FINAL REPORT

April 2017

SCHOOL OF PUBLIC HEALTH

AE 481 – SENIOR THESIS PROJECT
THESIS ADVISOR: STEPHEN J. TREADO

Angie Tejada
Mechanical Option

SCHOOL OF PUBLIC HEALTH

WASHINGTON D.C.

ANGIE TEJADA

MECHANICAL OPTION

THESIS ADVISOR: DR. TREADO

OWNER:

GEORGE WASHINGTON UNIVERSITY

OCCUPANCY: EDUCATIONAL

SIZE: 161 000 FT^2

NUMBER OF STORIES: 7 ABOVE GRADE + 2 BASEMENT LEVELS

DESIGN AND CONSTRUCTION TEAM:

⇒ DESIGN ARCHITECT: PAYETTE

⇒ ASSOCIATE ARCHITECT: AYERS-SAINT-GROSS

⇒ MEP.FP: AFFILIATED ENGINEERS INC

⇒ STRUCTURAL: TADJER-COHEN-EDELSON ASSOCIATES

⇒ LIGHTING DESIGN: ATELIER TEN

⇒ CM: WHITING-TURNER

ARCHITECTURAL

Located just by Washington Circle, and a few blocks away from the White House, design proved to be a challenge due to the historical character of the neighborhood, strict zoning regulations and unusual geometry of the site. The design was driven by the program requirements, a desire to create an integrative space to promote interaction between faculty and students, and a strong commitment to sustainable design. These spaces are located around a 7-story central sky-lit atrium, which serves as the core of the building and brings daylight penetration into the narrow interior.

SUSTAINABILITY

Overall, the project achieved LEED Platinum certification . Some sustainable features in the HVAC systems are DOAS with energy recovery wheel technology, chilled beams, displacement ventilation, and a heat recovery chiller providing free heat rejection. The building enclosure incorporates high performance windows, as well as southern exposure shading elements and a large green roof surrounding the mechanical penthouse. Innovative wastewater technologies using low flow fixtures and on-site storm water retention achieve water use reduction by 50%.

MECHANICAL

The building is served by two systems. Located on the lower basement, two air-handling units supply a VAV reheat system serving large auditoriums, lecture rooms, and exercise rooms located on the basement levels and level 1. Located on the mechanical penthouse, two DOAS units, packed with energy recovery wheel technology, serves the central atrium as well as classrooms and offices from levels 2-7. Ceiling mounted 2-pipe active chilled beams provide sensible cooling for partial space cooling in these areas.

LIGHTING/ELECTRICAL

A complete lighting system for all indoor and outdoor illumination was includes energy efficient lighting fixtures, selected to achieve maximum energy usage, lighting output, and comfort. The lighting system features advanced control systems, including dual technology occupancy sensors for offices, corridors, and common areas; as well as a programmable relay system for common public spaces.

STRUCTURAL

A 7th floor was introduced into the program by reducing the typical floor height to 12 ft. This was achieved with the use of exposed post-tensioned, cast-in-place slabs, which were selected for their ability to span rooms of varying sizes with relatively shallow depth. The structural design, essential for the sky-lit atrium, enabled portions of each floor level to be removed and create numerous floor openings.

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Acknowledgments

I would like to thank the following people for their constant support during this past year and help with the completion of this senior thesis design project:

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Executive Summary

The following report reviews previous studies conducted on the School of Public Health, and an analysis of proposed design alternatives. Design considerations and goals include the integration of different spaces for occupant interaction, minimizing energy consumption, and maintaining the architectural design. Previous studies include general information about the building and site conditions, assessment of minimum ventilation requirements and compliance with ASHRAE Standard 62.1, load calculations and current energy consumption, as well as a detailed analysis of the existing mechanical system.

The School of Public Health project pursued and obtained a LEED Platinum rating. Proposed alternatives were explored with the purpose of further reducing energy consumption and focus of the current Dedicated Outdoor Air System serving levels 2-7. Within these levels, active chilled beams meet any additional heating or sensible cooling requirements for spaces with regular or high occupancy; such as offices, conference rooms, and classrooms. Remaining spaces, such as circulation and open-study areas, are maintained at design conditions with air-terminal units. Displacement ventilation was integrated into the design in order to minimize the DOAS unit required capacity, and demand controlled ventilation was incorporated into the controls system.

After considering the high efficiency of the existing systems, the proposed design focuses on reducing the energy consumption of the existing Dedicated Outdoor Air System by extending the use of the building's relief airflow as a source/sink to completely condition the outside air without the need for energy recovery wheels, cooling coils, and heating coils. The proposed system consists of a reversible heat pump and high efficiency coils at the exhaust and outside airstreams. Two configurations were analyzed: Configuration A, consisting of the heat pump only, and Configuration B, which consists of the reversible heat pump integrated with an energy recovery wheel.

With the purpose of exploring ways of optimizing the building's efficiency, the analysis includes two breadths that focus on reducing the operating hours and capacity requirements of mechanical systems. The first focuses on implementing natural ventilation to meet cooling loads and ventilation requirements at ideal outdoor conditions. It includes an assessment of the spaces that could potentially benefit from natural ventilation, and a study of airflow behavior within the building. The second breadth consists of a structural analysis of the south-east façade, with the purpose of studying the feasibility of incorporating a double-skin façade into the existing structural system.

Energy consumption calculations for the proposed mechanical design showed an overall annual reduction of 29% in energy consumption for configuration A, while configuration B had an annual reduction of 31%. Both alternatives presented the largest potential for energy savings during the heating season. The study performed for natural ventilation indicates that there is potential the system to be integrated into the building. Computational Fluid Dynamics simulation was performed to test the behavior of airflow within the building. At residual values of 1E-05 or lower, the desired flow behavior was achieved as well as adequate temperature conditions. However, further analysis evaluating the airflow on the exterior side of the building would aid in performing a more complete evaluation of behavior of the flow. The structural analysis indicated that the existing structural system has the potential to support an additional layer, with the purpose of integrating a double-skin façade into the design.

Building Overview

The School of Public Health is located in the heart of Washington D.C., right by Washington Circle. Construction was completed in 2014, with a total building area of 161,100 ft^2 which includes seven stories above grade plus two basement levels and a mechanical penthouse. The building houses offices, laboratories, study areas, classrooms, auditoriums, and a convention center. The west portion contains business occupancies; such as offices, and conference rooms. It is separated from the atrium space by a wall, which is partly made of glass in order to allow occupants to overlook the space. The eastern half consists of an atrium connecting levels 1-7, which is surrounded by various enclosed classrooms, lounges, and study areas.

The design features a seven-story central sky-lit open atrium, which serves as the core of the building and brings daylight penetration into the narrow interior. A second atrium space overlooking Washington Circle was added near the south-eastern end to allow natural daylight to reach the entire building through a curtainwall, which features an integrated solar shading screen to reduce solar heat gain.

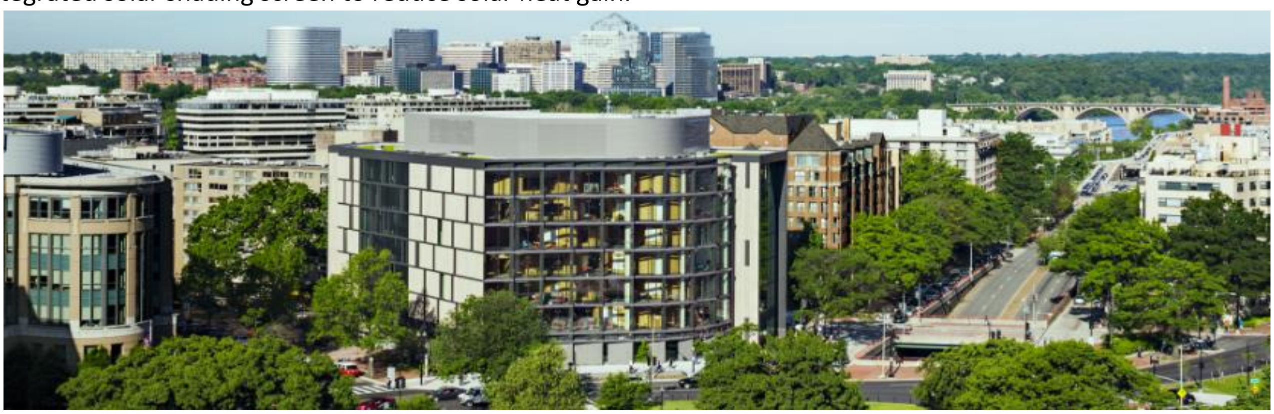


Figure 1: Elevated view from Washington Circle

Figure 2: Site Plan – Courtesy of Payette

Figure 3: Building Program – Courtesy of Payette

Mechanical Systems Overview

The building integrates different mechanical systems with controlled operation by a building automation system and many sustainability features. Ventilation rates and adequate Indoor Air Quality are guaranteed with the use of dedicated outdoor air (DOAS) systems serving most of the spaces. Two air-handling units in the basement supply a VAV reheat system serving level B1 and level 1. Within these levels, displacement ventilation was implemented for large auditoriums in order to minimize the required ventilation equipment and maximize use of building space.

The dedicated outside air system consists of two air-handling units located in the mechanical penthouse which provide heating, cooling, and humidification to a single duct constant air volume reheat system serving levels 2-7 with 54 F primary air. Each DOAS unit has two energy recovery wheels incorporated for energy savings and air treatment: one full-energy wheel, and one sensible heating wheel. Within these levels, spaces with regular occupancy and loads; such as offices, conference rooms, and classrooms, have 2-pipe active chilled beams providing additional sensible cooling. Atrium, circulation, and support areas are supplied conditioned air directly from the DOAS units. In addition, all spaces were provided with terminal reheat devices. Air balancing was implemented to transfer return air from the spaces to the corridors and atrium. Return air is centralized at the top of the atrium, and either relieved to outside via return fans or returned to the units. This system operates in both occupied and unoccupied modes, including demand control ventilation.

Basement units, AHU-1 and AHU-2, serve a VAV reheat system. AHU-1 serves exercise science, convening center, and support areas located on basement 1 and level 1. It provides heating and cooling through a single duct VAV reheat system. AHU-2 serves an auditorium and two large classrooms, where air is distributed through a combination of overhead VAV and under-floor air distribution (UFAD) system. Temperature control occurs through air terminal boxes for overhead supply, and a combination of duct coils and control dampers for under-floor distribution, where air is supplied at a minimum of 64 °F to maintain occupant comfort. These AHUs also implement demand control ventilation and operate in occupied and unoccupied modes.

The cooling plant includes cooling towers, VFD pumps, and three primary-flow centrifugal chillers, Chilled water is distributed at 42 °F through insulated piping. One chiller is a dedicated heat recovery chiller which provides free heating for reheat loads when adequate capacity is available, and operates year round as a base chiller load. The remaining two chillers, designed in parallel configuration, have minimum flow control and variable speed flow for energy savings. The variable volume chilled water system is modulated by a 2-way control valve at each cooling coil, and VFD distribution pumps. A fraction of the building return chilled water diverts to a secondary loop and heat exchanger, where it provides partial heating for the chilled beams water system.

Hot water is supplied by a combined heating and reheat system composed of four hot water boilers, primary pumps and distribution pumps. The heating system loop serves the AHU preheat coils, and air terminal heating devices, such as unit heaters, convectors, cabinet unit heaters, and finned tube radiators. The reheat system loop serves all the reheat coils, and is provided with free heating from the heat recovery chiller when available. Hot water is distributed at a temperature range of 130 F-160 F, based on outside air temperature reset.

Design Considerations

Objectives

The project involved the design of a building containing seven stories above grade plus two basement levels and a mechanical penthouse. The design was driven by the different space types required in the program, a desire to create an integrative space which promotes interaction between faculty and students, and a strong commitment to sustainable design. Another design objective for the mechanical systems was to contribute to the sustainability features of the project, and the owner's goal to achieve LEED Platinum rating.

Design Conditions

Outdoor and Indoor design conditions

The School of Public Health is located in Washington D.C., in a mixed-humid region part of zone 4a, as defined by ASHRAE 90.1. Outdoor design conditions were based on 2% ASHRAE values per acceptance with the university. Actual data for outdoor design conditions used in the energy simulation as set by the university are shown on Table 1.1. Indoor design conditions specified on Table 1.2 were specified in the design documents, and include temperature set points and adequate humidity levels for most spaces. Spaces with similar occupancies and loads share the same thermostat settings, such as classrooms, offices, corridors, conference rooms, and support spaces. Some exceptions are high-density equipment rooms, such as electrical, mechanical, and telecom/data rooms; exercise science and support spaces in which there is high physical activity, and the north and south stair towers. Indoor temperature control features temperature setbacks, which are operated by a demand control temperature system. Occupancy sensors control detects when occupants are not sensed and reduces temperature and air changes set points.

Table 1.1: Outdoor Design Conditions

Heating DB [°F]	Cooling [°F]		Dehumidification		
	DB	MCWB	DP	HR	MCDB
13	95	76	76	136	83

Table 1.2: Indoor Design Conditions

Space	Cooling DB [°F]	Heating DB [°F]	RH [%]	Cooling Driftpoint [°F]	Heating Driftpoint [°F]
Atrium, Classroom, Office, Circulation, Misc.	75	72	50	76	71
Electrical Rooms	95	60	50	95	60
Exercise Science & Support	72	72	60	73	71
Mechanical Rooms	104	70	50	104	70
North & South Stair Towers	70-80	70-80	30-60	80	70
T/D	85	70	50	85	70
Unconditioned	80	50	50	81	49

Requirements

Design Ventilation Requirements

Minimum ventilation rates were assigned per ASHRAE 62.1 guidelines or IMC 2006 Chapter 4, depending on which had more stringent values for each specific category. The ventilation airflow required for each room was calculated using excel spreadsheets prior to the energy modeling, and then used as an input for the rooms created. In the energy model, CO2 based demand ventilation controls were included for office spaces, conference, and classrooms.

Table 2: Design Ventilation Rates

Space Type	Ventilation Rate	
	cfm/person	cfm/ft²
Auditorium	7.5	0.06
Classroom	7.5	0.06
Conference	5	0.06
Corridor	0	0.06
Exercise	20	0.06
Janitorial	0	0.06
Laboratory	10	0.18
Lobby	7.5	0.06
Office	5	0.06
Storage	0	0.12

Building Envelope

The building façade varies with orientation. The north end, facing Washington circle, has a glass curtainwall with a granite base, which extends to the north-east with a layout of large windows arranged within angular concaved frame. The south end has a more open glass curtainwall that extends all the way to the ground, and features an integrated aluminum solar shading screen to reduce heat gain. The west end, which faces a more residential area, has terracotta rain screen panels as the primary material, with smaller windows embedded in them. Finally, the east end uses a combination of terracotta panels and curtainwall bringing light to the atrium. Figures 5.1, 5.2 and 5.3 show renderings and details for all the building's facades.

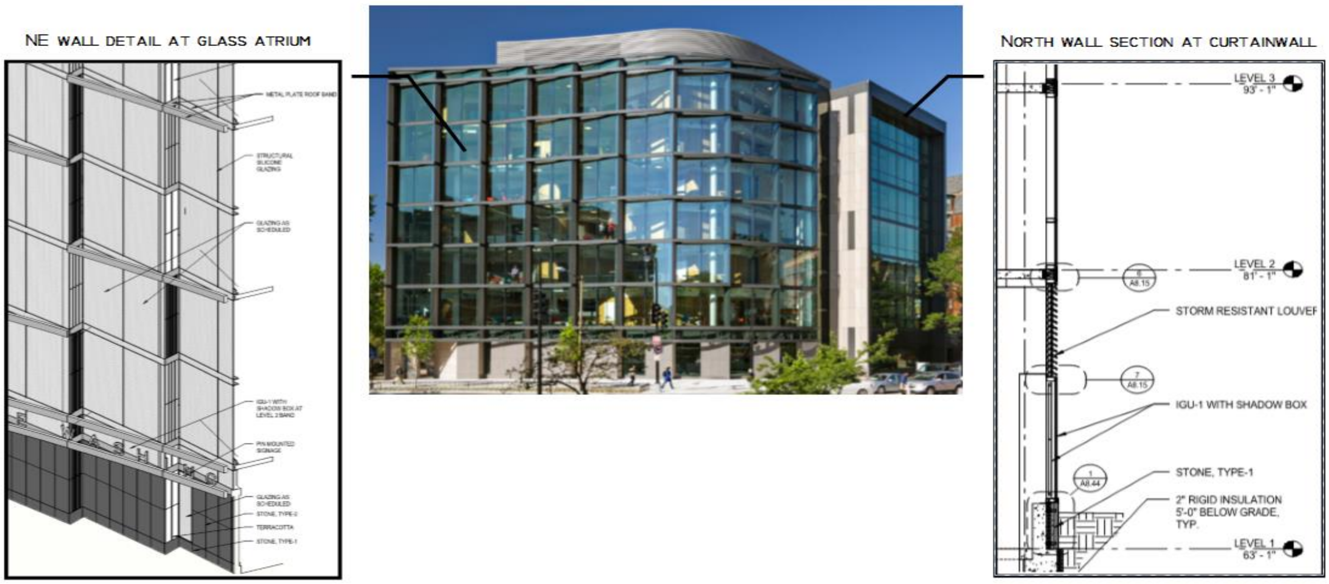


Figure 5.1: North and North East Facades

Figure 5.2: South-east façade glass and terracotta details

Figure 5.3: West and South façade details

Due to the complex building enclosure and variety of construction types, a standard wall with the design U-value was created to include all the common components of each wall, as well as the glazing types for both the curtain wall and skylight. The standard construction template fits most spaces from levels 1 to 7, while below-ground spaces on the two basement floors required different types of exterior walls.

Design Heating and Cooling Loads

Internal electrical loads due to both lighting and equipment were specified in the design documents for each type of space. The number of occupants in each space used for the energy model were based on actual occupant density as listed in the facility program when available, or per ASHRAE standards otherwise. Heat loss calculations included an infiltration load of 0.3 ACH for the entire building. Heating and cooling loads were calculated using Trace 700, with an energy model based on the 100% CD architectural program and HVAC thermal zoning, which included over 400 individual zones. Calculated loads were then included in an airflow calculations spreadsheet, along with the required ventilation airflows. The purpose of this spreadsheet is to specify the heating, cooling, and ventilation airflows required for each space. These values were then used as an input for the energy model in order to achieve more accurate results.

In the block load energy analysis performed for technical report 2, five different systems were modeled on Trace 700. AHU-1 was modeled as a VAV with reheat system, while AHU-2 was modeled as a UFAD with bypass VAV system to account for the majority of the air being supplied with under-floor air distribution. The DOAS units located on the penthouse primarily supply chilled beams, as well as some VAV air terminal units supplying regular diffusers. Since it is not possible to assign two different types of air terminals to a chilled beam system on Trace 700, these had to be modeled as two separate systems: DOAS with Chilled Beam, and DOAS with VAV reheat. The total cooling and heating loads of these two systems were added and compared to the total capacity of the DOAS units, as specified on the design documents. Table 3 contains a comparison between calculated and design loads.

Values calculated for AHU-1 are relatively close to the actual design values for this system. However, the Trace 700 AHU-2 values are significantly lower than the ones specified on the schedules, most likely because the system was modeled as having under-floor air distribution only and the few ceiling diffusers were not taken into consideration. The loads calculated for the DOAS system have larger variation from the design values. For this project, AEI performed load and ventilation calculations for each individual rooms using excel spreadsheets. These calculations included air balancing and minimum VAV % cooling turndown. These results were then input into the Trace energy model for each room, which results in significantly different results for constant volume systems, which is the case of the DOAS and chilled beam system. For the block analysis, these inputs were not calculated prior to the energy model. Instead, the values were left for Trace to calculate.

Table 3: Equipment Load and Ventilation Comparison

Equipment	Criteria	Cooling Coil Load [MBH]		Heating [MBH]	Airflow [CFM]	
		Sensible	Total	Pre-heat	Total	Outside Air
AHU-1	Estimated	558	898	552	24,785	8,427
	Designer	1,112	1,868	832	33,500	11,390
AHU-2	Estimated	185	339	110	6,650	1,995
	Designer	488	816	486	15,000	4,950
DOAS 1&2	Estimated	-	3,388	561	51,686	36,457
	Designer	-	4,376	670	63,000	63,000

Energy

Site Energy Sources

Site primary electric service is derived from PEPCO, an electrical distribution service in the District of Columbia. The PEPCO grid is located at the northwest corner of the site. The emergency/standby power source is derived from a single 760 kW/938 kVA diesel-powered engine generator set. The generator is supplied by a 1500 gallon tank located in the mechanical basement, which has the capacity to operate the generator for at least 24 hours. Another much smaller energy source is natural gas, used for boiler operation and for the steam generators which form part of the humidification system.

Site Energy Rates

On-peak utility rates for electric consumption, electric demand, and gas price were obtained from design documents. These values were based on actual data from 2009 provided by the university, and can be found on tables 4.1 and 4.2. Results show that electricity is the source for roughly 90% of annual utility costs in the building, while gas consumption accounts for less than 10%. Electric on-peak consumption was the largest source of operating cost, with values significantly higher than electric on-peak demand and gas on-peak consumption. This trend continues year-round, as can be observed on Figure 4.

Table 4.1: On-peak Utility Rates based on 2009 data

Utility	Rate [$ per kWh or therm]
Electric Consumption	0.156
Gas Price	1.474
Electric Demand	2.889

Table 4.2: Base Utility Demand Rates

Utility Type	Hourly Demand	Energy Type
Domestic Hot Water	100 MBh	Process hot water Load
Elevator	134 kW	Electricity
Parking lot lights	0.1 kW	Electricity

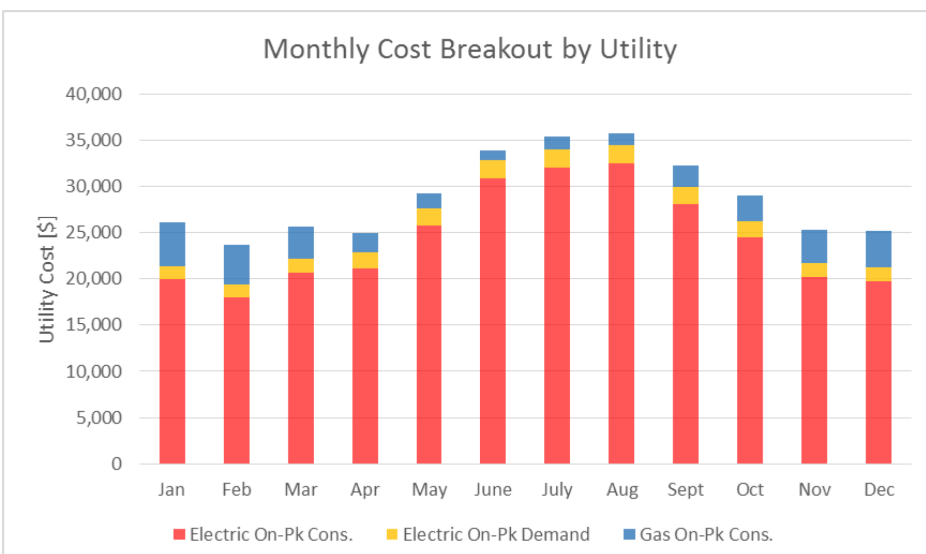


Figure 4: Utility Monthly Cost Breakout

Annual Energy Use

Summarized results for annual energy use analysis as performed by the designer were obtained from design documents. However, a more detailed breakdown of the energy consumption from the designer energy model was not available. Table 5 summarizes the energy use and costs comparison between the design documents and the estimate developed for technical report 2. Figure 4 displays the annual energy consumption by end-use resulting from the block load analysis. Overall calculated values for energy use are lower than the design ones, which resulted in lower operating costs as well. However, the EUI and utility cost per area obtained show that the block analysis performed is a relatively good representation of the building systems and overall energy consumption.

Table 5: Energy Use and Costs Comparison

Source	Energy Use [MMBtu]								Energy Cost [$]	EUI [kBtu/SF]	Utility Cost per Area [$/SF]
	Plug	Lights	Heating	Cooling	Heat Rej	Pump	Fan	Total			
Designer	1,630	718	3,716	1,450	76	277	2,906	10,773	404,407	67	2.53
Estimate	2,300	887	2,264	1,260	76	124	1,814	8,725	346,566	64	2.55

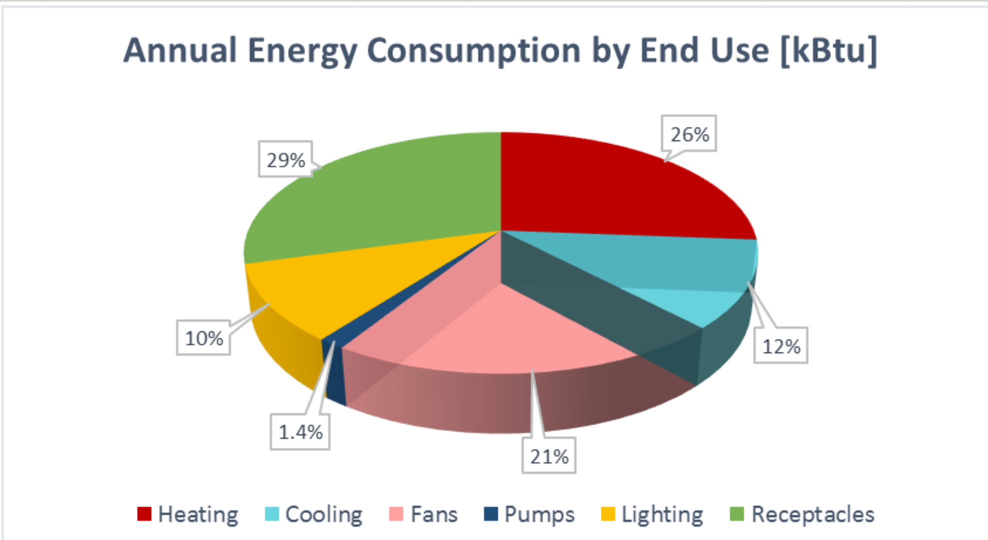


Figure 5: Annual Energy Consumption Breakout

Other Factors

Site

The site is located in R-5-E Zone District. Zoning regulations allow college and university uses in residential zone districts, provided that the campus plan has been approve. The site of the project is one of sixteen development sites for the university's First-Stage Planned Unit Development. It follows the District of Columbia Comprehensive Plan, D.C. Law 16-300, 10A DCMR (Planning and Development). Architectural design proved to be a challenge due to the important historical character of the neighborhood, strict zoning regulations and the unusual triangular geometry of the site. Zoning in the area restricted building height to a maximum of 90 ft. Since the site footprint was already small for the required program, the typical floor-to-floor height was reduced to 12 feet in order to insert a 7th floor. With the reduced height, it was essential to design a mechanical system which would optimize space use while maintaining occupant comfort and adequate indoor air quality.

Existing Mechanical Systems

Plants

Cooling Plant

Cooling source for the building is generated by three primary flow centrifugal chillers, which include one heat recovery chiller, located in the basement 2 level. The chillers, along with three cooling towers and pumps, form part of the cooling system. Single-cell cooling towers serve as the main form of heat rejection for the cooling plant, and can be found on Table 6.2. Three primary pumps were sized to each match a chiller's flow, and one of them serves as backup pump.

Other components include chemical feeders, air separators, expansion tanks, and a heat exchanger serving the cooling towers. Equipment details for heat exchangers and pumps can be found on Tables 8 and 12.

Table 6.1: Chillers

Equipment	Type	Capacity	Max KW/ton	NPLV [KW/ton]	Evaporator			Condenser			Input Power [KW]	Basis of Design
					Flow [GPM]	EWT [°F]	LWT [°F]	Flow [GPM]	EWT [°F]	LWT [°F]		
CH-1	Centrifugal Chiller	350	0.59	0.35	540	58	42	1,050	85	95	206	McQuay WMC400D
CH-2	Centrifugal Chiller	350	0.59	0.35	540	58	42	1,050	85	95	206	McQuay WMC400D
CH-3	Multi-Scroll	102	-	-	244	60	50	293	127	138	46	York YCWL0126HE

Table 6.2: Cooling Towers

Equipment	Type	Service	Water Flow [GPM]	Max Static Lift [ft]	Temperature			Fan Max HP	Basis of Design
					WB [°F]	EWT [°F]	LWT [°F]		
CT-1,2&3	Single Cell	CHW Plant	770	12	76	95	85	15	Marley NC8402

Heating Plant

The hot water plant provides heating source for the buildings and is composed of the four gas-fired condensing boilers shown on Table 7, one of which is 100% stand-by. Hot water is distributed with three primary hot water pumps, and two secondary distribution pumps with one pump as standby. Equipment specifications for pumps can be found on Table 12. Other components of the hot water plant are a chemical pot feeder, air separator, expansion tank, preheat and reheat coils, and air terminal heaters.

Table 7: Boilers

Equipment	Type	Service	Min Efficiency [%]	Max Flow [GPM]	Capacity				Basis of Design
					Input [MBH]	Output [MBH]	EWT [°F]	LWT [°F]	
B-1,2,3,4	Condensing Boiler	Heating	90	140	2000	1700	136	160	AERCO 2.0 LN

Chilled Beam Water Loop

A chilled beam cooling system provides sensible cooling for partial space cooling in office and classroom areas. The system is composed of active 2-pipe cooling panels, two water-to-water heat exchangers, two process water circulating pumps, and two chilled water circulating pumps. The heat exchangers serving the chilled beam water system, HX-1A and HX-1B, are found below on Table 8.

Table 8: Heat Exhangers

Equipment	Location	Service	Type	Total MBH	Cold Side			Hot Side			Basis of Design
					Flow [GPM]	EWT [°F]	LWT [°F]	Flow [GPM]	EWT [°F]	LWT [°F]	
HX-1A,1B	Level B2	Chilled Beams	Plate	963	120	42	58	760	60.5	58	Gea Ecoflex NT100T BYF
HX-2	Level B2	Recovery Chiller	Plate	1709	210	85	101	293	138	126.3	Gea Ecoflex NT100T CYF
HX-3	Penthouse	Domestic Hot Water	Plate	455	10	40	128	70	130	117	Gea Ecoflex VT20 DS

Systems

Basement Air Handling Units

AHU-1 serves spaces on Basement 1 and Level 1, which include the exercise science area, a convening center, conference rooms, and support areas. AHU-2 is dedicated to serve one large auditorium located on level 1, and two large classrooms on Basement 2. The two air-handling units shown on Table 9 are located in the basement and serve a spaces located on Basement 1 and Level 1. The packaged units supply two separate single duct variable volume systems. Both units feature outside air intake dampers and air mixing devices. As part of air treatment, the AHUs are incorporated with 30% efficient pre-filters and 65% efficient pre-fillers, resulting in 95% efficient final filters, as rated on ASHRAE 52.1. Other components of the AHUs are hot water preheating coils, steam humidifiers, chilled water cooling coils, supply fans, attenuating devices, and isolation/smoke dampers.

Table 9: Basement MER Air-Handling Units

Equipment	Service	CFM	Min OA %	Heating Coil			Cooling Coil				Basis of Design
				EAT [°F]	LAT [°F]	Capacity [MBH]	EAT [°F]	LAT [°F]	Sen. Capacity [MBH]	Total Capacity [MBH]	
AHU-1	Level B1 & Level 1	33,500	34	31	54	832	79.6	49	1112	1868	McQuay
AHU-2	Lecture Halls (B1 & L1)	15,000	33	20	50	486	80	50	488	816	McQuay

Penthouse DOAS Units

Two custom package air-handling units, DOAS-1 & DOAS 2, are located on the penthouse are dedicated outside air and serve the atrium as well as office and classroom areas for levels 2-7. Each unit is incorporated with energy and sensible heat recovery wheels for heat recovery and air treatment. The supply fans for the DOAS system are double inlet centrifugal type with airfoil blades, and return fans are plug-type. Other unit components are outside air intake dampers, air mixing devices, 95% efficient final filters, hot water preheating coils, steam humidifiers, chilled water cooling coils, attenuating devices, and isolation/smoke dampers. More details of these components can be found on Figure 10.

