Thesis Final Report

201 Rouse Boulevard

The Navy Yard

Philadelphia, PA 19112

201 ROUSE BOULEVARD

THE NAVY YARD PHILADELPHIA, PA

STATISTICS

LOCATION: 201 ROUSE BOULEVARD
PHILADELPHIA, PA 19112
FUNCTION: SPEC OFFICE SPACE
OCCUPANTS: FRANKLIN SQUARE CAPITAL PARTNERS
SIZE: 84.730 GROSS SQFT
CONSTRUCTION: SEPTEMBER 2013 - Q1 2015

TEAM

DIGSAU , FRANCIS CAUFFMAN , FURY DESIGN: **ARCHITECTURE**
ENVIRONETICS: **ENGINEER**
PENNONI ASSOCIATES: **LANDSCAPE**
IN POSSE, RE:VISION ARCHITECTS: **ENERGY**
TURNER CONSTRUCTION: **CONTRACTOR**
LIBERTY PROPERTY TRUST: **OWNER**

ARCHITECTURE

MATERIALS:
GLASS, ZINC, ALUMINUM, STONE
FACADE:
REPETITIVE ZINCE CLADDING, VERTICAL SHADING FINS
FLOOR TO CEILING WINDOWS, GLASS PEDESTAL
SUSTAINABILITY:
LEED SILVER
SITE:
MANICURED CORPORATE CENTER

MECHANICAL

HEATING AND COOLING:
THREE AIR HANDELING UNITS CAPABLE OF 70,000 CFM
EXHAUST:
DUAL CONTINUOUS ROOFTOP EXHAUST FANS
ENERGY RECOVERY:
100% AIR ECONOMIZER
CONTROLS:
MULTI-MODE CONTROL SEQUENCE WITH BUILDING AUTOMATION SYSTEM CAPABLE OF DATA TRENDING

LIGHTING/ELECTRICAL

FIXTURES:
4' T-5 LOW HG, DAYLIGHTING CONTOL IN TENNANT SPACES
MAIN DISTRIBUTION:
277/480 3PH 2,000 A
TRANSFORMER:
75 KVA TRANSFORMER (1 PER FLOOR)
1500 KVA PAD MOUNTED EXTERNAL (PRIMARY)

STRUCTURAL

FOUNDATION:
PILE CAP WITH TIMBER PILES AT COLUMNS
STRIP FOOTINGS FOR WALLS
SUPERSTRUCTURE:
STEEL FRAME, 30' BAYS, JOISTS AT 5'
FLOORS:
SLAB ON METAL DECK

NICHOLAS W. MATTISE MECHANICAL OPTION

http://www.engr.psu.edu/ae/thesis/portfolios/2014/nwm5064

Table of Contents

Executive Summary 6
Building Overview 7
Existing Conditions 8
    Architecture 8
        Building Facades 8
        Roofing 8
        Sustainability 8
    Primary Engineering Systems 9
        Construction 9
        Lighting 9
        Electrical 9
        Structural 9
        Mechanical 10
    Engineering Support Systems 11
        Fire Protection 11
        Transportation 11
        Telecommunications 11
    Energy 11
    LEED 14
        Energy and Atmosphere 15
        Indoor Air Quality 16
Proposal 17

Mechanical Depth: Geothermal System 18
Background 18
Geothermal System Selection 18
Site Characteristics 19
Well Sizing 20
Bore Length Variables and Assumptions 21
Layout 24
Equipment 25
Well Field Pump 25
Heat Pumps 26
DOAS 27
Active Chilled Beams 31
Energy, Cost, and LEED Comparison 34
Building the Energy Model 34
Energy Performance 35
Energy Comparison 37
New System Cost 37
Payback Period 38
Revised LEED Analysis 38
Breath Analysis: Electrical 39
Breath Analysis: Rooftop Structural Load 41
Conclusion 44
Acknowledgements 45
Appendix 46

Appendix A: Ground Coupled Heat Pump 46
Appendix B: Dedicated Outdoor Air System 49
Appendix C: Active Chilled Beams 50
Appendix D 52
Appendix E: Structural Breadth 55
References 59

Executive Summary

Long before any building goes up substantial decisions are made, designs sketched, and engineering systems are contemplated. Since ground was broken on 201 Rouse back in September 2013 that type of work has been ongoing on with this Thesis Report to critically assess those previous decisions, designs, and chosen engineering solutions. By looking at all this, the goal was to ascertain new mechanical solutions that could increase the building energy performance and upgrade the LEED rating all the while remaining economically feasible. As this report would take many hours of research the utilization of new equipment or programs was desired.

201 Rouse is a mid-rise high-end office building just like many others going up across the country. Located at The Navy Yard in Philadelphia, PA the 85,000 ft^2 building is a speculative office building being built by Turner Construction for Liberty Property Trust. The project's mechanical equipment consists mainly of conventional 250 cooling tons rooftop packaged air handling units and local variable air volume with reheat terminals. The project team had the goal to reach LEED (Leadership in Energy and Environmental Design) Silver accreditation and provide suitable occupant space conditions for this high-end corporate building.

To reach both the project's and this report's goals a mechanical depth looking into the performance capability of a ground coupled water to water heat pump, dedicated outdoor air system, and active chilled beams was analyzed. The ground coupled water to water heat pump (GCHP) provides a steady year round heatsink upon which the building can draw or reject building loads into. These systems are low maintenance and provide an effective, yet expensive way to condition a building. To meet the ventilation requirement and condition the spaces directly a combination of a dedicated air handling unit and active chilled beams were selected. The combination of these allows for a reduction in airflow requirements as the ACB units provide a high cooling (and forced convection heating) capacity at relatively low airflows.

With the substantial changes to the mechanical system there was a multitude of cascading changes to the building. For the report breadths, 201 Rouse's electrical and structural roof loads were analyzed with respect to the changes that the new HVAC system had upon them. The electrical equipment of the DOAS, pump and heat pumps required a new panelboard, while also removing hundreds of feet of conduit for VAV boxes and heavy conduit for the high capacity rooftop air handling units. In the change from the initial HVAC system the roof loads, area and vibrations were diminished. With these changes it was possible to reduce the joist size of all the joists on the east side and remove half of the acoustical screen.

In the end, the changes to the building's mechanical system yielded saving on the order of $3,500 a month, at an additional cost of $680,000, and boosted the building's accreditation potential to LEED Gold; all the while maintaining a high level of thermal comfort.

Building Overview

Name:

201 Rouse Boulevard

Location:

201 Rouse Boulevard

The Navy Yard

Philadelphia, PA 19112

Occupant:

Franklin Square Capital Partners

Function:

Class A Office Space, Cafe, Fitness Center

Size:

84,500 square feet

Construction:

September 2013 to Q1 2015

Project Team:

Architects:
- DIGSAU (Primary Architect)
- Re:vision Architects (LEED Consultant)
- Francis Cauffman (Interior Architecture)
- Fury Design (Interior Design)

Engineers:
- Environetics (Structural Design)
- Pennoni Associates (Site and Civil)
- In Posse (Energy Consultants)

Owners:
- Liberty Property Trust (Owner)
- Synterra Partners (Developers)

Construction:
- Turner Construction (General Contractor)

Existing Conditions

Architecture

201 Rouse Boulevard is a high-end high-performance building. With a glass walled ground floor pedestal and copious windows wrappings, the building will glow with natural light in the retail spaces and offer beneficial daylight in the workspace. The top three floors, primarily office space, will have an exotic zinc clad facade punctuated with floor to ceiling windows; giving stunning views of the Navy Yard and the Philadelphia skyline to the occupants. The lobby, which houses a health cafe and fitness center, is enriched with wood flooring, Jerusalem limestone and Venetian plaster. The ground floor pedestal also plays as the main architectural feature of the predominantly rectangular office building. Those features being a 8 ft cantilever of the office spaces over the main entrances and a curved glass facade on the south-west side of the building.

Building Facades

201 Rouse Boulevard has two primary facade types, the top three office floors and the ground floor pedestal. The ground floor pedestal facade is composed of three components: floor to ceiling glass "store-front" panels with aluminum mountings and mullions, full length brushed aluminum panels, and to "weigh" down this light and airy facade, the building uses light textured terrazzo paneling. The top three office space floors are a different story, though they do keep the vertical lines created by the base window panels, and have large arrays of windows. These large floor to ceiling windows come in four types to match the four patterns of the primary facade system. The primary system is consisted of four repeating patterns of exotic zinc cladding punctuated by vertically rising aluminum fins, which serve a small additional part in sun shading. The building's design used these zinc facade elements to hide almost all structural elements.

Roofing

201 Rouse Boulevard has a standard asphalt covered high R value rigid insulation on steel deck roof. The roof slopes (¼"/1') to the center of the building where the drains and mechanical equipment are. To help obfuscate the rooftop mechanical systems there is a 13 ft. high mechanical screen setback 15-25 ft from the parapet.

Sustainability

The project at 201 Rouse Boulevard is to be LEED Certified under Core and Shell (v2009). To achieve this LEED rating, the project is relying upon modern lighting systems with ample daylighting, an efficient economized cooling Variable-Air Volume HVAC system, and points awarded to the project for its location and support of amenities and transportation. For more information into 201 Rouse's LEED performance see LEED and Energy, Cost and LEED Comparison.

Primary Engineering Systems

Construction

Turner Construction is leading the construction, which broke ground on October 21st 2013, of 201 Rouse at the Navy Yard Corporate Center. The project, costing upwards of $25 million, is one of a series of design build projects designed and developed by DIGSAU and Turner for Liberty Property Trust at the Navy yard Corporate Center; these project advanced rapidly via the usage of similar project teams for multiple projects. 201 Rouse is slated to be fully constructed in Q1 of 2015.

Lighting

The occupied areas of 201 Rouse are fit with modern ceiling hung single T5 Lamp fixtures, while the utility areas are fit with standard dual T5 fluorescent fixtures. 201 Rouse has an exterior that is over 40% windows, to take advantage of this abundant daylight there are several photocells to provide daylighting control to the building automation systems. The exterior of the building is lit with recessed can lights, illuminating paths and occupied exterior areas. The 100+ parking lot is lite by single or dual downward facing halogen lamps, while the landscaped areas of the site are illuminated by round diffuse halogen light posts.

Electrical

Two 600 Amp 3 phase high voltage electrical service lines connect 201 Rouse's 1,500 3 Phase wye transformer to the local utility grid, with service provided by PECO. A main panel board of 2000 Amps is located in the electrical room of the main floor; an 800 amp bus distributes electricity to electrical rooms on the upper three floors. Each of these floors have their own high density panels and 75 kVA step down transformers to 120/208 V. The main distribution panel handles the emergency equipment. Through an automatic transfer switch additionally connected to a 30 kW outdoor generator the system provides continuous emergency power to two life support panels (one at 120/208 after a 9 kVA step down transformer).

Structural

The superstructure of 201 Rouse is structural steel, a substructure of poured concrete, and slab on metal deck floors. The foundation of the building is a wooden pile and concrete cap foundation system, with piles and cap for each column of the superstructure. With no basement, the foundation of 210 Rouse utilizes a 2 foot footing for the exterior walls, and a slab on grade for the floor. The superstructure of the building consists of steel columns, ranging W14X120 to W12X40, beams (typically W21X44 exterior and W24X62 interior), girders(W16X36 and larger), and joist girders (typically 30k7). Typical floor construction is 3"x20 gage galvanized type B composite deck topped with 2 ½" normal weight reinforced concrete (compressive strength of 3500 psi at 28 days).

Mechanical

Heating & Cooling

201 Rouse Boulevard's heating and cooling is provided via three rooftop packaged units in conjunction with four electric unit heaters (used at entrances and equipment spaces). The building's primary spaces are conditioned by two large 33,600 SCFM (standard cubic feet per min.) rooftop air handling units (AHUs) with variable frequency drives (VFDs) that provide up to 1,500 kBTU/hr cooling (using R-410A refrigerant and an Energy Efficiency Ratio of 9.8) and 750 kBTU/hr heating each. Both AHUs utilize an economizer system balancing the return air and outside air based upon outside air (OA) requirements and relative humidity. The third rooftop unit is a smaller 1,600 SCFM packaged unit that conditions the bathrooms and building core. Additionally, 201 Rouse Boulevard utilizes single duct Variable Air Volume (VAV) Terminals of four varying sizes; all with electric reheat coils. The locations of the VAVs have not been specified yet as the layout of the office spaces have yet to be finalized.

Ventilation

Building ventilation is handled by providing over 16,000 SCFMs of outside air during occupied times. Additional exhaust is handled by two rooftop exhaust fans, with additional localized exhaust provided by transfer fans. The rooftop units are belt driven centrifugal exhaust fans that provide 5,300 SCFM and 865 SCFM for toilet exhaust and janitor's closets (always on) respectively. The smaller (~400 SCFM) transfer fans handle the ventilation from the electric closets and machine rooms and are controlled by the space's thermostat. In addition to the exhaust systems, each of the two large rooftop AHUs have a return system with 27,500 SCFM capacity each. This air return system uses the mechanical riser shaft as the return system and is integrated in the AHUs with air side economizers.

Controls

201 Rouse Boulevard has a web accessed native BACnet control system. The primary space AHUs have four scheduling modes: occupied, unoccupied, morning warm-up, and morning cool-down. The smaller core AHU has only two scheduling modes, occupied or unoccupied. When in occupied modes, the control sequence maintains a minimum outside

air flow (set by ASHRAE 62.1), manages the variable volume control of the supply and return fans using system air balancing, uses stepped electric resistance heating to maintain the temperature set point, and utilizes economizer cooling when the outdoor air enthalpy is lower than the return air enthalpy. When in unoccupied mode, the outside air dampers are closed and the AHUs cycle to maintain the discharge air temperature set points.

Engineering Support Systems

Fire Protection

201 Rouse is a fully covered by sprinklers (per IBC Table 601) business class building. All exterior load bearing walls and stair/shaft enclosures have a 2 hour fire rating and the building occupants have a max exit access travel distance of 300 feet (full sprinkler coverage).

In the tenant spaces the sprinkler system is spaced in a 12 x14' grid and is feed by two independent standpipes with a rate of 0.10/1500 GPM/ft^2. The utility and mechanical spaces of the building are also sprinkler protected with 0.15/1500 GPM/ft^2.

Transportation

Within the building there are two hydraulic elevators that are publicly available and service every floor. On the building site there will be ~150 automobile parking spots along with racks for bicycle storage. 201 Rouse is in close proximity to a campus shuttle, Southeastern Pennsylvania Transportation Authority (SEPTA) bus and subway stations.

Telecommunications

201 Rouse has telephone and networking connections through the local utilities and is distributed throughout the building from the first floor's electrical room.

The building's security system includes magnetic swipe readers for two of the building's entrances and camera equipment covering the lobby and elevator bank; all controlled/recorded with equipment in the first floor electrical room. Additional security to be provided as per tenant fit out.

Energy

In any potential redesign of a building a baseline model of the initial systems should be analyzed. The reason for this is twofold, firstly it allows one to assess the performance of the building and decide where substantial improvements can be made that align with the project goals; secondly this baseline analysis allows for a comparison both to the redesigned model and different energy benchmarks.

To perform the energy modeling analysis of 201 Rouse the DOE2 backed Quick Energy Simulation Tool (eQUEST) was used. This comprehensive energy modeling program utilizes both a "wizard" builder and a detailed mode to strike a balance between usability and complexity.

To analyze the energy performance of the existing systems of 201 Rouse the thermal zones were set to coincide with the zones that the three rooftop air handling units would condition. See Figure 1 below to see the WNW, SE, and Core zones of 201 Rouse, in the figure North is towards the top of the page. Figure 2 details the 3D model that eQUEST creates to simulate the building performance, pay specific attention to the roughly 48% glass curtain walls as this will have a large effect upon the energy performance of the building.

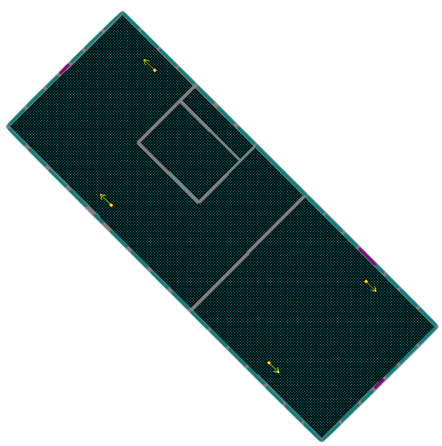


Figure 1: Thermal Zones of 201 Rouse

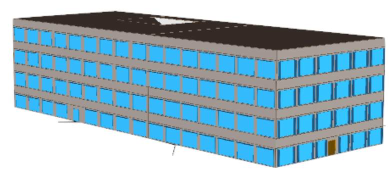


Figure 2: 3D View of eQUEST Created Building

The model is built to the existing system specifications and the base building properties as outlined above and detailed in the construction documents. All of the HVAC equipment and building components are electric and as such it is the only energy analyzed in the model. To predict cost of operation a uniform charge of $0.162 per kWh was used as that is the average for the Philadelphia region of the last year, notably it is significantly above the national average of $0.12 The energy model simulates a full year's performance of the building, this yields monthly consumption (Figure 3), annual electricity use (Figure 4), and a monthly breakdown of operating cost (Figure 5).

