Walter Reed National Military Medical Center
Bethesda, MD

Final Thesis Report:

System Alternatives Analysis

Prepared For: Dr. James D. Freihaut

Prepared By: Justin Herzing

Date: 04/07/10

Construction Team:

Owner - Naval Facilities Engineering Command
Architect - HKS Inc.
General Contractor - Clark/Balfour Beatty, A Joint Venture
Mechanical Engineer - Southland Industries
Structural Engineer - Cagley & Associates
Plumbing Engineer - Southland Industries
Electrical Engineer - M.C. Dean

Project Information:

Size - 598,895 sf
Occupancy - Medical/Office
Cost - $641 Million
Delivery - Design-Build
Duration - July 2008 to November 2010

Structural System:

-Building A uses a two way flat plate concrete structural superstructure and spread footing foundation. The concrete thickness is 9" and is thickened around structural columns an additional 8"-11"
-Building B uses an all steel superstructure with a concrete slab on metal deck and drilled piers with spread footings for the foundation . Steel beam sizes range from W8 to W33

Lighting System:

-2x4 direct/indirect fluorescent fixtures with two F32 T8 lamps
-Recessed down lights with CFL's
-Task lighting for medical procedures

Architecture:

-Two new buildings are being constructed flanking the existing 1940's era tower
-The building facade is comprised of precast concrete panels and Centria panels above windows
-Building A houses Children's Health, Cancer Treatment Center, Neurology, and Physical Therapy
-Building B houses Operating Rooms, Patient Bedrooms, and The Ambulance Receiving Center

Mechanical System:

-100% Outdoor Air CAV supply
- Eleven custom 50,000 CFM AHU's supply both buildings
-Three 1,000 ton centrifugal chillers and two heat recovery chillers
-Dedicated packaged AHU for the pool in Building A
-Campus steam is reduced for use in domestic hot water and heating hot water
-75 psig steam is supplied to a humidification steam generator

Electrical System:

-13.2 KV is switched to 480/277 V 3-phase 4-wire
-Both buildings have dedicated switchgears for rooms with life safety requirements
-Two new generators will supply both buildings with emergency power

Justin Herzing
Mechanical Option
CPEP SITE: http://www.engr.psu.edu/ae/thesis/portfolios/2010/jmh5093/

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Acknowledgements

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All of my Family for their continued support throughout the years

All my fellow AE students especially Calvin Douglass and Pavel Likhonin, thank you for all of your help throughout the years and making my time and Penn State enjoyable.

Executive Summary:

Buildings A and B are both being constructed on the existing National Naval Medical Center Campus located in Bethesda, Maryland. Building A will be housing areas for services such as the Cancer Treatment Center, Children's Health Area, Medical Staff Offices, and Examination Rooms. Building B is the smaller of the two buildings and is the location for the Ambulatory Receiving Center, Operating Rooms, and houses all of the Patient Bedrooms. The new buildings are striving towards a LEED Silver Rating from the United States Green Building Council.

The mechanical system that is currently designed uses a constant volume supply of 100% outdoor air. The air is supplied to remote CAV boxes located throughout both buildings which helps provide greater occupant comfort. Total energy wheels and heat recovery chillers have been implemented on this project in order to offset some of the costs associated with a 100% outdoor air system. The chilled water plant utilizes electricity to run and the heating demands for both buildings are met by a campus steam plant.

Alternatives were chosen in this report to meet the goals of either reducing the peak energy consumption or reducing the dependence on the campus steam plant. The alternative design options that were selected to be analyzed were decentralizing the supply air fans, adding a backpressure steam turbine, and two configurations for a combined heat and power plant. Decentralized supply fans can potentially reduce the total fan energy required in the building by being able to run at higher fan efficiencies. A backpressure steam turbine was analyzed in parallel with the existing pressure reducing station in order to expand the high pressure campus steam over the blades of the turbine which will reduce the steam to the distribution pressure required while also powering an electric generator. Combined heat and power (CHP) was analyzed with and without the use of a backpressure steam turbine. Utilizing CHP was hypothesized to be able to significantly reduce the quantity of steam required from the campus steam plant as well as utilizing the waste heat to generate electricity which can offset most of the electricity peaks throughout the year.

The CHP plant analyzed utilizes a natural gas fired internal combustion engine which can be very loud when running at full load. An acoustical analysis was performed in order to ensure that the proper noise criteria would still be met in the surrounding spaces through the use of sound absorbing material. Solar shading and day lighting were also analyzed in order to reduce some of the solar load on the building as well as provide a more aesthetically pleasing atmosphere in the exterior occupied spaces.

After the analysis was performed, combined heat and power without the use of the backpressure steam turbine had the lowest twenty year lifecycle cost. However, CHP is a significant investment and if the owner is unable to spend that much capital in the beginning of the project then it is recommended that a backpressure steam turbine be installed in parallel with the pressure reducing station. Both of these options will be able to last well beyond the twenty year life cycle cost assumed as long as proper maintenance is performed regularly. The longer that the owner is able to keep this equipment in good operating condition the more these systems are going to be able to pay off throughout the building life.

1.0 Mechanical System Description

1.1 New Construction Background

Two new buildings are being constructed on the existing National Naval Medical Center located in Bethesda, Maryland. Once complete, the campus will be renamed as the Walter Reed National Military Medically Center as part of the Government's Base Realignment and Closure Program (BRAC). Building A and B will flank an existing historical building that was originally sketched by Franklin Delano Roosevelt and constructed during the early 1940's. This large tower building can be seen on Figure 1 shown below. Building A is the larger of the two buildings and is the location for outpatient services such as Children's Health, Cancer Treatment Center, Neurology, and Physical Therapy. Building B is where Patient bedrooms, Operating Rooms, and the Ambulance Receiving Center are located.

The design of both of the new buildings was influenced heavily by the historic preservation requirements. Special considerations were taken into account in order to complement the existing architectural design as well as match the architectural materials that were used for the existing campus facades. Hartman Cox Architects was hired to be part of the team and to work directly with the State Historic Planning Office (SHPO) as well as the National Capitol Planning Commission (NCPC). The historical considerations of this building played a large role in the building material selection as well as the facade and glazing design.

Figure 1 - Walter Reed Hospital Final Rendering Provided by HKS, Inc.

1.2 Mechanical Design Objectives

An effective Heating, Ventilation, and Air Conditioning (HVAC) system was designed to be installed in the two new buildings being constructed on the WRNMMC Campus in order to provide a comfortable, productive, and safe atmosphere for all building occupants. The HVAC system was designed to exceed the minimum system efficiencies stated in ASHRAE Standard 90.1 and the minimum ventilation rates prescribed in ASHRAE Standard 62.1. Due to the need for this facility to operate year round for 24 hours a day the mechanical system installed must be reliable and robust in order to provide service to patient care areas without any interruption.

Due to the nature of the facility some of the occupants within the buildings may have decreased immune systems due to the medical treatment which they are undergoing. This decreased ability for the body to fight off disease and infection means that there must be a high regards to the air quality throughout both buildings in order to prevent the spread of illnesses. Building pressurization and envelope construction quality help to ensure the quality of air within the space by preventing unconditioned air from potentially leaking within the envelope, condensing on building materials, and being a site for mold or bacteria growth.

The first building that was constructed on the campus in 1940 still stands today which is a testament to the initial quality of construction and meticulous maintenance on the building systems. Both Building A and B must be constructed with this same quality in mind so that these new facilities can serve the needs of the owner well into future decades.

1.3 Mechanical Equipment Summaries

Both Buildings A and B are served from a 100% outdoor air system which supplies conditioned air at a constant volume to the occupied zone. Building A has eight AHU's and Building B has three AHU's as described in Table 1below. The air handling units are located in the each of the buildings respective basement mechanical spaces. Due to the large amount of energy consumption that is associated with having a 100% outdoor air system, eleven total energy wheels were installed in custom duct housings in order to offset some of the energy spent on cooling and dehumidifying such a large quantity of outdoor air. The specifications regarding the energy wheels installed within each specific buildings air handling units are listed below in Table 2. Building A also houses a rehabilitation pool which is served by a dedicated packaged air handler in order to better control the space conditions due to the pools large latent load.

	Airflow (cfm)	Supply Air Temperature (°F)	Filter Rating	EWT (°F)	LWT (°F)	Flow (gpm)
AHU 1A-8A	50,000	55	MERV 14	42	60	265
AHU 1B-3B	50,000	55	MERV 17	42	60	283

Table 1 - Air Handling Unit Specifications

	Sensible Efficiency (%)	Latent Efficiency (%)	Recovered Energy (Mbh)	RPM
EW 1A-8A	83.3	85.9	1778	20
EW 1B-3B	87.5	90.4	1655	20

Table 2 - Energy Wheel Specifications

Chilled water for both buildings is produced by three 1,000 ton water cooled centrifugal chillers which are located in Building A's basement mechanical space. A 180 ton and a 250 ton heat recovery chiller are located in the basement of Building A and B respectively. Both of these waterside device specifications are detailed further in Table 3 below. These heat recovery chillers are able to reduce some of the heating hot water energy consumed by recovering heat from the chillers exiting condenser water stream and using it to produce hot water. Condenser water is piped to the adjacent patient parking structure where three 1,000 ton induced draft cooling towers with specifications listed in Table 4 below are located.

	Type	Nominal Capacity (Tons)	kW/Ton (ARI)	2 Pass Evaporator		2 Pass Condenser	
				EWT (°F)	LWT (°F)	EWT (°F)	LWT (°F)
Chiller 1-3	Water Cooled Centrifugal	1000	0.627	60	42	83	98
HRC-1A	Water Cooled Scroll	180	1.1	60	42	104	125
HRC-1B	Water Cooled Scroll	225	1.1	60	42	104	125

Table 3 - Chiller and Heat Recovery Chiller Specifications

	Arrangement	Nominal Capacity (Tons)	EWT (°F)	LWT (°F)	Airflow (cfm)	Maximum Water Flow (gpm)
CT 1-3	Induced Draft Counter Flow	1000	98	83	190,900	1875

Table 4 - Cooling Tower Specifications

No boilers have been installed in either building due to the existing campus steam generation plant which supplies both buildings with 125 psig steam. This high pressure steam is reduced to either 75 psig or 15 psig and is supplied to either a humidification steam generator or fed to heat exchangers for all of the heating hot water and domestic hot water needs. Two pipe fan coils are used throughout both buildings to condition the electrical and telecommunication closets.

