounding wire is only 8 AWG, there will be enough room for it in the conduit.

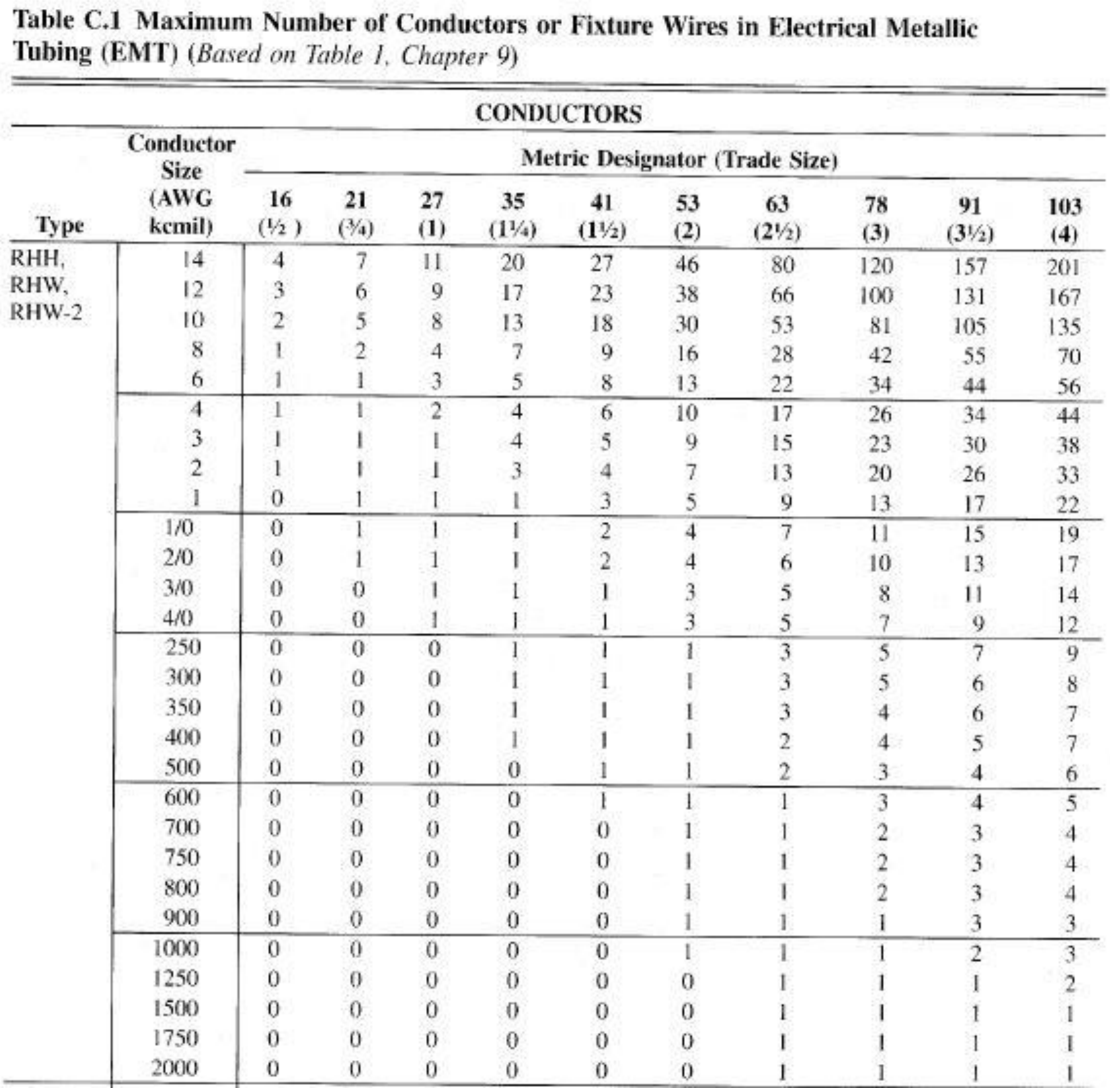


**Table C.1 Maximum Number of Conductors or Fixture Wires in Electrical Metallic Tubing (EMT)** (*Based on Table 1, Chapter 9*)