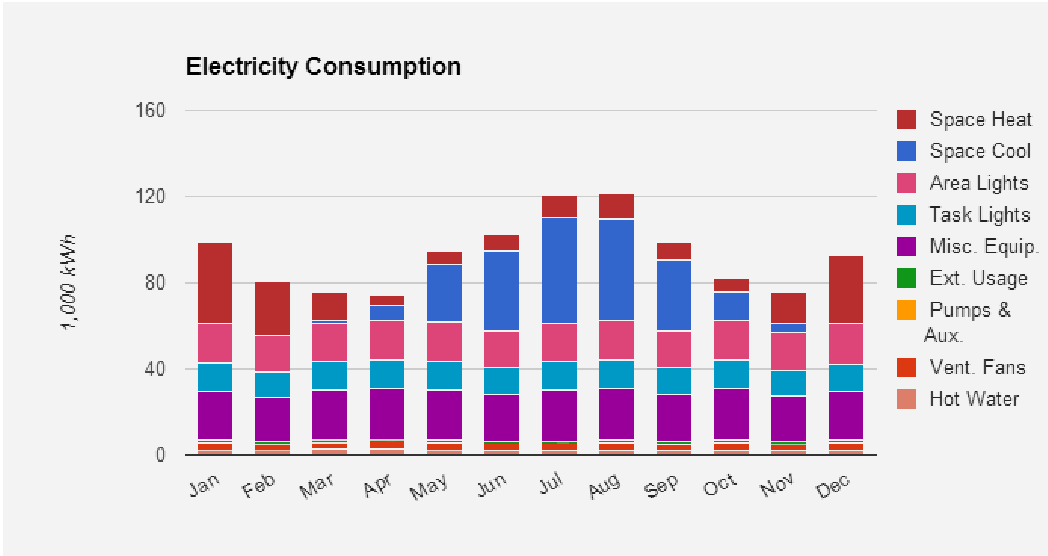


Figure 3: 201 Rouse Initial Monthly Consumption

As Figure 3 shows 201 Rouse hits a peak consumption in July and Aug, but it hits a peak demand (not shown) in January during the heating period. The cooling and heating equipment account for more than 40% of the building's annual electric usage. For the simulation year of 2013 eQUEST models that 201 Rouse would take $181,190 to operate. By reducing the electrical demand of the HVAC equipment the building's monthly cost and demand usage can be driven down.

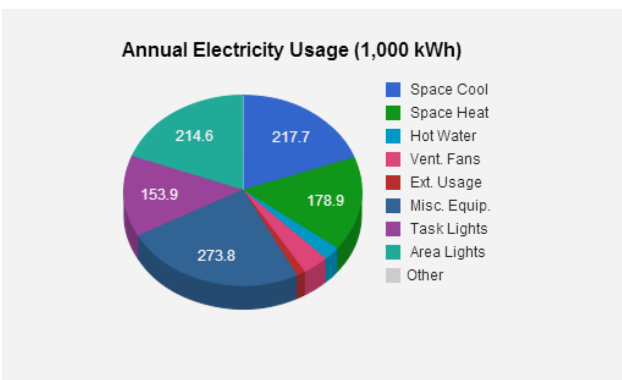


Figure 4: 201 Rouse Initial Annual Usage

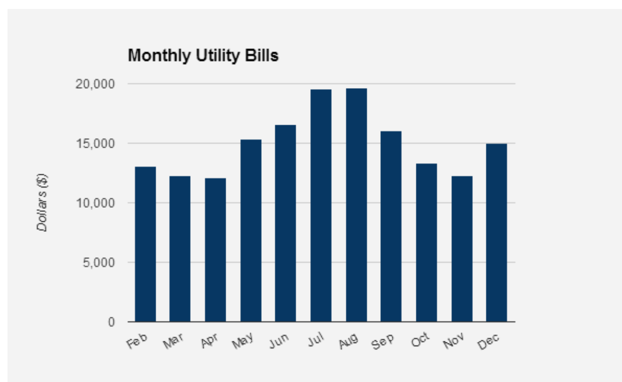


Figure 5:201 Rouse Initial Monthly Utility Bills

Table 1: 201 Rouse EUI and Comparison

Building	Site EUI (kBtu/sqft)	Source EUI (kBtu/sqft)	Performance Gain
201 Rouse	46.4	139.2	31% Site, 6% Source
CBECS National Average	67.3	148.1	-

Table 1 shows that energy use intensity (EUI) for 201 Rouse and the national average for office buildings from the Commercial Buildings Consumption Survey (CBECS). While 201 Rouse is comparatively energy efficient (leading to LEED points) it falls behind in its source EUI, which is where emissions come from while site EUI is more optimized to relate to price. Partly due the Philadelphia region and the building's sole use of electricity as its energy source the source EUI performance should be addressed in the system redesign to reduce emissions. For a more comprehensive breakdown of building energy use see Technical Report 2 and for more information into the building equipment and loads see Technical Report 3.

LEED

Since 1998 the US Green Building Council (a nonprofit that promotes sustainability in building design, construction and operation) has released the Leadership in Energy & Environmental Design (LEED) suite of ratings systems. These ratings provide a standard upon which to build "green" buildings and achieve a recognized level of accreditation.

The LEED ratings for new construction are based around seven categories: sites, water efficiency, energy and atmosphere, materials and resources, indoor air quality, innovation in design, and regional priorities.

Following the guidelines set out by LEED can yield substantial energy savings and minimize environmental impact. If that wasn't incentive enough, LEED rated sustainable properties produce a higher demand and lead toward comparably higher rents. WIth these factors in mind the team from Liberty Property Trust set the design team in motion to achieve Gold level certification for 201 Rouse. On the project team Re:Vision Architecture is the leader of the sustainability team in charge of achieving the LEED certification. With LEED Gold Certification entailing getting at least 60 of the 110 LEED checklist points broad integration between the teams was paramount.

To achieve the Gold level of certification, sustainability features would have to be utilized in many building systems along with its overall construction. With respect to 201 Rouse's mechanical system, the LEED categories of Energy and Atmosphere and Indoor Environmental Quality are most pertinent. To analyze the systems of 201 Rouse the 2009 LEED Standard for New Construction and Major Renovations were used.

Energy and Atmosphere

Credit	Description	Intent	Execution	Points
Prerequisite 1	Fundamental Commissioning of Building Energy Systems	To verify the project's energy-related systems are installed and calibrated to perform according to the Owner's project requirements, basis of design and construction documents.	The owner will document and monitor the Project Requirements while Bala Engineers will do the commissioning based off the Construction Documents	Required
Prerequisite 2	Minimum Energy Performance	Establish the min. level of energy efficiency for the building and systems.	Initial designs were based on AHSRAE Standard 90.1-2010 (see Tech. Report 1) and Energy models were performed during various phases of design by In-Posse to check compliance.	Required
Prerequisite 3	Fundamental Refrigerant Management	To reduce stratospheric ozone depletion by controlling CFCs.	The HVAC systems of 201 Rouse use R-410A, a CFC free refrigerant.	Required
Credit 1	Optimize Energy Performance	To increase the levels of energy efficiency beyond those of the latest baseline performance standards.	Using the Whole Building Energy Simulation option, the In-Posse model predicts more than 16% energy savings than the the baseline.	3 of 19
Credit 2	On-Site Renewable Energy	To promote the utilization of on-site renewable energy generation.	N/A	0 of 7
Credit 3	Enhanced Commissioning	To begin commissioning process early in design and execute additional activities post verification.	The integrated project team began commissioning and modeling from early stages in design.	2 of 2
Credit 4	Enhanced Refrigerant Management	Reduce Ozone depletion due to refrigerants	The building uses HVAC equipment that eliminates the emission of refrigerants.	2 of 2
Credit 5	Measurement and Verification	Promote ongoing accountability of building energy consumption over time.	The base building will be metered and monitored and fed back to check and calibrate the energy model.	3 of 3
Credit 6	Green Power	Encourage development and use of green power sources	201 Rouse has a contract to provide at least 35% of its baseline usages from green power sources.	2 of 2

Table 2: Initial LEED Energy & Atmosphere

Indoor Air Quality

Credit	Description	Intent	Execution	Points
Prerequisite 1	Minimum Indoor Air Quality Performance	Establish min. indoor air quality performance	201 Rouse meets the ventilation requirements of AHSRAE Standard 62.1-2010 (see Tech.Report 1)	Required
Prerequisite 2	Environmental Tobacco Smoke Control	Prevent/Minimize occupant exposure to tobacco smoke.	Smoking is prohibited in 201 Rouse	Required
Credit 1	Outdoor Air Delivery Monitoring	Provide ventilation system monitoring for occupant comfort	201 Rouse has a outdoor air monitoring station that controls OA flow and monitors CO2 concentrations.	1 of 1
Credit 2	Increased Ventilation	Provide OA ventilation beyond the minimum requirements	201 Rouse has a HVAC system with a min. of 24% outdoor air, more than 30% greater than the ASHRAE 62.1 standard (see Tech Report 1)	1 of 1
Credit 3.1	Construction Indoor Air Quality Management Plan-During Construction	Reduce Indoor Air Quality (IAQ) due to construction.	Met IAQ guidelines from SMACNA	1 of 1
Credit 3.2	Construction Indoor Air Quality Management Plan-Before Occupancy	Reduce Indoor Air Quality (IAQ) due to construction.	There will be a flush-out once construction ends.	1 of 1
Credit 4.1	Low-Emitting Materials - Adhesives and Sealants	Reduce Indoor Air Contaminants.	All adhesives were selected based on LEED Action Plan and VOC Limits	1 of 1
Credit 4.2	Low-Emitting Materials - Paints and Coatings	Reduce Indoor Air Contaminants.	All paints were selected based on LEED Action Plan and VOC Limits	1 of 1
Credit 4.3	Low-Emitting Materials - Flooring Systems	Reduce Indoor Air Contaminants.	All flooring systems were selected based on LEED Action Plan and VOC Limits	1 of 1
Credit 4.4	Low-Emitting Materials - Composite Wood and Agrifiber Products	Reduce Indoor Air Contaminants.	All wood products were selected based on LEED Action Plan and VOC Limits	1 of 1
Credit 5	Indoor Chemical and Pollutant Source Control	Minimize occupant exposure to hazardous particulates and chemical pollutants	Building entrances trap incoming particles, and there is ample exhaust and ventilation to deal with IAQ	1 of 1
Credit 6.1	Controllability of Systems - Lighting	Provide high level of lighting system control	Each floor and the exterior has independent daylighting sensors	1 of 1
Credit 6.2	Controllability of Systems - Thermal Comfort	Provide subzone control of HVAC systems	N/A	0 of 1
Credit 7.1	Thermal Comfort - Design	Provide a comfortable thermal environment	The HVAC system is compliant with ASHRAE 55	1 of 1
Credit 7.2	Thermal Comfort - Certification	Assessment of building occupant thermal comfort over time	N/A	0 of 1
Credit 8.1	Daylight and Views - Daylight	Provide occupants connection to outdoors and natural light	N/A	0 of 1
Credit 8.2	Daylight and Views - Views	Provide occupants connection to outdoors and natural light	201 Rouse has large perimeter windows on all faces and floors	1 of 1

Table 3:Initial LEED Indoor Air Quality

Proposal

The comprehensive mechanical redesigns include:

To create a more sustainable building, capture additional LEED certification points and lower monthly utility costs the current conventional all-electric rooftop air handling units and variable air volume boxes with reheat will be replaced.

Ground Coupled Heat Pump: To utilize the constant ground temperature of the earth a ground coupled heat pump system will be specified, priced, and installed in 201 Rouse to provide hot and chilled water for building HVAC systems.

Dedicated Air Handling Unit: To meet the ventilation requirements of the building

Active Chilled Beams:

Corresponding to the changes of the mechanical depth redesign two corresponding depths are analyzed:

Electrical: A substantial part of 201 Rouse's electrical system is devoted to supporting the current all electrical packaged units and the VAV boxes. With the mechanical breath's change of the specified HVAC system to an efficient ground source heat pump system with chilled beams airside this portion of the building's electrical arrangement has changed. With all of the water pumps, heat pumps, and active chilled beams the building's main distribution will have to be adjusted and new panels and wiring put in place to power this replacement mechanical equipment. By configuring the electrical backbone of the geothermal heat pump system a better idea of cost is developed. There is potential savings in downsizing the main distribution or in the number of supporting panels.

Structural: The current structural system of 201 Rouse uses a simple steel frame, with the member selection driven by the building core, glass heavy facade, and an equipment laden roof. With the proposed sustainable mechanical improvements removing over 36,000 lbs. in mechanical equipment from the roof of 201 Rouse, the structural frame of the building can be readjusted to these lower load requirements. As the requirements for the roof's structural support are diminished new I beam or truss members could replace the current system.

Mechanical Depth: Geothermal System

Background

201 Rouse utilizes a conventional DX packaged unit with VAV reheat system to condition its spaces. The design was modeled off previous speculative office buildings the architects and engineering partners had done previously on the Navy Yard Campus. While having to deal with large amounts of window area (~45%), open interior spaces, and a premium on occupant comfort the mechanical design team achieved design targets of “14-20%” above ASHRAE 90.1 Baselines (citation needed, In Posse Email). While efficient in energy and cost it does not take advantage of local resources nor add value to the building.

The initial inspiration for a geothermal system at this building site was the Delaware and Schuylkill Rivers and the vision of a water sourced heat pump system for the whole corporate campus at the Philadelphia Navy Yard. Based upon the practice of doing an initial test-bed before a large scale roll out of technologies a smaller scale geothermal heat pump system would be created for the newest building on the campus, 201 Rouse, which began groundbreaking in September of 2013. Geothermal heat pump (GHP) solutions offer numerous advantages over conventional HVAC systems including: level season electric demand, reduction of fossil fuel emissions, lowered operating costs and maintenance (citation needed, NYC Design Manual). The mechanical system of 201 Rouse would have to meet all the load, occupant, and LEED requirements of the previous system while simultaneously adding value to the property and proving the utility of geothermal systems.

Geothermal System Selection

Laying at the confluence of the Delaware and Schuylkill rivers, with a shallow water table and high bedrock the Philadelphia Navy Yard holds the potential for all different types of geothermal heat pump systems between standing column wells, open loops and closed loops. While an open loop system using the Delaware River as a heatsink would be preferable for a large scale campus system, it is preferable expensive due to distance to the river and temperature differential of the surface water with seasons. The other water based solutions of open loop and standing column well have the issue of having to line the well the whole depth (adding to the well cost) due to the sand/gravel bedrock of the region. All things considered, a closed loop ground source geothermal system was the most applicable to the geology and design loads of 201 Rouse.

The site of 201 Rouse has a 21,000 ft^2 footprint on a 190,000 ft^2 site. With all the available site space and the increased thermal efficiency and reduced costs a vertical well layout yields the best ratio of site usage/performance to cost. See Figure 6 for a schematic of a vertical well ground coupled heat pump.

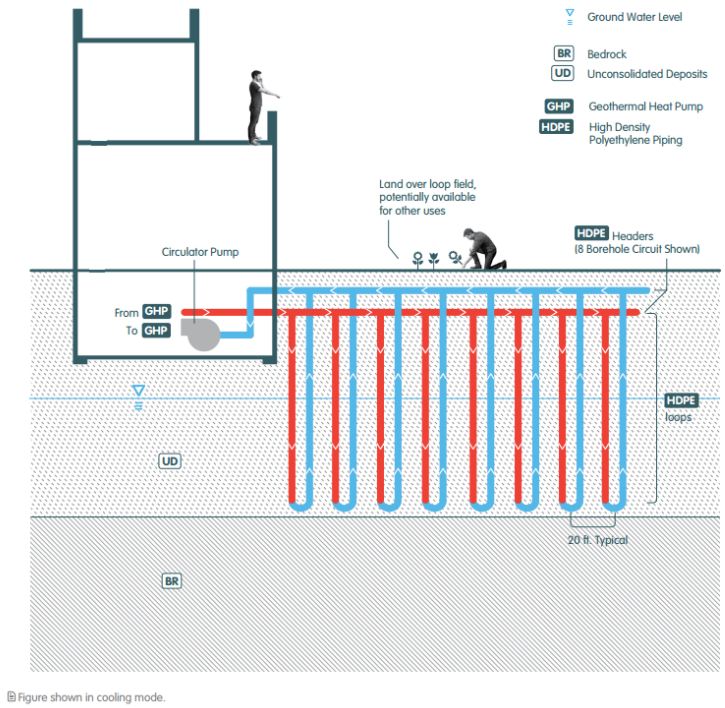


Figure 6: Vertical Well Ground Coupled Heat Pump

Site Characteristics

201 Rouse is in southern Philadelphia, PA. As seen in Figure 7 the region's geological bedrock is a mix of sand, gravel and silt.

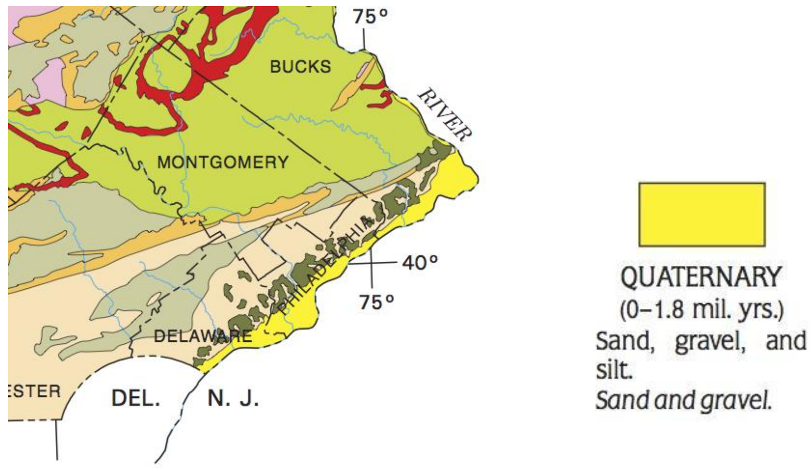


Figure 7: Geology of Philadelphia, PA

This soil and rock mixture yields an acceptable thermal performance (see Table 4) while the high water table and bedrock minimize the cost of drilling as a constant ground/water temperature is reached quickly. In the lower Philadelphia region a constant ground temperature of 55^{oF} is reached within 30 feet. Additionally the permeability of the bedrock along with the underlying Potomac-Raritan-Magothy aquifer allows for near constant flows of water around the wells increasing the thermal performance of the geology and retards any long term thermal changes to the geology due to the use of a ground coupled heat pump.