1.4 Airside System Operation

All of the air handlers in both buildings have variable speed drives installed on each of their supply fans. The initial start command is sent based upon an occupancy schedule within the energy management control system. The outside air damper then will start to open and once it has proven the open condition the supply fan will start. Due to the varying occupancies, Building A has an unoccupied mode while Building B does not. During Building A's unoccupied mode the CAV terminal boxes will set back to 30% of the design flow with the air handlers adjusting proportionally based upon the static pressure. Total energy wheels are installed for each air handler with both a heating and cooling mode of operation. The heating or cooling mode of operation is determined by the difference in outside air and return air temperature. The enthalpy wheels will slow their rotation if the freeze protection set point is being triggered in order to prevent the cooling coils from freezing.

1.5 Waterside System Operation

The chillers default mode of operation is that one of the main centrifugal chillers will be base loaded by both of the heat recovery chillers at all times during cooling mode. If the cooling load is not being met by both of the heat recovery chillers then the central chillers will start to come online. A second chiller will start up when the first chiller is running at greater than 70% of its rated load for more than a 20 minute interval as calculated by the chillers flow meter and temperature sensor shown in Figure 2. The same load rating is used to bring the third chiller online or if the chilled water supply temperature exceeds 47°F for longer than 10 minutes the third chiller will begin its start up procedure.

When either two or three chillers are running and the total load falls below 32% of the rated capacity one of the chillers will be shut off. When only one chiller is running and the total load chiller load falls below 10% the chiller shuts down and the chilled water header bypass line is opened. Figure 2 shows an evaporator bypass line which remains closed unless the VFD on the chilled water pump has modulated down to its minimum evaporator flow rate. At this minimum evaporator flow rate the bypass line begins to open in order to ensure that the minimum flow is always going through the evaporator.

Three cooling towers with variable frequency drive motors along with three constant speed condenser water pumps operating in a lead/lag fashion are shown in Figure 3. When the first chiller is required to start, one of the condenser water pumps starts and the cooling tower bypass line begins to open. When another chiller is being brought online it uses the same sequence of pump starting except that this is done five seconds before the additional chiller is brought online in order to maintain minimum flow through the first chiller. When the condenser water supply temperature exceeds its set point for a set duration of time the tower isolation valve begins to open the bypass valve starts closing. Due to one of the chillers being base loaded, cooling tower freeze protection is obtained by pipe heat tracing and having one condenser water pump being on at all time when the outdoor drybulb temperature falls below 32°F.