Table 10: Mechanical Penthouse Dedicated Outside Air Units

Equipment	Location	Service	CFM	Energy Recovery		Heating Coil			Cooling Coil 1			Cooling Coil 2			Sensible Recovery		Basis of Design
				EAT [°F]	LAT [°F]	EAT [°F]	LAT [°F]	Capacity [MBH]	EAT [°F]	LAT [°F]	Capacity [MBH]	EAT [°F]	LAT [°F]	Capacity [MBH]	EAT [°F]	LAT [°F]	
DOAS-1	Penthouse	Levels 2-7	31,500	92	78.7	50.2	60	335	78.7	51	1467	51	45	721	45	49.9	Annexair Custom
DOAS-2	Penthouse	Levels 2-7	31,500	92	78.7	50.2	60	335	78.7	51	1467	51	45	721	45	49.9	Annexair Custom

Fans & Pumps

Table 11: Fan Schedule

Equipment	Location	Service	Type	CFM	SP ["WG]	Motor BHP	Basis of Design
SF-1A,1B,2A,&2B	Penthouse	DOAS-1,2	Centrifugal	15,750	8.8	31.11	Annexair
RF-1A,1B,2A,&2B	Penthouse	DOAS-1,2	Centrifugal	14,000	3.2	11.62	Annexair
RF-1	Basement 2	AHU-1	Centrifugal	25,785	1.9	18	Greenheck 30-AFD
RF-2	Basement 2	AHU-2	Centrifugal	13,500	2.81	11.6	Greenheck 30-AFD
EF-1	Basement 2	MER EXH	In-line	3,600	1	1.35	Greenheck BSQ 180
EF-6	Basement 2	Tank Room Exh	In-line	1,200	2.1	0.9	Greenheck BSQ 140
SPF-1,2	Roof	Stair Pressure	In-line	8,200	2.45	5.71	Greenheck VAB
SPF-3	Basement 2	Elev. Shaft Pressure	In-line	10,900	2.45	7.99	Greenheck VAB
AEF-1,2,3	Penthouse	Atrium Exh.	Tube	49,250	1.85	33.63	Greenheck TBI
AEF-4,5,6	Penthouse	Level 7 bridge exh.	Tube	40,000	1.6	24.37	Greenheck TBI
ASF-1	Basement 2	Atrium Pressure	VA	36,000	2.1	23.21	Greenheck VAB

Table 12: Pump Schedule

Equipment	Location	Service	Type	Capacity [GPM]	Disch. Head [ft]	Min Eff. [%]	Motor HP	Basis of Design
PHWP-1,2,3&4	Penthouse	Boiler	In-line	130	26	70	2	B&G 80-7B
SHWP-1&2	Penthouse	Heating System	End Suction	750	89	70	25	B&G 1510-4E
CBP-1&2	Level B2	Chilled Beams	End Suction	250	91	69	10	B&G 1510-2E
CWP-1,2&3	Level B2	Cooling Towers	End Suction	1090	127	82	50	B&G 1510-5G
CHP-1,2,3	Level B2	Chillers	End Suction	540	142	73	30	B&G 1510-3G
RCP-1,2	Level B2	CH-3 Chiller	End Suction	293	70	77	10	Weinman 3Q
CCP-1	Level B2	AHU-1	In-line	150	50	62	5	B&G 80-2
CCP-2	Level B2	AHU-2	In-line	60	50	62	3	B&G 90-2A
CCP-3,4	Penthouse	DOAS-1,2	In-line	150	50	62	5	B&G 80-2

System Operation & Schematics

A Building Automation System (BAS) was installed to control the operation of the new HVAC systems, and uses Direct Digital Controls (DDC) with distributed intelligence. The building HVAC systems operation was designed to satisfy the following: space temperature and humidity, cooling/heating loads, ventilation, adequate make-up air for proper space pressurization, and minimum air exchange rates. Space temperature and humidity is maintained by controlling the volume of air delivered by the air terminal units, and controlling the supply air temperature by modulating two-way valve for reheat water flow. In the air handling units, leaving supply air temperature is controlled by chilled water, hot water, and pre-heat water valves. Adequate humidity of the supply air leaving the AHUs is maintained via a steam humidifier, which is controlled by a duct thermostat and humidistat. Distribution equipment, such as pumps and fans, are controlled via VFDs operating with pressure sensors to maintain adequate system pressure. The following sections consist of a more detailed breakdown of each system's operation.

Chilled Water System

The primary type chiller hydronic system shown on figure is composed of three water-source chillers, three cooling towers, and pumps. One chiller is a dedicated heat recovery chiller which provides heating source for reheat loads in the building when adequate capacity is available for reheat. The heat recovery chiller operates year-round as the base load chiller, and the remaining two chillers were designed in parallel configuration. Chilled water is distributed to the basement AHUs and DOAS units cooling coils at approximately 42 °F, with a temperature differential set point of 14°F. The distribution system utilizes variable speed flow for energy savings. Flow rate is modulated by 3 primary pumps provided with a variable frequency drive each. The VFDs vary the speed of the pumps in order maintain a constant differential pressure between the piping mains, which is controlled by a differential pressure transmitter. Heat is rejected using three cooling towers, which are modulated by fans via VFD. A storm water reclaim system serves the cooling towers with make-up water. All major control and balance valves were sized by engineering calculations for linear control. The terminal device-control valve interaction incorporates sub-circuits selected for linear control characteristics.

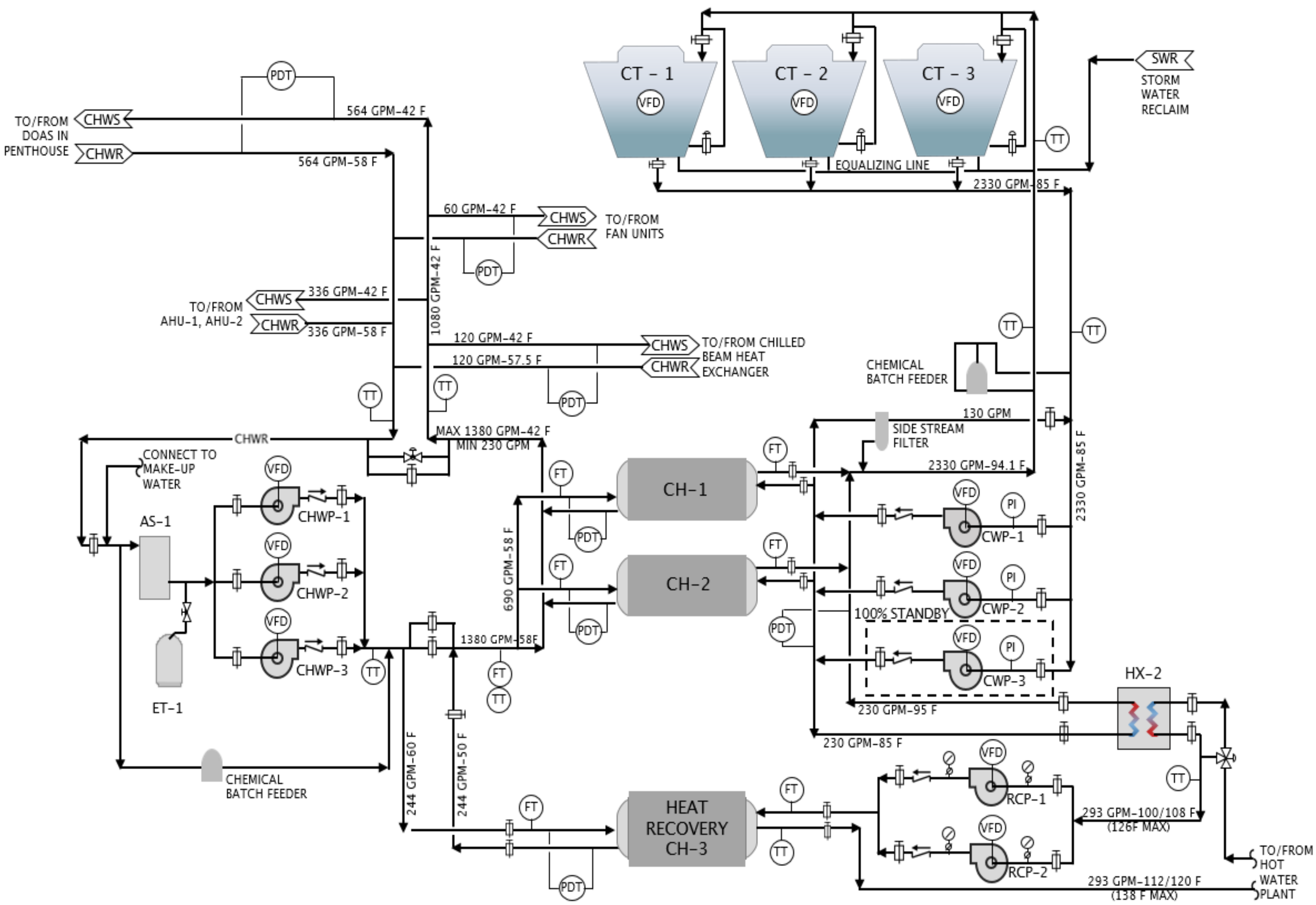


Figure 6: Chilled Water System Diagram

Combined Heating and Reheat Water System

The heating and reheat water system is composed of four hot water condensing boilers, primary pumps and distribution pumps. It was designed with N+1 redundancy; distribution pumps are each designed for 80% of the design load, and if one boiler fails, three boilers are able to cover the load. The system supplies hot water to a variable volume distribution system, consisting of a main heating loop serving AHU preheat coils and terminal heating devices, and a reheat loop serving reheat coils. When adequate capacity is available to reheat system, free heating is provided by the heat recovery chiller in the chilled water plant. Hot water in the heating loop is distributed at a supply temperature of 140 ^{o}F. Flow rate is modulated by varying the speed of the primary hot water pumps, which are controlled via VFD utilizing differential pressure transmitters. These sensors are installed between the hot water supply and return mains, to maintain a constant pressure differential between the piping mains. An additional heat exchanger for domestic hot water preheat is connected to the hot water return loop, which has a minimum temperature of 100 ^{o}F.

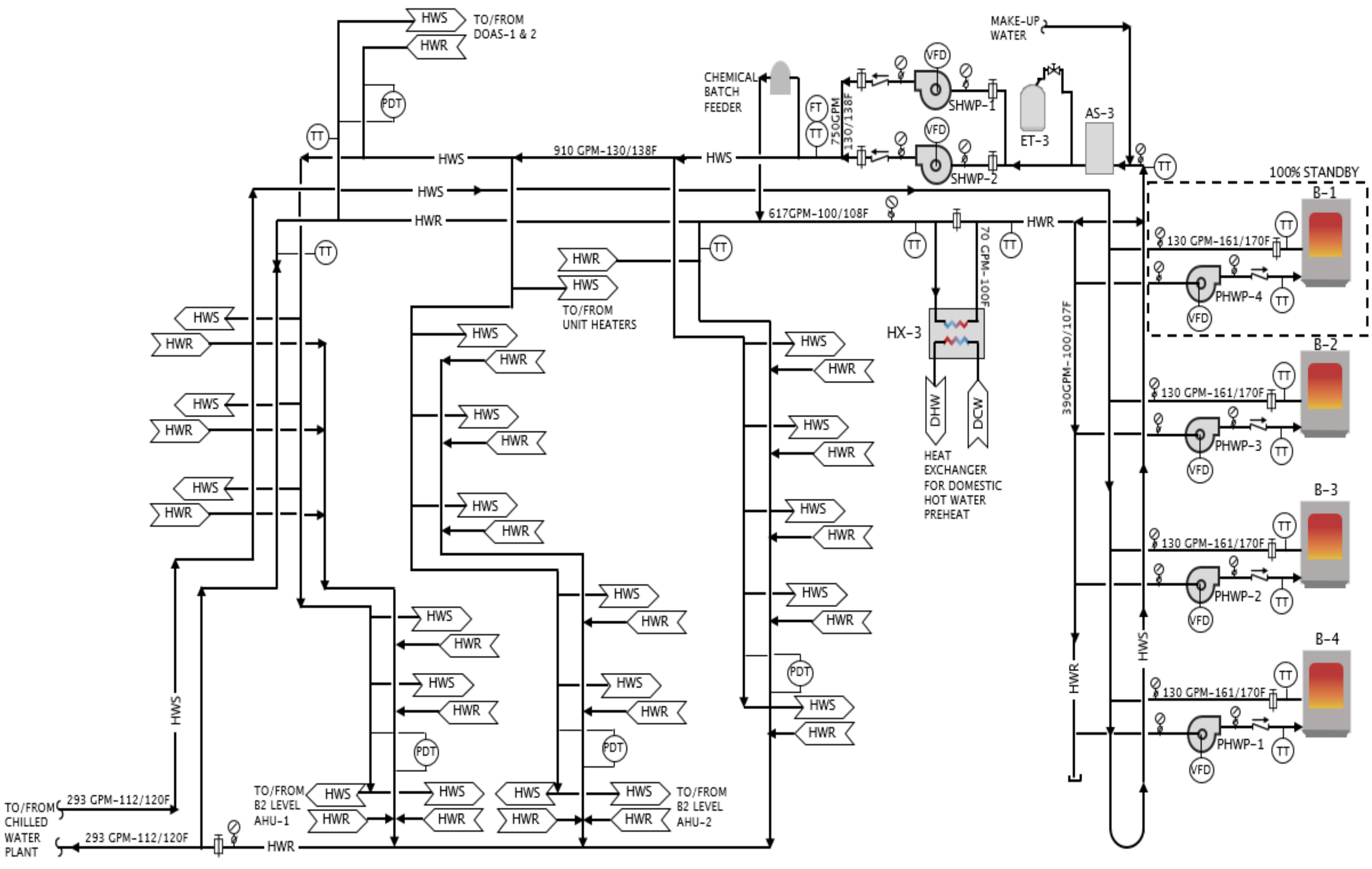


Figure 7: Hot Water System Diagram

Chilled Beam Water System

The chilled beam system consists of cooling panels, air supply system, and cooling water system. Primary air is supplied to the cooling panels from the DOAS units. For redundancy and reserve capacity purposes, heat exchangers, chilled water pumps, and distribution pumps, are each sized for 100% of the design system flow. The heat exchangers generate process cooling water, and are provided with automatic valves to isolate the inactive heat exchanger from the pumping system. The variable flow system distributes cooling water to the active cooling panels at 58 ^{o}F. VFDs vary the speed of the distribution pumps to maintain a constant pressure differential, monitored by a differential pressure transmitter located between the supply and return mains. A temperature sensor located in the leaving water line from each heat exchanger controls the process water supply temperature by modulating the chilled water via 2-way control valves at each terminal device. On startup, the lead process water pump starts and the lead heat exchanger is enabled by opening the automatic isolation valves, causing the lead chilled water pump to start as well. The system operates continuously, with the chilled water pump operating at constant flow via three-way control valves. At the room level, condensation and relative humidity sensors are installed in order to control condensation detection and chilled water temperature.

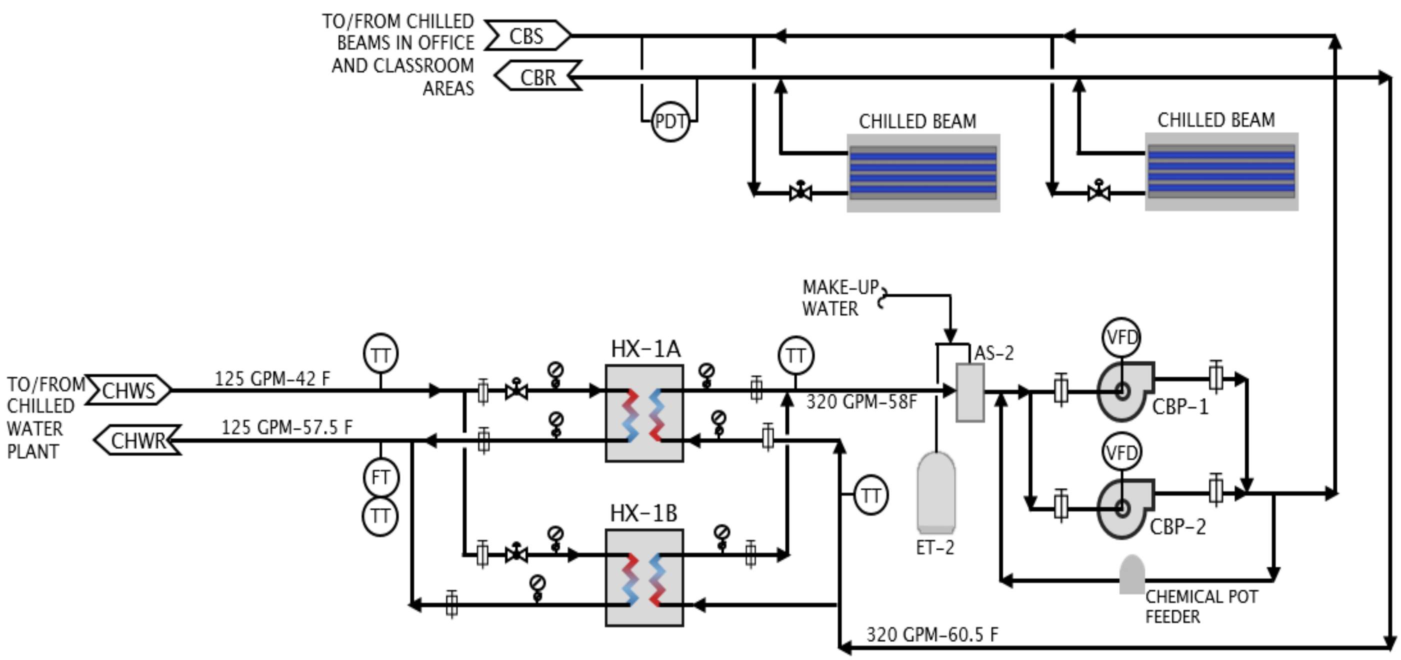


Figure 8: Chilled Beam Water System Diagram

Basement Air Handling Units

Schematics for the two basement air handling units are found on the figure below. AHU-1 consists of a package air handling unit, and provides cooling and heating through a single duct, variable air volume reheat system. Additional space heating is provided by reheat coils in air terminal devices located in each room. Supply airflow is modulated by double-inlet centrifugal fans with airfoil blades, whose speed and air volume is controlled by VFDs and supply duct static pressure controllers. Speed and air volume for the return fans is modulated through VFDs controlled by return fan discharge static pressure. AHU-2 consist of a single-duct variable volume system as well, but features a combination of overhead VAV and Under Floor Air Distribution (UFAD). Control dampers and duct coils are provided for temperature control of the under floor supply air, which is delivered to the floor levels of the classrooms at a minimum of 64 ^{o}F to maintain occupant comfort, as shown on Figure 8. The temperature of the overhead supply air is controlled via air terminal boxes. Both units operate in occupied and unoccupied modes, including demand control ventilation. CO2 sensors are located in the rooms and return ducts, as shown on the diagram.

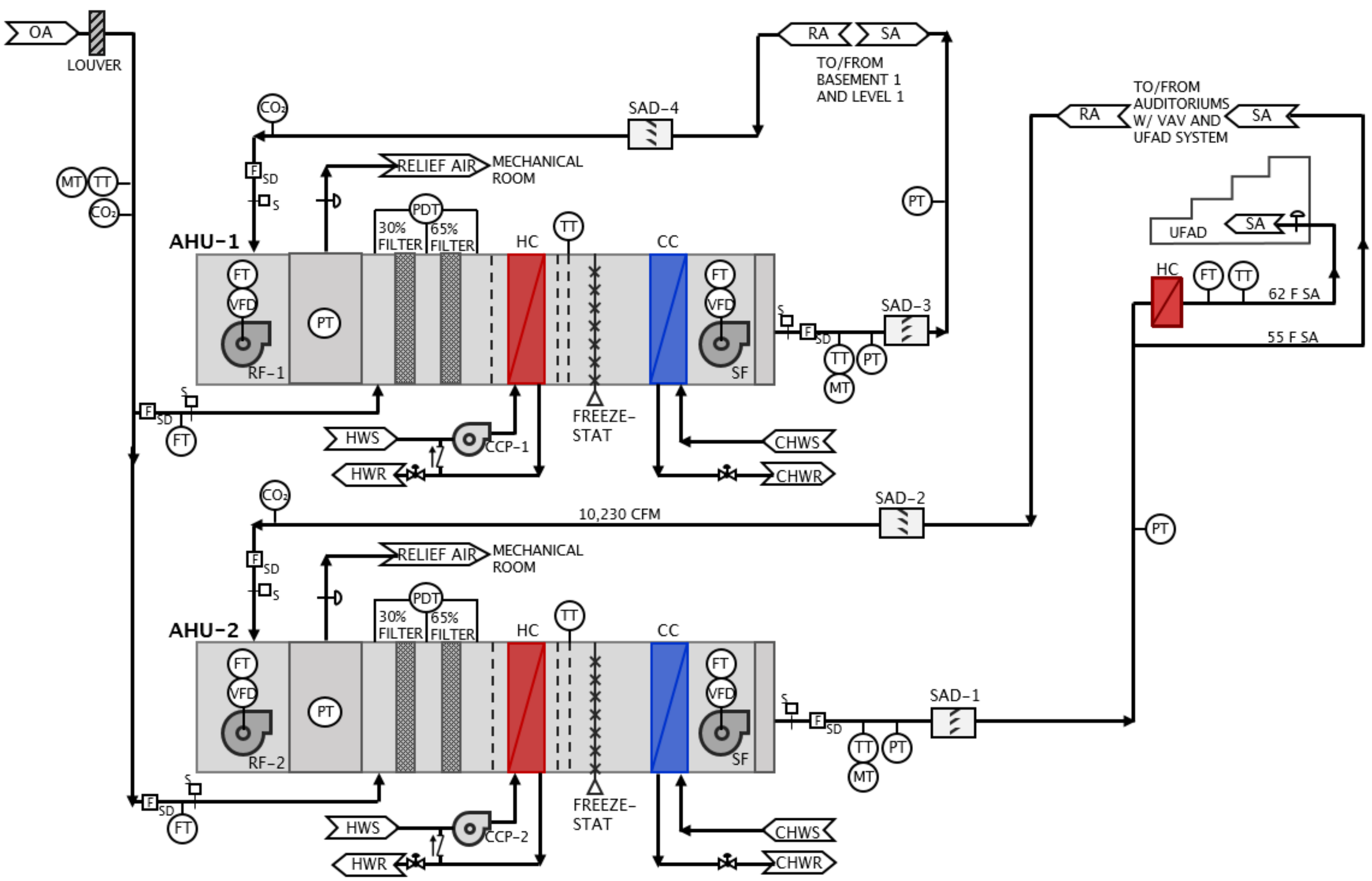


Figure 9: Basement AHU 1&2 Diagram

Dedicated Outside Air System with Chilled Beam

The DOAS with Chilled Beam system is served by two package air-handling units, DOAS-1 & DOAS 2, located on the penthouse. The units are interconnected for better reliability, operate in occupied and unoccupied modes, and include demand control ventilation. Each unit is incorporated with energy and sensible heat recovery wheels for heat recovery and air treatment. They provide heating, cooling, and dehumidification through a single-duct constant air volume system, which supplies air to ceiling mounted 2-pipe active chilled beams. Return air is centralized at the top of the atrium, and is either returned to the units or relieved to the outside via return fans. Centralized return air is achieved with transfer ducts, proper space pressurization and air balancing design. The speed and airflow of the supply and return fans is controlled by VFDs, which operate with duct static pressure controllers to maintain adequate duct static pressure. Return fans include isolation/smoke damper for fire protection, and return/relief air dampers for air volume control.

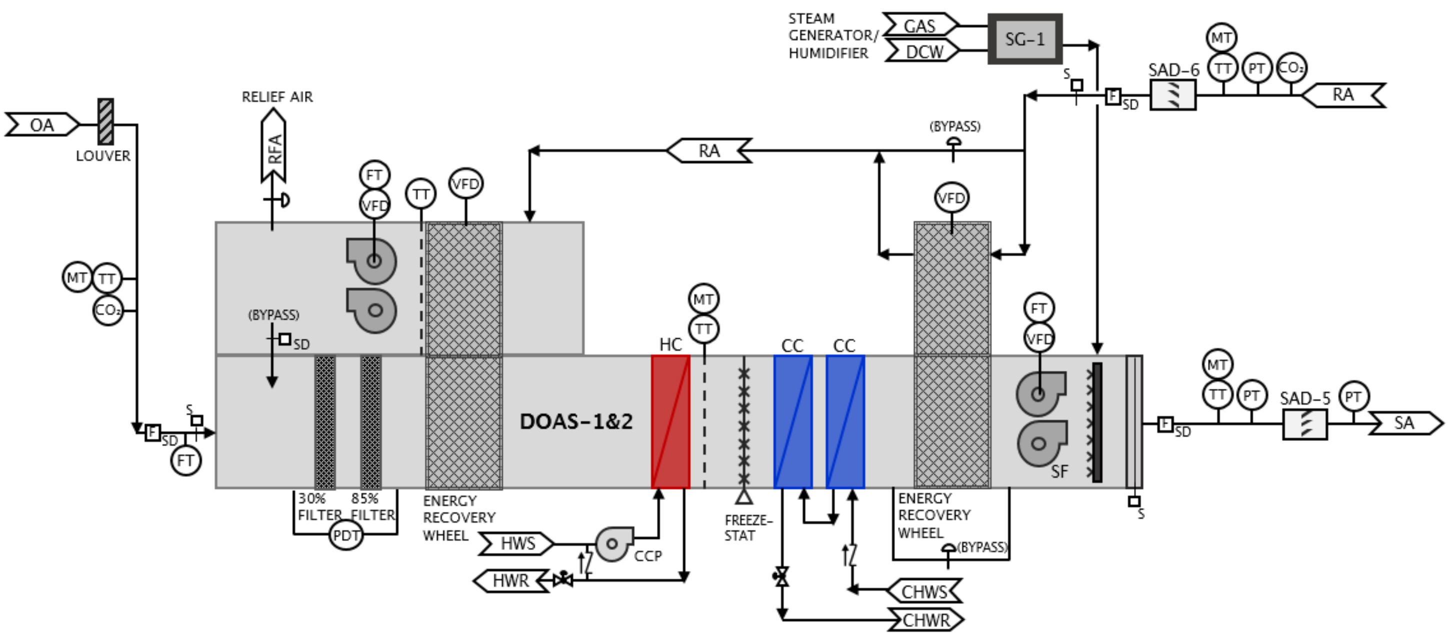


Figure 10: DOAS 1&2 Flow Diagram

Space Considerations for Mechanical Systems

The majority of the lost usable space associated with mechanical systems is concentrated in the basement, and is twice as much as the mechanical penthouse area or the total building vertical shaft area. Levels 1-7 have a gross floor area of approximately 16,000 SF, and vertical shaft areas of approximately 330 SF. Therefore, for the main occupied levels the total vertical shaft area per floor barely accounted for 2% of the total floor area. A summary of the spaces and areas utilized for the building's mechanical systems can be found on Table 13.

Table 13: Space Utilized for HVAC Systems

Space Type	Area [SF]
Basement Main Mechanical Room	4,488
B2 Mechanical Room	217
B2 Plumbing/Fire Protection	864
L7 Mechanical Room	330
Mechanical Penthouse	2,860
Vertical Shaft Area	2,501
Total	11,260

LEED Assessment

The School of Public Health Project obtained a LEED Platinum rating through the LEED 2009 Building Design and Construction certification program, LEED BD+C New Construction v3. It was awarded the highest LEED rating, with a total of 85 points, out of 110 total possible points. Energy use optimization was a primary design objective for the mechanical systems. Because of the site location, additional regional priority credits were awarded to the project for its innovative wastewater technologies, storm water design for quantity control, restoration of habitat during site development, and optimized energy performance demonstrated by energy models, with an estimated energy cost savings of 46% resulting in over $353,000 annual savings.

The credit categories the project missed the most amount of points in are Energy and Atmosphere, and Materials and Resources. Zero points were achieved for On-site renewable energy, as well as Measurement and Verification. Building and Material reuse credits were not obtained because the building was a new construction that required the design of a new structure and interior materials. A summary of the LEED/ASHRAE energy model results are shown on Table 14 and Figure 11 at the end of this section

Table 14: Proposed Design vs. Baseline Model Results Summary

Model	Energy Use [MMBtu]								Energy Cost [$]	Savings		EUI [kBtu/SF]
	Plug	Lights	Heating	Cooling	Heat Rej	Pump	Fan	Total		Energy	Cost	
Baseline	1,602	856	21,235	2,281	395	974	3,040	30,382	757,993	-	-	189
Proposed	1,630	718	3,716	1,450	76	277	2,906	10,773	404,407	65%	46.6%	67

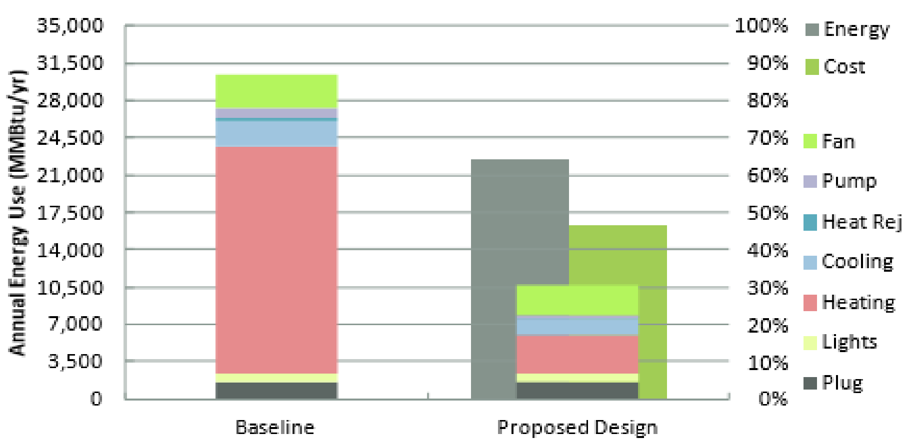


Figure 11: Baseline vs. Proposed Design Energy Use Breakout

Overall Evaluation of Mechanical Systems

Analysis performed for the two previous reports, which include ventilation compliance, load calculation, and energy consumption, indicate that the mechanical systems designed for the School of Public Health satisfies and often exceeds the requirements set by ASHRAE 62.1 and 90.1 standards.

The limited space to house the entire building program as well as support spaces and building structure was challenging factor. With a reduced floor to floor height after introducing a 7^{th} floor, air plenum space was not available for large air distribution systems. The resulting design of mechanical system managed to meet all the design goals and requirements without compromising significant amounts of building space, taking less than 2% of the gross floor area in most levels. The DOAS and Chilled Beam system allowed the spaces to be conditioned through a distribution system with smaller ducts, does not invade the open spaces located around the atrium, and delivers adequate ventilation air.

Energy performance in the building was optimized through various strategies. Envelope loads were reduced with the design exterior walls and roofs with improved thermal performance, as well as improved fenestration and solar heat gain performance. The significant amount of glass in the atrium spaces, as well as the façade facing Washington Circle, lead to the design of external shading devices and building self-shading characteristics.

Mechanical systems operations are controlled by an optimized Building Automation System, which is interconnected to the existing BAS of the remaining campus buildings to improve efficiency. Some control methods within the building are occupancy sensor lighting controls, daylighting controls, and CO2 based ventilation controls. The chilled water system was designed with chiller plant controls to optimize chiller operation at part load efficiency through demand limiting when load permits. The overall project cost for the School of Public Health was approximately $57 million. However, specific costs for the mechanical systems first cost or operating costs were not provided by the owner.

Proposed Redesign

Design Goals and Considerations

The DOAS and Chilled Beam system is currently served by two air-handling units, DOAS-1 and DOAS-2, located in the mechanical penthouse. The units are packaged with two energy recovery wheels, two cooling coils, and a heating coil. A Dedicated Outdoor Air System reduces energy consumption by decoupling the cooling and heating loads from the ventilation air requirement in the building, so the individual systems can be designed at a better efficiency. Ventilation air is conditioned to a low dew point to meet the space humidity requirements, therefore the cold-air DOAS system allows for part of the space sensible load to be met by the conditioned outside air, which reduces the required sensible cooling capacity of the chilled beams, energy use, and cooling airflow.