CONDUCTORS

| Type | Conductor Size (AWG kcmil) | Metric Designator (Trade Size) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 16 (½) | 21 (¾) | 27 (1) | 35 (1¼) | 41 (1½) | 53 (2) | 63 (2½) | 78 (3) | 91 (3½) | 103 (4) |
| RHH, RHW, RHW-2 | 14 | 4 | 7 | 11 | 20 | 27 | 46 | 80 | 120 | 157 | 201 |
| | 12 | 3 | 6 | 9 | 17 | 23 | 38 | 66 | 100 | 131 | 167 |
| | 10 | 2 | 5 | 8 | 13 | 18 | 30 | 53 | 81 | 105 | 135 |
| | 8 | 1 | 2 | 4 | 7 | 9 | 16 | 28 | 42 | 55 | 70 |
| | 6 | 1 | 1 | 3 | 5 | 8 | 13 | 22 | 34 | 44 | 56 |
| | 4 | 1 | 1 | 2 | 4 | 6 | 10 | 17 | 26 | 34 | 44 |
| | 3 | 1 | 1 | 1 | 4 | 5 | 9 | 15 | 23 | 30 | 38 |
| | 2 | 1 | 1 | 1 | 3 | 4 | 7 | 13 | 20 | 26 | 33 |
| | 1 | 0 | 1 | 1 | 1 | 3 | 5 | 9 | 13 | 17 | 22 |
| | 1/0 | 0 | 1 | 1 | 1 | 2 | 4 | 7 | 11 | 15 | 19 |
| | 2/0 | 0 | 1 | 1 | 1 | 2 | 4 | 6 | 10 | 13 | 17 |
| | 3/0 | 0 | 0 | 1 | 1 | 1 | 3 | 5 | 8 | 11 | 14 |
| | 4/0 | 0 | 0 | 1 | 1 | 1 | 3 | 5 | 7 | 9 | 12 |
| | 250 | 0 | 0 | 0 | 1 | 1 | 1 | 3 | 5 | 7 | 9 |
| | 300 | 0 | 0 | 0 | 1 | 1 | 1 | 3 | 5 | 6 | 8 |
| | 350 | 0 | 0 | 0 | 1 | 1 | 1 | 3 | 4 | 6 | 7 |
| | 400 | 0 | 0 | 0 | 1 | 1 | 1 | 2 | 4 | 5 | 7 |
| | 500 | 0 | 0 | 0 | 0 | 1 | 1 | 2 | 3 | 4 | 6 |
| | 600 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 3 | 4 | 5 |
| | 700 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 2 | 3 | 4 |
| | 750 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 2 | 3 | 4 |
| | 800 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 2 | 3 | 4 |
| | 900 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 3 | 3 |
| | 1000 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 2 | 3 |
| | 1250 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 2 |
| | 1500 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1 |
| | 1750 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1 |
| | 2000 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1 |

**Figure 13: Maximum Number of Conductors in Electrical Metallic Tubing**

### 4.2.5 Subpanel Breaker and Wire Sizing

The subpanel from the main panel must be large enough to handle all five of the units. Each breaker to the units is 70A which means that the subpanel must be able to handle 350A. After looking at article 240.6(A) of the NEC, the size of breaker that would be able to accommodate this load is a 350A breaker. The wire coming from the main distribution panel must also be sized accordingly. After examining table 310.15(B)(16) of the NEC previously shown above, the size of the wire for this load using copper at 75°C would have to be 500kcmil. This wire is rated for 380A which will be able to handle the load of the subpanel as well as be protected by the breaker. Using table 250.122 of the NEC also previously shown above, the size of the grounding wire can be found. Since there is no size for a 350A breaker, a 400A breaker will be used instead. This will cause the grounding wire to be slightly oversized which is needed to comply with article 250.4(A)(5) of the NEC. This will result in a grounding wire size of 3 AWG. Finally the conduit from the main distribution panel to the subpanel must be sized. Using the same table as shown above for conduit sizing, a 3 ½ conduit should be used to ensure there will be enough space for the ground wire as well as the three phase wires.