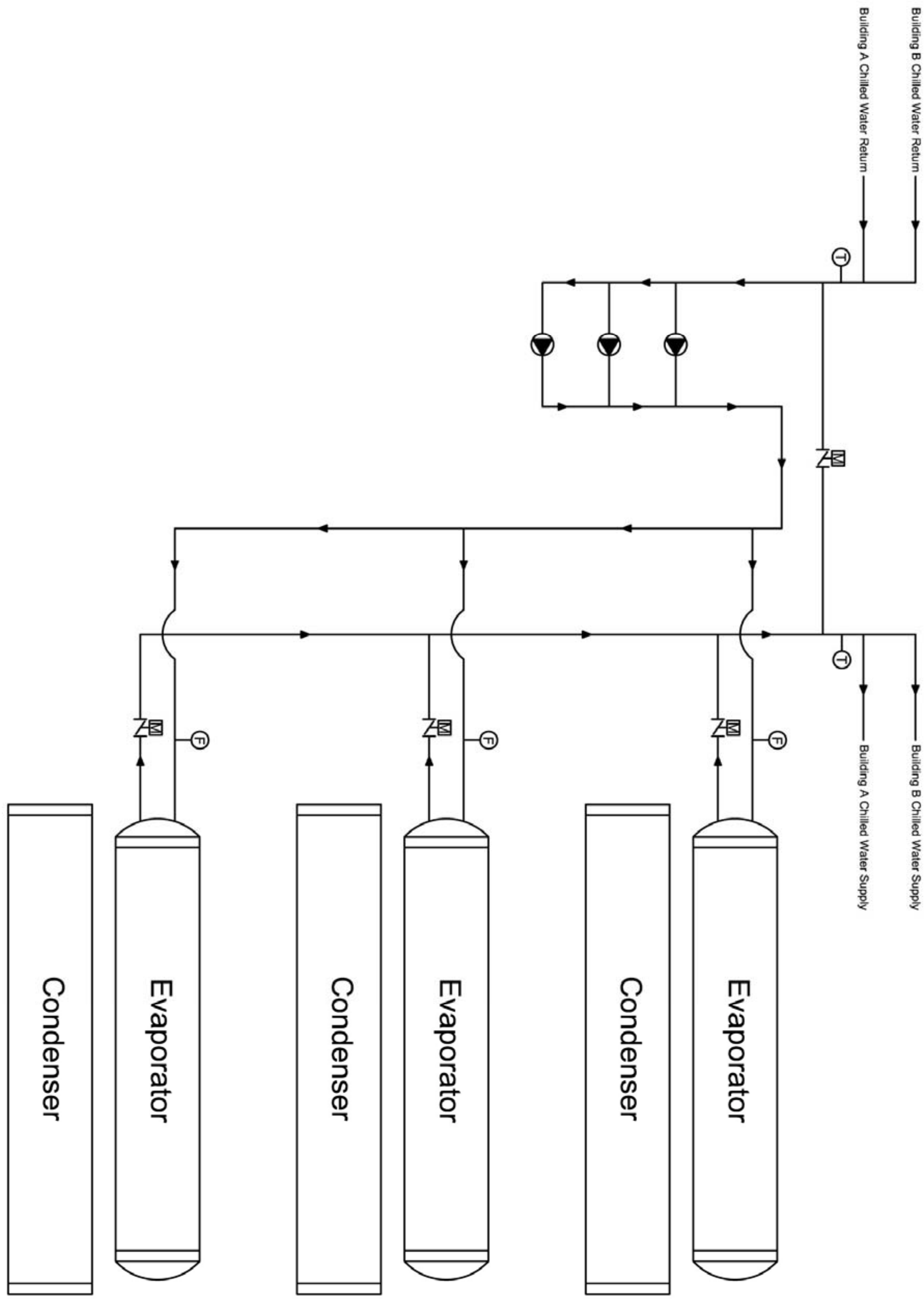


Figure 2 - Chilled Water Schematic

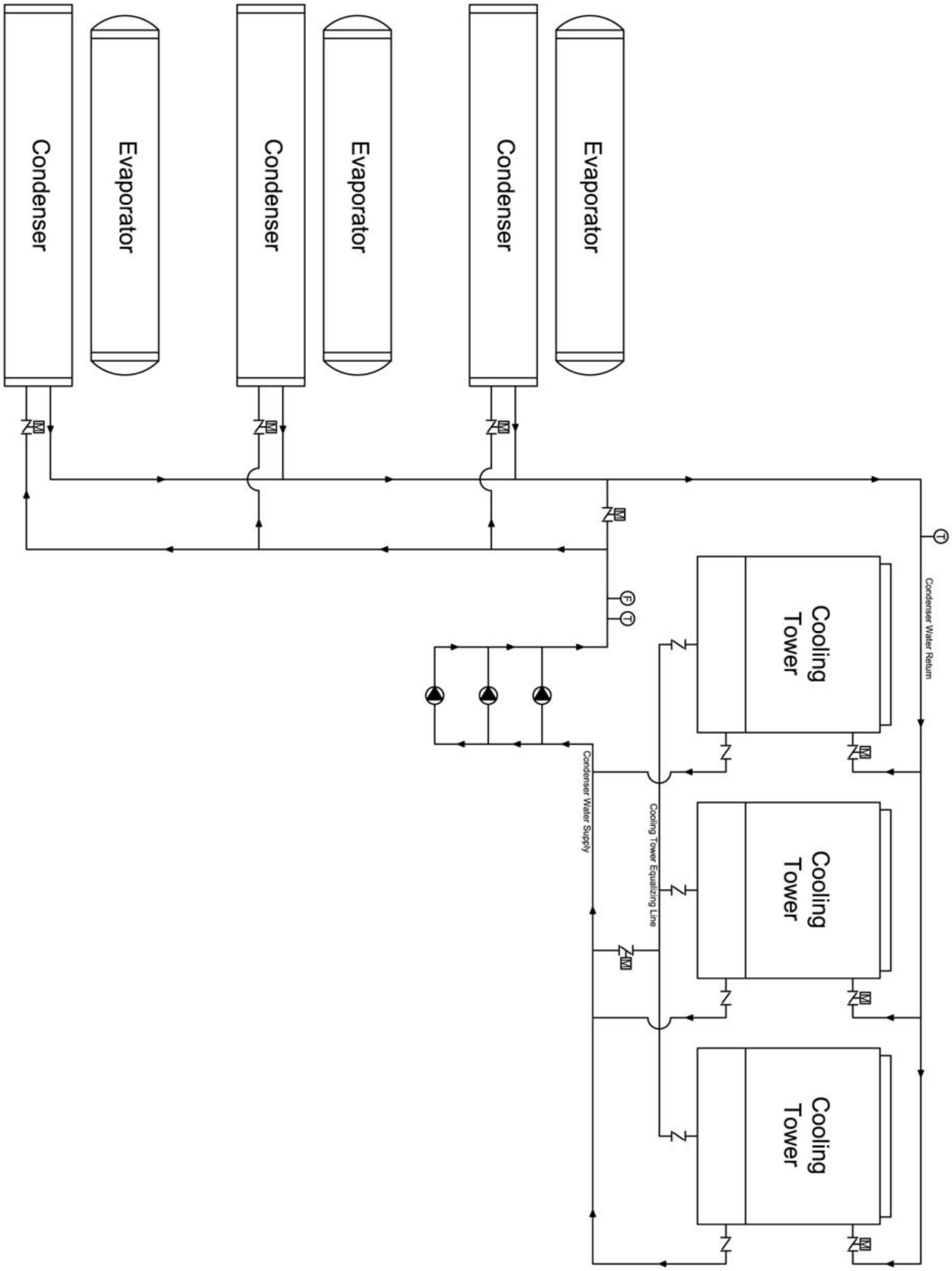


Figure 3 - Condenser Water Schematic

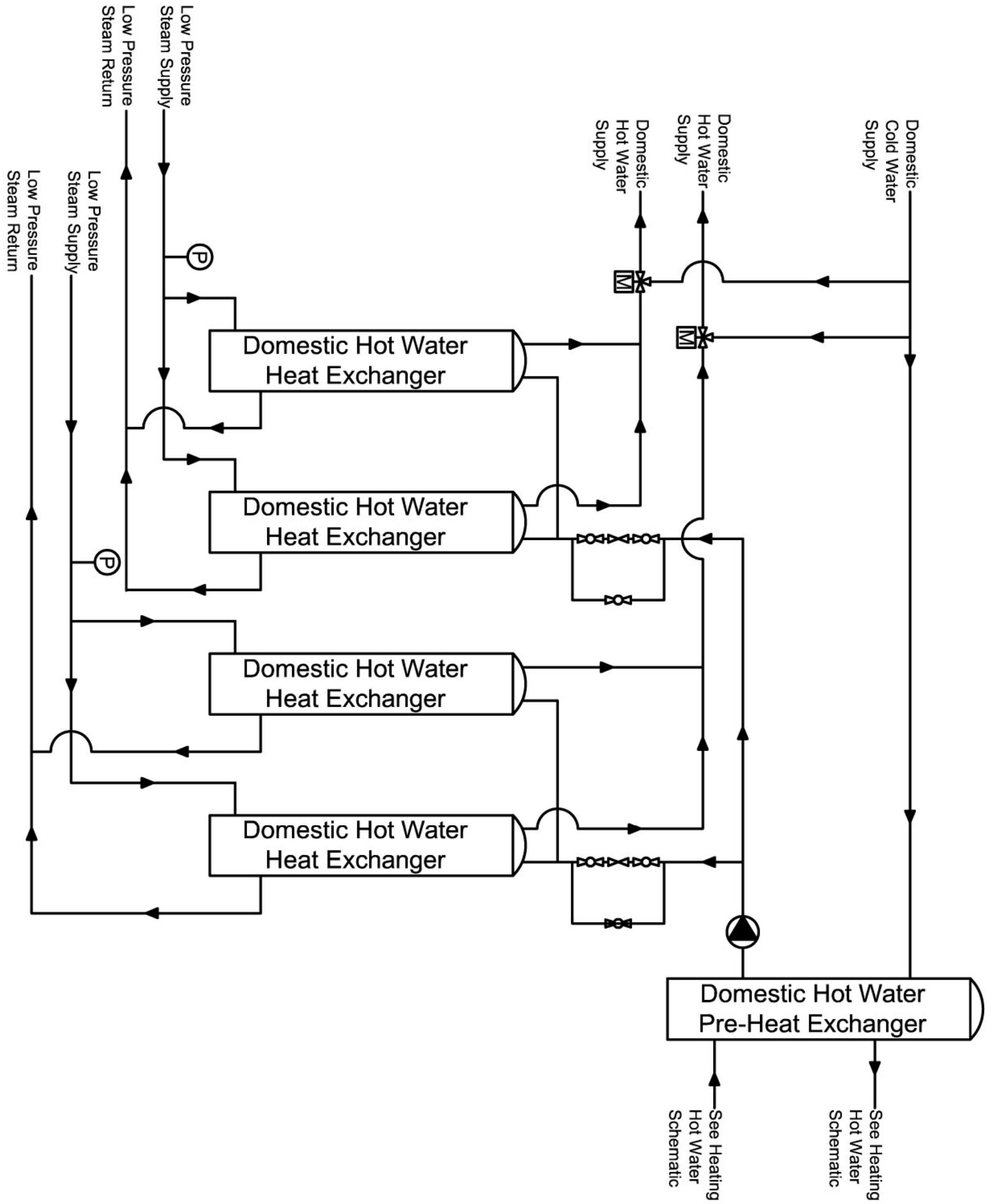


Figure 4 - Domestic Hot Water Schematic

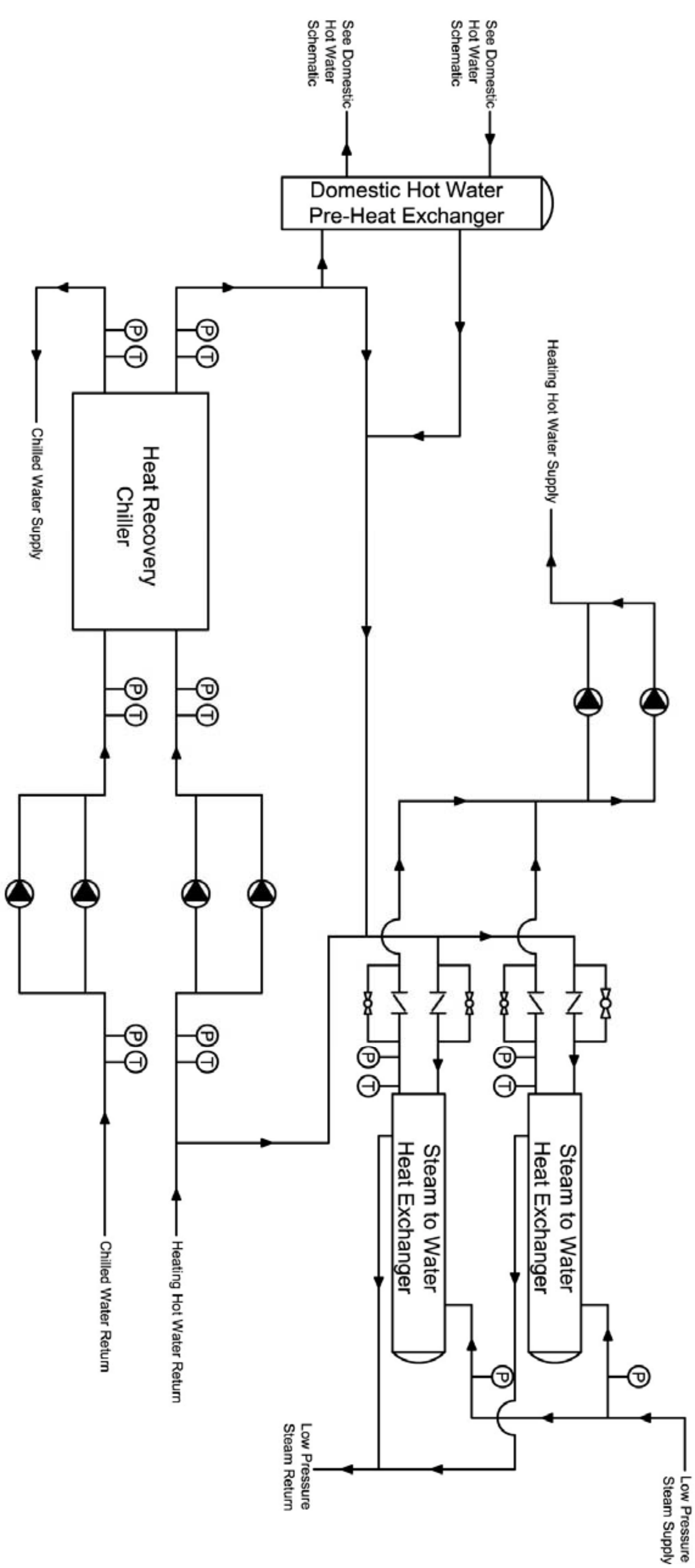


Figure 5 - Heating Hot Water Schematic

1.6 Energy Sources

Possible energy sources that are able to be utilized at WRNMMC include electricity, natural gas, and district steam generated from the campus steam plant. The electricity rates that are available to this site are provided by Baltimore Gas and Electric and the consumption and demand charges are listed below in Table 5 and Table 6. The rates that are charged to the buildings using campus steam were taken from the RFP and are listed in Table 7 below. Natural gas service for this location is provided by Washington Gas and the rate that applies to WRNMMC is outlined in Table 8.

	January - May	June - October	November - December
Electric Demand ($/kW)	4.15	6.15	4.15

Table 5 - Electric Demand Utility Rates

	January - December
Electric Consumption On Peak ($/kWh)	0.13
Electric Consumption Mid Peak ($/kWh)	0.124
Electric Consumption Off Peak ($/kWh)	0.122

Table 6 - Electric Consumption Utility Rates

	January-December
Purchased Steam ($/therm)	2.985

Table 7 - Purchased Steam Utility Rates

	$/therm
Washington Gas	0.89

Table 8 - Natural Gas Utility Rates

In order to better compare the different fuel options available at WRNMMC all of the potential sources have been converted to a price per Btu basis shown in Table 9. This shows that the least expensive source of energy that is available to the site is natural gas and the most expensive is the campus steam. These prices however do not include the added infrastructure cost that needs to be added in order to get utility service from each source. These added costs from excavation, material, space, and schedule requirements need to be considered when deciding what utility service to use.

	$/Mbtu
Electricity	0.0357
Natural Gas	0.0089
Campus Steam	0.0299

Table 9 - Source Energy Comparison

1.7 Design Conditions

The outdoor design conditions that were used for this site are listed in Table 10 and Table 11 along with the indoor design conditions for each space type. The outdoor design conditions were taken from either the ASHRAE Handbook of Fundamentals or from the weather data that was loaded within the TRACE 700 program. The weather data highlighted are the values that were used during this analysis and provide the most conservative values regarding design loads. The indoor design conditions were taken from the mechanical design documents and are listed for both the winter and summer seasons.

	Summer		
	Indoor Design (°F)	Outdoor Design 0.4% (°F)	TRACE 700 Default (°F)
Office	75	94.5	93.2
Exam	75		

Table 10 - Summer Design Conditions

	Winter		
	Indoor Design (°F)	Outdoor Design 99.6% (°F)	TRACE 700 Default (°F)
Office	68	15.9	9.6
Exam	73		

Table 11 - Winter Design Conditions

1.9 Mechanical System Cost

The total mechanical and plumbing system package cost for both of the new buildings is $109,500,000. This system price includes both the design and construction portions due to the project using the design-build delivery method. When this mechanical system cost is broken down on a per square foot basis it yields a cost of $182.84/sf. This mechanical system cost is greater than other building types but due to the size of this facility and the increased ventilation supplied to the building it is a reasonable installed cost.

2.0 ASHRAE Standard and LEED Evaluation

2.1 Design Ventilation Requirements

An analysis was performed using ASHRAE Standard 62.1 to determine the minimum ventilation rates that need to be supplied to the occupied spaces. The HVAC system that was designed supplies a constant volume of 100% outside air to both buildings. This use of a Dedicated Outdoor Air System (DOAS) ensures that the minimum ventilation rates prescribed by ASHRAE Standard 62.1 will always be exceeded.