The existing design was designed to optimize the operation of the DOAS, using displacement ventilation, demand controlled ventilation, and various utilization schedules based on occupancy hours. However, the required cooling capacity for the system still makes up for roughly half of the total chilled water plant. The implementation of energy recovery wheels for large amounts of airflow increases the pressure drop, which results in higher fan power required. When compared to the LEED baseline, the existing system resulted in large energy savings for cooling and heating, but the energy analysis results show that the design did not cause a significant reduction in fan energy consumption. A summary of annual energy consumption by end use can be found in Table 6, and shows that fan energy use decreased by less than 5%.

Common methods of air-to-air energy recovery for dedicated outside air applications include enthalpy wheels, heat pipes, and run around loop coils. Air-Source VRF Heat Pumps are currently implemented in smaller applications, where one outdoor unit is connected to multiple indoor units by refrigerant piping. A heat pump with variable refrigerant flow has the capacity to operate in all conditions for air-to-air heat recovery and condition the required ventilation air, while avoiding air pressure drops as large as the ones caused by energy recovery wheels.

Integration of Reversible Heat Pump and DOAS for Optimized Energy Recovery of waste heat

The proposed alternative consists in implementing a reversible heat pump, possibly with variable refrigerant flow, for energy recovery and conditioning between the exhaust air and outside air supply streams. Operating a reversible heat pump between the exhaust and outdoor air should theoretically be more efficient, as it allows it to pre-conditioning warm outside air by rejecting heat into the 70 °F return air, instead of the typical design summer condition of 95° F, or extracting heat from the return instead of the outside air in the winter.

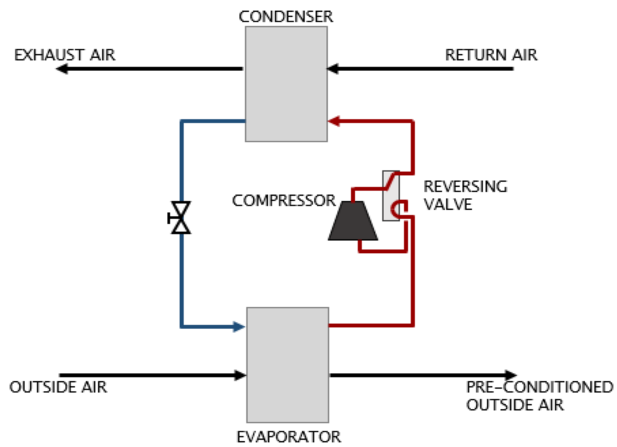


Figure 12: Reversible Heat Pump Schematic

The diagram on Figure 12 shows the energy recovery scheme between the return and outside air streams for cooling operation. For summer conditions, the outdoor air is conditioned by the evaporator, where heat is absorbed and transferred to the condenser through a vapor-compression cycle. During the heating season, outdoor air flows through the condenser, where it is pre-conditioned by heat absorbed from the return air stream at the evaporator.

The proposed alternative will test the efficiency of this system for energy recovery purposes in the two dedicated outside air units serving the chilled beam system in the building. The proposed system is not currently available in energy modeling software such as Trace 700, so different methods of calculating energy consumption are being explored. In order to assess system performance, a bin analysis will be conducted using bin weather data from Washington, D.C., following the steps established in ASHRAE Fundamentals Handbook, Chapter 31: Energy Estimating and Modeling Methods.

The bin method is a steady-state model where efficiency or conditions of use vary with outdoor air temperature and number of hours. Energy consumption is calculated for several values of outdoor air temperature and multiplied by the number of hours in the temperature interval, or bin. Internal loads, ventilation requirements, infiltration rates, and other components of the total building load will be obtained from the design documents and existing data. Occupancy schedules and operation hours are available from the design documents will be considered into the analysis as well.

Tasks and Tools

I. Optimizing Energy Recovery with Heat Pump

Task 1. Gather Weather Data and Building Design Conditions

a) Obtain TMY3 weather data for Washington D.C.
b) Identify the balance point temperature of the building
c) Obtain indoor design conditions from design documents

Task 2. Establish Building Loads and Schedules

a) Obtain the building's internal and envelope loads
b) Obtain operating schedules from design documents

Task 3: Perform Bin Analysis

a) Calculate the annual heating and cooling energy consumption using the bin method as established in ASHRAE Fundamentals Handbook.

Task 3. Determine Initial and Operating Costs

a) Identify equipment and required capacities for the system
b) Calculate operating costs and energy consumption
c) Comparison to existing system

II. Building Systems Integration with Natural Ventilation

Task 1. Existing Conditions

a) Analyze wind conditions for the site
b) Obtain weather data and identify periods where natural ventilation would be feasible

Task 2. Natural Ventilation Operation

a) Identify location of openings for outside air flow into the atrium space
b) Calculate amount of ventilation and cooling airflow

Task 3. Occupant Comfort Analysis

a) Develop computational fluid dynamics model using CFD software (Star CCM+)
b) Verify airflow behavior is adequate for natural ventilation and to maintain occupant thermal comfort

Task 4. Energy Savings Comparison

a) Calculate amount of energy that would be used by the existing system during natural ventilation operation periods
b) Compare to initial costs of proposed system and calculate payback period.

Mechanical Design Analysis

Evaluation of Existing Design

The existing Dedicated Outdoor Air System is conditioned by chilled water and hot water coil. Chilled water is supplied from the mechanical basement, where 3 centrifugal chillers supply all the buildings mechanical systems. Heat rejection is done by three cooling towers located on the mechanical penthouse. Hot water is produced in by the hot water and reheat system, composed of 4 gas-fired boilers. TRACE 700 was used to obtain the energy consumption associated with the current design, as well as the different systems load profiles. Load profiles and duration curves were used to analyze the current system demand and to identify the demand at which the equipment would be operating for most of the year. Figures 13.1 and 13.2 below shows the existing system's load profiles.

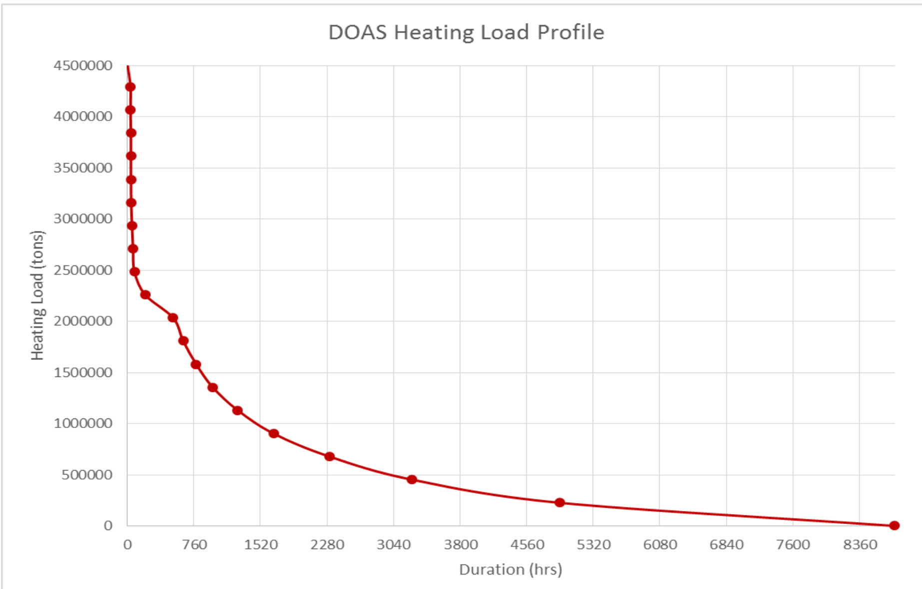


Figure 13.1: Heating Duration Curve

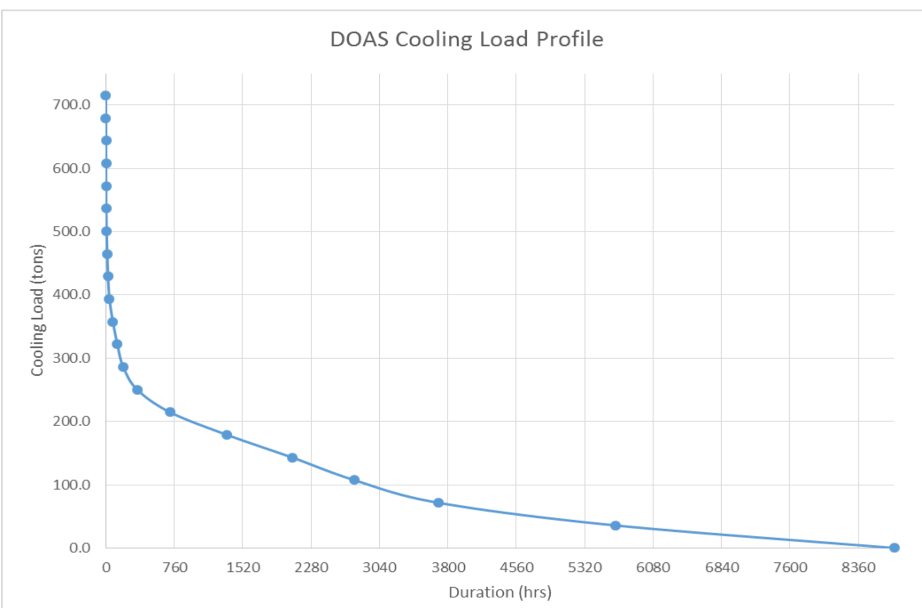


Figure 13.2: Cooling Duration Curve

Energy reports obtained from the simulation performed with TRACE 700 provide a detailed overview of the monthly electric power consumption for different equipment assigned to plants. In the previous TRACE simulation, the system was modeled as two separate ones: DOAS and chilled beams, and DOAS and reheat. Both of these systems are served by the two dedicated outdoor air units, which are supplied with chilled water and hot water from the cooling and heating plants, respectively. An overall monthly energy consumption breakout by utility is summarized in Table 15, which includes all systems associated with the DOAS units including chilled water plant, hot water plant, energy recovery wheels, and fans.

Table 15: Utility Consumption Breakout for Existing System

Component	January	February	March	April	May	June	July	August	September	October	November	December	Total
Chilled Water Plant													
Electric (kWh)	14,725	11,004	16,843	30,602	50,147	77,970	86,701	83,622	62,916	43,312	20,146	16,700	514,687
Water (1000 gal)	64	47	73	124	204	313	340	328	248	177	83	72	2,072
Hot Water Plant													
Electric (kWh)	2,606	2,400	2,443	2,138	2,313	2,239	2,293	2,284	2,410	2,343	2,455	2,497	28,422
Gas (therms)	6,319	5,736	4,986	2,470	2,549	2,158	2,230	2,051	2,942	2,806	4,736	5,207	44,189
DOAS Air Handling Unit													
Energy Recovery	244	222	251	246	243	303	303	290	299	247	244	227	3,119
Fans	26,041	22,056	24,955	29,124	36,563	50,129	56,140	54,312	44,828	33,091	27,027	23,768	428,034
Total Electri (kWh)	43,616	35,682	44,492	62,110	89,266	130,641	145,437	140,508	110,453	78,993	49,872	43,192	974,262
Total Gas (therms)	6,319	5,736	4,986	2,470	2,549	2,158	2,230	2,051	2,942	2,806	4,736	5,207	44,189
Total Water (1000 gal)	64	47	73	124	204	313	340	328	248	177	83	72	2,072

Since the equipment in the modeled chilled water and hot water plants serve the VAV Reheat, DOAS, FCU, and chilled beams systems; assessing the fraction of energy consumption due to the DOAS units from the simulation performed before was not too accurate. A second version of the energy model, in which the DOAS system was assigned to an additional cooling plant, was created to estimate the fraction of the cooling plant total load due to the DOAS units more accurately. The same procedure was followed for the existing heating plant, and the DOAS system was assigned to a separate hot water plant to estimate the fraction of energy of the original heating plant consumed to meet the system's demand.

The energy model results indicate that the cooling capacity requirement for the DOAS system accounts for at least 55% of the electric power consumed by the cooling plant year round, with a peak percentage of 75% occurring in July. Considering that the chilled water production from the cooling plant serves the remaining of the buildings systems, separating the DOAS load requirements has the potential of decreasing the required cooling plant capacity by almost 50%. In the case of the hot water plant, energy consumption is reduced by over 50% from the original value. However, the exact accuracy of energy savings has to be further assessed, given that the heating plant operates with hot water boiler and uses natural gas as an energy source, which can be significantly cheaper than electric power. The following tables summarize the energy consumption results for the original cooling and heating plants, and the plants modeled without the DOAS system assignment. Table 17 summarizes energy consumption due to energy recovery and air distribution systems, including the energy recovery wheels, supply, and return fans operating with the DOAS system. Figure 14.1 shows that the energy consumption reduction of 50% in the cooling plant is consistent throughout the entire year, while the energy consumption savings shown in Figure 14.2 for the heating plant is more significant during the heating season.

Table 15.1: Existing Cooling Plant Energy Consumption (kWh)

Equipment	January	February	March	April	May	June	July	August	September	October	November	December	Annual
Heat Recovery Chiller	1,389	1,063	1,600	2,552	3,941	5,940	6,581	6,241	4,827	3,433	1,765	1,526	40,859
HRC Pump	57	45	64	97	150	230	245	235	181	132	70	62	1,567
Chiller 1	5,395	4,136	6,219	9,895	15,182	22,698	25,185	23,897	18,562	13,237	6,850	5,920	157,174
Cooling Tower 1	1,439	975	1,611	4,243	7,833	12,868	14,463	14,293	10,275	6,651	2,468	1,813	78,933
CH Pump 1	187	145	213	334	528	821	877	843	643	463	235	206	5,496
CT Pump 1	275	213	313	491	777	1,206	1,290	1,239	946	680	346	303	8,079
Chiller 2	4,861	3,722	5,600	8,934	13,804	20,810	23,059	21,870	16,910	12,020	6,180	5,340	143,108
Cooling Tower 2	1,438	975	1,609	4,238	7,826	12,862	14,461	14,290	10,267	6,642	2,467	1,811	78,885
CH Pump 2	308	243	351	527	813	1,249	1,331	1,280	983	716	382	337	8,519
CT Pump 2	275	213	313	491	777	1,206	1,290	1,239	946	680	346	303	8,079
Total	15,625	11,728	17,893	31,802	51,630	79,891	88,782	85,427	64,539	44,653	21,108	17,622	530,699

Table 15.2: Cooling Plant - No DOAS Energy Consumption (kWh)

Equipment	January	February	March	April	May	June	July	August	September	October	November	December	Annual
Heat Recovery Chiller	1,115	861	1,212	1,903	3,129	4,359	4,657	4,617	3,521	2,709	1,216	1,160	30,459
HRC Pump	47	38	51	74	116	154	160	162	127	102	51	49	1,130
Chiller 1	4,334	3,350	4,711	7,398	12,147	16,877	18,045	17,884	13,653	10,515	4,730	4,510	118,153
Cooling Tower 1	1,403	974	1,586	4,116	7,676	12,742	14,407	14,235	10,077	6,420	2,438	1,770	77,844
CH Pump 1	153	121	166	250	400	540	562	568	440	352	166	159	3,878
CT Pump 1	226	177	244	368	588	795	826	835	647	518	243	234	5,701
Total	7,278	5,520	7,969	14,109	24,057	35,467	38,658	38,301	28,464	20,616	8,844	7,881	237,165

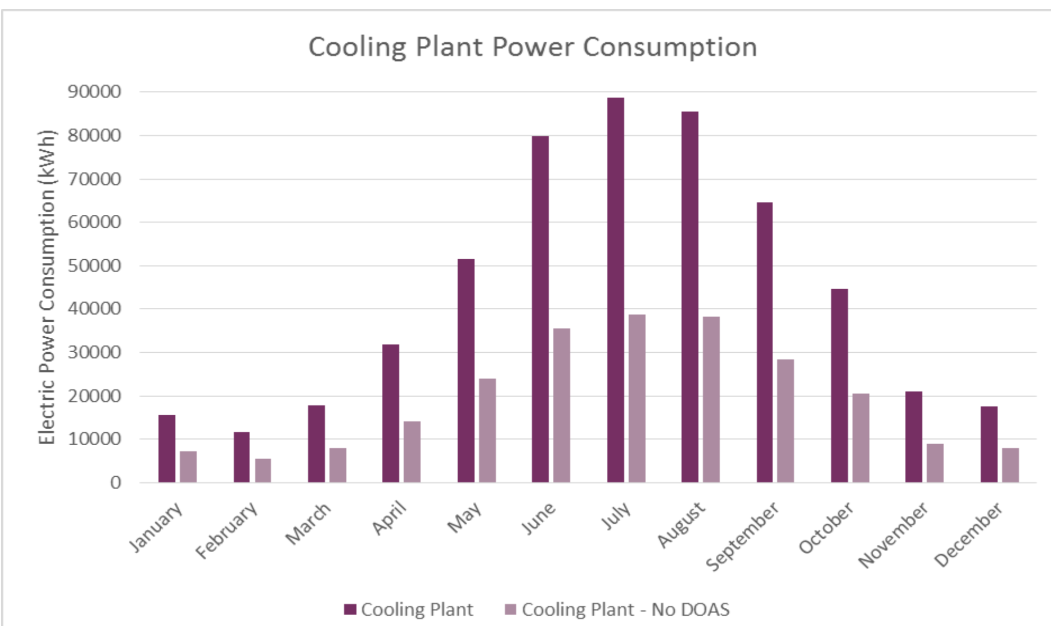


Figure 14.1: Consumption Comparison – CHW Plant

Table 16.1: Existing Heating Plant Energy Consumption													
Equipment	**January**	**February**	**March**	**April**	**May**	**June**	**July**	**August**	**September**	**October**	**November**	**December**	**Annual**
Boilers 1, 2 & 3 (therms	6,319	5,736	4,986	2,470	2,549	2,158	2,230	2,051	2,942	2,806	4,736	5,207	44,189
Boilers 1, 2 & 3 (kWh)	185,136	168,071	146,095	72,364	74,683	63,243	65,325	60,082	86,208	82,217	138,767	152,554	1,294,744
Pumps	1,443	1,310	1,306	1,036	1,100	1,037	1,058	1,069	1,134	1,129	1,274	1,342	14,238
Boiler draft fan	1,100	1,016	1,086	1,052	1,130	1,108	1,140	1,132	1,151	1,130	1,096	1,096	13,237
Total (kWh)	187,679	170,397	148,487	74,452	76,913	65,388	67,523	62,283	88,492	84,476	141,137	154,992	1,322,219

Table 16.2: Heating Plant - No DOAS Energy Consumption													
Equipment	**January**	**February**	**March**	**April**	**May**	**June**	**July**	**August**	**September**	**October**	**November**	**December**	**Annual**
Boilers 1, 2 & 3 (therms	3,248	2,872	2,427	1,598	1,850	1,752	1,749	1,730	2,306	1,955	2,659	2,801	26,948
Boilers 1, 2 & 3 (kWh)	95,175	84,141	71,099	46,831	54,193	51,339	51,259	50,688	67,578	57,294	77,897	82,076	789,570
Pumps (kWh)	1,141	1,020	1,065	988	1,064	1,038	1,066	1,060	1,120	1,078	1,080	1,111	12,831
Boiler draft fan (kWh)	1,033	930	1,045	1,048	1,112	1,090	1,122	1,121	1,123	1,117	1,035	1,051	12,826
Total (kWh)	97,349	86,091	73,209	48,867	56,369	53,467	53,446	52,869	69,821	59,488	80,013	84,237	815,227

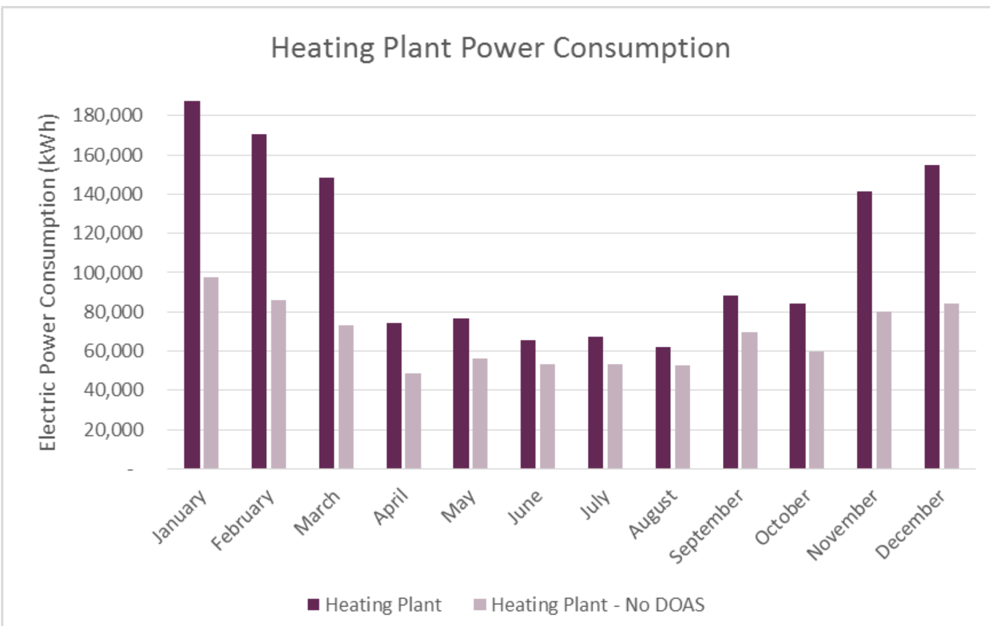


Figure 14.2: Consumption Comparison – HW Plant

Table 17: Distribution and Energy Recovery Energy Consumption (kWh)													
Equipment	**January**	**February**	**March**	**April**	**May**	**June**	**July**	**August**	**September**	**October**	**November**	**December**	**Annual**
Energy Recovery Wheel	244	222	251	244	235	288	286	273	281	244	240	226	3,035
Main Supply Fan	17,474	14,758	16,600	19,955	25,176	34,485	38,831	37,562	30,943	23,137	18,471	16,169	293,561
Return Fan	8,371	7,113	8,133	8,974	11,164	15,421	17,076	16,515	13,664	9,754	8,347	7,393	131,924
Total (kWh)	26,090	22,092	24,984	29,174	36,575	50,194	56,193	54,350	44,887	33,134	27,058	23,788	428,520

Capacity Requirements and Control Set points

Using the operating schedule shown on Table 18 specified by the owner, which is based on percentage airflow of the total ventilation air, the building cooling and heating loads were obtained for each condition of degree temperature of outside air and % airflow. The weather data was organized by month, and the obtained number of hours for each bin was used to calculate monthly and annual total loads. Operating hours for weekdays were taken into consideration, as well as the constant value of 10% capacity for the weekends.

Table 18: General Utilization Schedule

Start	End	Percentage	Airflow (CFM)	Peak Load (tons)
12:00:00 AM	6:00:00 AM	0%	0	-
6:00:00 AM	7:00:00 AM	5%	3150	23
7:00:00 AM	8:00:00 AM	10%	6300	46
8:00:00 AM	9:00:00 AM	35%	22050	160
9:00:00 AM	12:00:00 PM	70%	44100	320
12:00:00 PM	1:00:00 PM	30%	18900	140
1:00:00 PM	4:00:00 PM	70%	44100	320
4:00:00 PM	5:00:00 PM	35%	22050	160
5:00:00 PM	9:00:00 PM	10%	6300	46
9:00:00 PM	10:00:00 PM	5%	3150	23
10:00:00 PM	12:00:00 AM	0%	0	-
Saturday	Sunday	10%	6300	15

The operating sequence of the new DOAS units was based on the controls of the existing system. Loads for every operating hour of the year were calculated using excel, where the logical IF function was used to return the operating mode if a specified set of conditions were satisfied. The set point values used for the DOAS operation and the leaving supply air set points are shown on Tables 19 and 20.

Table 19: DOAS Operating Mode

Operating Mode	Pyschrometric Conditions
Dehumidification	OA Dew Point > SA Dew Point
	OA enthalpy > RA enthalpy
Sensible Cooling	OA DB> SA DB High
	OA Dew Point < SA Dew Point
Ventilation Only	SA DB Low < OA DB < SA DB High
	OA Dew Point < SA Dew Point
Heating	OA DB < SA DB Low

Table 20: Supply Air Setpoint

Dry-Bulb (°F)		**Dew-Point (°F)**
High	Low	45
50	45	

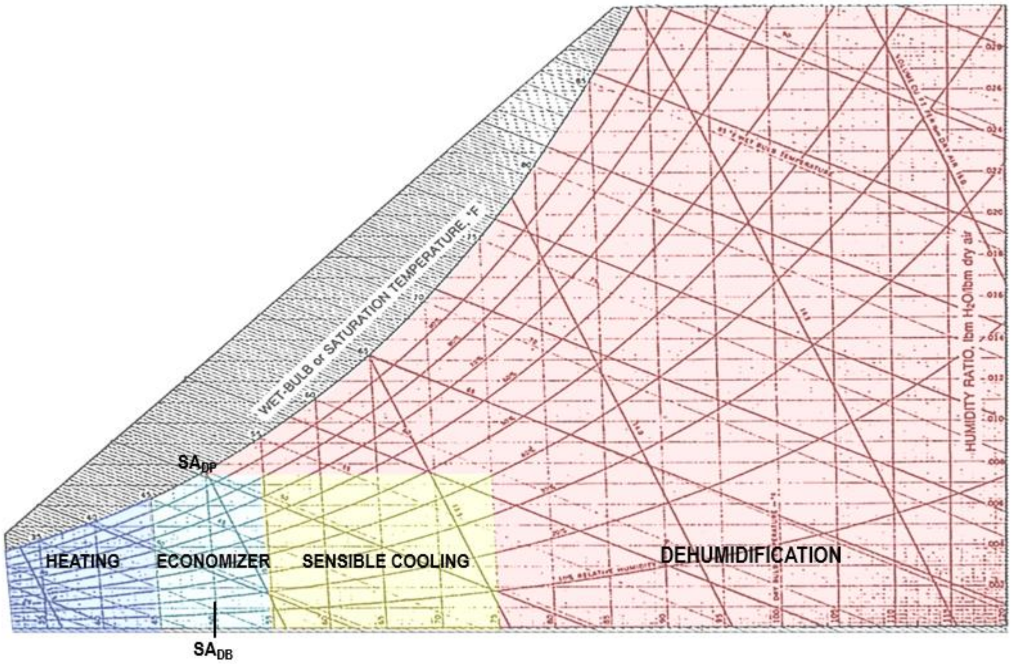


Figure 14.3: DOAS Operating Modes

The capacity of the existing system was sized based on 100% capacity and airflow, even though the operating schedule only requires 70% of the total airflow at the highest occupancy hours. It has a total capacity of roughly 4,380 MBtu (365 tons), sized for a cooling capacity able to operate at EAT 95 °F DB/76 °F WB, LAT 50 °F DB. Each DOAS unit can handle up to 31,500 CFM at 100% load conditions. Due to the lack of availability of performance data for air-to-air heat pumps with a capacity comparable to one of the existing DOAS unit, the total airflow and capacity required was split into smaller modular units in order to avoid extrapolating capacities for existing equipment capacity and performance data, which could lead to less accurate results.

In order to split the capacity of the units in an efficient way, the highest cooling and heating load for each condition specified in the operating schedule were calculated. To avoid operating at part load capacity at the most energy consuming hours, the total capacity was divided into 5 units. The use of 5 smaller units for conditioning the outside air allows for better control at different capacities. The final configuration, shown on Figure 15, consists of one 55 ton unit and four 95 ton units, which would be able to meet the peak load for both cooling and heating conditions at all hours specified in the utilization schedule. Table 21 specifies details on the selected configuration, capacities and ratings.

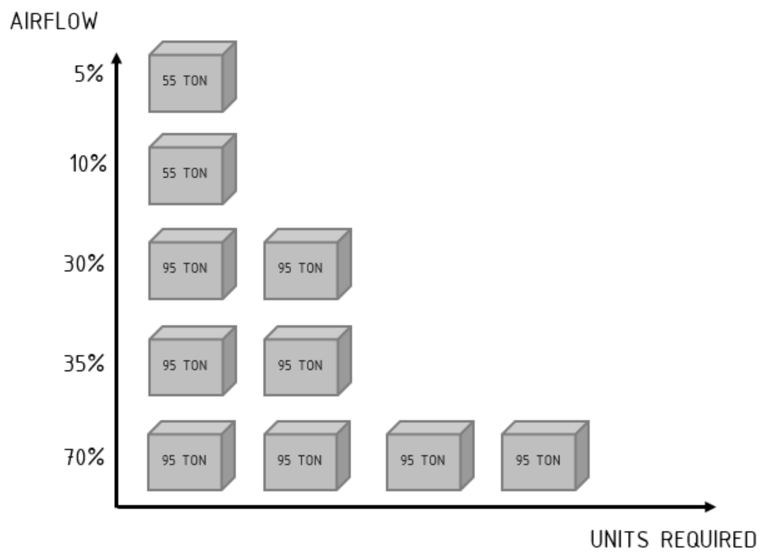


Figure 15: Units required at every percentage airflow

Table 21: Selected Unit Configuration and Ratings

DOAS Unit	Rated Cooling Capacity (Mbtu)	Rated Heating Capacity (Mbtu)	EER	COP	Airflow (cfm)
55 ton (1)	660	600	11	3.4	6500
Compressor 1	325	300			
Compressor 2	325	300			
95 ton (4)	1150	1050	10.9	3.2	11300
Compressor 1	380	350			
Compressor 2	380	350			
Compressor 3	380	350			

Methods for Energy Use and Performance Evaluation

In order to evaluate the energy consumption and efficiency of the proposed system, information about the loads, operating schedules, ventilation requirements, and available equipment was gathered. A bin analysis was performed using TMY3 data for Washington D.C., using a temperature range of 1 °F and the ventilation airflow rates specified in the utilization schedule. To compare the results more accurately, the hourly load was calculated at every temperature bin for each specific outside airflow percentage specified in the operating schedule used for the energy analysis done with TRACE 700.

Performance Curves

The energy consumption of the system was evaluated using coefficients based on performance curves obtained from EnergyPlus. EnergyPlus provides a wide range of performance coefficients which are modeled from performance data obtained from many manufacturers. After evaluating many options, the model selected was the rooftop packaged heat pump with double-stage cooling mode. This model presented a better alternative than the regular air-to-air heat pump due to its higher rated capacity and operating range. The evaporator and condenser coils are modeled as a DX cooling coil and heat pump DX heating coil, and the packaged unit operates with a scroll compressor and R-410 refrigerant. To simulate the proposed alternative, the capacity, performance rating, and rated airflow were adjusted to match the data obtained for the 3-stage compressor system. Specific equations and coefficients used to model the capacity and energy consumption are listed below.