# Chapter 5: Structural Breadth

Since the ground coupled system has caused the need for added units on the roof, the structural roof system must be examined to determine if it is substantial enough to support the added weight of the units.

## 5.1 Loads

To begin to complete a redesign of the structural system under the rooftop units, the loads that will be acting on the roof much be defined. Since the Medical Office Building is located in the northeast, snow loads must be taken into consideration in the design of the roof. According to the International Building Code (IBC), the snow load for the location of the building will be taken as 20 pounds per square foot (psf). The live load for the roof will be taken as 30 psf. From the structural drawings provided, the dead load of the roof and insulation material will be taken as 8 psf. The drawings also give a load for the weight of interior materials that will be supported by the roof. This value will be taken to be 7 psf. Finally the dead load for the mechanical systems must be defined. The structural drawings use a value of 75 psf for the mechanical load. Since the new rooftop units will be smaller than the current units, this value will be acceptable to use in the redesign.

## 5.2 Original Design

In the original structural design of the Medical Office Building, the area of the roof that was designed for a mechanical load was an area that was set back one bay from the perimeter of the building. This can be seen in the figure below where the shaded area is the area designed for a mechanical load. The non-mechanical portion of the roof is framed with K-series open web steel joists and the mechanical section is designed with I-beams. The bays of the Medical Office Building are 30’ by 30’.