A ventilation calculation for using a DOAS system was performed and compared the ventilation rates that were calculated by the design engineer. The ventilation rates that were calculated by both the design engineer and within the 62.1 analysis are shown within Table 12. The value that was calculated using Standard 62.1 is 6% lower than the value calculated by the design engineer. The reason for this difference is most likely the simplifying assumptions used. An example of an assumption that was used is that rooms were modeled on a zone basis so individual loads were unable to be tailored to each room modeled. These average miscellaneous and lighting loads that were used are able to provide a reasonably accurate model but if more detail is required then each room should be modeled individually in order to ensure the accuracy of the model.

	CFM
Calculated	489898
Designed	519040

Table 12 - Calculated vs. Design Ventilation

2.2 Design Load Estimates

A Trane TRACE model was created in order to perform a building energy consumption analysis as well as to determine the design heating and cooling loads. This model was also used to help in the LEED certification process in proving the amount of energy that is saved over the ASHRAE Standard 90.1 baseline building. The design engineer performed this analysis using a model that was created on a room by room basis so that the most accurate results could be obtained. A block load model was created for this report in order to compare these results to what the design engineer calculated.

Various cooling, heating, and ventilation check values are listed in Table 13 to compare the block load model results to those that were calculated by the design engineer's model. The values that were calculated using the block load model resulted in larger values in each of the areas except the ventilation air requirements. This result in larger values is most likely due to the simplifying assumptions that were made during the creation of the block load energy model. These values, even though slightly different, still represent an accurate model of the ventilation requirements along with the design heating and cooling load for both Building A and B.

	Cooling (ft²/ton)	Heating (Btuh/ft²)	Supply and Ventilation Air (cfm/ft²)
Building A	230.81	27.48	0.84
Building A Designed	242.34	20.81	0.89
Building B	197.76	41.70	0.82
Building B Designed	224.29	32.93	0.87

Table 13 - Block Loads vs. Design Loads

2.3 Estimated Annual Energy Use

The Trane TRACE model that was used to determine the design heating and cooling load values was also used to perform a full 8,760 hour energy analysis of the designed HVAC system. All of the cooling equipment uses electricity to operate while the heating equipment uses purchased steam from the campus steam generation plant. The equipment that was modeled is based upon the data provided within the mechanical equipment schedules from the design documents. Other design parameters that were modeled are the use of occupancy, lighting, and equipment schedules which are detailed more within Appendix B of this report.

The design engineer performed a yearly energy analysis as well which resulted in a use of 69,351 MMBtu. The block load model that was created for this report resulted in a yearly energy consumption of 74,010 MMBtu. These two models differ by only 7% in their energy consumption values which is most likely a result of the simplifying assumptions that were discussed earlier.

The energy consumption breakdown by mechanical subsystem for the block load energy model is shown in Figure 6 below. The category which consumes the largest portion of energy is the supply fans due to the large volume of air that they need to push from the basement throughout the entire building. Another reason that the fans consume a large portion of energy is their need to overcome the large static pressure drop created by the total energy wheels.

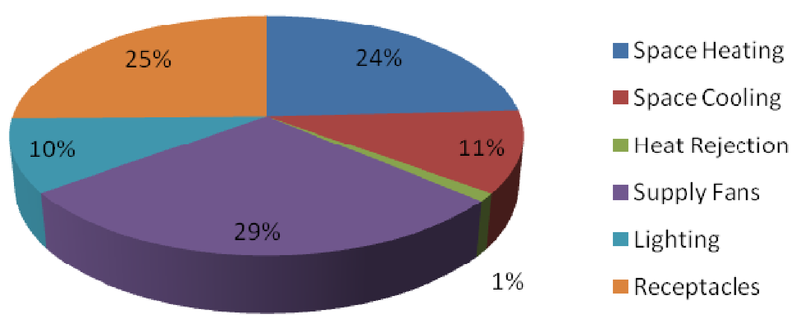


Figure 6 - Mechanical Equipment Energy Consumption

2.4 LEED®-NC Analysis

The Leadership in Energy and Environmental Design (LEED®) was created by the United States Green Building Council (USGBC) in order to help both building owners and design teams realize the importance of energy efficient and environmentally friendly construction practices. LEED has two primary categories that are influenced directly by the mechanical design engineer which are Energy and Atmosphere (EA) along with Indoor Environmental Quality (IEQ). Currently WRNMMC is seeking to receive the LEED Silver certification. During this analysis only the potential credits from these two sections that are affected by the mechanical system were analyzed.

2.4.1 Energy and Atmosphere

EA Prerequisite 1: Fundamental Commissioning of Building Energy Systems - Yes

Intent: To ensure that the buildings mechanical system is installed and adjusted as specified by the design engineer

WRNMMC: A commissioning authority with previous new construction commissioning experience will perform a full controls and mechanical system run through. All results that are gathered from the commissioning reports will be compiled and reported directly to the owner upon completion of the project.

EA Prerequisite 2: Minimum Energy Performance - Yes

Intent: To set forth minimum energy efficiency levels that must be met by the designed systems.

WRNMMC: As detailed in Technical Report One both Building A and B comply with ASHRAE Standard 90.1-2007 along with exceeding the minimum 10% energy improvement over the ASHRAE 90.1-2007 Appendix G baseline building.

EA Prerequisite 3: Fundamental Refrigerant Management - Yes

Intent: To make a reduction in the use of CFC based refrigerants that contribute to stratospheric ozone depletion.

WRNMMC: All of the refrigeration equipment that is used within the facility uses R-134a or R-407c which are both HFC refrigerants.

EA Credit 1: Optimize Energy Performance - Yes

Intent: To achieve higher levels of energy efficiency within the buildings systems

WRNMMC: The ASHRAE Standard 90.1-2007 baseline building was calculated to consume 94,063 MMbtu/year at a cost of $2,255,330. The model that was created by the design engineer showed an energy use of 69,351 MMbtu/year resulting in a utility cost of $1,623,215. This energy cost reduction results in a savings of 28% a year on the buildings utility bills. A 28% reduction in energy costs results in a total of 9 points being awarded using the table given within this subsection of the LEED manual.

EA Credit 2: On-site Renewable Energy - No

Intent: To help reduce the associated impacts from using fossil fuel energy sources.

WRNMMC: The design engineers on this project did not incorporate the use of any renewable energy sources such as solar, wind, geothermal, or biomass. The result is that this project does not receive any points for this credit.

EA Credit 3: Enhanced Commissioning - Yes

Intent: To extend the commissioning process early into the design phase as well as extend it to after the design is complete for performance verification testing.

WRNMMC: A separate commissioning authority, Goetting & Associates, Inc., have been hired by the MEP team for all of their commissioning needs. Training and systems operations manuals will be turned over to the owner upon completion of the project in compliance with this section. The commissioning agent will also provide the results of any findings directly to the owner of the project. This results in the project receiving two points for completion of this credit.

EA Credit 4: Enhanced Refrigerant Management - Yes

Intent: To reduce atmospheric ozone depletion and support of the Montreal Protocol

WRNMMC: Since refrigerants are being used within the building the following formula must be followed.

$$LCGWP + (LCODP \times 10^5) \leq 100$$

Where:

$$LCODP = \frac{[ODPr \times (Lr \times Life + Mr) \times Rc]}{Life}$$

$$LCGWP = \frac{[GWPr \times (Lr \times Life + Mr) \times Rc]}{Life}$$

LCODP: Lifecycle Ozone Depletion Potential

LCGWP: Lifecycle Direct Global Warming Potential

GWPr: Global Warming Potential of Refrigerant

ODPr: Ozone Depletion Potential of Refrigerant

Lr: Refrigerant Leakage Rate (2%)

Mr: End of Life Refrigerant Loss (10%)

Rc: Refrigerant Charge (lb/ton)

Life: Equipment Life (20 years)

When using this equation for all of the equipment containing refrigerant along with the associated values corresponding to each type of refrigerant used, a total of 89.27 was obtained which is less than the maximum of 100 for this point. This results in two points being received for this credit.

EA Credit 5: Measurement and Verification - No

Intent: To make buildings accountable for the energy that they use.

WRNMMC: This project will not be monitoring their energy use for an entire year after post construction occupancy. This credit is expensive to obtain and was not required by any contract documents. However, the mechanical engineer will be monitoring the performance of the energy wheels and heat recovery chillers to verify that the expected performance is being obtained. The result is that this project does not receive any points for this credit.

EA Credit 6: Green Power - No

Intent: To use renewable energies through the electricity grid.

WRNMMC: This project will not be purchasing any of its power through such a program that generates electricity using green power. The result is that this project does not receive any points for this credit.

2.4.2 Indoor Environmental Quality

IEQ Prerequisite 1: Minimum Indoor Air Quality Performance - Yes

Intent: To enhance occupant well being by establishing minimum indoor air quality performance requirements.

WRNMMC: Sections four through seven in ASHRAE Standard 62.1-2007 have been met as detailed in Technical Report 1. Mechanical ventilation was used in all of the spaces and has been designed using the ventilation rate procedure outlined in ASHRAE Standard 62.1-2007.

IEQ Prerequisite 2: Environmental Tobacco Smoke (ETS) Control - Yes

Intent: To minimize building occupants and indoor surfaces exposure to ETS.

WRNMMC: Both of the new buildings do not allow smoking inside them due to the nature of the work being performed. Smoking is also only permitted in designated smoking areas throughout the entire campus which is in compliance with this credits requirement.

IEQ Credit 1: Outdoor Air Delivery Monitoring - No

Intent: To promote occupant well being within ventilated spaces.

WRNMMC: With the ventilation system being 100% outdoor air it was not deemed necessary to measure the CO_2 concentrations within the spaces due to the constant volume of air being supplied. The result is that this project does not receive any points for this credit.

IEQ Credit 2: Increased Ventilation - Yes

Intent: To supply additional outdoor air to occupied spaces to improve indoor air quality (IAQ).

WRNMMC: The ventilation rates supplied to each occupied zone exceed the 30% increase over ASHRAE Standard 62.1-2007 as stated within this section. The design engineer thought that it was important for the occupant's safety to try and eliminate the spread of particles and disease by the use of a constant volume 100% outdoor air system. This results in the project receiving one point for successful completion of this credit.

IEQ Credit 3.1: Construction Indoor Air Quality Management Plan (During Construction) - Yes

Intent: To reduce Indoor Air Quality (IAQ) related problems resulting from the construction process.

WRNMMC: A standard practice adopted by the mechanical team is that all ductwork being shipped to the site have a protective plastic sheathing already installed prior to entering the construction site. This protective sheathing prevents building construction products from being entrained within the ductwork while it is waiting to be installed. All of the filters on the air handling systems exceed the minimum MERV 8 rating that is stated within this section. The result is that this project receives one point for this credit.

