Final Report

Analysis of Internal Thermal Mass, Radiant Heating and Cooling, Energy Recovery and Solar Sorption Cooling and Heating.

Date Submitted: April 4, 2012

Biobehavioral Health Building

The Pennsylvania State University | Biobehavioral Health Building | University Park, PA | Mechanical | Ling | Jake Copley

Jake Copley | Mechanical | Biobehavioral Health Building | University Park, PA

Building Statistics

Building Size: 93,500 SF

Number of Stories: 4 Above +Mech Penthouse + 1 Below Grade

Estimated Project Completion Date: November 2012

Overall Project Cost: $48.1 Million

Project Delivery Method: Design-Bid-Build

Mechanical

- Six variable air volume air handling units with economizers.
- Perimeter heating use in conjunction with VAV system.
- Heating and cooling supplied via campus steam and chilled water loops.

Electrical/Lighting

- PSU owned transformer connected to the campus normal power loop.
- Emergency power is provided from the campus emergency power loop.
- T8 luminaires with dimming ballasts and LED down lights are typical in common areas.
- T5HO luminaires with dimming ballasts are typical in classrooms.

Northeast entrance and plaza off the HUB lawn

Southeast entrance near the Henderson South Building and Health and Human Development Building

West entrance off the Old Main Lawn

http://www.engr.psu.edu/ae/thesis/portfolios/2012/RJC5149

Project Team

Owner:
The Pennsylvania State University

Architect:
Bohlin Cywinski Jackson

CM:
Massaro CM Service

MEP/Fire Protection:
Bruce E. Brooks Associates

Structural Engineer:
Robert Silman Associates

Civil Engineer:
Gannett Fleming, Inc.

Landscape Architect:
Michael Vergason

Architecture

- Aesthetically similar to the Henderson North Building.
- Provides general purpose classroom space, office and research space.
- HUB Lawn Plaza will provide a new venue for events and performances.

Structure

- Continuous concrete spread footing with isolated spread footings for interior support.
- Moment, braced frame steel structure.

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Credits and Acknowledgements

I would like to say thank you to several individuals who have provided support, advice, encouragement and more throughout the course of this capstone thesis project as well as my time in the Penn State Architectural Engineering program as a whole. I greatly appreciate the positive impact they have made on my educational experience and overall well being. To the following I say thank you:

Benjamin Hibbard - Sales Representative, SunMaxx Solar Inc.

Greg Hlatky, P.E., LEED AP - H & H Sales Associates, Inc.

Tim Jones, P.E., LEED AP - Project Engineer, Massaro Corporation Inc.

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Kevin Nestor - Project Manager, Massaro Corporation Inc.

Kevin Parfit, P.E. - Thesis Instructor

Mike Prinkey - Operations Engineer, The Pennsylvania State University

Rachel Prinkey - Project Manager, The Pennsylvania State University

Matt Ritsko - Previous Project Manager, The Pennsylvania State University

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Stephen Treado, Ph.D., P.E. - Mechanical Instructor

Brad Wilson, P.E., LEED AP BD+C - Senior Associate, PAE Consulting Engineers, Inc.

My family and friends for all of their encouragement.

Executive Summary

The goal of this analysis is to find methods that reduce the annual building energy consumption. Four alternatives were investigated to meet this goal.

The first alternative explored internal thermal mass. The goal of increasing the thermal mass, was to reduce the modeled heating and cooling loads, in order to reduce the size of mechanical equipment required to make more room for addition equipment that would be added in the fourth alternative.

Shifting heating and cooling loads from an all air system to partial VAV and radiant heating and cooling system was the second system explored. The goal of this system was to convert from fan power to pump power. This system also provided the opportunity to reduce the size of the AHUs to make room for equipment in the last alternative

Heat recovery units are the third system that was explored and added to each AHU to further reduce the annual energy consumption.

The fourth alternative considered was the addition of a solar thermal system that would provide supplemental heating and cooling to the radiant system. This system required additional equipment that required space which was provided by reducing other mechanical equipment sizes in the first two alternative systems. This system provides greater flexibility, because it can be altered to supplement heating and cooling loads, not only the radiant system, but also the AHUs or DHW if necessary.

Following the mechanical system alternatives, two breadth topics were studied: one, a structural analysis that considered the additional structure required from the load of solar panels on the roof and the weight of the internal thermal mass on the floors, and two, an electrical analysis that looked at the effects on the electrical distribution equipment from adding additional pumps and including a chiller and cooling tower into the system.

A brief summary of the findings in my mechanical depth are as follows:

- Thermal Mass
  - 3.5% reduction in the modeled cooling load and a 2.5% reduction in annual building energy consumption.
- Radiant System
  - 2% reduction in annual building energy consumption.
- Heat Recovery
  - 7.6% reduction in annual building energy consumption with a 23 year payback period.
- Solar Thermal System
  - 13% reduction in heating and 4% reduction in cooling energy consumption with a 23 year payback period.

Section 1: Mechanical System Description

1.1 General Building Information

Building Name	Henderson Addition - Biobehavioral Health Building (BBH)
Location and Site	The Pennsylvania State University, University Park, PA. The site is located between Henderson North and Henderson South just north of College Ave. between Old Main and the HUB.
Building Occupant Name	Biobehavioral Health (College of Health and Human Development)
Occupancy or Function Type	Assembly Group A-3, Business Group B, Mixed Occupancies
Size	93,500 SF
Number of Stories	4 Above + Mechanical Penthouse + 1 Below
Start/End Construction Dates	October 25th 2010/November 2012
Cost	$48.1 Million (Overall Project Cost)
Project Delivery Method	Design-Bid-Build

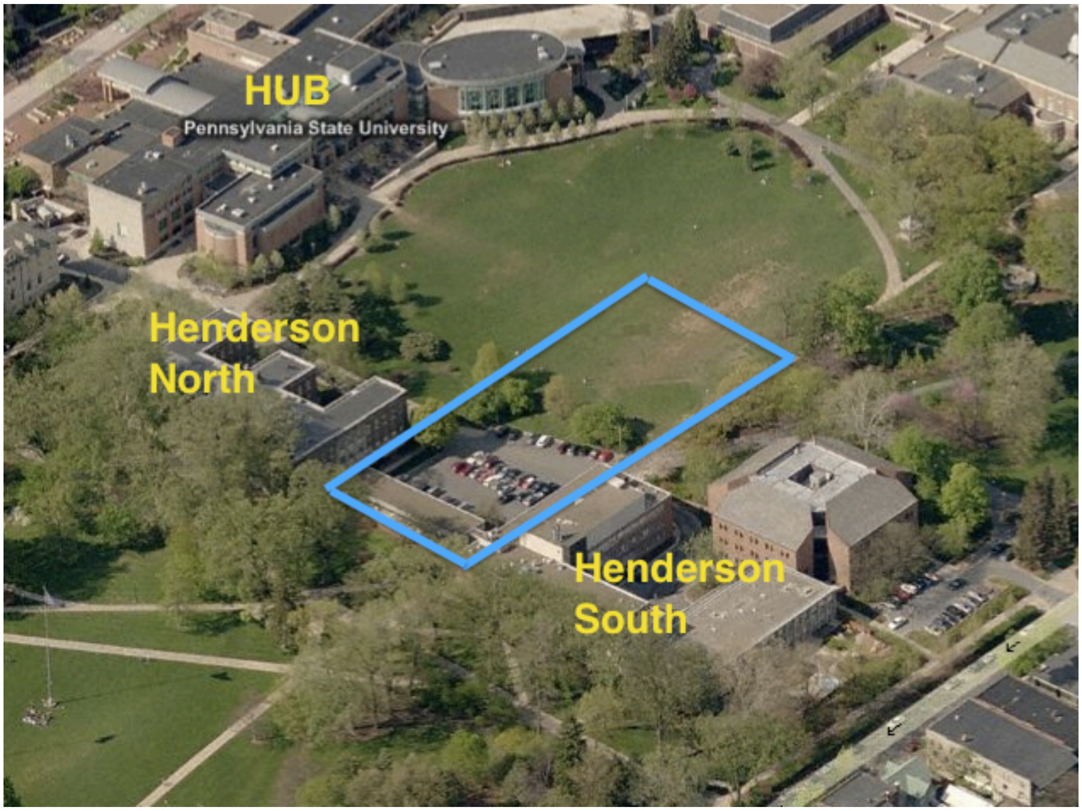


Figure 1.1.1: *Site Location*

1.2 Architecture

Due to the historic nature of Henderson North, BBH was designed to be aesthetically similar it. The differences between the two buildings are responses of the growth of sustainable design and the need for student activities. The building is served with main double loaded corridors down the middle of the building, connecting the three main entrances on the east and west sides of the building. General purpose classrooms are located on the ground and first floors for ease of access for students. Offices, project and research spaces are located on the upper floors.

Figure 1.2.1: *Old Main Mall Entrance*

Limestone and brick clad the building, paying their respects to Henderson North. The limestone veneer wraps into the main entry ways on both the east and west entrances. All three entrances are located on heavy cross campus traffic areas. One entrance is on the West end off the Old Main Lawn as seen in Figure 1.2.1. Another entrance is located on the HUB lawn (Figure 1.2.2) on the Northeast corner of the building along with the third entrance on the Southeast corner (Figure 1.2.3). Salvaged Elm wood from the Penn State Campus can be seen as accent pieces, benches and cabinetry throughout the building.

Figure 1.2.2: *HUB Lawn Entrance*

1.3 Building Enclosure

The facade is aesthetically very similar to Henderson North with limestone veneer up to the second floor followed by brick on the remaining floors. There are also limestone

Figure 1.2.3: *Southeast Entrance*

accent pieces around the building in similar fashion to Henderson North. On the northeast and southeast corners of the building there are glass curtain walls surrounding the main stairwell and entrances.

The roofing system of the steep slope roof on the penthouse is slate over rigid insulation. Surrounding the penthouse is an adhered EPDM roofing membrane over rigid insulation. There are also large green roof areas surrounding the penthouse that are composed of a vegetated exposed roof with four inches of lightweight planting mix over a drainage/water retention mat on top of rigid insulation as shown in Figure 1.3.1.

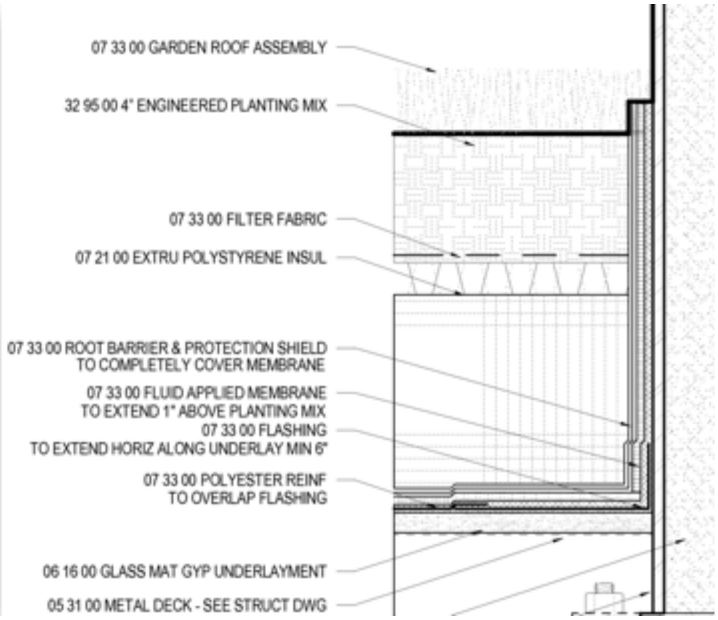


Figure 1.3.1: *Green Roof Detail*

1.4 Existing Mechanical System Summary

BBH was designed with Penn State's University-wide Environmental Stewardship Initiative in mind. The building was designed to meet the U.S. Green Building Council's (USGBC) LEED Green Building Rating System. The University desired the building to meet the requirements for LEED Silver.

The main HVAC system consists of six central variable air volume (VAV) air handling units (AHUs) located in the basement and penthouse. Generally, the AHUs are located as close to the zone(s) they serve to minimized unnecessary ductwork. Supply VAV terminals with individual thermostats are located in each space. A direct digital control (DDC) building automation system is used throughout the building. The DDC system will interface with the University's Office of Physical Plant to allow for building level control. Table 1.4.1 shows the AHUs in the building with their airflow rates, heating and cooling capacities. Table 1.4.2 shows the five main pumps used for chilled and hot water.

Table 1.4.1: Existing Air Handling Units

AHU	Airflow (CFM)	Minimum OA (CFM)	Cooling Capacity (Tons)	Heating Capacity (kBTU/hr)
Core Offices	16,500	1,450	29.0	392.7
Classrooms	9,500	2,400	23.0	236.7
South Offices	13,300	650	19.0	335.8
North Offices	7,100	360	12.0	179.8
Core	14,300	1,000	32.0	386.3
Conference	9,200	250	17.0	226.3

Table 1.4.2: Existing Pump Schedule				
Mark	GPM	RPM	HP	VFD? (Y/N)
1 (Chilled Water)	350	1,750	5	Y
2 (Chilled Water)	350	1,750	5	Y
3 (Chilled Water Supplement)	22.5	1,750	0.75	Y
4 (Heating Hot Water)	400	1,750	5	Y
5 (Heating Hot Water)	400	1,750	5	Y

1.5 Mechanical Space Required

There are a total of three mechanical rooms, as shown in Table 1.5.1,comprised of just over 8,000 square feet or 9% of the building area is used for mechanical equipment. Two mechanical rooms are located in the basement and house one AHU each, and the remaining four AHU's are located in the penthouse. There are a total of four duct shafts that extend through the entire height of the building.

Table 1.5.1: Mechanical Room Area	
Room	**Area (SF)**
M004	1,926
M021	533
Penthouse	5,018
Mechanical Shafts	560
Total	8,037
Total Building Area %	9%

1.6 System Description

A building automation system (BAS) is used throughout BBH to ensure proper control of chilled and hot water systems along with controlling all AHU's. The chilled and hot water loops are monitored to ensure proper pressure differential to properly condition the building.

Air-side Operations

BBH uses VAV systems to condition all its spaces. Each AHU contains a preheat coil and cooling coil along with mixed air, preheat and cooling coil discharge air temperature sensors. Each VAV terminal unit receives air from their associated AHU which is controlled by the DDC control system. Each terminal unit is also supplied with hot water for reheat. All the AHUs are identical except for AHU-1 which uses a relief fan while AHU2-6 use return fans as shown in Figures 1.6.1 and 1.6.2 below.

Water-side Operations

Hot Water System

Hot water is produced from two plate frame heat exchangers (HTX1, HTX 2) that are connected to the campus steam loops. Hot water is circulated through the building by two pumps with variable frequency drives (VFDs) feeding the hot water supply (HWS) lines as shown below in Figure 1.6.3. The pumps are staged in a primary/standby configuration. Steam also feeds a shell and tube heat exchanger to provide domestic hot water (DHW).

Chilled Water System

Similar to the hot water system, chilled water is provided via campus chilled water loops. Chilled water is circulated to the AHU's by the chilled water supply (CHWS) lines by three pumps each with a VFD as shown in Figure 1.6.4 below. Two of the pumps are staged in a primary/standby configuration, the third pump is non-simultaneous with primary/secondary. This third pump feeds the secondary flow in the system which is mainly the fan coil units that serve the server and telecom rooms which required year round cooling.