Table 22: Performance Curve Coefficients

		CAP_FT	CAP_FF	EIR_FT	EIR_FF	PLF_FPLR
Cooling Coil	a	0.589312	0.7396061	0.5130155	1.2714955	0.85
	b	0.0300284	0.249453	0.026827	-0.331635	0.15
	c	0.000144	0.0109409	-0.000515	0.0601399	0
	d	0.0028769		-0.006014		
	e	-8.98E-05		0.0006857		
	f	-0.000321		-0.00069		
Heating Coil	a	0.758363	0.8655321	1.254257	1.7343289	0.85
	b	0.0254357	0.140471	-0.025183	-1.084197	0.15
	c	3.928E-05	-0.006003	0.0009262	0.3498679	0
	d	-4.22E-06		-3.98E-05		

DX Cooling Coil Temperature functions:

Total Cooling Capacity modifier for temperature dependence:

$$\boldsymbol{CAP_{FT} = a + bT_{wb,i} + cT_{wb,i}{}^2 + dT_{c,i} + eT_{c,i}{}^2 + fT_{wb,i}T_{c,i}}$$

Energy Input Ratio modifier for temperature dependence:

$$\boldsymbol{EIR_{FT} = a + bT_{wb,i} + cT_{wb,i}{}^2 + dT_{c,i} + eT_{c,i}{}^2 + fT_{wb,i}T_{c,i}}$$

$T_{wb,i} = wet - bulb\ temperature\ of\ air\ entering\ the\ evaporator$
$T_{c,i} = dry - bulb\ temperature\ of\ air\ entering\ the\ air - cooled\ condenser$

Heat Pump DX Heating Coil Temperature functions:

Total Heating Capacity modifier for outdoor temperature dependence:

$$\boldsymbol{CAP_{FT} = a + bT_{db,o} + cT_{db,o}{}^2 + dT_{db,oi}{}^3}$$

Energy Input Ratio modifier for outdoor temperature dependence:

$$\boldsymbol{EIR_{FT} = a + bT_{db,o} + cT_{db,o}{}^2 + dT_{db,oi}{}^3}$$

$T_{db,} = dry - bulb\ temperature\ of\ air\ entering\ the\ outdoor\ coil$

Flow-fraction and part-load ratio functions:

Total Cooling Capacity modifier for flow fraction dependence

$$\boldsymbol{CAP_{FF} = a + b\iint + c\iint{}^2}$$

Energy Input Ratio modifier for flow fraction dependence:

$$EIR_{FF} = a + b\iint + c\iint^2$$

$$\iint = flowfraction = \frac{Actual\ air\ mass\ flow\ rate}{Rated\ air\ mass\ flow\ rate}$$

Part Load Fraction correlation for part load ratio dependence:

$$PLF = a + bPLR + cPLR^2$$

Part-load ratio:

$$PLR = \frac{Cooling\ Load}{Steady - state\ cooling\ capacity}$$

Coil Capacity and Electric power input:

Total gross cooling capacity of the DX unit:

$$\dot{Q}_{total} = \dot{Q}_{rated} \times CAP_{FT} \times CAP_{FF}$$

Total electric power consumed by the DX unit:

$$Power = \dot{Q}_{total} \times EIR \times RTF$$

Energy Input Ratio:

$$EIR = \frac{EIR_{FT} \times EIR_{FF}}{COP_{rated}}$$

Runtime Fraction of the coil:

$$RTF = \frac{PLR}{PLF}$$

Fan Energy Consumption

The existing DOAS unit, as shown on Figure 15.1, design consists of an energy recovery wheel, two cooling coils, a heating coil, and a sensible wheel. The pressure drop resulting from air passing through multiple coils increases the amount of fan energy consumption, due to the required pressure head and power input that the fan needs to overcome this pressure drop.

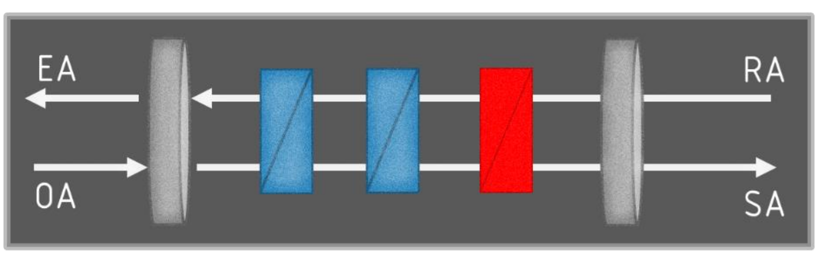


Figure 15.1: Components of existing DOAS unit

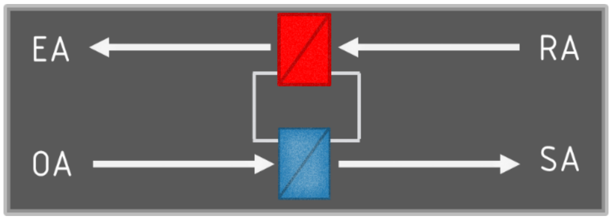


Figure 15.2: Configuration A Components

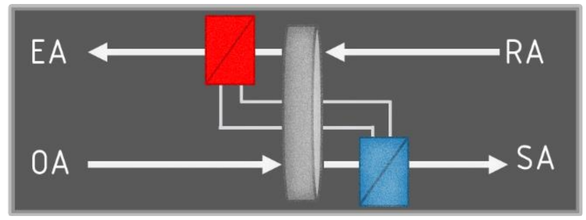


Figure 15.3: Configuration B Components

An advantage of the proposed alternatives, as shown on Figures 15.2 and 15.3, is that they eliminate the need for airflow to pass through the same amount of coils and heat exchangers, reducing the pressure drop and therefore the required fan energy for distributing the air. The pressure drop for the components of the existing unit are specified on the tables below.

Table 22.1: Max. Pressure Drop

Component	Pressure Drop (in. wg)
Enthalpy Wheel	0.68
Cooling Coil 1	0.75
Cooling Coil 2	0.7
Heating Coil	0.15
Sensible Wheel	0.58

Table 22.2: Reduced Pressure Drop and Fan Power

Fan	Supply Side		Return Side	
	SP (in. wg)	BHP	SP (in. wg)	BHP
Existing	8.80	31.11	3.20	11.62
Alt. A	6.48	19.65	2.07	6.05
Alt. B	6.72	20.77	2.65	8.76

Given that the same amount of airflow as the previously sized fan was being distributed, the new fan energy consumption was estimated by obtaining the new pressure drop for both alternatives. Assuming the fan wheel diameter remained constant, the new pressure differential and affinity laws specified in the equations below were used to calculate the new fan energy consumption for the proposed alternatives with and without the energy recovery wheel option.

Head or Pressure:

$$\frac{\Delta p_1}{\Delta p_2} = \left(\frac{n_1}{n_2}\right)^2$$

Power:

$$\frac{P_1}{P_2} = \left(\frac{n_1}{n_2}\right)^3$$

Optimizing Part-Load Performance

To optimize performance at part-load, the 95-ton units were designed to operate with 3 staged scroll compressors. This modulation method offers better capacity control and part-load efficiencies, while still being able to meet the required full capacity of the unit. The performance curve coefficients obtained from EnergyPlus were used to estimate the part-load capacity and energy consumption for every capacity step of the unit, as well as the energy input for the compressors running at full load capacity.

The compressor configuration selected achieves a total capacity of 1146 MBtu (~95.5 tons) with 3 capacity steps. The use of a digital or variable-speed compressor staged with fixed capacity scroll compressor was considered because of its ability to deliver continuous capacity modulation and operate the remaining compressors at full capacity. Unfortunately, the available products found were only offered in a dual, or tandem compressor configuration, resulting in a smaller capacity than required. Instead, this compressor configuration was selected for the 55-ton unit. Product information for the compressors referenced in this model can be found on Appendix B.

Staging of Heat Pump Units

During utilization hours that require 5% and 10% of the ventilation capacity, the 55-ton unit is able to meet the loads at all the outdoor air conditions the system is designed for. For the remaining hours of occupancy which required 30% of capacity or more, the 95-ton units were staged accordingly. The power consumption was calculated using the performance curves mentioned in the previous section. To account for the difference in performance of the compressors operating at part load and the compressors operating at full load, the power consumption was calculated in two stages.

1. Power consumption of the full load equipment at specific temperature dependent capacity
2. Power consumption of part-load equipment at specific temperature, flow fraction and part-load ratio

Since load calculations were performed for every specific temperature and flow percentage, the rated cooling and heating capacities were used to determine how many compressors would be operating at full load, and the remaining load that would be met by the compressor operating at part-load. The power input of the full-load equipment was calculated for specific temperatures obtained from the weather data using the rated capacities and the temperature-dependent performance curves. The power consumption was multiplied by the number of compressors operating at full load and added to the calculated power consumption for the part-load compressor. Finally, the total power consumption calculated at every percentage of flow fraction and temperature was multiplied by the amount of hours assigned to that temperature bin, obtained from the TMY3 weather data.

Proposed Alternative Evaluation

Two reversible heat pump configurations were evaluated for the DOAS air-handling units. The first relies only on the three-staged compressor heat pump system to condition the ventilation air at all capacities. This configuration satisfies the initial goal of decreasing pressure drop across the unit by eliminating the need of the enthalpy and sensible recovery wheel, two cooling coils, and a heating coil. The second configuration incorporates a rotary recovery wheel with the purpose of pre-conditioning when outdoor air temperature is too low, or when the outdoor air enthalpy content exceeds the enthalpy of the return air. Both of these conditions can significantly increase the energy consumption of the heat pumps when operating at conditions that are not ideal.

Dedicated Outside Air System with Reversible Heat Pump

The configuration for alternative 1, as shown on Figure 16, utilizes a reversible air-to-air heat pump to meet the entire cooling and heating requirements for the DOAS system.

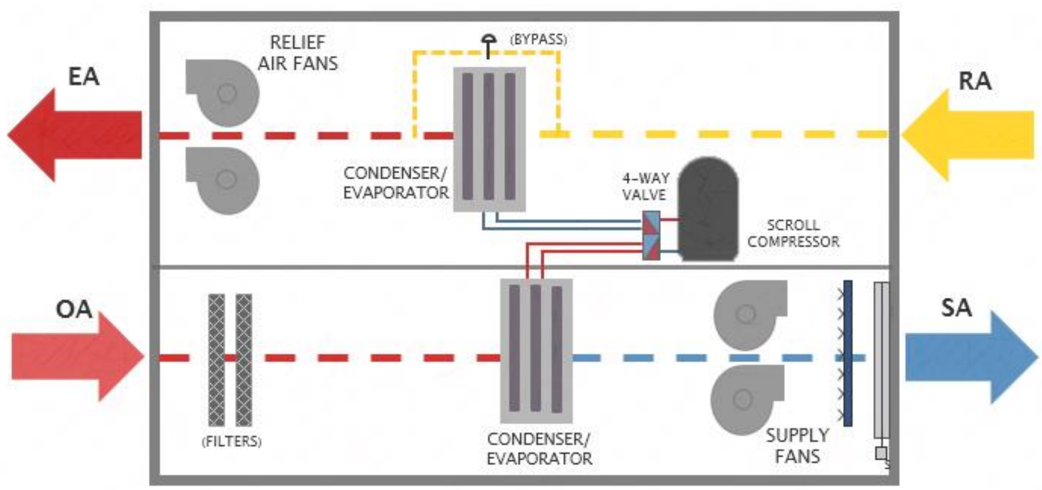


Figure 16: Configuration A – Detailed Schematic

Energy Use

The calculated cooling and heating loads for the DOAS units were compared to the load analysis performed using TRACE and found to be very similar to the load profile and peak load for the DOAS system. The calculated energy consumption was also compared to the values obtained from the TRACE energy consumption results from assigning the DOAS system to a separate cooling plant. The equipment assigned to this plant was removed from the existing cooling plant were the rest of the systems were assigned, and includes a water-cooled centrifugal chiller, a cooling tower for heat rejection, and pumps for the distribution system. This comparison is summarized on the Tables 23.1 and 23.2.

Table 23.1: Cooling Energy Consumption Comparison (kWh)													
	January	February	March	April	May	June	July	August	September	October	November	December	Annual
Existing System													
CHW Plant	15,625	11,728	17,893	31,802	51,630	79,891	88,782	85,427	64,539	44,653	21,108	17,622	530,699
Energy Recovery	244	222	251	246	243	303	303	290	299	247	244	227	3119
Total	15869	11949	18145	32048	51873	80194	89084	85717	64838	44900	21352	17849	533818
Proposed Alternative 1: Heat Pump Only													
CHW Plant	7,278	5,520	7,969	14,109	24,057	35,467	38,658	38,301	28,464	20,616	8,844	7,881	237,165
DOAS Heat Pump	1,130	113	2,077	13,016	19,999	39,413	41,200	42,847	28,298	17,110	1,922	1,398	208,523
Total	8,408	5,633	10,046	27,125	44,056	74,880	79,858	81,149	56,762	37,725	10,767	9,279	445,688
Energy Savings	47%	53%	45%	15%	15%	7%	10%	5%	12%	16%	50%	48%	17%

Table 23.2: Heating Energy Consumption Comparison (kWh)													
	January	February	March	April	May	June	July	August	September	October	November	December	Annual
Existing System													
HW Plant	187,679	170,397	148,487	74,452	76,913	65,388	67,523	62,283	88,492	84,476	141,137	154,992	1,322,219
Energy Recovery	244.0	221.6	251.2	245.7	243.1	303.5	302.7	290.4	298.9	247.1	243.9	226.6	3118.74
Total	187,923	170,618	148,739	74,697	77,156	65,692	67,826	62,573	88,791	84,724	141,381	155,218	1325338.2
Proposed Alternative 1: Heat Pump Only													
HW Plant	97,349	86,091	73,209	48,867	56,369	53,467	53,446	52,869	69,821	59,488	80,013	84,237	815,227
DOAS Heat Pump	16,688	15,737	9,825	449	26	-	-	-	-	471	4,894	8,994	57,085
Total	114,038	101,828	83,034	49,316	56,395	53,467	53,446	52,869	69,821	59,960	84,907	93,231	872,312
Energy Savings	39%	40%	44%	34%	27%	19%	21%	16%	21%	29%	40%	40%	34%

In the case of the chilled water plant, the energy use reduction was significant for most of the year. During periods of high cooling capacity demand, the proposed system still results in 5-10% savings in energy consumption. This comparison only includes energy consumption at the chilled water and hot water plant level. The monthly energy consumption breakout by utility was calculated for every system associated with the Dedicated Outdoor Air System, including the chilled water plant, hot water plant, heat pumps, and supply/return fans. Table 24 includes the utility breakout and the percentage reduction in energy use as compared to the calculated values for the existing system shown on Table 15.

Table 24: Utility Consumption Breakout - Alternative A													
Component	**January**	**February**	**March**	**April**	**May**	**June**	**July**	**August**	**September**	**October**	**November**	**December**	**Total**
Chilled Water Plant													
Electric (kWh)	7278	5520	7969	14109	24057	35467	38658	38301	28464	20616	8844	7881	237165
Water (1000 gal)	22	17	24	39	66	92	96	97	73	58	24	23	632
Hot Water Plant													
Electric (kWh)	2174	1950	2110	2035	2177	2129	2188	2181	2244	2194	2115	2161	25657
Gas (therms)	3248	2872	2427	1598	1850	1752	1749	1730	2306	1955	2659	2801	26948
DOAS Unit with Heat Pump													
Heat Pump (kWh)	17818	15850	11902	13465	20025	39413	41200	42847	28298	17581	6817	10392	265608
Fans	15588	13207	14938	17468	21933	30027	33643	32551	26874	19888	16218	14265	256600
Total Electric (kWh)	42859	36527	36919	47078	68191	107035	115689	115881	85880	60279	33994	34699	785031
% Reduction	2%	-2%	17%	24%	24%	18%	20%	18%	22%	24%	32%	20%	19%
Total Gas (therms)	3248	2872	2427	1598	1850	1752	1749	1730	2306	1955	2659	2801	26948
% Reduction	49%	50%	51%	35%	27%	19%	22%	16%	22%	30%	44%	46%	39%
Total Water (1000 gal)	22	17	24	39	66	92	96	97	73	58	24	23	632
% Reduction	65%	64%	67%	69%	68%	71%	72%	70%	70%	67%	71%	67%	69%

Dedicated Outside Air System with Reversible Heat Pump and Energy Recovery Wheel

A Dedicated Outdoor Air System is sized to be able to handle a wide range of outdoor air temperature and humidity entering conditions, and supply the ventilation air at the specified dew-point and dry-bulb temperature set point. This means that at design conditions, for both heating and cooling, the compressors will most likely be operating at full capacity and consuming a large amount of electric power. The proposed system results in improved performance at lower outside temperatures is improved with the use of the building's exhaust air as heat source. However, during the dehumidification mode the results show that energy consumption is relatively high. The School of Public Health is located in a mixed hot-humid climate region, where buildings can have large latent loads due to the high moisture content of the outside air during the summer. At conditions when the outside air enthalpy and temperature is higher than the return air, using energy recovery can significantly reduce the mechanical cooling work done by the heat pump. The second configuration for the DOAS system evaluates the integration of an energy recovery wheel with the reversible heat pump, shown on Figure 17.

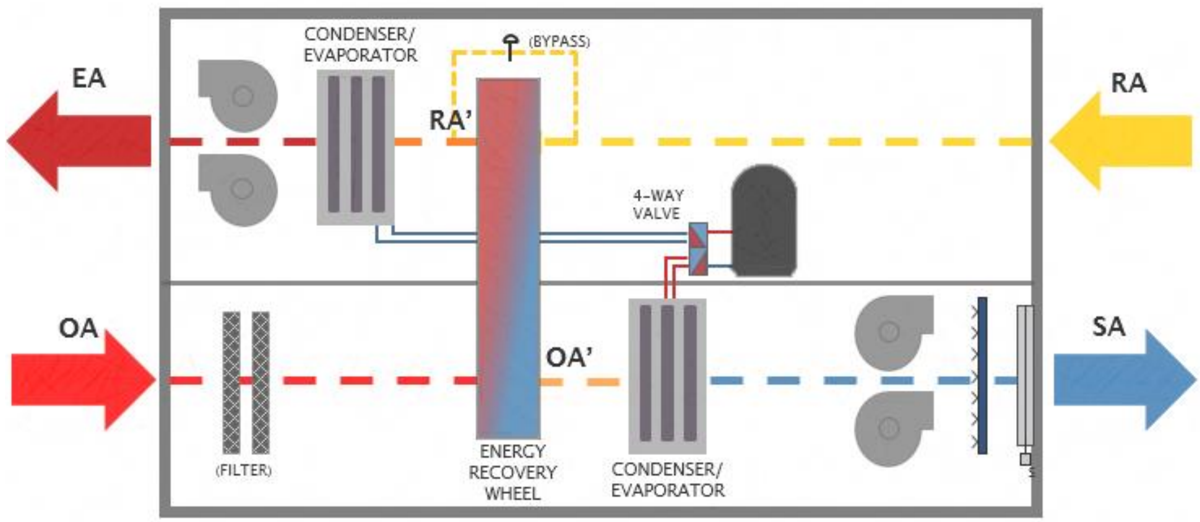


Figure 17: Proposed Alternative – Configuration B

Operation of the energy recovery wheel was based on return air and outdoor air conditions. A rotary heat exchanger with an effectiveness of 75% was selected to avoid over-estimating the amount of energy recovered by the ERV. Using the same calculation method as in the previous configuration, outside air conditions where the energy recovery wheel would be operated where identified. Table 22 shows the control sequence for the operation of the energy recovery system. For the purpose of this analysis, the energy recovery wheel was only operated in its Full-Recovery mode, when the outside air enthalpy was higher than the return air enthalpy.

Table 25: Energy Recovery Control Sequence

Control Mode	Pyschrometric Conditions
Full Energy Recovery Partial Cooling	OA Dew Point > SA Dew Point
	OA enthalpy > RA enthalpy
Partial Recovery Partial Cooling	OA Dry-Bulb > SA Dry-Bulb
	OA Dew Point < SA Dew Point
Energy Recovery OFF	SA DB < OA DB < RA DB
	OA enthalpy < RA enthalpy
Partial Recovery only	OA DB < SA DB Low
	OA DP < SA DP
Full Recovery Supplemental Heating	OA DB < Critical Temperature

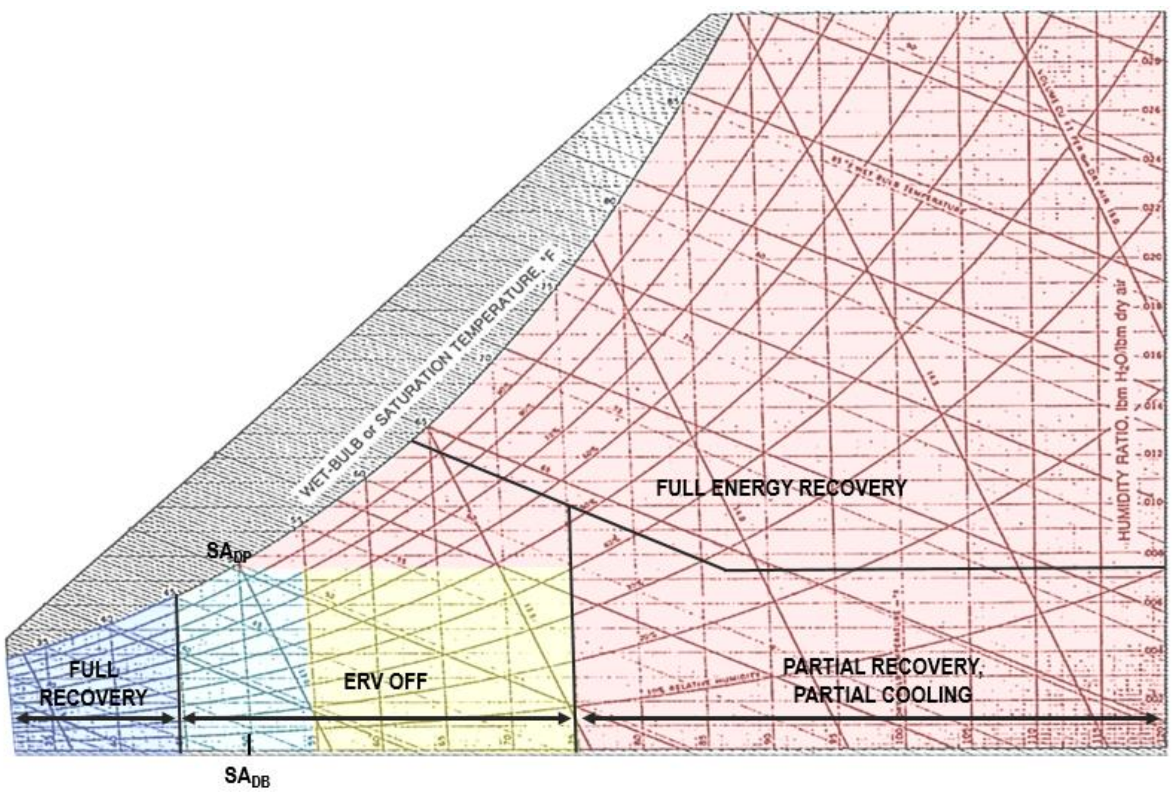


Figure 18: Control for Energy Recovery Wheel – Configuration B

Operating the energy recovery wheel reduces the dehumidification load on the heat pump system, and also changes the entering conditions of the outdoor and return air entering the condenser and evaporating coils. The conditions of both airstreams after pre-conditioning the outside air, including dry-bulb temperature, humidity ratio, and enthalpy, were calculated using the following equations:

$$\boldsymbol{\varepsilon = \frac{w_s \cdot (x_{OA} - x_{OA'})}{w_{min} \cdot (x_{OA} - x_{RA})} = \frac{w_e \cdot (x_{RA'} - x_{RA})}{w_{min} \cdot (x_{OA} - x_{RA})}}$$

$\varepsilon = sensible, latent, or\ total\ ERV\ effectiveness$

$w_s = mass\ flow\ of\ outdoor\ air$

$w_e = mass\ flow\ of\ exhaust\ air$

$w_{min} = smaller\ mass\ flow\ (outdoor\ or\ exhaust)$

$x_{OA} = dry - bulb, humidity\ ratio, or\ enthalpy\ of\ entering\ outdoor\ air$

$x_{OA'} = dry - bulb, humidity\ ratio, or\ enthalpy\ of\ leaving\ outdoor\ air$

$x_{RA} = dry - bulb, humidity\ ratio, or\ enthalpy\ of\ entering\ return\ air$

$x_{RA'} = dry - bulb, humidity\ ratio, or\ enthalpy\ of\ leaving\ return\ air$

The total heat recovered by the wheel was subtracted from the load calculated in the previous sections for the temperature bins at which energy recovery was activated. The new loads, and entering air conditions, were used to calculate the new performance and power consumption of the reversible heat pump system. The total heat recovered was calculated using the following equations:

$$\boldsymbol{Q_t = \varepsilon \cdot 4.5 \cdot V_{min} \cdot (h_{OA} - h_{OA'})}$$

$Q_t = Total\ heat\ flow, Btu/h$

$V_{min} = smaller\ airflow, cfm$

$h_{OA} = Entering\ outdoor\ air\ enthalpy, Btu/lb$

$h_{OA'} = Leaving\ outdoor\ air\ enthalpy, Btu/lb$

Energy consumption comparison with the existing design was performed using the same method as the previous configuration. Additional electric power consumption due to operating the energy recovery wheel was added to the new configuration and estimated using a parasitic energy consumption of 0.4 kW. The energy consumption results for the second configuration are summarized in Table 26 below. Table 26.2 includes the utility breakout and the percentage reduction in energy use as compared to the calculated values for the existing system shown on Table 15.

Table 26: Cooling Energy Consumption Comparison (kWh)

	January	February	March	April	May	June	July	August	September	October	November	December	Annual
Existing System													
CHW Plant	15,625	11,728	17,893	31,802	51,630	79,891	88,782	85,427	64,539	44,653	21,108	17,622	530,699
Energy Recovery	244.0	221.6	251.2	245.7	243.1	303.5	302.7	290.4	298.9	247.1	243.9	226.6	3118.74
Total	15,869	11,949	18,145	32,048	51,873	80,194	89,084	85,717	64,838	44,900	21,352	17,849	533,818
Proposed Alternative 2: Heat Pump with Energy Recovery Wheel													
CHW Plant	7,278	5,520	7,969	14,109	24,057	35,467	38,658	38,301	28,464	20,616	8,844	7,881	237,165
DOAS Heat Pump	1,123	113	2,070	12,206	17,615	31,623	32,597	34,006	24,565	16,218	1,922	1,398	175,457
Energy Recovery Wheel	0	-	0	24	47	148	170	168	83	23	-	-	664
Total	8,402	5,633	10,040	26,340	41,719	67,238	71,425	72,475	53,112	36,856	10,767	9,279	413,286
Energy Savings	47%	53%	45%	18%	20%	16%	20%	15%	18%	18%	50%	48%	23%

Table 26.2: Utility Consumption Breakout - Alternative B

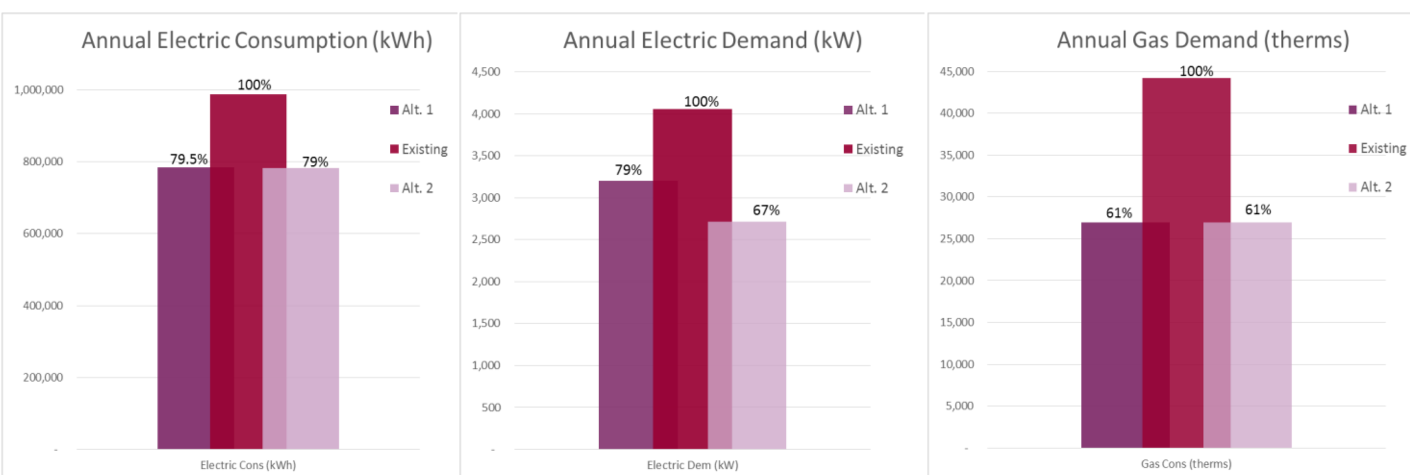
Component	January	February	March	April	May	June	July	August	September	October	November	December	Total
Chilled Water Plant													
Electric (kWh)	7278	5520	7969	14109	24057	35467	38658	38301	28464	20616	8844	7881	237165
Water (1000 gal)	22	17	24	39	66	92	96	97	73	58	24	23	632
Hot Water Plant													
Electric (kWh)	2174	1950	2110	2035	2177	2129	2188	2181	2244	2194	2115	2161	25657
Gas (therms)	3248	2872	2427	1598	1850	1752	1749	1730	2306	1955	2659	2801	26948
DOAS Unit with Heat Pump													
Heat Pump (kWh)	17812	15850	11895	12656	17641	31623	32597	34006	24565	16689	6817	10392	232542
Fans (kWh)	15588	13207	14938	20280	25444	34867	39026	37757	31177	22997	16218	14265	285764
Energy Recovery (kWh)	0	0	0	24	47	148	170	168	83	23	0	0	664
Total Electric (kWh)	42852	36527	36912	49105	69366	104234	112638	112413	86532	62519	33994	34699	781793
% Reduction	2%	-2%	17%	21%	22%	20%	23%	20%	22%	21%	32%	20%	20%
Total Gas (therms)	3248	2872	2427	1598	1850	1752	1749	1730	2306	1955	2659	2801	26948
% Reduction	49%	50%	51%	35%	27%	19%	22%	16%	22%	30%	44%	46%	39%
Total Water (1000 gal)	22	17	24	39	66	92	96	97	73	58	24	23	632
% Reduction	65%	64%	67%	69%	68%	71%	72%	70%	70%	67%	71%	67%	69%

Results Summary

Both of the proposed alternative resulted in energy consumption savings when compared to the existing system. The first alternative explored consists of a heat pump only. Reductions in energy consumption average around 40% during the heating season. This can be attributed to the improved performance of the heat pump when locating the evaporator coil on the exhaust airstream for heat absorption. During the cooling season, the proposed alternative resulted in less energy savings when compared to the heating season, with an average of 11% reduction in energy consumption. Lower performance can possibly be due to the high moisture content of the outdoor air when the unit is operating in dehumidification mode to meet the dew point temperature set point of the air leaving the DOAS unit. Table 27 summarizes the comparison of energy consumption by utility for the existing system and both alternatives, as well as the energy savings for each case.

Table 27: Overall Energy Consumption Comparison

	January	February	March	April	May	June	July	August	September	October	November	December	Annual
Existing Systems													
Electric Cons (kWh)	44,320	36,220	45,321	63,115	90,527	132,339	147,284	142,078	111,855	80,134	50,625	43,907	987,725
Electric Dem (kW)	257	194	247	284	385	429	454	416	418	371	314	291	4,060
Gas Cons (therms)	6319	5736	4986	2470	2549	2158	2230	2051	2942	2806	4736	5207	44,189
Total	50,895	42,151	50,554	65,870	93,461	134,926	149,968	144,544	115,215	83,311	55,674	49,404	1,035,973
Proposed Alternative 1: Heat Pump Only													
Electric Cons (kWh)	42,859	36,527	36,919	47,078	68,191	107,035	115,689	115,881	85,880	60,279	33,994	34,699	785,031
Electric Dem (kW)	218	175	206	289	322	330	332	332	309	288	207	195	3,202
Gas Cons (therms)	3,248	2,872	2,427	1,598	1,850	1,752	1,749	1,730	2,306	1,955	2,659	2,801	26,948
Total	46,325	39,574	39,552	48,965	70,362	109,117	117,771	117,943	88,495	62,523	36,860	37,695	815,181
Proposed Alternative 2: Heat Pump with Energy Recovery Wheel													
Electric Cons (kWh)	42,852	36,527	36,912	49,105	69,366	104,234	112,638	112,413	86,532	62,519	33,994	34,699	781,793
Electric Dem (kW)	218	175	199	227	243	250	255	251	252	243	207	195	2,715
Gas Cons (therms)	3,248	2,872	2,427	1,598	1,850	1,752	1,749	1,730	2,306	1,955	2,659	2,801	26,948
Energy Recovery (kWh)	0	-	0	24	47	148	170	168	83	23	-	-	664
Total	46,319	39,574	39,538	50,955	71,505	106,383	114,812	114,562	89,174	64,740	36,860	37,696	812,120



Figures 19.1a, b, c: Annual utility energy consumption comparison (kWh, kW, therms)

As Figures 19.1a to 19.1c show, the most significant impact of alternative B in terms of energy consumption is reduced Electric On-Peak Demand. The electric consumption is slightly higher than alternative A, due to the additional energy recovery wheel and added fan energy needed.

