SHA HEADQUARTERS

707 N. Calvert St. | Baltimore, MD

Final Thesis Report

AE Senior Thesis

Spring 2011

Stephanie Kunkel | www.engr.psu.edu/ae/thesis/portfolios/2011/slk5061 | Mechanical Option

Dr. Bahnfleth | April 7, 2011

SHA HEADQUARTERS

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Project Synopsis

Owner:	Maryland State Highway Administration
AE Firm:	Johnson, Mirmiran & Thompson (JMT)
Mechanical Contractor	G.E. Tignall & Co., Inc.
Architect:	The INTEC Companies H.O. Whitcomb
Occupancy Type:	Office Building
Gross Building Area:	226,000 SF
Total Number of Stories:	8 (including 2 below grade)
Total Renovation Cost:	Approx. $4,435,500
Dates of Renovation:	9/1/2010 – 2011
Project Delivery Method:	Design-Bid-Build

Mechanical Systems

The mechanical system for 707 is comprised of:

- 2 Gas-Fired Steam Boilers
- 1 Centrifugal Chiller
- 3 Constant Volume Built-Up AHUs
- 534 Perimeter Induction Units
- 18 VAV Boxes
- 1 Chilled Water/Hot Water Indoor Unit
- 1 Chilled Water/Steam Indoor Unit

Lighting/Electrical

The original electrical distribution system consists of 13.2kV S&C switchgear, 2 medium voltage transformers, and 1 low voltage switchgear. Power and lighting distribution comes through two power bus ducts: 1 mainly for mechanical (1200A, 480Y/277V, 3-phase, 4wire) and 1 for lighting (480Y/277V).

Structural System

Foundation: Reinforced concrete slab-on-grade and CMU

Structure: One-way system of concrete columns and beams with reinforced concrete walls

Façade: Precast concrete lintels; each 8" deep panel is reinforced with both top and bottom rebar

Roofing: Inverted membrane roof with IKO 2-ply "Armourplast Classic" membrane

Architectural Features

After recent renovations to the building shell, the current architecture of the State Highway Administration Headquarters falls under the category of International Style, popular between the 1930s-1980s. The building façade is constructed of precast concrete lintels. The fenestration consists of aluminum framed glass windows and entrance doors.

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ACKNOWLEDGEMENTS

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Sincere appreciation of **family** and **friends** for putting up with all of the Thesis talk over the past year

AE Class of 2011

EXECUTIVE SUMMARY

The Maryland State Highway Administration (SHA) Headquarters is located in downtown Baltimore and occupies two office buildings, 707 and 211, which were both originally built in 1959. This report's focus is on the 707 N. Calvert Street building, a 6 story office building with two levels of parking in the Basement and Subbasement; the Basement level also includes a print shop as well as some office space. With each floor approximately 29,000 square feet, the total renovation cost is $4,435,500.

The objective of this Final Report is to analyze the proposed redesign for the 707 Building. A mechanical depth was analyzed by exploring design alternatives that apply changes that could, in some way, enhance the present system in the 707 Building. The intent of renovating the 707 Building was to improve system reliability, energy efficiency, and occupant safety and comfort. The options for renovation were compared using the following criteria: disturbance to Operations (during construction), maintenance requirements of the proposed system, simplicity of the system control strategy, robustness (system resistance to failure – may be in conflict with maintainability). Prior to the Thesis Proposal in the fall, studies of the available chilled beams were completed; active chilled beams were determined to be the best replacement of the current 534 perimeter induction units – since they themselves are modern induction units. Interchanging the active chilled beams in the office space will lead to lower energy consumption, improved comfort, no regular maintenance, and an increase in building usable square footage. A two-pipe to four-pipe water distribution system study was performed to enhance overall occupancy comfort. Although there will most definitely be an increase in cost from doubling the amount of pipework, the flexibility is undeniable.

Two breadth topics were also evaluated based on the implementation of this redesign. An electrical breadth will examine the benefits of the decrease in energy used by the chilled beams in the office space. The other breadth, construction management, will evaluate the potential cost, including life-cycle cost, and schedule savings of the active chilled beam systems. Although the initial cost of the proposed system surpasses the original renovation cost, a payback period of 12 years was determined for the installation of these new systems.

BUILDING OVERVIEW

The Maryland State Highway Administration (SHA) Headquarters is located in downtown Baltimore and occupies two office buildings, 707 and 211, which were both originally built in 1959. A connector between both buildings was built across Hunter Street in 2000, as seen below in Figure 1.

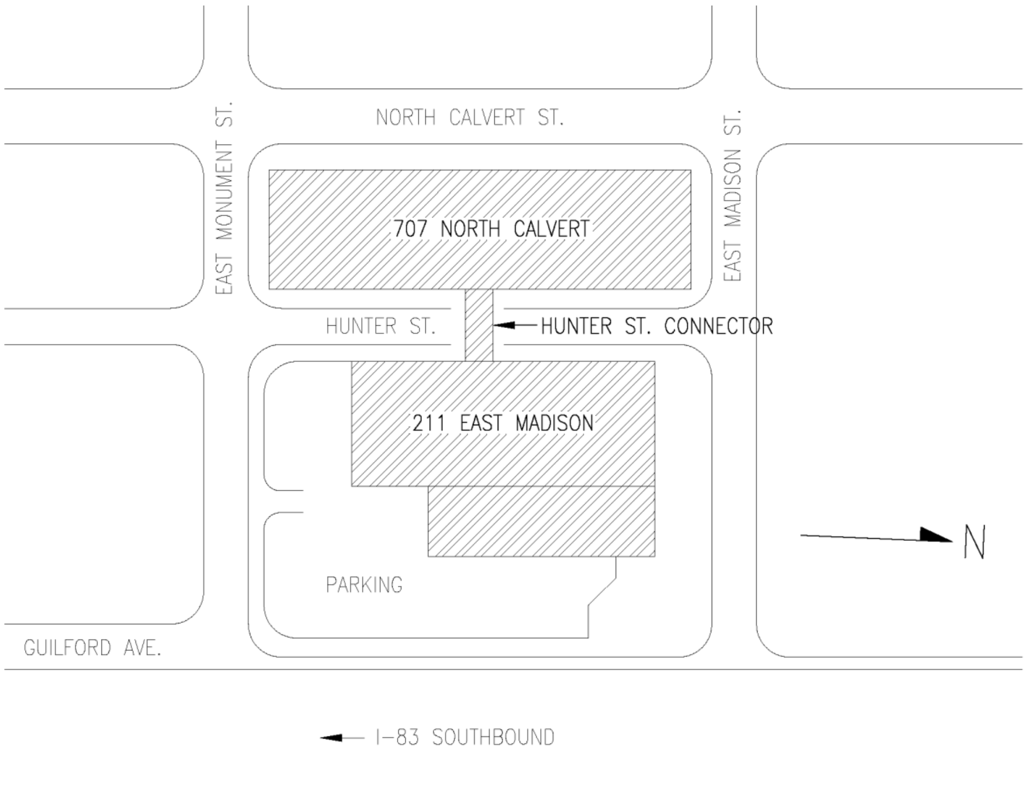


Figure 1: Site Layout

This report's focus is on the 707 N. Calvert Street building which has recently undergone significant renovations including building façade renovation, glazing replacement, roofing replacement, chiller/cooling tower replacement, branch electrical panel replacement, and air distribution ductwork (horizontal) replacement. The 707 building is a 6 story office building with two levels of parking in the Basement and Subbasement; the Basement level also includes a print shop and some office space. Each floor is approximately 29,000 square feet.

Construction

The 707 Building design-bid-build $4.5 million systems renovation is led by AE firm JMT, with Mechanical Contractor G.E. Tignall & Co. This renovation will take place in multiple phases due to the occupancy limitations – only 20 occupants can be relocated at a time.

Electrical

The original electrical distribution system in the 707 Building consists of 13.2kV S&C switchgear, two medium voltage transformers, and low voltage switchgear. Power and lighting distribution comes through two power bus ducts. One of the bus ducts runs from main switchgear located in subbasement electrical room to the penthouse level. This bus duct is labeled "Power" and feeds the penthouse panel "PA" (1200A, 480Y/277V, 3-phase, 4wire). For the most part, this panel feeds the mechanical equipment in the penthouse area. The second bus duct labeled "Lighting" runs from the main switchgear and feeds floor distribution panel boards (480Y/277V) located in the electrical room of each floor.

Lighting

The primary lighting for the 707 Building consists of 2X4 fluorescent and compact fluorescent light fixtures. Each floor is controlled separately by the lighting control system located in the first floor lobby. This system functions with a low voltage, momentary push-button control station for central lighting control. Toggle switches operate the lighting for the offices, while the central lighting control system is used for the open office spaces and corridors. Each floor's emergency light fixtures are attached to an unswitched lighting circuit so that night security lighting can be supplied.

Structural

The SHA Headquarters 707 Building is a reinforced concrete structure. The building is supported by concrete columns and the floor consists of a one-way joist and beam system. The joists are 30" pan joists and are generally 14" deep with a 3 ¼" thick slab, and typically span between 18' and 27'. The beams are 17 ¼" thick to be consistent with the depth of the slab and pan joists, and range from 13" to 31" wide. At many areas throughout the building, the beams are wider at the columns to account for the large negative bending moment at those points. The roof structure also consists of a one way 30" pan joist system, although the slab is only 3" thick.

Fire Protection

"Simplex 4020" is the current fire protection analog-addressable system for 707. This system has emergency battery backup and is comprised of central fire alarm control panels (FACPs), digital alarm transmitter, automatic detection mechanisms, manual reporting stations, and audible and visual strobe notification devices. Interconnected to the main FACP are individual FACPs for both the CADD room (on the 2nd floor) and the Computer room (on the 6th floor). Each room is outfitted with an under floor and ceiling mounted smoke detectors system as well as double interlocked, pre-action sprinkler systems that are valved separately from the sprinkler system for the rest of the building.

Telecommunications

The main service entrance telecommunication room is located on the Basement level. Backbone cables are used to connect service entrance protectors to the main distribution frame (MDF) on the 1st floor - the main telephone hub for 707. Located inside the MDF is the building PBX, horizontal backbone voice terminations, and a battery back-up system. The Computer Room on the 6th floor of 707 is the building data hub. The equipment is connected to floor data distribution racks on each floor by backbone fiber optic cables. 707's voice distribution is achieved by backbone cables beginning at the MDF and terminating in wall mounted punch down blocks on each floor's North and South IT rooms.

EXISTING MECHANICAL SYSTEM SUMMARY

The 707 building's mechanical system is comprised of two low pressure central station air handling units (AHUs) serving the central core of the building and one high pressure central station AHU serving the central core of the building. Cooling is provided by a chilled water plant, utilizing a centrifugal chiller and an updraft cooling tower, while heating is provided by two low pressure steam boilers and a steam-to-hot water heat exchanger. Overall, the components of the system include 3 constant volume built-up AHUs, 534 perimeter induction units with no operating fans on the 6 office levels, 18 VAV boxes that serve individual areas, a chilled water/hot water indoor unit, and a chilled water/steam indoor unit. An expansive description about the mechanical system design can be found in the following sections.

Planned Design Objectives, Requirements & Influences

The intent of renovating the 707 Building is to improve system reliability, energy efficiency and occupant safety and comfort. The options for renovation were compared using the following criteria: disturbance to Operations (during construction), maintenance requirements of the proposed system, simplicity of the system control strategy, robustness (system resistance to failure – may be in conflict with maintainability). The winning bid for the following renovation plans totaled at $4,435,500, or about $18.90/sf.

Many options were considered for the HVAC renovation of the 707 Building. The current plan is to have nine total phases that will be performed so that work can be completed while maintaining building operations. Due to limited relocation space, a maximum of 20 people can be removed from their areas at a time during the renovation. The contractor will be responsible for submitting a phasing plan and coordinated schedule which will achieve this goal.

To prevent system failure and improve the current levels of building comfort, system reliability and operating efficiency, much of the outdated and dilapidated mechanical system will be replaced. This option is intended to improve comfort to occupants and system efficiency, and lessen maintenance costs as the equipment will be new.

Since much of the equipment at the 707 Building has exceeded its expected service life, it will be replaced to maintain reliable building operation. The following equipment should be replaced with similar equipment: AHU's, the original boiler and pumps. The new AHU's will be equipped with supply fan and return fan VFD's; adding return fans and VFD's will allow proper control of building pressurization and ventilation. The induction unit secondary water system will be modified to only provide reheat water. Also, the existing building automation system will be replaced. Once there are supply fan VFD's and a new controls system, zone dampers can be added for each half of a floor.

The current option for the perimeter spaces' replacement is for the 534 induction units to be replaced, in kind. This requires installation of new floor mounted induction units, cleaning the vertical ducts, adding new branch ducts from the existing verticals, and all new dual temp piping, control valves, and thermostats and tie into BAS. Advantages of this option include limited building operation disturbance, little architectural work needed, and increased system efficiency. The main disadvantage is that this option does not provide any increase in usable floor area. Other impacts of these interior improvements are the cause of the occupant relocation (2 weeks per floor), and system outages of approximately 1 week during equipment replacement.

Outdoor and Indoor Design Conditions

The weather data was taken from the 2009 ASHRAE Handbook of Fundamentals (HOF), and they represent the 0.4% and 99.6% values, respectively. Below, Table 1 shows these values used in the building analysis. Actual weather conditions that were used in TRACE are displayed in the TRACE schedules in Appendix C. The entire Baltimore, MD weather data from ASHRAE 2009 HOF can also be found in Appendix C.

Table 1: ASHRAE Weather Data – Baltimore, MD

ASHRAE Values	Summer Design Cooling (0.4%)	Winter Design Heating (99.6%)
OA Dry Bulb (°F)	93.9	12.9
OA Wet Bulb (°F)	78.1	-

Indoor design conditions, in Table 2 below, were assessed from ASHRAE 90.1. Other indoor design inputs such as "Typical Office Airflows" and "Typical Office Internal Loads" can be seen in Appendix A.

Table 2: Indoor Design Conditions

Thermostat Settings	
Cooling DB	5°F
Cooling Setback	0°F
Heating DB	0°F
Heating Setback	5°F
Relative Humidity	0%

Heating Water System

The heating system consists of two steam boilers which feed steam heating coils in the built-up air handler that serves the perimeter, a steam coil in a basement H&V unit, a steam unit heater in the penthouse, and two heat exchangers. One heat exchanger serves a heating water loop which serves a basement H&V and basement fan coil units; the other heat exchanger serves a secondary water loop which serves the perimeter induction units on the main office floors. The heating water system will be reconfigured to provide pumping redundancy and flow to all equipment.

The 707 basement is served solely by two H&V units, labeled AHU-4&5, and 8 fan coil units (FCU's). One H&V provides ventilation to the zones conditioned by FCU's. Both H&V units were at one point retrofitted with chilled water coils on their discharge. One H&V has a steam coil, while the other has a hot water coil. The Heating Water Schematics can be seen in Appendix B. All of the mechanical systems discussed can be seen in Appendix D.

Chilled Water System

The chilled water system consists of a chiller and cooling tower from 1997, served by redundant condenser and chilled water pumps. One of each set of pumps is original to the building and one pump was installed in 1997. There are three original, built-up air handlers in the penthouse: unit S1 serves the perimeter of floors 1 through 6; unit S2 serves the south interior area of floors 1 through 6; and unit S3 serves the north interior area of floors 1 through 6. All three of these AHU's, as well as the steam and chilled water coils will be replaced during the renovation. The Cooling Water Schematics can be seen in Appendix B. All of the mechanical systems discussed can be seen in Appendix D.