IEQ Credit 3.2: Construction Indoor Air Quality Management Plan (Before Occupancy) - Yes

Intent: To reduce IAQ related problems resulting from the construction process.

WRNMMC: After construction is complete a total building flush out will be performed by letting the HVAC system run in order to help reduce the levels of indoor contaminants that the building occupants are initially exposed to from material off gassing. One point is able to be awarded based upon completion of this credits requirements.

IEQ Credit 4.1: Low-Emitting Materials Adhesives and Sealants - Yes

Intent: To reduce the quantity of contaminants which are harmful to the construction team or building occupants.

WRNMMC: All adhesives that were used within the building met or exceeded the maximum VOC limits stated within this subsection. The result is that this project receives one point for this credit.

IEQ Credit 6.2: Controllability of Systems (Thermal Comfort) - No

Intent: To promote thermal comfort control for individual occupants.

WRNMMC: Due to the large size of this building, rooms with similar occupancies were zoned together and served by a single CAV box with one corresponding thermostat. Due to this zoning technique less than 50% of the occupants within the building have access to individual temperature control systems making this credit unattainable. The result is that this project does not receive any points for this credit.

IEQ Credit 7.1: Thermal Comfort (Design) - Yes

Intent: To provide a thermally comfortable environment to help promote occupant well-being.

WRNMMC: All of the Heating Ventilation and Air Conditioning (HVAC) systems that were designed for both buildings meet the criteria stated by ASHRAE Standard 55-2004. The result is that this project receives one point for this credit.

IEQ Credit 7.2: Thermal Comfort (Verification) - No

Intent: To asses that acceptable thermal comfort is achieved after occupancy

WRNMMC: A thermal comfort survey must be conducted 6 to 18 months after occupancy and result in less than 20% of the occupants being dissatisfied. There are currently no plans to provide a survey of this nature which results in no points being awarded for this credit.

3.0 Overall System Evaluation

Due to the large size of the building and the type of occupancy, this projects mechanical system needed to provide a healthy atmosphere for its occupants at a low operating cost due to the year round operation. A constant volume 100% outdoor air system was selected to be used for this project due to the inherent IEQ benefits, improved constructability, and reliability. The design engineer realized that this system would consume more energy than comparable VAV systems with OA minimum intakes but the engineer and owner felt that this was the best system for the project. In order to reduce some of the associated energy costs total energy wheels and heat recovery chillers have been installed.

The cost to for the design and installation of the mechanical system is $109,500,000 or roughly $182.84/sf. The mechanical system represents approximately 17% of the buildings entire construction cost. Typically building mechanical system costs represent 15%-20% of the total budget so this system falls in the middle of this estimate. The operating cost of the designed mechanical system saves the owner over $600,000 a year when compared to the baseline building.

The space that the mechanical system occupies is mainly concentrated in the basement of both buildings. This can be viewed as a positive aspect in that all of the equipment is centrally concentrated making for easy installation as well as convenient for the maintenance staff. However, potential fan energy savings may be realized once a study is completed for decoupling the centralized fans from the basement to individual floors.

Large plenum spaces are also required on this project to allow both the supply and exhaust ductwork to be routed simultaneously. Ductwork size may be able to be reduced by using a cooling system that is water based. Water is an effective means of transferring thermal energy due to the large heat capacity relative to air. Reducing the size of plenum spaces will also reduce the overall cost of construction due to the direct reduction in floor heights.

The indoor air quality throughout both buildings should be a significant improvement over the baseline building due to the use of improved filters as well as dedicated outdoor air supplied to each room. With no recirculation aspect throughout the mechanical system potential building contaminants will not be spread easily throughout the interior zones.

The buildings thermal comfort and environmental control are provided by distributed CAV boxes throughout the building. Each of these CAV boxes usually serves more than one room of similar occupancy. These room zones should not prove to have problems with thermal comfort due to the similar occupancy and load types that were grouped together during zone assignments.

Overall the mechanical system that was designed for Buildings A and B uses the foundation of a reliable CAV system while adding energy reduction measures to provide an advanced HVAC system for the owner. The mechanical engineer has been able to provide such a system by using creative system design and coupling it with an integrated building control system. Making improvements on this system will provide a challenge but areas of potential redesign have risen and will be investigated.

4.0 Mechanical System Redesign Proposal

4.1 Proposed System Alternatives

The existing constant volume system that was designed meets the needs of the facility owner at a justifiable system cost. Other system options to help reduce the initial cost, total energy cost, decrease the payback period, or require less physical space have been chosen to be investigated. Making changes in each of these aspects requires an in depth evaluation into system redesign options.

There is an extensive list of areas that can be redesigned or adjusted within the entire mechanical system for such a large building in order to optimize the system design as a whole. Due to time limitations, all of these specific options are unable to be considered in this project. Below is a list of changes that could be made to the existing system design with varying levels of complexity associated with each alternative.

-Reduce OA fraction and supplement with space radiant panels
-Replace the existing pressure reducing station with a backpressure steam turbine
-Investigate changing to a Primary/Secondary pumping system
-Decentralize the fans from the basement to individual floors
-Investigate the use of boilers instead of the campus steam plant
-Change from CAV to VAV (also investigate demand control ventilation)
-Investigate utilizing Combined Heat and Power (CHP)

This is just a portion of the list that could be compiled for a project of this size and occupancy. Three topics have been chosen out of the list above to be studied further. These topics were chosen based upon initial investigations as shown below and their educational interest to study. When changes are made to the mechanical system they usually affect many other parts of the entire system. Due to this fact a lifecycle cost analysis will be performed on all of the system alternatives investigated to see which option results in the lowest lifecycle cost.

4.1.1 Decentralizing Supply Fans

Having centralized supply fans for an air distribution system has inherent benefits that need to be addressed before decentralizing the supply fans can be discussed. When there are a central group of supply fans located in one area of the building the installation cost goes down per supply air cfm designed compared to using a distributed fan arrangement. This is due to the installation team only having to set up equipment in one area instead of moving to remote locations throughout the building. Even though the physical size of the fan is larger the time and cost are both less for the larger fan size.

Another benefit of having large fans, or any mechanical equipment, is that the total equipment cost is less than when compared to a larger quantity of smaller capacity items. The area of savings that comes from decentralizing fans from one area is in the total fan energy usage. The way that the fan horsepower is calculated is based upon the equation below.

$$W_{sh} = \frac{Q \times \Delta P}{6350 \times \eta_{total}}$$

Where:
Q = Total Flow (CFM)
ΔP = Total Pressure Drop (in. wg)
η = Total Fan Efficiency
W_{sh} = Shaft Horsepower

The following example is used to illustrate on a preliminary basis the potential fan energy savings that could be realized for the building. The subscript numbers designate which floor the value is representing. The first calculation was done assuming that one centrally located supply fan is serving both floors.

Q_1 = 25,000 cfm

Q_2 = 15,000 cfm
ΔP_1 = 2 in wg.
ΔP_2 = 2.75 in wg.
η = .85

$$W_{sh\ total} = \frac{(25{,}000 + 15{,}000) \times (2.75)}{6350 \times .85}$$

$$W_{sh\ total} = 20.4\ HP$$

When the fans are centrally located this results in a fan shaft horsepower of 20.4. The next set of calculations shows what the fan sizes would be for individual fans serving the first and second floor individually.

$$W_{sh\ 1} = \frac{(25{,}000) \times (2)}{6350 \times .85}$$

$$W_{sh\ 1} = 9.26\ HP$$

$$W_{sh\ 2} = \frac{(15000) \times (2.75)}{6350 \times .85}$$

$$W_{sh\ 2} = 7.64\ HP$$

$$W_{sh\ total} = 16.9\ HP$$

When decentralizing the fans it results in a 17% reduction in total horsepower. Since the supply air quantities are much larger in Building A and B it can be assumed that the potential total fan horsepower savings could be significant. A study will be completed in order to determine if the total energy savings potential is able to offset the additional cost of the fan installation and provide a reasonable payback period to the owner.

4.1.2 Backpressure Steam Turbines

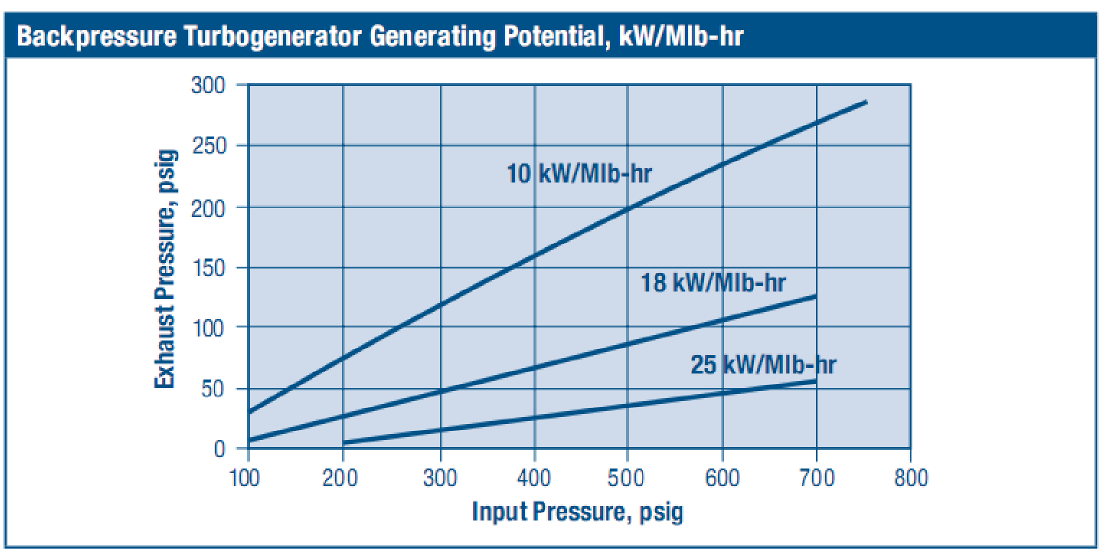
The steam pressure reducing stations that are designed to be installed in Building A will be reducing the steam generated by the campus steam plant to lower pressure to be supplied through the building by using pressure reducing valves in combination with fixed orifice plates. In reducing the pressure of the steam this way there is a significant amount of wasted energy that is released by changing the pressure of such a large mass flow rate. An alternative approach to using pressure reducing stations is through the use of backpressure steam turbines.