To further decrease the amount of energy consumption of the proposed system, a second alternative was evaluated. This alternative integrates a reversible heat pump and a full-energy recover wheel. For the purpose of this analysis, the energy recovery wheel was only operated at its “Full-Energy Recovery” mode, when the outside air enthalpy content and dew point were higher than the return air. The application of an energy recovery wheel in the proposed design resulted in approximately 5% more energy savings in the months of June, July, and August. Both systems resulted in approximately 26% savings in annual operating costs.

Table 28: Overall Energy Operating Costs ($)

	January	February	March	April	May	June	July	August	September	October	November	December	Annual
Existing Systems													
Electric Cons	6,914	5,650	7,070	9,846	14,122	20,645	22,976	22,164	17,449	12,501	7,897	6,850	154,085
Electric Dem.	742	561	714	822	1,112	1,239	1,312	1,202	1,207	1,071	906	840	11,728
Gas Cons.	9,314	8,455	7,350	3,640	3,757	3,182	3,286	3,023	4,337	4,136	6,981	7,675	65,135
Total	16,970	14,666	15,134	14,308	18,992	25,065	27,575	26,388	22,994	17,708	15,785	15,364	230,948
Proposed Alternative 1: Heat Pump Only													
Electric Cons	6,686	5,698	5,759	7,344	10,638	16,697	18,047	18,077	13,397	9,404	5,303	5,413	122,465
Electric Dem.	630	506	596	833	930	952	959	960	892	832	597	564	9,251
Gas Cons.	4,788	4,233	3,577	2,356	2,726	2,583	2,579	2,550	3,400	2,882	3,919	4,129	39,721
Total	12,103	10,437	9,933	10,534	14,294	20,232	21,586	21,587	17,689	13,118	9,819	10,106	171,437
Savings	29%	29%	34%	26%	25%	19%	22%	18%	23%	26%	38%	34%	26%
Proposed Alternative 2: Heat Pump with Energy Recovery Wheel													
Electric Cons	6,685	5,698	5,758	7,660	10,821	16,260	17,572	17,536	13,499	9,753	5,303	5,413	121,960
Electric Dem.	631	507	575	655	702	721	736	726	728	701	598	565	7,844
Gas Cons.	4,788	4,233	3,577	2,356	2,726	2,583	2,579	2,550	3,400	2,882	3,919	4,129	39,721
Total	12,104	10,438	9,910	10,672	14,249	19,564	20,886	20,813	17,627	13,336	9,820	10,107	169,525
Savings	29%	29%	35%	25%	25%	22%	24%	21%	23%	25%	38%	34%	27%

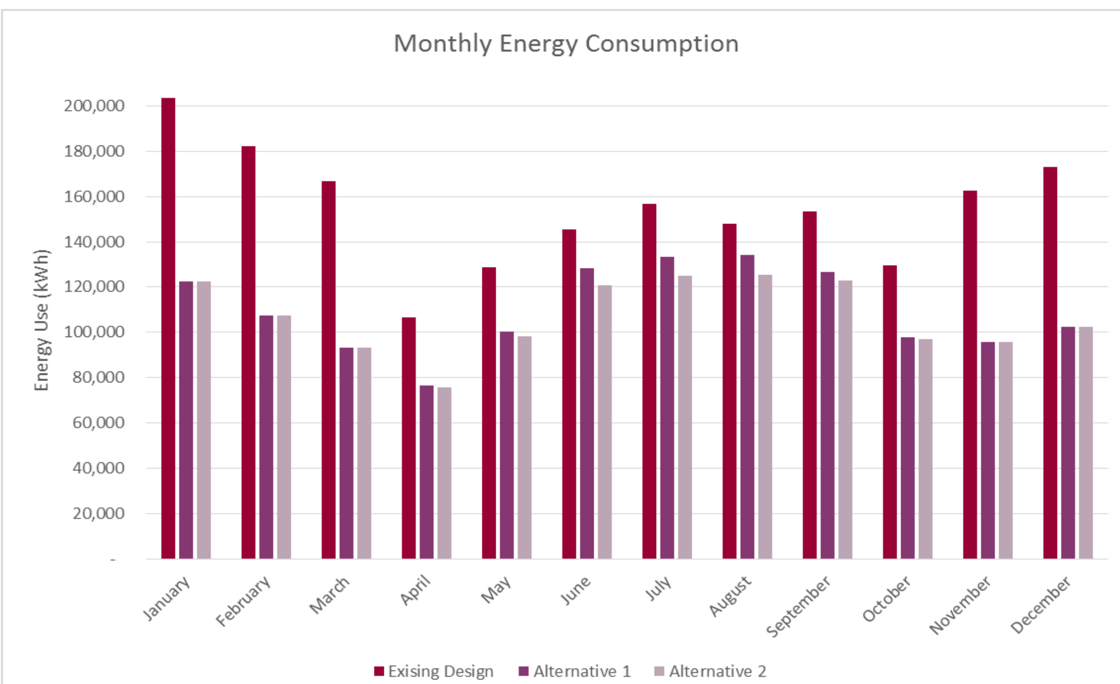


Figure 19.2: Overall Energy Consumption Comparison

Breadth 1: Building Systems Integration with Natural Ventilation

The School of Public Health's design features a central sky-lit atrium, with a south-east facing curtain-wall system. A DOAS with Chilled Beam system serves spaces located on levels 2-7, as well as the atrium space. The existing design implements air balancing through adequate space pressurization to transfer return air from the office and classroom areas towards the atrium space. Return air is centralized at the top of the atrium, where it is either exhausted or directed to the DOAS units for heat recovery purposes via 6 exhaust fans. The large airflow handled by the atrium exhaust fans represents a significant amount contributing to the overall fan energy use mentioned on Table 14.

This breadth topic studies the integration of natural ventilation using the existing atrium space, with the goal of reducing energy consumption and hours of operation of the return fan atrium system. The site of the building is located in a mixed-humid region (climate zone 4A per ASHRAE classification), where outdoor air conditions are adequate for natural ventilation for up to 40% of the year. When outdoor conditions are ideal, operable windows will open and provide natural ventilation to the occupied spaces. Effects of thermal buoyancy will cause the warmer return air transferred to the atrium space to rise. The stack effect can be enhanced with the installation of a solar chimney at the top of the atrium, which collects heat from solar radiation, increasing the temperature of the rising return air and the encouraging air flow to exit the building. This process simultaneously induces cool air to be drawn into the building through operable windows and into the atrium. An example of the airflow of natural ventilation through the atrium space during summer conditions is shown on Figure 20.

Figure 20: Natural Ventilation Flow through Atrium Space

Design Considerations and Feasibility Analysis

In order to assess the feasibility of natural ventilation in the School of Public Health, TMY3 weather data obtained for Washington, D.C. was used to find the outside air conditions during spring, summer and winter. Specific times of the year when the building could operate in natural ventilation mode were identified, along with values for average wind speed, wind direction, and pressure conditions of the site.

After evaluating the weather data, months with mild weather conditions were selected for the scope of this analysis, as shown on Table 29. The selection was based on average outdoor air temperatures which fell between the supply air temperature set point of 50 °F and the design room conditions of 75 °F and 50% RH.

Table 29: Months Selected for Natural Ventilation Evaluation

Temperature (F)	January	February	March	April	May	June	July	August	September	October	November	December
Average	36.39	34.26	43.10	**57.46**	**63.61**	75.55	80.93	78.64	**67.32**	**59.65**	46.97	43.60
Maximum	72.68	62.06	73.04	**87.98**	**96.08**	93.92	98.06	98.06	**86.00**	**82.94**	71.96	71.06
Minimum	11.48	6.98	17.96	**35.96**	**42.08**	57.92	62.06	62.06	**48.02**	**37.94**	28.04	28.94

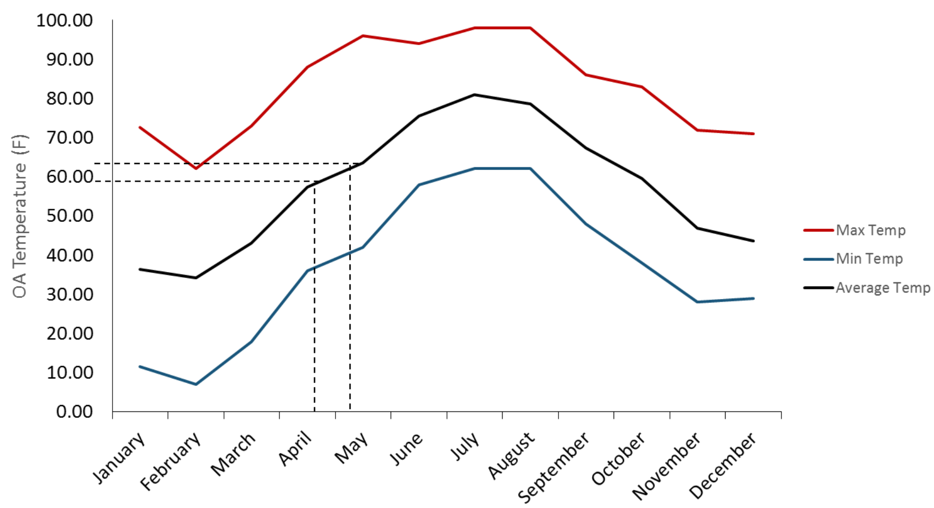


Figure 20.1: Monthly Weather Data (Max, Min, and Average)

The west portion of the building containing office spaces, along with the few classrooms located on the east portion, are supplied ventilation air from the DOAS units as well, but space design conditions are maintained by air terminal units for reheat and chilled beams for additional sensible cooling. Therefore, these spaces were not selected for the natural ventilation analysis due to the low flexibility for the supply air dew point required and risk of condensation forming on the chilled beams.

The Dedicated Outdoor Air Systems serves spaces located on level 2 to level 7. Within those levels, the application of natural ventilation was limited to the east portion of the building, where the atrium space, corridors, and open study areas are located. The spaces selected are supplied ventilation air from the DOAS units, and temperature control at the zone level is only modulated with reheat via air terminal units. The red areas on Figure 21.1 below represent the selected spaces for the natural ventilation analysis.

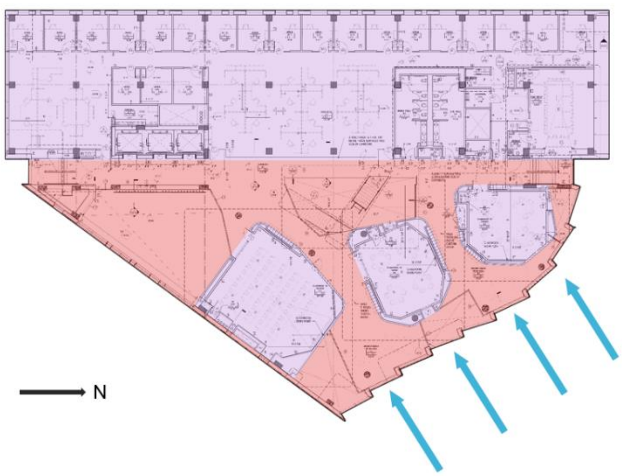


Figure 21.1: Spaces selected and wind direction

Figure 21.2: Site view

Ventilation Requirements for Spaces Selected

Spaces selected as part of the analysis were identified and organized in the space schedule shown below to calculate the minimum ventilation requirements. Guidelines established in ASHRAE Standard 62.1 were followed to maintain adequate indoor air quality and ventilation rates. Table 30 lists the spaces selected for the ventilation analysis.

Table 30: Spaces Selected for Natural Ventilation

Room Number	Room Name	Level	Area (SF)	Height (FT)	Occupant Count	Ventilation Category	People Outdoor Airflow Rate (CFM/person)	Area Outdoor Airflow Rate (CFM/SF)	Ventilation Airflow (CFM)
2	Atrium Wall	2	404	12	7	Conference-ext	5	0.06	59.24
2.10A	Food Vendor	2	273	12	0	Kitchenette	0	0	0
2.10B	Storage	2	18	12	0	Storage	0	0.12	2.16
2.12	Student Lounge	2	1782	12	53	Conference-ext	5	0.06	371.92
2.12C	Kitchenette	2	173	12	0	Kitchenette	0	0	0
2.14	Satelite Library/Media Are	2	434	12	15	Conference-ext	5	0.06	101.04
2.C1	Corridor	2	1722	12	0	Corridor	0	0.06	103.32
2.S1	Stair 1	2	174	12	0	Corridor	0	0.06	10.44
2.S2	Stair 2	2	174	12	0	Corridor	0	0.06	10.44
3	Atrium	3	1148	12	0	Corridor	0	0	0
3.12	Group Study Area	3	531	12	13	Conference-ext	5	0.06	96.86
3.14	Group Study Area	3	327	12	8	Conference-ext	5	0.06	59.62
3.C1	Corridor	3	2251	12	0	Corridor	0	0.06	135.06
3.S1	Stair 1	3	171	12	0	Corridor	0	0.06	10.26
3.S2	Stair 2	3	172	12	0	Corridor	0	0.06	10.32
4	Atrium	4	1190	12	0	Default	0	0	0
4.1	Group Study Area	4	1262	12	40	Conference-ext	5	0.06	275.72
4.10A	Kitchenette	4	144	12	0	Kitchenette	0	0	0
4.12	Group Study Area	4	373	12	12	Conference-ext	5	0.06	82.38
4.14	Quiet Study Area	4	226	12	7	Conference-ext	5	0.06	48.56
4.C1	Corridor	4	2009	12	0	Corridor	0	0.06	120.54
4.S1	Stair 1	4	171	12	0	Corridor	0	0.06	10.26
4.S2	Stair 2	4	174	12	0	Corridor	0	0.06	10.44
5	Atrium	5	1017	12	0	Corridor	0	0	0
5.12	Group Study Area	5	626	12	18	Conference-ext	5	0.06	127.56
5.14	Group Study Area	5	355	12	8	Conference-ext	5	0.06	61.3
5.C1	Corridor	5	2383	12	0	Corridor	0	0	0
5.S1	Stair 1	5	171	12	0	Corridor	0	0.06	10.26
5.S2	Stair 2	5	171	12	0	Corridor	0	0.06	10.26
6	Atrium	6	1105	12	0	Corridor	0	0	0
6.1	Group Study Area	6	1409	12	40	Conference-ext	5	0.06	284.54
6.10A	Kitchenette	6	144	12	0	Kitchenette	0	0	0
6.12	Group Study Area	6	349	12	12	Conference-ext	5	0.06	80.94
6.14	Quiet Study Area	6	269	12	7	Conference-ext	5	0.06	51.14
6.C1	Corridor	6	1966	12	0	Corridor	0	0.06	117.96
6.S1	Stair 1	6	171	12	0	Corridor	0	0.06	10.26
6.S2	Stair 2	6	174	12	0	Corridor	0	0.06	10.44
7	Atrium	7	845	13.5	0	Default	0	0	0
7.12	Group Study Area	7	926	13.5	18	Conference-ext	5	0.06	145.56
7.14	Quiet Study Area	7	280	13.5	7	Conference-ext	5	0.06	51.8
7.C1	Corridor	7	1974	13.5	0	Corridor	0	0.06	118.44
7.S1	Stair 1	7	170	13.5	0	Corridor	0	0.06	10.2
7.S2	Stair 2	7	174	13.5	0	Corridor	0	0.06	10.44
7.SW	Skywell	7	1076	13.5	0	Unconditioned	0	0	0

Ventilation airflow requirements calculated were compared to design cooling airflow specified in the air balancing schedule obtained from the design documents. The higher airflow was selected as basis to calculate the total opening area required for natural ventilation to meet the design airflow. Total required opening area was used to select the size and quantity of openings per level. Due to its proximity to the selected spaces, the north-east façade of the building was selected for the openings. Measurements were taken to quantify the amount of exterior wall available, as well as the wall direction and average speed of wind normal to the façade. These calculations were organized by levels and are shown on Table 31.

Table 31: Cooling and Ventilation Airflow Requirements

Level	Space	Ventilation Airflow (CFM)	Cooling Airflow (CFM)	Transfer Airflow (CFM)	Total Airflow (CFM)	Total Required Opening Area (SF)	# of openings	Ext Wall Length (ft)	Average Wind Speed (ft/s)	Degrees from North
2	2.14	101.04	600	-	600	19.05	2	34.5	78.74	33
2	Others	557.52	3345	775	4720	106.20	9	69	78.74	67
3	All	312.12	3030	765	3795	96.20	8	80.5	78.74	61
4	4.14	48.56	525	-	525	16.67	2	34.5	78.74	33
4	Others	499.34	3100	765	4390	98.43	8	69	78.74	67
5	All	209.38	2465	765	3230	78.26	7	80.5	78.74	61
6	6.14	51.14	510	-	510	16.19	2	34.5	78.74	33
6	Others	504.14	3600	765	4875	114.30	9	69	78.74	67
7	7.14	51.8	545	-	545	17.30	2	34.5	78.74	33
7	Others	284.64	2945	785	4275	93.50	8	69	78.74	67

Computational Fluid Dynamics Simulation

The design goal involves airflow movement within the atrium space with a solar chimney where the existing skylight is located. A Computational Fluid Dynamics simulation using STAR CCM+ was developed to predict the effectiveness of the buoyancy-driven natural ventilation design. Even though the application of CFD to predict flow behavior driven by internal heat sources within buildings is increasing, there is little available resources for guidelines on the right methods for modeling natural ventilation.

The portion of the building used for the natural ventilation analysis was modeled using the 3D CAD Models tool. The geometry included an accurate representation of the existing building façade, the openings on each level that form part of the atrium space, and the classrooms on each level. An addition to the existing building geometry was designed with the purpose of modeling the effect of a solar chimney and the airflow outlet. Figure 22 displays a view of the final geometry modeled.

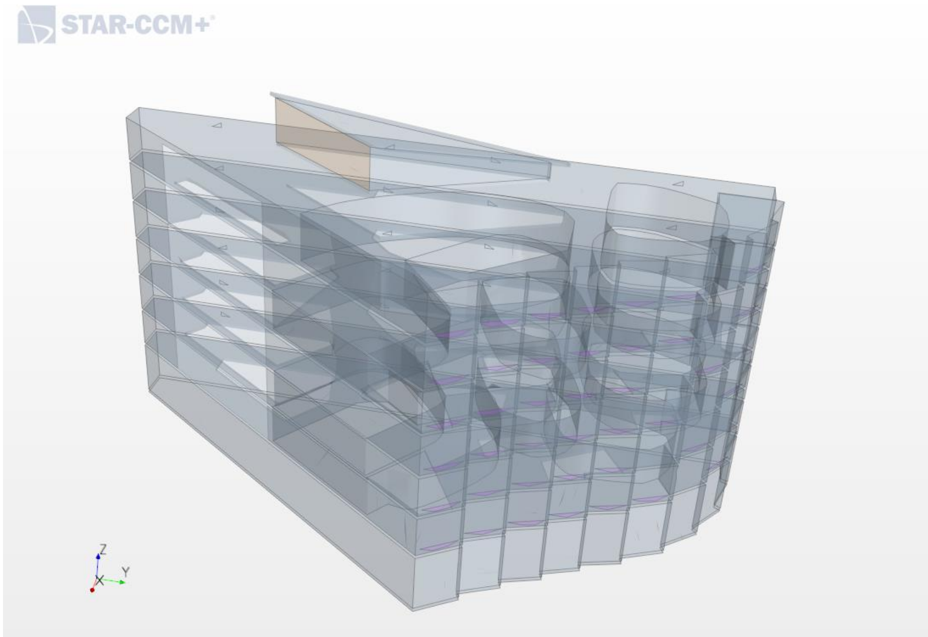


Figure 22: Building Geometry for CFD simulation

Methodology

Computational Fluid Dynamics uses numerical analysis to solve problems related to fluid flows. The methodology used with this software was the finite volume method, in which CFD problems are solved using governing equations including Navier-Stokes equations, turbulence equations, as well as mass and energy conservation equations. Turbulence models are based on the Reynolds-averaged Navier-Stokes (RANS) equations. Star CCM+ physical model selection offers different types of RANS equations. Turbulence models are necessary to solve all the governing equations in turbulent flows.

The selected approach required two simulations: a full domain simulation and an internal flow simulation. The full domain simulation consisted in modeling the conditions of the building's exterior and surroundings. With wind conditions obtained from weather data, the external flow and its interaction with the building was simulated in order to extract boundary conditions that were then used for the internal flow simulation. These boundary conditions were then used in the internal flow simulation to better represent the impact of surrounding buildings and building height on the performance of natural ventilation and internal flow behavior. Reference material for the simulation approach can be found on the list of references (Meroney, 2009).

Full Domain Calculations

The area surrounding the building which was selected for the full domain calculations is shown on Figures 23.1 and 23.2, along with the recreated volume mesh constructed in STAR CCM+. The area includes buildings located within a 150 ft. radius of the School of Public Health. The turbulence model selected was the STT k-omega model.

Figure 23.1: Building Site

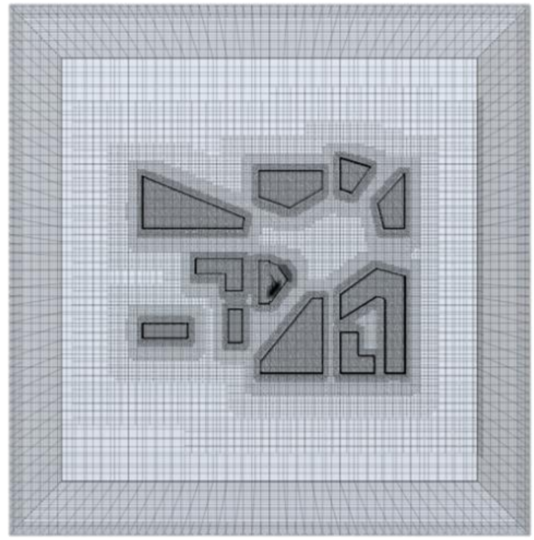
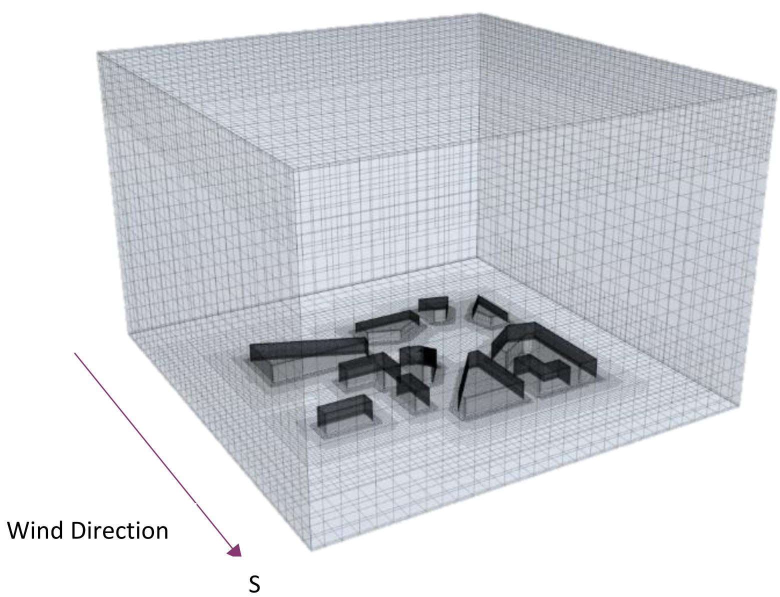


Figure 23.2: Generated Volume Mesh of Site

Boundary Conditions

The wind tunnel simulation was performed using the north side and south sides of the tunnel as boundary conditions. The north side of the tunnel was modeled as a velocity inlet, where wind conditions were specified as having a turbulence viscosity ratio of 0.05, and velocity vector of (-2.0i,-4.0j, 0.0k) m/s, flowing in the direction shown on Figure 24. The building model for the full domain simulation includes surfaces for the inlet and outlet later modeled on the internal flow simulation. Figure 24.2 shows a closer scalar view of the specified inlet and outlet surfaces of the building, displaying surface pressure coefficients.



GENERATED MESH
CELLS: 1,242,912
FACES: 3,719,256
VERTICES: 1,375,663

Figure 24.1: Generated Volume Mesh Properties

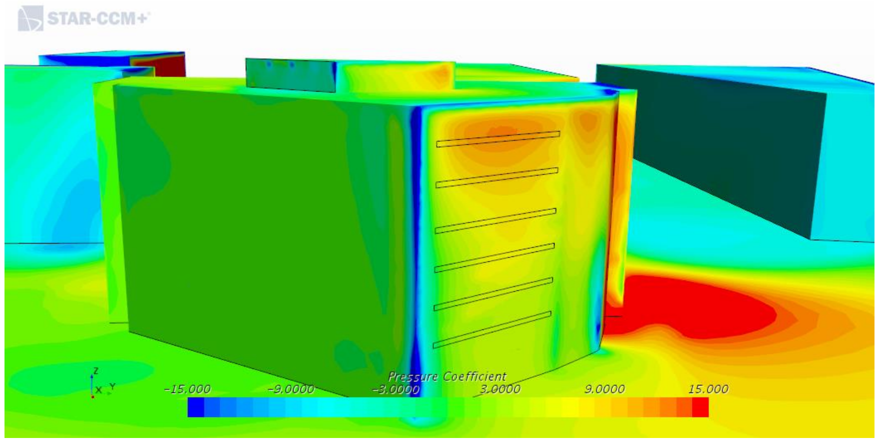


Figure 24.2: Pressure Coefficient at Building's Surfaces

The following pressure coefficient values were obtained from the simulation results and used for the domain decomposition calculations:

Surface Average of Pressure Coefficient on Volume Mesh

Part	Value
Plane Section 2	3.640664e+00
Region: Body 13.GWU	2.457292e+00
Region: Body 13.GWU Outlet	-3.629543e+00
Region: Body 13.GWU-Inlet	6.427483e+00
	Total: 3.607008e+00

A line probe was created to obtain values for air velocity at the building north-east façade. The plot on Figure 24.3 shows the change in air velocity at different building heights.

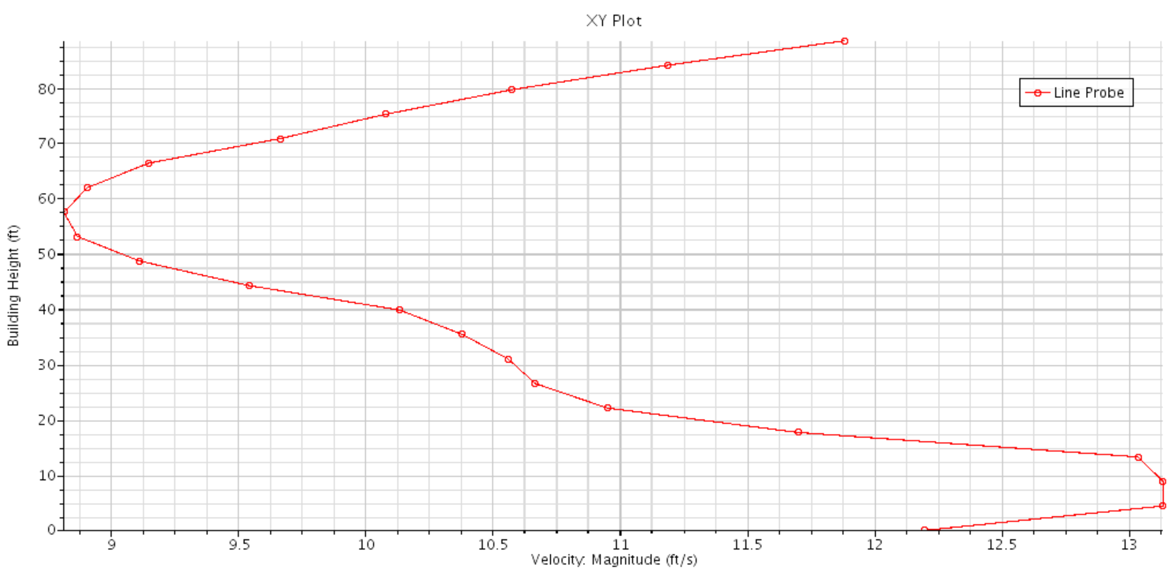


Figure 24.3: Air velocity vs. Building Height

Domain Decomposition Calculations

Obtained boundary conditions from the full domain simulation were used to calculate the boundary conditions for the internal flow analysis. Using the pressure coefficient at the inlet and outlet, a discharge coefficient with an assumed value of 0.67, the designed opening areas, and the obtained wind speed, the ventilation flow rate entering the building was calculated using the following equations:

$$Q_{air} = C_{D,in} \cdot A \cdot V_H \cdot \sqrt{Cp_{in} - Cp_{internal}}$$

$$Cp_{internal} = \frac{Cp_{in} + Cp_{out}}{2}$$

Where:

$Q_{air} = air\ volume\ flow\ rate, m^3/s$

$A = effective\ area\ of\ openings, m^2$

$V_H = approach\ wind\ speed\ at\ building\ height, m/s$

$C_{D,in} = discharge\ coefficient$

$Cp_{in}, Cp_{out} = pressure\ coefficients\ at\ opening\ locations$

$Cp_{internal} = internal\ pressure\ coefficient$

The total area for the openings modeled was 434 ft^2 (40 m^2), and the approach wind speed at building height was 11 m/s.

Boundary Conditions

Boundary conditions at the building surface were created to simulate the flow of natural ventilation within the building. Openings on the N-E façade were set as mass flow inlets at atmospheric pressure, and the exhaust area was set as a pressure outlet. The calculated air volume flow was used to specify the physics values for the mass flow inlets, and the internal pressure coefficient was used at the pressure outlet to simulate the pressure differential of the two openings due to their location relative to the wind direction.

Physics Models

The selected turbulence model was the two-layer realizable k- ε equation, a two equation model that solves for turbulent kinetic energy k and dissipation rate epsilon. It relies on the Boussinesq approximation method for solving transport equations. K-epsilon models have good performance for large flows involving complex recirculation. The advantage of the two-layer k-e approach when compared to the standard k-e is that it allows for the model to be applied in the viscous sublayer. The two-layer approach accounts for near-wall behavior by solving for the turbulent dissipation rate and turbulent viscosity of the layer next to the wall as a function of wall distance. These values of epsilon are then blended with values obtained from solving the governing equations at a point far from the wall. Finally, the equation for turbulent kinetic energy is solved for the entire flow. The realizable k-e model involves a new formulation for both turbulent viscosity and the transport equation for the dissipation rate. It satisfies certain mathematical constraints on the Reynolds stresses which are consistent with the physics of turbulent flows, a quality that the standard k-ε model and RNG k-ε model both lack. The two-layer realizable k-e model combines the advantages of both of these approaches.

Computational Grid

In order to assess the performance of the physical models selected and boundary layer conditions, a coarse mesh, displayed on Figure 25.1, was generated with an initial base size of 6.4 m. The surface remesher model was selected, along with trimmer and prism layer model to generate the volume mesh. After the residuals reached convergence, the base size was reduced, with a final value of 3.0 m.

Final mesh: Cells: 58129, Faces: 165428, Vertices: 71224

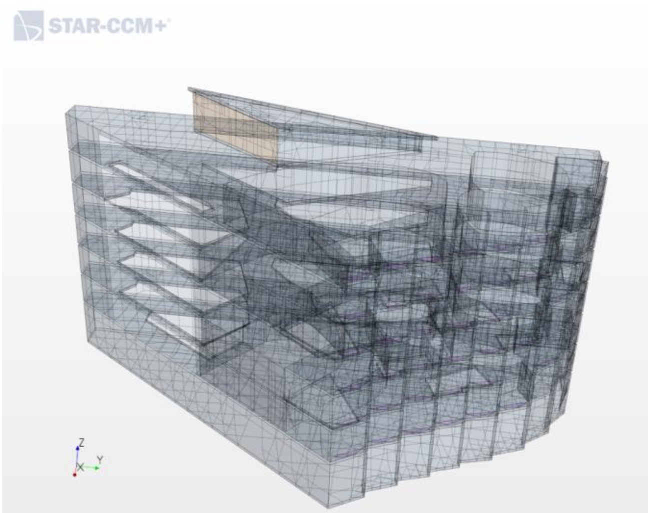


Figure 25.1: Coarse Mesh

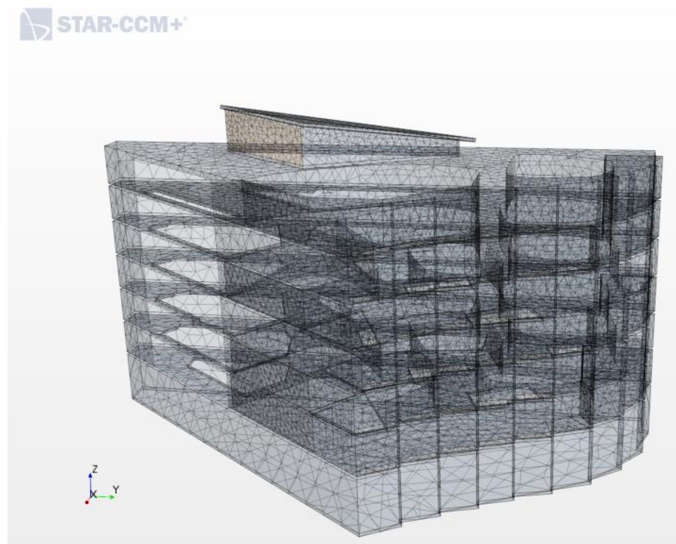


Figure 25.2: Refined Mesh

Results

The CFD simulation proved to be challenging, especially because of the complex building geometry. The approach using both external and internal flow simulation simplified greatly reduced the inaccuracy of the internal flow model. Once values for boundary conditions obtained from the domain decomposition calculations were used, imbalance of mass flow rate for the entire volume decreases significantly. Residuals for the final simulation reached convergence at 1.0E-05. The mass flow imbalance report for the entire volume was less than -2.8E-07.