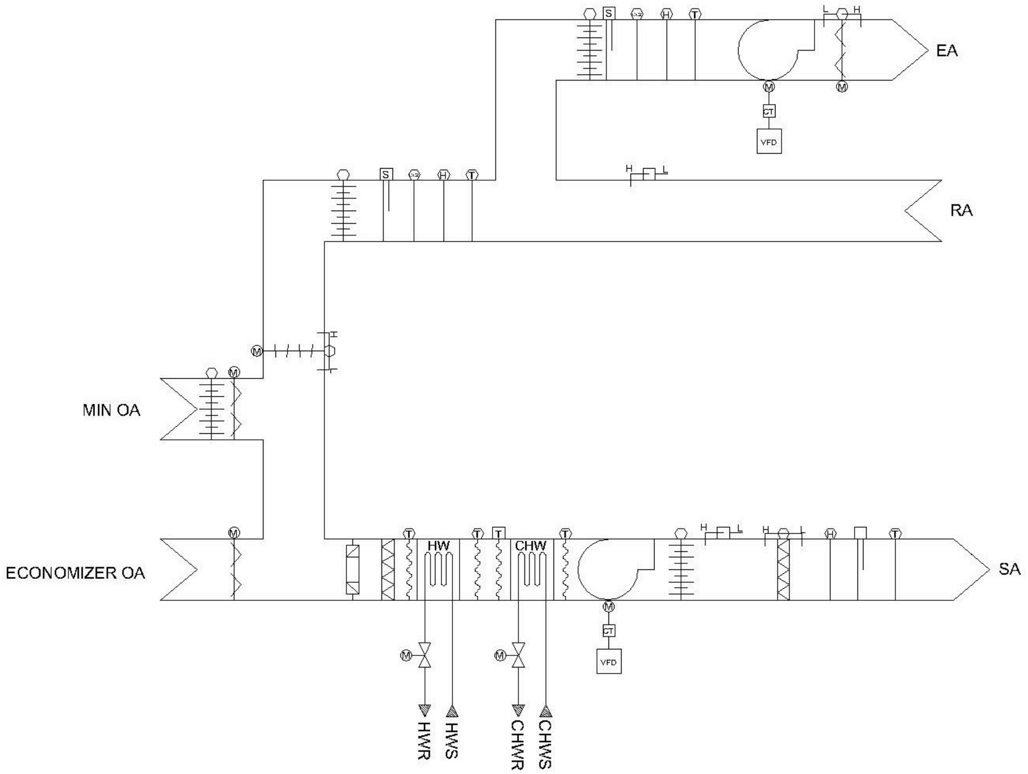


Figure 1.6.1: *AHU 1 Flow Diagram*

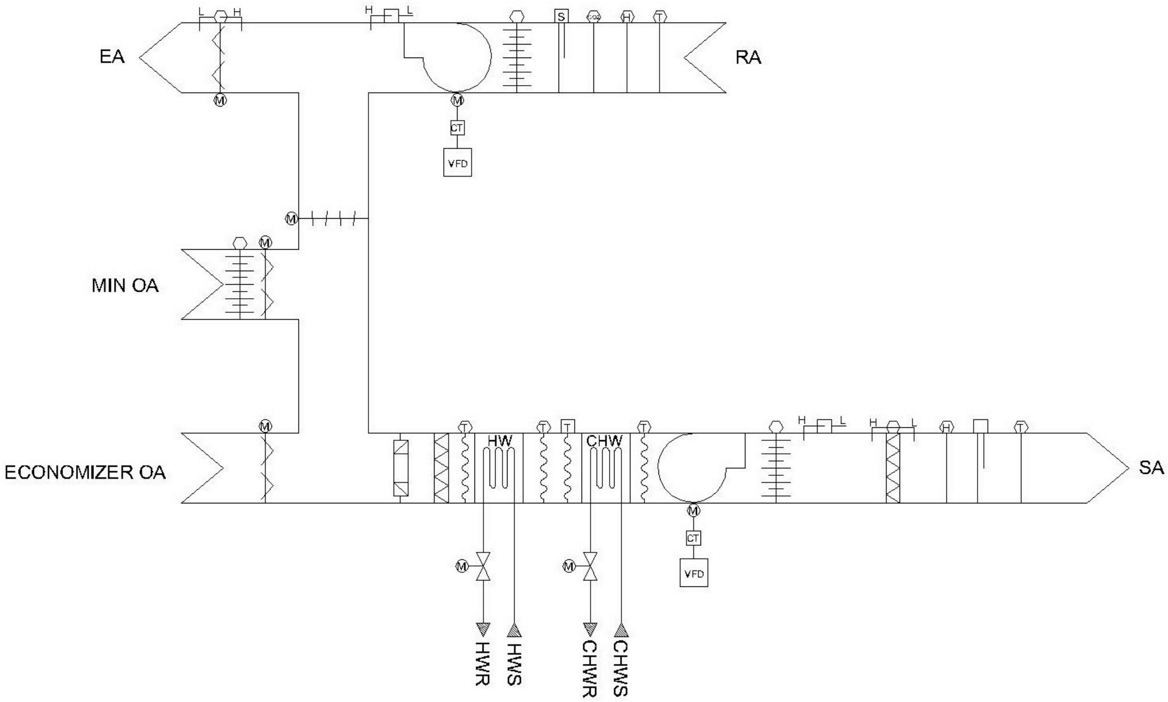


Figure 1.6.2: *AHU 2-6 Flow Diagram*

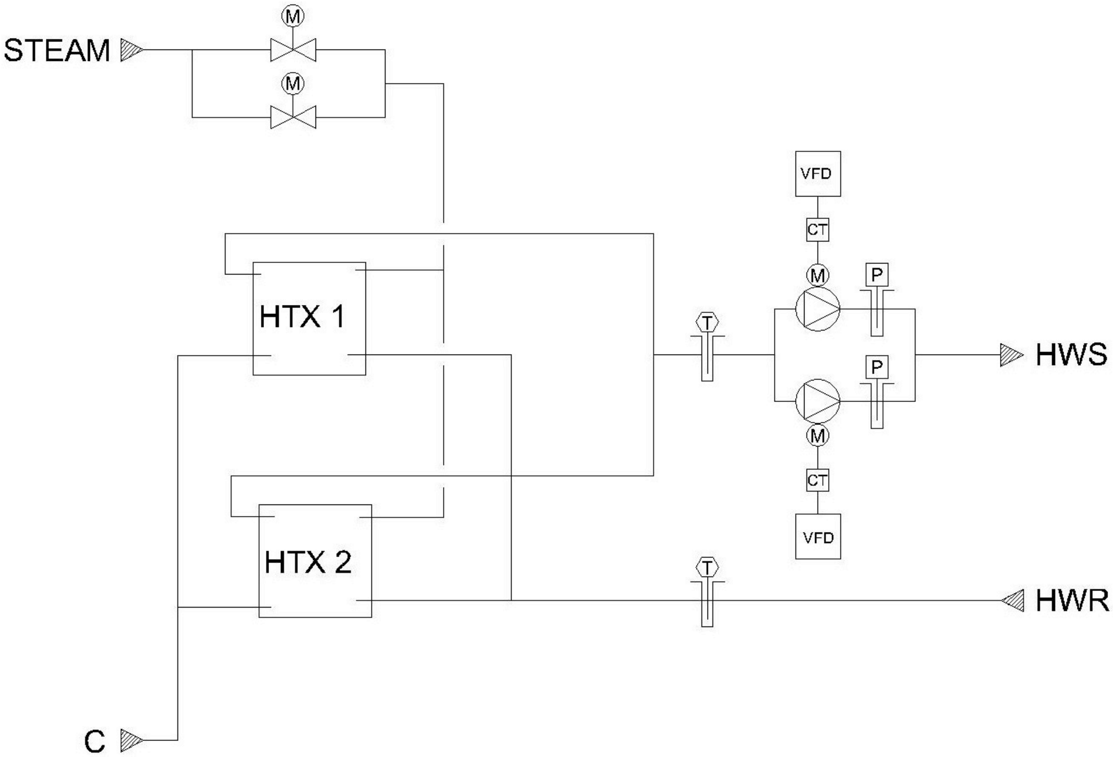


Figure 1.6.3: *Hot Water Flow Diagram*

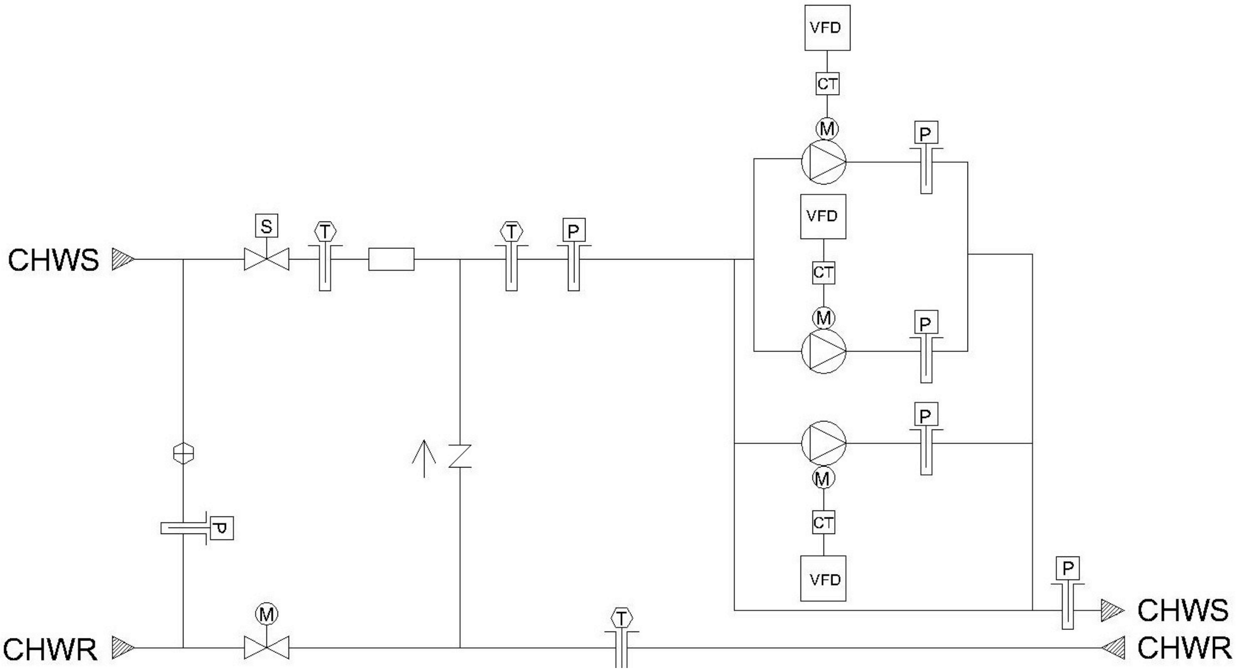


Figure 1.6.4: *Chilled Water Flow Diagram*

1.7 Energy Sources

BBH's energy sources consist of chilled water and steam from the campus supplied loops along with electricity. Electricity for the campus is supplied through five substations by Allegheny Power. Campus rates of chilled water, electricity and steam are shown below in Table 1.7.1.

Table 1.7.1: Energy Rates	
Energy Source	**Campus Rate**
Chilled Water ($/ton-hour)	0.22
Electricity ($/kWh)	0.09387
Steam ($/1000lbs)	24.59

1.8 Design Conditions

BBH is located in University Park, PA, however weather data of Pittsburgh, PA was used for the modeling purposes while Erie, PA weather data was used for the design. The outdoor design conditions for Pittsburgh were obtained from TMY2 weather data and can be seen in Table 1.8.1 where they can be compared to Erie design conditions. Indoor design conditions were obtained from Penn State design intent documents and can be see in Table 1.8.2.

Table 1.8.1: Outdoor Design Conditions				
Season	**Pittsburgh, PA**		**Erie, PA**	
	Dry Bulb (ºF)	**Wet Bulb (ºF)**	**Dry Bulb (ºF)**	**Wet Bulb (ºF)**
Summer	89.1	72.5	90	74

Table 1.8.1: Outdoor Design Conditions				
Season	Pittsburgh, PA		Erie, PA	
	Dry Bulb (°F)	Wet Bulb (°F)	Dry Bulb (°F)	Wet Bulb (°F)
Winter	1.76	-	0	-

Table 1.8.2: Indoor Design Conditions				
Space		Dry Bulb (occupied)	Humidity	Dry Bulb (unoccupied)
Typical Space	Cooling	75	50%	85
	Heating	70	-	60
Server and Telecom Room	Cooling	72	50%	72
	Heating	-	-	-

1.8 Mechanical System Cost

The estimated cost of the mechanical system is $3,424,000, which is about 7% or about $36.60/SF of the total project cost.

Section 2: ASHRAE Standard and LEED Evaluation

2.1 Design Ventilation Requirements

Ventilation rate calculations from ASHRAE Standard 62.1-2007 were performed to verify BBH's mechanical systems provide enough ventilation air to the building. Standard 62.1 looks at the outdoor air intake rates based on space types, along with the number of occupants and floor area of each space.

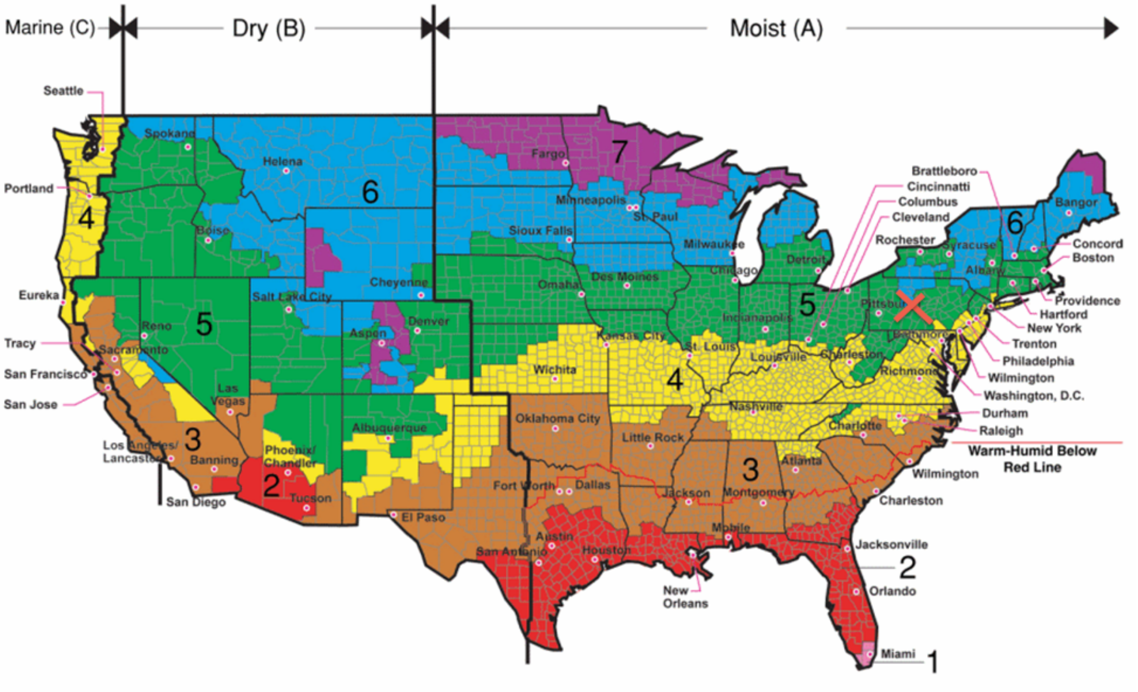
Table 2.1.1 below is a summary of the ventilation rates determined from Tech Report One, where a more detailed analysis of minimum ventilation rates can be found.

Table 2.1.1: Minimum Ventilation			
AHU	Max Occupied OA CFM	ASHRAE 62.1 OA CFM	Compliance (Y/N)
1 (Core Offices)	4500	3476	Y
2 (Classrooms)	2750	4112	N
3 (South Offices)	4750	993	Y
4 (North Offices)	3150	962	Y
5 (Core)	5000	2041	Y
6 (Conference)	2700	2075	Y

Six AHUs were analyzed, it was determined that all but one of the AHUs comply with the minimum ventilation specified by ASHRAE Standard 62.1-2007 as seen above in Table 2.1.1. A possible reason for this could be the variation in occupancy values used for the classrooms (AHU-2). A reduced occupant density of 35 persons/1000sf was used in lieu of 150 persons/1000sf to more accurately model the approximately known occupant density of the space. The occupancy estimate of the lecture hall is to be around 250 persons.

2.2 Design vs Modeled Heating and Cooling Load Estimates

The location is University Park, PA, which lies in zone 5A. Zone 5A is described as a cool humid climate. This climate zone was determined using Figure 2.2.1 from ASHRAE Standard 90.1 - 2007.



All of Alaska in Zone 7 except for the following Boroughs in Zone 8: Bethel, Dellingham, Fairbanks, N. Star, Nome North Slope, Northwest Arctic, Southeast Fairbanks, Wade Hampton, and Yukon-Koyukuk

Zone 1 includes: Hawaii, Guam, Puerto Rico, and the Virgin Islands

Figure 2.2.1: *ASHRAE Climate Zones for United States Locations*

The energy model was created using DesignBuilder with EnergyPlus to simulate the annual energy consumption of BBH. A more detailed analysis of the energy model can be found in Tech Report Two.

Table 2.2.1: Modeled vs. Design Heating and Cooling Loads		
System	**Load**	**SF Per Basis**
Cooling Modeled (Tons)	143	654 SF/ton
Cooling Designed (Tons)	178	438 SF/ton
Heating Modeled (kBTU/hr)	2381	39 SF/kBTU
Heating Designed (kBTU/hr)	1758	44 SF/kBTU
Modeled SA CFM	62633	0.803 CFM/SF
Design SA CFM	69900	0.896 CFM/SF

Table 2.2.1 above, shows the modeled heating and cooling loads compared to the design loads.

2.3 Existing Modeled Energy Usage Estimate

The energy model was created of the existing building to determine the heating and cooling loads as well as the annual energy consumption. Table 2.3.1 shows the internals load assumptions. The occupancy schedules used in the model can be seen in Table 2.3.2.

Table 2.3.1: Lighting and Equipment Loads

Space/Equipment	Load	Source
DHW Consumption (gal/SF/day)	0.008099	Assumption
Computer Gain (W/SF)	0.2	Assumption
Office Equipment Gain (W/SF)	2	Assumption
Lighting Density (W/SF)	1	Assumption

Table 2.3.2: BBH Occupancy Schedules

Space	Monday-Friday	Weekends	Holiday
Classrooms	7am to 11pm	Unoccupied with Override	Heating Setback: 50F Cooling Setback: 85F
Office, Labs, Support Spaces	7am to 8pm		

Table 2.3.3 below shows the annual energy consumption of BBH broken down by source for comparison. BBH costs approximately $2.10/SF to operate annually. Figure 2.3.2 shows the percentage of total energy usage for each building source.

Comparing the results to the Commercial Building Energy Consumption Survey (CBECS) 2003, BBH annually consumes 90.7 kBTU/SF compared to about 88.7 kBTU/SF for buildings sizes of 50,001 to 100,000 SF.

Table 2.3.3 Annual Building Energy Consumption

Source	kBTU	kWh	Ton-hour	Lbs Steam (x1000)	Utility Rate	Cost ($/Year)
Heating	2,110,561	618,570	-	1,768	24.59	$43,466
Cooling	2,235,736	655,257	186,311	-	0.22	$40,988
DHW	183,818	53,874	-	154	24.59	$3,786
Plug Load	2,357,301	690,885	-	-	0.09387	$64,853
Lighting	1,071,500	314,039	-	-		$29,479
System Fans	141,818	41,564	-	-		$3,902
System Pumps	384,232	112,612	-	-		$10,571

Table 2.3.3 Annual Building Energy Consumption

Source	kBTU	kWh	Ton-hour	Lbs Steam (x1000)	Utility Rate	Cost ($/Year)
Total	8,484,966	2,486,801	186,311	1,922	-	$197,045

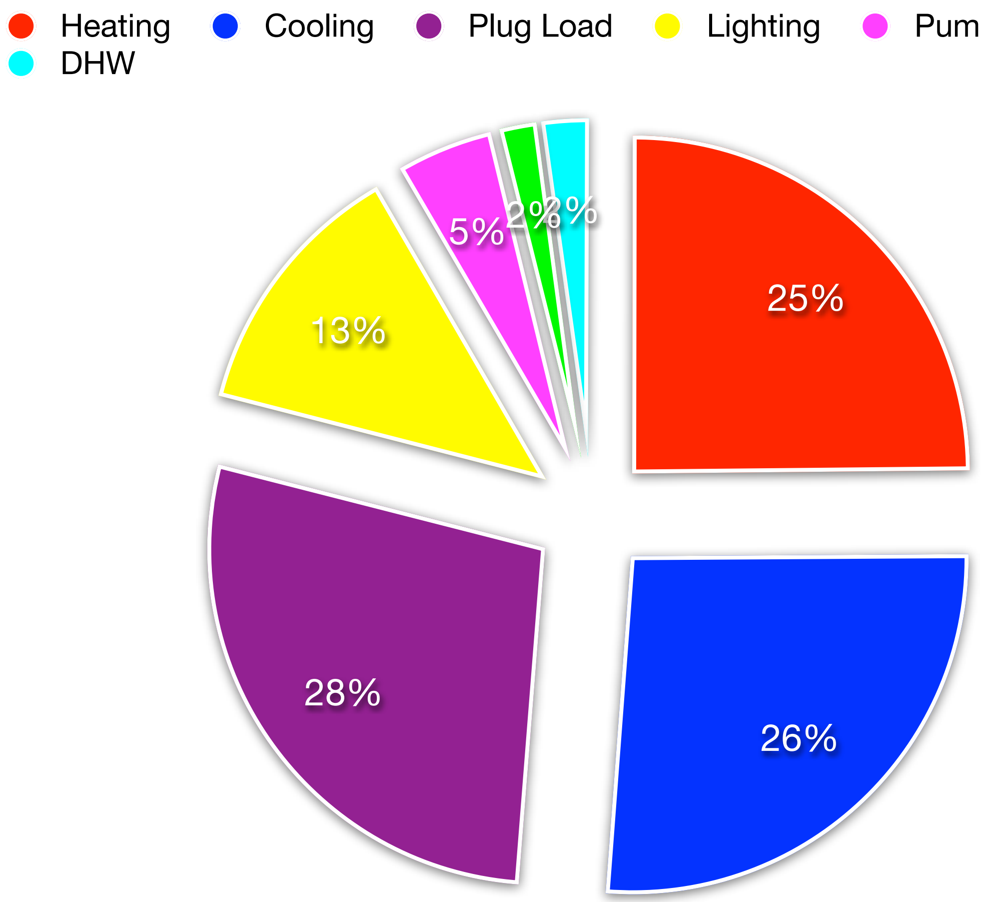


Figure 2.3.1: *Energy Consumption Breakdown (% of Total)*

2.4 LEED Analysis

A LEED assessment was completed for BBH using LEED-NC V2.2 by the designers. This report was prepared using the current version of LEED, LEED 2009 for New Construction and Major Renovations.