Table 4: Bedrock Properties

	Dry Density (lb./ft^3)	Conductivity (Btu/hr* ft*^{o}F)	Diffusivity (ft^2/day)
Heavy Sand (15% Water)	120	1.6	0.75

Well Sizing

In a ground coupled geothermal heat pump system the vertical wells have to be sized in flow, diameter, and length to meet the load requirements of the building. 201 Rouse has a peak cooling load of 250 tons in cooling and 190 tons in heating (for more information on 201 Rouse building load see Energy). To size the wells of 201 Rouse the design conditions of a 1 inch polyethylene thermally fused U-tube and a flow of three gallons per minute were chosen for the system. To size the required total length of wells for the heating and cooling load the procedure from chapter 34 (Geothermal Energy) of the ASHRAE Handbook were used.

Finding the required length of well to successfully thermal transfer the building load of 201 Rouse two equations were used, both are adaptations of the Ingersoll and Zobel heat transfer equation for

U bend GCHP loops. Equation 1 yields the length to handle the cooling load while Equation 2 determines the length to handle the building's heating load.

Equation 1&2: Bore Length Equations

Equation 1: Required Bore length, Cooling (L_C)

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

Equation 2: Required Bore Length Heating (L_h)

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

Bore Length Variables and Assumptions

Short Circuit Heat Loss Factor (Fsc): With the design assumption of a three gallons per minute flow per ton and one U-Tube pipe boor per loop the Short Circuit heat loss factor is 1.01.

Net Annual Average Heat Transfer to Ground: The net annual average heat transfer to ground was assumed to be the difference of the peak building loads, 100,000 Btu/hr.

Building Design Load Block (Cooling q_{lc} and heating q_{lh}): 201 Rouse's peak hourly design block load were calculated previously to be 2,200,000 Btu/hr for cooling (sensible load) (q_{lc}) and 2,300,000 Btu/hr for heating (q_{lh}) using eQUEST models and initial design specifications.

Effective Thermal Resistance of Ground: The effective thermal resistance of the ground is a major component to the GCHP's performance and required length. To calculate an effective thermal resistance for the ground underneath a combination of time pulses of Fourier numbers and G-Factors are used which can bee seen in Equation 3 and the calculated values for 201 Rouse in Tables 5. For additional tables and G-Factor Plot see Appendix A.3.

Equation 3:Time Pulse, Fourier and Thermal Resistance

$\tau_1 = 3650$ days
$\tau_2 = 3650 + 30 = 3680$ days
$\tau_f = 3650 + 30 + 0.25 = 3680.25$ days

Time Pulse Equations
(10 Year, Month, Daily)

$$Fo_f = 4\alpha\tau_f/d_b^2$$
$$Fo_1 = 4\alpha(\tau_f - \tau_1)/d_b^2$$
$$Fo_2 = 4\alpha(\tau_f - \tau_2)/d_b^2$$

Fourier Number

$$R_{ga} = (G_f - G_1)/k_g$$
$$R_{gm} = (G_1 - G_2)/k_g$$
$$R_{gd} = G_2/k_g$$

Thermal Resistance

Table 5: Thermal Resistance of 201 Rouse Ground Wells (Use of Fourier Number and G-Factor)

	Annual Pulse (1)	Monthly Pulse (2)	Daily Pulse (f)
Time of Operation (days)	3650	3680	3680.25
Diffusivity (ft^2/day)	0.75	0.75	0.75
Bore diameter (ft)	0.5	0.5	0.5
Fourier Number, Fo	363	3	44163
G Factor	0.535	0.2	0.915

Variable	Value	Units
kg	1.6	Btu/ft*hr*^{o}F
Rga	0.2375	ft*hr*^{o}F / Btu
Rgm	0.209375	ft*hr* ^{o}F / Btu
Rgd	0.125	ft*hr*^{o}F / Btu

Thermal Resistance of Bore (R_b): With a 1 inch diameter tube, a six inch bore and an average bore fill conductivity of 1 Btu/hr*ft*^{o}F the thermal resistance of the bore well is 0.10 hr*ft*^{o}F/Btu

Undisturbed Ground Temperature (t_b): As discussed in Site Characteristics, within 30 ft of the surface the ground will reach a annual constant of 55 ^{O}F.

*Temperature Penalty for Interference of Adjacent Bores (t_p):*With the bores spaced at 20 feet and the permeable bedrock and aquifers there is not likely to be much thermal transfer from well to well, however to be conservative for long term ramifications of using a GCHP a temperature penalty of 2 ^{O}F was used.

Liquid Temperatures at Heat Pump (t_{wo} output and t_{wi} at inlet): As per recommendations of the ASHRAE Handbook for efficiency the water in the bore loops should start at 20 ^{O}F above ground temperature for cooling and 10^{O}F below for heating. With a ΔT set by the chosen Trane heat pump (see _Heat Pumps) the inlet temperatures are 75 ^{O}F (cooling) and 45^{O}F (Heating) and out of the heat pump: 87 ^{O}F (cooling) and 30^{O}F (Heating). Getting these values was an iterative optimizing process between the ΔT of the load side to utilize the active chilled beams

System Power input at Design Load (W_c Cooling and W_h Heating): Using a eQUEST energy model based upon the current building HVAC equipment the system power input for both the heating and cooling load was estimated (and even major changes has little effect upon the total length requirement).

Table 6 below shows the final arrangement of variables and factors that went into the Ingersoll and Zobel Bore Length Equations. In the final tally, to adequately meet the building load of 201 Rouse 47,000 ft of bore well are required, this is ~260 ft/ton and corresponds to a minimum 125 wells. By having a 8x16 well field yielding 128 wells, the ground coupled source for the heat pumps would be better able to meet load and do so at low operating cost.

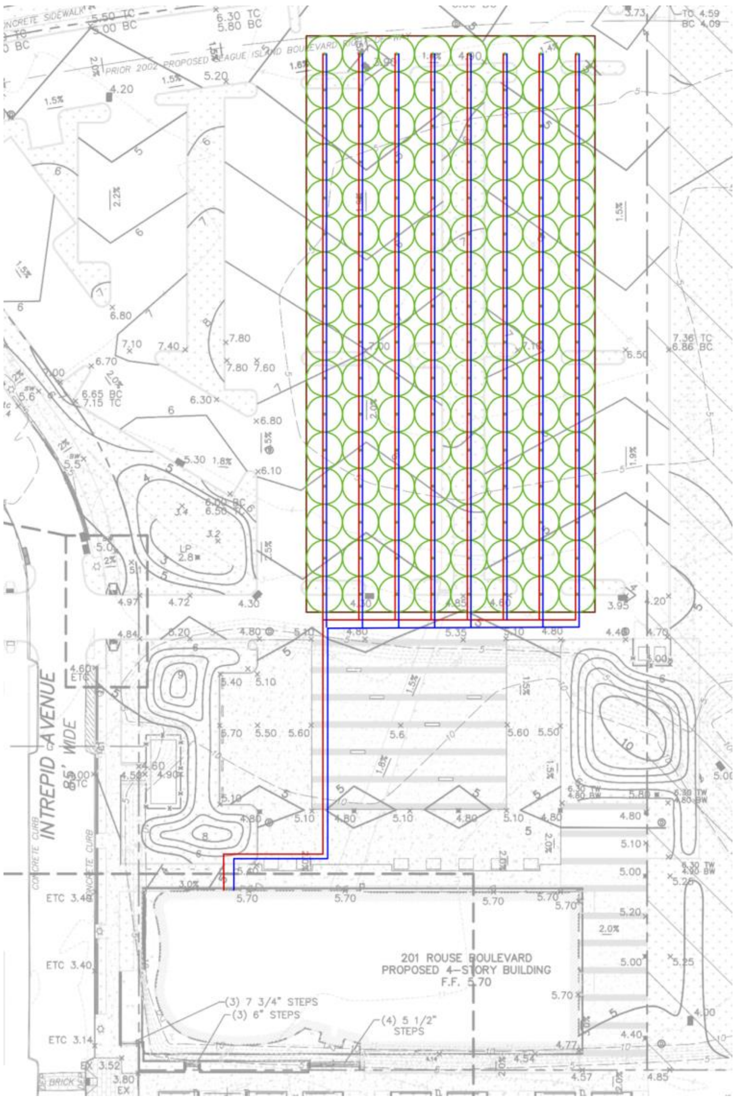
Table 6: Bore Length Calculation Results

Ingersoll and Zobel Bore Length Equations

	Cooling	Heating	Units
Short Circuit Heat Loss Factor, Fsc	1.04	1.04	-
Part Load Factor , PFLm	1.00	1.00	-
Net annual heat transfer to ground, Qa	700,000	700,000	btu/hr
Building Design Block Load Cooling, Qlc	3,000,000	-	btu/hr
Building Design Block Load Heating, Qlh	-	2,300,000	btu/hr
Effective thermal resistance of ground annual pulse, Rga	0.24	0.24	ft*hr*^{O}F / Btu
Effective thermal resistance of ground daily pulse, Rgd	0.13	0.13	ft*hr*^{O}F / Btu
Effective thermal resistance of ground monthly pulse, Rgm	0.21	0.21	ft*hr*^{O}F / Btu
Effective thermal resistance of bore, Rb	0.10	0.10	ft*hr*^{O}F / Btu
Undisturbed ground Temperature, tg	55.00	55.00	^{O}F
Temp penalty for interference of adjacent bores, tp	2.00	2.00	^{O}F
Liquid temp at HP inlet, twi	75.00	35.00	^{O}F
Liquid temp at HP outlet, two	85.90	30.00	^{O}F
System power input at design cooling load, Wc	100,000	-	W
System power input at design heating load, Wh	-	100,000	W
Required Length	**48,617.42**	**50,096.86**	**ft**

Layout

201 Rouse has a 21,000 ft^2 footprint on a 190,000 ft^2 site, leaving 169,000 ft^2 to place the roughly 50,000ft^2 area of wells that are necessary at a 20 ft spacing to achieve the 124 wells necessary to meet the building load. Another benefit of using a closed loop GCHP is that the land above the wells can be used once the construction of the well field is completed. As such the well field of 201 Rouse will be under the parking lot. As seen in Figure 8, the field is located over 130 feet from the building, it preserves the surrounding area for construction activities such that the installation of the field has little impact upon the final timeline. The 50,000 ft^2 of well field extends 400 feet into the earth and the header pipes connect back to the building in the first floor mechanical room.



Legend:
Green: Wells
Blue: Return Lines
Red: Supply Lines

Statistics:
Wells: 128
Depth: 400 ft.
Area: 51,200 ft^2
Grid: 8x16
Total Well Length: 51,200 ft

Figure 8: Well Field Layout

Equipment

Well Field Pump

A pump is necessary to achieve the flow of water/antifreeze mixture through the well field to achieve the necessary heat transfer to meet 201 Rouses's building load. Table 7 below details the determination of a 750 Gallons per minute (GPM) flow based upon these building loads. Using the layout described in Figure 8 and the prescribed flow characteristics of 750 GPM for the field and 5.85 GPM per well the head loss of the system was calculated. Using the Hazen-Williams equation and the equivalent length method the head loss of the longest run of the well field was calculated, see Table A.1 in Appendix A for the full calculation and Table 8 below for the summary.

Table 7 : Well field Pump GPM Specification

Peak Design Load	Design Flow	Required GPM
250 tons	3 GPM/ton	750 GPM

Table 8 :Head loss through Longest Run of Well Field Pump Selection (curves and specs)

Section	Pipe Size (in)	Head Loss
Header	6.00	18.75
Bore Loop	2.00	21.51
Well	1.00	23.47
Sub Total	-	63.73
Multiplier		1.50
Total		**95.59**

Using a head loss of 95 feet and a design flow of 750 GPM a pump was selected from pioneer pump, see Appendix Figure A-4 for the product information. Figure 9 below is the pump curve for Pioneer standard centrifugal pump SC54C75 and Table 9 shows the selected pump characteristics. See Appendix A for the Pioneer Pump SC54C75 cut sheet.

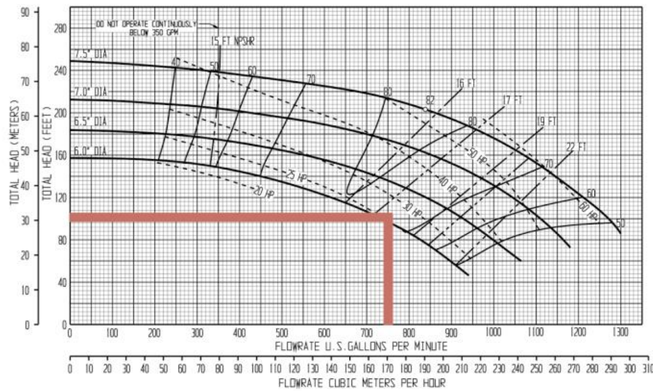


Figure 9: Pioneer SC54C75 Pump Curve

Table 9: Pioneer Pump Selection for Well Field

Manufacturer	Model	Flow Rate (GPM)	Head (ft)	RPM	HP
Pioneer Pump	SC54C75	750 GPM	95 ft (up to 205 ft)	2,700	25 bhp

Heat Pumps

The water to water heat pumps that couple to the ground sourced well system have to be sized upon the design flow, peak heating/cooling capacity of 201 Rouse, and the designed temperature differential used in the well length calculations. 201 Rouse will utilize a water to water heat pump that links the air side active chilled beams to the previously designed ground loop wells for heat exchange.

Water to water heat pumps from Trane are in the 3-20 ton range and can be as large as 6.75'x2.5x2.5; as such having this equipment inside was unacceptable as it is larger than the existing interior equipment spaces and it will be placed upon the roof adjacent to the new DOAS equipment.

To meet the 250 ton load requirement of 201 Rouse the Trane EXWE240 a 20 ton water to water heat pump that can handle both heating and cooling operations; see Figure A-5 in Appendix A for general Data on the heat pump. To meet the load 13 of these 20 ton heat pumps will be installed and linked to the air side 4 pipe system. Table 10 shows the cooling and heating performance of a single EWE240 HP and Table 11 shows the cooling and heating performance based upon a 50 GPM flow, the entering and leaving HP temperatures used in the design of ground loop, and the base cooling and heating supply temperatures for the active chilled beams (57 ^{O}F and 120 ^{O}F respectively). See Appendix A for a cut sheet of Trane EWE240.

Table 10: Trane EXWE 240 General Data

EXWE 240			

Width (in)	81.5	**Ground Loop Coupled**	
Height (in)	30	Cooling Capacity (Btuh)	204,000
Depth (in)	31.375	Cooling EER	15.7
Compressor Type	Scroll	Heating Capacity (Btuh)	172,600
Approx Weight (lb)	1222	Heating COP	2.8
Water in/out (in)	2		

Table 11: Trane EXWE 240 Cooling and Heating Performance

Heating

Source			**Load**							
EWT (deg F)	Flow (GPM)	Head Loss	EWT	Source LWT	HC (MBtuh)	Power (kW)	HA (MBtuh)	LWT	COP	Head Loss
35	50	9.9	110	30.3	180.9	18.9	116.4	117.2	2.8	7.4

Cooling

Source			**Load**							
EWT (°F)	Flow (GPM)	Head Loss	EWT	Source LWT (°F)	TC (MBH)	Power (kW)	HR (MBH)	LWT (°F)	EER	Head Loss
75	50	6.75	57	85.9	228.8	12.52	271.55	50.85	18.35	8.4

DOAS

To handle the ventilation air requirements set by ASHRAE 62.1 and the latent loads of 201 Rouse, a designated outdoor air system (DOAS) will be used. A DOAS system has the added benefit of increasing the indoor air quality (IAQ) , leads to the downsizing of other air-side components, and lowers the required airflow over traditional VAV. The system in 201 Rouse will be set up to deliver conditioned outside air (OA) to the supply-side of each local active chilled beam (ACB) unit, see Figure 10.

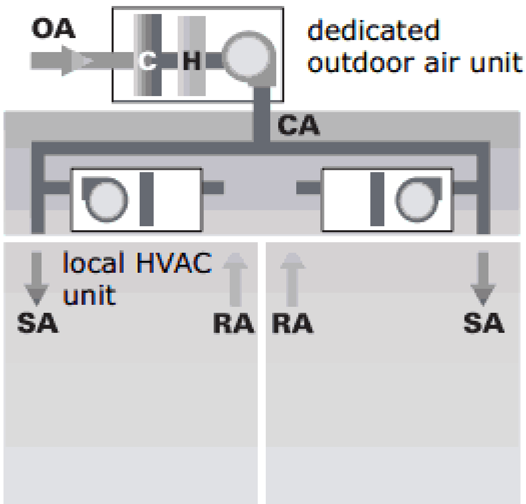


Figure 10:Configuration of DOAS and ABC

The air supplied will be cold air as the DOAS will dehumidify the air and in the process lower the dry bulb temperature. This process is beneficial as this leads to a lessened overall cooling capacity and lowers required airflows to zones. The first step to sizing a dedicated outdoor air unit is to determine the entering-air conditions; using the TMY-2 weather files for Philadelphia, PA the design conditions of peak dry bulb (DB), peak wet bulb (WB) and dew point (DP) were collected, see Table 12 and see Appendix B for the whole psychrometric chart. The maximum limit for zone space humidity in 201 Rouse is set at 60% relative humidity; this is an extreme condition and not often to occur.