Design Ventilation Requirements

The 707 building meets, and in some cases, exceeds the minimum ventilation requirements based upon Section 6. When determining the population density, the conference rooms were left empty so that the block load would be more accurate. The occupied floors had a combined occupancy of 1,099 people, which considerably surpasses both the current (833) and projected (930) number of occupants, even with the empty conference rooms. As shown in Table 3, AHU-S1 is low on OA, which is reasonable because the minimum OA damper and pre-heat coil are boarded-up. Airflow of the 707 Building airflow was assessed by Whitman Requardt and Associates, LLP. Assuming a design Supply Air Temperature of 55 F (Increased to 57 by time entering space) for the AHU's and H&V's, the following was determined:

Table 3: Design Ventilation Measured vs TRACE Calculated (Courtesy of JMT)

Unit	Measured		TRACE Calculated		
	Total CFM	OA CFM	Total CFM	OA CFM	Tons
AHU-S1	24189	2559	89904	8520	162.8
AHU-S2	35111	9175	23001	6380	70.5
AHU-S3	42033	7884	24341	7080	76
H&V-1	2763	151	8159	280	11.9
H&V-2	8534	2962	7288	960	15.3
TOTAL	**112630**	**22731**	**152693**	**23220**	

Although there was a larger people load in the calculations, the total building block cooling load was less than 320 tons, meaning the 450 nominal ton existing chiller is sufficient. The initial AHU configuration remains - all 6 office floors are served by 3 built-up AHUs in the penthouse. One unit (AHU-S1) provides high pressure air to the perimeter induction units on the office levels and is a constant volume unit with preheat, cooling and reheat coils. The remaining units (AHU-S2 & S3) serve the north and south halves of the building respectively and are constant volume, cooling-only units that provide supply air to the core of all of the office floors. Calculations showed that Outdoor Air quantities for the internal AHU's (S2&S3) were also appropriate.

There are two Heating and Ventilating Units (H&V-1 and 2) serving parts of the building, and are the only means of ventilating the spaces they serve. H&V-1 supplies the print shop and has a hot water heating coil. The DX unit in the Print Shop (served by H&V-1) reduces the actual building block cooling load; however, H&V-1 is low on ventilation air. H&V-2 serves Archeology and the Basement lobby and has a steam heating coil. H&V-1&2 appear to be low on CFM because there is Unitary DX cooling equipment in the space served by H&V-1 and FCU's in the spaces served by H&V-2; therefore, H&V-1&2 do not see the full load of the spaces they serve. Figure 2 below shows the layout of the AHU's S-1,2&3 and H&V-1&2.

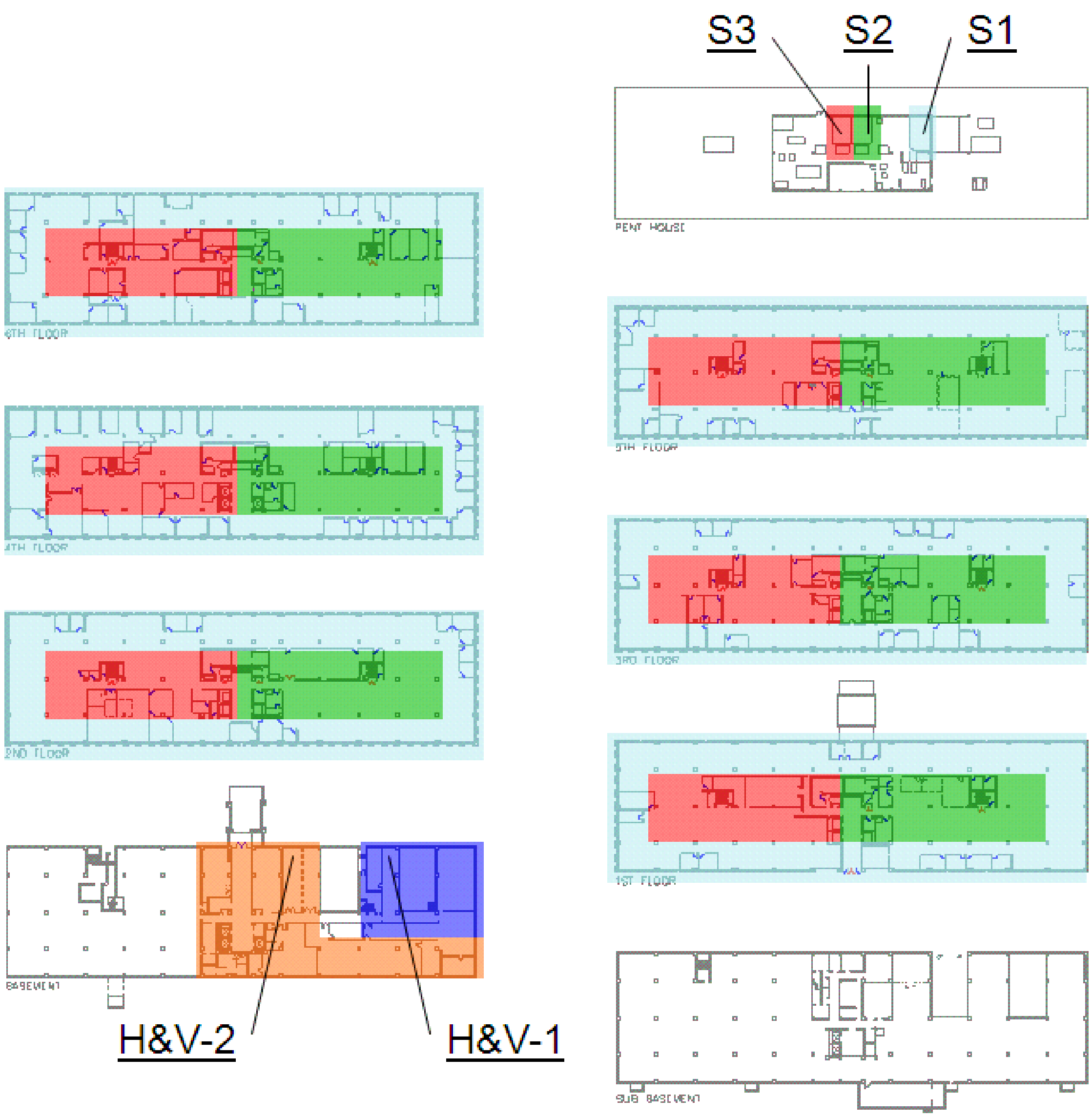


Figure 2: 707 Air Distribution System (Courtesy of JMT)

Existing System Design Load Estimation

Trane TRACE 700 Version 6.2 was used to simulate the design load energy consumption of the Maryland State Highway Administration (SHA) 707 Building. Operator experience and previously performed analyses were determinants for using TRACE for this energy study. A yearlong energy evaluation was executed to find the peak design heating and cooling loads of the system. A schematic of the system is located in Appendix B.

Block Load Elements

There are multiple advantages for a block load analysis to be performed, including model calculation time reduction, manageable model file sizes, and accurate results. The inputs, such as room areas, equipment characteristics, and building construction materials, were taken from the building design specifications and drawings; additional information was provided by the design engineer. The load calculation was performed by splitting each floor into 8 zones; Interior South, Interior North, North, North East, North West, South, South East, and South West.

Load Sources and Modeling Information

Occupants, ventilation, infiltration, artificial lights, electrical and mechanical equipment, ambient conduction/convection and direct solar gain are the core load sources for the 707 building model. TRACE data templates are located in Appendix A.

Design Occupancy and Ventilation

As design occupancy was provided for each space in the 707 building, the ASHRAE recommended occupancies were not utilized. The low-rise office schedule in TRACE was used to determine the fraction of cooling needed during the weekdays; Table 4 depicts these times and percentages. TRACE produced all ventilation rates used in the energy analysis in accordance with ASHRAE Standard 62.1 - 2007.

Table 4: Weekday Cooling Design for People Loads

Start Time	End Time	Percentage
Midnight	7 a.m.	0
7 a.m.	8 a.m.	30
8 a.m.	11 a.m.	100
11 a.m.	Noon	80
Noon	1 p.m.	40
1 p.m.	2 p.m.	80
2 p.m.	5 p.m.	100
5 p.m.	6 p.m.	30
6 p.m.	9 p.m.	10
9 p.m.	Midnight	5

Electrical Loads

Since it is required to "use lights and equipment electrical loads on a W/sf basis," the typical office space heat gain from recessed fluorescent, non-vented 80% load to space lighting was calculated to be 1.45 W/ft^2 by the design engineer. The lighting schedule of a low-rise office building was selected in TRACE; the weekday schedule timings and percentages can be seen in Table 5 below. The miscellaneous loads were 1 W/ft^2 to account for medium sized computer loads in the open office space.

Table 5: Weekday Cooling Design for Lighting Loads

Start Time	End Time	Percentage
Midnight	7 a.m.	5
7 a.m.	8 a.m.	80
8 a.m.	10 a.m.	90
10 a.m.	Noon	95
Noon	2 p.m.	80
2 p.m.	4 p.m.	90
4 p.m.	5 p.m.	95
5 p.m.	6 p.m.	80
6 p.m.	7 p.m.	70
7 p.m.	8 p.m.	60
8 p.m.	9 p.m.	40
9 p.m.	10 p.m.	30
10 p.m.	Midnight	20

Weather Information

The weather data was taken from the 2009 ASHRAE Handbook of Fundamentals (HOF), and they represent the 0.4% and 99.6% values, respectively. Below, Table 6 shows these values used in the building analysis. Actual weather conditions that were used in TRACE are displayed in the TRACE schedules in Appendix C. The entire Baltimore, MD weather data from ASHRAE 2009 HOF can also be found in Appendix C.

Table 6: ASHRAE Weather Data – Baltimore, MD

ASHRAE Values	Summer Design Cooling (0.4%)	Winter Design Heating (99.6%)
OA Dry Bulb (°F)	93.9	12.9
OA Wet Bulb (°F)	78.1	-

System Load Analysis Results

Below, Table 7 indicates cooling, heating, supply, and ventilation rates for the TRACE block load compared to the original loads calculated by the design engineer. The block load values are greater than those of the original calculations; this is most likely due to the simplified load estimations and assumptions of the block load. Specific information for every single room/space must be known and analyzed exactly to obtain the most accurate cooling and heating loads for 707. Nonetheless, even with the simplifications that were made for the block load, the findings show a plausible portrayal of the loads that the design engineer calculated.

Table 7: Block Loads vs. Original Loads and Ventilation

	Cooling (ft^2/ton)	Heating (Btu/h*ft^2)	Supply Air (cfm/ft^2)	Ventilation Air (cfm/ft^2)
707 Block Load	405.4	27.9	0.85	0.15
707 Original	535.2	21.6	0.37	0.14

Existing System Energy Consumption & Operating Costs

A year-long energy simulation was composed by the TRACE model that was used to find the building design cooling and heating loads. Cooling is provided by a chilled water plant operated by electricity, while heating is provided by two low pressure steam boilers and a steam-to-hot water heat exchanger.

System Energy Classification

According to the energy analysis results, the 707 building consumes 1,743,765 kWh of energy annually. The breakdown of this energy consumption is shown in both Table 8 and Figure 3 below. Typical for an office building in this region, space heating and lighting are large energy consumers. Since there are no fans within any of the 534 induction units for the cooling system, the amount of energy expended is reduced when compared to a standard office building.

Table 8: Energy Consumption Breakdown

	Energy (kBtu/yr)	Total Energy (%)
Lighting	2951.2	35
Space Heating	2533.5	30
Receptacles	1986.7	24
Space Cooling	566.2	7
Heat Rejection	310.4	4

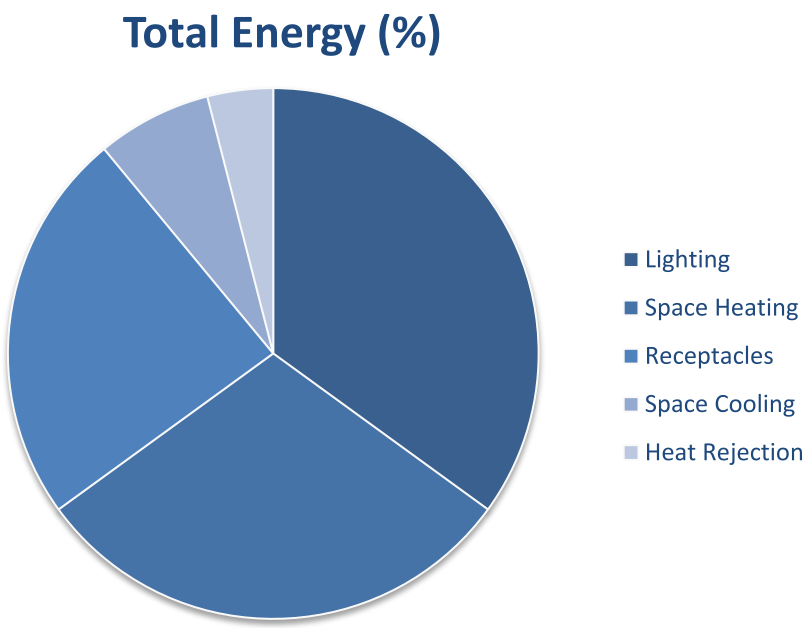


Figure 3: Energy Consumption Pie Chart

A monthly breakdown of the electrical and natural gas energy consumption can be seen in Figures 4 and 5, respectively. Typically, winter months and peak summer months consume the most energy, since the building is most heavily heated and cooled during those times. Since the heating system runs on natural gas and not electricity, Figure 4 shows the greatest electrical energy use during the summer months when the maximum AHU use occurs. Similarly, Figure 5 displays peaks in energy of the natural gas usage in the winter months.

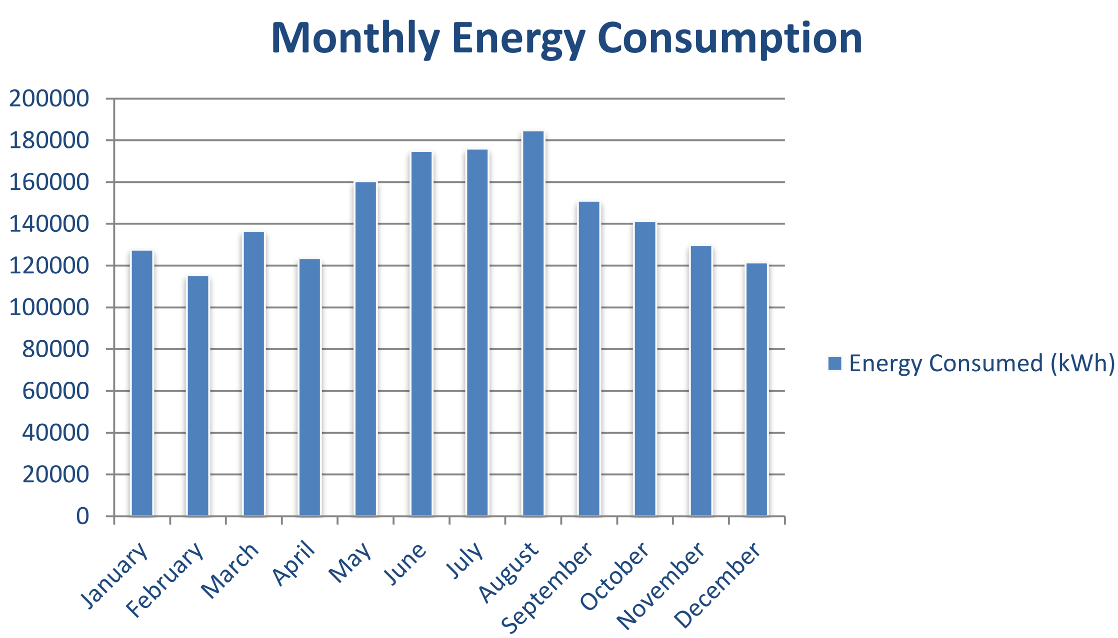


Figure 4: Monthly Electrical Energy Consumption Chart

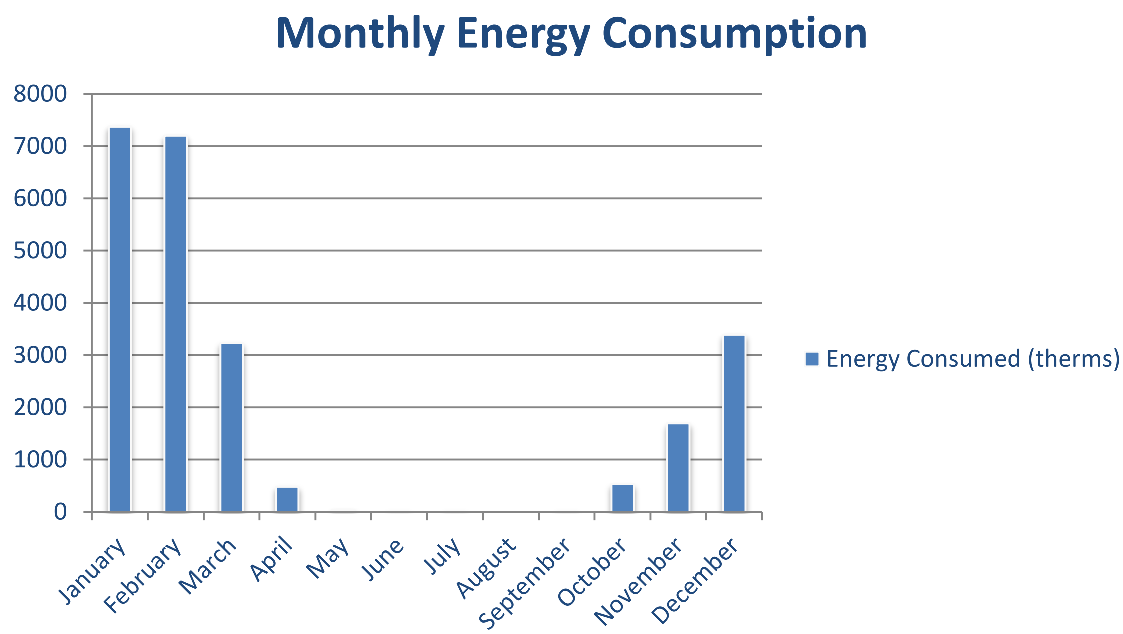


Figure 5: Monthly Natural Gas Energy Consumption Chart

Building Energy Cost Analysis

Knowing the monthly energy usages, an annual building operating cost analysis can be performed. Tables 9 and 10 display the utility rates for both electricity and natural gas, respectively, from the Baltimore Gas and Electric Company (BGE) website. These values were manually inserted into TRACE in the form of utility schedules, seen in Table 11, so that the energy consumption could be calculated in a yearlong energy simulation. Table 11 below shows the schedule of BGE Off-Peak, Mid-Peak, and Peak rates.