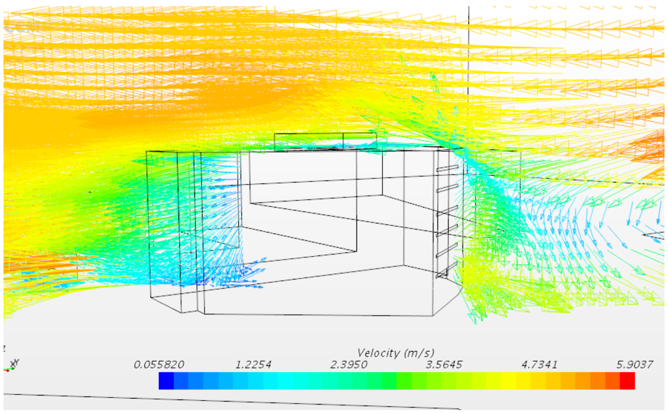


Figure 26.1: Vector Section view – External Flow

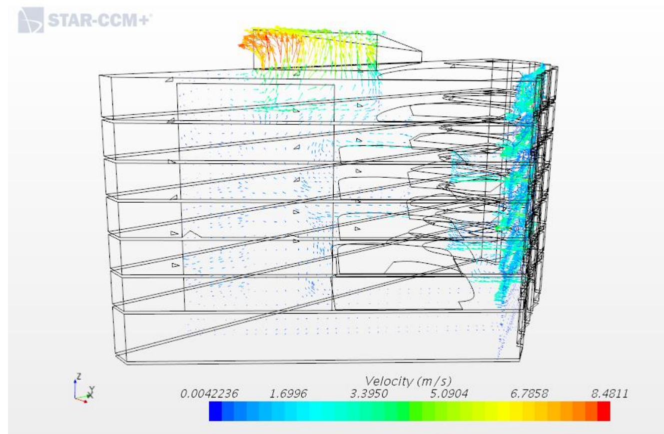


Figure 26.2: Vector Section view – Internal Flow

Figure 27 shows a temperature scalar scene, displaying horizontal sections cut at mid-height of every level. Reports show a volume average temperature of approximately 60 F, which is consistent on every level seen on the figure.

Surface Average of Temperature on Volume Mesh Report:

Part	Value (F)
-------------------------------	-------------
Plane Section L2	6.001124e+01
Plane Section L3	6.001192e+01
Plane Section L4	6.001207e+01
Plane Section L5	6.001221e+01
Plane Section L6	6.001201e+01
Plane Section L7	6.001257e+01

Total:	6.001201e+01

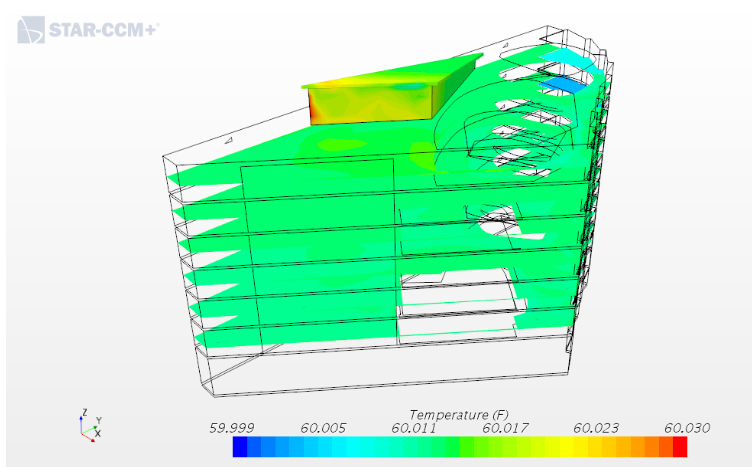


Figure 27: Scalar Field – Temperature Function

The final simulation was modeled with boundary conditions for the air openings and did not include a thermal specification for a solar chimney. The pressure differential calculated and assigned to the boundary conditions was sufficient to drive flow from the designed inlets into the atrium space and through the pressure outlet. Mass flow reports indicate that the mass flux into the building is slightly higher than the mass flux leaving the building through the pressure outlet. This could be due to calculation errors when estimating the pressure differential required for the target airflow rate. A vector scene displaying velocity vector shown in Figure 28 indicates that the flow direction does satisfy the design goals.

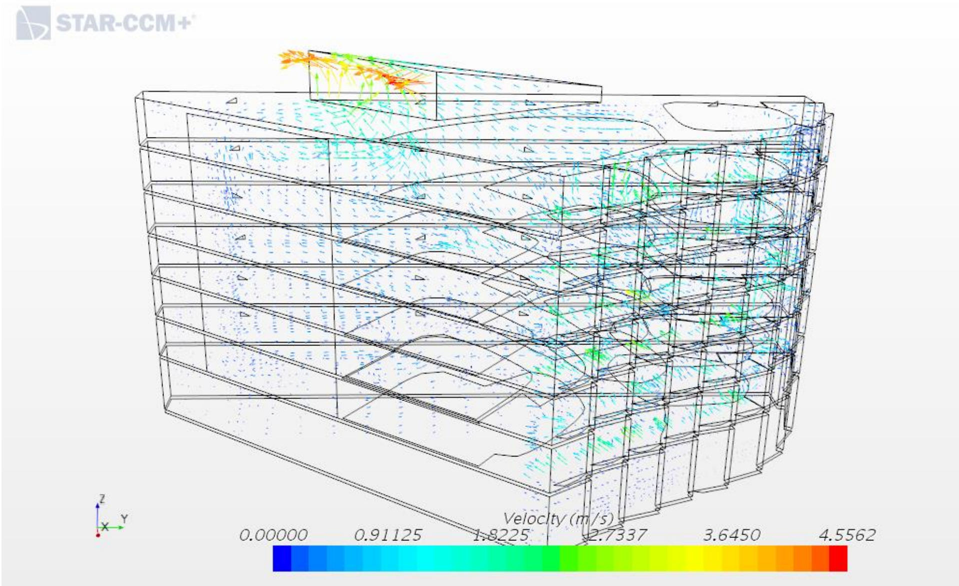


Figure 28: Vector Field – Velocity Function

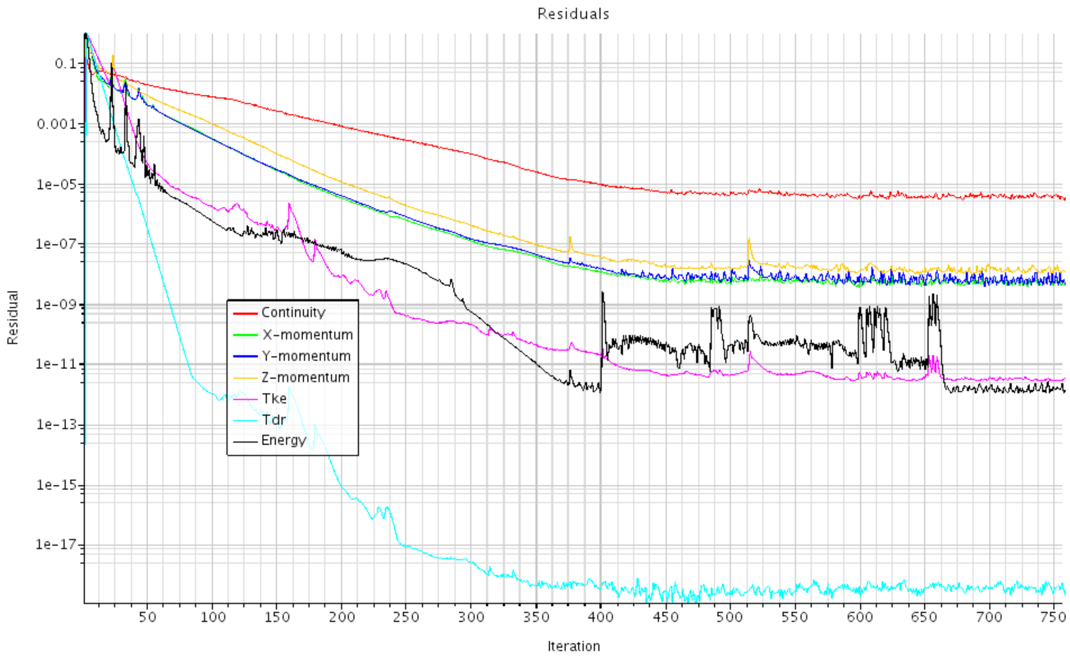


Figure 29: Residuals Plot

Breadth 2: Structural Analysis for Integration of a Double-Skin Façade

This breadth consists of a façade study with the purpose of integrating a double-skin façade in place of the existing curtainwall on the south-east façade of the building. A double-skin façade consists of a regular building façade, placed on the interior of the wall, an air cavity, and a second skin placed in front of the regular building façade. The second screen is typically made of glazing, and can be designed to operate with natural ventilation systems. The air cavity between the two skins creates a thermal buffer for the building, reducing energy consumption while allowing day lighting into the interior spaces.

Structural Evaluation of Existing Façade System

The existing curtainwall system consists of single glazing façade extending from the ground level to the top of the building, with a U-value of 0.42 and Shading Coefficient (SC) value of 0.33. It is supported by spandrels which are hung from rods. These rods extend up to a truss constructed out of rectangular HSS members. Because the same type of facade will be implemented, connections and implementation of the curtain wall does not need to change from the original design. The spandrels have distributed load due to the curtain wall load with multiple supports; thus creating a spandrels that must be analyzed as an indeterminate beam. For the purpose of this breadth, tributary width for the tension rods will be used to simplify the structural analysis. The figure below shows the side of the building where the curtainwall is located, as well as a more detailed section.

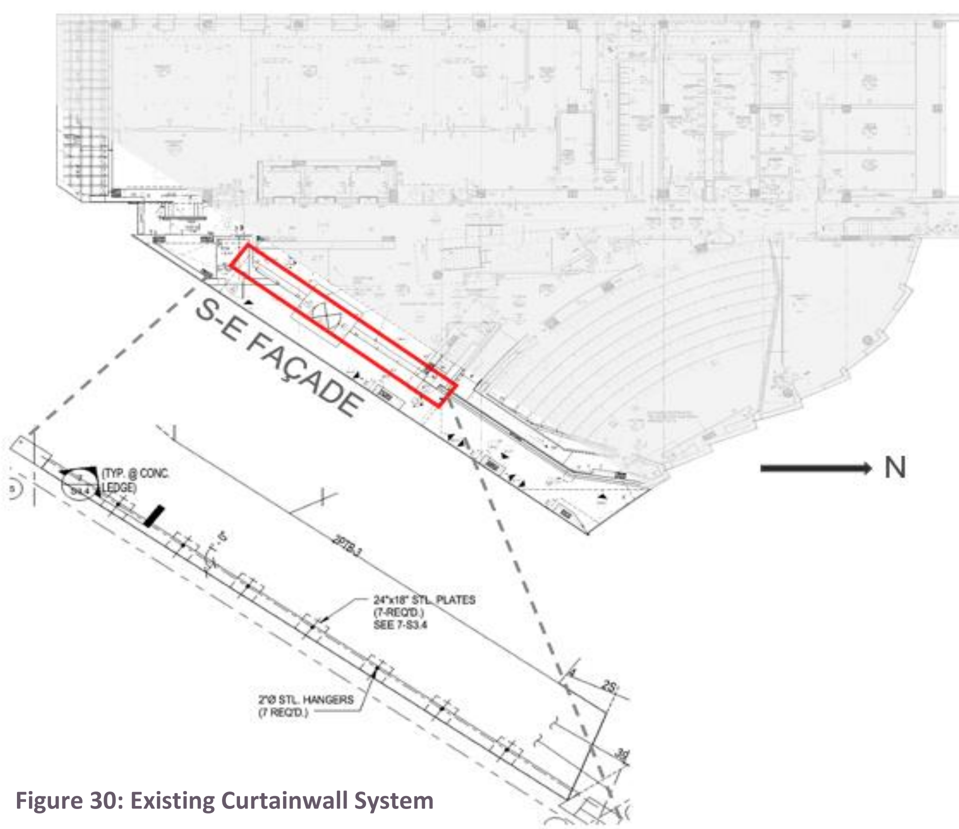


Figure 30: Existing Curtainwall System

As shown on the detailed section of Figure 27, 2” diameter hanging rods are called out on the structural plan. These rods are most likely the controlling component when the second curtain wall would be added to the structure. In Figure 31.1, the profile of the HSS steel truss is shown with the hangers installed. A detail of the connection between the steel truss and hangers is shown in Figure 31.2.

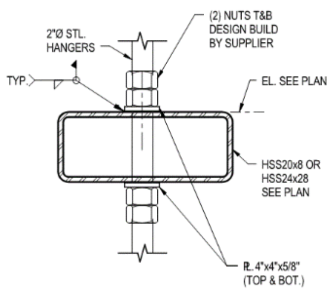


Figure 31.1: HSS Steel Truss and Hangers

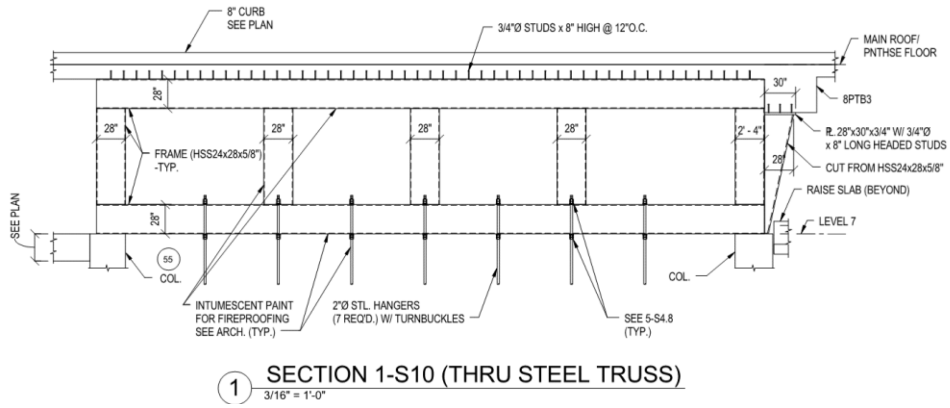


Figure 31.2: HSS Steel Truss Detail

By inspection, the existing structure can remain the same, with the possible exception of the steel rod hangers. These tension rods will see the most stress increase. A simple stress analysis was conducted to evaluate whether the existing tension rods were adequate to support the second façade.

Stress Analysis:

Assumption: Existing Façade weight: 15 psf

Allowable Tensile Stress (for threaded rod) = 9000 psi

Self-Weight of Spandrel Supports: 8 plf → w/ 5 spandrels

Building Height: 90 ft.

Total Supporting Load: 1390 plf

Simple Tributary Width of Tension Rod: 3 ft.

Load on Tension Rod: 4170 lb.

$$Rod\ stress = \frac{Load\ on\ tension\ rod}{Simple\ tributary\ width} = \frac{4170\ lb.}{3.14\ in^2} = 1328\ psi$$

Conclusions:

Assuming the second skin has similar weight and connections to the existing curtainwall, it can be estimated that the load of a second façade will double the existing load. If Load is doubled due to adding another curtain façade:

Rod stress= 1328 psi x 2 = 2656 psi < 9000 psi

Based on this evaluation, adding an additional curtain façade, the current structure is adequate and the double skin façade can be added with no needed changes to the structure.

Masters Courses Application

Multiple courses taken as a part of the integrated program were applied for the analysis conducted in this report.

Central Cooling Systems (AE-557) was applied for the mechanical depth. Numerical modeling methods were used to assess the energy consumption of the designed system. Performance curves coefficients were used to calculate the energy input of the heat pump design at different temperatures entering the evaporator and condenser coils, as well as for different part-load conditions. Knowledge gained in that class also helped design the 3-staged compressor configuration to optimize the part-load performance of the reversible heat pump.

Computational Fluid Dynamics (AE-559) was applied in developing the CFD simulation for the natural ventilation system. The software used in class, Star CCM+, was used to create the building geometry and simulate airflow behavior at different conditions.

Building Automation and Control Systems (AE-555) was applied to develop the control set points and operating modes of the proposed systems.

References

Affiliated Engineers, Inc. (2012). *GWU School of Public Health and Health Services Building - MEPFP Basis of Design.*

Ahmed, M., Abel-Rahman, A., Ali, A., & Suzuki, M. (2016). Double-Skin Facade: The State of Art of Building Energy Efficiency. *Journal of Clean Energy Technologies*, 84-89.

ANSI/AHRI. (2015). *Standard 920, Performance Rating of DX Dedicated Outdoor Air System Units.* Air-Conditioning, Heating, and Refrigeration Insitute.

ANSI/ASHRAE. (2010). *Standard 62.1 - Ventilation for Acceptable Indoor Air Quality.* Atlanta, GA.

ANSI/ASHRAE. (2010). *Standard 90.1 - Energy Standard for Buildings Except Low Rise Residential Buildings.* Atlanta, GA.

ANSI/ASHRAE. (2012). *Handbook of Fundamentals.* Atlanta, GA: ASHRAE.

Betz, F., McNeill, J., Talbert, B., Thimmanna, H., & Repka, N. (2012). *Issues arising from the use of chilled beams in energy models.* Research Gate.

Deru, M., & Torcellini, P. (2007). *Source Energy and Emission Factors for Energy Use in Buildings.* National Renewable Energy Laboratory.

Hunt, G., & Linden, P. (1999). The fluid mechanics of natural ventilation - displacement ventilation by buoyancy-driven flows assisted by wind. *Building and Environment*, 708-720.

Kirshenbaum, M. (2017). Optimized Energy Recovery. *ASHRAE Journal*, 30-40.

Meroney, R. N. (2009). CFD Prediction of Airflow in Buildings for Natural Ventilation. *11th Americas Conference on Wind Engineering* . San Juan, Puerto Rico.

Potter, M. (2010). Comparing Direct-Expansion DOAS Units and Standard A/C Equipment. *RSES Journal*, 14-16.

Raustad, R. (2012). *Creating Performance Curves for Variable Refrigerant Flow Heat Pumps in Energy Plus.* Florida: Florida Solar Energy Center .

Richichi, C. (1987). *Simulation and Parametric Study of a Direct Expansion Energy Recovery System Utilizing 100 % Supply and Exhaust Air.* The Pennsylvania State University, Department of Architectural Engineering. The Pennsylvania State University.

Shameri, M., M.A., A., Sopian, K., Zain, M., & O., E. (2010). Perspectives of double skin facade systems in buildings and energy savings. *Renewable and Sustainable Energy Reviews*, 1468-1475.

TRANE. (2000). Energy-conscious design ideas for Air-to-Air Energy Recovery. *Engineering Newsletter, 29*(5), pp. 1-8.

Trane. (2016). Rating Standard for DX Dedicated Outdoor-Air Units. *Engineering Newsletter, 45*(4), pp. 1-8.

U.S. Green Building Council. (2009). *LEED 2009 for New Construction and Major Renovations.* Washington, D.C.: U.S. Green Building Council.

Appendix A

Bin Analysis Calculations

Table A.1: Bin Analysis

Tdb (F)	Tdp (F)	Operating Mode	Q 5%	Q 10%	Q 30%	Q 35%	Q 70%	Q 100%	CAP_FT	EIR_FT
13	-3	Sensible Heating	159.2	318.5	955.8	1114.5	2229.0	3184.8	1.353	0.582
14	-6	Sensible Heating	155.8	311.6	935.3	1090.6	2181.2	3116.5	1.353	0.582
15	-4	Sensible Heating	152.4	304.9	914.9	1066.9	2133.7	3048.7	1.353	0.582
16	-6	Sensible Heating	149.1	298.1	894.6	1043.2	2086.4	2981.0	1.353	0.582
17	-4	Sensible Heating	145.7	291.3	874.3	1019.5	2038.9	2913.2	1.353	0.582
18	-2	Sensible Heating	142.3	284.6	854.0	995.8	1991.5	2845.5	1.353	0.582
19	0	Sensible Heating	138.9	277.8	833.6	972.0	1944.1	2777.7	1.353	0.582
20	2	Sensible Heating	135.5	271.0	813.3	948.4	1896.7	2710.0	1.353	0.582
21	5	Sensible Heating	132.1	264.2	793.0	924.6	1849.3	2642.2	1.353	0.582
22	4	Sensible Heating	128.7	257.5	772.7	900.9	1801.9	2574.5	1.353	0.582
23	7	Sensible Heating	125.3	250.7	752.3	877.2	1754.4	2506.7	1.353	0.582
24	9	Sensible Heating	121.9	243.9	732.0	853.5	1707.0	2438.9	1.353	0.582
25	6	Sensible Heating	118.6	237.1	711.6	829.8	1659.6	2371.3	1.353	0.582
26	10	Sensible Heating	115.2	230.3	691.3	806.1	1612.2	2303.5	1.353	0.582
27	11	Sensible Heating	111.8	223.6	671.0	782.4	1564.8	2235.8	1.353	0.582
28	14	Sensible Heating	108.4	216.8	650.6	758.7	1517.3	2168.0	1.353	0.582
29	14	Sensible Heating	105.0	210.0	630.3	735.0	1470.0	2100.3	1.353	0.582
30	17	Sensible Heating	101.6	203.2	610.0	711.3	1422.5	2032.5	1.353	0.582
31	17	Sensible Heating	98.2	196.5	589.6	687.6	1375.1	1964.8	1.353	0.582
32	21	Sensible Heating	94.8	189.7	569.3	663.8	1327.7	1897.0	1.353	0.582
33	23	Sensible Heating	91.5	182.9	549.0	640.1	1280.3	1829.2	1.353	0.582
34	24	Sensible Heating	88.1	176.2	528.7	616.4	1232.9	1761.5	1.353	0.582
35	24	Sensible Heating	84.7	169.4	508.3	592.7	1185.4	1693.7	1.353	0.582
36	24	Sensible Heating	81.3	162.6	488.0	569.0	1138.0	1626.0	1.353	0.582
37	27	Sensible Heating	77.9	155.8	467.6	545.3	1090.6	1558.2	1.353	0.582
38	28	Sensible Heating	74.5	149.1	447.3	521.6	1043.2	1490.5	1.353	0.582
39	29	Sensible Heating	71.1	142.3	427.0	497.9	995.8	1422.7	1.353	0.582
40	29	Sensible Heating	67.8	135.5	406.7	474.2	948.4	1355.1	1.353	0.582
41	31	Sensible Heating	64.4	128.7	386.3	450.5	900.9	1287.2	1.353	0.582
42	31	Sensible Heating	61.0	121.9	366.0	426.7	853.5	1219.4	1.353	0.582
43	31	Sensible Heating	57.6	115.2	345.7	403.1	806.1	1151.8	1.353	0.582
44	33	Sensible Heating	54.2	108.4	325.3	379.3	758.6	1084.0	1.353	0.582
45	35	Sensible Heating	50.8	101.6	305.0	355.6	711.3	1016.3	1.353	0.582
46	34	Ventilation Only								
47	35	Ventilation Only								
48	36	Ventilation Only								
49	37	Ventilation Only								

Table A.1: Bin Analysis

Tdb (F)	Tdp (F)	Operating Mode	Q 5%	Q 10%	Q 30%	Q 35%	Q 70%	Q 100%	CAP_FT	EIR_FT
56	46	Dehumidification	3.7	7.3	21.9	25.6	51.2	73.1	0.783	0.835
57	46	Dehumidification	8.2	16.3	49.0	57.2	114.3	163.3	0.787	0.835
58	47	Dehumidification	14.0	28.0	84.1	98.1	196.2	280.3	0.795	0.835
59	49	Dehumidification	26.3	52.7	158.0	184.2	368.5	526.5	0.825	0.836
60	49	Dehumidification	31.0	61.9	185.8	216.7	433.3	619.1	0.828	0.836
61	51	Dehumidification	44.2	88.5	265.5	309.6	619.3	884.8	0.859	0.835
62	51	Dehumidification	44.7	89.3	268.1	312.6	625.2	893.4	0.850	0.835
63	52	Dehumidification	55.1	110.2	330.7	385.6	771.1	1101.8	0.871	0.834
64	53	Dehumidification	64.7	129.4	388.4	452.9	905.9	1294.3	0.888	0.832
65	55	Dehumidification	76.4	152.8	458.7	534.8	1069.7	1528.3	0.911	0.829
66	55	Dehumidification	81.4	162.8	488.7	569.8	1139.6	1628.3	0.915	0.829
67	58	Dehumidification	97.4	194.8	584.5	681.5	1363.1	1947.6	0.948	0.823
68	58	Dehumidification	101.8	203.5	610.8	712.3	1424.5	2035.3	0.950	0.823
69	59	Dehumidification	111.1	222.2	666.8	777.5	1555.0	2221.8	0.965	0.820
70	60	Dehumidification	122.0	244.0	732.3	853.9	1707.7	2440.0	0.983	0.816
71	60	Dehumidification	126.1	252.3	757.1	882.9	1765.7	2522.8	0.984	0.815
72	61	Dehumidification	135.3	270.7	812.4	947.3	1894.5	2706.9	0.998	0.812
73	64	Dehumidification	155.3	310.7	932.3	1087.1	2174.3	3106.6	1.035	0.801
74	64	Dehumidification	158.8	317.6	953.2	1111.5	2222.9	3176.1	1.035	0.801
75	66	Dehumidification	182.0	364.0	1092.5	1274.0	2547.9	3640.5	1.076	0.787
76	66	Dehumidification	183.8	367.6	1103.2	1286.3	2572.6	3675.8	1.072	0.788
77	64	Dehumidification	169.7	339.3	1018.3	1187.4	2374.8	3393.0	1.036	0.801
78	66	Dehumidification	189.2	378.4	1135.7	1324.3	2648.6	3784.3	1.069	0.790
79	66	Dehumidification	193.4	386.7	1160.6	1353.3	2706.6	3867.1	1.070	0.789
80	66	Dehumidification	197.5	395.0	1185.4	1382.3	2764.6	3950.0	1.072	0.789
81	65	Dehumidification	194.3	388.5	1166.1	1359.7	2719.4	3885.4	1.058	0.793
82	66	Dehumidification	206.0	412.1	1236.7	1442.0	2884.0	4120.6	1.075	0.787
83	66	Dehumidification	205.4	410.7	1232.6	1437.3	2874.6	4107.2	1.067	0.790
84	67	Dehumidification	219.4	438.9	1317.1	1535.8	3071.7	4388.8	1.088	0.783
85	67	Dehumidification	222.5	445.1	1335.8	1557.6	3115.2	4450.9	1.087	0.783
86	67	Dehumidification	224.3	448.6	1346.4	1569.9	3139.9	4486.3	1.084	0.784
87	65	Dehumidification	211.0	422.1	1266.6	1477.0	2953.9	4220.6	1.049	0.796
88	67	Dehumidification	233.3	466.5	1400.2	1632.6	3265.3	4665.4	1.087	0.783
89	65	Dehumidification	221.1	442.2	1327.0	1547.3	3094.7	4421.7	1.056	0.794
90	66	Dehumidification	229.2	458.4	1375.6	1604.1	3208.1	4583.8	1.065	0.791
91	65	Dehumidification	229.1	458.3	1375.3	1603.6	3207.3	4582.6	1.058	0.793
92	67	Dehumidification	245.6	491.2	1474.0	1718.8	3437.6	4911.6	1.084	0.784
93	68	Dehumidification	256.8	513.6	1541.3	1797.3	3594.5	5135.9	1.099	0.778
94	69	Dehumidification	273.5	547.0	1641.6	1914.1	3828.3	5469.8	1.124	0.768
95	69	Dehumidification	275.4	550.9	1653.3	1927.8	3855.6	5508.8	1.121	0.769

Table A.1: Bin Analysis										
Tdb (F)	**PLR 5%**	**PLR 10%**	**PLR 30%**	**PLR 35%**	**PLR 70%**	**PLF 5%**	**PLF 10%**	**PLF 30%**	**PLF 35%**	**PLF 70%**
13	0.530	0.530	0.746	0.202	0.403	0.929	0.929	0.962	0.880	0.910
14	0.518	0.518	0.687	0.133	0.266	0.928	0.928	0.953	0.870	0.890
15	0.507	0.507	0.628	0.065	0.129	0.926	0.926	0.944	0.860	0.869
16	0.496	0.991	0.570	0.997	0.993	0.924	0.999	0.935	0.999	0.999
17	0.484	0.969	0.511	0.928	0.857	0.923	0.995	0.927	0.989	0.979
18	0.473	0.946	0.453	0.860	0.721	0.921	0.992	0.918	0.979	0.958
19	0.462	0.924	0.395	0.792	0.585	0.919	0.989	0.909	0.969	0.938
20	0.451	0.901	0.336	0.724	0.449	0.918	0.985	0.900	0.959	0.917
21	0.439	0.879	0.278	0.656	0.312	0.916	0.982	0.892	0.948	0.897
22	0.428	0.856	0.220	0.588	0.176	0.914	0.978	0.883	0.938	0.876
23	0.417	0.834	0.161	0.520	0.040	0.913	0.975	0.874	0.928	0.856
24	0.406	0.811	0.103	0.452	0.903	0.911	0.972	0.865	0.918	0.986
25	0.394	0.789	0.044	0.384	0.767	0.909	0.968	0.857	0.908	0.965
26	0.383	0.766	0.986	0.316	0.631	0.907	0.965	0.998	0.897	0.945
27	0.372	0.743	0.927	0.248	0.495	0.906	0.962	0.989	0.887	0.924
28	0.360	0.721	0.869	0.179	0.359	0.904	0.958	0.980	0.877	0.904
29	0.349	0.698	0.811	0.111	0.223	0.902	0.955	0.972	0.867	0.883
30	0.338	0.676	0.752	0.043	0.086	0.901	0.951	0.963	0.856	0.863
31	0.327	0.653	0.694	0.975	0.950	0.899	0.948	0.954	0.996	0.993
32	0.315	0.631	0.635	0.907	0.814	0.897	0.945	0.945	0.986	0.972
33	0.304	0.608	0.577	0.839	0.678	0.896	0.941	0.937	0.976	0.952
34	0.293	0.586	0.519	0.771	0.542	0.894	0.938	0.928	0.966	0.931
35	0.282	0.563	0.460	0.703	0.405	0.892	0.934	0.919	0.955	0.911
36	0.270	0.541	0.402	0.635	0.269	0.891	0.931	0.910	0.945	0.890
37	0.259	0.518	0.343	0.566	0.133	0.889	0.928	0.902	0.935	0.870
38	0.248	0.496	0.285	0.498	0.997	0.887	0.924	0.893	0.925	1.000
39	0.237	0.473	0.227	0.430	0.860	0.885	0.921	0.884	0.915	0.979
40	0.225	0.451	0.168	0.362	0.724	0.884	0.918	0.875	0.904	0.959
41	0.214	0.428	0.110	0.294	0.588	0.882	0.914	0.866	0.894	0.938
42	0.203	0.406	0.051	0.226	0.452	0.880	0.911	0.858	0.884	0.918
43	0.191	0.383	0.993	0.158	0.316	0.879	0.907	0.999	0.874	0.897
44	0.180	0.360	0.934	0.090	0.179	0.877	0.904	0.990	0.863	0.877
45	0.169	0.338	0.876	0.022	0.043	0.875	0.901	0.981	0.853	0.856
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Table A.1: Bin Analysis