Sustainable Sites

Table 2.4.1: Sustainable Sites

Credit: Sustainable Sites	**Action**
Prerequisite 1: Construction Activity Pollution Prevention Intent: To reduce pollution from construction activities by controlling soil erosion, waterway sedimentation and airborne dust generation.	Stockpiles are protected to prevent water and wind erosion. A tire wash is used to help prevent sedimentation of storm sewers.
Credit 1: Site Selection Intent: To avoid the development of inappropriate sites and reduce the environmental impact from the location of a building on a site.	The site selected for BBH was previously a parking lot for Henderson North, Bridge and South. This complies with the requirements of site selection of LEED 2009.
Credit 2: Development Density and Community Connectivity Intent: To channel development to urban areas with existing infrastructure, protect greenfields and preserve habitat and natural resources.	BBH's site is located on a previously developed site, has pedestrian access, is within half a mile of at least 10 basic services and residential area.
Credit 4.1: Alternative Transportation - Public Transportation Access Intent: To reduce pollution and land development impacts from automobile use.	A bus stop is located within a quarter of a mile from BBH.
Credit 4.2: Alternative Transportation - Bicycle Storage and Changing Rooms Intent: To reduce pollution and land development impacts from automobile use.	Secure bicycle racks are provide around BBH and showers are provided for the occupants.
Credit 4.4: Alternative Transportation - Parking Capacity Intent: To reduce pollution and land development impacts from automobile use.	No new parking is provided.

Table 2.4.1: Sustainable Sites	
Credit: Sustainable Sites	**Action**
Credit 5.2: Site Development - Maximize Open Space Intent: To promote biodiversity by providing a high ratio of open space to development footprint.	Green roofs are provided, covering the majority of the roof and a large outdoor pedestrian-oriented hardscape is provided.
Credit 6.1: Stormwater Design - Quantity Control Intent: To limit disruption of natural hydrology by reducing impervious cover, increasing on-site infiltration, reducing or eliminating pollution from stormwater runoff and eliminating contaminates.	A cistern is provided that collects rainwater runoff from the roofs and is used to irrigate the landscape. A storm retention system was also installed to reduce the load on the storm system during heavy rain.
Credit 7.2: Heat Island Effect - Roof Intent: To reduce heat islands to minimize impacts on microclimates and human and wildlife habitats.	A vegetated roof will be installed which will cover at least 50% of the roof area.

Water Efficiency

Table 2.4.2: Water Efficiency

Credit: Water Efficiency	**Action**
Prerequisite 1: Water Use Reduction Intent: To increase water efficiency within the building to reduce the burden on municipal water supply and wastewater systems.	The building specifications call for low flow and sensor operated plumbing fixtures.
Credit 1: Water Efficient Landscaping Intent: To limit or eliminate the use of potable water or other natural surface or subsurface water resources available on or near the project site for landscape irrigation.	Storm water runoff from the roof is collected in a underground cistern. The collected water is utilized to irrigate the surrounding landscaping.

Energy and Atmosphere

Table 2.4.3: Energy and Atmosphere

Credit: Energy and Atmosphere	**Action**
Prerequisite 1: Fundamental Commissioning of Building Energy Systems Intent: To verify that 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.	Facility Dynamics will be the commissioning agent and will check/test all major mechanical and electrical systems used throughout BBH.
Prerequisite 2: Minimum Energy Performance Intent: To establish the minimum level of energy efficiency for the proposed building and systems to reduce environmental and economic impacts associated with excessive energy use.	A whole building energy simulation was completed using Carrier HAP v4.4 and the simulated proposed building had 28.5% improvement over the baseline.
Prerequisite 3: Fundamental Refrigerant Management Intent: To reduce stratospheric ozone depletion.	Building specifications call for refrigerations that comply with ASHRAE 15: Safety Standard for Refrigeration Systems.
Credit 1: Optimized Energy Performance Intent: To achieve increasing levels of energy performance beyond the prerequisite standard to reduce environmental and economic impacts associated with excessive energy use.	The proposed building was modeled and has an expected 28.5% improvement in energy efficiency compared to the baseline building.

Table 2.4.3: Energy and Atmosphere

Credit: Energy and Atmosphere	Action
Credit 3: Enhanced Commissioning Intent: To begin the commissioning process early in the design process and execute additional activities after systems performance verification is completed.	The commissioning process was utilized during the design phase of BBH.
Credit 4: Enhanced Refrigerant Management Intent: To reduce ozone depletion and support early compliance with the Montreal Protocol while minimizing direct contributions to climate change.	None of the the AHU's use refrigerants. The back-up split system uses R-410a which is a non-ozone depleting refrigerant. The fire suppression system does not use CFC, HCFC or halons as a suppressant.
Credit 6: Green Power Intent: To encourage the development and use of grid-source, renewable energy technologies on a net zero pollution basis.	Penn State currently purchases about 20% of its annual power demand from renewable sources.

Materials and Resources

Table 2.4.4: Materials and Resources

Credit: Materials and Resources	Action
Prerequisite 1: Storage and Collection of Recyclables Intent: To facilitate the reduction of waste generated by building occupants that is hauled to and disposed of in landfills.	BBH will have recycle collection stations throughout the building.
Credit 2: Construction Waste Management Intent: To divert construction and demolition debris from disposal in landfills and incineration facilities. Redirect recyclable recovered resources back to the manufacturing process and reusable materials to appropriate sites.	All waste material is collected in two dumpsters on site and is later separated off site in Tyrone, PA. All materials that can be salvaged or recycled will be logged.
Credit 4: Recycled Content Intent: To increase demand for building products that incorporate recycled content materials, thereby reducing impacts resulting from extraction and processing of virgin materials	Recycled materials are used throughout the building.

Table 2.4.4: Materials and Resources	
Credit: Materials and Resources	**Action**
Credit 5: Regional Materials Intent: To increase demand for building materials and products that are extracted and manufactured within the region, thereby supporting the use of indigenous resources and reducing the environmental impacts resulting from transportation.	Regional materials and products are used throughout the project.
Credit 7: Certified Wood Intent: To encourage environmentally responsible forest management.	The majority of wood materials used in the building are certified with the Forest Stewardship Council's criteria.

Indoor Environmental Quality

Table 2.4.5: Environmental Quality	
Credit: Indoor Environmental Quality	**Action**
Prerequisite 1: Minimum Indoor Air Quality Performance Intent: To establish minimum indoor air quality (IAQ) performance to enhance indoor air quality in buildings, thus contributing to the comfort and well-being of the occupants.	All spaces are mechanically ventilated.
Prerequisite 2: Environmental Tobacco Smoke (ETS) Control Intent: To prevent or minimize exposure of building occupants, indoor surfaces and ventilation air distribution systems to environmental tobacco smoke (ETS).	Smoking is prohibited in all PSU buildings.
Credit 1: Outdoor Air Delivery Monitoring Intent: To provide capacity for ventilation system monitoring to help promote occupant comfort and well-being.	Co_2 sensors are provide throughout the building to ensure proper ventilation rates are being provided.

Table 2.4.5: Environmental Quality	
Credit: Indoor Environmental Quality	**Action**
Credit 3.1: Construction Indoor Air Quality Management Plan - During Construction Intent: To reduce indoor air quality (IAQ) problems resulting from construction or renovation and promote the comfort and well-being of construction workers and building occupants	Equipment is stored in a clean dry location. Duct openings are protected with plastic.
Credit 3.2: Construction Indoor Air Quality Management Plan - Before Occupancy Intent: To reduce indoor air quality (IAQ) problems resulting from construction or renovation to promote the comfort and well-being of construction workers and building occupants.	Low VOC materials are used in the building thus reducing the need for an extensive “flush out”. Air filtration media will be changed as deemed necessary.
Credit 4.1: Low-Emitting Materials - Adhesives and Sealants Intent: To reduce the quantity of indoor air contaminants that are odorous, irritating and/or harmful to the comfort and well-being of installers and occupants.	Low VOC adhesives, sealants, paints, coatings, flooring materials and composite wood and agrifiber products are used extensively throughout the project. Each material is logged and submitted to LEED.
Credit 4.2: Low-Emitting Materials - Paints and Coatings Intent: To reduce the quantity of indoor contaminants that are odorous, irritating and/or harmful to the comfort and well-being of installers and occupants.	
Credit 4.3: Low-Emitting Materials - Flooring Systems Intent: To reduce the quantity of indoor air contaminants that are odorous, irritating and/or harmful to the comfort and well-being of installers and occupants.	

Table 2.4.5: Environmental Quality

Credit: Indoor Environmental Quality	Action
Credit 4.4: Low-Emitting Materials - Composite Wood and Agrifiber Products Intent: To reduce and quantity of indoor air contaminants that are odorous, irritating and/or harmful to the comfort and well-being of installers and occupants.	
Credit 5: Indoor Chemical and Pollutant Source Control Intent: To minimize building occupant exposure to potentially hazardous particulates and chemical pollutants.	Low VOC materials are used extensively throughout the building, reducing the need for extensive air purging and filtration.
Credit 6.1: Controllability of Systems - Lighting Intent: To provide a high level of lighting system control by individual occupants or groups in multi-occupant spaces and promote their productivity, comfort and well-being.	BBH uses occupancy sensors extensively throughout the building.
Credit 6.2: Controllability of Systems - Thermal Comfort Intent: To provide a high level of thermal comfort system control by individual occupants or groups in multi-occupant spaces and promote their productivity, comfort and well-being.	Individual controls are provided for the majority of building spaces. The controls allow occupants to enable adjustments to meet individual needs and preferences.
Credit 7.1: Thermal Comfort - Design Intent: To provide a comfortable thermal environment that promotes occupant productivity and well-being.	All spaces are designed with independent temperature control to allow for maximum comfort and control.
Credit 7.2: Thermal Comfort - Verification Intent: To provide for the assessment of building occupant thermal comfort over time.	A thermal comfort survey of building occupants will be conducted.

There are numerous changes from V2.2 to LEED 2009, but most changes are simply assigned point values to various credits. A couple credits from V2.2 were condensed in LEED 2009 and increased in point value.

Comparing LEED V2.2 to LEED 2009, BBH still has the ability to achieve a minimum of LEED Certification. The differences between the two versions are minimal, resulting in a well ranked building.

Section 3: Overall System Evaluation

Overall, the mechanical system of BBH is well designed with flexibility, comfort and efficiency in mind. A unique combination of a full VAV air system and perimeter radiant heat system was used to effectively create a comfortable environment for students and faculty. The various building zones/spaces were cleverly divided amongst six air handling units. The six units are divided into the following zones: core offices, classrooms, south offices, north offices, core and conference.

The estimated cost of the mechanical system is $3,424,000 which is about 7% of the total building cost. This is approximately $36/SF. This low cost could be due to the overall simplicity of the system. Since the entire building is conditioned by campus supply loops, expensive heat pumps, chillers, cooling towers and other equipment are not necessary. Using campus supplied utilities greatly simplified portions of the design and reclaimed potentially lost space due to extra mechanical equipment.

Section 4: Proposed Redesign Overview

The main objective of the mechanical depth is to reduce the energy consumption of BBH. This section explains the proposed system alternatives and some expected results. These four alternatives were analyzed and compared to determine which system or combination of systems provides the greatest reduction in energy consumption in an economic fashion. Table 4.1.1 organizes the different components in each alternative. After modifying the wall composition and mechanical system, the effects of these modifications on the structure and electrical distribution system will be explored in electrical and structural breadths.

Table 4.1.1: System Alternatives

Variable	Alternatives			
	1 (Existing)	*2*	*3*	*4*
Mechanical System	Full VAV	Full VAV	New AHU + Radiant Heating and Cooling	New AHU + Radiant Heating and Cooling
Economizer	X	X	X	X
Heat Recovery			X	X
Thermal Mass	Existing	Option 1	Option 1	Option 1
Solar Thermal System				X
Sorption Cooling				X

4.1 Alternatives Considered

Thermal Mass

Increasing the internal thermal mass of BBH can provide the ability to shave peak heating and cooling loads, reducing the size of the mechanical equipment required, thus reducing upfront costs of the air system. When pre-heating and pre-cooling the building over night, the thermal mass will store that energy and release it during the day when it is needed. Pre-Cooling the building can save more energy because cooling equipment will run more efficiently at night due to lower ambient temperatures. Using the thermal mass can allow for a more flat load profile to downsize mechanical equipment and allow the equipment to run near full load more often, improving system performance.

Heating and Cooling Distribution

By altering the cooling and heating delivery method, energy can be saved by switching from fan power to pump power. Radiant heating and cooling will be investigated, in effort to reduce the energy required to move energy around the building. This can also reduce the space required for mechanical equipment, which will provide more room for additional equipment being proposed by the solar energy conversion system. An VAV air system will still be employed to provide adequate ventilation for the building.

Heat recovery

By incorporating a heat recovery system into the mechanical system of BBH, a reduction in energy consumption required to heat and cool the various spaces within the building can be achieved. By combining the savings of the heat recovery system and the ability of onsite energy generation, the annual energy consumption can be reduced.

Solar Thermal System

BBH is well oriented and suited for solar energy conversion systems along with having a roof height that is well above any surrounding buildings or vegetation. By implementing a solar energy conversion system consisting of solar thermal panels, an adsorption chiller and associated cooling tower, the total energy demand from the campus chilled water and steam loops can be reduced.

4.2 Tools and Methods

Extensive research was done with the proposed alternatives being considered to ensure a proper understanding of each element. Tools such as Excel and DesignBuilder with EnergyPlus were used throughout the research and design process.

DesignBuilder with EnergyPlus were be used to obtain reasonably accurate cooling, heating and electrical loads. The effects of increased thermal mass were explored, then the radiant heating and cooling system was be designed to offset loads from the air system to the new hydronic radiant system. Once the radiant system was design, each AHU was resized with its new respective load and, based on air face velocities in the AHU's, enthalpy wheels were selected for each AHU.

Excel was used for detailed design calculations of the radiant heating and cooling system along with the solar energy conversion system. The radiant system must be sized to provide adequate heating and cooling to the various building spaces. The solar energy conversion must be size to provide the maximum amount of hot water to properly operate the adsorption chiller and provide heating in the winter.

Section 5: Thermal Mass

A thermal mass study was the first area explored with the goal of reducing the design loads of BBH. Three combinations of partition mass were compared under three separate sets of conditions to see the effects of pre-heating and pre-cooling. Table 5.0.1 shows the three preconditioning conditions that were examined.

Table 5.0.1: Precondition Conditions

Condition	Hours
Precool Only	9
Preheat and PreCool	9
Preheat Only	9

The three mass options that were explored can be see below in Figures 5.0.1, 5.0.2, 5.0.3. Option one reflects the existing mass that is currently in the building which is composed of traditional drywall, one layer each side, on 2x4 steel studs. Option two is composed of 4” brick on 8” heavyweight CMU block against 4” steel studs with drywall and a cork board finish. The last mass that was studied was the heaviest, composing of 8” heavyweight CMU block finished on both sides with 4” brick. The potential energy storage of each mass option was calculated.

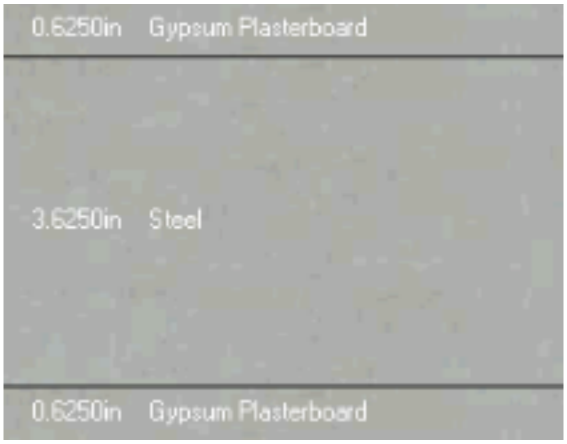


Figure 5.0.1: *Existing Internal Mass*

Figure 5.0.2: *Internal Mass Option One*

Figure 5.0.3: *Internal Mass Option Two*

$$Q_{stored} = \rho \, d \, c$$

$$b = \sqrt{(\rho \, c \, k)}$$

Where,

b= *heat absorption coefficient*

ρ= *density*

c= *specific heat*

k= *thermal conductivity*

d= *layer density*

Table 5.0.2: Thermal Mass Capacity

Material	**C (BTU/lb F)**	ρ (lb/ft^3)	K (BTU/hr ft F)	B	Q_{stored} (BTU/SF F)
8” Concrete	0.156	144	0.54	3.48	14.98
4” Brick	0.2	123	0.4	3.14	8.20
2 x 5/8” Gypsum	0.259	78	0.25	2.25	2.10
1/4” Cork Board	0.485	5.4	0.028	0.27	0.05

Table 5.0.2 above shows the different heat absorption coefficients and capacities. These values were used in the guidance of selecting a new wall composition with a greater capacity to store energy and reduce design heating and cooling loads. The final option that was chosen was option one, with pre-cooling only. It performed equally as well as option two, but option one was chosen because the additional cork finish helps the acoustics of the room since a significant portion of the acoustical ceiling

tiles will be replaced with radiant panels. Option two results in a 5 ton reduction in the modeled cooling load as well as a 1.3 kBTU/SF reduction in energy consumption.

Section 6: Radiant Heating and Cooling

A radiant heating and cooling distribution system was investigated to reduce the energy consumption by shifting from fan power to pump power. Floors 1-4 were divided into four zones: north, south, core and corridor. The ground floor was broken into two zones, lecture hall and office. A radiant system was not included in the ground floor.