Table 9: BGE Electric Rates

	Demand Charge ($/kW)	Peak ($/kWh)	Mid-Peak (cents/kWh)	Off-Peak (cents/kWh)
Electricity	3.95	0.1155	0.0927	0.0882

Table 10: BGE Natural Gas Rates

	Up to first 10,000 therms ($/therm)	Above 10,000 therms ($/therm)
Natural Gas	0.198	0.095

Table 11: Schedule of BGE Rates

Start Time	End Time	Rate
11 p.m.	7 a.m.	Off-Peak
7 a.m.	10 a.m.	Mid-Peak
10 a.m.	8 p.m.	Peak
8 p.m.	11 p.m.	Mid-Peak

The total annual utility cost that was totaled for the consumed electricity and natural gas is $200,808 or 1.17 $/sf. TRACE's monthly breakdown of this analysis is shown in Figure 6. As displayed below, the highest monthly cost occurred in August. The reasoning for the drastic cost differentiations between the winter and summer months is most likely due to the low natural gas rate.

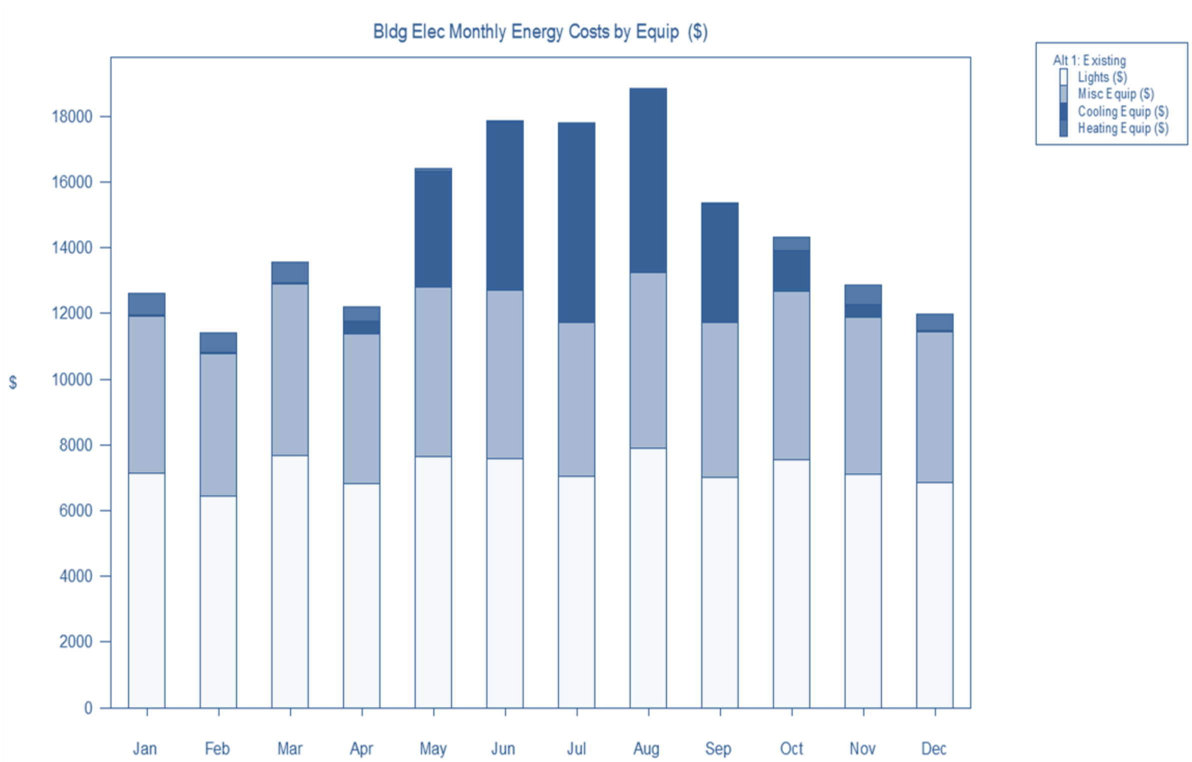


Figure 6: Monthly Building Electricity Costs by Equipment Chart

Building Energy and Cost Analysis Results

The generated block load energy model for the 707 building calculated the total annual energy consumption for cooling and heating loads to be 44.305 MBtu/year. The total load calculated by the design engineer was 42.232 MBtu/year, which indicates that the load energy consumptions are within 4.9% of each other. No energy cost analysis was run by the design engineer, therefore results could not be compared.

An estimated operating cost was determined by using individual utility consumptions. The total annual utility cost that was totaled for the consumed electricity and natural gas is $200,808 or 1.17 $/sf. The final operating cost per square foot will provide a unit of measurement that can be used to compare the building's energy performance to the redesign.

OVERALL SYSTEM EVALUATION

Evaluations of the existing and renovated design systems in the areas of construction cost, maintainability, and operating cost were made. With each floor approximately 29,000 square feet, the total renovation cost is $4,435,500.

The 707 building meets, and in some cases, exceeds the minimum ventilation requirements based upon Section 6. When determining the population density, the conference rooms were left empty so that the block load would be more accurate. The 707 building was mostly compatible with Standard 90.1 – 2007. The non-compliant fields only make up a fraction of the total building system. ASHRAE Standards 62.1 and 90.1 are necessary items to improve upon when striving towards an energy efficient, healthy building. Overall, 707 should be evaluated as adequate, but definitely needs enhancement, in both Standards. Consistent with these Standards, through more renovations and efficient equipment choices, the 707 building could advance its current condition to one that features commendable indoor air quality and energy efficiency.

According to the energy analysis results from Technical Report II, the 707 building consumes 1,743,765 kWh of energy annually. Knowing the monthly energy usages, an annual building operating cost analysis was performed in Technical Report II. Utility rates for both electricity and natural gas, from the Baltimore Gas and Electric Company (BGE) website were manually inserted into TRACE in the form of utility schedules, so that the energy consumption could be calculated in a yearlong energy simulation. The total annual utility cost that was totaled for the consumed electricity and natural gas is $200,808 or 1.17 $/sf.

Areas of improvement may produce hefty savings in energy and renovation costs. From increasing building usable square footage, to quickening the construction schedule, there are many opportunities for improvement of this 51 year-old building. These, and more, design modifications were studied as part of the proposed alternatives.

RESEARCH INTRODUCTION

The objective of Thesis Research is to explore design alternatives, ultimately applying changes that would, in some way, enhance the present system in the 707 Building. The intent of renovating the 707 Building is to improve system reliability, energy efficiency, and occupant safety and comfort. The options for renovation were compared using the following criteria: disturbance to Operations (during construction), maintenance requirements of the proposed system, simplicity of the system control strategy, robustness (system resistance to failure – may be in conflict with maintainability). Prior to the Thesis Proposal in the fall, studies of the available chilled beams were completed; active chilled beams were determined to be the best replacement of the current 534 perimeter induction units – since they themselves are modern induction units. Interchanging the active chilled beams in the office space will lead to lower energy consumption, improved comfort, no regular maintenance, and an increase in building usable square footage. A two-pipe to four-pipe water distribution system study was performed to enhance overall occupancy comfort. Although there will most definitely be an increase in cost from doubling the amount of pipework, the flexibility is undeniable.

Two breadth topics were also evaluated based on the implementation of this redesign. An electrical breadth will examine the benefits of the decrease in energy used by the chilled beams in the office space. The other breadth, construction management, will evaluate the potential cost, including life-cycle cost, and schedule savings of the active chilled beam systems.

TWO-PIPE TO FOUR-PIPE SYSTEM – MECHANICAL DEPTH

Objective

The main objective of this portion of the 707 Building system redesign was to improve overall occupancy comfort by additional flexibility in temperature control.

Background

There are two types of water distribution systems which serve the climate control equipment in a building – the two-pipe and four-pipe. Figure 7 shows the 707's current system – a two-pipe system which includes only one supply line and one return line to the unit so that only heating or only cooling is performed at any given time. This system is much less flexible than a four-pipe system.

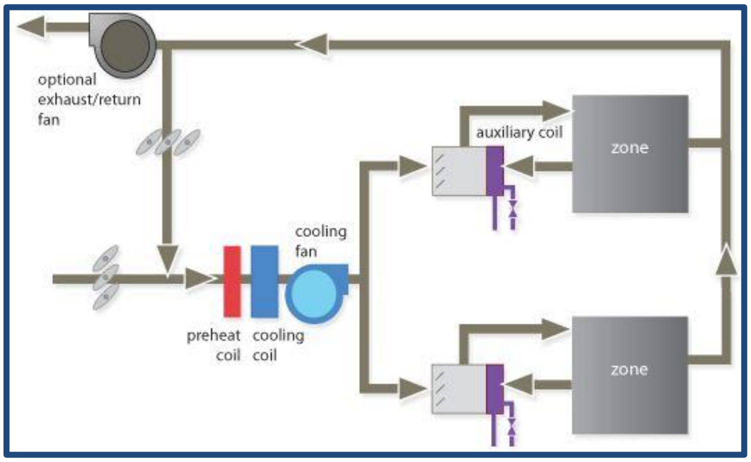


Figure 7: 2-pipe Configuration

A four-pipe system is a water distribution system that contains both hot and chilled water supplies with respective return lines (seen in the figure below). This system is able to supply cooling to one room or zone while heating another. Therefore, the four-pipe system could be well utilized in 707 especially with certain perimeter zones being warmer than others due to solar heat through the fenestration.

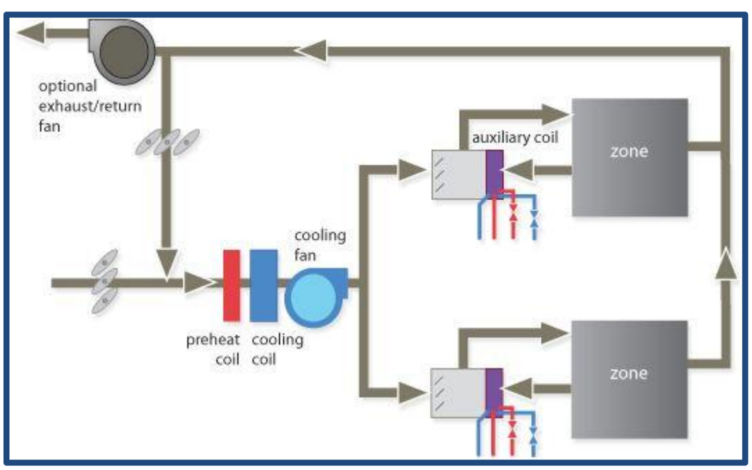


Figure 8: 4-pipe Configuration

Existing Piping Analysis

The planned renovated piping layout – for both heating and chilled systems – was fundamental to analyze. The existing 2-pipe system includes 15 vertical runs along the perimeter of the building serving the induction units. A portion of the induction unit air and water schematic can be seen in the figure below.

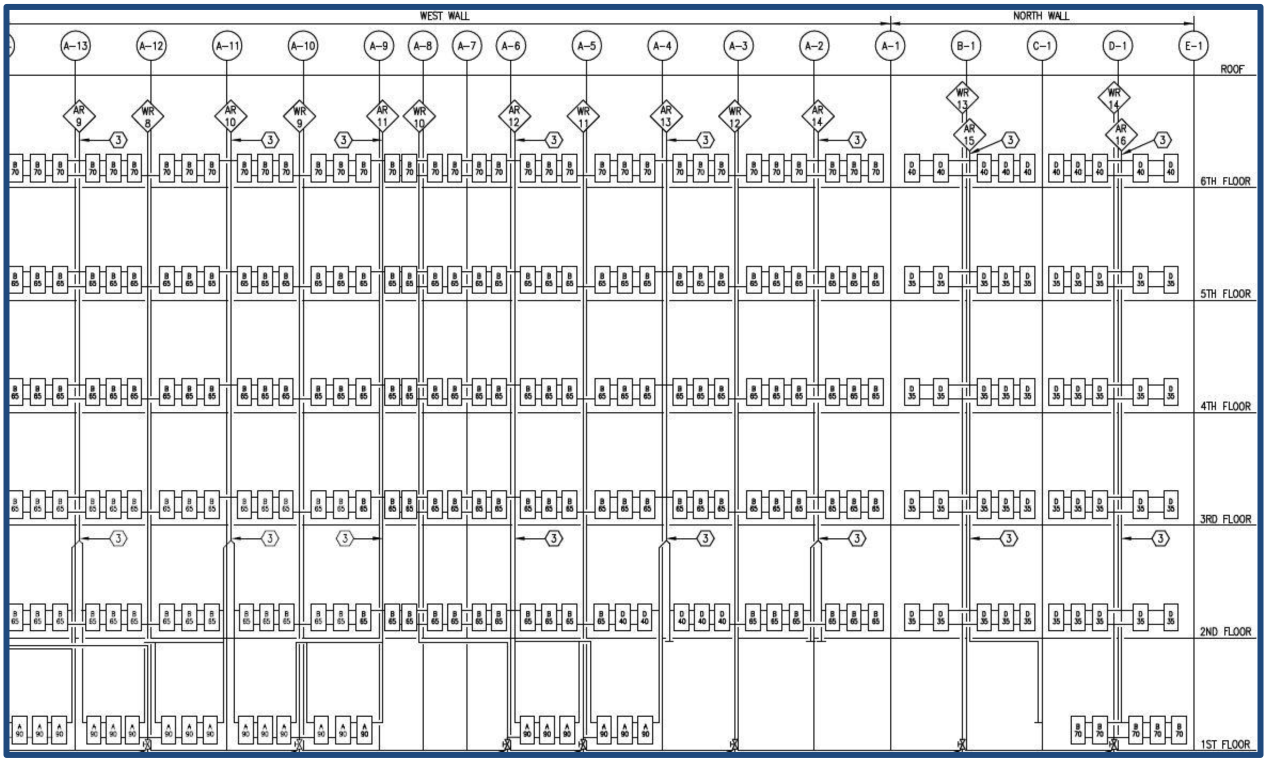


Figure 9: Induction Unit Air and Water Schematic (JMT)

As part of the planned renovation, a single 5,000MBH water-tube boiler will be replacing the existing two steam boilers. According to the TRACE calculations (more details in the Active Chilled Beam section), the heating load for the entire hot water system will be sufficient enough to supply the new chilled beam units, and therefore will not need to be resized.

Consistent with the Owner Project Requirements, all piping must be copper for 2-inches and smaller; the proposed hot water pipes that will be installed in parallel with the existing 2-pipe system will be 1 ½ -inches. The new ACB's contain 4-pipe connections and separate heating and cooling coils inside of each unit (Figure 10), therefore further conversion from 2-pipe to 4-pipe within the equipment is unnecessary.