Tdb (F)	PLR 5%	PLR 10%	PLR 30%	PLR 35%	PLR 70%	PLF 5%	PLF 10%	PLF 30%	PLF 35%	PLF 70%
56	0.012	0.024	0.057	0.067	0.134	0.852	0.854	0.859	0.860	0.870
57	0.027	0.054	0.128	0.150	0.299	0.854	0.858	0.869	0.872	0.895
58	0.047	0.093	0.220	0.257	0.514	0.857	0.864	0.883	0.889	0.927
59	0.088	0.175	0.414	0.482	0.965	0.863	0.876	0.912	0.922	0.995
60	0.103	0.206	0.486	0.567	0.134	0.865	0.881	0.923	0.935	0.870
61	0.147	0.294	0.695	0.811	0.621	0.872	0.894	0.954	0.972	0.943
62	0.149	0.297	0.702	0.818	0.637	0.872	0.895	0.955	0.973	0.946
63	0.183	0.366	0.866	0.009	0.019	0.877	0.905	0.980	0.851	0.853
64	0.215	0.430	0.017	0.186	0.371	0.882	0.915	0.853	0.878	0.906
65	0.254	0.508	0.201	0.400	0.800	0.888	0.926	0.880	0.910	0.970
66	0.271	0.541	0.279	0.492	0.983	0.891	0.931	0.892	0.924	0.997
67	0.324	0.648	0.530	0.784	0.568	0.899	0.947	0.930	0.968	0.935
68	0.338	0.677	0.599	0.865	0.729	0.901	0.952	0.940	0.980	0.959
69	0.369	0.739	0.745	0.035	0.071	0.905	0.961	0.962	0.855	0.861
70	0.406	0.811	0.917	0.235	0.470	0.911	0.972	0.988	0.885	0.921
71	0.419	0.839	0.982	0.311	0.622	0.913	0.976	0.997	0.897	0.943
72	0.450	0.900	0.127	0.480	0.959	0.918	0.985	0.869	0.922	0.994
73	0.517	0.517	0.441	0.846	0.692	0.927	0.927	0.916	0.977	0.954
74	0.528	0.528	0.495	0.910	0.819	0.929	0.929	0.924	0.986	0.973
75	0.605	0.605	0.860	0.335	0.670	0.941	0.941	0.979	0.900	0.950
76	0.611	0.611	0.888	0.367	0.735	0.942	0.942	0.983	0.905	0.960
77	0.564	0.564	0.666	0.108	0.217	0.935	0.935	0.950	0.866	0.882
78	0.629	0.629	0.973	0.467	0.933	0.944	0.944	0.996	0.920	0.990
79	0.643	0.643	0.038	0.543	0.085	0.946	0.946	0.856	0.931	0.863
80	0.657	0.657	0.103	0.618	0.237	0.949	0.949	0.865	0.943	0.886
81	0.646	0.646	0.052	0.559	0.119	0.947	0.947	0.858	0.934	0.868
82	0.685	0.685	0.237	0.775	0.550	0.953	0.953	0.886	0.966	0.932
83	0.683	0.683	0.227	0.763	0.525	0.952	0.952	0.884	0.964	0.929
84	0.730	0.730	0.448	0.020	0.041	0.959	0.959	0.917	0.853	0.856
85	0.740	0.740	0.497	0.077	0.155	0.961	0.961	0.925	0.862	0.873
86	0.746	0.746	0.525	0.110	0.219	0.962	0.962	0.929	0.866	0.883
87	0.702	0.702	0.316	0.866	0.733	0.955	0.955	0.897	0.980	0.960
88	0.776	0.776	0.665	0.274	0.548	0.966	0.966	0.950	0.891	0.932
89	0.735	0.735	0.474	0.051	0.101	0.960	0.960	0.921	0.858	0.865
90	0.762	0.762	0.601	0.199	0.398	0.964	0.964	0.940	0.880	0.910
91	0.762	0.762	0.600	0.198	0.396	0.964	0.964	0.940	0.880	0.909
92	0.817	0.817	0.859	0.499	0.999	0.972	0.972	0.979	0.925	1.000
93	0.854	0.854	0.035	0.705	0.410	0.978	0.978	0.855	0.956	0.911
94	0.909	0.909	0.297	0.011	0.021	0.986	0.986	0.895	0.852	0.853
95	0.916	0.916	0.328	0.046	0.093	0.987	0.987	0.899	0.857	0.864

Table A.1: Bin Analysis										
Tdb (F)	Q_{tot} 5% (Mbtu)	Qtot 10% (Mbtu)	Qtot 30% (Mbtu)	Qtot 35% (Mbtu)	Qtot 70% (Mbtu)	EIR 5%	EIR 10%	EIR 30%	EIR 35%	EIR 70%
13	758.55	810.50	450.91	468.01	465.03	0.2349641	0.1842046	0.2116557	0.1855692	0.1894555
14	758.55	810.50	450.91	468.01	465.03	0.2349641	0.1842046	0.2116557	0.1855692	0.1894555
15	758.55	810.50	450.91	468.01	465.03	0.2349641	0.1842046	0.2116557	0.1855692	0.1894555
16	758.55	810.50	450.91	468.01	465.03	0.2349641	0.1842046	0.2116557	0.1855692	0.1894555
17	758.55	810.50	450.91	468.01	465.03	0.2349641	0.1842046	0.2116557	0.1855692	0.1894555
18	758.55	810.50	450.91	468.01	465.03	0.2349641	0.1842046	0.2116557	0.1855692	0.1894555
19	758.55	810.50	450.91	468.01	465.03	0.2349641	0.1842046	0.2116557	0.1855692	0.1894555
20	758.55	810.50	450.91	468.01	465.03	0.2349641	0.1842046	0.2116557	0.1855692	0.1894555
21	758.55	810.50	450.91	468.01	465.03	0.2349641	0.1842046	0.2116557	0.1855692	0.1894555
22	758.55	810.50	450.91	468.01	465.03	0.2349641	0.1842046	0.2116557	0.1855692	0.1894555
23	758.55	810.50	450.91	468.01	465.03	0.2349641	0.1842046	0.2116557	0.1855692	0.1894555
24	758.55	810.50	450.91	468.01	465.03	0.2349641	0.1842046	0.2116557	0.1855692	0.1894555
25	758.55	810.50	450.91	468.01	465.03	0.2349641	0.1842046	0.2116557	0.1855692	0.1894555
26	758.55	810.50	450.91	468.01	465.03	0.2349641	0.1842046	0.2116557	0.1855692	0.1894555
27	758.55	810.50	450.91	468.01	465.03	0.2349641	0.1842046	0.2116557	0.1855692	0.1894555
28	758.55	810.50	450.91	468.01	465.03	0.2349641	0.1842046	0.2116557	0.1855692	0.1894555
29	758.55	810.50	450.91	468.01	465.03	0.2349641	0.1842046	0.2116557	0.1855692	0.1894555
30	758.55	810.50	450.91	468.01	465.03	0.2349641	0.1842046	0.2116557	0.1855692	0.1894555
31	758.55	810.50	450.91	468.01	465.03	0.2349641	0.1842046	0.2116557	0.1855692	0.1894555
32	758.55	810.50	450.91	468.01	465.03	0.2349641	0.1842046	0.2116557	0.1855692	0.1894555
33	758.55	810.50	450.91	468.01	465.03	0.2349641	0.1842046	0.2116557	0.1855692	0.1894555
34	758.55	810.50	450.91	468.01	465.03	0.2349641	0.1842046	0.2116557	0.1855692	0.1894555
35	758.55	810.50	450.91	468.01	465.03	0.2349641	0.1842046	0.2116557	0.1855692	0.1894555
36	758.55	810.50	450.91	468.01	465.03	0.2349641	0.1842046	0.2116557	0.1855692	0.1894555
37	758.55	810.50	450.91	468.01	465.03	0.2349641	0.1842046	0.2116557	0.1855692	0.1894555
38	758.55	810.50	450.91	468.01	465.03	0.2349641	0.1842046	0.2116557	0.1855692	0.1894555
39	758.55	810.50	450.91	468.01	465.03	0.2349641	0.1842046	0.2116557	0.1855692	0.1894555
40	758.55	810.50	450.91	468.01	465.03	0.2349641	0.1842046	0.2116557	0.1855692	0.1894555
41	758.55	810.50	450.91	468.01	465.03	0.2349641	0.1842046	0.2116557	0.1855692	0.1894555
42	758.55	810.50	450.91	468.01	465.03	0.2349641	0.1842046	0.2116557	0.1855692	0.1894555
43	758.55	810.50	450.91	468.01	465.03	0.2349641	0.1842046	0.2116557	0.1855692	0.1894555
44	758.55	810.50	450.91	468.01	465.03	0.2349641	0.1842046	0.2116557	0.1855692	0.1894555
45	758.55	810.50	450.91	468.01	465.03	0.2349641	0.1842046	0.2116557	0.1855692	0.1894555
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Table A.1: Bin Analysis

Tdb (F)	Q_{tot} 5% (Mbtu)	Qtot 10% (Mbtu)	Qtot 30% (Mbtu)	Qtot 35% (Mbtu)	Qtot 70% (Mbtu)	EIR 5%	EIR 10%	EIR 30%	EIR 35%	EIR 70%
50	405.08	465.44	247.89	268.06	264.47	0.265085	0.237198	0.2534411	0.2381242	0.2406663
51	412.63	474.11	252.51	273.05	269.40	0.2658983	0.2379258	0.2542188	0.2388548	0.2414048
52	419.48	481.98	256.70	277.59	273.87	0.2665415	0.2385013	0.2548336	0.2394325	0.2419886
53	420.23	482.84	257.16	278.08	274.36	0.2666064	0.2385593	0.2548957	0.2394908	0.2420475
54	437.18	502.32	267.53	289.30	285.43	0.2677932	0.2396214	0.2560304	0.240557	0.2431251
55	444.60	510.84	272.07	294.21	290.27	0.2681473	0.2399382	0.2563689	0.240875	0.2434465
56	446.22	512.71	273.07	295.28	291.33	0.2682116	0.2399958	0.2564304	0.2409328	0.243505
57	448.26	515.05	274.31	296.63	292.66	0.2682858	0.2400621	0.2565014	0.2409995	0.2435723
58	453.05	520.56	277.25	299.80	295.79	0.2684315	0.2401925	0.2566406	0.2411303	0.2437045
59	469.69	539.67	287.43	310.81	306.65	0.2686301	0.2403702	0.2568305	0.2413087	0.2438848
60	471.92	542.23	288.79	312.29	308.11	0.2686211	0.2403622	0.2568219	0.2413007	0.2438767
61	489.26	562.16	299.41	323.77	319.43	0.2682734	0.240051	0.2564895	0.2409883	0.243561
62	483.98	556.09	296.17	320.27	315.98	0.2684309	0.240192	0.2566401	0.2411298	0.243704
63	495.93	569.82	303.48	328.18	323.78	0.2680112	0.2398164	0.2562388	0.2407528	0.243323
64	506.06	581.46	309.68	334.88	330.39	0.2674801	0.2393412	0.2557311	0.2402757	0.2428408
65	519.09	596.43	317.66	343.50	338.90	0.2665664	0.2385236	0.2548574	0.2394549	0.2420112
66	521.39	599.07	319.06	345.02	340.40	0.2663793	0.2383562	0.2546786	0.2392868	0.2418414
67	540.00	620.46	330.45	357.34	352.56	0.264577	0.2367435	0.2529555	0.2376679	0.2402051
68	541.29	621.94	331.24	358.19	353.40	0.2644337	0.2366152	0.2528184	0.2375391	0.240075
69	549.65	631.55	336.36	363.73	358.86	0.2634485	0.2357337	0.2518765	0.2366541	0.2391806
70	559.86	643.28	342.61	370.48	365.52	0.2621141	0.2345397	0.2506007	0.2354554	0.2379691
71	560.71	644.26	343.13	371.05	366.08	0.2619964	0.2344343	0.2504882	0.2353497	0.2378622
72	568.37	653.05	347.81	376.11	371.08	0.2608941	0.233448	0.2494343	0.2343595	0.2368615
73	589.35	677.16	360.65	389.99	384.77	0.2574785	0.2303917	0.2461687	0.2312913	0.2337605
74	589.35	677.16	360.65	390.00	384.77	0.2574773	0.2303907	0.2461676	0.2312903	0.2337595
75	612.81	704.12	375.01	405.52	400.09	0.2529948	0.2263798	0.241882	0.2272637	0.2296899
76	610.82	701.83	373.79	404.21	398.79	0.2534011	0.2267433	0.2422704	0.2276286	0.2300587
77	589.86	677.75	360.97	390.34	385.11	0.257387	0.2303098	0.2460812	0.2312091	0.2336774
78	609.03	699.78	372.70	403.02	397.62	0.2537624	0.2270665	0.2426158	0.2279531	0.2303867
79	609.75	700.60	373.14	403.50	398.09	0.2536182	0.2269375	0.242478	0.2278236	0.2302558
80	610.53	701.50	373.61	404.01	398.60	0.2534601	0.2267961	0.2423269	0.2276817	0.2301123
81	602.71	692.51	368.83	398.84	393.49	0.255009	0.228182	0.2438077	0.229073	0.2315185
82	612.32	703.56	374.71	405.20	399.77	0.2530947	0.2264691	0.2419775	0.2273534	0.2297805
83	607.56	698.08	371.79	402.04	396.66	0.2540579	0.227331	0.2428984	0.2282186	0.230655
84	619.61	711.93	379.17	410.02	404.53	0.2515689	0.2251038	0.2405187	0.2259827	0.2283953
85	619.17	711.42	378.90	409.73	404.24	0.2516637	0.2251886	0.2406093	0.2260679	0.2284813
86	617.23	709.20	377.72	408.45	402.98	0.2520738	0.2255556	0.2410015	0.2264363	0.2288537
87	597.79	686.86	365.82	395.58	390.28	0.2559443	0.229019	0.244702	0.2299132	0.2323677
88	619.44	711.73	379.07	409.91	404.42	0.2516056	0.2251367	0.2405538	0.2260157	0.2284286
89	601.44	691.05	368.05	397.99	392.66	0.2552535	0.2284008	0.2440415	0.2292926	0.2317405
90	606.81	697.23	371.34	401.55	396.17	0.2542055	0.2274631	0.2430396	0.2283512	0.230789
91	602.74	692.55	368.85	398.86	393.52	0.2550027	0.2281764	0.2438017	0.2290673	0.2315127
92	617.61	709.63	377.95	408.70	403.22	0.2519948	0.2254849	0.2409259	0.2263653	0.2287819
93	626.12	719.41	383.16	414.33	408.78	0.2501516	0.2238357	0.2391637	0.2247096	0.2271086
94	640.28	735.67	391.82	423.70	418.02	0.2469001	0.2209262	0.236055	0.2217888	0.2241566
95	638.63	733.79	390.81	422.61	416.95	0.2472892	0.2212743	0.236427	0.2221383	0.2245098

Table A.1: Bin Analysis						
Tdb (F)	**P,in 5% (W)**	**P,in 10% (W)**	**P,in 30% (W)**	**P,in 35% (W)**	**P,in 70% (W)**	**P,full load compressor (W)**
13	29760.5777	24929.261	71924.853	81190.134	162155.98	25121.07
14	29175.8821	24439.485	70397.81	79250.426	158436.44	25121.07
15	28593.2351	23951.424	68853.415	77278.603	154569.12	25121.07
16	28009.51	43431.674	67282.926	75623.489	151279.48	25121.07
17	27422.5915	42588.029	65679.862	74132.064	148218.88	25121.07
18	26834.5791	41740.164	64049.141	72612.257	145033.5	25121.07
19	26243.3419	40884.964	62384	71057.606	141703.33	25121.07
20	25650.9948	40025.447	60689.513	69472.68	138231.08	25121.07
21	25055.3912	39158.454	58958.618	67850.696	134594.09	25121.07
22	24458.6613	38287.042	57196.551	66196.374	130794.39	25121.07
23	23858.6426	37408.01	55395.93	64502.585	126806.14	25121.07
24	23256.3959	36522.859	53558.82	62771.059	124155.99	25121.07
25	22652.9981	35633.133	51687.509	61003.739	121016.01	25121.07
26	22046.2622	34735.56	52753.898	59192.926	117734.31	25121.07
27	21438.3581	33833.305	51348.389	57343.743	114313.7	25121.07
28	20827.0825	32923.05	49915.183	55448.07	110732.02	25121.07
29	20214.6215	32007.999	48458.757	53511.202	106991.4	25121.07
30	19598.7551	31084.789	46973.157	51524.56	103066.62	25121.07
31	18981.2402	30155.998	45461.898	50033.302	100081.5	25121.07
32	18361.1767	29220.225	43922.075	48533.205	96982.679	25121.07
33	17738.7734	28277.733	42353.441	47001.698	93750.784	25121.07
34	17114.2424	27328.791	40755.76	45438.351	90378.298	25121.07
35	16486.6681	26371.951	39125.851	43839.837	86850.656	25121.07
36	15857.8456	25409.9	37467.558	42209.71	83167.764	25121.07
37	15225.4954	24439.095	35773.99	40540.961	79304.944	25121.07
38	14591.8783	23462.95	34050.292	38838.415	75991.285	25121.07
39	13954.6973	22477.872	32289.262	37094.699	72933.852	25121.07
40	13316.2306	21487.323	30496.211	35314.798	69751.838	25121.07
41	12674.1634	20487.653	28663.607	33490.947	66425.264	25121.07
42	12029.6297	19480.56	26793.534	31624.902	62950.454	25121.07
43	11383.7813	18467.792	27802.722	29718.657	59323.957	25121.07
44	10734.2763	17445.614	26397.682	27763.793	55521.644	25121.07
45	10083.4369	16417.619	24970.131	25765.723	51545.104	25121.07

Table A.1: Bin Analysis						
Tdb (F)	P,in 5% (W)	P,in 10% (W)	P,in 30% (W)	P,in 35% (W)	P,in 70% (W)	P,full load compressor (W)
56	500.664215	1027.2871	1373.136	1624.0619	3201.4328	20911.80
57	1120.60738	2293.3027	3043.8483	3592.87	6985.5109	21013.10
58	1938.42155	3953.6105	5200.7311	6123.3245	11704.24	21249.22
59	3750.48801	7596.3439	9812.1722	11494.74	21256.427	22045.86
60	4419.26415	8927.7856	11455.693	13395.845	25549.614	22149.82
61	6489.65499	13014.958	16395.221	19077.461	37950.164	22934.09
62	6483.70679	13000.014	16366.947	19041.651	37898.7	22699.79
63	8132.42645	16214.482	20133.548	23476.497	46950.727	23223.85
64	9676.64145	19195.207	24109.926	28639.563	56944.657	23651.20
65	11603.5786	22877.88	29587.905	34775.347	68182.604	24177.46
66	12373.5294	24333.438	31722.594	37144.454	72316.769	24267.25
67	15089.8703	29437.181	38934.386	45134.416	89971.283	24963.66
68	15760.4941	30678.536	40652.607	47015.198	93924.704	25009.75
69	17315.6266	33551.726	44546.975	51644.684	103270.62	25301.37
70	19155.8457	36922.325	49004.075	58073.287	115588.7	25640.81
71	19782.8202	38055.431	50472.098	60216.147	119505.52	25668.28
72	21318.0496	40830.778	55522.217	65259.707	128502.02	25909.30
73	24767.9973	25464.491	65542.896	75919.084	151688.56	26513.77
74	25274.7997	25985.545	66968.905	77403.6	154763.13	26513.94
75	29234.3468	30056.438	77532.388	91316.226	181515.88	27089.34
76	29442.0716	30270.004	78055.772	92076.96	182839.26	27044.81
77	26858.7241	27614.011	71299.362	82888.41	165636.62	26527.64
78	30178.5397	31027.182	79898.618	94669.42	187335.04	27004.08
79	30790.7734	31656.632	82242.036	96755.883	191793.7	27020.46
80	31402.7389	32285.807	84278.947	98800.798	196460.98	27038.23
81	30731.9335	31596.138	82176.293	96601.125	191633.58	26854.87
82	32661.5135	33579.979	88355.046	102886.01	205417.62	27078.52
83	32436.1007	33348.227	87698.108	102172.21	203947.52	26969.94
84	34744.7541	35721.802	94759.646	109592.21	219176.07	27235.63
85	35168.0304	36156.981	96035.338	111342.55	222606.59	27226.36
86	35361.7117	36356.109	96624.764	112174.88	224202.52	27185.54
87	32941.033	33867.359	89431.943	103765.2	207420.83	26733.33
88	36666.4567	37697.544	100414.96	117272.87	233764.67	27232.05
89	34446.6518	35415.317	94011.974	108872.34	217708.11	26823.92
90	35730.3409	36735.104	97769.351	113890.04	227347.4	26952.61
91	35593.4679	36594.382	97393.385	113447.53	226468.32	26855.66
92	38303.3092	39380.426	104992.23	123413.63	244556.21	27193.50
93	40076.9601	41203.953	110561.5	129590.62	258529.66	27366.84
94	42716.438	43917.655	119491.9	138454.67	276906.06	27621.61
95	42936.0069	44143.399	120250.18	139462.25	278892	27594.21

TRACE 700 Simulation

Existing System - Equipment Energy Consumption

EQUIPMENT ENERGY CONSUMPTION
By ACADEMIC

Alternative: 2 Proposed Design

Equipment - Utility	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Total
					------- Monthly Consumption -------								
Lights													
Electric (kWh)	19,614.6	17,732.9	20,636.7	18,817.0	20,125.7	19,839.1	19,103.6	20,636.8	18,817.0	20,125.7	19,328.1	19,103.6	233,880.8
Peak (kW)	85.3	85.3	85.3	85.3	85.3	85.3	85.3	85.3	85.3	85.3	85.3	85.3	85.3
Misc. Ld													
Electric (kWh)	59,928.5	54,178.4	62,989.5	57,501.6	61,459.0	60,562.6	58,398.0	62,989.5	57,501.6	61,459.0	59,032.2	58,398.1	714,397.9
Peak (kW)	268.1	268.1	268.1	268.1	268.1	268.1	268.1	268.1	268.1	268.1	268.1	268.1	268.1
Cooling Coil Condensate													
Recoverable Water (1000gal)	1.4	0.3	1.4	4.8	16.1	31.0	33.3	30.3	23.6	13.6	3.4	2.5	161.6
Peak (1000gal/Hr)	0.1	0.0	0.1	0.1	0.3	0.3	0.3	0.3	0.3	0.2	0.2	0.2	0.3
Bsu 1: Domestic Hot Water Load													
Proc. Hot Water (therms)	264.6	240.2	281.8	256.0	273.2	270.8	258.4	281.8	256.0	273.2	262.2	258.4	3,176.6
Peak (therms/Hr)	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1
Cpl 1: Basement MER [Sum of dsn coil capacities=798.5 tons]													
HR chiller - 001 [Clg Nominal Capacity/F.L.Rate=100 tons / 58.70 kW] (Cooling Equipment)													
Electric (kWh)	1,388.9	1,063.4	1,599.9	2,552.5	3,943.9	5,945.8	6,588.2	6,248.4	4,831.3	3,434.2	1,765.6	1,525.8	40,888.0
Peak (kW)	11.3	6.3	10.5	13.3	22.7	27.4	31.0	25.4	26.1	21.3	15.8	14.6	31.0
GWU Cooling Tower [Design Heat Rejection/F.L.Rate=116.7 tons / 5.83 kW]													
Electric (kWh)	410.8	278.5	459.8	1,210.8	2,236.0	3,674.9	4,131.6	4,082.8	2,933.5	1,897.7	704.7	517.6	22,538.5
Peak (kW)	5.2	1.2	4.2	5.8	5.8	5.8	5.8	5.8	5.8	5.8	5.8	5.8	5.8
GWU Cooling Tower													
Make Up Water (1000gal)	8.0	5.9	9.1	15.4	25.4	38.9	42.3	40.8	30.8	22.0	10.3	8.9	257.7
Peak (1000gal/Hr)	0.1	0.0	0.1	0.1	0.2	0.2	0.2	0.2	0.2	0.2	0.1	0.1	0.2
90.1 Min VV Chilled Water pump [F.L.Rate=3.70 kW] (Misc Accessory Equipment)													
Electric (kWh)	56.6	44.7	64.5	97.0	149.5	229.7	244.9	235.5	180.7	131.7	70.2	61.9	1,566.8
Peak (kW)	0.4	0.2	0.4	0.5	1.1	1.4	1.6	1.3	1.3	1.0	0.7	0.6	1.6
Var vol cnd water pump [F.L.Rate=5.63 kW] (Misc Accessory Equipment)													
Electric (kWh)	78.7	60.8	89.6	140.4	221.9	344.7	368.5	354.0	270.2	194.3	98.8	86.7	2,308.4
Peak (kW)	0.7	0.3	0.6	0.8	1.7	2.1	2.4	2.0	2.0	1.6	1.1	0.9	2.4

Project Name: 08624-00
Dataset Name: GWU TMY3 BT5B.TRC

TRACE® 700 v6.3.2 calculated at 10:39 PM on 03/13/2017
Alternative - 2 Equipment Energy Consumption report page 3 of 8

EQUIPMENT ENERGY CONSUMPTION
By ACADEMIC

Alternative: 2   Proposed Design

Equipment - Utility	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Total
					------- Monthly Consumption -------								
Cpl 1: Basement MER [Sum of dsn coil capacities=798.5 tons]													
Water-cooled chiller - 003 [Clg Nominal Capacity/F.L.Rate=350 tons / 205.4 kW] (Cooling Equipment)													
Electric (kWh)	5,394.7	4,135.5	6,218.6	9,895.3	15,181.6	22,697.7	25,185.0	23,896.7	18,562.2	13,237.0	6,850.0	5,919.7	157,174.0
Peak (kW)	43.3	24.4	40.4	50.6	83.6	100.1	112.8	93.1	95.6	78.8	59.4	55.1	112.8
GWU Cooling Tower [Design Heat Rejection/F.L.Rate=408.4 tons / 20.42 kW]													
Electric (kWh)	1,439.4	974.7	1,610.7	4,243.3	7,833.2	12,868.2	14,463.5	14,292.6	10,274.9	6,651.1	2,468.0	1,813.2	78,932.7
Peak (kW)	18.1	4.3	14.7	20.4	20.4	20.4	20.4	20.4	20.4	20.4	20.4	20.4	20.4
GWU Cooling Tower													
Make Up Water (1000gal)	28.2	20.9	32.2	54.6	89.8	137.6	149.5	144.2	109.1	77.9	36.4	31.6	912.0
Peak (1000gal/Hr)	0.3	0.1	0.3	0.3	0.6	0.6	0.7	0.6	0.6	0.5	0.4	0.4	0.7
90.1 Min VV Chilled Water pump [F.L.Rate=13.42 kW] (Misc Accessory Equipment)													
Electric (kWh)	187.4	144.7	213.2	334.2	528.3	820.5	877.3	842.8	643.3	462.6	235.2	206.3	5,495.8
Peak (kW)	1.6	0.8	1.5	1.9	4.0	5.0	5.7	4.8	4.7	3.7	2.6	2.3	5.7
Var vol cnd water pump [F.L.Rate=19.72 kW] (Misc Accessory Equipment)													
Electric (kWh)	275.5	212.7	313.5	491.3	776.7	1,206.3	1,289.7	1,239.0	945.7	680.0	345.8	303.3	8,079.4
Peak (kW)	2.3	1.2	2.1	2.8	5.9	7.3	8.4	7.1	6.9	5.5	3.8	3.3	8.4
Water-cooled chiller - 004 [Clg Nominal Capacity/F.L.Rate=350 tons / 205.4 kW] (Cooling Equipment)													
Electric (kWh)	4,861.0	3,722.0	5,599.7	8,933.6	13,803.7	20,810.4	23,058.6	21,869.5	16,909.6	12,019.8	6,179.5	5,340.4	143,107.9
Peak (kW)	39.6	22.0	36.9	46.7	79.3	95.8	108.6	89.0	91.3	74.5	55.4	51.1	108.6
GWU Cooling Tower [Design Heat Rejection/F.L.Rate=408.4 tons / 20.42 kW]													
Electric (kWh)	1,437.7	974.7	1,609.2	4,237.7	7,826.0	12,862.3	14,460.7	14,290.0	10,267.3	6,641.9	2,466.5	1,811.5	78,885.3
Peak (kW)	18.0	4.3	14.6	20.4	20.4	20.4	20.4	20.4	20.4	20.4	20.4	20.4	20.4
GWU Cooling Tower													
Make Up Water (1000gal)	27.9	20.6	31.7	53.9	88.8	136.3	148.0	142.8	107.9	77.0	35.9	31.2	902.0
Peak (1000gal/Hr)	0.3	0.1	0.3	0.3	0.6	0.6	0.7	0.6	0.6	0.5	0.4	0.4	0.7
90.1 Min VV Chilled Water pump [F.L.Rate=20.15 kW] (Misc Accessory Equipment)													
Electric (kWh)	308.0	242.8	350.6	527.4	813.1	1,248.9	1,331.5	1,280.3	982.8	716.1	381.6	336.6	8,519.4
Peak (kW)	2.4	1.2	2.2	2.8	6.0	7.5	8.6	7.2	7.0	5.6	3.8	3.4	8.6

EQUIPMENT ENERGY CONSUMPTION
By ACADEMIC

Alternative: 2 Proposed Design

Equipment - Utility	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Total
					------- Monthly Consumption -------								
Cpl 1: Basement MER [Sum of dsn coil capacities=798.5 tons]													
Var vol cnd water pump [F.L.Rate=19.72 kW] (Misc Accessory Equipment)													
Electric (kWh)	275.5	212.7	313.5	491.3	776.7	1,206.3	1,289.7	1,239.0	945.7	680.0	345.8	303.3	8,079.4
Peak (kW)	2.3	1.2	2.1	2.8	5.9	7.3	8.4	7.1	6.9	5.5	3.8	3.3	8.4
Cpl 2: Chilled Beam HX [Sum of dsn coil capacities=94.70 tons]													
Hpl 1: Penthouse [Sum of dsn coil capacities=5,693 mbh]													
Boiler - 001 [Nominal Capacity/F.L.Rate=1,375 mbh / 15.28 Therms] (Heating Equipment)													
Gas (therms)	6,178.3	5,598.5	4,892.2	2,373.9	2,377.9	1,978.7	2,079.9	1,861.9	2,699.2	2,611.6	4,571.0	5,077.4	42,300.5
Peak (therms/Hr)	15.3	15.3	15.3	15.3	15.3	15.3	15.3	15.3	15.3	15.3	15.3	15.3	15.3
90.1 Min CV Hot Water pump [F.L.Rate=1.11 kW] (Misc Accessory Equipment)													
Electric (kWh)	828.6	748.4	828.6	801.9	828.6	801.9	828.6	828.6	801.9	828.6	801.9	828.6	9,756.5
Peak (kW)	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1
Boiler forced draft fan [F.L.Rate=1.38 kW] (Misc Accessory Equipment)													
Electric (kWh)	1,023.0	924.0	1,023.0	990.0	1,023.0	990.0	1,023.0	1,023.0	990.0	1,023.0	990.0	1,023.0	12,045.0
Peak (kW)	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4
Cntl panel & interlocks - 0.5 KW [F.L.Rate=0.50 kW] (Misc Accessory Equipment)													
Electric (kWh)	372.0	336.0	372.0	360.0	372.0	360.0	372.0	372.0	360.0	372.0	360.0	372.0	4,380.0
Peak (kW)	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Variable Volume HW circ pump [F.L.Rate=11.14 kW] (Misc Accessory Equipment)													
Electric (kWh)	614.6	561.1	477.2	234.1	267.6	233.2	229.7	235.6	327.3	297.5	471.3	513.3	4,462.5
Peak (kW)	4.7	5.1	4.9	4.5	10.9	11.1	6.6	11.1	11.1	11.0	11.1	4.2	11.1
Boiler - 002 [Nominal Capacity/F.L.Rate=1,375 mbh / 15.28 Therms] (Heating Equipment)													
Gas (therms)	140.4	137.7	94.0	95.8	169.2	178.8	149.6	186.6	241.5	192.7	164.7	129.3	1,880.3
Peak (therms/Hr)	8.4	8.9	8.6	8.7	15.3	15.3	11.9	15.3	15.3	15.3	15.3	8.4	15.3
90.1 Min CV Hot Water pump [F.L.Rate=1.11 kW] (Misc Accessory Equipment)													
Electric (kWh)	62.4	74.6	51.2	50.1	83.5	93.6	94.7	83.5	125.9	83.5	84.6	59.0	946.7
Peak (kW)	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1
Boiler forced draft fan [F.L.Rate=1.38 kW] (Misc Accessory Equipment)													
Electric (kWh)	77.0	92.1	63.3	61.9	103.1	115.5	116.9	103.1	155.4	103.1	104.5	72.9	1,168.8
Peak (kW)	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4