Backpressure steam turbines operate similar to turbines that are used in a conventional Rankine cycle power plant. Steam at a high pressure is introduced into the turbine and fed through the blades of the turbines rotor. The blades of the rotor are connected to a shaft which is attached to an electrical generator. The supply steam pressure is reduced when some of the energy in the high pressure steam is used to rotate the turbine rotor blades. After the steam passes through the turbine it exits at the same low pressure that would be achieved after using the pressure reducing station.

Obviously the main advantage in using this approach compared to the conventional steam pressure reduction is the additional electric generation that is achieved from this mechanical process. The main downfall in using a backpressure steam turbine is the large initial cost of the equipment and still the need to install a pressure reducing station in parallel with the turbine in case of turbine failure. While the initial cost may be significant, both of the new buildings on the campus will be utilized well into the future. This presents an opportunity for a case study to take place comparing the payback period to the upfront cost of the equipment.

In order to get a preliminary approximation on how much generation capacity is available in replacing the pressure reducing stations Figure 7 was used from the department of energy. The steam that is supplied to the pressure reducing stations in Building A is at 120 psig and is reduced to 15 psig. When this point is plotted on it falls close to a value of 18 kW/Mlb-hr. The total steam capacity that the pressure reducing station is rated at is 22,650 lb/hr. To get an estimate on the maximum potential electricity generation when using a backpressure steam turbine the steam flow rate and the value from the chart are multiplied by each other to yield a value of 408 kW.

This 408 kW generation would only occur when both buildings are simultaneously calling for their design capacities. The likelihood of this occurrence is rare but if the buildings call for roughly 50% - 75% of their load during the heating season this can result in roughly five months at an electric generation capacity in the range of 204 kW–306 kW. This electric generation will be able to offset a significant portion of the electric demand for both of the buildings and may prove to be a worthwhile investment.



Note: Assumes a 50% isentropic turbine efficiency, a 96% efficient generator, and dry saturated inlet steam.

Figure 7 - Backpressure Steam Turbine Generating Potential

4.1.3 Combined Heat and Power

Combined Heat and Power (CHP) is an alternative technique to conventional heating and electricity distribution. CHP is unlike separate heat and power (SHP) because it is the production of steam while using the exhaust gas for electricity generation. CHP's largest advantage over SHP is that the distribution losses associated with the transmission of electricity across the grid are greatly reduced. Figure 8 below shows the associated losses and thermal input requirements for the same electricity and heat output demands for both CHP and SHP.

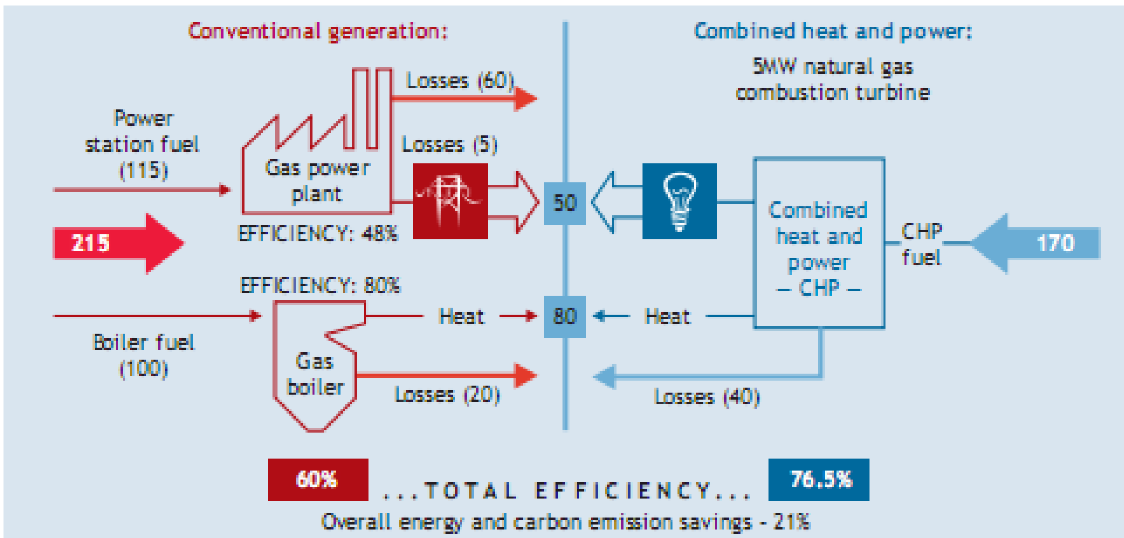


Figure 8 - SHP vs. CHP Input and Losses

The operation of a CHP plant starts with a prime mover which converts the fuel input directly into mechanical power which commonly drives an electric generator. Common prime movers that are utilized for CHP are reciprocating engines, gas turbines, and fuel cells. The hot exhaust gas from the combustion process within the prime mover is then diverted through a heat recovery steam generator or an absorption chiller to produce heating or cooling capacity.

There are a few basic checks that need to take place in order to determine the potential effectiveness of a CHP system for a site. The first value that needs to be investigated is the occurrence of the heating and electricity loads. What is desired about these values are a generally flat load profile throughout the entire day with simultaneous thermal and electric demands due to the large efficiency drop off when prime mover is throttled to fractional operation. The load profiles of both buildings will be more level than other facilities due to the fact that Building B has 24 hour operation.

Another factor that needs to be considered for the viability of CHP systems is the spark gap which is the price difference between electricity and the fuel that you are using for your system. The larger the spark gap means that utilizing CHP will be more realistic for that particular site application. The spark gap between electricity and natural gas for WRNMMC is 8.9 and the spark gap between campus steam and natural gas is 21. As suggested by the Midwest CHP Application Center a spark gap of greater than $12/MMbtu is usually recommended in order for CHP to be a realistic alternative.

Even though the spark gap between electricity and natural gas is not as high as recommended CHP still may be a worthwhile investment for the owner due to the large spark gap that exists between the campus steam that is currently used. Further investigation will need to be done in order to determine the added initial cost to the system and the total lifecycle cost of the system.

4.2 Tools for Analysis

In order to provide a complete analysis on all of the potential system changes that have been previously described, numerous tools are need to be utilized. Descriptions of these tools will be utilized to examine each of the alternatives is given below.

4.2.1 Tools for Decentralizing Supply Fan Analysis

The main tool that will be utilized to perform the analysis for decentralizing the supply fans will be a customized program using Engineering Equation Solver (EES). This program along with various Microsoft Excel charts will be able to compare the benefits of adding smaller fans throughout the system while incorporating the additional associated costs. These results may also be entered as an input into the Trane TRACE model that was created for earlier technical reports.

EES is a valuable tool when used for solving large sets of simultaneous equations with exact state property values. Performing parametric studies to conclude how changes with set points such as supply temperature affect other variables within the system is done with relative ease. The main drawback in using this program is the limited user knowledge and difficulty in analyzing errors when they arise within equation sets.

Microsoft Excel is very similar in use to EES except that state functions are not built directly into the program. Excel will mainly be used for this project in setting up large spreadsheets of data with numerous equations and values built within each cells. Again the drawback with using this program is the user knowledge, but for the capacity in which it will be used within the study this is not foreseen to be an issue.

Trane TRACE is a load and energy modeling software that is able to model in depth various mechanical systems with different configurations. Advantages to using this program are that TRACE is able to run yearly simulations quickly with multiple alternatives to simultaneously compare the results calculated. TRACE also has an excellent user support staff that has been used on numerous occasions to help in creating accurate models and diagnosing file errors. A drawback when using this program is that the equations that are used for the calculations are buried within written code and not easily accessible to the user to investigate how results are calculated. One further drawback, that is associated with all computer programs, is the results that are solely based upon the accuracy of the inputs given.

4.2.2 Tools for Backpressure Steam Turbine and CHP Analysis

The tools that will be used for this analysis are the same as described in section 2.1. These tools are very versatile in their uses and can be applied to model many different cases. The main tool that will be used within this subsection is Trane TRACE for all of the reasons stated above. Having hourly energy simulations will be able to most accurately convey the benefits of the simultaneous generation of electricity and heat.

Equipment cost data needs to be gathered in order to determine the upfront and life cycle cost data for the proposed system redesign. In order to obtain the most accurate pricing information given today's economy, equipment vendors are going to be utilized as often as possible to ensure pricing accuracy. Some aspects of the redesign will be unable to have cost information provided by the manufacturer so other references such as R.S. Means will be utilized for these areas. Another area that may be used for installation cost information is actual HVAC contractors to receive rough man hour prices to perform various installation tasks.

4.3 Additional Topics

4.3.1 Solar Load Reduction

An analysis on the inherent value of solar shading will be considered for both Building A and B. External solar shading was not initially included on the architectural façade due to the requirements set forth by State Historic Planning Commission for the new buildings constructed. With these requirements noted, an analysis will be performed to see the load reduction possibilities for electronically controlled solar shading. External electronically controlled solar shading is proposed due to all of the solar energy reduced not entering the interior space as would be the case with traditional interior shading.

The building load reduction that may be seen after solar shading is analyzed will be put in terms of a total cost savings with energy and equipment. This cost savings when presented to the owner may justify the added cost or architectural façade redesign that may need to take place in order to have this idea approved by the State Historic Planning Commission.

4.3.2 Central Plant Acoustics

When a change is proposed to the existing mechanical room by the addition of new equipment such as a gas fired turbine, an acoustic evaluation must take place to see what effects have been rendered on the acoustic performance within the space itself and in the adjacent spaces. The acoustics in the mechanical room will change greatly with the addition of equipment for the proposed CHP and backpressure steam turbine investigations. Most likely the result will be an increase in sound level within the space which will need additional absorption and isolation in order to mitigate the travel of sound to the surrounding occupied spaces. This investigation will be into the changes in sound level within the mechanical room and proposed solutions to achieve acceptable sound reduction so disturbances are not noticed within the surrounding spaces.

5.0 Decentralized Fan Analysis

5.1 Analysis Procedure

In order to calculate the potential savings using decentralized supply fans new fan zones had to be selected. The zones were selected by assigning a single fan to each specific floor for each specific supply shaft. For example, if a supply shaft was serving six floors it would have six total fans for that supply shaft. The ductwork layout and rooms served from each shaft were not changed during this analysis procedure.

In order to only compare the savings associated with the decentralizing the supply fans the same fan type and configuration were used during the energy analysis and life cycle cost analysis. The type of fan that was used for this analysis was a backward inclined centrifugal fan with a variable speed motor. These new fans would be located in the existing shaft space provided. However, a slight architectural redesign of these spaces may need to take place to allow for adequate clearance for the ductwork elbows and fittings. This architectural redesign was not examined within this report but it seems as if it would be a feasible task with a slight rearrangement of spaces and perhaps a slight adjustment to the size of adjacent rooms.