6.1 Component Selection

Radiant ceiling tiles were chosen for ease of installation and future renovations. Each panel is silk screened to match the appearance of a typical acoustical ceiling tile. A maximum of 60% ceiling coverage was applied in an effort to prevent a significant acoustical effect on the spaces. Figure 6.1.1 and 6.1.2 show how the radiant panels would be laid out and piped together in a typical office and classroom respectively.

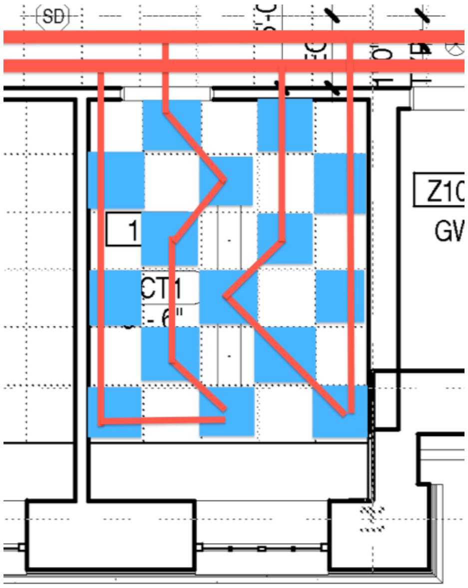


Figure 6.1.1: *Typical Office Radiant Panel Layout*

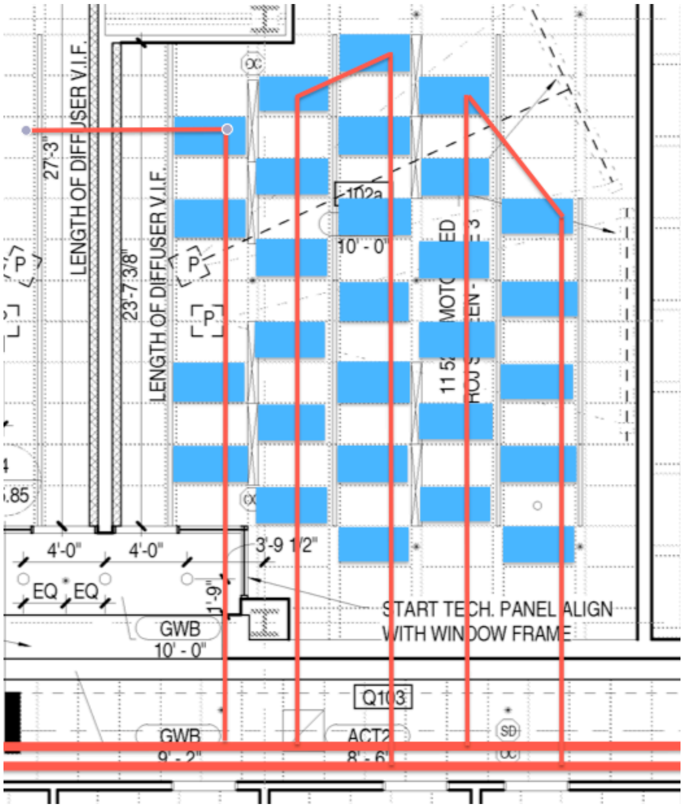


Figure 6.1.2: *Typical Classroom Radiant Panel Layout*

6.2 Calculations

SA temperature was pushed down to 45 F which reduced the air flow required to meet the latent load. This also allowed more of the sensible load to be shifted onto the radiant system. An entering water temperature of 50 F was chosen to supply each series of radiant panels with a ΔT of 22.5 F.

When in heating mode, the entering water temperature was design to be 128 F with a ΔT of 55.5 F. This was chosen to supply adequate heating and be able to operate off the hot water outlet from the adsorption chiller.

In order to calculate heating and coolings loads required of the radiant system, the heating and cooling capacity of the supply air (SA) had to be determined. Starting with the ventilation supply rate, the heating and cooling capacity of the air was determined as a starting point. If the latent cooling capacity of the SA was unable to meet the latent load in the spaces, the SA rate was increased until all of the latent load was met by the SA. To determine the cooling capacity of the SA the following were used:

$$Q_{latent}=4840\ V_r\ (W_{room}-W_{SA})$$

Where,

Q_{latent}=Latent Load

V_r=Air Flow

W_{room}=Room Humidity Ratio

W_{SA}=Supply Air Humidity Ratio

$$Q_{sensible}=1.1\ V_r\ (T_{room}-T_{SA})$$

Where,

$Q_{sensible}$=Sensible Load

T_{room}=Room Temperature

T_{SA}=Supply Air Temperature

The same procedure was applied for calculating the heating load, except the adjusted SA flow rates from cooling were used to calculate SA heating capacity.

Since a large portion of the heating and cooling load was transferred from the air system to the radiant system, new air handling units were selected. The number of air handling units was reduce from 6 to 5 and broken up by zone; north, south, core, corridor and lecture hall. To simplify the task of selecting fans, the worst case scenario for the largest fan size was selected providing room for improvement in actual system sizing and performance. Fan sizes and loads can be seen in more detail under section 9.

6.3 Controls

Each room will be independently controlled with a four pipe system. The air system will remain as a VAV system and the radiant system will meet reheat loads if required. Before reheat is used, the terminal unit will reduce the air flow until the minimum ventilation rate is reached. Once the minimum air flow is reached, reheat will be activated by the BAS in the radiant system. Each space will be equipped with CO2 sensors to detect occupants and increase supply air flow to meet the latent load requirements to prevent condensation from forming on the radiant panels. 6.4 Pump and Pipe Sizing

Riser piping was sized to handle the volume of water required to heat and cool the building. Pumps were selected based on the head loss in the system and the flow required. Table 6.4.1 shows the pump sizing requirements and the HP and impeller size required.

Table 6.4.1: Radiant Pump Sizes

Pump	System Head loss (ft)	System Flow (gpm)	Pump HP	Impeller Size (in)
Radiant Heating	25	48.1	0.75	8
Radiant Cooling	31	67.1	1	9

Section 7: Heat Recovery

Heat recovery units were explored to further reduce the annual energy consumption. An enthalpy wheel was chosen and incorporated into the design. An enthalpy wheel was added to each AHU with an efficiency of approximately 80.5% at a face air speed of around 600 FPM. Approximately 2.5 kBTU/SF or a 5% mechanical system energy reduction was see when adding an enthalpy wheel to the system.

Section 8: Solar Thermal System

8.1 Component Selection

A solar thermal array was designed to be installed on the roof of the penthouse and the south green roof. Evacuated tube collectors were selected to provide reliable and efficient operation in the cold weather seen in State College, PA. Shading calculations were done to ensure that none of the panels would be shaded by other panels or the dormer covering the door from the penthouse to the green roof.

An adsorption chiller was selected to produce chilled water for the radiant cooling system during the summer. An adsorption chiller was chosen due to the small sizes they are available in and the low electrical demand of the equipment.

8.2 Calculations

The design of the solar thermal system was guided by the heat input requirements of the adsorption chiller and by the area available on the roof for the panels. Table 8.2.1 shows the constraints that controlled the design.

Table 8.2.1: Solar Thermal System Design Constraints	
Chiller Heat Input	195 F HW at 40 GPM
Available Roof Area	4921 SF

The most limiting constraint is the available room area for solar panels. Due to shading issues, the entire area of available roof was not used. Rather the entire sloped roof covering the penthouse was covered in panels along with a single strip on the green roof below, along the south wall. All panels were set at a slope of approximately 40°. To simplify the analysis, the hours of 9am to 4pm were considered as hours that provided reasonable solar insolation. Due to geographical location there are dangers of freezing and contrary due to the high load demand there are dangers of boiling in the solar loop and in order to keep the system as simple as possible a drain-back configuration was avoided. A 85% by volume propylene glycol-water mixture was used that will decrease the freezing and increase the boiling temperature below and above all danger points in the system. Figure 8.2.1 shows the areas where the solar panels would be installed.

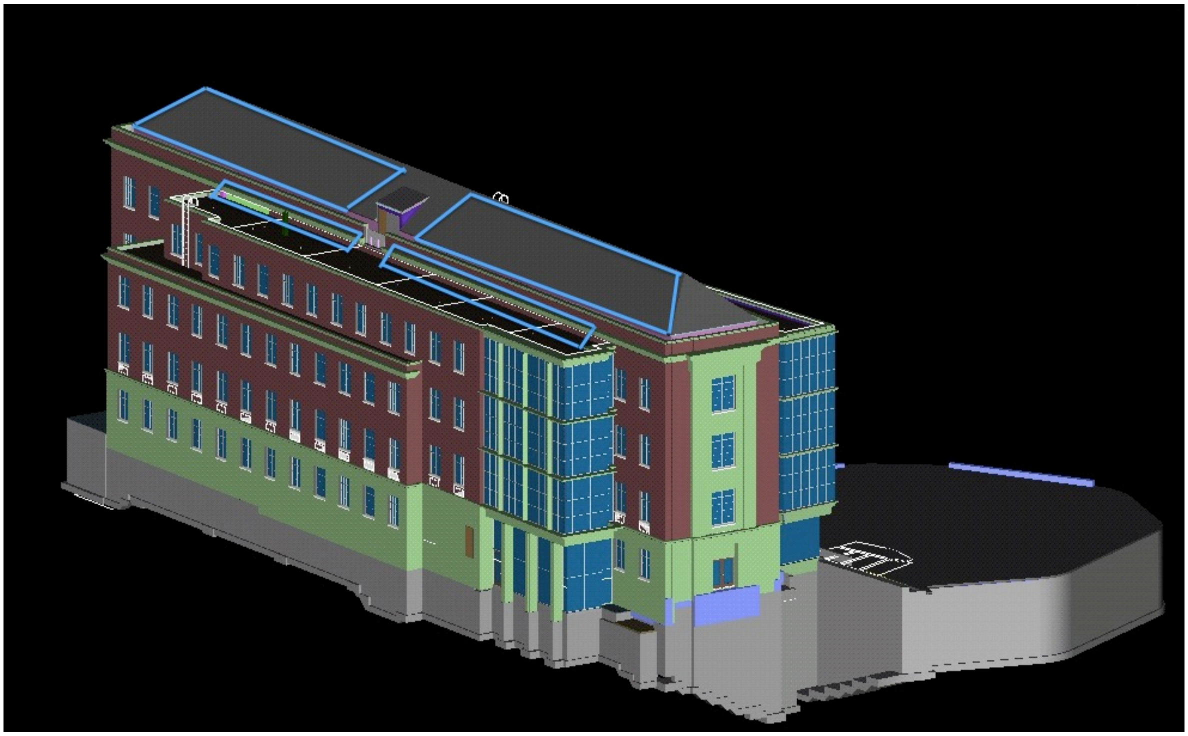


Figure 8.2.1: *Solar Panel Locations*

TMY 2 weather data was used to obtain average hourly direct normal solar radiant for a typical day in each month. The direct normal solar radiant and daily average dry bulb (DB) temperatures, also from TMY2 weather data, were used to calculate the collector outlet temperature. The following equations were used to determine collector outlet temperature:

$$Q_u=A_c\ F_r\ [S-U_L(T_i-T_a)]$$

Where,

Q_u=Useful Energy

A_c=Collector Area

F_r=Collector Heat Removal Factor

S=Average Direct Normal Solar Radiation

U_L=Thermal Losses

Ti=Inlet Temperature

T_a=Ambient Temperature

$$Q_u=m\ C_p\ (T_o-T_i)$$

Where,

m=Mass Flow

C_p=Specific Heat

T_o=Outlet Temperature

The heat exchanger effectiveness was also considered in the solar system performance:

$$Q_{HX}=\varepsilon\ (mC_p)_{min}\ (T_{co}-T_i)$$

Where,

Q_{HX}=Heat Exchanged through Heat Exchanger

ε=Heat Exchanger Effectiveness

T_{co}=Collector Outlet Temperature

After taking all the constraints into consideration, an array configuration of 15 circuits of 4 panels in series with a flow rate of 0.84 gpm/circuit was chosen. This system was analyzed using Excel and the performance of the system was examined throughout the analysis period of 9am to 4pm for a typical day in each month of the year. The hours of operation of the system were determined by looking at the system performance during the analysis period. The system will turn on once the system can produce a hot water temperature of at least 183 F for cooling and 113 F for heating. Any time the system operates below these temperature points the entire solar system, chiller and cooling tower would be shut off.

The cooling tower that was selected for the adsorption chiller was size at 116.6% the capacity of the chiller. The cooling tower sizing conditions can be seen in Table 8.3.1. Oversizing the cooling tower allowed for a significant increase in CHW output by decreasing the CW return temperature as low as possible; by combining an increase CHW temperature of 50 F, a HW input of at least 195 F and a CW return temperature of 76 F the chiller has the ability to operate upwards of 140% of its nominal capacity. Figure 8.2.1 shows the chiller performance curves for various condenser water return temperatures at 50 F CHW output, and to further encourage the oversizing of the cooling tower, the price difference between the selected tower and the model rated at 100% capacity is only $3000. Unfortunately this performance advantage is not seen in any energy modeling done for this thesis project due to the lack of sophistication in modeling software used.

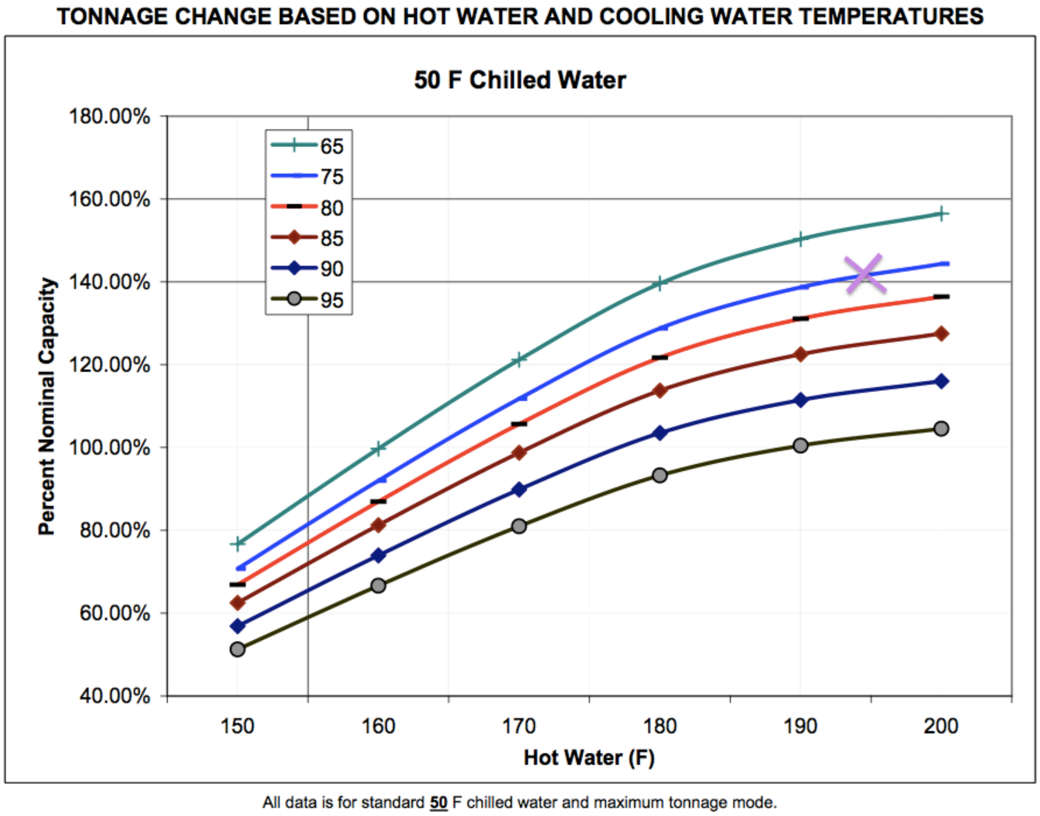


Figure 8.3.1: *Chiller Performance Curve at 50 F CHW (Provided by PowerPartners, Inc.)*

Table 8.3.1: Cooling Tower Sizing Conditions	
Tower Water Flow	72 GPM
Hot Water Temperature	95 F
Cold Water Temperature	76 F
Wet-Bulb Temperature	71 F

8.4 System Configuration

Due to the area limitation, the solar thermal system is unable to meet the demand of the chiller, however it does provide a significant amount of energy throughout the year. The chiller selected was a 10 ton chiller which is not capable of meeting the entire radiant cooling load. This requires campus chilled water to be coupled with the radiant system through a heat exchanger in order to meet the rest of the radiant cooling load as well as compensate for the fluctuations in CHW temperature due to the cycling of the adsorption chiller. This configuration will ensure a constant CHW water temperature of 50 F is being delivered to the system. The sun is also not constant, so hot water temperature will fluctuate throughout the day. Auxiliary steam heat will be used to ensure a constant temperature of 195 F HW will be supplied to the chiller for proper operation. Figure 8.4.2 shows the heating and cooling load relationship with useful direct normal solar radiation gain.

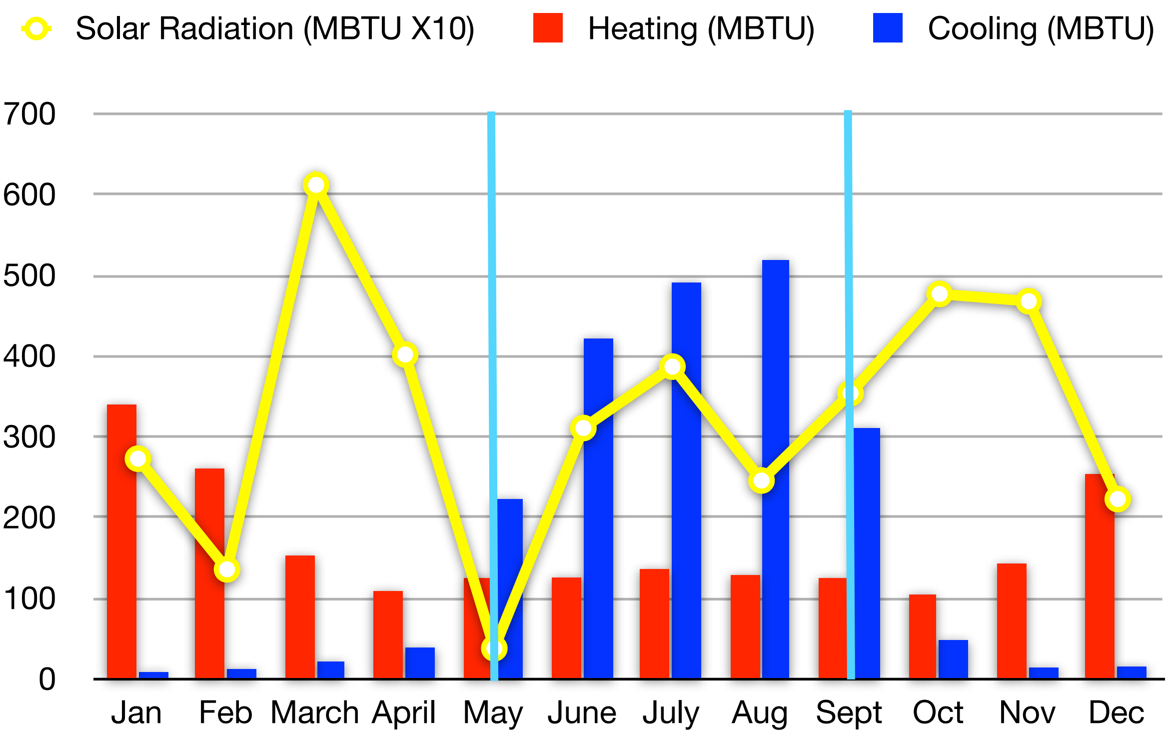


Figure 8.4.1: *Heating, Cooling and Solar Exposure Relationship*

The cyan lines in Figure 8.4.1 represent a switch in the solar system operation from heating to cooling mode. During the months of May to September, the solar radiant levels appear to be lower because the solar radiant line is the useful energy consumed in either the heating or cooling modes. Solar cooling is an energy intensive process compared to solar heating, where 20,000 BTUs are required to produce one ton of cooling compared to around 15,000 BTUs per ton for an electric compression driven system.