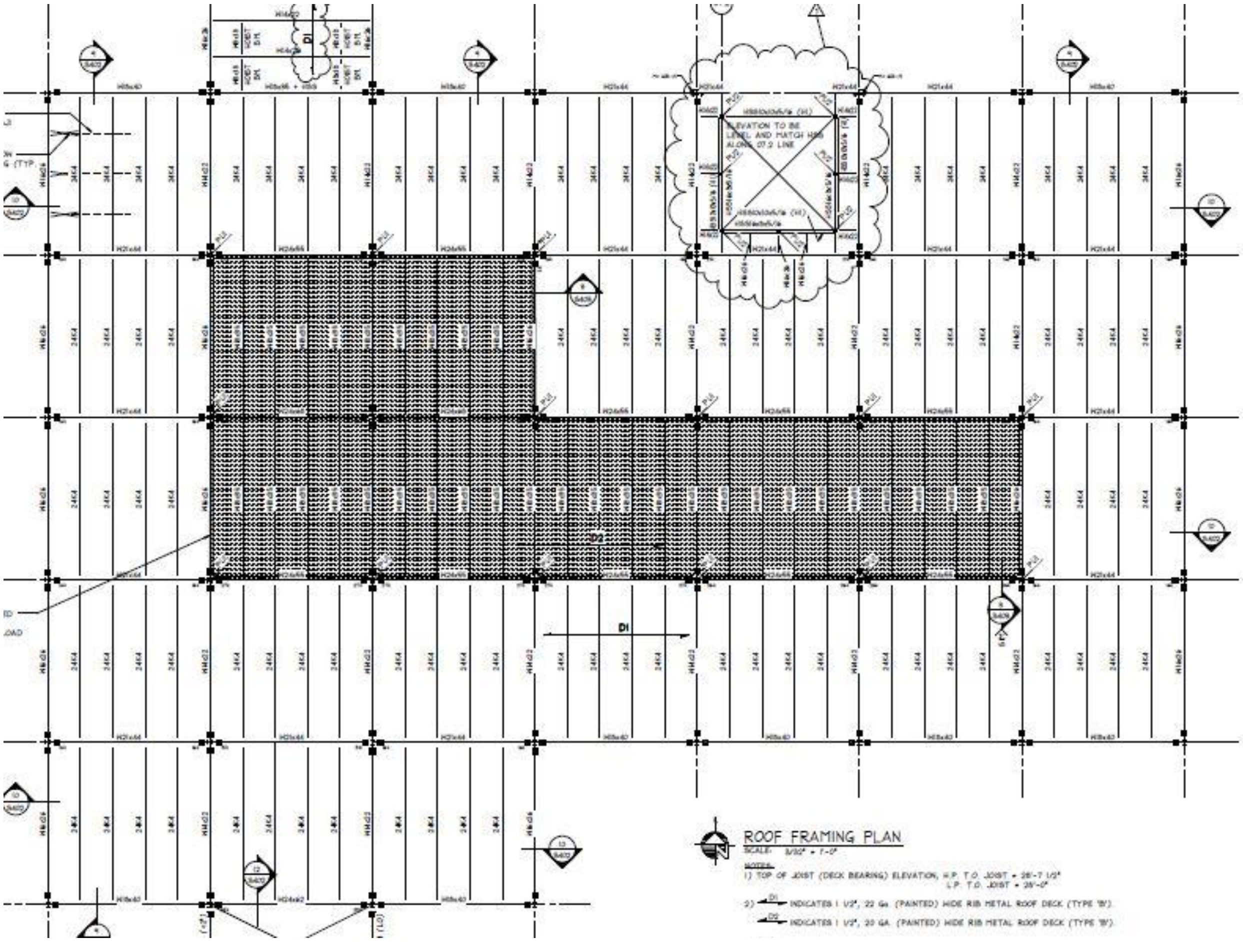


**Figure 14: Roof framing plan with shaded area designed for mechanical load**

## 5.3 Redesign

After comparing the size of the new rooftop units to the area that has already been designed for a mechanical load, the new rooftop units will fit inside of this area. Since the mechanical area is designed using I-beams, it may be more economical to design the area using open web steel joists like the rest of the roof. A redesign of the roof using open web steel joists will be conducted and the cost compared to determine if indeed would be a valid alternative. Detailed calculations for the redesign of the roof structural system can be seen in Appendix B. All values for the joists were determined using the LRFD values from the 42nd Edition Catalog of Standard Specifications and Load and Weight Tables for Steel Joists and Joist Girders and all values for the girders were determined using the W-Shapes table in the Steel Construction Manual.

First the factored load on the roof must be calculated. This is done by using the equation:

$$W_{u+l} = 1.2D + 1.6(S\ or\ L_R)$$

Since the live load on the roof is greater than the snow load, it will be used in the equation. The total dead load is the summation of the roof and insulation weight, the collateral load, and the mechanical load. This comes to a total dead load of 100 psf. The factored load is then multiplied by the joist spacing of six feet to obtain a value of 1008 pounds per linear foot (plf). This load plus 1.2 of the self-weight of the joist must be less than the factored load in the joist table for the specific joist.

### 5.3.1 18LH08 Joist

After looking at the K-series joist table, none of the joists will satisfy the value and stay within a reasonable depth so longspan steel joists (LH-series) will have to be considered. The first joist that will satisfy the load for a 30ft span is an 18LH08 joist. This joist has a factored load of 1075 plf. When 1.2 of the self-weight (19 plf) is added to the factored load, the total value is 1030 plf which is lower than the table value. Next the total load on the joists must be less than 1.5 of the nominal live load on the joist (red value on the LRFD table). The total load on the roof is 130 psf which must be multiplied by 5, the number of joist spaces, to obtain the total load in plf. This comes to a value of 650 plf which must be added to the self-weight of 19 plf for a total of 669 plf. The nominal live load from the LRFD table is 387 plf which is then multiplied by 1.5 to obtain a value of 580 plf. This value is lower than the total load on the roof which is not acceptable, so the next joist up will have to be examined. The next joist is an 18LH09 but the nominal live load of this joist still is not greater than the total load which means the 20LH series of joist will have to be examined.

### 5.3.2 20LH08 Joist

The first joist in the 20LH series to satisfy the factored load is the 20LH07, but this joist has a multiplied nominal live load of 657 plf which still will not satisfy the total load on the joists. The next joist, 20LH08, has a factored load value of 1140 which is greater than the factored load plus the self-weight of the joist. It also has a nominal live load of 468 plf, which when multiplied by 1.5, has a value of 702 which is greater than the total load (650 plf) plus the self-weight (20 plf).