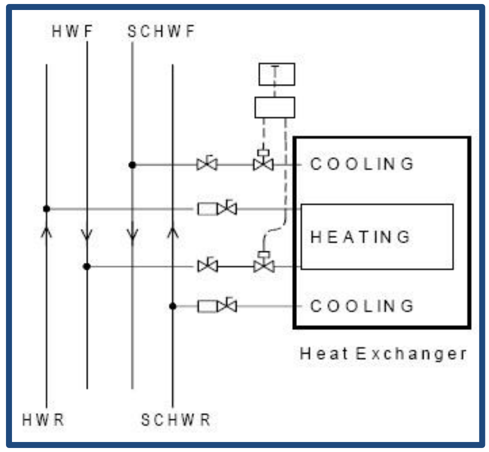


Figure 10: 4-pipe Connection to Chilled Beam

A schematic of the existing piping layout (Figure 11) shows how the pipes are routed from the main equipment in the penthouse down through the building. The three circles on the 6th floor are where the secondary water is then delivered to the induction units.

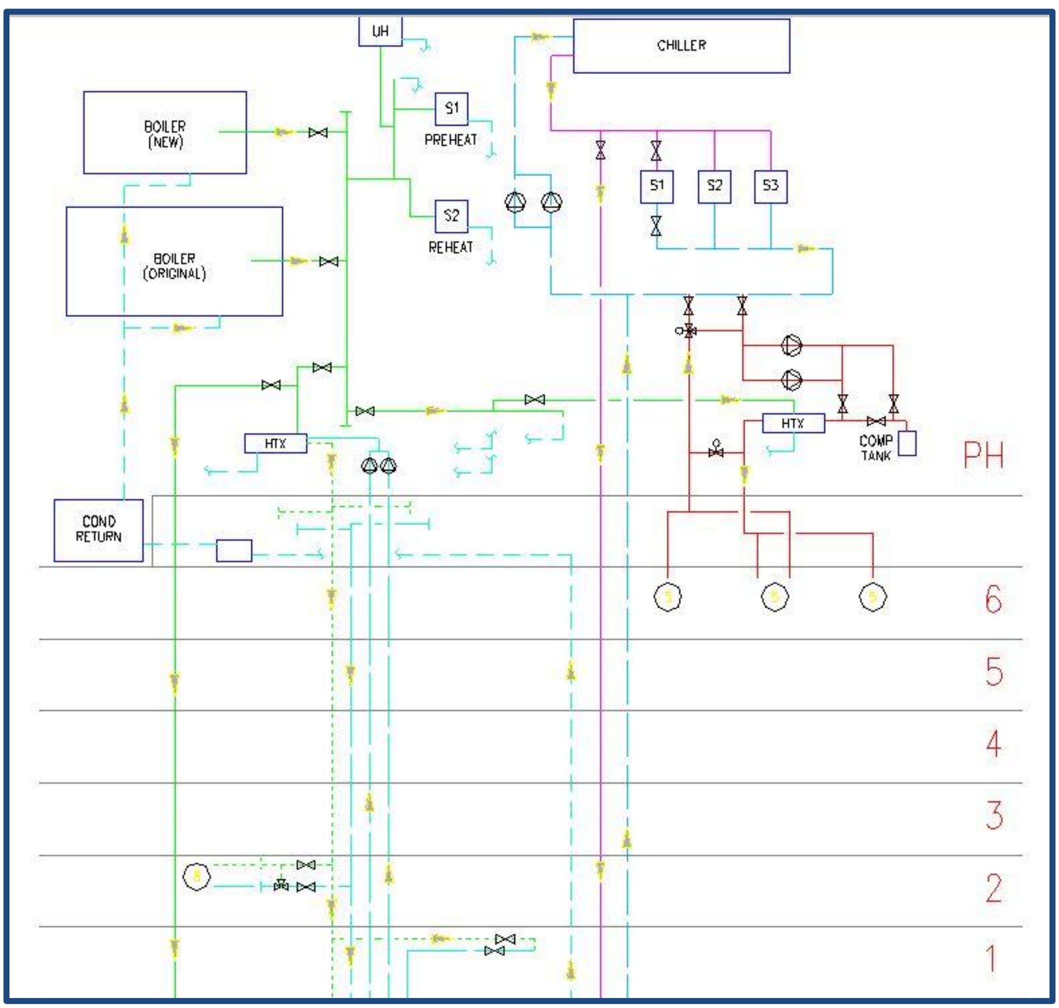


Figure 11: Existing 707 Building's Piping Schematic (JMT)

Results

From summing the vertical and horizontal piping that will be needed for the chilled beams, an additional 6,000 linear feet of hot water copper piping will be installed to account for the added 2-pipe system that will be installed. An initial cost and a life cycle cost analyses were performed and is included in the Construction Management section of this report. As assumed, there was definitely a cost increase associated with this alteration.

CHILLED BEAMS – MECHANICAL DEPTH

Objective

The objectives of altering the designed system to one with chilled beams exceed the Owner's requests of improving system reliability, energy efficiency, and occupant safety and comfort. The options for renovation were compared using the following criteria: disturbance to tenants (during construction), maintenance requirements of the proposed system, simplicity of the system control strategy, and robustness (system resistance to failure – may be in conflict with maintainability). Interchanging the induction units with chilled beams in the office space will ultimately lead to lower energy consumption, improved comfort, no regular maintenance, and an increase in building usable square footage.

Background

Chilled beams, which have been applied primarily in Europe thus far, are finally breaking through more and more in mechanical designs in the United States. Chilled beam systems can both heat and cool spaces. For cooling, the use of chilled water pipes in ceiling mounted modular units is applied. For heating, the heat is transferred primarily through convection, instead of radiation as in radiant chilled ceiling panels. The system can be either passive, which only supplies cooling and is typically used in conjunction with a larger system, or active, which are similar to induction diffusers (seen in Figure 12 below).

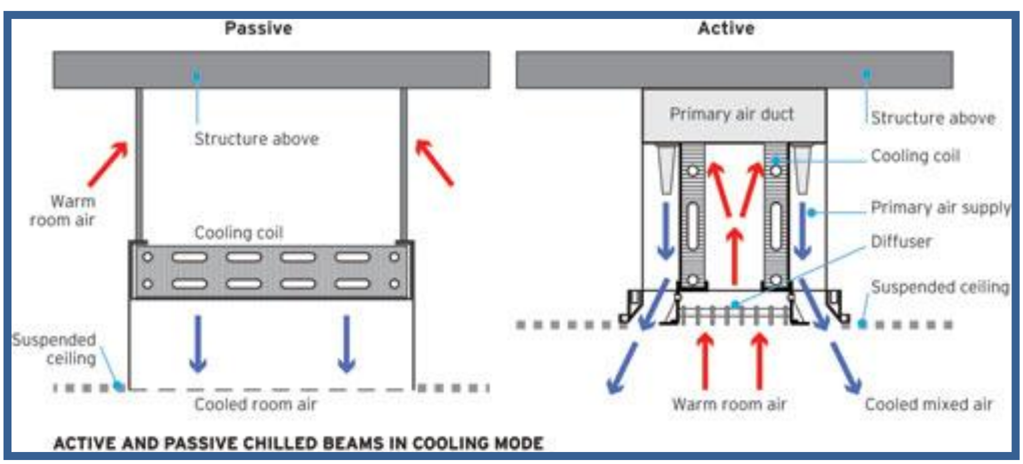


Figure 12: Active and Passive Chilled Beams in Cooling Mode

How Chilled Beams Work

Chilled beam units have finned chilled water heat exchanger cooling coils, capable of providing 1,100 BTU/hr of sensible cooling per foot of beam. Since water can transport energy more efficiently than air, a 1" diameter water pipe can transfer the same cooling capacity as an 18" x 18" air duct (as seen in Figure 13). Therefore, chilled beams can drastically reduce AHU and duct sizes – increasing both horizontal and vertical building space. Three types of chilled beams were researched to determine which to use in the 707 Building: passive, active, and multiservice.

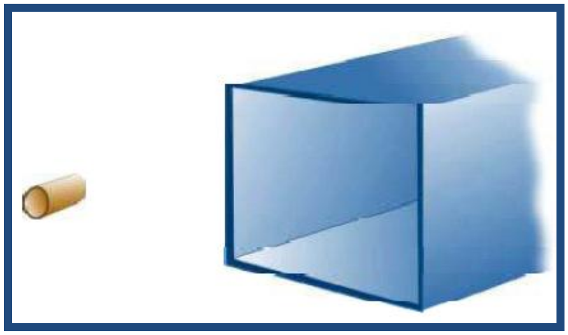


Figure 13: Cooling by Water and Air

Passive Chilled Beams

Passive chilled beams implement a finned tube heat exchanger coil (Figure 14) to convectively deliver cool air to a space. Chilled water is piped to a coil, which usually consists of aluminum fins on copper tubing within a perforated metal casing. There, it cools the surrounding air, which drops into the room.

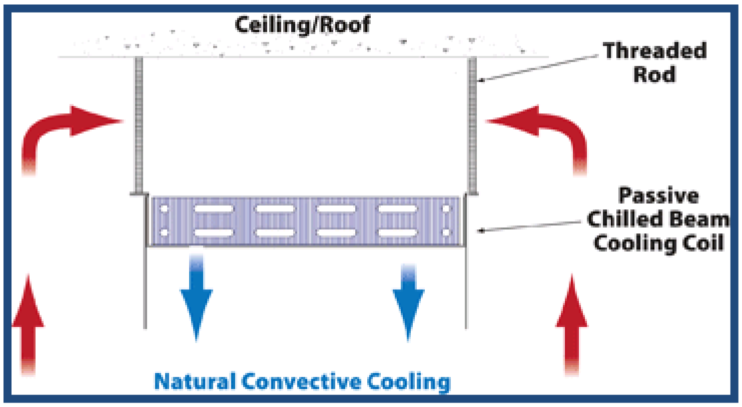


Figure 14: Passive Chilled Beam Section

Passive chilled beams do not use fans, ductwork, or any other component; as an alternative, they rely on natural convection to drive the warmer, more buoyant room air up to the ceiling and into the casing, where it is cooled and naturally drops again. A small space between the top of the chilled beam and the underside of the structure allows the warm air to rise above the beam, turn, and accelerate past the fins of the heat exchanger.

Active Chilled Beams (ACB's)

Active chilled beams (ACB's) use forced air induction to both heat and cool a room. Since the induction principle causes a secondary air flow through the heat exchanger, induction units don't require an additional fan – decreasing the amount of energy consumed.

As seen in Figure 15, the operation of ACB's occurs when primary/ventilation air supply is introduced into the beam through a series of nozzles. This process induces room air to rise to the ceiling and into the ACB, which in turn pulls the air through a secondary water coil. Induced room air is cooled and/or heated by the water coil to the extent needed to control the room temperature. Induced room air is then mixed with the primary/ventilation air and discharged into the space through a diffuser. This ACB induction is less noisy than traditional induction units and also requires less maintenance.

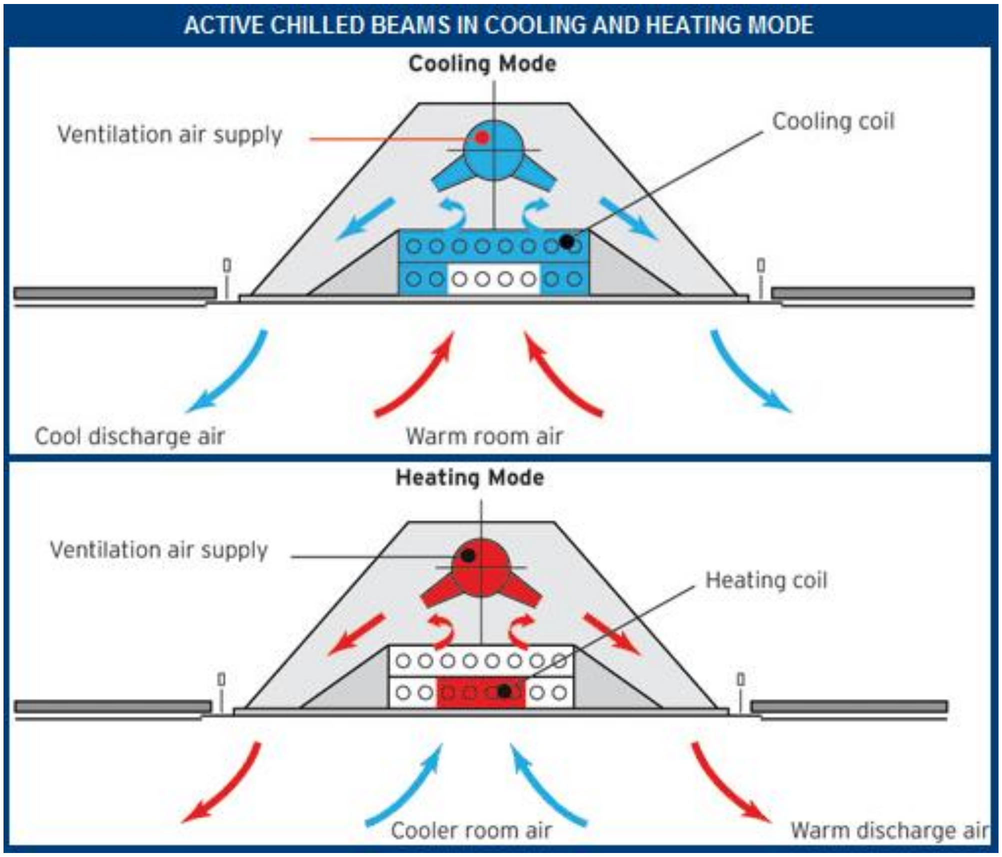


Figure 15: Active Chilled Beams in Cooling and Heating Modes

ACB's are the 3rd generation of chilled beam technology and can take care of both the sensible and latent heat gains of a room in a single package and can be operated singly or grouped for zone control. While the room still requires air ducts and the ventilation must be hooked up to the beam, all HVAC requirements can be handled in a single unit.

Multiservice Chilled Beams

The third class of chilled beam is compact, or "multiservice." These units, either passive or active, can be customized to contain a plethora of additional building-service systems, including lighting, building management system sensors, information technology cabling, and sprinklers (Figure 16). As expected, these units are more expensive than the simpler ones, but they offer several advantages. The components can be fitted optimally into the casing so the whole is more compact than the collection of parts would be. Installation scheduling is made easier and potentially more reliable.

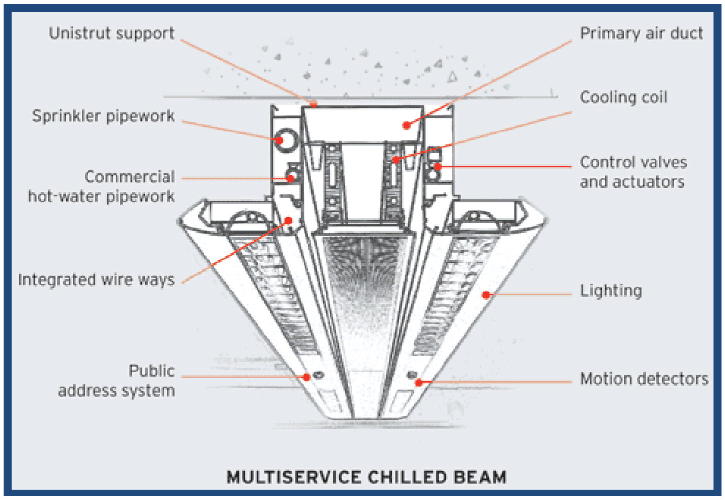


Figure 16: Multiservice Chilled Beam Diagram

In some cases, the integrated services can be sophisticated enough to include cooling, ventilation, lighting and associated controls, speakers, and sprinkler distribution. By concealing the various services within the chilled-beam unit, architects are able to eliminate suspended ceilings, maximize floor-to-ceiling heights, and reduce ceiling clutter. Prefabrication of the integrated units also supports the accelerated construction schedule. Furthermore, the beams are designed to ensure tenant flexibility. Each has its own control valve so that in the future, adding a sensor and wiring back to the floor outstation can provide any new zone with individual comfort control.

Chilled Beam Sizing and Selection

To determine the dimensions and number of chilled beams to be implemented in the 707 Building, calculations were made based on DADANCO Active Chilled Beam Technical Data Guide and tables. A breakdown of the sizing calculations are below, followed by a table as an example (from the 1st floor, South West Zone) of how the calculations are applied to a zone.