All new equipment was added to the penthouse. Figure 8.3.2 shows the arrangement of the new equipment in the penthouse. Figure 8.4.3 shows the interactions between each piece of added equipment.

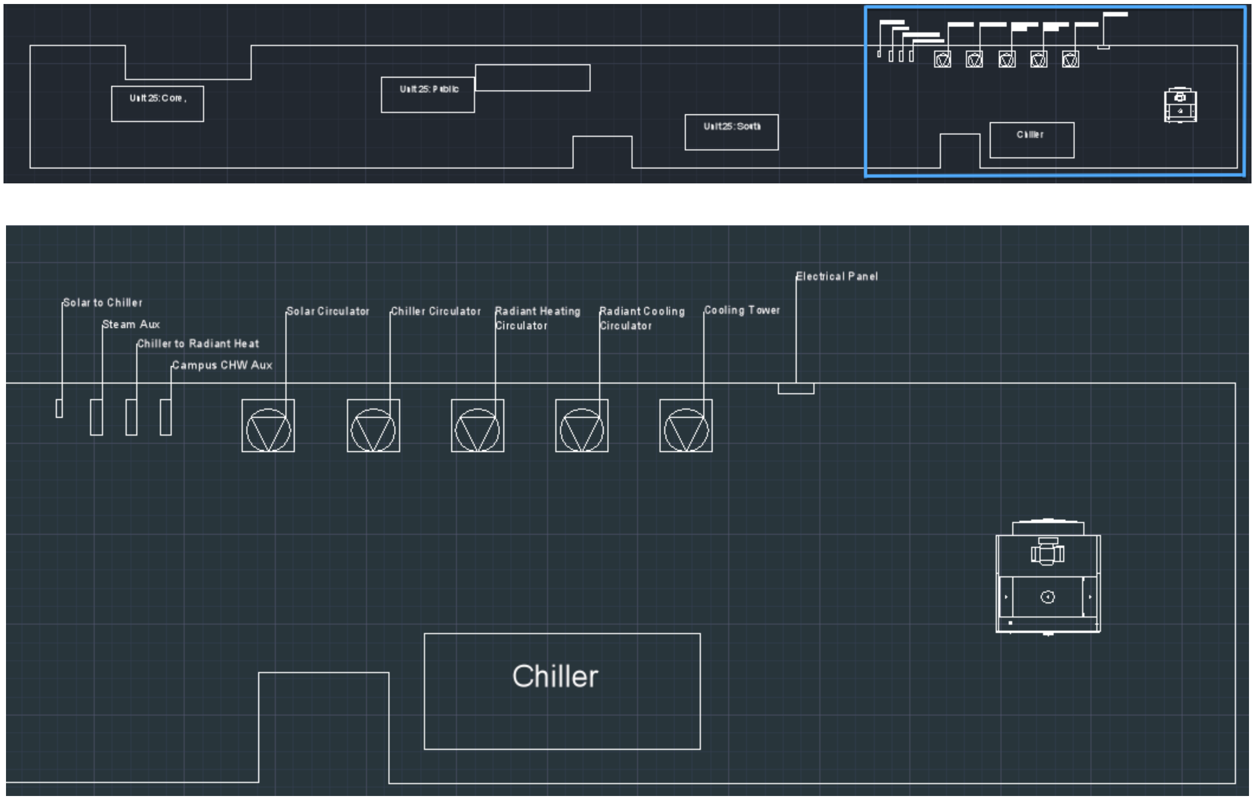


Figure 8.4.2: *Penthouse Equipment Layout*

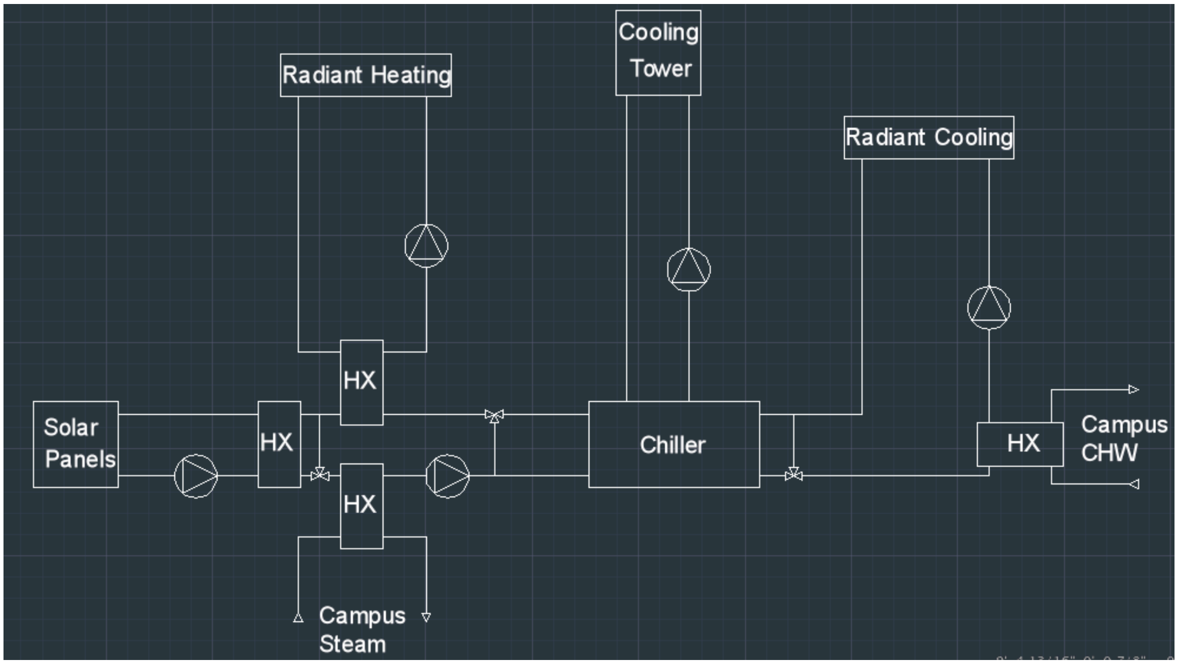


Figure 8.4.3: *System Flow Diagram*

8.5 Pump and Pipe Sizing

Piping was sized to meet the requirements of the system. Table 8.5.3 shows the pump sizing requirements for the solar circulator pump, chiller pump and condenser water pump.

Table 8.5.1: Solar, Chiller, Condenser Pump Sizes

Pump	System Head Loss (ft)	System Flow (gpm)	Pump HP	Impeller Size (in)
Solar System	29	10.08	0.25	5.25
Chiller Pump	48	40	1	6.5
Condenser Water	17	72	0.5	4.75

Section 9: Electrical Breadth

9.1 Objective

Account for the additional electrical load from the new equipment added. The reduction of each AHU will also have a reduction in electrical demand due to lower fan power requirements. The additional pumps, chiller and cooling tower loads will be accounted for in the new electrical components.

9.2 Calculations

Once the horsepower of each pump was determined, the full load amps was determined using NEC 2008. Table 9.2.1 shows the full load amps, branch circuit wire size and break size for each new piece of equipment. Chiller full load amps were taken from the product data sheet. All new equipment with the exception of the solar circulator pump was selected to run at 208V three phase, the solar circulator pump will operate at 120V single phase.

Table 9.2.1: New Equipment Power Requirements

Equipment	HP	V/PH/HZ	FLA	Branch Circuit Wire	Breaker Size
Solar Circulator Pump	0.25	120/1/60	5.8	#12 AWG	20
Radiant Heating Pump	0.75	208/3/60	3.5	#12 AWG	20
Radiant Cooling Pump	1	208/3/60	4.6	#12 AWG	20
Condenser Water Pump	0.5	208/3/60	2.4	#12 AWG	20
Chiller Pump	1	208/3/60	4.6	#12 AWG	20
Cooling Tower Fan	2	208/3/60	7.5	#12 AWG	20
Chiller	-	208/3/60	4.72	#12 AWG	20

The panel being used for the new equipment is a spare panel that was unused from the original design, the feeder and panel size was left as is since it can easily accommodate the additional load. None of the equipment added had a large electrical load, all components branch circuits were sized at #12 AWG wires with 20 A breakers. VFDs and motor starters that were capable of handling each of the loads were also selected. Table 9.2.2 shows which motors were equipped with VFDs and which are single speed.

Table 9.2.2: Schedule of VFD/Single Speed Motors	
Solar Circulator Pump	Single Speed
Radiant Heating Pump	VFD
Radiant Cooling Pump	VFD
Condenser Water Pump	Single Speed
Chiller Pump	VFD
Cooling Tower Fan	Single Speed

9.3 Equipment Adjustment and Additions

The additional electrical panel shown in the electrical design documents will be relocated from the ground floor electrical room to the penthouse. The panel provides power to the new equipment: chiller, cooling tower and pumps. Since a size-able amount of the heating and cooling load was shifted from the air system to the radiant system the air handling unit fans were reduced in size. Table 9.3.2 shows the new fan sizes, their respected power requirements, breaker and branch circuit wire sizes. All fans for the new air handling units will operate on 480V three phase as the original design called for. The new location for the panel can be seen in figure 8.3.1.

Table 9.3.2: New AHU Fan Power Requirements

AHU Fan by Zone	HP	FLA	Branch Circuit Wire	Breaker Size (A)
Core	7.5	11	#10	30
Lecture Hall	5	7.6	#12	20
North	7.5	11	#10	30
South	7.5	11	#10	30
Public	7.5	11	#10	30

Section 10: Structural Depth

10.1 Objective

Due to the addition of solar energy conversion systems being installed on the roof of BBH, the extra weight on the solar panels will have to be considered when installing the system. The roof structure will be analyzed and modified if necessary to accommodate the extra load from the solar panels. A typical floor will also be analyzed to account for the additional weight of the internal thermal mass.

10.2 Calculations

The fourth floor was analyzed to accommodate the additional weight of the new internal walls.

Table 10.2.1: Wall Dead Load Calculations	
Material	**Weight (PSF of Wall Area)**
8” HW CMU	65
4” Brick	38
4” Steel Stud w/ 1/2” GYP	8
New Wall Dead Load	111
Floor to Floor Wall Height (ft)	14
Estimated Length of Walls (ft)	947
Area of Wall (SF)	13258
Total Weight of Wall (lbs)	1471638
Area of Floor (SF)	12934
New Dead Load (PSF)	114

Table 10.2.1 shows the new dead load of 114 PSF due to the additional thermal mass; the original design dead load was 20 PSF for comparison. A single interior bay was analyzed where the beam spacing is approximately 10.33’. The loads used for the calculation can be found in Table 10.2.2.

10.2.2: Deck Loads	
Dead Load (PSF)	114
Live Load (PSF)	80
Super Imposed Dead Load (PSF)	10
Total Load on Deck	204

Unshored composite deck was selected with normal weight concrete. This was the same type of selection originally made in the design, however with the switch from lightweight concrete to normal weight. Using a deck span of 10’ 6” with a three span continuous scenario from the Vulcraft deck catalogue 2” deep 17 gauge VLI deck (2VLI17) with a topping of 4.5” normal weight concrete was selected, which can hold up to 10’ 7” unshored clear span and 219 PSF load at at space of 10’ 6” and has a deck weight of 69 PSF. The original deck selected was a 3” deep, 18 gauge deck with 3.25” topping of lightweight concrete.

The beams in this interior bay have a span of 29.5’ and are spaced 10.33’ apart. Using factored loads, the distributed load on the beam was determined to be W=3.6976 KLF. The loads used for the beam analysis can be seen in Table 10.2.3.

Table 10.2.3: Beam Loads	
Deck Weight (PSF)	69
Dead Load (PSF)	113
Super Imposed Dead Load (PSF)	10
Live Load (PSF)	80

$$W=1.2DL+1.6LL$$

$$M=WL^2/8$$

The maximum moment seen on the beam was determined to be M=402 ft K. A W 24x68 was determined to be an adequate size to support the additional load. Live and total load deflection checks were done to ensure proper serviceability requirements are met.

The live load deflection was determined to be 0.26" which is less than the code required 0.983". The total load deflection was determined to be 0.9" which is less than the code required 1.474". Both requirements are met with the selected W24x68 beam, for comparison the original beam specified was a W 16x31.

In review a new deck size of 2" deep 17 gauge VLI deck with 4.5" topping of normal weight concrete on W 24x68 beams will support the newly added weight of the thermal mass on the fourth floor.

The solar panels being added to the sloped slate roof come with mounting kits that attach to a subframe at six points. A frame consisting of HSS 2x1x1/8 members was designed to attach the mounting kits with solar panels to the roof framing, with the additional framing and panels, the roof framing would have to be analyzed to account for the extra load but due to the complexity of the roof structure, only the sub-framing was design to accommodate the additional load. Table 10.2.4 shows the weight of each panel and the approximate load at each connection point. Since the panels butt up to each other the load at each point will be double to account for each panel.

Table 10.2.4: Solar Panel Loads	
Weight of Each Panel (lbs)	252
Load per Connection (lbs)	84

Three cross beams will run the length of the room to support the weight of the panels. Each cross beam will be attached to the existing roof structure. Figure 10.2.1 shows the layout of the additional structural members. Each red box represents a solar panel and the blue lines represent the additional HSS structural members that were added to support the panels.

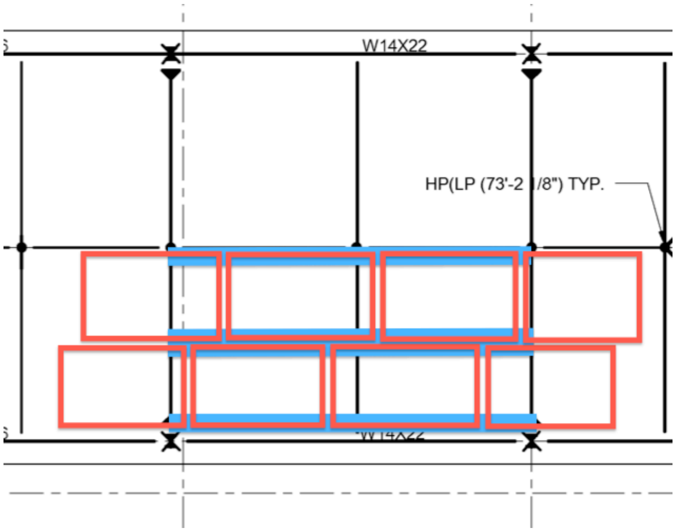


Figure 10.2.1: *Typical solar Panel Layout with Supporting Structure*

Section 11: Energy and Cost Evaluation

11.1 Energy Savings

Figure 11.1.1 shows the comparison of annual energy intensity for each of the four system configurations. Alternative four, which consists of all explored systems combined together results in an energy consumption of approximately 40 kBTU/SF, where the existing system consumed around 52 kBTU/SF this is about a 23% reduction in energy consumption.

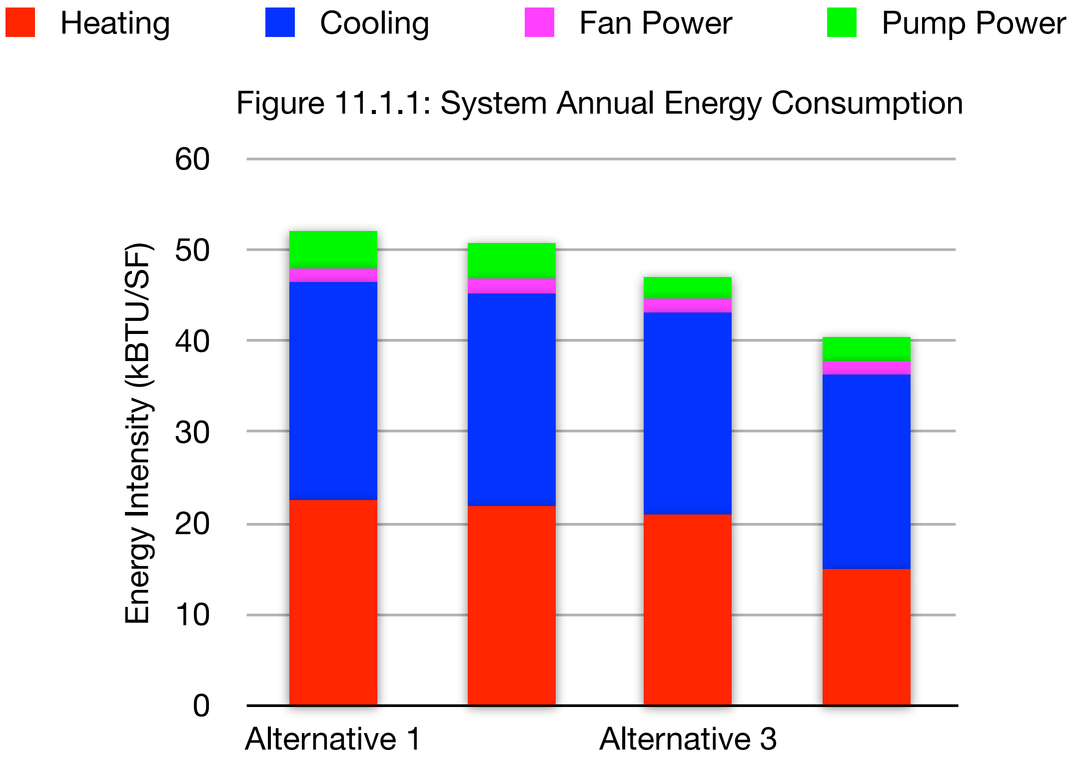


Figure 11.1.1: System Annual Energy Consumption

11.1 Cost

Table 11.1.1 shows the cost of the existing mechanical system, equipment being replaced, new equipment and the additional cost that would be added to the existing system cost.