The total number of supply fans that are installed using the centralized approach is eleven and the number of fans using the decentralized approach is forty eight. The static pressure for each of these decentralized fans was calculated and ranges from 2.1 in. wg to 6.5 in. wg. The fans were identified using the building location, shaft number, and floor number. Each of the proposed fans along with the unit price is listed in Table 14 below. An excerpt from the spreadsheet for one day is shown in Appendix C to show the calculation procedure.

Increasing the total number of supply fans by such a significant amount is going to add drastically to the first cost of this system in the unit pricing as well as the installation cost. Also, having fans located on each floor will be more difficult for the crews installing them because they are going to have to set up their tools in multiple locations. Having to move the fan installation crew around to various locations in the building will add both time and money to the job. These are things that must be discussed with the project manager early in the design phase so that the scheduling of these crews does not interfere with other trades who need to be in that area.

Seeing all of these areas of increased cost and time to the project means that the decentralizing the supply fans will have to save a fairly large portion of energy a year in order to have a reasonable payback period. The fan controls will also need to be examined by the design engineer to make sure that fans that supply areas within the office building whose airflows are able to be reduced are able to still make the total static pressure to draw air through the AHU, enthalpy wheel, and the supply duct run. All of the fans must also convey information back to the position of the supply and economizer dampers in the AHU in order to ensure that everything works properly and in the most efficient manner.

Fan Tag	Flow Rate (CFM)	Total Static Pressure (in. wg)	Cost	Fan Tag	Flow Rate (CFM)	Total Static Pressure (in. wg)	Cost
WRA-1-1	6220	4.2	$4,228	WRA-6-1	9400	2.1	$4,839
WRA-1-2	12210	4.3	$5,853	WRA-6-2	13440	2.7	$6,613
WRA-1-3	12615	5.2	$6,180	WRA-6-3	9960	3.7	$5,305
WRA-1-4	11075	5.4	$5,565	WRA-6-4	9010	4.0	$5,037
WRA-1-5	10300	5.0	$5,565	WRA-7-1	9510	3.6	$5,305
WRA-1-6	8380	5.6	$5,282	WRA-7-2	14130	3.0	$6,312
WRA-2-1	12800	6.1	$6,333	WRA-7-3	8780	3.7	$5,305
WRA-2-2	11205	4.5	$5,565	WRA-7-4	10380	5.2	$5,628
WRA-2-3	13545	5.5	$6,333	WRA-7-5	8910	4.2	$5,037
WRA-2-4	13090	5.9	$6,333	WRA-7-6	9990	4.7	$5,565
WRA-2-5	13890	6.5	$6,665	WRA-8-1	5985	3.5	$4,386
WRA-2-6	23420	5.9	$8,622	WRA-9-1	8430	3.7	$5,037
WRA-3-1	3220	3.1	$3,591	WRA-B1-B	17510	3.1	$6,850
WRA-3-2	7360	2.9	$4,563	WRA-B2-B	5310	2.9	$4,098
WRA-3-3	10420	4.2	$5,565	WRB-1-B	2025	2.2	$3,474
WRA-3-4	9390	4.7	$5,297	WRB-1-1	19305	4.4	$7,298
WRA-3-5	5640	4.5	$4,228	WRB-1-2	12975	3.7	$5,853
WRA-3-6	6780	4.9	$4,860	WRB-1-3	12060	4.9	$5,565
WRA-5-B	5175	2.7	$4,098	WRB-1-4	10765	4.9	$5,565
WRA-5-1	4800	2.1	$3,963	WRB-2-B	4105	2.8	$3,812
WRA-5-2	7660	2.9	$4,563	WRB-2-1	12575	4.2	$5,853
WRA-5-3	7450	2.8	$4,563	WRB-2-2	17645	4.5	$6,877
WRA-5-4	7920	3.8	$4,563	WRB-2-3	14535	5.3	$6,606
WRA-6-B	10871	3.1	$5,593	WRB-2-4	9600	4.2	$5,305

Table 14 - Decentralized Supply Fans

5.2 Analysis Results

A Trane TRACE model was created to calculate the potential savings that may result from using decentralized supply fans. A separate system was created for each supply fan with the associated static pressure drop and rooms assigned to it. The only parameters that were changed from the centralized model were associated with the supply fan and no parameters were changed with respect to the exhaust fans.

A full 8,760 hour yearly energy analysis was then run to calculate the fan energy with and without the decentralized supply fans. Utilizing a decentralized fan approach was able to reduce both the electric consumption and demand for the building. The total yearly savings, initial costs, O/M costs, and simple payback period are shown in Table 15 below. The yearly savings that were obtained through this study are a substantial savings but when the operation and maintenance costs are subtracted out it results in a savings of $38,000 a year. This savings resulted in a simple payback period of 8 years for this system setup.

Total Savings ($/yr)	$59,944.45
Initial Cost ($)	$259,496.00
Initial Labor	$38,400.00
O/M Cost ($/yr)	$21,600.00
Simple Payback	7.8

Table 15 - Decentralized Fan Analysis Results

6.0 Backpressure Steam Turbine Analysis

6.1 Analysis Procedure

The use of a backpressure steam turbine instead of a pressure reducing station for the reduction of supply steam from the campus steam plant has been investigated in a yearly analysis. A Trane TRACE model was used to calculate the hourly steam demand that would be required to pass through the steam turbine. The hourly steam demand is shown below in Figure 9. As shown in this figure the steam demand peaks in the winter months due to the increased heating demand. The demand in the summer months is generally due to domestic hot water heating and pool heating and is significantly lower than the winter heating months demand.

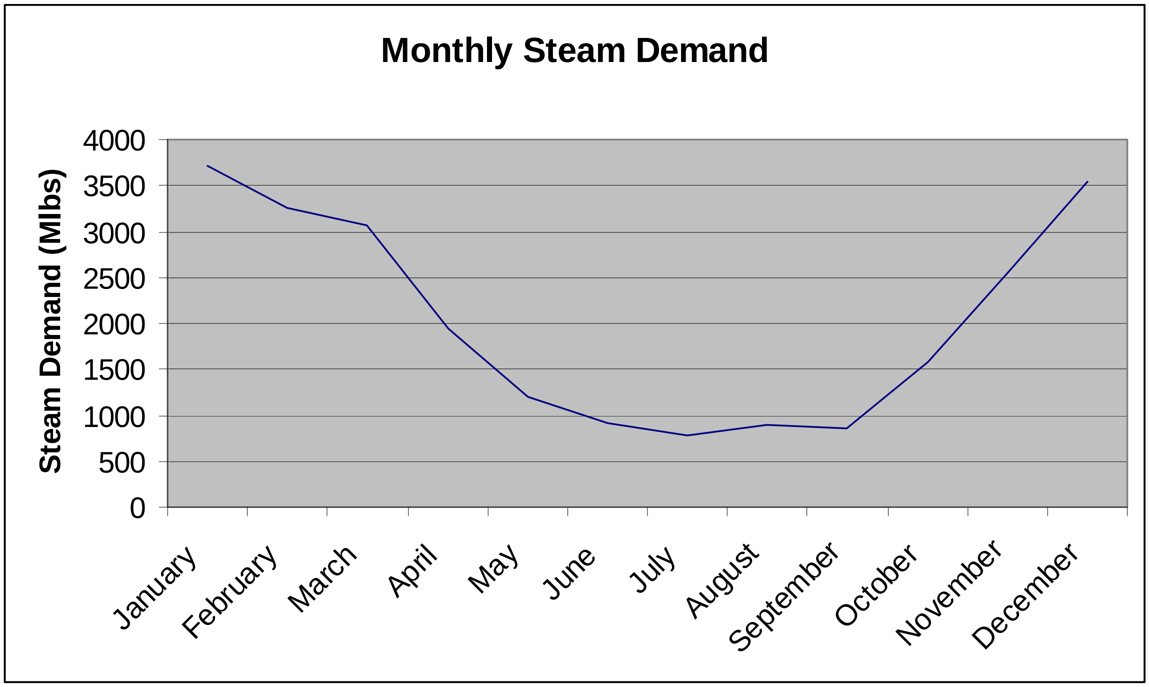


Figure 9 - Hourly Steam Demand

An abridged version of the spreadsheet that shows the procedure utilized for this hour by hour analysis is shown in Appendix D. The backpressure steam turbine output of 15 kWh/Mlb of steam delivered was taken from Figure 7. Hourly electric consumption savings were calculated using this spreadsheet along with monthly electric demand savings.

Steam is generated in a central campus steam plant and distributed to various buildings on the Walter Reed campus at 125 psi. The high pressure steam supply line enters into the basement of Building A where it currently passes through the pressure reducing station to be reduced to 15 psi. This 110 psi pressure reduction is well suited for the use of a backpressure steam turbine.

The efficiency of steam turbines falls off significantly at part loads. This reduction in efficiency is one reason why when sizing the turbine; one must size it so that it is able to run at a fairly high percentage of its capacity. However, if the steam turbine is not operating at its highest efficiency at all times it is not necessarily a large financial loss. It must be realized that even though the electrical generation efficiency has declined at part load, there is still electric generation taking place which is in turn reducing the consumption and demand the owner has to pay every month.

Due to the steam demand profile having such a large fluctuation in demand rates a steam turbine was sized for 6,000 pounds per hour. This 6,000 pounds per hour rate is able to be reduced through the backpressure steam turbine close to eighty percent of the time. When the steam demand is greater than the capacity of the steam turbine it will be diverted to a parallel pressure reducing station. This pressure reducing station will be sized for the peak steam demand to provide redundancy if the backpressure steam turbine is down for maintenance. A schematic of how the pressure reducing station is in parallel with the backpressure steam turbine is shown in Figure 10 below. As shown, the steam will be able to flow through either the turbine, pressure reducing station, or both. The turbine also has two isolation valves that can be shut in order to safely perform maintenance on this piece of equipment. The electricity produced from the electric generator will have to then be integrated into the buildings current electrical system. The electricity produced must also be directly in phase with the electricity from the grid so there are no sinusoidal fluctuations in power delivered to the buildings medical equipment.