Table 12:Entering Air Design Conditions

	Design Condition	Enthalpy (grains/lb dry air)
Peak DB	98 deg F DB	106.6
	77 deg F WB	
Peak WB	90 deg F DB	146
	81 deg F WB	
Peak DP	87 deg F DB	144
	80 deg F WB	

Table 13 below shows the latent loads for the two building spaces (SE and WNW as seen in Energy) that are supplied by the DOAS, they are typical for each of the 4 floors.

Table 13:Space Latent Loads

Space	# of Typical	Latent Load
WNW (office)	4	7.45 kBtu/hr
SE (office)	4	11.4 kBtu/hr
Total	**8**	**75,400 Btu/hr**

The DOAS has to supply enough ventilation air to meet the minimum ventilation airflow as set by ASHRAE 62.1, see Table 14 or the minimum air requirements to meet the latent loads of the space for the active chilled beams (see_ Active Chilled Beams). The air requirements of the ACBs are comparable to the ASHRAE requirements and the total airflow the DOAS must deliver is ~8,500 CFM.

Table 14: ASHRAE 62.1 Building Ventilation Requirement

Zone 1 North- West Side

Space	Function	Size (ft^2) (Az)	Populations (persons) (Pz)	Rp (CFM/person)	RA (CFM/ft^2)	Vbz (CFM)
1st Floor Lobby	Lobby	2,200	22	7.5	0.06	297
116 Tenant	Cafe/Multi Use	3,833	39	7.5	0.18	982
201 Tenant	Office	8,400	84	5	0.06	924
300 Tenant	Office	8,400	84	5	0.06	924
401 Tenant	Office	8,400	84	5	0.06	924
Sub Total		**31,232**	**313**			**4,051**

Zone 2 South- East Side

Space	Function	Size (ft^2)	Populations (persons)	Rp (CFM/person)	RA (CFM/ft^2)	Vbz (CFM)
115 Tenant	Office	9,804	99	5	0.06	1,083
201 Tenant	Office	10,040	101	5	0.06	1,107
300 Tenant	Office	10,040	101	5	0.06	1,107
401 Tenant	Office	10,040	101	5	0.06	1,107
Sub Total		**39,924**	**402**			**4,405**
Total		**71,156**	**715**			**~8,500**

The DOAS must be able to meet the largest zone latent load and supply the driest conditioned outdoor air. Zone SE has the largest zone load of 11.4 kBtu/hr (see Table __) and a zone max humidity ratio of 70.5 grain/lb. To meet that load at the airflow rate of 1,107 CFM needed for the zone the DOAS system will have to be able to create air at a humidity ratio of 55.6 grains/lb.

Using a psychometric chart (see Figure __) a humidity ratio of 55.6 grains/lb corresponds to a dry bulb temperature of 51.5 ^{O}F. To dehumidify 8,500 CFM of outside air at the peak WB to the supply conditions stated previous it takes 73 tons of cooling.

Equation 4:Cooling Capacity for DOAS Dehumidification

$$Q_t = 4.5 \times 8500 \text{ CFM} \times (44.7 \text{ Btu/hr} - 21.8 \text{ Btu/hr}) = 875{,}925 \text{ Btu/hr} = 73 \text{ tons}$$

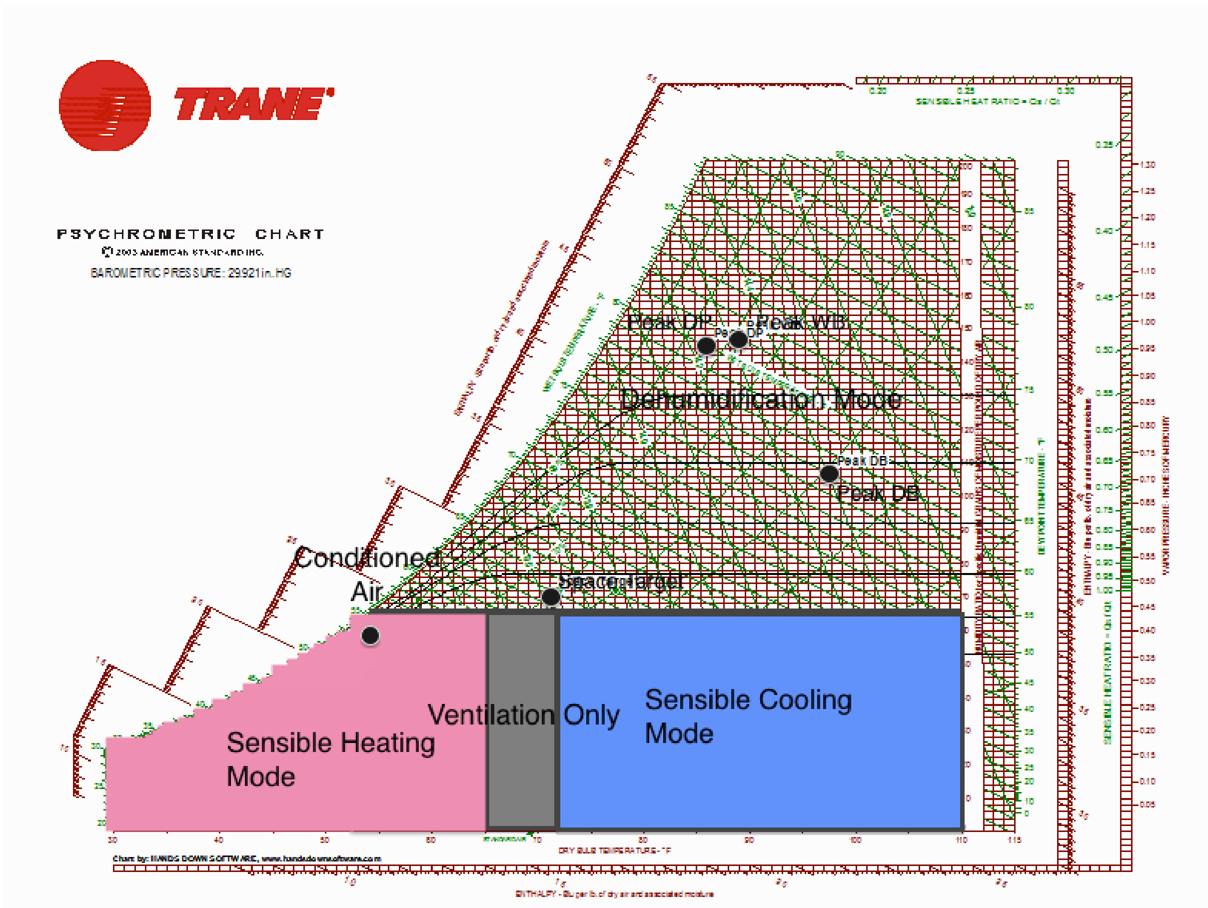


Figure 11: DOAS Psychometric Chart and Control Periods

Figure 11 above details the control zones of the designated outdoor air system and the design points. The system has four primary modes: sensible heating, ventilation only, sensible cooling, and dehumidification. By having the building control systems run the DOAS in these cycles it leverages the sensible cooling and airflow savings that the DOAS system provides.

Using the selecting criteria calculated above: 8,500 CFM and 73 tons of cooling a DesertAire

TotalAire 100% Outdoor air system was selected (pictured left). The unit uses the chilled and hot water of the GCHP system for dehumidification/cooling and heating respectively and meets the airflow and dehumidification requirements. The unit can provide up to 12,500 CFM which meets the flow capacity of the selected active chilled beams (which all together can deliver 12,000 CFM to the building).

With the new dedicated outdoor air system in 201 Rouse the previously specified ducts are no longer necessary as the max airflow has been reduced by two thirds. Table 15 displays the duct requirements and their new sizes for the main rooftop and riser ducts and an approximation for the ducts on each floor. On average the ducts have been reduced by one half to one quarter of their initially specified sizes, this leads to cost savings and increased plenum space to accommodate the chilled beams.

Table 15:Duct Sizing for DOAS

Space	Duct Type	Velocity Target (FPM)	Air Flow (CFM)	Area (sq.in)	Approx. Linear Feet (ft.)
DOAS output	Main	1,080	8,500	1,133	5
Riser 1.1	Main	1,080	3,975	530	5
Riser 1.2	Main Branch	790	2,981	543	15
Riser 1.3	Main Branch	790	1,988	362	15
Riser 1.4	Main Branch	790	994	181	15
Riser 1 Floor (typ.)	Branch	600	994	239	280
Riser 2.1	Main	1,080	4,525	603	105
Riser 2.2	Main Branch	790	3,394	619	15
Riser 2.3	Main Branch	790	2,263	412	15
Riser 2.4	Main Branch	790	1,131	206	15
Riser 2 Floor (typ.)	Branch	600	1131	271	200

Active Chilled Beams

Chilled beams are effective induction based air side HVAC components designed to cool or heat large spaces. Chilled beams lead to lowered monthly utility use as the local chilled beam units are more effective at cooling/heating a space than corresponding VAV solutions and when coupled with a DOAS unit require less supply air, saving fan energy. Active chilled beams were selected to be coupled directly to the DOAS's supply air to drive convection during heating periods and serve as a well-suited solution to the large solar load driven perimeter zones of 201 Rouse; this efficiency is due to the ACB's high water to air side cooling ration with the primary air. To satisfy the latent loads of the space the DOAS is already supplying dehumidified "cold" primary air directly to the active chilled beams.

The first step to specifying ACBs for use is to discern the ventilation requirement to keep the latent load of the space below set points as condensation in the ACBs could be an issue. Table 16 below shows the sensible, latent and heating loads of the two zones in 201 Rouse while Equation 5 details the ventilation requirements for both the WNW and SE zones.

Table 16: Zone Loads and Air Requirements

Space	Qsen	Qlat	Qh	Vreq	Vlat
SE	277 kBtu/hr	11.4 kBtu/hr	60.1 kBtu/hr	1107 CFM	1132 CFM
WNW	244 kBtu/hr	7.45 kBtu/hr	64.1 kBtu/hr	924 CFm	750 CFM

Equation 5:Ventilation Requirements for Latent Load

$$V_{lat,SE} = \frac{Q_{lat,SE}}{0.68 \times \Delta W} = \frac{11.4 \text{ kBtu/hr}}{0.68 \times (70.5 - 56)\text{gr/lb}} = 1132 \text{ CFM For SE Zone}$$

$$V_{lat,WNW} = \frac{Q_{lat,WNW}}{0.68 \times \Delta W} = \frac{7.45 \text{ kBtu/hr}}{0.68 \times (70.5 - 56)\text{gr/lb}} = 750 \text{ CFM For WNW Zone}$$

For the Southeast Zone the ventilation requirement to meet the zone's latent load is above the ASHRAE ventilation air requirement so 1132 CFM will be used to size the DOAS and the selected ACBs. In the West North West Zone the required airflow to meet the latent load of the space is below the ventilation requirement so the ASHRAE ventilation requirement of 924 CFM will be used in sizing.

The active chilled beams have to also meet the sensible cooling and heating capacity of the 201 Rouse spaces also. Due to the "cold" air delivery of the DOAS system there is sensible heating capacity in the air delivered, to calculate the sensible capacity needed in the ACB the cooling capacity of the primary air (Q_{pr}) is subtracted from the peak zone sensible cooling requirement.

Table 17: Zone Requirements for ACB Selection

Space	Qsen	Qpr	Qcw	Qh	V
SE	277 kBtu/hr	120.4 kBtu/hr	106.6 kBtu/hr	60.1 kBtu/hr	1132 CFM
WNW	244 kBtu/hr	98.5 kBtu/hr	145.5 kBtu/hr	64.1 kBtu/hr	925 CFM

To meet these load and and airflow requirements a 8ft active chilled beam from Trox was selected;

the Trox DID632-HC, see Appendix C for cut sheet and unit selection. The active chilled beams will be connected in a four pipe system with the geothermal heat pumps so that different ACBs and zones can cool and heat at the same time as this occurs with the large solar loads in the perimeter regions of 201 Rouse. Table 18 below details the capabilities of this ACB and details the required quantities for the zones of 201 Rouse (shown in a sample layout in Figure 12).

Table 18: Active Chilled Beam Capabilities and Utilization in 201 Rouse Zones

Selected ACB	V	Qcw	Qh	GPM	Head Loss
8 ft DID632 Z Nozzle	50 CFM	4,305 Btu/hr	7,803 Btu/hr	1	5.8 ft H20
Space	**# ACBs**	**Airflow**	**Sensible Cooling**	**Heating**	**GPM**
SE	26	1,300 CFM	112.3 kBtu/hr	202 kBtu/hr	26
WNW	34	1,700 CFM	146 kBtu/hr	265 kBtu/hr	34
Total	60	2,950 CFM	258.3 kBtu/hr	467 kBtu/hr	60

To effectively condition the space and avoid any occupant uncomfortability the active chilled beams have to be spaced to according to the linear throw capabilities at 50 fpm; which for the selected ACBs is 7 feet. The layout detailed in Figure 12 is a sample placement layout that meets all the linear throw limitations and space cooling, the layout isn't final or intended for use as the interior spaces are not yet designed but the ACB and DOAS setup is flexible enough to accommodate any future occupancy changed in their layout.

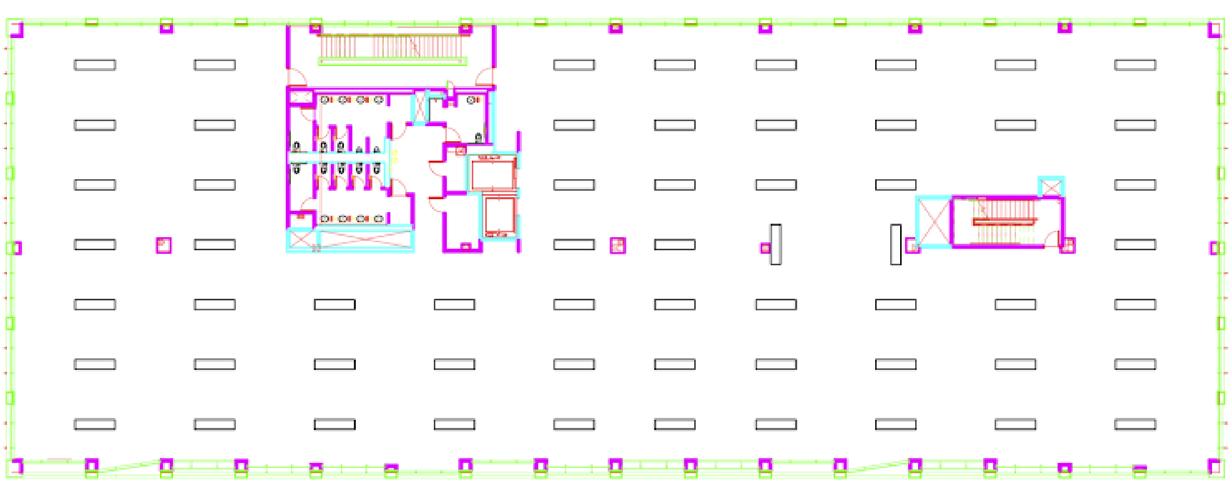


Figure 12:Sample Layout of Active Chilled Beams in 201 Rouse Office Space

Sizing for the four pipe hot and chilled water used by the DOAS, heat pumps, and active chilled beams is driven by the flow requirements of the ACBs and the total head loss of all the piping/components. The 240 active chilled beams specified in 201 Rouse each require 1 GPM while the heat pumps require a flow of 50 GPM which at that flow is enough to supply all the branches of the ACBs in the building. The approximate longest run of pipe in the building's four pipe system plus the head loss of the components accounts to ~25 ft. H_2O of head loss. There will have to be redundant pumps size to this capacity to meet the hot and chilled water loops of the building side water loops. Figure C.2 details the pump selection and curve for the hot and chilled loop pumps.

Energy, Cost, and LEED Comparison

Building the Energy Model

The aforementioned mechanical redesign was wholly comprehensive as it removed and replaced all the major components of 201 Rouse's HVAC system. Each component was iteratively designed and sized together to ensure that the system meets all the load, ventilation, and comfort requirements of the office spaces. To simulate the energy performance of this new HVAC system eQUEST was to be used as it was the platform upon which the initial baseline simulation was performed. However with the complexity of the system designed to be installed in 201 Rouse this was looking to be unlikely the case; few of the modeling software out there (Trane Trace, IES, EnergyPlus, eQUEST) are full featured to all the components involved: active chilled beams, water to water heat pumps, ground couple, and dedicated outdoor air system. Therefore a creative solution had to be made to test the equipment specified and also get feedback about energy use. To this end two eQUEST models were created one to get an accurate idea about the energy use and another to check that the equipment met the thermal loads of the building.

The model to simulate energy performance of a similar system in eQUEST a ground coupled water to air HVAC was modeled. To get the performance as close to the equipment specified and real world conditions calculated in the sections above the ground loop and pumps were sized accordingly to the Pumps and Well Sizing sections while the water to air heat pumps were sized by the thermal performance and in/out temperatures of the water to water heat pumps specified in Heat Pumps. The major difference between this model and the actual specified system is the use of water to air heat pumps so to get an accurate idea of energy use the fan supplying outside energy recovered air was sized to that of the DOAS unit. Due to this the model was never able to reach the required airflow to cooling the zones with the water to air heat pumps, yet it does provide a reasonable simulation of the intended design system as the DOAS unit would be running close to its full flow capacity during occupied hours. For more information on its results see Energy Performance.

On the other hand, eQUEST does have powered induction units as one of its airside modules. These powered induction units are the active chilled beams that are specified to provide sensible cooling and heating to the spaces of 201 Rouse. However in eQUEST these induction units cannot be hooked up to the hot and chilled water loops of a ground coupled heat pump, as such they have to be connected to library created CHW and HW lines created by cooling towers and boilers respectively. While not an accurate indication of energy performance gained by the active chilled beams this model would allow the testing of their ability to adequately condition the space. The model found that the specified capacity of cooling and heating (including the DOAS unit's capacity) was able to meet the heating requirements of the building 100% of the time and the zones were only out of their cooling range a few hours a year. All this is well within the acceptable standards for an office building. Also of note is that this ACB system was more energy efficient alone than the initially specified packaged unit and VAV; though recent work by ASHRAE is showing that when utilized correctly VAV and packaged units are both a cheaper and less energy intensive option, though that study focused solely on San Francisco (Stein & Taylor).