### 5.3.3 Girders

There are two different types of girders that need to be redesigned. Girders at the edge of the mechanical area shown in the figure below in blue, and girders that are in the center of the mechanical area shown in green. The difference in these two girders are that the edge girders have half of their load coming from the mechanical area and half from the non-mechanical area where the center girders have all of their load coming from the mechanical area.

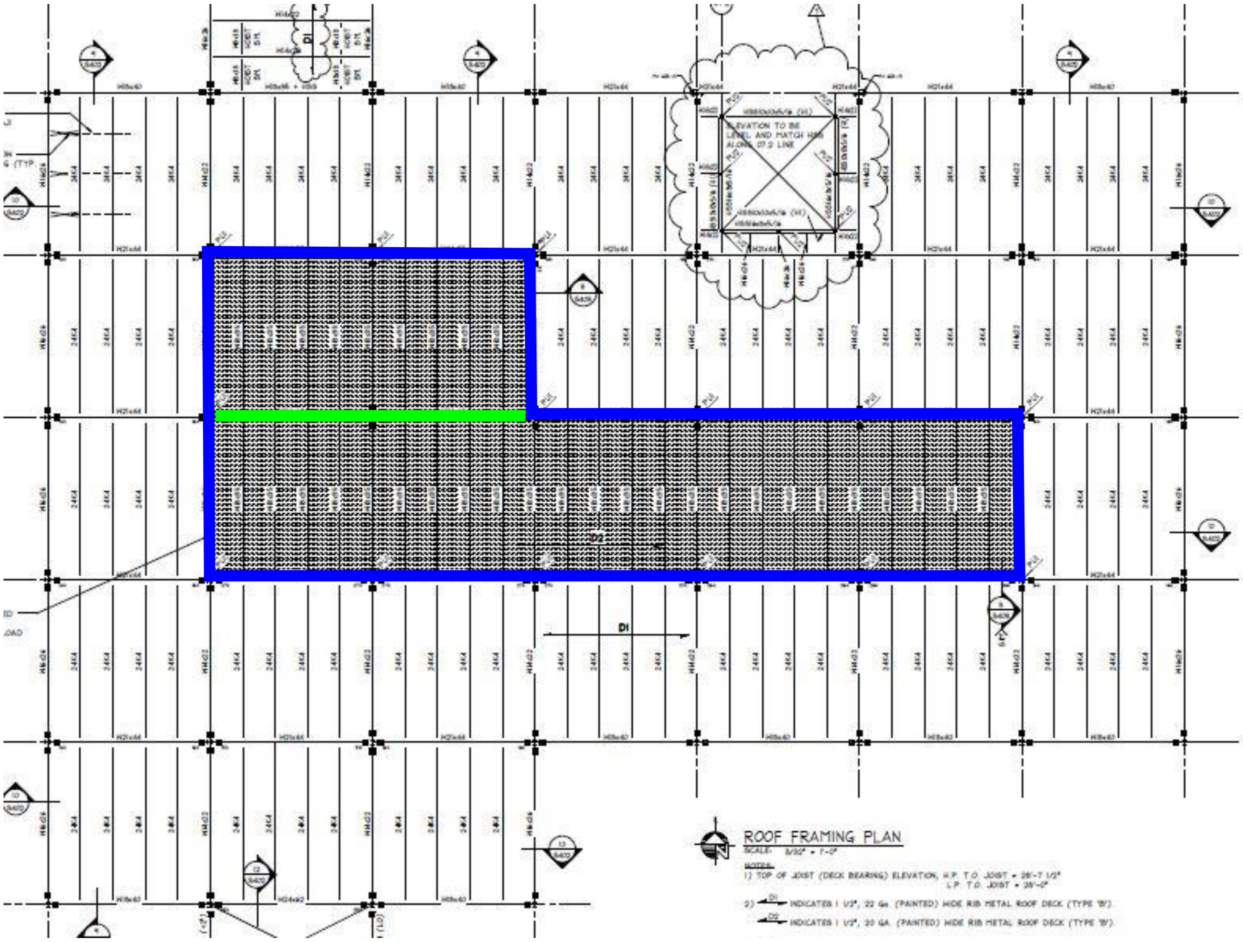


**Figure 15: Girders affected by change in joist in mechanical section of roof**

### 5.3.4 Edge Girders

The edge girders have their load coming from two different areas, the mechanical area and the non-mechanical area. To calculate the load on the girder, the factored load equation from above must be used.

$$W_{u+l} = 1.2D + 1.6(S\ or\ L_R)$$

For the non-mechanical side, a dead load of 25 psf will be used opposed to 100 psf. The equation must then be multiplied by the area that will affect the girder which is 15 feet. The factored load must then be added to the self-weight of the joist (8.4 plf) multiplied by the tributary area. The total load for the non-mechanical side is 1296 lb/ft. The same process is used to determine the load from the mechanical side but instead using a dead load of 100 psf and a self-weight of 20 plf. The load on the girder from the mechanical area is 2820 lb/ft. To determine the size of girder that will be needed, the bending moment must be calculated. This is done by using the following equation:

$$M_u = \frac{wl^2}{8}$$

L is the span of the girder which is 30 feet. W is the load which is the sum of the load from the mechanical and non-mechanical side. This gives a value of 463 kip-ft. Looking at the W-shape tables in the AISC Steel Construction Manual, an economical size that would satisfy the LRFD above would be W21X55, which has a rating of 473 kip-ft.

### 5.3.5 Center Girders

The center girders were calculated in a similar way as the edge girders. Using the factored load equation, the load was determined for one side of the girder. This was then doubled because the load on each side of the center girders is symmetrical which gives a value of 5640 lb/ft. Using the $M_u$ equation from above, an LRFD value was determined to be 634 kip-ft. After consulting the tables in the AISC manual, a size of W21X73 was selected, having a rating of 645 kip-ft.