Table 11.1.1: Alternative 4 (Total) First Cost

System	Cost ($)
Existing System	$3,424,000.00
Equipment Replaced	$213,151.00
Equipment Added	$1,365,924.00
New System	$4,576,773.00
Difference	$1,152,773.00

When performing a discounted payback, the system should pay for itself in just under 58 years. Given the design goal of the building to last 100 years, this system will produce a net savings of $742,746.24 or compared to the existing system it would save $1,852,237.56 over the life of the building. The payback of each individual system can be seen in Table 11.1.2. This table clearly shows that the solar thermal system has the quickest return on investment with a simple payback period of 12 years.

Table 11.1.2: System Payback Period

System	First Cost	Estimated Savings/ Year	Simple Payback Period (years)
Heat Recovery	$104,458	$4,600	23
Radiant Heating/ Cooling	$1,100,923	$3,406	323
Solar Thermal	$160,544	$6,932	23
Combined Systems	$1,365,925	$14,938	91

Section 12: Conclusion and Recommendation

When analyzing the payback period of each system configuration, the Penn States goal of building a 100 year building was taken into account and used as the analysis period.

Unfortunately, some of the performance advantages of the system are not seen in any of the energy model predictions. Due to the lack of sophistication of the software used for energy usage estimation, the additional performance boost of the chiller from the over size cooling tower, or increase in performance from boosting chilled water from 45 F to 50 F is seen in the results. Another issue that was encountered was the difficulty in modeling a radiant heating and cooling system. Efforts to represent the performance of a radiant system, both heating and cooling systems were modeled as radiant fin tube systems. This modeling technique allows for a reasonable estimate of the energy consumption of the system, without modeling the exact system designed. In the modeling software, both design heating and coolings loads were set as design constraints and allowed the software to simulate the annual energy consumption to heat and cool the space, as well as the pump energy required to operate each system. Since the modeled system is not exact, there will be difference between the performance of the modeled system and the performance of the actual system designed.

12.1 Thermal Mass

Thermal mass option 1 reduced the modeled cooling load by 5 tons as well as a 1.3 kBTU/SF or about 2.5% reduction in annual mechanical system energy consumption. This option also has the ability to counter the negative acoustical effects imposed on each space from the radiant ceiling tiles that replace acoustical ceiling tiles. The additional material needed for the walls was not priced but the savings from the new wall composition was not significant enough to say that the upfront cost is worth the investment.

12.2 Radiant System

The radiant system turned out to be the most expensive system explored in this analysis. The total system provided a 1 kBTU/SF or about 2% reduction in annual mechanical system energy consumption. Three recommendations to improve the investment would be one, to reduce the area that is conditioned by radiant panels to reduce the first cost and slightly improve the payback period, two; increase the flow rate or HW temperature through the panels, this would increase the BTU output for each panel which would reduce the number of panels needed and three; avoid using a radiant heating and cooling system. BBH is already an efficient, well designed building.

12.3 Heat Recovery

The heat recovery system was the least expensive system that was explored. Incorporating this system into the building resulted in approximately a 4 kBTU/SF or 7.6% reduction in annual mechanical system energy consumption. This is the first system encountered that would provided a reasonable simple payback period of 23 years which is well within the life of the building.

12.4 Solar System

The solar thermal system is the second most expensive system investigated. This system provided approximately a 13% reduction in heating energy and a 4% reduction in cooling energy required. Like the heat recovery system, this solar system had a 23 year payback period.

12.5 Recommendation

In conclusion, the object of this thesis was satisfied in finding methods to reduce the building energy consumption. However, not all systems that were investigated provided an energy reduction in an economic fashion. It would be recommended to not follow through with increasing internal thermal mass or install a radiant heating and cooling system. The first cost of the radiant system is too high and the savings do not justify the means. However, a useful system that can be drawn out of this is keeping the existing VAV system and incorporating the heat recovery system and the solar thermal system. The solar thermal system could be readjusted to feed into the AHU hot and chilled water loops and still provide a reasonable return on investment. However, without reducing the size of the existing AHUs, there may not be enough room in the building for the additional equipment required for the solar system.

The combination of the heat recovery and solar system greatly reduce the first cost of the system while still providing a 8.6 kBTU/SF or 16.5% reduction in annual mechanical system energy consumption. The discounted payback for this system is about 16 years, a significant improvement over the alternative that included the radiant system. Over the 100 year analysis period, this new system will save about $1.6 million dollars which is about 4 times what the additional equipment costs. Figure 12.5.1 shows the comparison of the new recommended system to the previous 4 alternative systems explored.

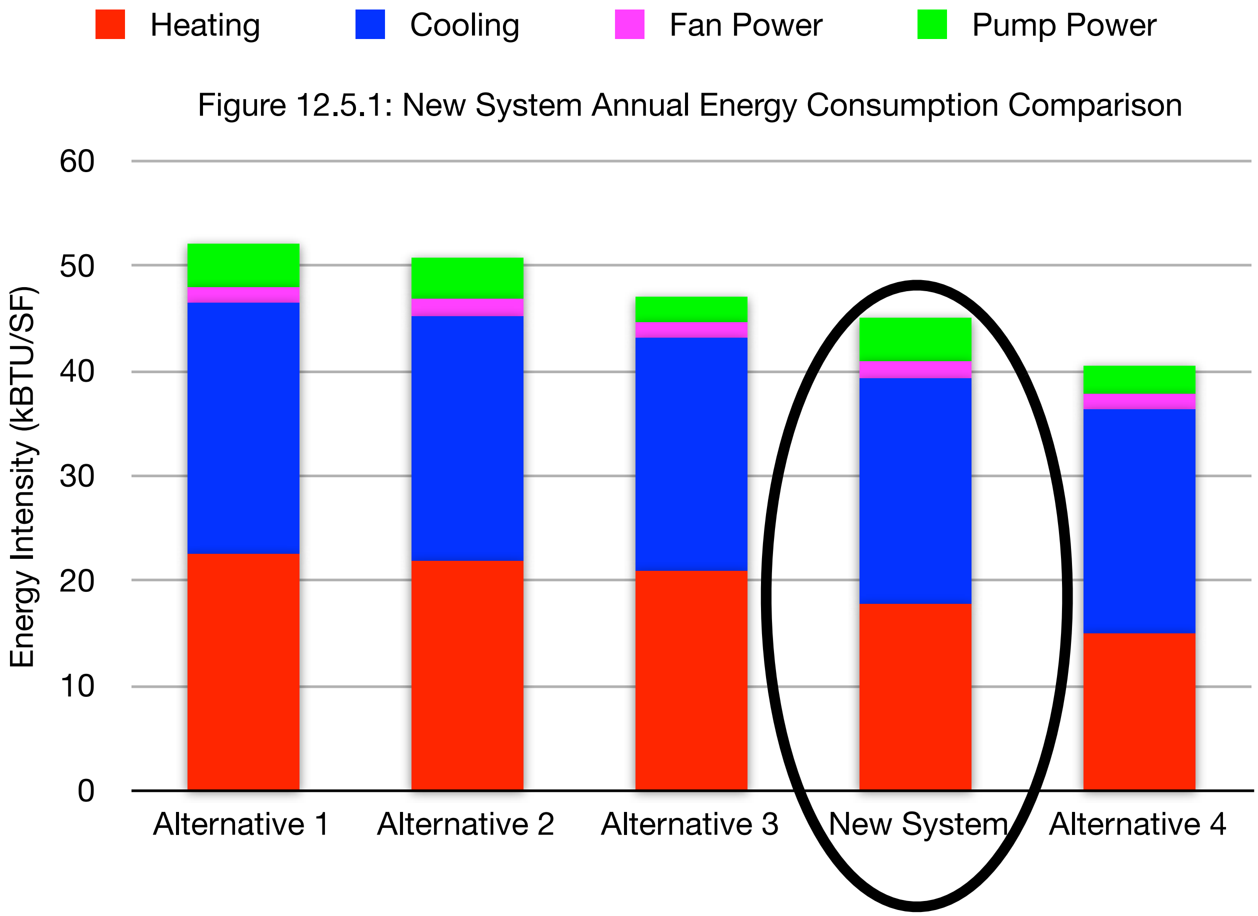


Figure 12.5.1: New System Annual Energy Consumption Comparison

References

ASHRAE. (2007). *Standard 62.1 - 2007, Ventilation for Acceptable Indoor Air Quality.* Atlanta, GA: American Society of Heating Refrigeration and Air Conditioning Engineers, Inc.

ASHRAE. (2007). *Standard 90.1 - 2007, Energy Standard for Buildings Except Low-Rise Residential Buildings.* Atlanta, GA: American Society of Heating Refrigeration and Air Conditioning Engineers, Inc.

ASHRAE. (2001). *Handbook of Fundamentals.* Atlanta: ASHRAE

ASHRAE. (2007). *Handbook of HVAC Applications.* Atlanta: ASRHAE

Bohlin Cywinski Jackson. Architectural Construction Documents. Wilkes-Barre, PA.

Bruce E. Brooks & Associates. Electrical Construction Documents. Philadelphia, PA.

Bruce E. Brooks & Associates. Mechanical Construction Documents. Philadelphia, PA.

Copley, Jake. *Project Charter - Biobehavioral Health Building.* Working Paper. University Park, PA: Penn State, 2011. Print

Duffie, John A., and William A. Beckman. Solar Engineering of Thermal Processes. 3. Hoboken: John Wiley & Sons, Inc, 2006. Print.

Kalogirou, Soteris A. Solar Energy Process and Systems. 1. Burlington: Elsevier Inc., 2009. Print.

"Radiant Panel Example-Cooling." Radiant Heating & Cooling Systems. Price, n.d. Web. 2 Apr 2012. <http://www.price-hvac.com/Catalog/Section_H/Design_Guide/Cooling_Design_Calculations/Radiant_Panel_Example.asp&xgt;.

United States. Energy Information Administration. Table E2A. Major Fuel Consumption (BTU) Intensities by End Use for All Buildings, 2003. 2003. Web

USGBC. (2009). *LEED 2009 for New Construction and Major Renovations*. United States Green Building Council.

Appendix: Radiant Calcs

Floor	Zone	Sensible Load (BTU/hr)	Latent Load (BTU/hr)	Area (SF)	Maximum # of Panels	EWT	MWT	DT (Degrees F)	Ventilation Rate (CFM/SF)	Ventilation Air (CFM)	Wv	Wroom	Cooling Capacity of Ventilation Air (BTU/hr)		Adjusted Ventilation Air (CFM)	Adjusted Cooling Capacity of Ventilation Air (BTU/hr)		Required Radiant Sensible Cooling (BTU/hr)	BTU/h/SF	Panel Size (Feet)	Panel Cooling Capacity (BTH/hr)	Number of Panels Required	Max # of Panels	Zone Max Number of Panels in Series	Zone Flow Rate Required (GPM)
													Latent	Sensible		Latent	Sensible								
Ground	Core	204200	121100	24149.8	3622	50	52.5	22.5	0.128	3091.2	0.0032	0.0102	104729.(	102008.8	3,574.4	121,100.0	117,954.5	86,245.5	4	2			3,622		0.0
First	North	40300	11600	2354.8	353					301.4			10211.9	9946.7	342.4	11,600.0	11,298.7	29,001.3	12	2	121	240	353	12	2.6
	South	46600	13300	2650.6	398					339.3			11494.7	11196.1	392.6	13,300.0	12,954.5	33,645.5	13	2	121	278	398		3.0
	Core	41900	15700	3436.6	515					439.9			14903.3	14516.2	463.4	15,700.0	15,292.2	26,607.8	8	4	181	147	515		2.4
	Public	105000	33700	7053.4	1058					902.8			30588.1	29793.6	994.7	33,700.0	32,824.7	72,175.3	10	2	121	596	1,058		6.4
Second	North	47500	11900	2350.7	353					300.9			10194.1	9929.4	351.2	11,900.0	11,590.9	35,909.1	15	2	121	297	353		3.2
	South	79900	19900	3896	584					499			16895.5	16456.7	587.4	19,900.0	19,383.1	60,516.9	16	2	121	500	584		5.4
	Core	53400	17900	3770.7	566					482.6			16352.2	15927.4	528.3	17,900.0	17,435.1	35,964.9	10	2	121	297	566		3.2
	Public	92900	27000	5454.4	818					698.2			23653.8	23039.4	796.9	27,000.0	26,298.7	66,601.3	12	2	121	550	818		5.9
Third	North	52000	12100	2354.7	353					301.4			10211.5	9946.3	357.1	12,100.0	11,785.7	40,214.3	17	2	121	332	353		3.6
	South	98100	22900	4410.6	662					564.6			19127.2	18630.4	675.9	22,900.0	22,305.2	75,794.8	17	2	121	626	662		6.7
	Core	55800	18000	3770.7	566					482.6			16352.2	15927.4	531.3	18,000.0	17,532.5	38,267.5	10	2	121	316	566		3.4
	Public	78400	23900	4935.8	740					631.8			21404.8	20848.8	705.4	23,900.0	23,279.2	55,120.8	11	2	121	456	740		4.9
Forth	North	55100	15300	2950.3	443					377.6			12794.4	12462.1	451.6	15,300.0	14,902.6	40,197.4	14	2	121	332	443		3.6
	South	92600	19700	3582.6	537					458.6			15536.4	15132.9	581.5	19,700.0	19,188.3	73,411.7	20	2	121	607	537		6.5
	Core	30400	9300	1849.8	277					236.8			8021.9	7813.6	274.5	9,300.0	9,058.4	21,341.6	12	2	121	176	277		1.9
	Public	70600	20500	4005.3	601					512.7			17369.5	16918.4	605.1	20,500.0	19,967.5	50,632.5	13	2	121	418	601		4.5
		1244700	413800												12,213.7	292,700.0	285,097.4	755,402.6				6,170			67.1
		138														48		62.95021645							

Floor	Zone	Heat Loss (BTU/hr)	Area (SF)	Maximum # of Panels	EWT	MWT	DT (Degrees F)	Ventilation Rate (CFM/SF)	Ventilation Air (CFM)	Heating Capacity of Ventilation Air (BTU/hr)	Required Radiant Sensible Heating (BTU/hr)	BTU/h/SF	Panel Size (Feet)	Panel Heating Capacity (BTH/hr)	Number of Panels Required	Max # of Panels	Zone Max Number of Panels in Series	Zone Flow Rate Required (GPM)	Number of Series Circuits	Flow per Series Circuit	Delta P/L	Length of Pipe per Series Circuit	Number of 180 Turns
Ground	Core	80048000	24149.8	3622	128	125.5	55.5	0.128	3574.4	39318.2	80,008,681.8	3,313				3,622		0.0					72.0
First	North	68430	2354.8	353					342.4	3766.2	64,663.8	27	2	237	273	353	12	2.3	23	0.1	0.5	144.0	
	South	76470	2650.6	398					392.6	4318.2	72,151.8	27	2	237	304	398		2.6	25	0.1	0.5	144.0	
	Core	66410	3436.6	515					463.4	5097.4	61,312.6	18	4	485	126	515		2.2	11	0.2	0.5	288.0	
	Public	169770	7053.4	1058					994.7	10941.6	158,828.4	23	2	237	670	1,058		5.7	56	0.1	0.5	144.0	
Second	North	71410	2350.7	353					351.2	3863.6	67,546.4	29	2	237	285	353		2.4	24	0.1	0.5	144.0	
	South	113240	3896	584					587.4	6461.0	106,779.0	27	2	237	451	584		3.8	38	0.1	0.5	144.0	
	Core	70300	3770.7	566					528.3	5811.7	64,488.3	17	2	237	272	566		2.3	23	0.1	0.5	144.0	
	Public	124960	5454.4	818					796.9	8766.2	116,193.8	21	2	237	490	818		4.2	41	0.1	0.5	144.0	
Third	North	74980	2354.7	353					357.1	3928.6	71,051.4	30	2	237	300	353		2.6	25	0.1	0.5	144.0	
	South	133790	4410.6	662					675.9	7435.1	126,354.9	29	2	237	533	662		4.6	44	0.1	0.5	144.0	
	Core	72370	3770.7	566					531.3	5844.2	66,525.8	18	2	237	281	566		2.4	23	0.1	0.5	144.0	
	Public	10948	4935.8	740					705.4	7759.7	3,188.3	1	2	237	13	740		0.1	1	0.1	0.5	144.0	
Forth	North	87480	2950.3	443					451.6	4967.5	82,512.5	28	2	237	348	443		3.0	29	0.1	0.5	144.0	
	South	132860	3582.6	537					581.5	6396.1	126,463.9	35	2	237	534	537		4.6	44	0.1	0.5	144.0	
	Core	45520	1849.8	277					274.5	3019.5	42,500.5	23	2	237	179	277		1.5	15	0.1	0.5	144.0	
	Public	110200	4005.3	601					605.1	6655.8	103,544.2	26	2	237	437	601		3.7	36	0.1	0.5	144.0	
										95032.5	1,334,105.5				5,497			48.1					

Floor	Zone	Number of Series Circuits	Flow per Series Circuit	Delta P/L	Length of Pipe per Series Circuit	Number of 180 Turns	45 Degree Elbows (K)	Equiv Length of Fittings (ft)	Pipe Friction Loss for Each Series Circuit	Flow Rate per Floor (GPM)	Length of Run (ft)	Floor Pipe Size (in)	Delta P/100ft	Rise Pipe Flow (GPM)	Rise Pipe Size (in)	Delta P/100ft	Rise Height (ft)	Head Loss per Zone (ft)	Floor Head Loss (ft)	System Head Loss (ft)
Ground	**Core**					72.0	16.0													
First	**North**	20	0.1	0.5	144.0			192.0000	1.7	14.3	317.0	1.5	1.7	67.1	3.0	1.0	28.0	7.1	8.1	13.5
	South	23	0.1	0.5	144.0			192.0000	1.7									7.1		
	Core	12	0.2	0.5	288.0			192.0000	2.4									7.8		
	Public	50	0.1	0.5	144.0			192.0000	1.7									7.1		
Second	**North**	25	0.1	0.5	144.0			192.0000	1.7	17.7		2.0	0.7	52.8	3.0	0.7	14.0	3.9	4.2	
	South	42	0.1	0.5	144.0			192.0000	1.7									3.9		
	Core	25	0.1	0.5	144.0			192.0000	1.7									3.9		
	Public	46	0.1	0.5	144.0			192.0000	1.7									3.9		
Third	**North**	28	0.1	0.5	144.0			192.0000	1.7	18.6		2.0	0.8	35.1	2.5	0.9	14.0	4.2	4.7	
	South	52	0.1	0.5	144.0			192.0000	1.7									4.2		
	Core	26	0.1	0.5	144.0			192.0000	1.7									4.2		
	Public	38	0.1	0.5	144.0			192.0000	1.7									4.2		
Forth	**North**	28	0.1	0.5	144.0			192.0000	1.7	16.5	295.0	1.5	2.0	16.5	1.5	2.0	14.0	7.6	9.0	
	South	51	0.1	0.5	144.0			192.0000	1.7									7.6		
	Core	15	0.1	0.5	144.0			192.0000	1.7									7.6		
	Public	35	0.1	0.5	144.0			192.0000	1.7									7.6		
																	70.0			