Energy Performance

The geothermal and water to air heat pump model of 201 Rouse was used to simulate its energy performance. Figure 13 below details the monthly consumption of 201 Rouse with a redesigned mechanical system that includes DOAS, ground loops, and active chilled beams.

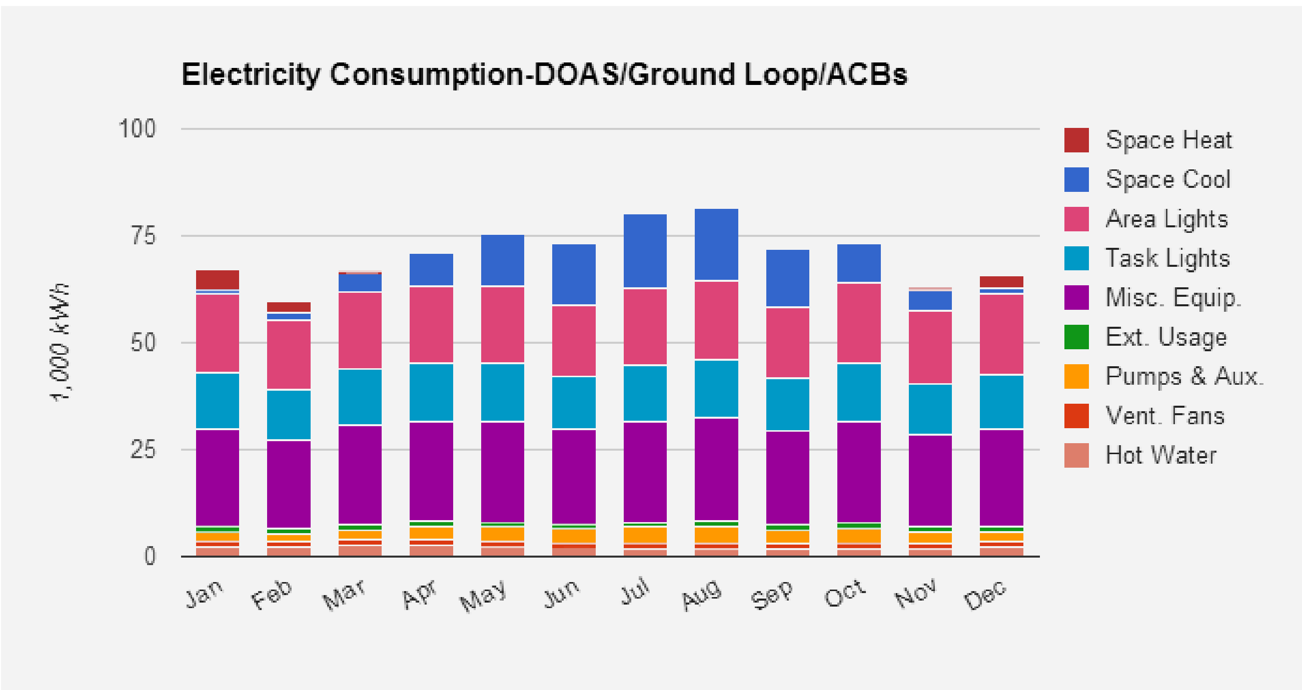


Figure 13: Energy Performance of Redesigned 201 Rouse

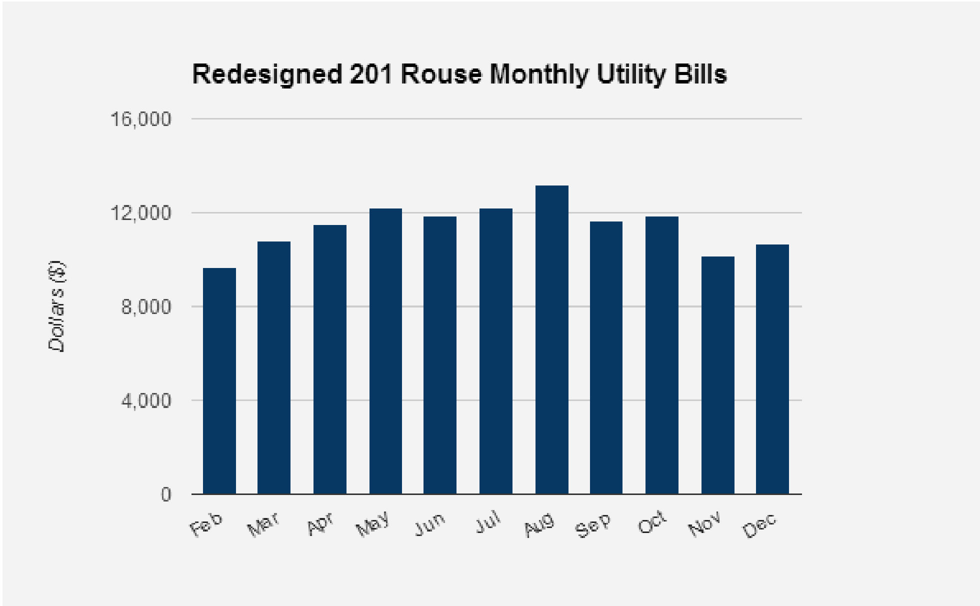


Figure 14: Monthly Costs of Redesign

Table 19: EUI of Initial, Redesign and Benchmark

Building	Site EUI (kBtu/sqft)	Source EUI (kBtu/sqft)	Performance Gain Over Benchmark	Performance Gain over Initial
201 Rouse Initial	46.4	139.2	31% Site, 6% Source	-
201 Rouse Redesigned	35.2	105.6	48% Over Site, 28% Source	24% Site, 24% Source
CBECS National Average	67.3	148.1	-	-

Energy Comparison

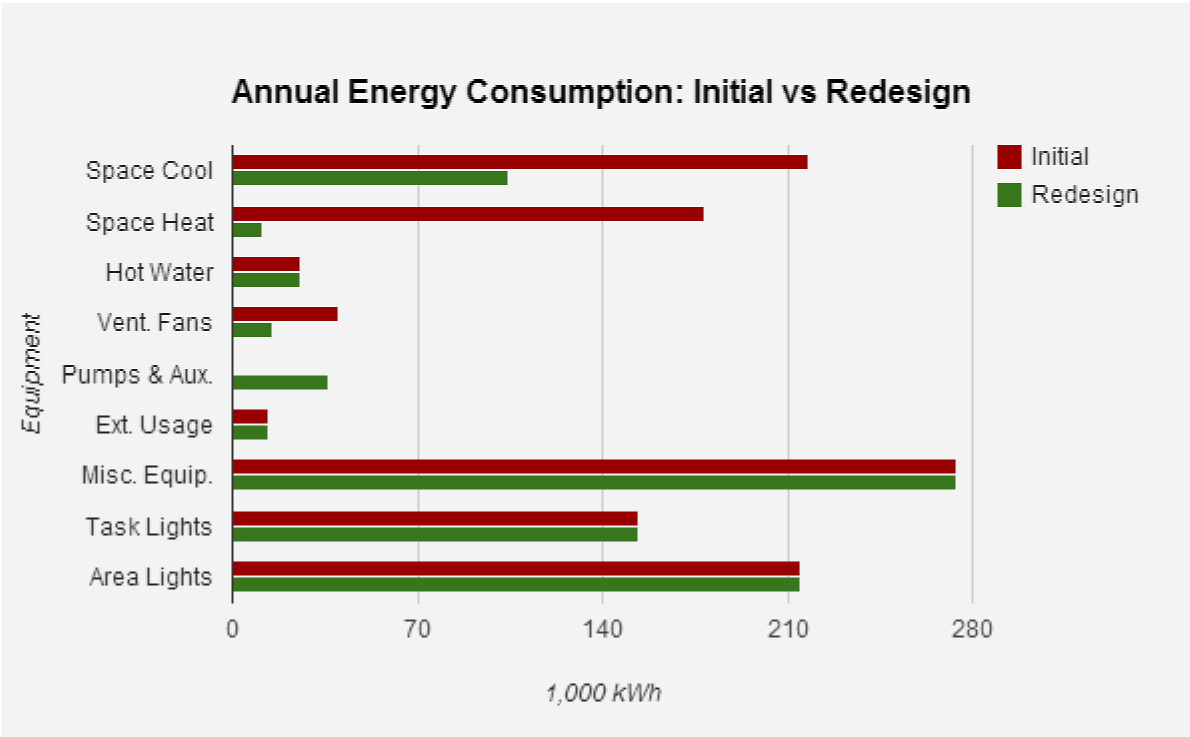


Figure 15: Total Energy Use Initial Vs. Redesign

New System Cost

Using a combination of RSMeans assemblies and detailed data the equipment specified previously in the mechanical depth section was priced. Table 20 below details all the components involved the unit costs and the subtotal for that component. All costs are overhead and profit calculated to account for actual subcontractor bids. The total cost for the system was found to be $2.19 million dollars which compared to the cost of the existing system (Table 21) is $680,000 more or approximately 3.1%

Table 20: Component and Total Costs of Redesigned Mechanical System.

Component	Unit Cost	Unit	Units	Cost
Heat Pumps	$41,387	each	13	$538,031
Geothermal Wells and Headers	$16	per foot	51200	$819,200
DOAS	$209,958	each	1	$209,958
Ducts	$12.82	linear foot	2800	$35,896.00
Return Grills	$30.02	each	120	$3,602.40
Building Side Pumps	$10,163	each	2	$20,326
Well Field Pumps	$21,050	each	2	$42,100
Core HVAC Unit	$14.90	sqft	5312	$79,148.80
Active Chilled Beams	$1,404	each	240	$336,960
Piping	$16.35	linear foot	6600	$107,910.00
Total				**$2,193,132**

Table 21: Cost Differential between Initial and Revised

Building	Mechanical Systems Cost	Total Building Cost	Mechanical %
201 Rouse Initial	$1,513,000	$19,402,000	7.80%
201 Rouse Thesis Revised	$2,193,132	$20,082,132	10.92%
Difference	-	**$680,132**	**3.12%**

Payback Period

As can be seen previously in Figure 15 the new HVAC system in 201 Rouse saves substantial amounts of money couple with the fact that it is more energy efficient. With a total increase in mechanical system costs of $680,132 over the initially specified AHU and VAVs and an average monthly savings of $3,644 compared to the initial it will take 187 months or fifteen and half years to pay back the extra cost of the ground coupled, DOAs, chilled beam system.

Revised LEED Analysis

The project team designing and building 201 Rouse is seeking LEED accreditation for their “green” building. Under the initial building designs the project was firmly in the Silver rating (see LEED) which meets the minimum project goals, but the owner, Liberty Property Trust, would like to see a "Gold" rating. The systems specified for redesign contribute to the LEED rating in the Energy & Atmosphere and Indoor Air quality area. In the Energy & Atmosphere category the geothermal system confirms the two points for green energy in EA credit 6. Additionally in EA the holistic HVAC system earns 13 of the 21 points in Credit 1 for its increase in energy efficiency and optimized performance. Finally in the Indoor Air Quality section the DOAS unit earns another LEED point for its increase of outside air ventilation and retains all the points previously allocated to monitoring and materials. With the addition of these 8 points due to the revisions to the initial HVAC equipment 201 Rouse will firmly fall above the 60 point threshold of the "Gold" accreditation.

Breath Analysis: Electrical

201 Rouse is served by dual 600 amp three phase utility connections to a 1,500 KVA wye transformer; service is provided by PECO. The building's electrical distribution system is headlined by a 277/480 Volt 3 phase main distribution panel with a 2,000 amp capacity. The current system is setup to allow for further development of the office and retail spaces, with capacity and breakers defined loosely based upon common needs of these tenants. By potentially decreasing the electrical load of the HVAC equipment the main distribution equipment may be able to be downsized or just provide additional capacity for the future growth of the tenant spaces.

In the mechanical depth the currently specified HVAC system was replaced; the pertinent equipment included two rooftop air handling units and an unknown number of variable air volume units. The equipment, detailed in Table 22, are connected to the main distribution bus, the air handling units (AHUs) are connected directly while the VAV boxes would be connected to a panel for each floor. As the VAV's are not specified in the drawings assumptions were made as to their number based upon required zone heating and the flow capacities set by the AHUs.

Table 22:Initial HVAC Equipment Electrical Specifications

Equipment	Quantity	Full Load Amps	MCA	Volts	Phase	KW
Rooftop Air Handling Unit	2	369.2	400	460	3	294.2
VAV-A	8	10.83032491	15	277	1	3
VAV-B	8	21.66064982	25	277	1	6
VAV-C	8	36.10108303	40	277	1	10
VAV-D	8	45.12635379	50	277	1	12.5
Total		**1648.147292**	**1840**			**840.4**

As detailed previously in Mechanical Depth the new 201 Rouse HVAC system consists of ground coupled heat pumps, a dedicated outside air system, and active chilled beams. To support this new system the electrical components detailed in Table 23 below are needed. The new equipment are high voltage, 277/480, and will attach via a panelboard to the main distribution panel.

Table 23: Revised HVAC Equipment Electrical Specification

Equipment	Quantity	Full Load Amps	MCA	Voltage	Phase	KW
Well Field Pump	2	23.3	30	460	1	18.6
Heat Pump	13	33.4	40	460	3	18.9
Hot/Chilled Water Pump	4	4.04	15	230	1	1.12
DOAS Unit	1	37.8	50	460	3	37.8

All of this new equipment yields 47 single pole circuits. To accommodate these new circuits a new panelboard will have to be installed for the rooftop DOAS unit and the 13 water to water heat pumps, while the pumps will be kept in the first floor mechanical room and their circuits attached to the current HH1 panelboard (seen in Appendix D) which has enough spare capacity for the mechanical room pumps. The panelboard for the rooftop HVAC equipment will be placed in the 4th floor's electrical closet. This layout was selected as it provided the shortest amount of wiring necessary to connect the new equipment.

The revised panelboard HH1 can be seen in Appendix Figure D.2 and its location in the building in Appendix Figure D.3. The remaining HVAC equipment, DOAS unit and heat pumps, were added to the new panelboard HVH1 that is to be places in the 4th floors electrical room (see Appendix D.5). Panelboard HVH1 is specified in Appendix D.4. Table 24 below details the wire and conduit configurations of the newly specified HVAC equipment.

Table 24: Wire and Conduit Specification for New Equipment and Panelboard

Equipment	Quantity	Amps	Wire Type	Wires	Wire Size	Ground Size	Conduit
Well Field Pump	2	23.3	THHW	3 Current 1 Neutral 1 Ground	10 AWG	14 AWG	1" EMT
Heat Pump	13	22.73	THHW	3 Current 1 Neutral 1 Ground	10 AWG	14 AWG	(3) 1 1/2" EMT
Hot/Chilled Water Pump	4	4.04	THHW	1 Current 1 Neutral 1 Ground	14 AWG	14 AWG	1" EMT
DOAS Unit	1	37.8	THHW	3 Current 1 Neutral 1 Ground	8 AWG	12 AWG	3/4" EMT
Panelboard HVH1	1	350	THHW	3 Current 1 Neutral 1 Ground	(2) 2/0 AWG	4 AWG	2" EMT

With all the electrical requirements of the new equipment specified there will not be much in the terms of cost savings as the specified panelboard replaces one that would have been the distribution for the variable air volume units while only removing the two 400 amp direct connects that were used by the rooftop AHUs. There will be savings in terms of wiring for the VAVs vs the active chilled beams but this is incalculable as the quantity of VAVs is unspecified.

Breath Analysis: Rooftop Structural Load

201 Rouse is a curtain wall on steel construction, with the superstructure of structural steel, a substructure of poured concrete and a foundation of concrete caps on wooden piles. With the building going up in South Philadelphia there are few structural considerations that went into the design of the building apart from cost savings and the soil support (required the cap and pile foundation). There are some particular structural occurrences at the roof that may be part of the Environetics's modus operandi; such examples are the use of beams instead of joists between column lines on the roof just to support the stub columns of the rooftop architectural screen. As with everything in engineering there are repercussions to every design change and consideration.

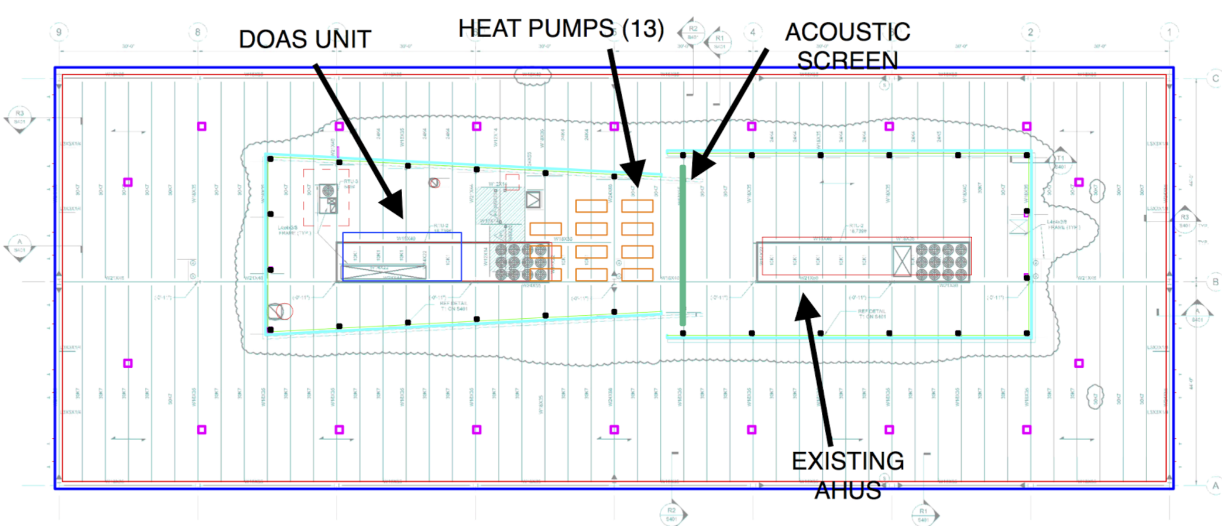
As outlined in the _Mechanical Depth section there was a massive overhaul to 201 Rouse's heating, ventilation and air conditioning system. With the replacement of the rooftop air handling units with a ground coupled geothermal heat pump system not only did this change the building energy performance, and require adjustments to the electrical distribution but will also have changes to the mechanical equipment's effect upon roof loads. The existing and new equipment (seen in Table 25) differ in: weight, lost 8,430 lbs, area, saved 211 ft^2, and reduced the potential vibrations by lowering fan power and compressor size.