EQUIPMENT ENERGY CONSUMPTION

By ACADEMIC

Alternative: 2 Proposed Design

Equipment - Utility	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Total
					------- Monthly Consumption -------								
Hpl 1: Penthouse [Sum of dsn coil capacities=5,693 mbh]													
Cntl panel & interlocks - 0.5 KW [F.L.Rate=0.50 kW] (Misc Accessory Equipment)													
Electric (kWh)	28.0	33.5	23.0	22.5	37.5	42.0	42.5	37.5	56.5	37.5	38.0	26.5	425.0
Peak (kW)	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Boiler - 003 [Nominal Capacity/F.L.Rate=1,375 mbh / 15.28 Therms] (Heating Equipment)													
Gas (therms)	0.0	0.0	0.0	0.0	1.7	0.9	0.0	2.1	1.5	1.8	0.4	0.0	8.5
Peak (therms/Hr)	0.0	0.0	0.0	0.0	0.7	0.6	0.0	0.8	0.6	0.7	0.4	0.0	0.8
90.1 Min CV Hot Water pump [F.L.Rate=1.11 kW] (Misc Accessory Equipment)													
Electric (kWh)	0.0	0.0	0.0	0.0	3.3	2.2	0.0	4.5	4.5	3.3	1.1	0.0	18.9
Peak (kW)	0.0	0.0	0.0	0.0	1.1	1.1	0.0	1.1	1.1	1.1	1.1	0.0	1.1
Boiler forced draft fan [F.L.Rate=1.38 kW] (Misc Accessory Equipment)													
Electric (kWh)	0.0	0.0	0.0	0.0	4.1	2.8	0.0	5.5	5.5	4.1	1.4	0.0	23.4
Peak (kW)	0.0	0.0	0.0	0.0	1.4	1.4	0.0	1.4	1.4	1.4	1.4	0.0	1.4
Cntl panel & interlocks - 0.5 KW [F.L.Rate=0.50 kW] (Misc Accessory Equipment)													
Electric (kWh)	0.0	0.0	0.0	0.0	1.5	1.0	0.0	2.0	2.0	1.5	0.5	0.0	8.5
Peak (kW)	0.0	0.0	0.0	0.0	0.5	0.5	0.0	0.5	0.5	0.5	0.5	0.0	0.5
Sys 1: AHU-1													
AF Centrifugal var freq drv [DsnAirflow/F.L.Rate=40,059 cfm / 30.26 kW] (Main Clg Fan)													
Electric (kWh)	6,575.2	5,975.4	6,898.6	6,772.6	7,435.5	8,326.4	8,459.8	8,867.8	7,371.7	7,268.0	6,552.2	6,572.4	87,075.6
Peak (kW)	16.6	15.8	17.9	23.0	23.9	23.9	24.0	24.0	23.7	22.9	19.4	17.6	24.0
AF Centrifugal var freq drv [DsnAirflow/F.L.Rate=5,540 cfm / 2.26 kW] (Room Exhaust Fan)													
Electric (kWh)	217.0	197.3	260.7	277.2	186.5	76.2	78.4	82.6	129.7	208.5	241.3	239.8	2,195.3
Peak (kW)	0.9	0.9	1.0	1.0	1.0	0.3	0.9	0.9	1.0	1.0	0.8	0.9	1.0
AF Centrifugal var freq drv [DsnAirflow/F.L.Rate=41,957 cfm / 13.13 kW] (Main Return Fan)													
Electric (kWh)	2,604.5	2,364.5	2,704.5	2,589.7	2,955.1	3,378.3	3,427.7	3,594.1	2,966.6	2,832.5	2,543.8	2,568.2	34,529.4
Peak (kW)	6.4	6.1	6.5	8.7	9.5	9.6	9.5	9.5	9.3	8.9	7.7	6.3	9.6
Sys 2: AHU-2													
AF Centrifugal var freq drv [DsnAirflow/F.L.Rate=11,833 cfm / 8.87 kW] (Main Clg Fan)													
Electric (kWh)	2,174.0	2,015.1	2,342.3	2,380.6	2,581.2	2,672.0	2,601.0	2,799.3	2,476.2	2,515.9	2,267.9	2,270.8	29,096.2
Peak (kW)	8.4	8.9	8.8	8.9	8.9	8.9	8.9	8.9	8.9	8.9	8.9	8.9	8.9

EQUIPMENT ENERGY CONSUMPTION
By ACADEMIC

Alternative: 2 Proposed Design

Equipment - Utility	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Total
					------- Monthly Consumption -------								
Sys 2: AHU-2													
AF Centrifugal var freq drv [DsnAirflow/F.L.Rate=12,072 cfm / 3.84 kW] (Main Return Fan)													
Electric (kWh)	925.7	856.6	999.2	1,009.4	1,095.8	1,132.0	1,101.4	1,186.5	1,050.9	1,061.5	962.7	963.4	12,345.1
Peak (kW)	3.5	3.7	3.6	3.7	3.8	3.8	3.8	3.8	3.8	3.7	3.7	3.7	3.8
Sys 3: DOAS													
Total-energy wheel (OA precondition) [Stage 1 Energy Recovery]													
Energy Recovered (therms)	465.0	362.9	266.0	112.5	91.8	86.7	98.5	79.7	76.2	103.0	190.8	194.6	2,127.6
Peak (therms/Hr)	9.2	8.0	8.1	0.9	1.4	2.7	3.4	2.9	1.6	0.9	5.7	6.0	9.2
Total-energy wheel (OA precondition) [Stage 1 Parasitics]													
Electric (kWh)	168.8	154.8	189.2	175.2	154.4	92.8	65.6	68.0	140.8	166.0	181.2	179.2	1,736.0
Peak (kW)	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
Sensible wheel (parallel SA tempering) [Stage 2 Energy Recovery]													
Energy Recovered (therms)	0.0	0.0	0.0	307.8	915.4	1,031.4	1,385.4	1,003.7	845.1	746.3	88.7	47.9	6,371.6
Peak (therms/Hr)	0.0	0.0	0.0	4.9	5.5	4.9	6.1	8.2	6.8	5.1	3.4	1.7	8.2
Sensible wheel (parallel SA tempering) [Stage 2 Parasitics]													
Electric (kWh)	0.0	0.0	0.0	1.3	8.3	15.1	16.7	17.2	17.7	3.1	3.9	0.2	83.5
Peak (kW)	0.0	0.0	0.0	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.2	0.4
AF Centrifugal var freq drv [DsnAirflow/F.L.Rate=25,187 cfm / 36.90 kW] (Main Clg Fan)													
Electric (kWh)	9,225.4	7,379.9	8,634.7	8,222.6	9,810.4	10,733.8	11,375.2	11,667.0	10,590.6	9,101.6	9,379.7	7,695.7	113,816.4
Peak (kW)	31.8	31.8	31.8	35.0	35.0	35.0	35.0	35.0	35.0	35.0	33.1	33.0	35.0
AF Centrifugal var freq drv [DsnAirflow/F.L.Rate=690 cfm / 0.20 kW] (Room Exhaust Fan)													
Electric (kWh)	50.4	44.7	61.5	52.6	59.8	56.2	58.4	60.5	54.8	51.3	50.0	48.8	648.9
Peak (kW)	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
AF Centrifugal var freq drv [DsnAirflow/F.L.Rate=31,112 cfm / 23.77 kW] (Main Return Fan)													
Electric (kWh)	4,475.3	3,658.9	4,427.9	3,966.9	4,633.4	4,674.6	4,731.3	4,874.8	4,877.9	4,118.8	4,459.3	3,737.0	52,636.1
Peak (kW)	19.2	19.9	18.7	16.4	18.5	18.2	18.2	22.5	19.9	18.6	17.7	17.7	22.5
Sys 4: DOAS no Beams													
Total-energy wheel (OA precondition) [Stage 1 Energy Recovery]													
Energy Recovered (therms)	369.3	318.4	236.7	77.1	161.7	479.3	640.0	638.3	167.7	90.6	90.6	134.1	3,403.7
Peak (therms/Hr)	8.4	6.8	5.9	2.6	5.1	4.8	5.9	5.8	3.2	3.2	4.1	4.4	8.4

EQUIPMENT ENERGY CONSUMPTION
By ACADEMIC

Alternative: 2 Proposed Design

Equipment - Utility	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Total
					------- Monthly Consumption -------								
Sys 4: DOAS no Beams													
Total-energy wheel (OA precondition) [Stage 1 Parasitics]													
Electric (kWh)	75.2	66.8	62.0	69.2	80.4	195.6	220.4	205.2	140.4	78.0	58.8	47.2	1,299.2
Peak (kW)	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
AF Centrifugal var freq drv [DsnAirflow/F.L.Rate=40,794 cfm / 59.77 kW] (Main Clg Fan)													
Electric (kWh)	8,249.0	7,377.9	7,965.1	11,732.3	15,366.0	23,751.0	27,455.6	25,895.4	20,352.1	14,035.3	9,091.6	8,473.4	179,744.6
Peak (kW)	48.8	50.4	50.5	51.5	51.5	51.5	51.5	51.5	51.5	51.5	48.4	50.5	51.5
AF Centrifugal var freq drv [DsnAirflow/F.L.Rate=6,236 cfm / 1.81 kW] (Room Exhaust Fan)													
Electric (kWh)	145.1	140.6	160.9	142.4	162.9	166.4	175.1	174.2	167.3	149.0	158.7	157.3	1,899.8
Peak (kW)	0.7	0.7	0.7	0.7	0.7	0.8	0.8	0.8	0.8	0.8	0.7	0.7	0.8
AF Centrifugal var freq drv [DsnAirflow/F.L.Rate=45,605 cfm / 34.84 kW] (Main Return Fan)													
Electric (kWh)	3,896.0	3,454.2	3,705.0	5,007.6	6,530.8	10,746.5	12,344.7	11,639.7	8,785.7	5,634.7	3,887.6	3,655.6	79,288.0
Peak (kW)	20.1	18.4	20.5	23.3	26.0	26.3	25.5	26.0	25.8	23.9	23.3	19.4	26.3
Sys 5: T/D													
AF Centrifugal var freq drv [DsnAirflow/F.L.Rate=10,500 cfm / 6.05 kW] (Main Clg Fan)													
Electric (kWh)	2,825.5	2,552.0	2,818.1	2,735.6	2,821.9	2,728.2	2,829.3	2,818.2	2,735.6	2,821.9	2,731.9	2,829.3	33,247.4
Peak (kW)	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9
AF Centrifugal var freq drv [DsnAirflow/F.L.Rate=10,500 cfm / 6.05 kW] (Main Return Fan)													
Electric (kWh)	2,825.5	2,552.0	2,818.1	2,735.6	2,821.9	2,728.2	2,829.3	2,818.2	2,735.6	2,821.9	2,731.9	2,829.3	33,247.4
Peak (kW)	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9

Appendix B

Performance Data

Scroll Compressor

Ref.	Model with Voltage Variations	Compressor Combination	45°/130° 60Hz		Mechanical				Connection Size		Cap. Steps	Cap. (HP)
			Capacity (Btu/h)	EER (Btu/h)	L (in)	W (in)	H (in)	Net Wt. (lbs)	Suct. Dia. (In)	Disch. Dia. (In)		
Trios (reference drawings available)												
R-410A	ZPY309KCE-TF5/TF7/TFD/TFE	ZP103KCE + ZP103KCE + ZP103KCE	313,000	10.9	47.1	20.2	22.8	396	3.125	2.125	3	26
	ZPY360KCE-TF5/TF7/TFD/TFE	ZP120KCE + ZP120KCE + ZP120KCE	362,000	10.9	47.1	20.2	22.8	405	3.125	2.125	3	30
	ZPY411KCE-TF5/TF7/TFD/TFE	ZP137KCE + ZP137KCE + ZP137KCE	404,000	10.9	47.2	20.2	22.8	405	3.125	2.125	3	34
	ZPY462KCE-TFD	ZP154KCE + ZP154KCE + ZP154KCE	463,000	11.0	47.1	20.2	23.5	429	3.125	2.125	3	39
	ZPY462KCE-TW5/TW7/TWD/TWE	ZP154KCE + ZP154KCE + ZP154KCE	463,000	11.0	47.2	20.2	23.5	429	3.125	2.125	3	39
	ZPY546KCE-TFD	ZP182KCE + ZP182KCE + ZP182KCE	543,000	11.0	47.1	20.2	23.5	438	3.125	2.125	3	45
	ZPY546KCE-TW5/TW7/TWD/TWE	ZP182KCE + ZP182KCE + ZP182KCE	543,000	11.0	47.1	20.2	23.5	438	3.125	2.125	3	45
	ZPY708KCE-TE5/TE7/TED/TEE	ZP236KCE + ZP236KCE + ZP236KCE	707,000	11.0	59.9	22.0	28.4	990	2.625	1.625	3	59
	ZPY855KCE-TW5/TW7/TWC/TWD/TWE	ZP285KCE + ZP285KCE + ZP285KCE	827,000	11.1	61.3	25.6	29.4	1,215	3.625	2.125	3	69
	ZPY888KCE-TE5/TE7/TED/TEE	ZP296KCE + ZP296KCE + ZP296KCE	893,000	11.0	59.9	22.4	28.4	1,027	2.625	1.625	3	74
	ZPY115MCE-TW5/TW7/TWC/TWD/TWE	ZP385KCE + ZP385KCE + ZP385KCE	1,146,000	10.9	61.2	25.7	29.4	1,326	3.625	2.125	3	96
	ZPY145MCE-TED	ZP485KCE + ZP485KCE + ZP485KCE	1,425,000	10.7	62.1	25.0	30.6	1,479	3.625	2.125	3	119
R-407C	ZRY324KCE-TF5/TF7/TFD/TFE	ZR108KCE + ZR108KCE + ZR108KCE	317,000	11.4	47.1	20.2	22.8	396	3.125	2.125	3	26
	ZRY375KCE-TF5/TF7/TFD/TFE	ZR125KCE + ZR125KCE + ZR125KCE	373,000	11.4	47.1	20.2	22.8	405	3.125	2.125	3	31
	ZRY432KCE-TF5/TF7/TFD/TFE	ZR144KCE + ZR144KCE + ZR144KCE	425,000	11.4	47.1	20.2	22.8	405	3.125	2.125	3	35
	ZRY480KCE-TFD	ZR160KCE + ZR160KCE + ZR160KCE	460,000	11.0	47.1	20.2	23.5	429	3.125	2.125	3	38
	ZRY480KCE-TW5/TW7/TWD/TWE	ZR160KCE + ZR160KCE + ZR160KCE	460,000	11.0	47.1	20.2	23.5	429	3.125	2.125	3	38
	ZRY570KCE-TFD	ZR190KCE + ZR190KCE + ZR190KCE	541,000	10.8	47.1	20.2	23.5	438	3.125	2.125	3	45
	ZRY570KCE-TW5/TW7/TWD/TWE	ZR190KCE + ZR190KCE + ZR190KCE	541,000	10.8	47.1	20.2	23.5	438	3.125	2.125	3	45
	ZRY750KCE-TW5/TW7/TWC/TWD/TWE	ZR250KCE + ZR250KCE + ZR250KCE	715,000	11.0	61.5	24.7	29.5	999	3.125	2.125	3	60
	ZRY900KCE-TW5/TW7/TWC/TWD/TWE	ZR300KCE + ZR300KCE + ZR300KCE	872,000	11.2	61.2	25.8	29.4	1,293	3.625	2.125	3	73
	ZRY930KCE-TWC/TWD	ZR310KCE + ZR310KCE + ZR310KCE	884,000	10.6	61.2	25.7	29.4	1,137	3.625	2.125	3	74
	ZRY114MCE-TW5/TW7/TWC/TWD/TWE	ZR380KCE + ZR380KCE + ZR380KCE	1,119,000	11.4	61.2	25.7	29.4	1,293	3.125	2.125	3	93

Copeland Scroll compressor nomenclature

Z	P	D	4	2	K	5	E	–	T	F	D	–	1	3	0
Z scroll family series	AC, R-410A	D = Digital S = UltraTech® T = Tandem (even) U = Uneven Tandem	Nominal Capacity at Rating Condition		Capacity Multiplier K = 1,000 M = 10,000	Model Variation 4, 5, C	Oil type E = POE Oil = AK/ DA or 3MA		P = Single Phase Motor T = Three Phase Motor	F = Internal Inherent Protection W = External Protection Module E = CoreSense Module X = Internal and External Protection Combination TW* + TF* (Tandems Only) Y = Tandems/Trio TE* + TW*	**Code / 60 Hz. / 50 Hz.** D 460-3 380-420-3 5 200-230-3 200-220-3 E 575-3 — 7 380-3 — V 208-230-1 200-1* J 265-1 220-240-1 Z — 220-240-1 *only on some A/C scroll models		Bill of Material Product Variation		

ZP385KCE-TWD

HFC, R-410A, 60 Hz, 3 -Phase, 460 V
Air Conditioning

Production Status: Available for sale to all U.S. customers. Please check with your local Emerson Climate Technologies Representative for international availability.

Performance

Evaporator Temp. (°F)	45	35
Condensing Temp. (°F)	130	120
Return Gas Temp. (°F)	65	55
Liquid Temp. (°F)	115	105
Capacity (Btu/hr)	385000	343000
Power (W):	34700	30600
Current (Amps):	49.90	44.60
EER (Btu/Wh):	11.10	11.20
Mass Flow (lbs/hr):	5650	4790
Sound Data @		
Sound Power (dBA):	89 Avg	94 Max
Vibration mils(peak-peak):	3.5 Avg	5.0 Max
Record Date:	2013-01-09	

Mechanical

Displacment(in^3/Rev):	21.32
Displacment(ft^3/hr):	2590.98
Overall Length (in):	17.60
Overall Width (in):	16.80
Overall Height (in):	28.50
Mounting Length (in):	10.50
Mounting Width (in):	10.50
Mounting Height (in):	28.90 *
Suction Size (in),Type:	2 1/4 Rotalo
Discharge Size (in),Type:	1 3/4 Rotalo
Initial Oil Charge (oz):	213
Oil Recharge (oz):	203
Net Weight (lbs):	390.0
Internal Free Volume (in^3):	1931.0
Horse Power:	

*Overall compressor height on Copeland Brand Product's specified mounting grommets.

Electrical

LRA-High*(Amp):	310.0
LRA Low* (Amp):	
LRA-Half Winding (Amp):	
MCC (Amps):	85.0
Max Operating Current(Amp):	65.4
RLA, MCC/1.4;use for contactor selection (Amp):	60.7
RLA, MCC/1.56;use for breaker & wire size selection (Amp):	54.5
RPM:	3500
UL File No:	SA-2337
UL File Date:	2000-11-28

*Low and High refer to the low and high nominal voltage ranges for which the motor is approved.

Capacitors

Alternate Applications

Refrigerant	Voltage	Phase	Freq (Hz)	Application
R-410A HFC	380/420	3	50	Air Conditioning

Angie Tejada
04/08/2017

Rating Conditions
20 °F Superheat
15 F Subcooling
95 °F Ambient Air Over

60 Hz Operation

AIR CONDITIONING

ZP385KCE-TWD
HFC-410A
COPELAND SCROLL®
TWD 460-3-60

Condensing Temperature °F (Sat. Dew Pt. Pressure, psig)

Evaporating Temperature °F (Sat. Dew Pt. Pressure, psig)

Condensing Temperature °F (Sat. Dew Pt. Pressure, psig)		-10.0 (36)	0.0 (48)	10.0 (62)	20.0 (78)	30.0 (97)	40.0 (118)	50.0 (143)	60.0 (170)	68.0 (195)
150.0 (613)	C						289,000	352,000	421,000	
	P						43,100	43,700	44,400	
	A						61.4	62.0	62.8	
	M						5,040	6,043	7,151	
	E						6.7	8.1	9.5	
	%						67.9	70.9	72.0	
140.0 (541)	C					260,000	320,000	388,000	463,000	530,000
	P					38,200	38,600	39,100	39,800	40,600
	A					54.6	55.0	55.7	56.6	57.5
	M					4,217	5,114	6,109	7,214	8,183
	E					6.8	8.3	9.9	11.6	13.1
	%					67.0	70.9	72.8	72.7	71.0
125.0 (447)	C				240,000	298,000	364,000	439,000	523,000	597,000
	P				31,900	32,200	32,600	33,200	34,000	34,800
	A				46.3	46.6	47.1	47.9	48.9	49.9
	M				3,528	4,323	5,215	6,212	7,322	8,298
	E				7.5	9.3	11.2	13.2	15.4	17.2
	%				67.2	71.5	73.9	74.0	71.5	67.6
115.0 (391)	C			206,000	260,000	321,000	392,000	471,000	560,000	640,000
	P			28,200	28,500	28,800	29,200	29,900	30,700	31,600
	A			41.5	41.9	42.3	42.9	43.6	44.8	45.9
	M			2,886	3,584	4,376	5,268	6,269	7,386	8,370
	E			7.3	9.1	11.2	13.4	15.8	18.2	20.2
	%			64.9	70.0	73.3	74.4	72.8	68.4	62.7
100.0 (318)	C	140,000	181,000	229,000	287,000	353,000	430,000	516,000	614,000	700,000
	P	23,100	23,500	23,800	24,100	24,500	25,000	25,800	26,800	27,800
	A	35.3	35.7	36.1	36.5	37.0	37.6	38.6	39.8	41.2
	M	1,851	2,356	2,950	3,639	4,429	5,325	6,334	7,464	8,462
	E	6.1	7.7	9.7	11.9	14.4	17.2	20.0	22.9	25.2
	%	57.7	63.7	68.7	72.1	73.2	71.6	66.8	58.8	50.1
90.0 (274)	C	151,000	193,000	244,000	303,000	373,000	453,000	545,000	648,000	
	P	20,500	20,900	21,300	21,600	22,100	22,700	23,600	24,700	
	A	32.2	32.7	33.1	33.5	34.1	34.9	35.9	37.3	
	M	1,899	2,391	2,976	3,661	4,450	5,349	6,365	7,505	
	E	7.4	9.2	11.5	14.0	16.9	19.9	23.1	26.2	
	%	61.3	66.1	69.7	71.5	70.7	66.8	59.5	48.7	
75.0 (218)	C	167,000	210,000	263,000	326,000	401,000	487,000			
	P	17,200	17,700	18,100	18,600	19,200	20,000			
	A	28.4	28.9	29.4	29.9	30.6	31.5			
	M	1,948	2,421	2,995	3,674	4,464	5,369			
	E	9.7	11.9	14.5	17.5	20.8	24.3			
	%	65.0	67.3	68.2	66.9	62.4	54.4			
65.0 (185)	C	176,000	220,000	274,000	340,000	417,000				
	P	15,300	15,800	16,400	17,000	17,700				
	A	26.2	26.8	27.3	27.9	28.7				
	M	1,967	2,429	2,997	3,674	4,464				
	E	11.5	13.9	16.8	20.0	23.6				
	%	65.9	66.1	64.7	60.7	53.4				
50.0 (143)	C	188,000	233,000	290,000	359,000					
	P	12,800	13,500	14,200	15,000					
	A	23.2	23.9	24.5	25.3					
	M	1,983	2,430	2,989	3,662					
	E	14.6	17.3	20.4	23.9					
	%	64.4	60.6	55.0	46.4					

C: Capacity (Btu/hr), P: Power (W), A: Current (Amps), M: Mass Flow (lb/hr), E: EER (Btu/Wh), %: Isentropic Efficiency (%)

Nominal Performance Values (±5%) based on 72 hours run-in. Subject to change without notice. Current @ 460 V

Copeland brand products

Autogenerated Compressor Performance

Printed 2/9/2017

08-1179 2026

EMERSON Climate Technologies

EnergyPlus Data Set

Class List

[0007] Coil:Cooling:DX:SingleSpeed
[0005] Coil:Cooling:DX:TwoStageWithHumidityControlMode
[0010] CoilPerformance:DX:Cooling
[0012] Coil:Heating:DX:SingleSpeed
[0001] AirLoopHVAC:UnitaryHeatPump:AirToAir
[0082] Curve:Quadratic
[0014] Curve:Cubic
[0044] Curve:Biquadratic

Comments from IDF

Manufacturer = Lennox, Model Line = LH model (Heat pump -- LHA120H) (2 Stage unit)
Reference point (Cooling) = 95F (35C) OAT, 67F (19.44C) EWBT
Reference Cooling Capacity at Stage 1 = 18434.103 W
Reference Cooling Capacity at Stage 1&2 = 36340.68 W
Reference point (Heating) = 47F (8.33C) OAT, 70F (21.11C) EDBT
Reference Capacity (Heating) = 32559.84 W
Compressor Type = Scroll
Refrigerant = R-22

Explanation of Object and Current Field

Object Description: Direct expansion (DX) cooling coil and condensing unit (includes electric compressor and condenser fan), two-stage with humidity control mode (e.g. sub-cool or hot gas reheat). Optional inputs for moisture evaporation from wet coil when compressor cycles off with continuous fan operation. Requires two to four sets of performance data, see CoilPerformance:DX:Cooling. Stages are modeled as a face-split coil.

Field Description:

Field	Units	Obj1	Obj2	Obj3	Obj4	Obj5
Name		Lennox LHA120H Cooling	Lennox LHA240H Cooling	Lennox THA120S Cooling	Lennox KHA120S4 Cooling	Lennox KHA240S4 Cooling
Availability Schedule Name		CoolingCoilAvailSched	CoolingCoilAvailSched	CoolingCoilAvailSched	CoolingCoilAvailSched	CoolingCoilAvailSched
Air Inlet Node Name		DXCoilAirInletNode	DXCoilAirInletNode	DXCoilAirInletNode	DXCoilAirInletNode	DXCoilAirInletNode
Air Outlet Node Name		DXCoilAirOutletNode	DXCoilAirOutletNode	DXCoilAirOutletNode	DXCoilAirOutletNode	DXCoilAirOutletNode
Crankcase Heater Capacity	W					
Maximum Outdoor Dry-Bulb Temperature for Crankcase	C					
Number of Capacity Stages		2	2	2	2	2
Number of Enhanced Dehumidification Modes		0	0	0	0	0
Normal Mode Stage 1 Coil Performance Object Type		CoilPerformance:DX:Cooling	CoilPerformance:DX:Coolir	CoilPerformance:DX:Cooling	CoilPerformance:DX:Cooling	CoilPerformance:DX:Cooling
Normal Mode Stage 1 Coil Performance Name		Lennox LHA120H Stage 1	Lennox LHA240H Stage 1	Lennox THA120S Stage 1	Lennox KHA120S4 Stage 1	Lennox KHA240S4 Stage 1
Normal Mode Stage 1+2 Coil Performance Object Type		CoilPerformance:DX:Cooling	CoilPerformance:DX:Coolir	CoilPerformance:DX:Cooling	CoilPerformance:DX:Cooling	CoilPerformance:DX:Cooling
Normal Mode Stage 1+2 Coil Performance Name		Lennox LHA120H Stage 1&2	Lennox LHA240H Stage 1	Lennox THA120S Stage 1&2	Lennox KHA120S4 Stage 1&2	Lennox KHA240S4 Stage 1&2
Dehumidification Mode 1 Stage 1 Coil Performance Obj						
Dehumidification Mode 1 Stage 1 Coil Performance Nar						
Dehumidification Mode 1 Stage 1+2 Coil Performance C						
Dehumidification Mode 1 Stage 1+2 Coil Performance N						
Supply Water Storage Tank Name						
Condensate Collection Water Storage Tank Name						
Basin Heater Capacity	W/K					
Basin Heater Setpoint Temperature	C					
Basin Heater Operating Schedule Name						

Class List

[0007] Coil:Cooling:DX:SingleSpeed
[0005] Coil:Cooling:DX:TwoStageWithHumidityControlMode
[0010] CoilPerformance:DX:Cooling
[0012] Coil:Heating:DX:SingleSpeed
[0001] AirLoopHVAC:UnitaryHeatPump:AirToAir
[0082] Curve:Quadratic
[0014] Curve:Cubic
[0044] Curve:Biquadratic

Comments from IDF

Explanation of Object and Current Field

Object Description: Direct expansion (DX) heating coil (air-to-air heat pump) and compressor unit (includes electric compressor and outdoor fan), single-speed, with defrost controls.

Field Description:
ID: A1
Enter a alphanumeric value
This field is required.

Field	Units	Obj1	Obj2	Obj3	Obj4	Obj5	Obj6	Obj7	Obj8
Name		JCI J05XP Heating	JCI J10XP Heating	Carrier 50TFQ006 H	Carrier 50HJQ012 H	Carrier 50EZ060 He	Lennox LHA120H H	Lennox LHA240H H	Lennox THA060S2
Availability Schedule Name		HeatingCoilAvailSch	HeatingCoilAvailSch	HeatingCoilAvailSch	HeatingCoilAvailSch	HeatingCoilAvailSch	HeatingCoilAvailSch	HeatingCoilAvailSch	CoolingCoilAvailSch
Gross Rated Heating Capacity	W	16857.4	16857.4	14888.069	31476.156	17303.1085	32559.84	61977.83	16443.2
Gross Rated Heating COP	W/W	3.2	3.2	2.92	3.54	4.5	3.69	3.6	4.2
Rated Air Flow Rate	m3/s	0.944	0.944	0.944	1.888	0.944	1.888	3.54	0.944
Rated Supply Fan Power Per Volume Flow Rate	W/(m3/								
Air Inlet Node Name		DXCoilAirInletNode	DXCoilAirInletNode	DXCoilAirInletNode	DXCoilAirInletNode	DXCoilAirInletNode	DXCoilAirInletNode	DXCoilAirInletNode	DXCoilAirInletNode
Air Outlet Node Name		DXCoilAirOutletNod	DXCoilAirOutletNod	DXCoilAirOutletNod	DXCoilAirOutletNod	DXCoilAirOutletNod	DXCoilAirOutletNod	DXCoilAirOutletNod	DXCoilAirOutletNod
Heating Capacity Function of Temperature Curve Name		JCI J05XP Heating I	JCI J10XP Heating I	Carrier 50TFQ006 H	Carrier 50HJQ012 H	Carrier 50EZ060 He	Lennox LHA120H H	Lennox LHA240H H	Lennox THA060S2
Heating Capacity Function of Flow Fraction Curve Name		JCI J05XP Heating I	JCI J10XP Heating I	Carrier 50TFQ006 H	Carrier 50HJQ012 H	Carrier 50EZ060 He	Lennox LHA120H H	Lennox LHA240H H	Lennox THA060S2
Energy Input Ratio Function of Temperature Curve Nam		JCI J05XP Heating I	JCI J10XP Heating I	Carrier 50TFQ006 H	Carrier 50HJQ012 H	Carrier 50EZ060 He	Lennox LHA120H H	Lennox LHA240H H	Lennox THA060S2
Energy Input Ratio Function of Flow Fraction Curve Nan		JCI J05XP Heating I	JCI J10XP Heating I	Carrier 50TFQ006 H	Carrier 50HJQ012 H	Carrier 50EZ060 He	Lennox LHA120H H	Lennox LHA240H H	Lennox THA060S2
Part Load Fraction Correlation Curve Name		JCI J05XP Heating I	JCI J10XP Heating I	Carrier 50TFQ006 H	Carrier 50HJQ012 H	Carrier 50EZ060 He	Lennox LHA120H H	Lennox LHA240H H	Lennox THA060S2
Defrost Energy Input Ratio Function of Temperature Cur									