Sizing

1. Ventilation Air
   - To begin unit selections, the minimum ventilation air, set forth by ASHRAE Standard 62.1 – 2007, required for each zone will be determined. As seen in Figure 17, the ventilation air rate for office space is 5 CFM/person. This ventilation quantity will be the primary air delivered to the ACB's in each zone.
   - **Ventilation Air Required = 5 CFM/person x People in Zone**

TABLE 6-1 MINIMUM VENTILATION RATES IN BREATHING ZONE *(continued)*
(This table is not valid in isolation; it must be used in conjunction with the accompanying notes.)

Occupancy Category	People Outdoor Air Rate R_p		Area Outdoor Air Rate R_a		Notes	Default Values: Occupant Density (see Note 4)	Default Values: Combined Outdoor Air Rate (see Note 5)		Air Class
	cfm/person	L/s·person	cfm/ft²	L/s·m²		#/1000 ft² or #/100 m²	cfm/person	L/s·person	
Office Buildings									
Office space	5	2.5	0.06	0.3		5	17	8.5	1
Reception areas	5	2.5	0.06	0.3		30	7	3.5	1
Telephone/data entry	5	2.5	0.06	0.3		60	6	3.0	1
Main entry lobbies	5	2.5	0.06	0.3		10	11	5.5	1

Figure 17: ASHRAE Standard 62.1 – 2007 Ventilation Air Requirements for Office Buildings

2. Sensible Cooling Capacity of Primary Air
   - **Sensible Cooling Capacity = 1.08 x Primary Air CFM x (T_{room} – T_{supply})**
3. Latent Load
   - The latent loads in ACB systems must be completely satisfied by the primary air, since inadequate latent cooling capacities may lead to condensation concerns.
   - **Latent Load = 0.69 x Primary Air CFM x (RH_{room} – RH_{supply})**
4. Latent Cooling Capacity of Primary Air
   - The latent cooling being provided by the primary air can be determined based on the airflow, room design, and primary air temperatures selected.
   - **Latent Cooling = 4840 x Primary Air CFM x (W_{room} – $W_{primary}$)**
   - If the latent cooling capacity of primary air is greater than the latent load, the ventilation air is adequate in supporting the latent load for the zone.

Table 12: Example Cooling Calculation Load

Floor	Zone	People	Primary Air (CFM)	Sensible Cooling Capacity (BTU/hr)	Latent Load (BTU/hr)	Latent Cooling Capacity (BTU/hr)
1st	SW	10	50	1134	148	303

5. Primary Air Reduction
   - By decreasing the primary air CFM, the ductwork can be significantly reduced as well.
   - **Percent Primary Air Reduction = [1–(Primary Air CFM/Total Current Supply CFM)]*100**

Table 13: Example Percent Reduction Primary Air

Floor	Zone	Current Supply (CFM)	Primary Air (CFM)	Primary Air Reduction (%)
1st	SW	484	50	89.7

   - The average Percent of Primary Air Reduction in the 707 Building was 80%.

Selection

Prior to the Thesis Proposal in the fall, studies of the available chilled beams were completed; active chilled beams were determined to be the best replacement of the current 534 perimeter induction units – since they themselves are modern induction units. There are numerous advantages of ACB units. Those that directly apply to the Owner's concerns and are discussed within this report are listed in the left column in the table below:

Table 14: ACB Advantages

Crucial	Of Concern
✓ Lower operating cost	Noiseless
✓ Lower energy consumption	Higher ceiling heights
✓ Highly efficient	Future tenant flexibility
✓ Greater occupancy comfort	
✓ Little maintenance	
✓ Reduced ductwork	
✓ Increased usable square footage	

DADANCO Project Manager referred DADANCO's Active Chilled Beam ACB40 for the 707 Building System Renovations. The ACB40 is suited for perimeter zone in-ceiling installations in office buildings and HVAC refurbishment projects. Figure _ shows that this unit incorporates a 2-way supply air discharge, a one piece return air grill, a single 2-row horizontal secondary cooling coil, all while being a 4-pipe ceiling unit.

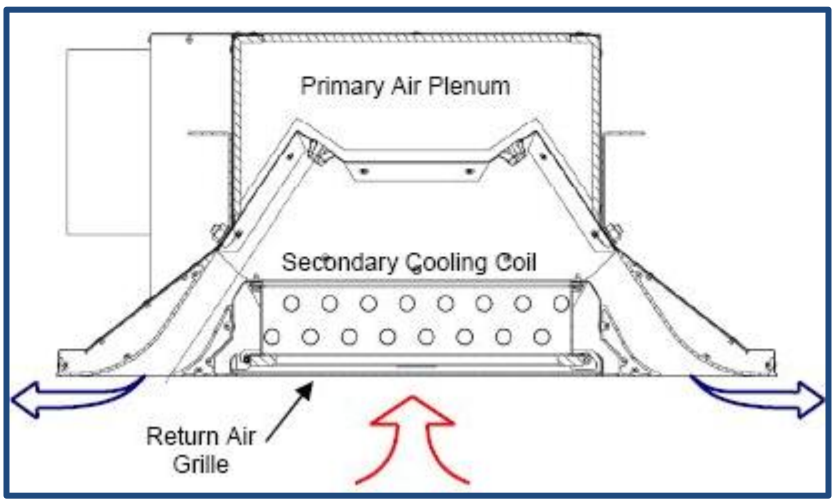


Figure 18: ACB40 from DADANCO

In an October 2010 product information release, the ACB40 is patented to deliver higher energy efficiency perimeter air conditioning using lower air quantities.

From Table 12: Example Cooling Calculation Load, the ACB 4-pipe Quick Selection Cooling Capacity table was used to select a length of cooling coil. In this case, a 4-foot, or full tile, nominal length is sufficient to fulfill the air flows and sensible and latent cooling capacities.

Table 15: ACB 4-pipe Quick Selection Cooling Capacity

Primary Airflow (CFM)	Primary Air Cooling: Sensible (Btuh)	Primary Air Cooling: Latent (Btuh)	Sensible Cooling (Btuh): Nominal 2 Foot Coil: Coil	Nominal 2 Foot Coil: Total	Nominal 3 Foot Coil: Coil	Nominal 3 Foot Coil: Total	Nominal 4 Foot Coil: Coil	Nominal 4 Foot Coil: Total	Nominal 5 Foot Coil: Coil	Nominal 5 Foot Coil: Total	Nominal 6 Foot Coil: Coil	Nominal 6 Foot Coil: Total
15	340	90	1075	1415								
20	455	120	1240	1695	1495	1950						
25	570	150	1365	1935	1665	2235	1840	2410				
30	684	180	1385	2070	1835	2520	2005	2690				
35	800	210			2030	2830	2165	2965	2415	3215		
40	910	240			2100	3010	2335	3245	2570	3480	2810	3720
45	1025	270			2140	3165	2525	3550	2720	3745	2965	3990
50	1140	300			2150	3290	2565	3705	2880	4020	3110	4250
55	1255	330					2610	3865	3050	4305	3240	4495
60	1365	365					2615	3980	3145	4510	3395	4760
65	1480	395							3230	4710	3565	5045
70	1595	425							3280	4875	3740	5335
75	1710	455							3295	5005	3795	5505
80	1825	485							3305	5130	3870	5695
85	1935	515									3920	5855
90	2050	545									3950	6000
95	2165	575									3960	6125
100	2280	605									3970	6250

DADANCO uses a rule of thumb to calculate the amount of ACB's needed in a zone: 1 perimeter chilled beam every 150 square feet. In the 1st Floor South West zone example, this amounts to 12 units, as seen in the table below.

Table 16: Example Number of Units

Floor	Zone	Area (ft^2)	Number of Units
1st	South West	1669	12

By using DADANCO's selection software program, a total of 391 ACB40 units were confirmed with the Excel calculations previously exampled.

Energy Consumption & Operating Costs

Similar to Technical Report II, a year-long energy simulation was composed by the TRACE model that was used to find the building design cooling and heating loads. Cooling is provided by a chilled water plant operated by electricity, while heating is provided by the new water tube boiler. Chilled beams can save energy in several ways, the first being that they deliver sensible cooling directly to the zones, reducing ventilation fan energy consumption. Second, chilled beam systems can use a higher chilled water temperature than conventional air-conditioning systems (55°F to 63°F vs. 39°F to 45°F). Therefore, the corresponding chiller can operate at a 15-20% higher efficiency because of this lower temperature lift.

System Energy Classification

According to the energy analysis results, with the ACB's in place, the 707 Building will consume 1,551,951 kWh of energy annually – an 11% decrease from the existing energy usage. The breakdown of this energy consumption is shown in both Table 17 and Figure 19 below. Typical for an office building in this region, space heating and lighting are large energy consumers. Since there are no fans needed for the ACB units in the cooling system, the amount of energy expended is reduced when compared to a standard office building.

Table 17: Energy Consumption Breakdown

	Energy (kWh/yr)	Total Energy (%)
Lighting	543,183	35
Space Heating	496,624	32
Receptacles	341,429	22
Space Cooling	170,714	11

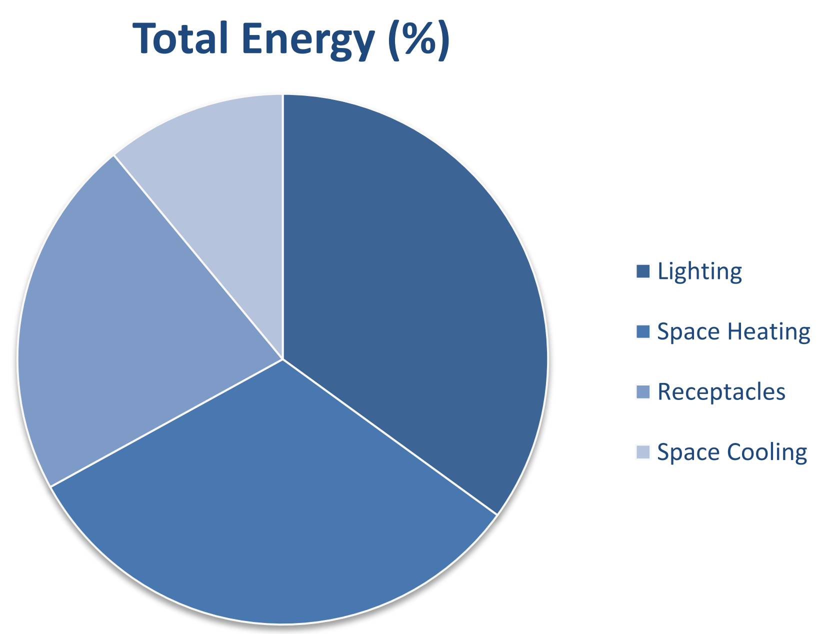


Figure 19: Energy Consumption Pie Chart

System Cost Analysis

Using the same BGE rate schedule in that was previously programmed in TRACE for the existing mechanical cost analysis, the total annual utility cost that was totaled for the consumed electricity and natural gas is $178,719 or $1.03/sf – an 11% decrease.

Comfort

The air flow characteristics of ACB40's 2-way discharge provides a unique air flow pattern that results in thorough purging of air in the occupied space compared to induction units. Undesirable drafts and hot spots in the room are eliminated by providing exceptional air movement with uniform air temperatures, as shown in Figure 20 below. As diagramed, fairly low terminal velocities can be sustained throughout the conditioned space. Accurate air temperature and load requirements are still supplied to the necessary zones according to the ventilation schedule. For humidity control, the primary air at constant volume is supplied with suitable moisture content to satisfy all calculated latent loads.

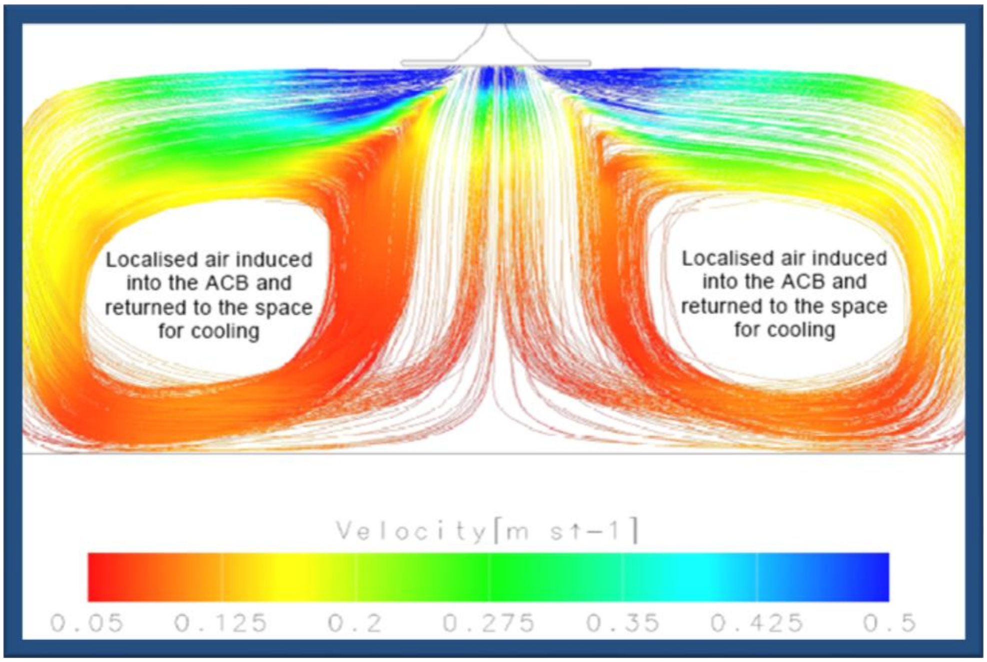


Figure 20: Typical Air Distribution by Active Chilled Beam ACB40 (from DADANCO)

Reduced Maintenance

User-friendly assembly (Figure 21) aids in the maintenance operations of the ACB40. Since there are no moving parts, no regular maintenance, other than occasional vacuuming/dusting of the heat exchanger coil and lint screen, is necessary.

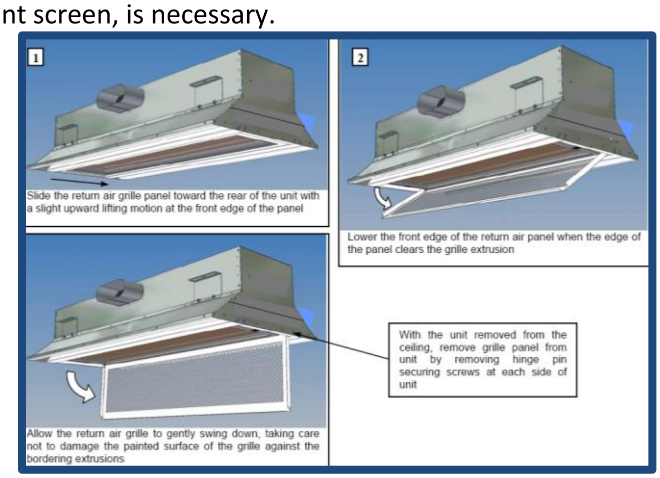


Figure 21: Gaining Access to Heat Exchanger and Lint Screen (from DADANCO)

Duct Reduction

As a result of the 80% reduction in primary air needed by the ACB40, the ductwork can be downsized from the planned installation of 2000lb. to a generous 1000lb. Figure 22 shows how flexible duct is used to connect the primary air duct and the primary air spigot of the ACB40 unit.

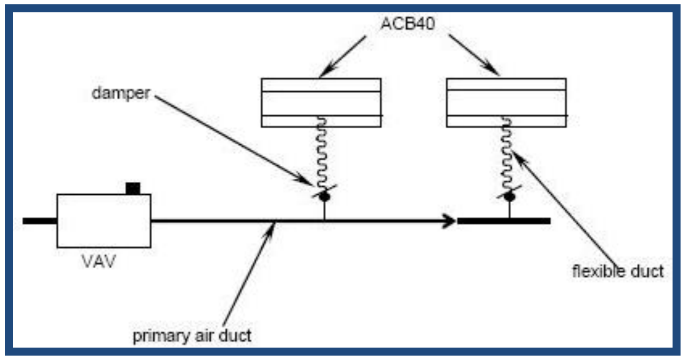


Figure 22: ACB40 Primary Air Duct Connection (DADANCO)

Increased Usable Square Footage

With the removal of the 534 perimeter induction units, floor area is increased. It is estimated that each induction unit takes up just over two usable square feet of space. The table below details the small increase in space.