Floor	Zone	45 Degree Elbows (K)	Equiv Length of Fittings (ft)	Pipe Friction Loss for Each Series Circuit	Flow Rate per Floor (GPM)	Length of Run (ft)	Floor Pipe Size (in)	Delta P/100ft	Rise Pipe Flow (GPM)	Rise Pipe Size (in)	Delta P/100ft	Rise Height (ft)	Head Loss per Zone (ft)	Floor Head Loss (ft)	System Head Loss (ft)
Ground	**Core**	16.0													
First	**North**		192.0000	1.7	12.9	317.0	1.5	1.0	48.1	3.0	0.6	28.0	4.9	5.7	8.6
	South		192.0000	1.7									4.9		
	Core		192.0000	2.4									5.6		
	Public		192.0000	1.7									4.9		
Second	**North**		192.0000	1.7	12.8		1.5	1.0	35.2	2.5	0.9	14.0	4.9	5.2	
	South		192.0000	1.7									4.9		
	Core		192.0000	1.7									4.9		
	Public		192.0000	1.7									4.9		
Third	**North**		192.0000	1.7	9.6		1.5	0.8	22.4	2.0	0.9	14.0	4.2	4.7	
	South		192.0000	1.7									4.2		
	Core		192.0000	1.7									4.2		
	Public		192.0000	1.7									4.2		
Forth	**North**		192.0000	1.7	12.8	295.0	1.5	1.0	12.8	1.5	1.0	14.0	4.6	5.3	
	South		192.0000	1.7									4.6		
	Core		192.0000	1.7									4.6		
	Public		192.0000	1.7									4.6		

Appendix: Solar Thermal Calcs

Hour																									
May	**Average Direct Normal (BTU/hr/sf)**	**Number of Collectors**	**Collector Area (sf)**	**Total Collector Area (sf)**	**Heat Removal Factor**	**Total Thermal Loss ((BTU/hr)/sfF))**	**Ambient Temperature**	**Useful Gain per Collector (BTU/hr)**	**Flow Rate (GPM)**	**Specific Heat of Fluid (BTU/lmbF)**	**Inlet Temperature (Degree F)**	**Outlet Temperature (Degree F)**	**HX Effectiveness**	**HX Surface Area (SF)**	**Overall Heat Transfer Coefficient (BTU/hfSFF)**	**C**	**NTU**	**Qhx**	**To (F)**	**VHP-30**	**Number of Circuits**	**Solar Side System Flow (gpm)**	**Specific Heat of Water (BTU/lmbF)**	**Chiller Side Loop Flow**	**Heat Supplied by Solar System (BTU/hr)**
9,10	66	4	30.04	120.16	0.92	0.006567	56	7296	0.84	0.7	56	81	0.9036	9	1331	0.2205	2.7163	-581718	154	60	15.0	12.6	1	40	-581718
10,11	49							5399	0.84		81	99						-477178	159			12.6			-477178
11,12	59							6491	0.84		99	121						-351490	165			12.6			-351490
12,1	69							7580	0.84		121	147						-204707	173			12.6			-204707
1,2	54							5903	0.84		147	167						-90395	178			12.6			-90395.1
2,3	59							6442	0.84		167	189						34337	185			12.6			34337.4
3,4	55							5991	0.84		179	199						93232	188			12.6			93231.7
June																									
Hour																									
9,10	135	4	30.04	120.16	0.92	0.006567	55.9	14924	0.84	0.7	55.9	107	0.9036					-434586	161	60	15.0	12.6	1	40	-434586
10,11	132							14555	0.84		107	156						-152743	175			12.6			-152743
11,12	123							13525	0.84		156	202						109140	188			12.6			109140
12,1	112							12292	0.84		179	221						215244	194			12.6			215244
1,2	120							13176	0.84		179	224						232368	195			12.6			232368
2,3	120							13176	0.84		179	224						232368	195			12.6			232368
3,4	128							14061	0.84		179	227						249493	195			12.6			249493
July																									
Hour																									
9,10	149	4	30.04	120.16	0.92	0.006567	69.6	16472	0.84	0.7	69.6	126	0.9036					-326626	167	60	15.0	12.6	1	40	-326626
10,11	125							13778	0.84		126	172						-59840	180			12.6			-59840
11,12	139							15291	0.84		172	225						236255	195			12.6			236255
12,1	143							15729	0.84		179	232						281794	197			12.6			281794
1,2	125							13739	0.84		179	226						243264	195			12.6			243264
2,3	143							15729	0.84		179	232						281794	197			12.6			281794
3,4	128							14071	0.84		179	227						249686	195			12.6			249686
August																									
Hour																									
9,10	80	4	30.04	120.16	0.92	0.006567	71.6	8844	0.84	0.7	71.6	102	0.9036					-462940	160	60	15.0	12.6	1	40	-462940
10,11	97							10701	0.84		102	138						-255726	170			12.6			-255726
11,12	114							12554	0.84		138	181						-12634	182			12.6			-12634.0
12,1	111							12193	0.84		179	220						213324	194			12.6			213324
1,2	113							12414	0.84		179	221						217605	194			12.6			217605
2,3	116							12746	0.84		179	222						224027	194			12.6			224027
3,4	90							9871	0.84		179	213						168371	191			12.6			168371
September																									
Hour																									
9,10	120	4	30.04	120.16	0.92	0.006567	60	13266	0.84	0.7	60	105	0.9036					-443354	161	60	15.0	12.6	1	40	-443354
10,11	122							13454	0.84		105	151						-182837	174			12.6			-182837
11,12	138							15190	0.84		151	203						111286	189			12.6			111286
12,1	151							16606	0.84		179	235						298784	198			12.6			298784
1,2	142							15611	0.84		179	232						279519	197			12.6			279519
2,3	134							14727	0.84		179	229						262394	196			12.6			262394
3,4	118							12958	0.84		179	223						228145	194			12.6			228145
October																									
Hour																									
9,10	120	4	30.04	120.16	0.92	0.006567	52.5	13266	0.84	0.7	52.5	98	0.9036					-87549	109	60	15.0	12.6	1	40	-87549.1
10,11	123							13565	0.84		98	144						175109	122			12.6			175109
11,12	135							14880	0.84		113	164						288129	127			12.6			288129
12,1	136							14990	0.84		113	164						290269	128			12.6			290269
1,2	140							15433	0.84		113	165						298832	128			12.6			298832
2,3	133							14659	0.84		113	163						283847	127			12.6			283847
3,4	120							13222	0.84		113	158						256020	126			12.6			256020
November																									
Hour																									
9,10	117	4	30.04	120.16	0.92	0.006567	57.4	12934	0.84	0.7	57.4	101	0.9036					-66076	110	60	15.0	12.6	1	40	-66075.7
10,11	128							14118	0.84		101	149						207301	123			12.6			207301
11,12	136							14994	0.84		113	164						290338	128			12.6			290338
12,1	139							15326	0.84		113	165						296760	128			12.6			296760
1,2	127							13999	0.84		113	161						271073	127			12.6			271073
2,3	125							13778	0.84		113	160						266792	126			12.6			266792
3,4	108							11899	0.84		113	153						230402	125			12.6			230402
December																									
Hour																									
9,10	105	4	30.04	120.16	0.92	0.006567	33.2	11607	0.84	0.7	33.2	73	0.9036					-229531	102	60	15.0	12.6	1	40	-229531
10,11	102							11247	0.84		73	111						-11746	112			12.6			-11745.8
11,12	92							10114	0.84		111	145						184095	122			12.6			184095
12,1	69							7570	0.84		113	139						146579	120			12.6			146579
1,2	58							6354	0.84		113	135						123032	119			12.6			123032
2,3	68							7459	0.84		113	138						144438	120			12.6			144438
3,4	69							7570	0.84		113	139						146579	120			12.6			146579
January																									
Hour																									
9,10	90	4	30.04	120.16	0.92	0.006567	27.8	9949	0.84	0.7	27.8	62	0.9036					-292381	168	60	15.0	12.6	1	40	1107619
10,11	97							10699	0.84		62	98						-85220	179			12.6			1314780
11,12	98							10783	0.84		98	135						123570	189			12.6			1523570
12,1	94							10330	0.84		113	148						200017	193			12.6			1600017
1,2	101							11103	0.84		113	151						215002	194			12.6			1615002
2,3	100							10993	0.84		113	150						212861	194			12.6			1612861
3,4	75							8229	0.84		113	141						159346	191			12.6			1559346

Hour May	Average Direct Normal (BTU/hr/sf)	Number of Collectors	Collector Area (sf)	Total Collector Area (sf)	Heat Removal Factor	Total Thermal Loss ((BTU/hr)/sfF))	Ambient Temperature	Useful Gain per Collector (BTU/hr)	Flow Rate (GPM)	Specific Heat of Fluid (BTU/lmbF)	Inlet Temperature (Degree F)	Outlet Temperature (Degree F)	HX Effectiveness	HX Surface Area (SF)	Overall Heat Transfer Coefficient (BTU/hfSFF)	C	NTU	Qhx	To (F)	VHP-30	Number of Circuits	Solar Side System Flow (gpm)	Specific Heat of Water (BTU/lmbF)	Chiller Side Loop Flow	Heat Supplied by Solar System (BTU/hr)
FEB																									
Hour																									
9,10	52	4	30.04	120.16	0.92	0.006567	35.9	5748	0.84	0.7	35.9	55	0.9036					-327611	97	60	15.0	12.6	1	40	-327611
10,11	59							6508	0.84		55	78						-201591	103			12.6			-201591
11,12	59							6492	0.84		78	100						-75883	109			12.6			-75882.6
12,1	55							6034	0.84		100	120						40953	115			12.6			40953.2
1,2	75							8235	0.84		113	141						159460	121			12.6			159460
2,3	62							6798	0.84		113	136						131633	120			12.6			131633
3,4	58							6356	0.84		113	135						123070	119			12.6			123070
March																									
Hour																									
9,10	156	4	30.04	120.16	0.92	0.006567	34.5	17245	0.84	0.7	34.5	93	0.9036					-112960	107	60	15.0	12.6	1	40	-112960
10,11	156							17203	0.84		93	152						220147	124			12.6			220147
11,12	163							17962	0.84		113	174						347812	130			12.6			347812
12,1	181							19952	0.84		113	181						386343	132			12.6			386343
1,2	189							20836	0.84		113	184						403467	133			12.6			403467
2,3	169							18625	0.84		113	176						360656	131			12.6			360656
3,4	151							16636	0.84		113	170						322125	129			12.6			322125
April																									
Hour																									
9,10	140	4	30.04	120.16	0.92	0.006567	46.7	15477	0.84	0.7	46.7	99	0.9036					-77756	109	60	15.0	12.6	1	40	-77756
10,11	132							14554	0.84		99	149						204061	123			12.6			204061
11,12	127							13991	0.84		113	161						270922	127			12.6			270922
12,1	112							12333	0.84		113	155						238814	125			12.6			238814
1,2	114							12554	0.84		113	156						243095	125			12.6			243095
2,3	95							10454	0.84		113	149						202424	123			12.6			202424
3,4	86							9459	0.84		113	145						183158	122			12.6			183158

Appendix: Pump Sizing Calcs

	Pump					
Head Loss	**Solar Panel Circulator**	**Chiller Circulator**	**Radiant Heating Circulator**	**Condenser Water Pump**	**Radiant Cooling Circulator**	
HX (ft)	11.5	39.2	16.2	-	13.9	
Chiller (ft)	-	2	-	6	4	
Radiant Panel (ft)	-	-	8.6	-	13.5	
Solar Panels (ft)	14	-	-	-	-	
Cooling Tower (ft)	-	-	-	7.375	-	
Building Height (ft)	-	-	-	-	-	
Flow (gpm)	10.08	40	48.1	72	67.1	
Pipe Size (in)	0.75	2.5	-	2.5	-	
Length of Pipe (ft)	250	350	-	65	-	
Delta P/100ft	0.6	1.3	-	3.5	-	
Friction Loss (ft)	2.25	6.825	-	3.4125	-	
Effect of Propylene Glycol	1.0381					
Total (ft)	29	48	25	17	31	
Pump HP	0.25	1	0.75	0.5	1	
Pump Impeller Size (in)	5.25	6.5	8	4.75	9	
Pump RPM	1750	1750	1150	1750	1150	
Model	Series 60 1x1x5.25	Series 60 1.5x.15x7	Series 80 1.5x1.5x9.5	Series 60 1.5x1.5x5.25	Series 80 1.5x.15x9.5	
V-PH-HZ	120/1/60	208/3/60	208/3/60	208/3/60	208/3/60	
Current (A)	5.8	4.6	3.5	2.4	4.6	
Power Factor	0.6	0.6	0.6	0.6	0.6	
Consumption (kW)	0.72384	0.99430656	0.7565376	0.51876864	0.99430656	

Appendix: Structural Breadth

LOAD ANAYSIS'S

DEADLOADS:

8" HW CMU : ≈ 65 PSF

4" BRICK: 38 PSF

STEEL STUD / ½" GYP : 8 PSF

65 + 38 + 8 = 111 PSF

WALL HEIGHT: = 14'

LIVE LOAD:

OFFICE: 80 PSF

LENGTH OF WALL ≈ 148 x 2

165

10 x 32

+ 40 x 2 ← ADDITIONAL MISC WALLS

861 x 1.1

947' OF WALL

TOTAL AREA OF WALL = 14 x 947' = 13258 SF OF WALL

NEW DEAD LOAD = 13258 SF x 111 PSF = 1471638 lbs

DISTRIBUTED DL = $\frac{1471638 \text{ lbs}}{12934 \text{ SF}}$ = $\boxed{113 \text{ PSF}}$ OLD DEAD LOAD 20 PSF

DECK ANALYSIS

BEAM SPACING ≈ 10.33'

LOADS:

DL = 113 PSF

LL = 80 PSF

SIDL = 10 PSF (ASSUMPTON)

- USE COMPOSITE DECK
- UNSHORED
- USE NORMAL WEIGHT CONC

SUPER IMPOSED LIVE LOAD = 113 + 80 + 10 = 203 PSF

USE 10'6" SPAN 3 SPAN

USE 2VLI17

6½" t = 4½"

69 PSF

10'7" UNSHORED CLEAR SPAN

219 PSF SUPERIMPOSED LIVE LOAD AT 10'6"

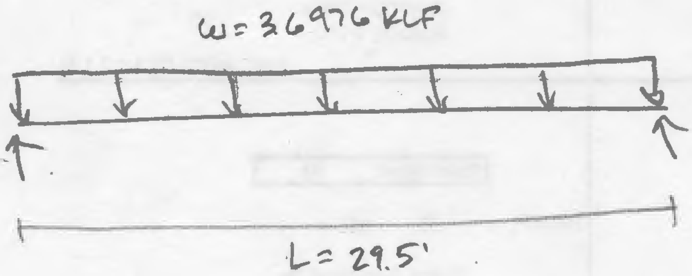
BEAM ANALYSIS

$w = 1.2D + 1.6L$ $D = 69 + 113 + 10 = 192 \text{ PSF} \times 10.33' = 1.98 \text{ KLF}$

$L = 80 \text{ PSF} \times 10.33' = 0.826 \text{ KLF}$

$w = 1.2(1.98 \text{ KLF}) + 1.6(0.826 \text{ KLF})$

$w = 3.6976 \text{ KLF}$



$$M = \frac{wL^2}{8}$$

$$M = \frac{3.6976(29.5)^2}{8}$$

$$\boxed{M = 402 \text{ ft}\cdot\text{K}}$$

W 21x50

$\phi_b M_{px} = 413 \text{ ft}\cdot\text{K} > 402 \text{ ft}\cdot\text{K} + \text{BEAM WEIGHT}$ X

$50 \text{ PLF} \times 29.5 = w_{DL}$ $M = \frac{wL^2}{8} = 160 \text{ Kf}$

$w_a = 1.475 \text{ KLF}$

W 24x62

$\phi_b M_{px} = 574 \text{ ft}\cdot\text{K} > 402 \text{ ft}\cdot\text{K} + \text{BEAM}$ x

$62 \times 29.5 = 1.829 \text{ KLF}$ $M = 198 \text{ ft}\cdot\text{K}$

$\boxed{W\,24\text{x}68} = 664 > \overbrace{402 + \text{BEAM}}^{619}$ ✓

$68 \times 29.5 = 2$

$M = 217$

LIVE LOAD DEFLECTON CHECK

$$\frac{5wL^4 \cdot 1728}{384EI}$$

E = 29000

I =

w = LIVE LOAD

L = Length (ft)

$$\frac{L}{360}$$

W 24x68 · $I_{\text{X-X AXIS}} = 1830 \text{ in}^4$

80 PSF x 10.33' = 0.8264 KLF

$$\frac{5 \cdot 0.8264 \cdot 29.5^4 \cdot 1728}{384(29000)(1830)} = 0.26 < 0.983 \checkmark$$

$$\frac{354}{360} = \boxed{0.983}$$

TOTAL LOAD DEFLECTON CHECK

$$\frac{5wL^4 \cdot 1728}{384EI}$$

L = 80 + 113 + 10 + 69 = 272 PSF

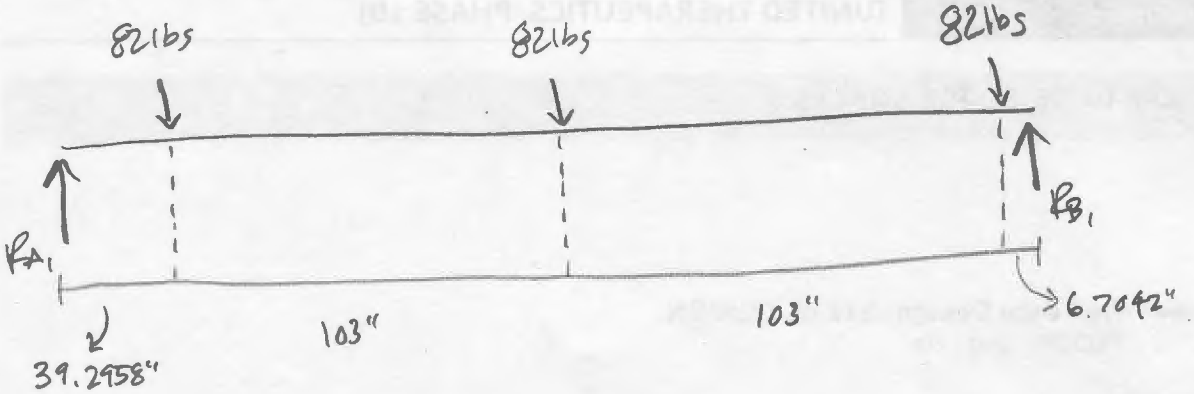
272 PSF x 10.33' = 2.809 KLF

$$\frac{L}{240} \qquad \frac{354}{240} = \boxed{1.475}$$

$$\frac{5 \cdot 2.809 \cdot 29.5^4 \cdot 1728}{384 \cdot 29000 \cdot 1830} = 0.9 < 1.475 \checkmark$$