Table 25: Removed and Potential Rooftop HVAC Equipment

Equipment	Length (in.)	Height (in.)	Width (in.)	Weight (lbs)
RTU 1	523	97	99	18,983
RTU 2	523	97	99	18,983
DOAS	310	102	126	13,650
Water to Water Heat Pumps (13)	82	30	31	1,222

With all the above considerations to be taken into account (weight, area, and vibrations) the rooftop structural system of joist and steel deck are analyzed to meet the different load conditions and for any possible downsizing for material savings. Figure 16 below shows the layout of the new HVAC equipment superimposed over the existing conditions. In addition to removing the two AHUs the 13' acoustical screen on the east side will be removed as the equipment there (piping and exhaust fans) is visually below the 1'8" parapet.

Figure 16:Layout of New Rooftop HVAC Equipment



The first major change to the roof load was the removal of AHU #2 and the acoustical screen on the east side of the building. The removal of these components required the reanalysis of the supportive beams and joists; see Figures E.2 and E.3 for the structural calculations. This analysis yielded the removal of the AHU supporting beams and the mid span beams for the acoustical screen and the sizing of a 28K7 joist to be used between lines 1-4 (the now unloaded portion of the roof) and a beam reduction from W21x50 to W21x48 in row B between 2 and 3.

On the west end of the roof the plenum roof curb for AHU #1 was resized to accommodate the new DOAS unit. The sizes of these members were kept the same, just their dimensions were changed. The next area to analyze was the region between columns 4 and 6 that hold the new heat pumps. Joist calculations yielded a 30k7 to be acceptable for the loads. Within the DOAS curb the 10k1s previously specified for AHU1 will suffice and the 24k4s that spanned between the curb and column C. The curb, see Figure E.4, serves multiple purposes of: isolating vibrations, creating the plenum space, and distributing the weight of the DOAS unit. Figure E.5 in Appendix E has the final structural roof plan for 201 Rouse.

In the end, by removing AHU-2 and its corresponding structural supporting components the eastern half of the roof was able to be simplified and have its joist members reduced. At the other end of the roof by replacing the initial AHU-1 with the lighter and smaller DOAS unit the already prescribed joists and beams were able to support the 13 heat pumps. By reducing the area occupied by HVAC equipment the 13' high acoustical screen was able to be shortened and the supporting beams converted to joists. In all by reducing the weight and area of the rooftop HVAC requirements the structural roof members were downsized and simplified.

Conclusion

Initial energy analyses and the current LEED scorecard of 201 Rouse displayed that the whole building's energy performance was already ahead of national averages and on track for LEED Silver certification. Yet with rising energy costs, especially electricity, and the property value increases of sustainable buildings and their LEED certifications better building performance is always a key goal.

The prescribed mechanical solution for 201 Rouse is an array of ground coupled water to water heat pumps (**GCHP**) connected to a dedicated outdoor air (**DOAS**) and active chilled beam (**ACB**) combination.

These systems end up costing **$680,000 more** than the conventional air handling units and variable air volume boxes of the initial mechanical design.

The redesigned mechanical system reduces the electrical consumption for cooling by **52%**, heating by **90%**, fan energy by **62%** and only at a pump energy usage of 36,000 kWh annually. The combined savings of these systems leads to an average monthly utility cost savings of **$3,500**.

At a savings rate of $3,500 it would take **15.5 years** at the current electrical rates to pay back the additional cost of the GCHP/DOAS/ACB mechanical system redesign.

Additionally, with its green power and **24% reduction of EUI** the redesigned mechanical system firmly places 201 Rouse in a position to **become LEED Gold Certified**.

The building systems affected by this comprehensive change to the mechanical system, electrical and structural, yield only minor cost savings and no engineering issues when reanalyzed.

Overall the **revised mechanical solution is recommended** as its increases the building performance significantly, achieves LEED Gold, increases property value, and pays for itself during the effective life of all its components.

Acknowledgements

The following should be acknowledged for their help and support of this senior thesis.

Liberty Property Trust

- Brian Berson

Turner Construction

- Maria Williams
- Bill Swanson

In Posse

- Aaron Dahlstrom

Penn State University

- Dr. Laura Miller
- Prof. Kevin Parfitt

Peers

- Kevin Martyn
- John "Jack" Risser
- Nicholas Stucklak
- Erin Miller

Josh Wentz

Dr. Jelena Srebric

Appendix

Appendix A: Ground Coupled Heat Pump

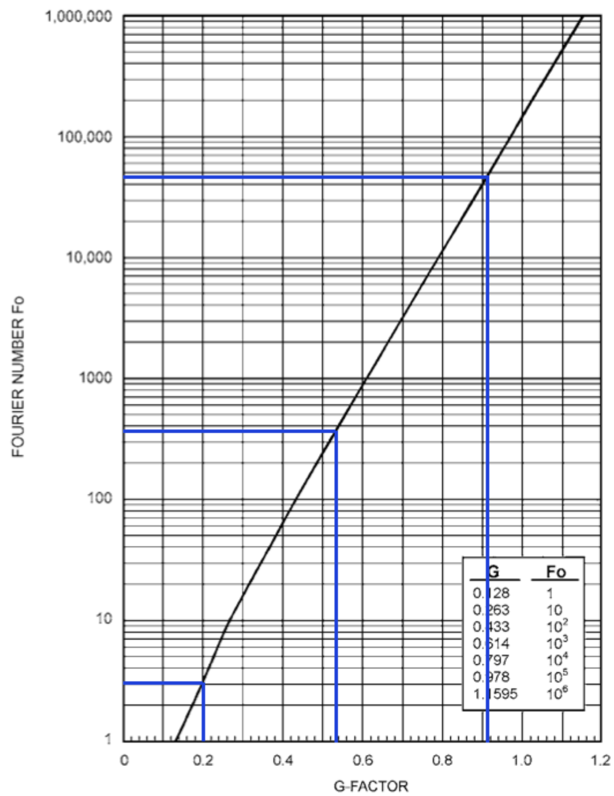
Figure A.1: Ingersoll and Zobel Bore Length Equation Variables

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 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), ft·h·°F/Btu
R_{gd} = effective thermal resistance of ground (peak daily pulse: 1 h minimum, 4 to 6 h recommended), 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 = 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 = system power input at design cooling load, W
W_h = system power input at design heating load, W

Figure A.2: Short-Circuit Heat Loss Factor

	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 A.3: Fourier/G-Factor Graph for Ground Thermal Resistance



G	Fo
0.128	1
0.263	10
0.433	10^2
0.614	10^3
0.797	10^4
0.978	10^5
1.1595	10^6

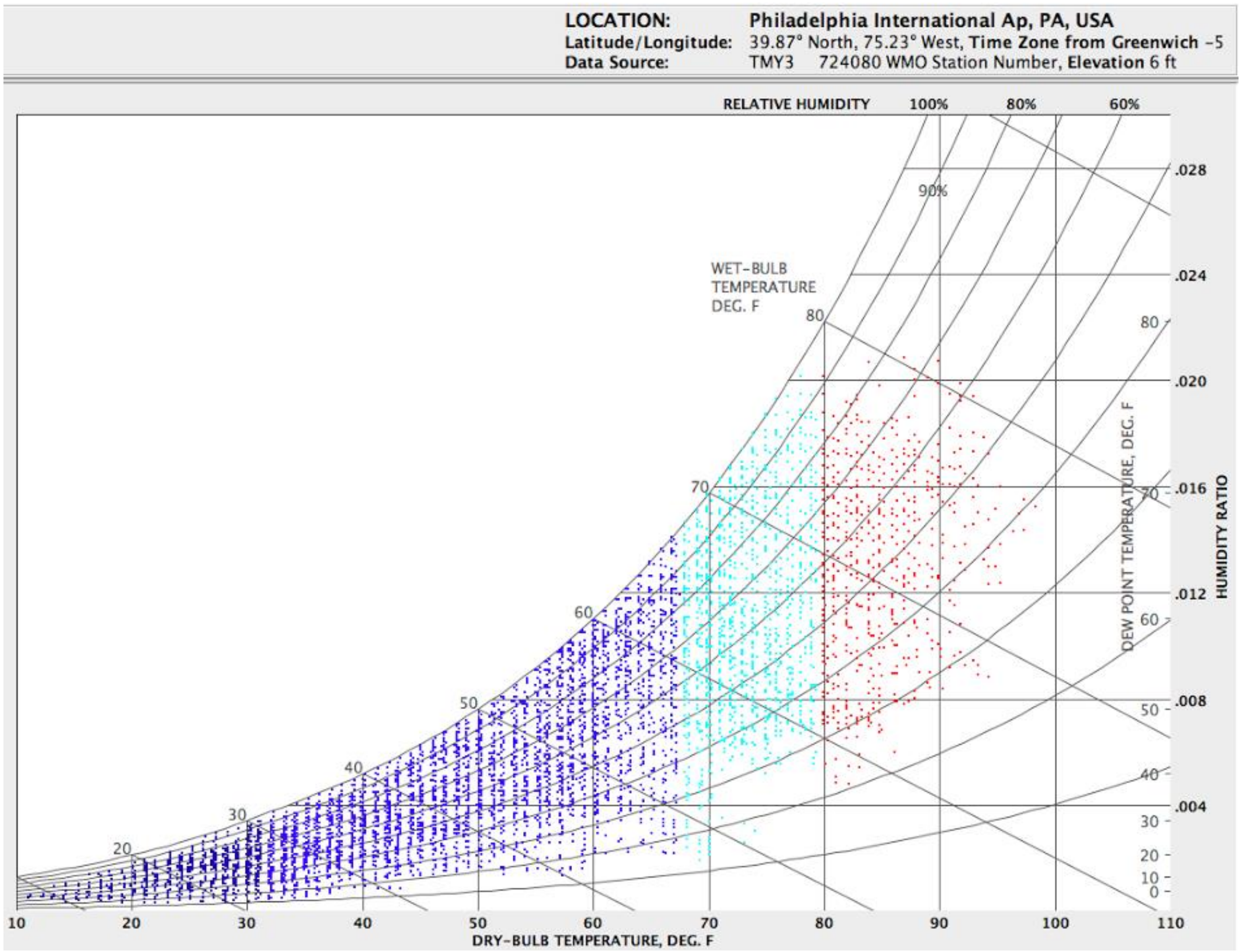
Fig. 15 Fourier/G-Factor Graph for Ground Thermal Resistance
(Kavanaugh and Rafferty 1997)

Table A.1: Head Loss Calculation of 201 Rouse Well Field

Section	Pipe Size	Flow	Pressure Loss	System	Equivalent	No.	Equivalent Length (ft)	Section Pressure Loss
1	6	750	6.445					
				Straight Pipe	1	20	20	
				90 deg Elbow	8.9	1	8.9	
				Straight Pipe	1	55	55	
				90 deg Elbow	8.9	1	8.9	
				Straight Pipe	1	130	130	
				90 deg Elbow	8.9	1	8.9	
				Tee Fitting	3.8	1	3.8	
				Sum			235.5	15.177975
2.1	6	656.25	5.035					
				Straight Pipe	1	20	20	
				Tee Fitting	3.8	1	3.8	
				Sum			23.8	1.19833
2.2	6	562.5	3.777					
				Straight Pipe	1	20	20	
				Tee Fitting	3.8	1	3.8	
				Sum			23.8	0.898926
2.3	6	468.75	2.69					
				Straight Pipe	1	20	20	
				Tee Fitting	3.8	1	3.8	
				Sum			23.8	0.64022
2.4	6	375	1.785					
				Straight Pipe	1	20	20	
				Tee Fitting	3.8	1	3.8	
				Sum			23.8	0.42483
2.5	6	281.25	1.047					
				Straight Pipe	1	20	20	
				Tee Fitting	3.8	1	3.8	
				Sum			23.8	0.249186
2.6	6	187.5	0.495					
				Straight Pipe	1	20	20	
				Tee Fitting	3.8	1	3.8	
				Sum			23.8	0.11781
2.7	6	93.75	0.137					
				Straight Pipe	1	20	20	
				90 Deg Elbow	8.9	1	8.9	
				Sum			28.9	0.039593
							Total	18.74687
Branches								
Section	Pipe Size	Flow	Pressure Loss	System	Equivalent	No.	Equivalent Length (ft)	Section Pressure Loss
3.1.1	2	93.75	17.00740513					
				Straight Pipe	1	10	10	
				Tee Fitting	2.3	1	2.3	
						Sum	12.3	2.091910831
3.1.2	2	87.890625	15.09137674					
				Straight Pipe	1	20	20	
				Tee Fitting	2.3	1	2.3	
						Sum	22.3	3.365377013
3.1.3	2	82.03125	13.28118944					
				Straight Pipe	1	20	20	
				Tee Fitting	2.3	1	2.3	
						Sum	22.3	2.961705244
3.1.4	2	76.171875	11.57793048					
				Straight Pipe	1	20	20	
				Tee Fitting	2.3	1	2.3	
						Sum	22.3	2.581878498
3.1.5	2	70.3125	9.982780382					
				Straight Pipe	1	20	20	
				Tee Fitting	2.3	1	2.3	
						Sum	22.3	2.226160025
3.1.6	2	64.453125	8.497029032					
				Straight Pipe	1	20	20	
				Tee Fitting	2.3	1	2.3	
						Sum	22.3	1.894837474
3.1.7	2	58.59375	7.122096425					

Appendix B: Dedicated Outdoor Air System

Figure B.1: Philadelphia Climate Psychometric Chart



Appendix C: Active Chilled Beams

Figure C.1: Trox Selection Table For ACB

Quick selection table

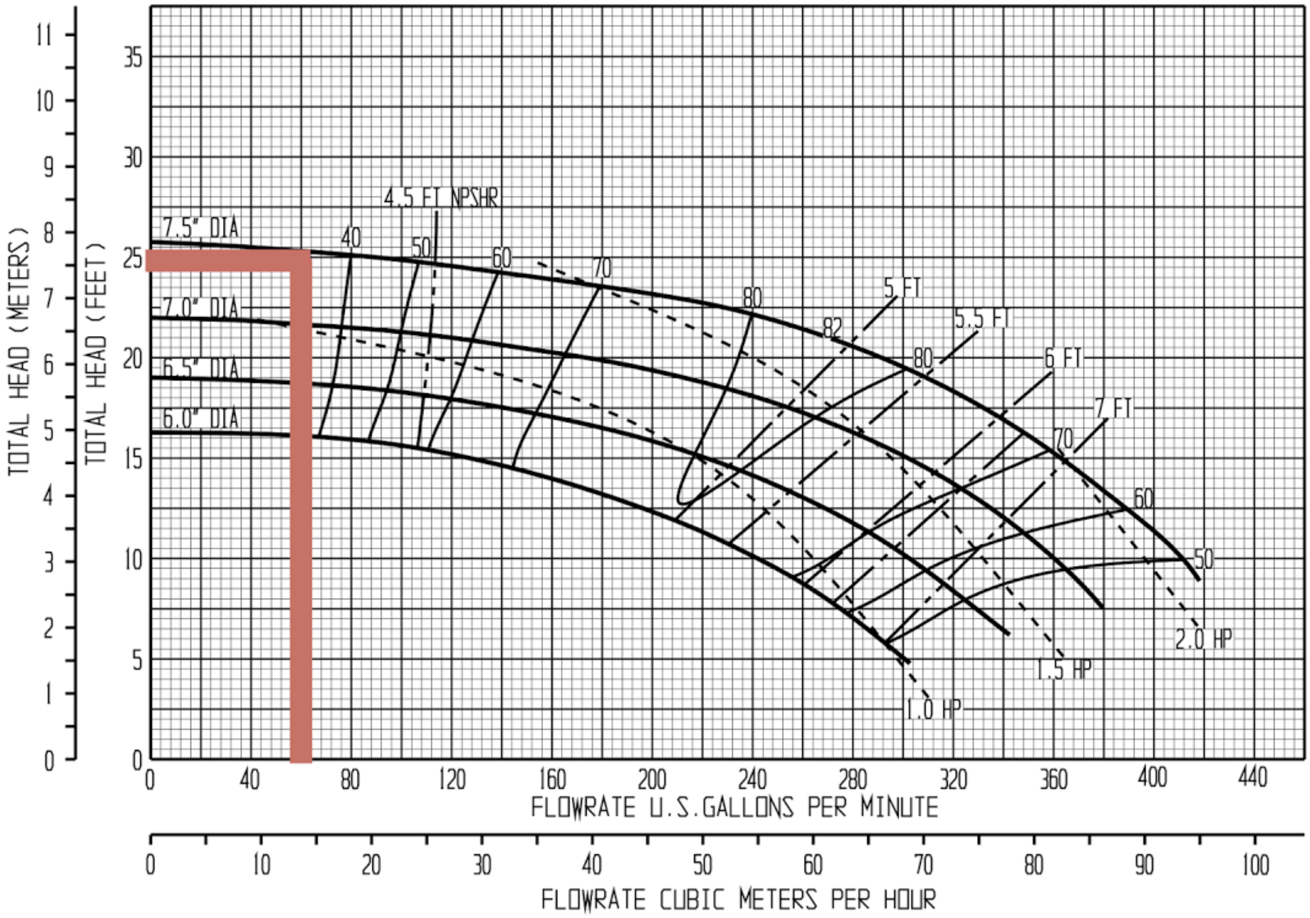
Reference Values - Cooling				Reference Values - Heating			
t_R	75 °F	t_{CWS}	57 °F	t_R	70 °F	t_{HWS}	120 °F
t_{Pr}	55 °F	$\dot{V}_{CW}$	1.0 GPM	t_{Pr}	55 °F		