Table 18: Energy Consumption Breakdown

	Total SF
Existing	171,630
Induction Units	1,112
Proposed	172,742

Results

Chilled beams offer various benefits to renovated buildings: lower energy consumption, improved comfort, no regular maintenance, and an increase in building usable square footage. According to DADANCO, when compared to all air systems, a 75-85% reduction in circulated air is typical when using chilled beams. According to the TRACE outputs, the 707 Building will reduce 80% of primary air. With this decrease, it is possible to reduce the ductwork, fans, AHUs, etc… by the equivalent extent. A generous 50% reduction in both AHU-1 and the ductwork was implemented in the system design. Since it is much more energy efficient to transport water rather than air, the reduction of ductwork with the replacement of water pipes results in less energy consumption. All of these factors, discussed in further detail in the following section, lead to substantial savings in the life-cycle cost of mechanical systems for a renovated building.

BREADTH TOPICS

When implemented, any mechanical system redesign will consequently alter other building systems. After feedback from design engineers, the following construction management and electrical breadths were analyzed.

Construction Management

Objective

This construction management breadth investigates the potential savings in construction costs and installation schedule. With the design engineer's current prediction of a lengthy 9 phases being implemented in the 707 Building systems renovation, a more rapid installation schedule was examined. Any cost information needed that was not obtained from the project manager, design engineer, or approved submittals was referenced from RS Means. Once the scheduling data was supplied by JMT, Microsoft Project was used to rework the renovation schedule. Specific research was performed for the cost (including those related to changes in schedule), schedule, and commissioning for any change to the mechanical system.

Cost Estimate

The cost estimate for materials and labor were created using the RS Means text. A previous budget study completed by JMT was edited to estimate and compare the new additions (chilled beams and 4-pipe study) to the 707 building system. A sales tax of 5% and Labor Overhead of 20% were assumed in this cost analysis.

The following tables summarize the initial cost of materials, labor, and equipment for the existing mechanical systems in the 707 Building and that of the proposed system. The changes between systems include a smaller AHU S-1 that serves the perimeter chilled beam units, a 50% reduction in ductwork, installation of the ACB's, and the addition of two more pipes running parallel to the already existing 2-pipe system.

Removal of induction units consists of the following: relocating tenants, verifying existing utilities, floor protection and furniture moving, draining the riser and capping the piping, demoing the existing induction units, and patching and painting the wall area.

Table 19: Existing Mechanical System Construction Cost Information

Description	QTY	Unit	Bare Unit Cost - Material	Bare Unit Cost - Labor	Bare Unit Cost - Equipment	Taxes - Material & Equipment	Labor Overhead	Sub-Total
AHU S-1 707	1	EA	$90,000	$12,000	$1,000	$4,550.00	$2,400.00	$109,950.00
Ductwork	2,000	lb.	$0.75	$3.75	$0.50	$0.06	$0.75	$11,625.00
Remove Induction Units	534	EA		$300		$0.00	$60.00	$192,240.00
Install New Induction Units	534	EA	$170	$100		$8.50	$20.00	$159,399.00
Floor by Floor Ductwork Modifications	12	LS	$2,550	$11,000		$127.50	$2,200.00	$190,530.00
Total			$92,721	$23,404	$1,001	$4,686	$4,681	$663,744

Table 20: Proposed Mechanical System Construction Cost Information

Description	QTY	Unit	Bare Unit Cost - Material	Bare Unit Cost - Labor	Bare Unit Cost - Equipment	Taxes - Material & Equipment	Labor Overhead	Sub-Total
New AHU S-1 707	1	EA	$70,000	$10,000	$1,000	$3,550.00	$2,000.00	$86,550.00
Ductwork	1,000	lb.	$0.75	$2.75	$0.50	$0.06	$0.55	$4,612.50
Remove Induction Units	534	EA		$300		$0.00	$60.00	$192,240.00
New Active Chilled Beam Units	391	EA	$750			$37.50	$0.00	$307,912.50
Floor by Floor Ductwork Modifications	12	LS	$2,550	$11,000		$127.50	$2,200.00	$190,530.00
4-way Pipe	6,000	LF	$11.80	$9.65		$0.59	$1.93	$143,820.00
Total			$73,313	$21,312	$1,001	$3,716	$4,262	$925,665

With a $261,921, or a 28% increase in first cost of the system, the proposed alternative has an increase in total mechanical cost/square foot of $1.49/sf (shown in Table 21 below).

Table 21: Mechanical Cost per Square Foot Comparison

System	Total Cost ($)	Total SF	Cost ($/ft^2)
Existing	663,744	171,630	3.87
Proposed	925,665	172,742	5.36
Difference	261,921	-	1.49

Life Cycle

A life cycle cost analysis was performed using the TRACE outputs for the costs associated with electric and natural gas use. Since the only available RS Means reference book to find overhaul and other maintenance costs is RS Means 2007 Facilities Maintenance and Repairs, it was unhelpful to locate information on chilled beams, induction units, etc… However, 1-1/2" copper pipe replacement was scheduled to be every 25 years at $42.25/LF; this cost includes removal and installation of the copper pipes. With escalation over the past four years, the cost per linear foot is $42.52/LF. AHU's were called to be repaired every 10 years, and replaced every 15. The table below shows the cost escalation between a 16,000CFM unit and a 33,500CFM AHU.

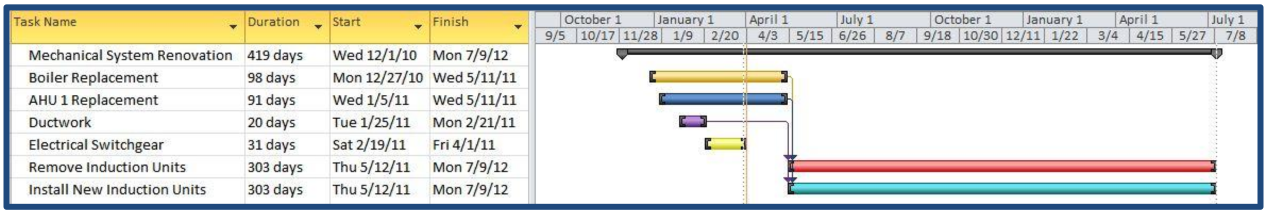
Table 22: AHU Cost Escalation

	AHU 16,000CFM Repair	AHU 16,000CFM Replace	AHU 33,500CFM Repair	AHU 33,500CFM Replace
2007	$1,062.00	$23,900.00	$2,697.00	$50,200.00
2008	$1,064.23	$23,950.19	$2,702.66	$50,305.42
2009	$1,066.47	$24,000.49	$2,708.34	$50,411.06
2010	$1,068.70	$24,050.89	$2,714.03	$50,516.92
2011	$1,070.95	$24,101.39	$2,719.73	$50,623.01

Even though no accurate way of determining the life cycle cost by using the RS Means was possible, a payback period was still calculated. Per the annual savings of the proposed system estimated at $22,089 (calculated earlier in this report), the $261,921 increase between the capital costs of both systems has a potential payback period of roughly 12 years.

Schedule

Microsoft Project 2010 was used to create a construction management schedule for both the currently planned renovation and this thesis' proposed alternative. Figure 23 shows the construction schedules complete with task names, durations, and start/finish dates for the planned renovation. The duration and crew sizes were projected by the Mechanical Contractor, G.E. Tignall and Co.

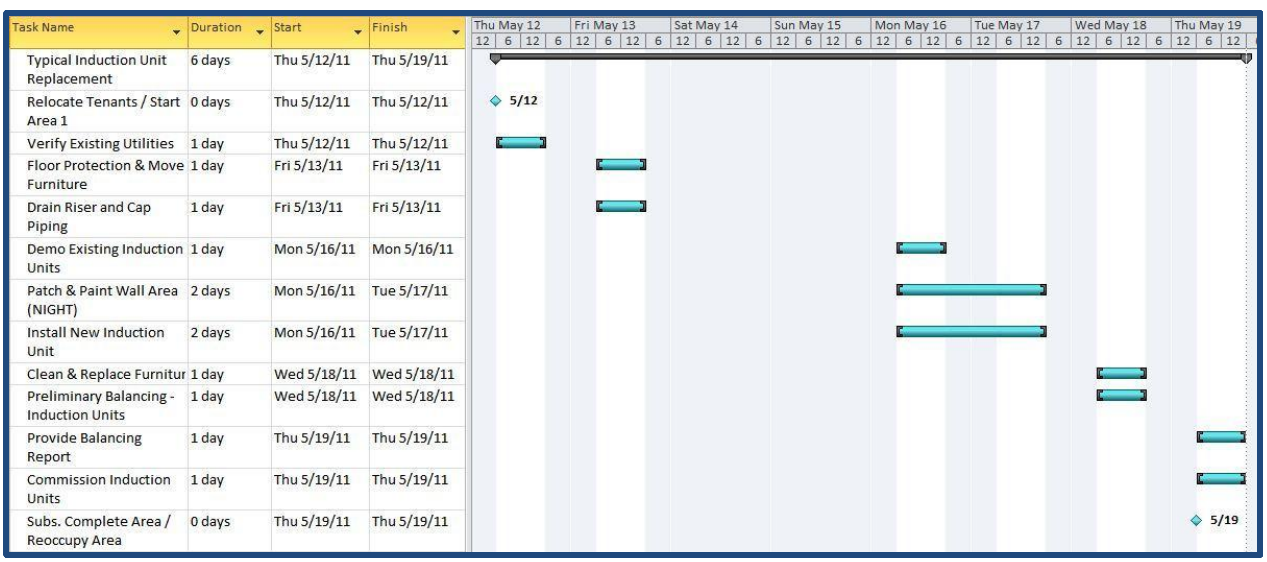


Task Name	Duration	Start	Finish
Mechanical System Renovation	419 days	Wed 12/1/10	Mon 7/9/12
Boiler Replacement	98 days	Mon 12/27/10	Wed 5/11/11
AHU 1 Replacement	91 days	Wed 1/5/11	Wed 5/11/11
Ductwork	20 days	Tue 1/25/11	Mon 2/21/11
Electrical Switchgear	31 days	Sat 2/19/11	Fri 4/1/11
Remove Induction Units	303 days	Thu 5/12/11	Mon 7/9/12
Install New Induction Units	303 days	Thu 5/12/11	Mon 7/9/12

Figure 23: Construction Schedule for Planned Renovation

The induction unit schedule calls for only 12 induction units being replaced per 6 working days, including night shifts to patch and paint the walls. This is due to the current estimate that just 20 tenants can be moved from their areas at a time. Although it appears as though the crews will be working non-stop for 303 days on the induction unit replacement, they will only be working weekdays and will have off for holidays. Induction unit substitution begins immediately following the replacement of the boiler and AHU-1, which serves the perimeter units.

Figure 24 shows the typical induction unit replacement schedule per area. Assuming that each area consists of 12 units, it is projected to take a crew six days to remove the existing induction units and install the new ones.



Task Name	Duration	Start	Finish
Typical Induction Unit Replacement	6 days	Thu 5/12/11	Thu 5/19/11
Relocate Tenants / Start Area 1	0 days	Thu 5/12/11	Thu 5/12/11
Verify Existing Utilities	1 day	Thu 5/12/11	Thu 5/12/11
Floor Protection & Move Furniture	1 day	Fri 5/13/11	Fri 5/13/11
Drain Riser and Cap Piping	1 day	Fri 5/13/11	Fri 5/13/11
Demo Existing Induction Units	1 day	Mon 5/16/11	Mon 5/16/11
Patch & Paint Wall Area (NIGHT)	2 days	Mon 5/16/11	Tue 5/17/11
Install New Induction Unit	2 days	Mon 5/16/11	Tue 5/17/11
Clean & Replace Furnitur	1 day	Wed 5/18/11	Wed 5/18/11
Preliminary Balancing - Induction Units	1 day	Wed 5/18/11	Wed 5/18/11
Provide Balancing Report	1 day	Thu 5/19/11	Thu 5/19/11
Commission Induction Units	1 day	Thu 5/19/11	Thu 5/19/11
Subs. Complete Area / Reoccupy Area	0 days	Thu 5/19/11	Thu 5/19/11

Figure 24: Typical Induction Unit Replacement Schedule

The proposed schedule accounts for both the 2-way to 4-way piping modification and the change in induction system – replacing 534 perimeter wall induction units with 391 ACB ceiling units. To create the 4-pipe system, the existing 2-pipe arrangement will remain, and an additional 2-pipe configuration will run parallel to them. From RS Means, 1 plumber can install 50 linear feet of copper piping per day. With 6,000LF to install, it would take 1 plumber 120 days; doubling the plumbers, the installation will only take 60 days. This growth in workers obviously affects the labor costs of the system, but is worth it in terms of scheduling.

According to DADANCO, a typical crew is estimated to install 6 ACB's per day. If this project was a new construction design, it would take roughly 66 days to complete a 391 ACB installation. However, since this is a renovation, all of the existing induction units, capping of the pipes, and tenant schedule must be considered. Assuming that verification of existing units, furniture protection and removal, and draining of the riser and capping the pipes can all happen in one day, it will take 2 days for 12 induction units to be demoed. The patching and painting can still occur overnight, while 6 ACB's are installed per day. An additional day will be needed to balance the units. Therefore, a total of 5 days will be required to remove and install 12 units (Figure 25).

Task Name	Duration	Start	Finish
Typical ACB Installation	5 days	Mon 5/16/11	Fri 5/20/11
Relocate Tenants / Start Area 1	0 days	Mon 5/16/11	Mon 5/16/11
Verify Existing Utilities	1 day	Mon 5/16/11	Mon 5/16/11
Floor Protection & Move Furniture	1 day	Mon 5/16/11	Mon 5/16/11
Drain Riser and Cap Piping	1 day	Mon 5/16/11	Mon 5/16/11
Demo Existing Induction Units	1 day	Tue 5/17/11	Tue 5/17/11
Patch & Paint Wall Area (NIGHT)	2 days	Tue 5/17/11	Wed 5/18/11
Install ACB Units	2 days	Tue 5/17/11	Wed 5/18/11
Clean & Replace Furniture	1 day	Thu 5/19/11	Thu 5/19/11
Preliminary Balancing - ACB Units	1 day	Thu 5/19/11	Thu 5/19/11
Provide Balancing Report	1 day	Fri 5/20/11	Fri 5/20/11
Commission ACB Units	1 day	Fri 5/20/11	Fri 5/20/11
Subs. Complete Area / Reoccupy Area	0 days	Fri 5/20/11	Fri 5/20/11

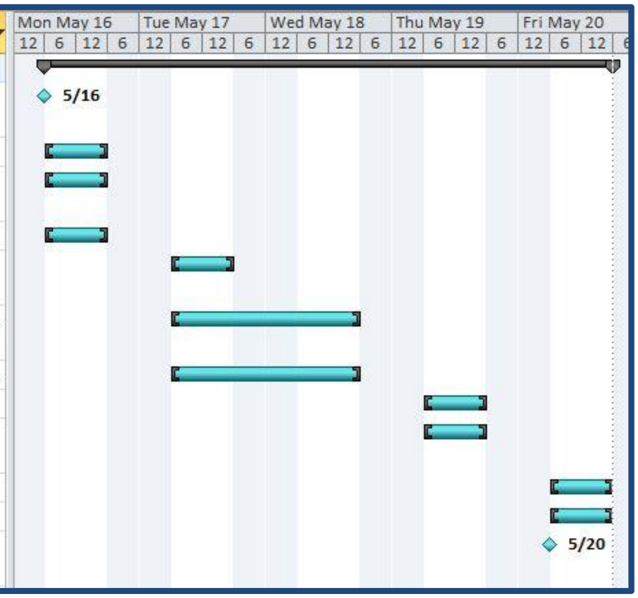


Figure 25: Typical ACB Installation Schedule

At 5 days per 12 induction unit removal and replacement with ACB, the duration of the activity decreases from 303 days to 225 days. The overall schedule will decrease by about one month for the proposed alternative (Figure 26).