## 5.4 Cost

To calculate the change in cost from the original roof design to the redesigned roof, RS Means was consulted to obtain the cost per linear foot of the different members that were used. This cost information is summarized in the following tables.

| Original Design | | | |
|---|---|---|---|
| Member | Cost per Member | # of Members | Total Cost |
| W18X35 | $1,530.00 | 28 | $42,840.00 |
| W24X55 | $2,640.00 | 10 | $26,400.00 |
| W24X68 | $2,970.00 | 2 | $5,940.00 |
| | | | $75,180.00 |

**Table 8: Cost for original framing of mechanical section of roof**

| Redesign | | | |
|---|---|---|---|
| Member | Cost per Member | # of Members | Total Cost |
| W21X55 | $2,190.00 | 10 | $21,900.00 |
| W21X73 | $2,970.00 | 2 | $5,940.00 |
| 20LH08 | $522.00 | 28 | $14,616.00 |
| | | | $42,456.00 |

**Table 9: Cost of redesigned framing of mechanical section of roof**

## 5.5 Conclusion

After performing a cost analysis on the original design, it was found that the cost for the area of the mechanical equipment would be $75,180. The same analysis was performed on the redesign and a cost of $42,456 was determined. This is a savings of $32,724 which is quite significant. This shows that the used of slightly larger open web joists would be beneficial in saving money in the structural roof design.

# Chapter 6: Conclusions

After completing analysis on a ground coupled system at the Medical Office Building, it was found that it would be possible and potentially successful. Both the vertical and horizontal loops would be possible to fit on the site and are reasonable in cost, although the horizontal loop has a much better payback period of 4.9 years where the vertical loop has a period of 28.9 years. The vertical loop cannot be put to the side due to the cost. It also has benefits of a smaller footprint area as well as more regular heat transfer since the wells go so deep. Overall, it does not matter which system would be selected, a ground coupled system would be saving the building energy every year and would eliminate the need to use a propane heating source.