Active Length	Nozzle Type	Primary Air		Cooling Two-pipe system			Cooling Four-pipe system			Heating Four-pipe system			Isothermal Throw[6]	NC[7]
		$\dot{V}_{Pr}$	Δp_t	$\dot{Q}_{tot}$[1]	$\dot{Q}_{CW}$[2]	Δp_w[3]	$\dot{Q}_{tot}$[1]	$\dot{Q}_{CW}$[2]	Δp_w[3]	$\dot{Q}_{NET}$[4]	$\dot{V}_{HW}$[5]	Δp_w[3]		
ft		CFM	in. H_2O	Btu/h	Btu/h	ft. H_2O	Btu/h	Btu/h	ft. H_2O	Btu/h	GPM	ft. H_2O	ft.	
		20	0.36	2,685	2,250		2,504	2,068		3,083	0.40	0.2	3-4-6	18
	Z	25	0.56	3,197	2,653		2,609	2,152		3,809	0.45	0.2	3-5-7	20
		30	0.81	3,621	2,968		3,392	2,739		4,611	0.55	0.3	4-5-8	23
		25	0.25	2,515	1,971		2,354	1,810		2,897	0.50	0.3	3-4-6	16
	M	35	0.48	3,398	2,636		3,191	2,429		4,104	0.60	0.4	3-5-7	21
		45	0.80	4,078	3,098		3,841	2,861		5,283	0.85	0.7	4-5-8	24
		35	0.23	2,828	2,066		2,660	1,898		3,303	0.75	0.6	3-4-6	17
	J	50	0.46	3,857	2,768		3,641	2,552		4,769	1.10	1.2	4-5-8	21
4		65	0.78	4,662	3,247	2.1	4,416	3,001	3.1	5,829	1.50	2.3	5-6-10	25
		45	0.22	3,249	2,270		3,067	2,087		3,817	1.15	1.4	3-4-6	18
	G	65	0.46	4,384	2,979		4,164	2,749		5,204	1.50	2.3	4-6-9	22
		85	0.79	5,307	3,457		5,049	3,198		5,989	1.50	2.3	5-7-12	27
		65	0.23	4022	2,606		3,816	2,401		4,354	1.50	2.3	4-5-7	19
	H	90	0.45	5093	3,134		4,854	2,895		5,154	1.50	2.3	5-6-10	23
		115	0.73	6011	3,508		5,750	3,246		5,628	1.50	2.3	6-8-14	26
		80	0.22	4,465	2,723		4,252	2,510		4,372	1.50	2.3	4-5-8	19
	U	110	0.42	5,587	3,192		5,344	2,949		4,962	1.50	2.3	5-7-12	23
		140	0.68	6,576	3,528		6,313	3,265		5,267	1.50	2.3	6-8-15	30
		25	0.24	3,257	2,712		3,044	2,500		3,899	0.45	0.3	3-4-5	16
	Z	35	0.48	4,339	3,547		4,045	3,283		5,495	0.55	0.4	3-4-6	21
		45	0.79	5,093	4,113		4,798	3,818		7,081	0.75	0.8	4-5-8	24
		45	0.35	4,274	3,294		4,025	3,045		5,245	0.65	0.6	3-4-6	21
	M	60	0.63	5,313	4,007		5,024	3,718		6,997	0.90	1.2	4-5-7	27
		75	0.98	6,147	4,515		5,833	4,200		8,778	1.50	3.2	4-6-9	34
		55	0.25	4,256	3,058		4,021	2,824		5,221	1.00	1.4	3-4-6	19
	J	75	0.46	5,489	3,856		5,208	3,575		7,129	1.50	3.2	4-5-8	23
		95	0.74	6,478	4,410		6,168	4,100		8,183	1.50	3.2	4-6-10	29
6		85	0.36	5,647	3,796	3.0	5,369	3,518	4.4	6,817	1.50	3.2	4-5-8	24
	G	105	0.55	6,585	4,300		6,281	3,995		7,739	1.50	3.2	4-6-10	30
		125	0.78	7,410	4,689		7,087	4,366		8,408	1.50	3.2	5-7-11	35
		100	0.23	5,878	3,701		5,606	3,429		6,340	1.50	3.2	4-5-8	19
	H	140	0.45	7,445	4,397		7,135	4,088		7,411	1.50	3.2	5-7-11	24
		180	0.75	8,792	4,874		8,461	4,542		7,988	1.50	3.2	6-8-14	27
		130	0.24	6,784	3,954		6,497	3,667		6,465	1.50	3.2	4-6-9	21
	U	180	0.47	8,472	4,554		8,156	4,237		7,156	1.50	3.2	5-7-13	25
		230	0.76	9,980	4,973		9,644	4,637		7,430	1.50	3.2	7-9-17	31
		35	0.27	4,360	3,507		4,020	3,330		5,337	0.60	0.6	3-4-5	18
	Z	50	0.55	5,714	4,626		5,394	4,305		7,803	0.70	0.9	3-5-7	23
		65	0.93	6,708	5,293		6,359	4,944		10,129	1.05	2.1	4-5-8	30
		60	0.34	5,446	4,140		5,150	3,844		7,032	0.80	1.2	3-4-6	21
	M	75	0.53	6,429	4,796		6,101	4,468		8,806	1.05	2.1	4-5-7	23
		90	0.76	7,247	5,288		6,898	4,939		10,569	1.50	4.3	4-6-8	28
		80	0.29	5,878	4,137		5,582	3,841		7,653	1.40	3.7	3-4-6	20
	J	105	0.49	7,222	4,936		6,888	4,602		9,383	1.50	4.3	4-5-8	24
		130	0.76	8,333	5,503		7,975	5,145		10,499	1.50	4.3	5-6-10	29
8		110	0.33	7,038	4,643	3.8	6,717	4,322	5.8	8,535	1.50	4.3	4-5-7	23
	G	140	0.53	8,359	5,311		8,009	4,961		9,810	1.50	4.3	4-6-10	29
		170	0.78	9,503	5,802		9,134	5,433		10,673	1.50	4.3	5-7-12	35
		140	0.26	7,790	4,742		7,464	4,416		8,299	1.50	4.3	4-5-8	21
	H	190	0.47	9,598	5,461		9,242	5,105		9,400	1.50	4.3	5-7-11	25
		240	0.76	11,186	5,961		10,812	5,587		9,975	1.50	4.3	6-8-14	31
		150	0.20	7,847	4,582		7,529	4,264		7,721	1.50	4.3	4-5-8	20
	U	220	0.42	10,350	5,424		9,859	5,069		8,805	1.50	4.3	5-7-12	27
		290	0.73	12,213	5,968		11,907	5,594		9,174	1.50	4.3	7-9-16	38

Refer to table continued on page 9 for performance notes...

8

Figure C.2: Pump Selection for Hot/Chilled Water Loops



Appendix D

Figure D.1: Initial HH1 Panelboard

PANEL	-	HH1	
FOR	-	COMMON AREA HVAC	
LOCATION	-	MAIN ELECTRICAL ROOM	
A.I.C.	-	25,000 A	
VOLTAGE -		277/ 480	
PHASE	-	3 PH-4W	
MAIN	-	225 A MLO	
MOUNTING-		SURFACE	

DESCRIPTION	LTG. VA	EQUIP. VA	HVAC VA	BKR. AMPS		BUS CONNECTION			BKR. AMPS		HVAC VA	EQUIP. VA	LTG. VA	DESCRIPTION
#EF-1 EXHAUST FAN			3,980	15	3	1	A	2	25	3	5,010			#CUH-C UNIT HEATER
						3	B	4	15	1	1,180			#FTU-A1 FAN TERMINAL UNIT
						5	C	6	15	1	1,180			#FTU-A2 FAN TERMINAL UNIT
#FTU-B FAN TERMINAL UNIT			10,180	20	3	7	A	8	15	1	1,180			#FTU-A3 FAN TERMINAL UNIT
						9	B	10	15	1				SPARE
						11	C	12	15	1				SPARE
#VAV-B1 VAV TERMINAL UNIT			6,000	15	3	13	A	14	20	1	3,000			#CUH-A1 UNIT HEATER
						15	B	16	20	1	3,000			#CUH-A2 UNIT HEATER
						17	C	18	20	1	3,000			#CUH-B UNIT HEATER
#UH-A1 UNIT HEATER			5,000	15	3	19	A	20	20	1				SPARE
						21	B	22	20	1				SPARE
						23	C	24	20	1				SPARE
#UH-A2 UNIT HEATER			5,000	15	3	25	A	26	20	1				SPARE
						27	B	28	20	1				SPARE
						29	C	30	20	1				SPARE
SPARE				15	3	31	A	32	20	1				SPARE
						33	B	34	20	1				SPARE
						35	C	36	20	1				SPARE
SPARE				15	3	37	A	38	60	3	10,880	18,860	0	PANEL "HP1" TRANSFORMER
						39	B	40						
						41	C	42						
TOTALS	0	0	30,160								28,430	18,860	0	TOTALS

LOAD DESCRIPTION	CONN. VA	DEMAND VA
LIGHTING	0	0
GENERAL POWER	18,860	9,430
HVAC EQUIPMENT	58,590	58,590
TOTAL	77,450	68,020
PERCENT LOADED	62%	55%

PANEL SCHEDULE
MULHERN CONSULTING ENGINEERS
AND ASSOCIATES, INC.
321 SOUTH YORK ROAD
HATBORO, PENNSYLVANIA 19040-3417
PHONE: 215-293-9900 / FAX: 215-293-9214
www.MulhernEngineers.com

PHASE VA	
A	25,817
B	25,817
C	25,817
TOTAL	77,450
ST.DEV.	0

Figure D.2: Revised Panelboard HH1

			PANEL:	HH1				VOLTAGE:	277/480			
			FOR:	COMMON HVAC AND PUMPS				PHASE:	3 PH-4W			
			LOCATION:	MAIN ELECTRICAL ROOM				MAIN:	225 A MLO			
			AIC:	25,000 A				MOUNTING:	SURFACE			
DESCRIPTION	LTG. VA	EQUIP. VA	HVAC VA	BREAKER AMPS	BUS			BREAKER	HVAC VA	EQUIP.	LTG. VA	DESCRIPTION
#EF-1 EXHAUST FAN			3,980	15	1	A	2	25	5,010			#CUH-C UNIT HEATER
					3	B	4	15	1,180			#FTU-A1 FAN TERMINAL
					5	C	6	15	1,180			#FTU-A2 FAN TERMINAL
#FTU-B TERMINAL UNIT			10,180	20	7	A	8	15	1,180			#FTU-A3 FAN TERMINAL
					9	B	10	15	1,120			CHW PUMP 1
					11	C	12	20	3,000			#CUH-C UNIT HEATER
#UH-A1 UNIT HEATER			5,000	15	13	A	14					SPARE
					15	B	16	20	3,000			#CUH-C UNIT HEATER
					17	C	18	20	3,000			#CUH-C UNIT HEATER
#UH-A2 UNIT HEATER			5,000	15	19	A	20					SPARE
					21	B	22					SPARE
					23	C	24					SPARE
HW PUMP 1			1,120	15	25	A	26					SPARE
HW PUMP 2			1,120	15	27	B	28					SPARE
CHW PUMP 2			1,120	15	29	C	30					SPARE
WELL FIELD PUMP 1			18,600	40	31	A	32					SPARE
					33	B	34					SPARE
					35	C	36					SPARE
WELL FIELD PUMP 2			18,600	40	37	A	38	60	10,880	18,860		PANEL "HP1" TRANSFORMER
					39	B	40					
					41	C	42					
Totals	0	0	64,720						29,550	18,860	0	Totals

LOAD DESCRIPTION	CONN.	DEMAND VA.
LIGHTING	0	0
GENERAL POWER	18,860	9,430
HVAC EQUIPMENT	94,270	94,270
TOTAL	113,130	103,700
PERCENT LOADED	90.50%	82.96%

PHASE VA	
A	37,677
B	36,787
C	38,667
TOTAL	113,130

Figure D.3: Location of Panelboard HH1

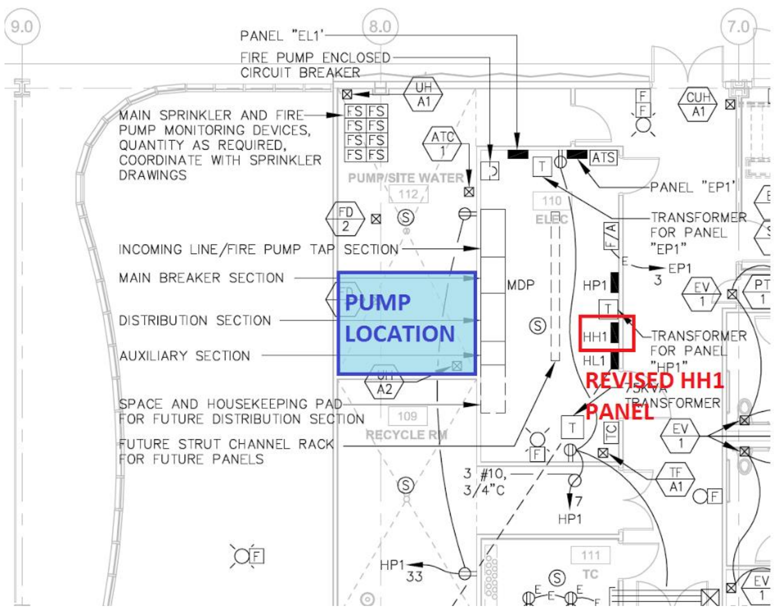


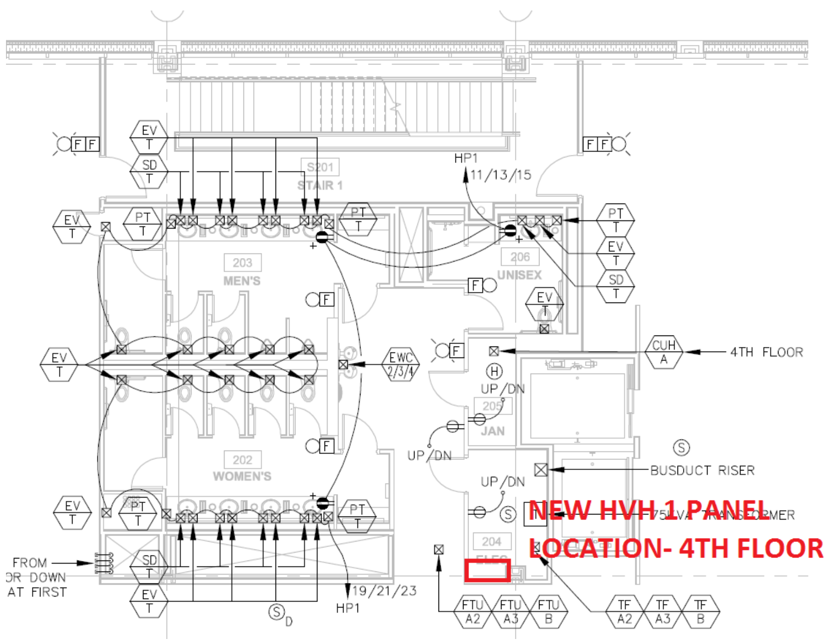
Figure D.4: HVH1 Panelboard

			PANEL:	HVH 1				VOLTAGE:	277/480			
			FOR:	DOAS AND HEAT PUMPS				PHASE:	3 PH-4W			
			LOCATION:	4TH FLOOR ELECTRICAL ROOM				MAIN:	350 A MLO			
			AIC:	25,000 A				MOUNTING:	SURFACE			
DESCRIPTION	LTG. VA	EQUIP. VA	HVAC VA	BREAKER AMPS	BUS CONNECTION			BREAKER AMPS	HVAC VA	EQUIP. VA	LTG. VA	DESCRIPTION
					1	A	2					
HP-1			18,600	30	3	B	4	30	18,600			HP-8
					5	C	6					
					7	A	8					
HP-2			18,600	30	9	B	10	30	18,600			HP-9
					11	C	12					
					13	A	14					
HP-3					15	B	16	30	18,600			HP-10
			18,600	30	17	C	18					
					19	A	20					
HP-4					21	B	22	30	18,600			HP-11
			18,600	30	23	C	24					
					25	A	26					
HP-5					27	B	28	30	18,600			HP-12
			18,600	30	29	C	30					
					31	A	32					
HP-6					33	B	34	30	18,600			HP-13
			18,600	30	35	C	36					
					37	A	38					
HP-7					39	B	40	30	37,800			DOAS-1
			18,600	30	41	C	42					
Totals	0	0	130,200						149,400	0	0	Totals

LOAD DESCRIPTION	CONN. VA	DEMAND VA.
LIGHTING	0	0
GENERAL POWER	0	0
HVAC EQUIPMENT	279,600	279,600
TOTAL	279,600	279,600
PERCENT LOADED	96.08%	96.08%