Task Name	Duration	Start	Finish
Mechanical System Renovation	401 days	Wed 12/1/10	Wed 6/13/12
Boiler Replacement	98 days	Mon 12/27/10	Wed 5/11/11
AHU 1 Replacement	60 days	Wed 1/5/11	Tue 3/29/11
Ductwork	15 days	Tue 1/25/11	Mon 2/14/11
Electrical Switchgear	31 days	Sat 2/19/11	Fri 4/1/11
4-way Piping Installation	60 days	Thu 5/12/11	Wed 8/3/11
Removal of Induction Units	225 days	Thu 8/4/11	Wed 6/13/12
Chilled Beams	225 days	Thu 8/4/11	Wed 6/13/12

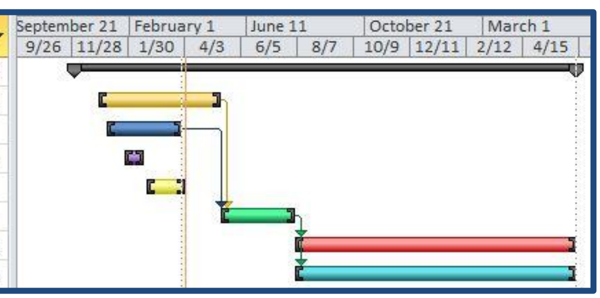


Figure 26: Construction Schedule for Proposed Alternative

Results

In summary, the construction management examination exhibits the cost, both upfront and life cycle, and schedule for the 707 Building. Although the initial cost in the system exceeds that of the current renovation by $261,921, the energy savings make up for this in 12 years. This is considered to be a reasonable payback period for this system. The overall schedule of the

Electrical

Objective

An electrical breadth examines the benefits of ACB's energy saving abilities with this renovation. Design loads for the building's current electrical distribution system were compared to the redesigned system.

Analysis

An electrical study was performed comparing the current electric load output to the renovated one by a redesign representation of the circuit/breaker or panel board. This electrical analysis was run using TRACE to determine the overall effect in reducing the cooling load by implementing active chilled beams. Data sheets in Microsoft Excel were also utilized to compare and contrast the differences between the systems.

The current plans for the 707 renovation include replacing the existing power branch circuit panel boards with associated feeder conduit and wiring should be considered by the owner. The added equipment that uses electricity includes the 391 ACB's, and the pumps from the 4-pipe system. The overall electrical usage from the ACB's is less than, but not significantly enough to alter the proposed designs. The NEC 2008 was used to verify the 480/277V, 3 phase switchboard design with a 4-wire and ground (Table 22).

Table 23: Switchboard Design

Load Description	Connected (KVA)	Demand (KVA)	Circuit Size	Circuit GRD	Conduit
EXISTING CHILLER CH-1	150.00	120.00	-	-	-
CHILLED WATER PUMP CHP-2	28.30	22.64	#8	#8	1”
MCC-PH	35.20	28.16	#500MCM	-	4”
EXISTING CHILLER CH-2	150.00	120.00	-	-	-
PRIMARY PUMP CWP	28.30	22.64	#8	#10	1”
HEATING WATER PUMP HWP-1	9.20	7.36	#12	#12	3/4”
CHILLED WATER PUMP CHP-1	28.30	22.64	#8	#8	1”
EXISTING COOLING TOWER	33.26	26.61	-	-	-
AHU-3	36.60	29.28	#6	#8	1”
AHU-1	80.00	64.00	#1	#6	1-1/2”
HEATING WATER PUMP HWP-2	9.20	7.36	#12	#12	3/4”
CONDENSOR WATER PUMP CWP-2	43.30	34.64	#4	#8	1”
AHU-2	20.00	16.00	#6	#8	1”
CONDENSOR WATER PUMP CWP-1	43.30	34.64	#4	#8	1”
BASIN HEATERS	20.00	16.00	#8	#10	1-1/4”
TOTAL LOADS	714.96	571.968	-	-	-

A single line diagram of how the above switchboard is wired in the penthouse is shown on the following page.

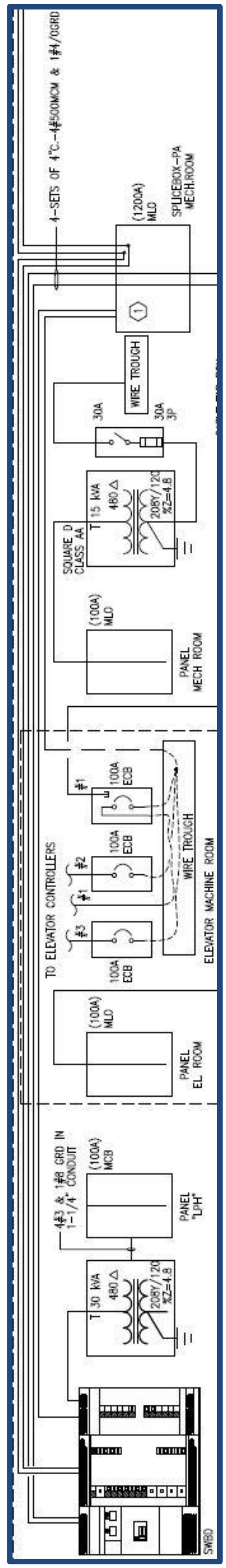


Figure 27: Switchboard Single Line Diagram

The planned and redesigned electrical annual usages are charted in the table below. The figures taken from TRACE outputs show that the proposed alternative will save electricity annually.

Table 24: Comparative Annual Electrical Usage

	Current Elec (kWh/yr)	Proposed Elec (kWh/yr)
Lighting	864,682	864,682
Space Heating	40,158	34,282
Receptacles	582,082	482,273
Space Cooling	256,843	170,714
Total	1,743,765	1,551,951

Results

The installation of the active chilled beams reduced the overall annual electrical usage of 191,814kWh for the 707 Building. Although this is a terrific savings, it is not substantial enough to alter the planned renovations to the electrical system.

REFERENCES

"Active Chilled Beams Frequently Asked Questions." DADANCO LLC, July 2009.

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

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Baltimore Gas and Electric (BGE). *www.bge.com*.

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"Designing Chilled Beams for Thermal Comfort." ASHRAE Journal, October 2009.

"Design Considerations for Active Chilled Beams." ASHRAE Journal, September 2008.

"Induction Units Frequently Asked Questions." DADANCO LLC, December 2007.

Industry Professionals Mentioned including:

Matt Keller, JMT – Facilities Senior Associate
Pat Harillal, JMT – Mechanical Engineer
Ron Saunders, JMT – Environmental Facilities CADD Technician
Adam Raver, JMT – Facilities CADD Technician
Jim Hovey, JMT – Construction Management
Alyssa Adams, McClure Company – Energy Services Specialist
Panda Aumpansub, Havtech Corporation – Application Engineer
Cassidy Bowman, DADANCO – Project Manager
Jan Kaczmarek, SHA Project Manager

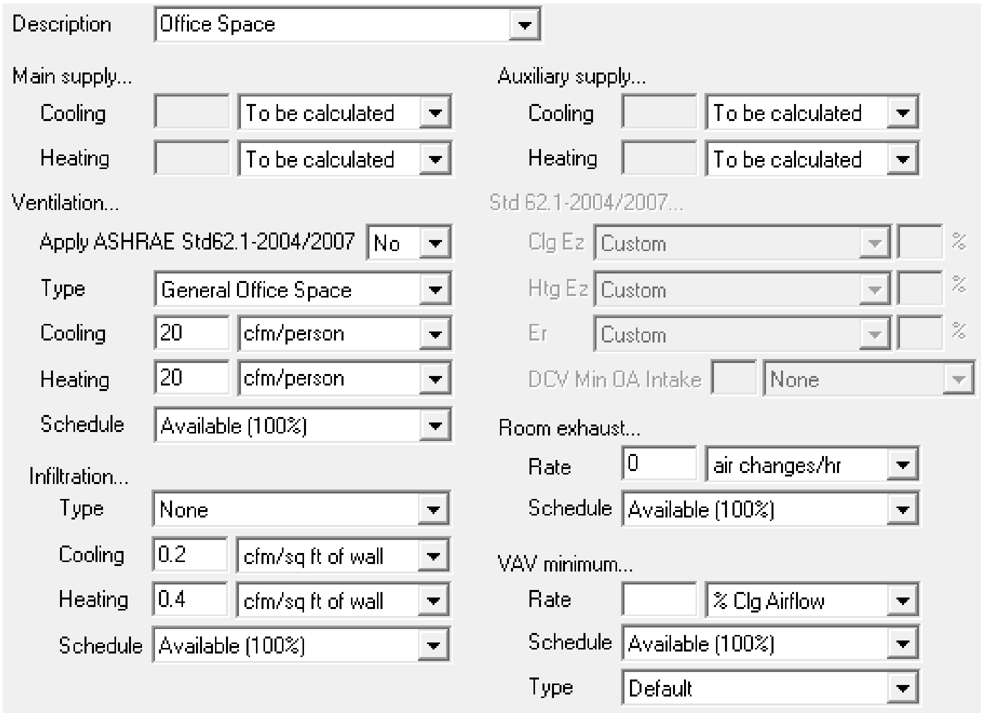
Johnson, Mirmiran & Thompson (JMT). Engineering Reports and TRACE Documents.

NEC 2008.

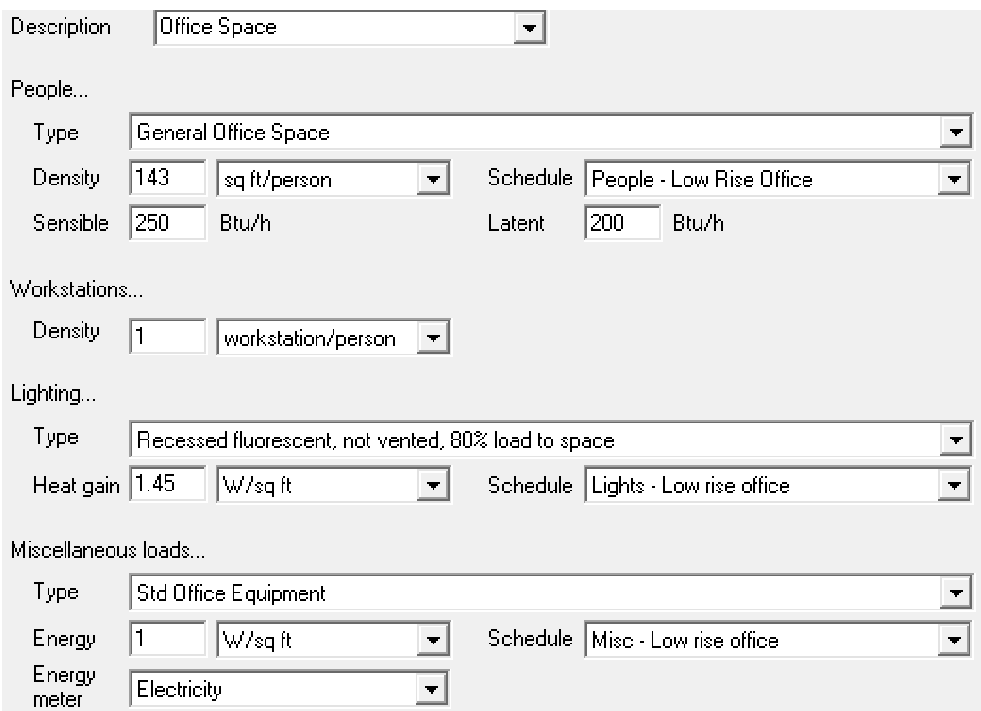
Previous Senior Thesis Reports from 2008-2010.

RegGridemissionfactors2007.pdf.

APPENDIX A – TRACE DATA TEMPLATES

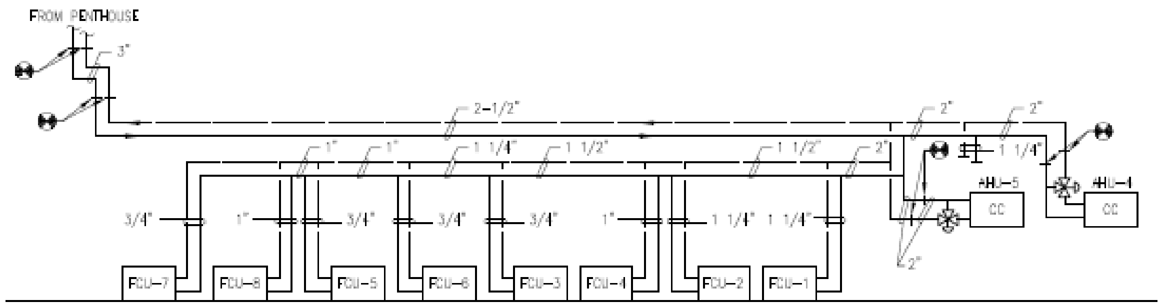


Typical Office Airflows

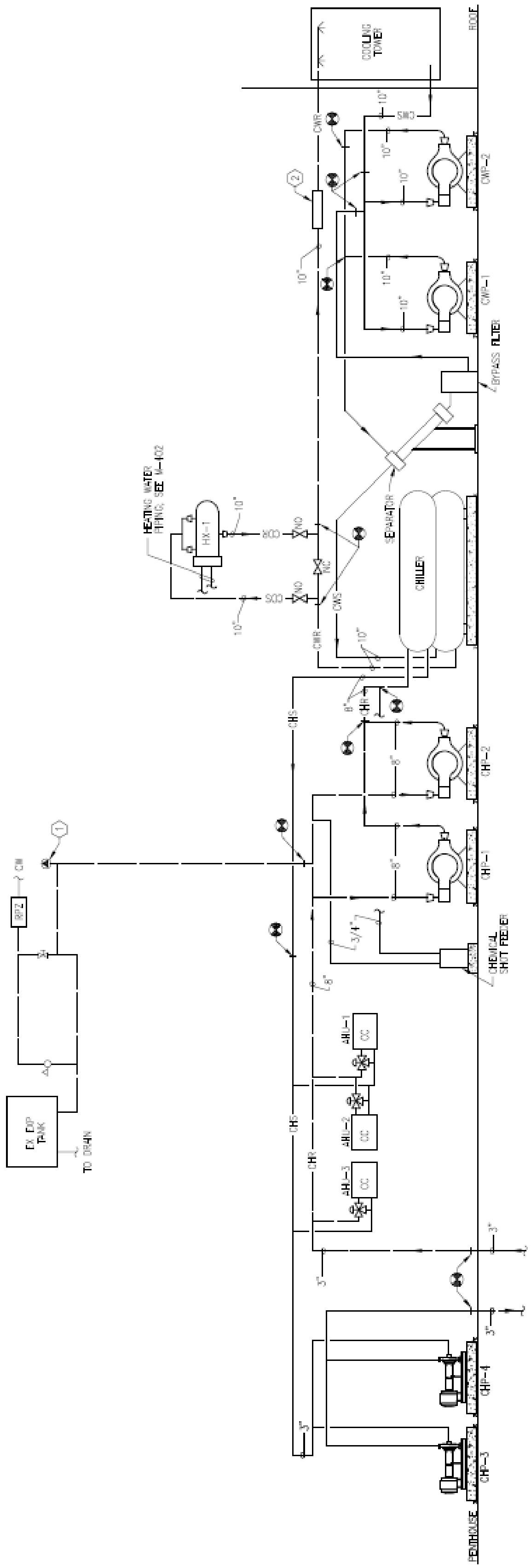


Typical Office Internal Loads

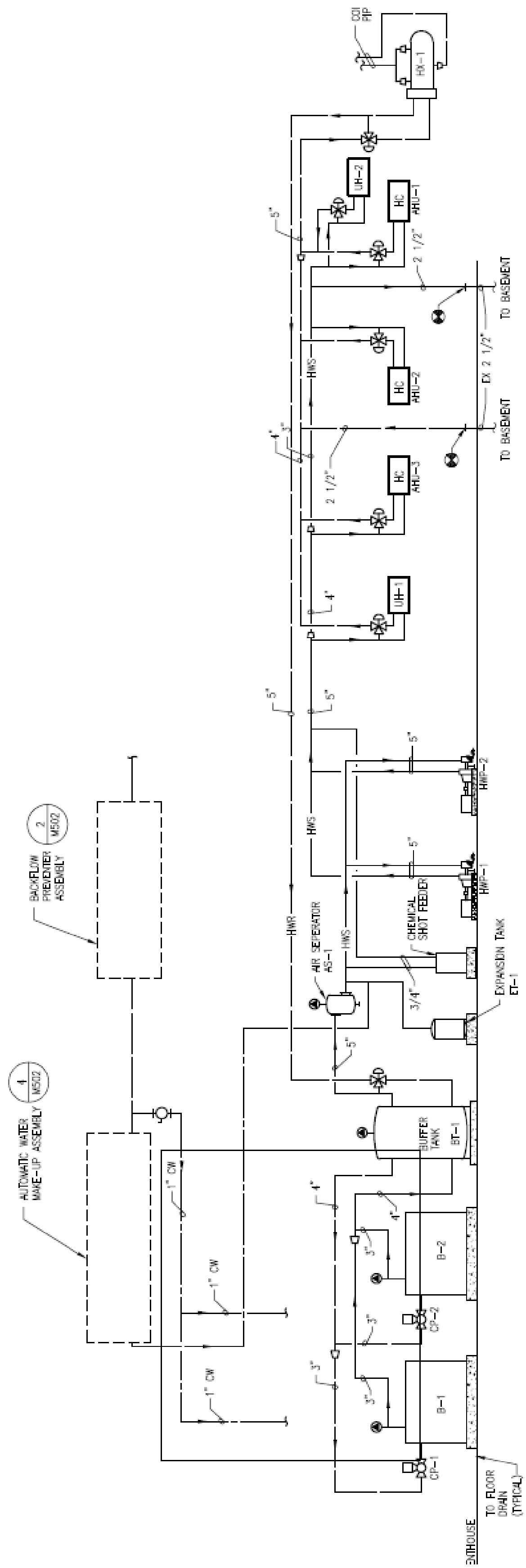
APPENDIX B – MECHANICAL SYSTEM SCHEMATIC