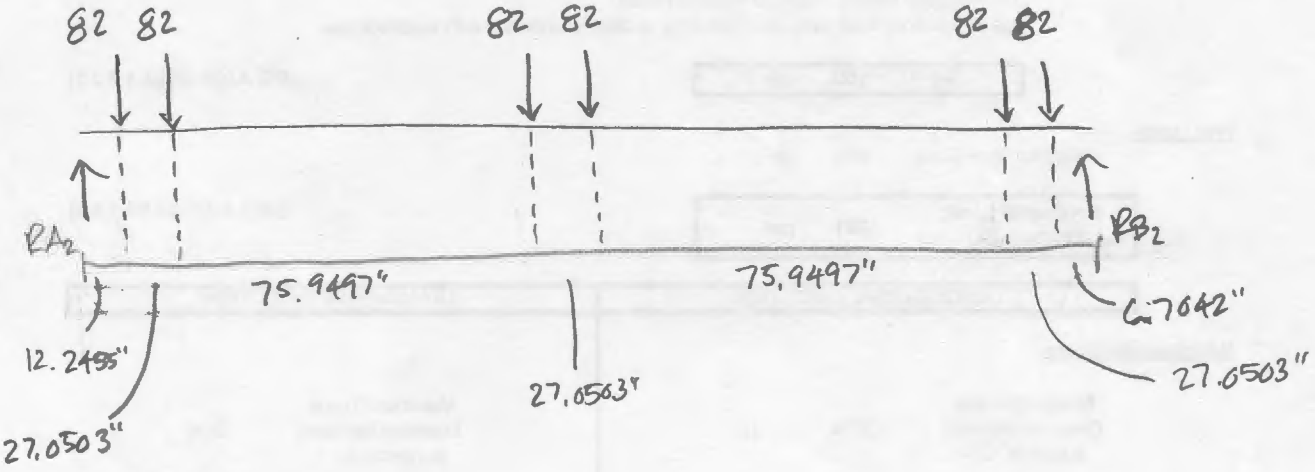
6½" 2VLI17 DECK t = 4½"
ON W24x68 BEAM INTERIOR BAY

①



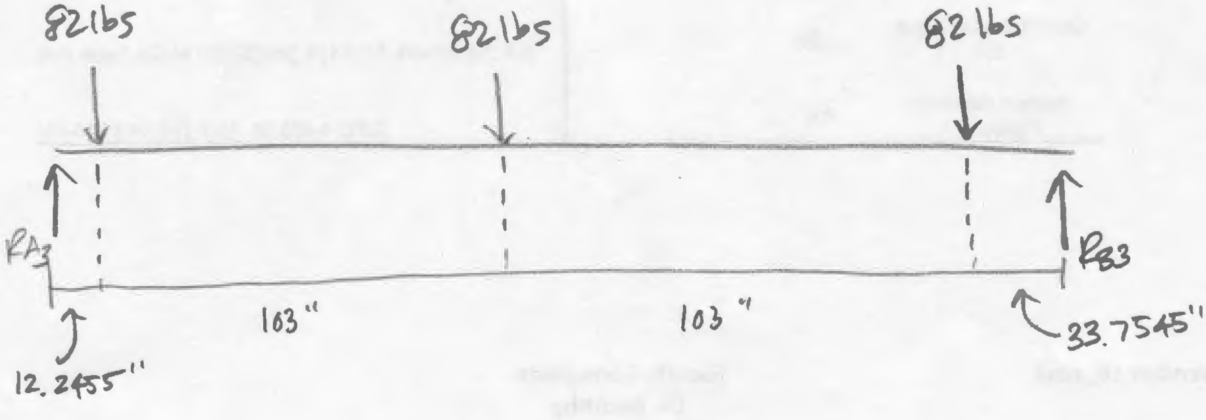
82lbs
82lbs
82lbs
RA1
RB1
39.2958"
103"
103"
6.7042"

②



82
82
82
82
82
82
RA2
RB2
12.2455"
27.0503"
75.9497"
27.0503"
75.9497"
6.7042"
27.0503"

③



82lbs
82lbs
82lbs
RA3
RB3
12.2455"
103"
103"
33.7545"

SOLAR STRUCTURE

① $\Sigma F_x = 0$

$\Sigma F_y = R_{A_1} + R_{B_1} - 3(82) = 0$

$\overset{+}{\circlearrowleft} \Sigma M_{A_1} = -82\left(\frac{39.2958}{12}\right) - 82\left(\frac{142.2958}{12}\right) - 82\left(\frac{245.2948}{12}\right) + R_{B_1}\left(\frac{252}{12}\right) = 0$

$R_{B_1} = 138.9$ lbs

$R_{A_1} = 107.1$ lbs

② $\overset{+}{\circlearrowleft} \Sigma M_{A_2} = -82\left(\frac{12.2455}{12}\right) - 82\left(\frac{39.2958}{12}\right) - 82\left(\frac{115.2455}{12}\right) - 82\left(\frac{142.2958}{12}\right)$
$- 82\left(\frac{218.2455}{12}\right) - 82\left(\frac{245.2958}{12}\right) + R_{B_2}\left(\frac{252}{12}\right) = 0$

$R_{B_2} = 251.4$ lbs

$\Sigma F_y = R_{A_2} + 251.4 - 6(82) = 0$

$R_{A_2} = 240.6$ lbs

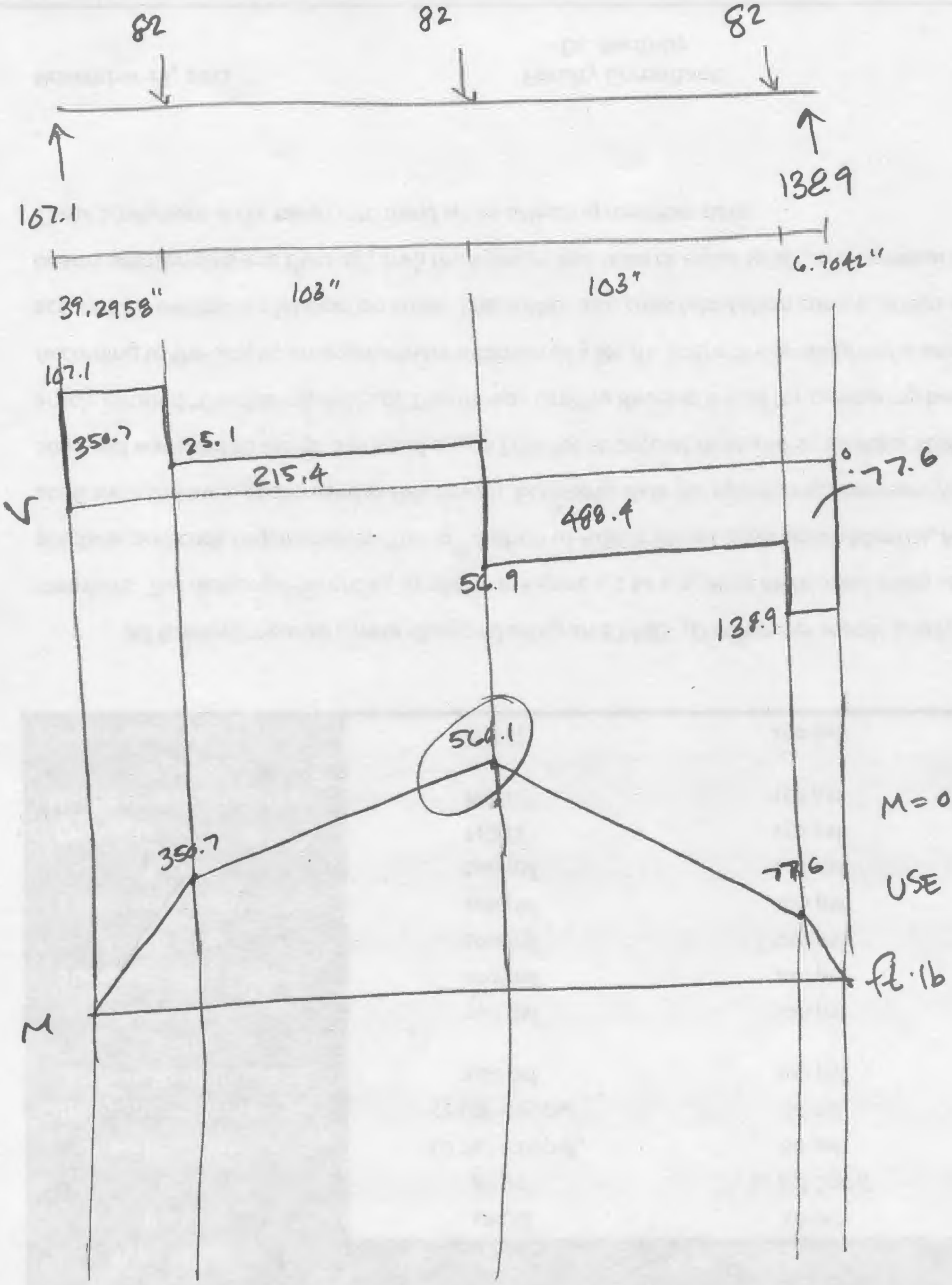
③ $\overset{+}{\circlearrowleft} \Sigma M_{A_3} = -82\left(\frac{12.2455}{12}\right) - 82\left(\frac{115.2455}{12}\right) - 82\left(\frac{218.2455}{12}\right) + R_{B_3}\left(\frac{252}{12}\right) = 0$

$R_{B_3} = 112.5$ lbs

$\Sigma F_y = R_{A_3} + 112.5 - 3(82) = 0$

$R_{A_3} = 133.5$ lbs

①

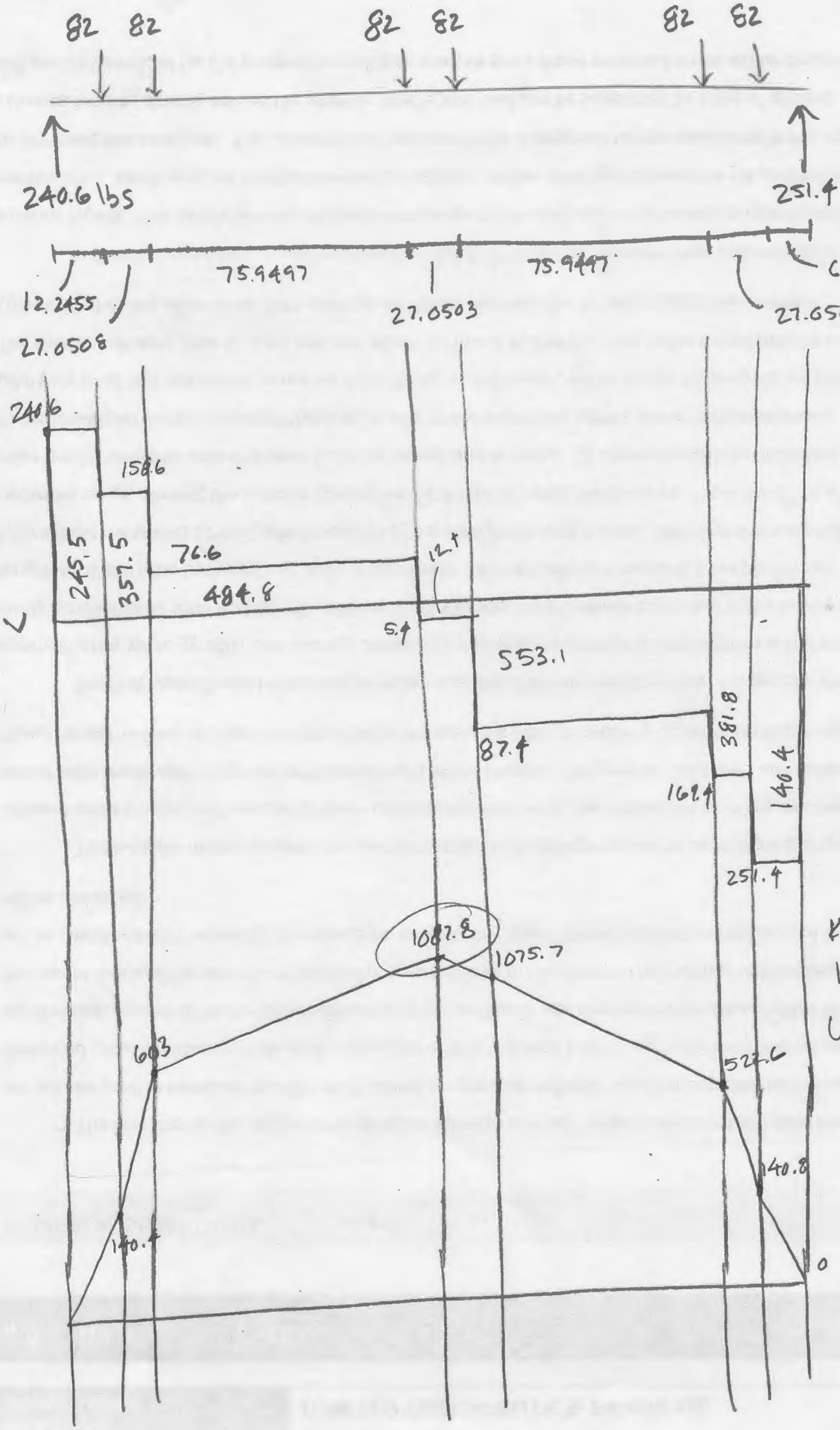


M=0.5661 k.ft

USE HSS 2x1x1/8

$\phi_b M_n = 1.26$ k.ft

②



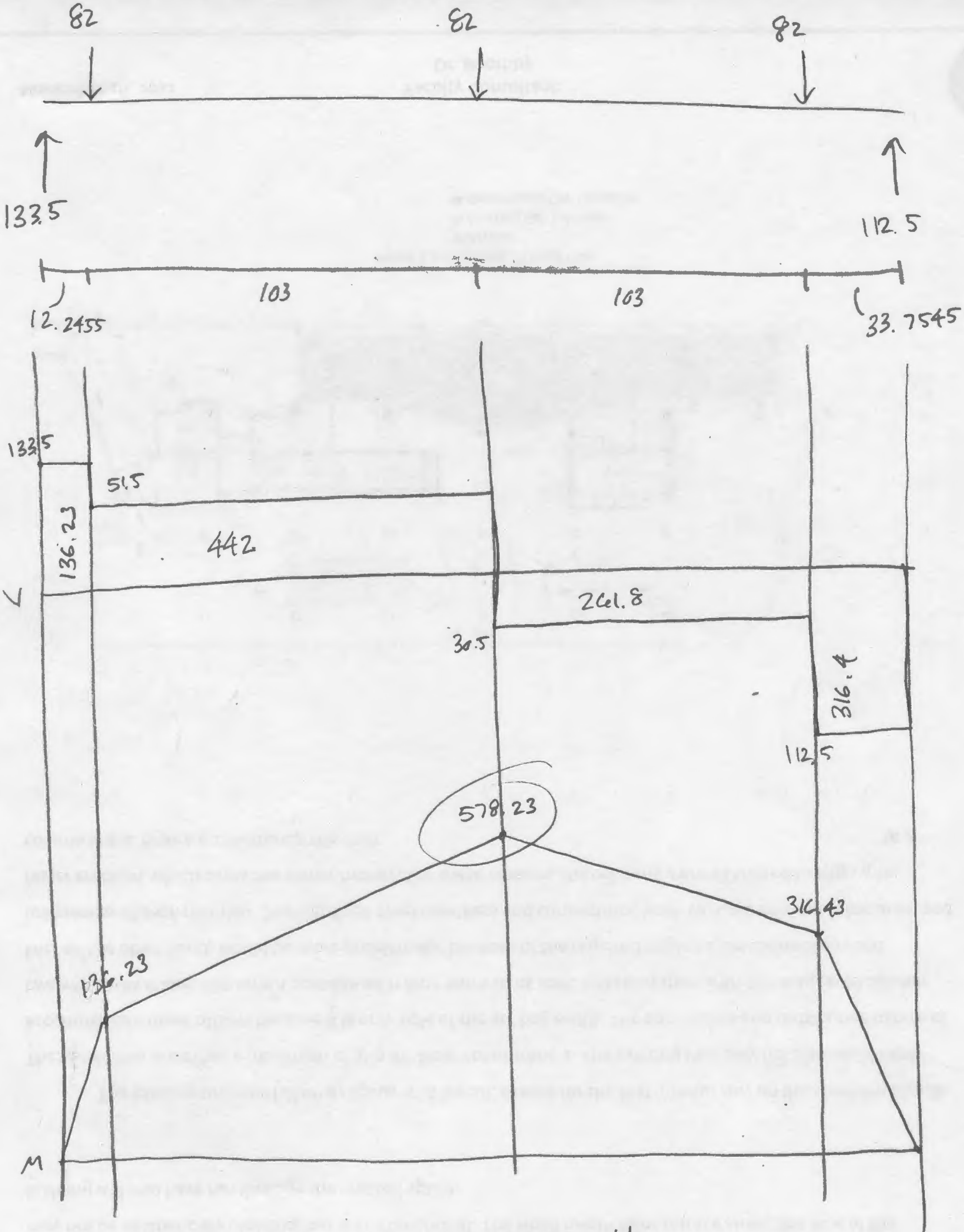
k ft

1.0878 = M

USE HSS 2×1×1/8

$\phi_b M_n = 1.26$ ft·k

③



k-ft 0.578=M

USE HSS 2x1x1/8

$\phi_b M_n = 1.26$ ft·k