PHASE VA	
A	93200
B	93200
C	93200
TOTAL	279600

Figure D.5: HVH1 Panel Location



Appendix E: Structural Breadth

Figure E.1: Existing Structural Supports for RTUs

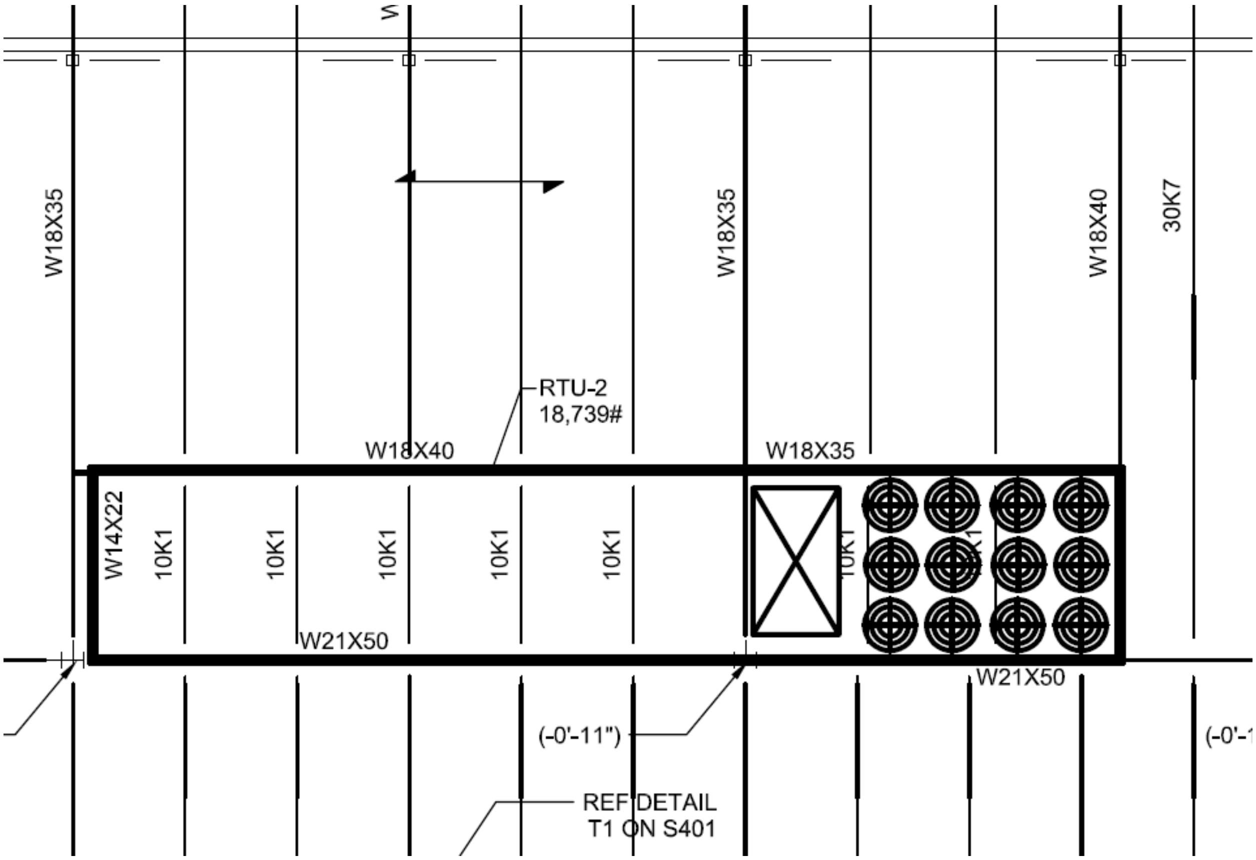
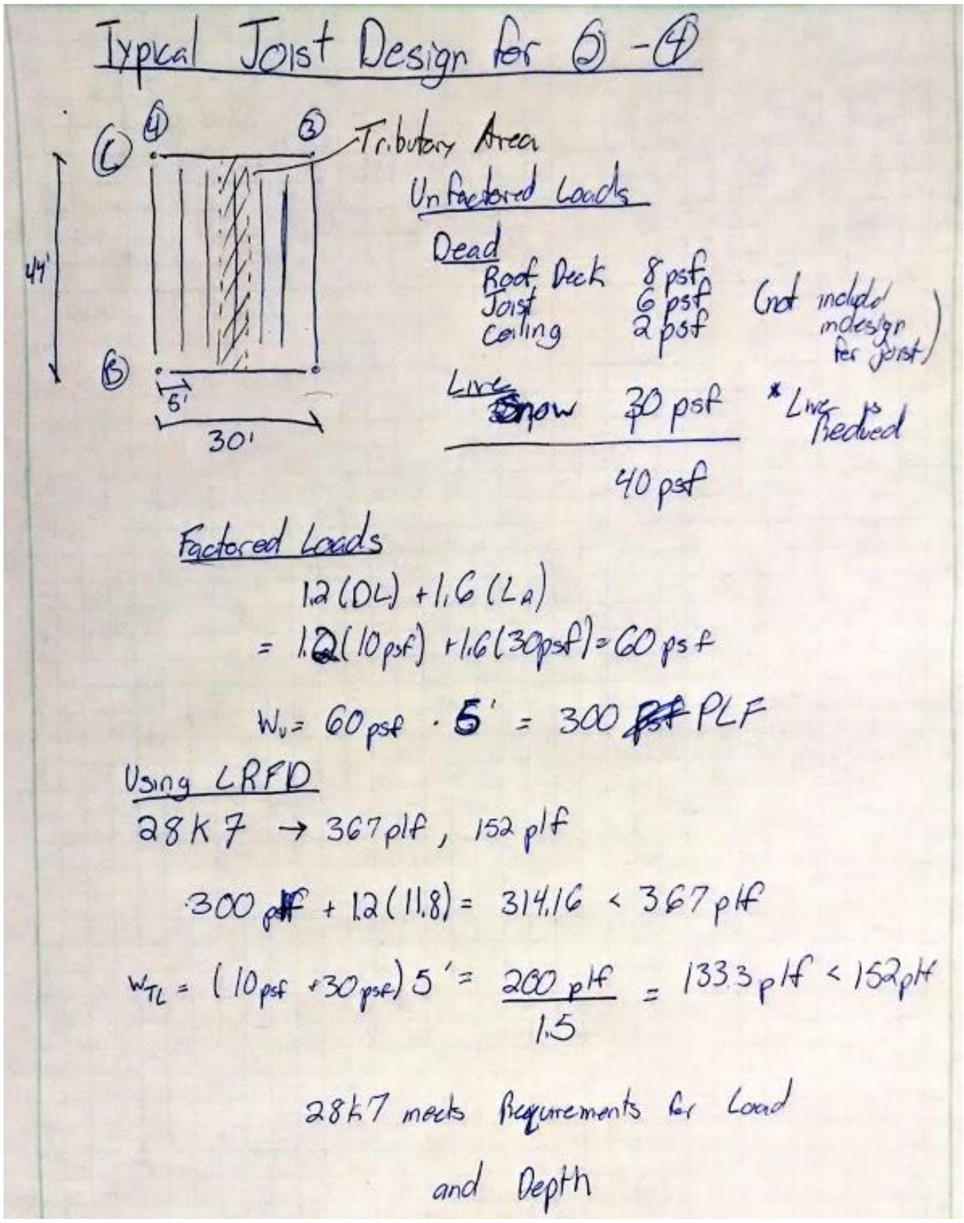


Figure E.2: Joist Calculation for Column Lines 2-4 (typical)


Typical Joist Design for ③ - ④

Unfactored Loads

Dead
Roof Deck 8 psf
Joist 6 psf
Ceiling 2 psf
(not included in design for joist)

Live Snow 30 psf *Live is Reduced

40 psf

Factored Loads

$1.2(DL) + 1.6(L_R)$

$= 1.2(10psf) + 1.6(30psf) = 60 psf$

$W_u = 60 psf \cdot 5' = 300$ PLF

Using LRFD

28K7 → 367 plf, 152 plf

$300 plf + 1.2(11.8) = 314.16 < 367 plf$

$W_{TL} = (10psf + 30psf) 5' = \frac{200 plf}{1.5} = 133.3 plf < 152 plf$

28K7 meets Requirements for Load and Depth

Figure E.3: Beam Calculation for Beam Line B between Columns 2 and 3

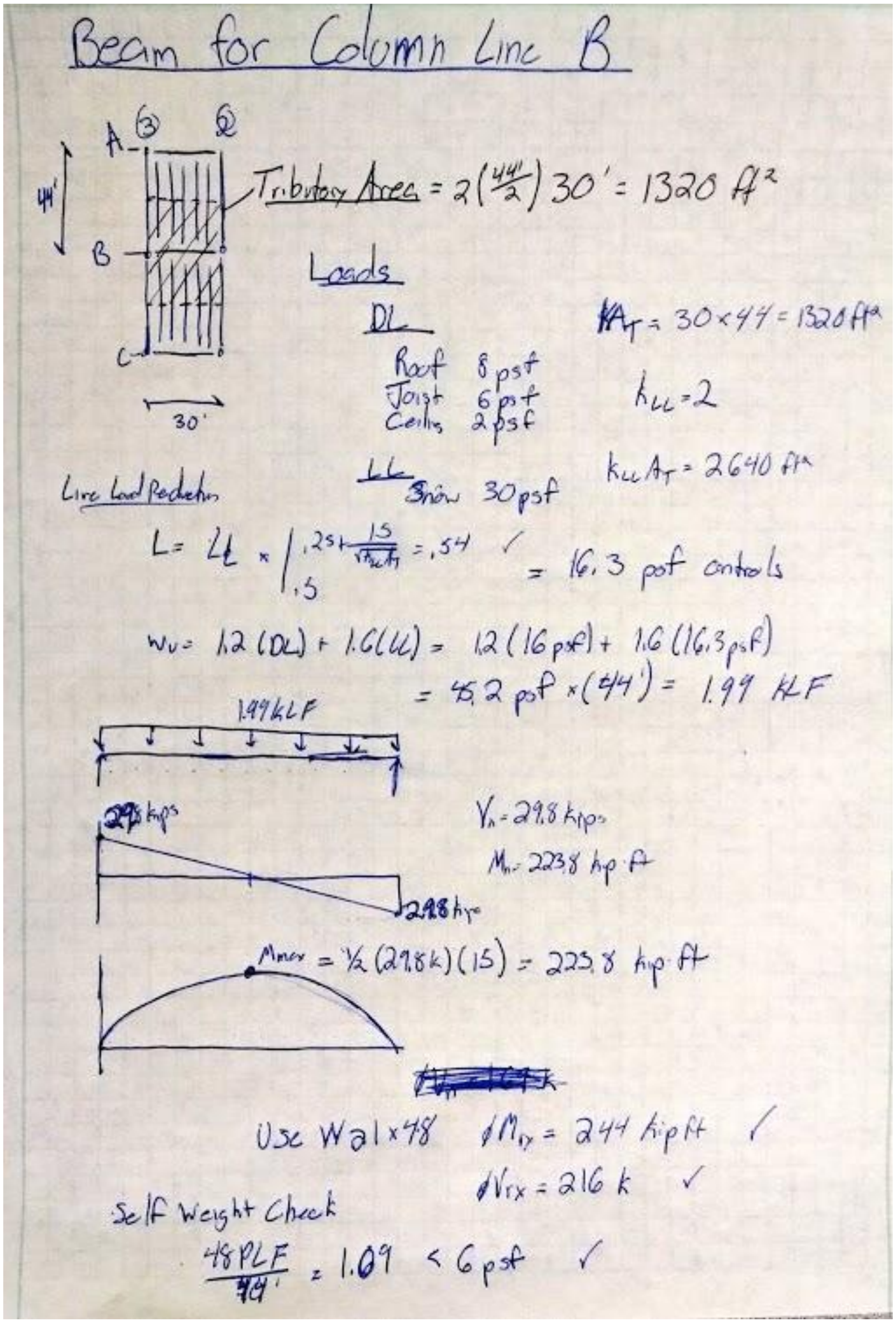


Figure E.4: Rooftop DOAS Curb

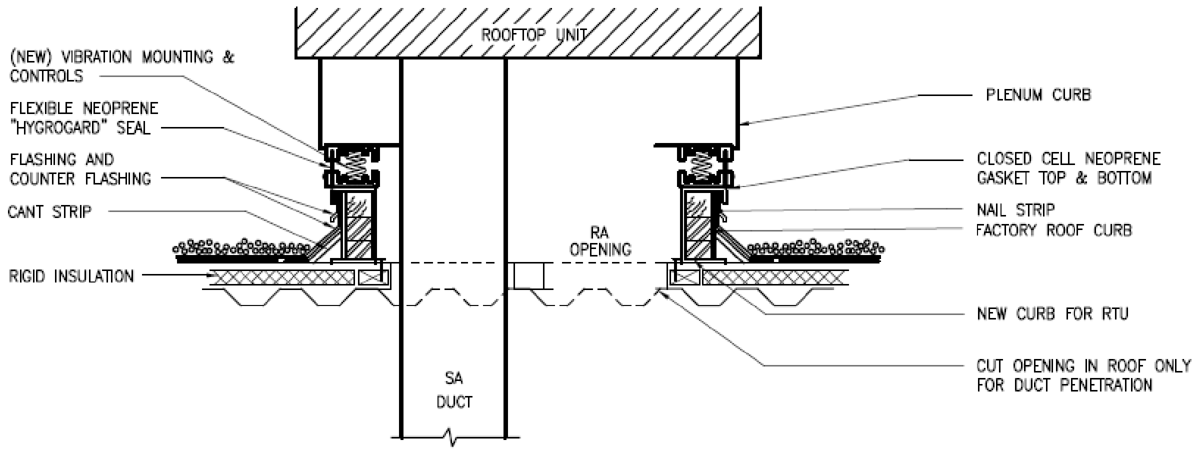
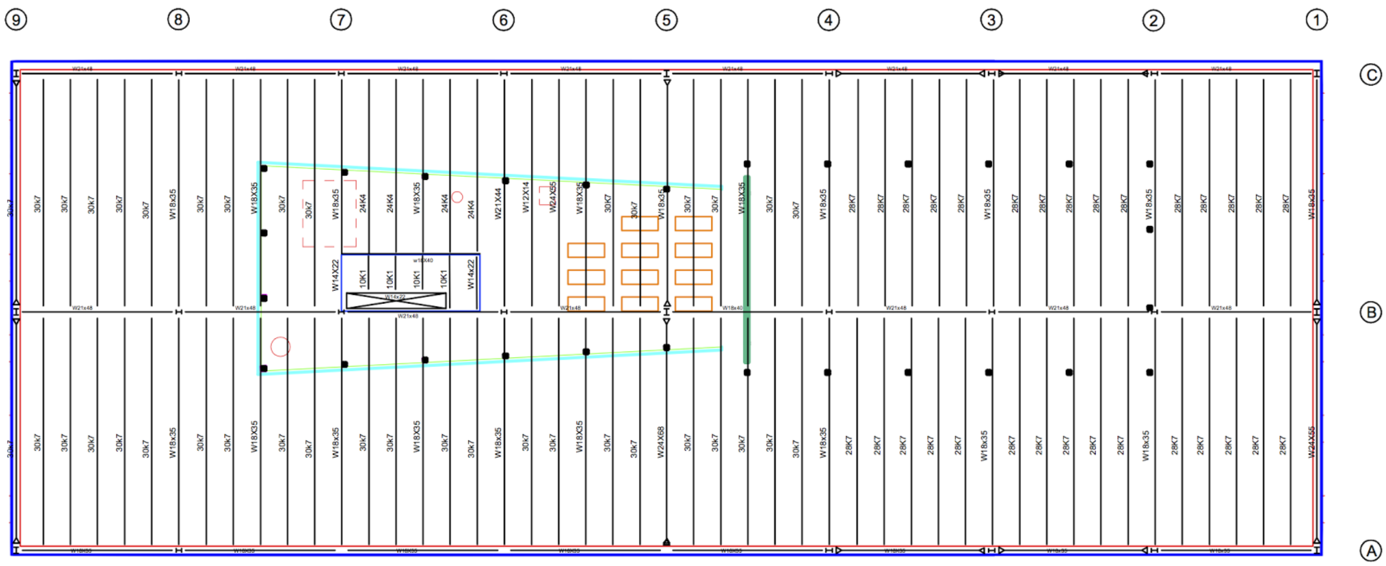


Figure E.5: 201 Rouse Structural Roof Plan



References

ASHRAE Handbook. Atlanta, GA: American Society of Heating, Refrigerating and Air Conditioning Engineers, 2009. Print.

"Commercial Prototype Building Models." Building Energy Codes Program. Department of Energy, n.d. Web. 1 Nov. 2013.

Construction Documents- 201 Rouse Boulevard. DIGSAU. October 17, 2013

Energy Standard for Buildings except Low-rise Residential Buildings. Atlanta, GA: American Society of Heating, Refrigerating and Air-Conditioning Engineers, 2010. Print.

"EnergyPlus." Building Technologies Office: Energy Simulation Software. N.p., n.d. Web. 30 October. 2013.

Mechanical Drawings- 201 Rouse Boulevard. Bala Engineers. October 17, 2013

Pentagram. Geothermal Heat Pump Manual. New York City: Pentagram, 2012. Nyc.gov. Web.

Stein, Jeff, and Steven T. Taylor. "VAV Reheat Versus Active Chilled Beams & DOAS."ASHRAE Journal 2013th ser. May (2013): 18-32. Web.

Ventilation for Acceptable Indoor Air Quality: ASHRAE Standard 62.1. Atlanta, GA: American Society of Heating, Refrigerating and Air-Conditioning Engineers, 2010. Print.