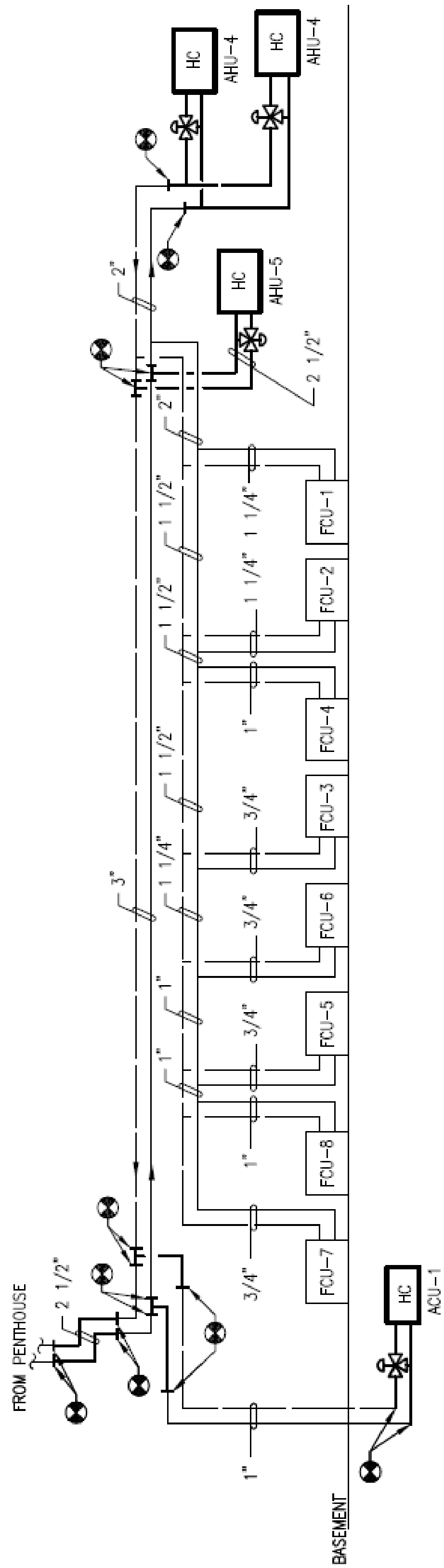
Basement Chilled and Condenser Water Schematic



Penthouse Chilled and Condenser Water Schematic

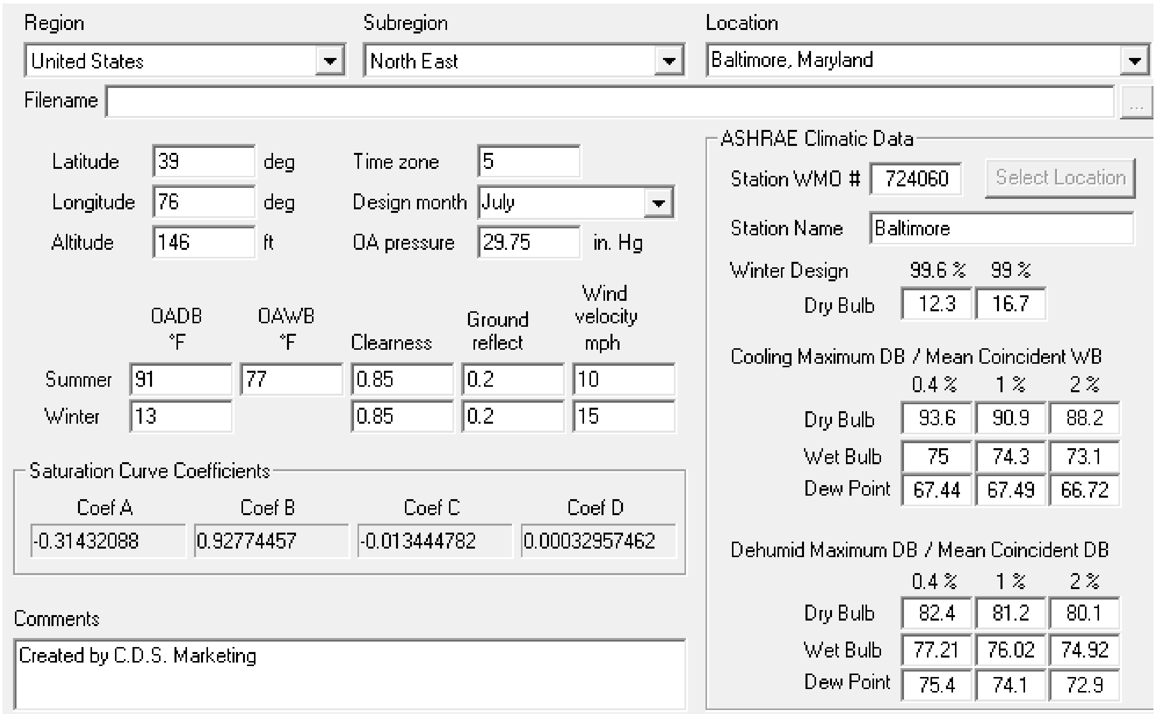


Penthouse Heating Water Schematic



Basement Heating Water Schematic

APPENDIX C – WEATHER INFORMATION



Region: United States
Subregion: North East
Location: Baltimore, Maryland
Filename:

Latitude	39	deg	Time zone	5	
Longitude	76	deg	Design month	July	
Altitude	146	ft	OA pressure	29.75	in. Hg

	OADB °F	OAWB °F	Clearness	Ground reflect	Wind velocity mph
Summer	91	77	0.85	0.2	10
Winter	13		0.85	0.2	15

Saturation Curve Coefficients

Coef A	Coef B	Coef C	Coef D
-0.31432088	0.92774457	-0.013444782	0.00032957462

Comments

Created by C.D.S. Marketing

ASHRAE Climatic Data

Station WMO # 724060 Select Location

Station Name: Baltimore

Winter Design	99.6 %	99 %
Dry Bulb	12.3	16.7

Cooling Maximum DB / Mean Coincident WB

	0.4 %	1 %	2 %
Dry Bulb	93.6	90.9	88.2
Wet Bulb	75	74.3	73.1
Dew Point	67.44	67.49	66.72

Dehumid Maximum DB / Mean Coincident DB

	0.4 %	1 %	2 %
Dry Bulb	82.4	81.2	80.1
Wet Bulb	77.21	76.02	74.92
Dew Point	75.4	74.1	72.9

Weather Conditions for Baltimore, MD

2009 ASHRAE Handbook - Fundamentals (IP)

BALTIMORE BLT-WASHNGTN INT'L, MD, USA

WMO#: 724060

Lat: 39.17N Long: 76.68W Elev: 154 StdP: 14.61 Time Zone: -5.00 (NAE) Period: 82-06 WBAN: 93721

Annual Heating and Humidification Design Conditions

Coldest Month	Heating DB		Humidification DP/MCDB and HR						Coldest month WS/MCDB				MCWS/PCWD to 99.6% DB	
			99.6%			99%			0.4%		1%			
	99.6%	99%	DP	HR	MCDB	DP	HR	MCDB	WS	MCDB	WS	MCDB	MCWS	PCWD
1	12.9	17.3	-3.3	4.6	17.8	1.3	5.9	22.1	26.2	31.6	24.2	32.1	8.7	290

Annual Cooling, Dehumidification, and Enthalpy Design Conditions

Hottest Month	Hottest Month DB Range	Cooling DB/MCWB						Evaporation WB/MCDB						MCWS/PCWD to 0.4% DB	
		0.4%		1%		2%		0.4%		1%		2%			
		DB	MCWB	DB	MCWB	DB	MCWB	WB	MCDB	WB	MCDB	WB	MCDB	MCWS	PCWD
7	18.7	93.9	74.9	91.2	74.2	88.5	73.1	78.1	88.6	76.8	86.5	75.6	84.3	10.2	280

Dehumidification DP/MCDB and HR									Enthalpy/MCDB						Hours 8 to 4 & 55/69
0.4%			1%			2%			0.4%		1%		2%		
DP	HR	MCDB	DP	HR	MCDB	DP	HR	MCDB	Enth	MCDB	Enth	MCDB	Enth	MCDB	
75.3	133.3	82.1	74.1	127.9	80.8	73.0	123.1	79.8	41.5	89.1	40.2	86.5	39.1	84.5	723

Extreme Annual Design Conditions

Extreme Annual WS			Extreme Max WB	Extreme Annual DB				n-Year Return Period Values of Extreme DB							
				Mean		Standard deviation		n=5 years		n=10 years		n=20 years		n=50 years	
1%	2.5%	5%		Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
22.4	19.2	17.3	84.6	5.1	98.0	6.3	3.3	0.6	100.3	-3.1	102.2	-6.7	104.0	-11.3	106.4

Monthly Climatic Design Conditions

			Annual	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Temperatures, Degree-Days and Degree-Hours	Tavg		55.9	33.9	36.9	44.2	54.2	63.6	72.7	77.6	75.7	68.3	56.8	47.3	37.8
	Sd			10.07	8.67	9.29	8.30	7.49	6.31	5.08	5.20	6.95	7.72	8.51	9.29
	HDD50		1726	507	376	231	45	1	0	0	0	0	22	152	392
	HDD65		4567	964	787	649	339	119	12	0	2	45	275	532	843
	CDD50		3861	8	9	50	171	424	680	855	796	550	232	71	15
	CDD65		1228	0	0	4	15	77	242	390	333	145	21	1	0
	CDH74		11317	0	1	42	195	792	2240	3853	2963	1071	148	11	1
	CDH80		4315	0	0	8	57	267	849	1669	1125	317	23	0	0
Monthly Design Dry Bulb and Mean Coincident Wet Bulb Temperatures	0.4%	DB		65.2	69.3	80.0	86.9	90.9	94.6	98.0	96.9	92.6	83.2	75.3	68.5
		MCWB		57.7	56.2	62.2	66.7	71.5	74.5	76.5	75.9	72.8	68.9	63.6	60.2
	2%	DB		59.5	61.4	71.1	79.6	86.8	91.3	94.7	92.6	87.1	78.1	69.8	62.1
		MCWB		54.5	53.5	58.1	63.2	69.3	73.9	75.7	75.0	71.7	66.9	60.2	55.3
	5%	DB		53.0	55.5	64.7	74.1	82.6	88.2	91.8	89.2	83.4	74.0	65.3	56.4
		MCWB		46.8	47.5	54.1	60.3	67.9	73.0	74.9	73.8	70.1	64.3	58.7	51.0
	10%	DB		47.6	50.4	59.4	69.3	78.1	85.1	88.7	86.1	80.2	70.2	61.4	51.6
		MCWB		42.7	44.3	50.1	57.3	65.5	71.8	74.0	72.5	69.0	62.5	55.6	46.1
Monthly Design Wet Bulb and Mean Coincident Dry Bulb Temperatures	0.4%	WB		60.1	60.1	64.6	68.9	74.8	78.8	80.2	79.4	77.0	72.2	66.5	62.1
		MCDB		63.2	66.0	76.5	80.5	86.0	88.3	91.3	90.0	85.0	77.8	70.8	67.1
	2%	WB		55.0	53.7	60.2	65.7	72.1	76.5	78.4	77.5	75.0	69.8	63.5	57.2
		MCDB		58.6	58.7	68.8	75.7	82.8	85.9	89.4	88.0	82.1	75.5	67.9	61.0
	5%	WB		47.9	49.1	55.7	62.4	69.7	75.2	77.2	76.2	73.3	66.6	60.1	52.1
		MCDB		50.9	54.0	62.1	71.4	79.4	84.2	87.6	85.0	79.2	71.9	64.1	55.5
	10%	WB		43.3	45.1	51.5	59.3	67.4	73.7	76.0	74.9	71.7	63.8	56.7	47.0
		MCDB		47.2	50.2	58.5	67.2	75.4	81.7	85.2	82.5	77.2	68.8	60.6	50.6
Mean Daily Temperature Range		MDBR		15.5	16.7	18.4	20.3	20.2	19.6	18.7	18.3	18.6	19.8	18.6	16.0
	5% DB	MCDBR		22.7	24.8	26.8	27.7	26.2	23.2	22.4	21.7	22.1	23.8	23.5	22.7
		MCWBR		17.1	17.3	16.6	14.6	12.2	9.6	8.1	8.3	9.7	13.7	16.1	17.5
	5% WB	MCDBR		20.1	21.3	23.7	24.0	22.7	19.6	19.1	18.6	17.7	19.3	19.6	19.8
		MCWBR		17.2	17.0	16.5	14.0	11.7	9.2	8.2	8.2	9.1	12.5	16.2	17.4
Clear Sky Solar Irradiance	taub			0.319	0.353	0.411	0.417	0.474	0.546	0.552	0.580	0.421	0.370	0.342	0.317
	taud			2.373	2.188	1.997	2.036	1.892	1.746	1.769	1.681	2.164	2.286	2.350	2.446
	Ebn,noon			269	272	266	273	258	239	237	225	261	264	258	262
	Edh,noon			30	40	52	53	62	72	69	74	44	36	31	27

ASHRAE 2009 HOF Weather Data for Baltimore, MD

APPENDIX D – MAJOR MECHANICAL EQUIPMENT

Air Handling Unit Specifications

	Area Served	Airflow (CFM)	Motor (RPM)	LAT (°F)	EWT (°F)	LWT (°F)
AHU-S1	Induction Units	32,000	1800	55	45	55
AHU-S2	South 707	30,000	1800	55	45	55
AHU-S3	North 707	37,000	1800	55	45	55

Chiller Specifications

	GPM	EAT (°F)	Volts/ ϕ	Rated from (°F to °F)
Chiller	1080	85	460/3	54 to 44

Existing Boiler Specifications

	Natural Gas (ft^3/hr)	Steam (psig)	BTU/ ft^3	lbs/hr	HP	BTU/hr
B-1959	10,420	15	1,030	-	250	8,368,750
B-1997	5250	15	-	4,312	125	-

Induced Draft Cooling Tower

	GPM	HP	Volts/ ϕ	Rated from (°F to °F)	OA Condition (°F/°F)
Cooling Tower	1350	30 two speed fan	460/3	95 to 85	95/87

Heating and Ventilating Units

	Airflow (CFM)	Fan Motor (HP)	Heating Coil (MBH)	Heating Coil (GPM)
H&V-1	2,200	3	141	14.0
H&V-2	2,200	7.5	141	14.0

Induction Unit Schedule

	CFM	Air Pressure (in w.g.)	Unit Size (in)
IU-A	90	1.20	40
IU-B	70	1.10	32
IU-C	60	1.28	32
IU-D	45	1.19	32

Pump Schedule

	Service	Type	GPM	Head (ft/H_2O)	RPM	HP
CHP-1	Chilled Water	Horiz. Split Case	1095	65	1780	25
CHP-2	Chilled Water	Horiz. Split Case	1095	65	1780	25
CHP-3	Chilled Water	End Suction	105	50	1750	3
CHP-4	Chilled Water	End Suction	105	50	1750	3
CWP-1	Condensing Water	Horiz. Split Case	1350	85	1780	40
CWP-2	Condensing Water	Horiz. Split Case	1350	85	1780	40
HWP-1	Heating Water	End Suction	315	45	1750	7.5
HWP-2	Heating Water	End Suction	315	45	1750	7.5
CP-1	Boiler	Inline Pump	120	20	1150	1.5
CP-2	Boiler	Inline Pump	120	20	1150	1.5