Since there was the need to use new rooftop units that were compatible with ground coupled systems, the electrical system would need to be modified. After examining tables in the NEC, new wire sizes of 4 AWG were needed to run from the panel to the new units with a breaker size of 70A. Since the existing panels did not have enough room to add 3 more units, a new panel would be dedicated to just the rooftop units. This panel would require a wire size of 500 kcmil to be run from the main distribution to the panel with a breaker of 400A.

Finally, the structural system of the roof was examined. At first it was thought that the original roof system would not be able to support the load of the new mechanical units that would be added, but after further examination it was found that the designers did design an area big enough to support the new units. The designers chose to use W-shaped beams as the support for the mechanical section of the roof and open web steel trusses for the rest. Since open web steel trusses are typically cheaper and lighter, an analysis was performed to determine if using an open web steel truss in the mechanical section of the roof would prove to be of benefit. After performing load analysis and sizing new joists as well as new girders, it was found that using an open web joist in the mechanical area would save $32,724. If this solution was implemented, this large savings could be used to further offset the cost of the ground coupled system, making it even more desirable to install.

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# Appendix A: Required Loop Length Calculations

## Effective Thermal Resistance of Ground ($R_{ga}$)

$$F_f = \frac{4 * 0.9 * 3680.25}{1.25^2} = 8479$$

$$F_1 = \frac{4 * 0.9 * (3680.25 - 3650)}{1.25^2} = 69.6$$

$$F_2 = \frac{4 * 0.9 * (3680.25 - 3680)}{1.25^2} = 0.576$$

$$R_{ga} = \frac{0.7699 - 0.4032}{0.9} = 0.4074$$

$$R_{gm} = \frac{0.4032 - 0.1271}{0.9} = 0.3067$$

$$R_{gd} = \frac{0.1271}{0.9} = 0.1412$$

## Required Length for Cooling

$$L_c = \frac{63173 * 0.4074 + (917038 - 3.41 * 10742)(0.09 + 1 * 0.3067 + 0.1412 * 1.04)}{53 - \frac{78 + 85}{2} - 0}$$

## Required Length for Heating

$$L_h = \frac{-63173 * 0.4074 + (853865 - 3.41 * 10742)(0.09 + 1 * 0.3067 + 0.1412 * 1.04)}{53 - \frac{38 + 33}{2} - 0}$$

# Appendix B: Structural Redesign Calculations

## Open Web Steel Joists

$W_{u+l} = 1.2D + 1.6(S\ or\ L_R)$

$W_{u+l} = (1.2 * 100 + 1.6 * 30) * 6 = 1008 + 1.2\ Self\ Weight$

### 18LH08

$1075 > 1008 + 1.2 * 19 = 1030\ \therefore OK$

$W_{tl} = 130 * 5 = 650 + 19\ (self\ weight) = 669 > 386 * 1.5 = 580\ \therefore Not\ Good$

### 20LH08

$1140 > 1008 + 1.2 * 20 = 1032\ \therefore OK$

$W_{tl} = 130 * 5 = 650 + 20\ (self\ weight) = 670 < 468 * 1.5 = 702\ \therefore OK$

## Edge Girders

### Non-Mechanical Section

$W_{u+l} = (1.2 * 25 + 1.6 * 30) * 15 = 1170\ lb/ft$

$W_{tl} = 1170 + 8.4 * 15 = 1296\ lb/ft$

### Mechanical Section

$W_{u+l} = (1.2 * 100 + 1.6 * 30) * 15 = 2520\ lb/ft$

$W_{tl} = 2520 + 20 * 15 = 2820\ lb/ft$

### Moment

$$M_u = \frac{wl^2}{8} = \frac{(1296 + 2820) * 30^2}{8} = 463\ kip - ft$$

# Center Girders

$W_{tl} = 2820 * 2 = 5640\ lb/ft$

$$M_u = \frac{wl^2}{8} = \frac{5640 * 30^2}{8} = 634\ kip - ft$$

# Appendix C: Trane TRACE Outputs for Ground Coupled Redesign