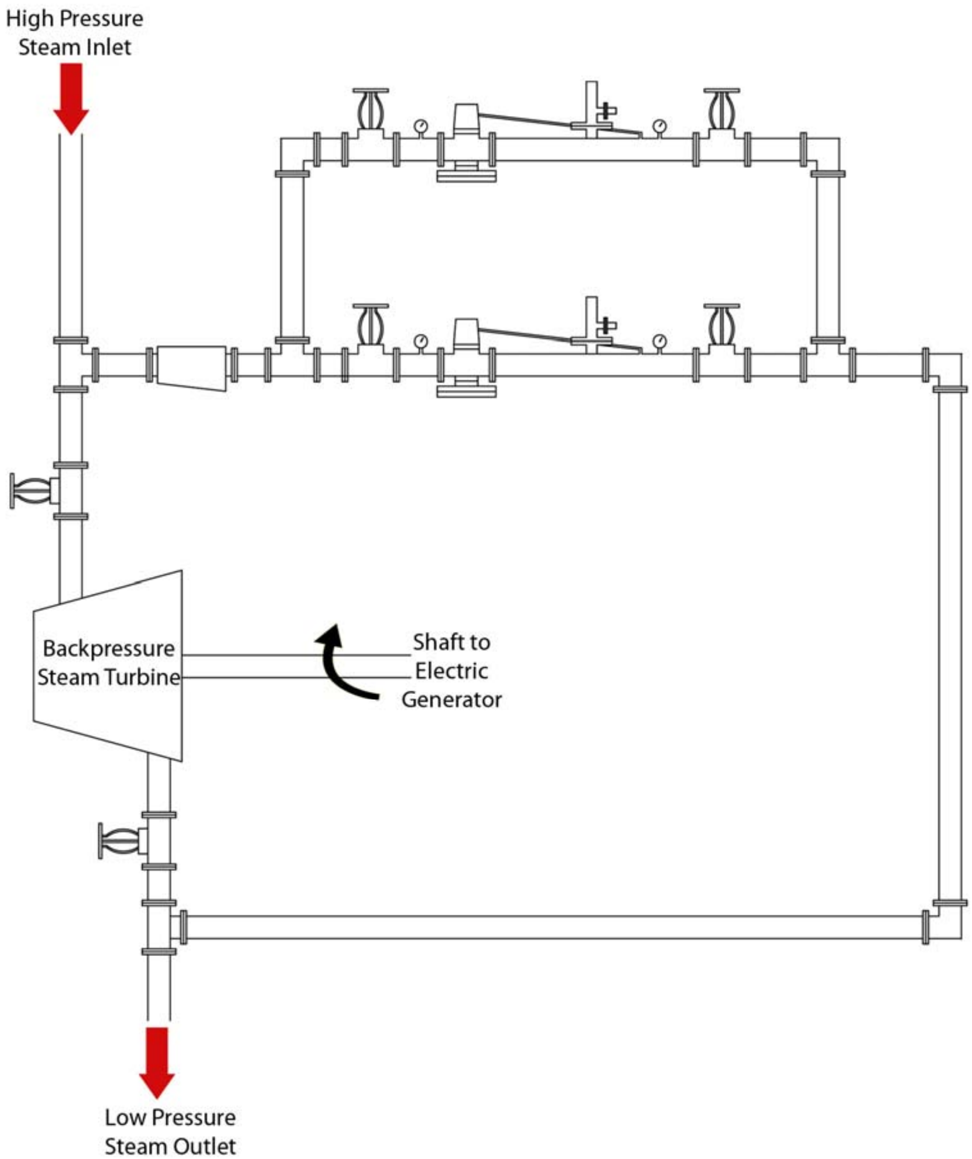


Figure 10 - Backpressure Steam Turbine and Pressure Reducing Station

The steam turbine is able to reduce both the total electric consumption and demand profile for both buildings. The average hourly electric generation throughout the year is 41.6 kWh. With the electric rates shown above in Table 6 the yearly consumption and demand savings are shown below in Table 16.

Total Yearly Electrical Savings	$40,092.52
Backpressure Steam Turbine Cost	$160,000.00
Backpressure Steam Turbine O/M	$15,240.53
Payback Period (Years)	6.44

Table 16 - Backpressure Steam Turbine Results

The simple payback period with the installation of the backpressure steam turbine is seven years. A seven year payback may be longer than owner prefers but considering a 20 year lifecycle for this piece of equipment the owner can expect to sell roughly $330,000 worth of electricity.

7.0 Combined Heat and Power

7.1 Analysis Procedure

Installing a combined heat and power plant in the basement mechanical space in Building A will be able to reduce some of the steam and electrical consumption for both buildings. Reducing these two utilities demand on both of the buildings will potentially be able to save a considerable amount of money due to these utilities being the two most expensive on a btu basis as shown in Table 9. In order to begin the combined heat and power analysis an hourly building energy model was run using Trane TRACE. The steam demand and electric consumption are shown below in Figure 11 on a monthly basis.

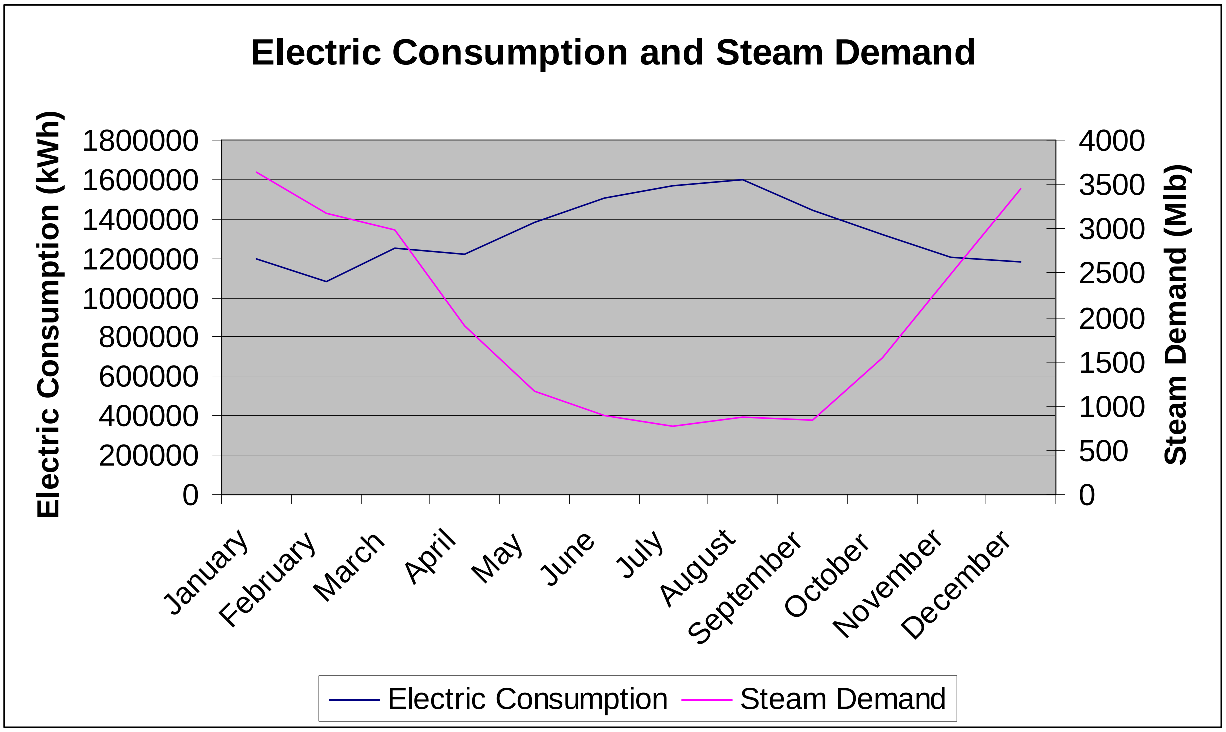


Figure 11 - Steam Demand and Electric Consumption Profiles

Figure 11 shows that the electric demand is relatively flat year round due to a relatively constant miscellaneous electric load and large amount of cooling being required year round. There is a slight increase in the electric demand during the summer months due to the increase in cooling demand for the electric driven chillers. The steam demand varies a greater amount than the electric load due to the large fluctuations in times throughout the year that the buildings require heating. The building does not require a significant portion of heating year round due to the significant amount of electronic equipment located throughout both buildings which generates a great deal of heat.

7.2 Prime Mover Selection

Internal combustion engines, gas turbines, and fuel cells are the three main types of prime movers that are utilized in combined heat and power systems. Each of these different prime movers has its own particular advantages. An overview of some of the operating characteristics and how they differ between each prime mover is shown below in Table 17.

	Gas Turbine	IC Engine	Fuel Cell
Electrical Efficiency	22 - 36%	22 - 40%	30 - 63%
Overall Efficiency	70 - 75%	70 - 80%	55 - 80%
Typical Capacity (MW)	0.5 - 250	0.01 - 5	0.0005 - 2
Power to Heat Ratio	0.5 - 2.0	0.5 - 1.0	1.0 - 2.0
Part load	poor	ok	good
Installed Cost ($/kW)	970 - 1300	1100 - 2200	5000 - 6000
Fuel Pressure Required (psig)	100 - 500	1.0 - 45	0.5 - 45
Fuels	Natural Gas, Biogas, Propane, Oil	Natural Gas, Biogas, Propane, Landfill Gas	Hydrogen, Natural Gas, Propane, Methanol
Noise	Moderate	High	Low

Table 17 - CHP Prime Mover Comparison

7.2.1 Gas Turbines

Gas turbines are able to produce large amounts of electricity along with large quantities of high quality exhaust. While the electric generation efficiency is not the best when compared to other prime movers the total megawatt capacity that is able to be installed dwarfs the other prime movers. For a varying load, such as the one in this paper, a gas turbine is not able to track with the load very well and maintain a reasonable efficiency. If a gas turbine was to be used for a building with highly varying load an aeroderivative type would have to be used. Aeroderivative gas turbines are very similar to those turbines that are used on commercial jet airlines. Aeroderivatives are able to be started quickly and track with loads very well but come at a premium price. These aeroderivative turbines are mainly used in peaking power plants throughout the nation and are only used for short periods of time throughout the year when the electric load on the grid is nearing its peak.

Gas turbines have a high temperature and high quality exhaust with a large mass flow rate which is able to generate a large quantity of high pressure steam. Because this exhaust is such a large temperature it is also able to be routed through a heat recovery steam generator as part of a combined cycle plant as shown below in Figure 12. After the exhaust is routed through a heat recovery steam generator it produces a high pressure steam which then must be reduced for use throughout the building. In order to reduce the steam it is then ran through a backpressure steam turbine which expands the steam over the turbine blades which creates low pressure steam along with generating additional electricity.

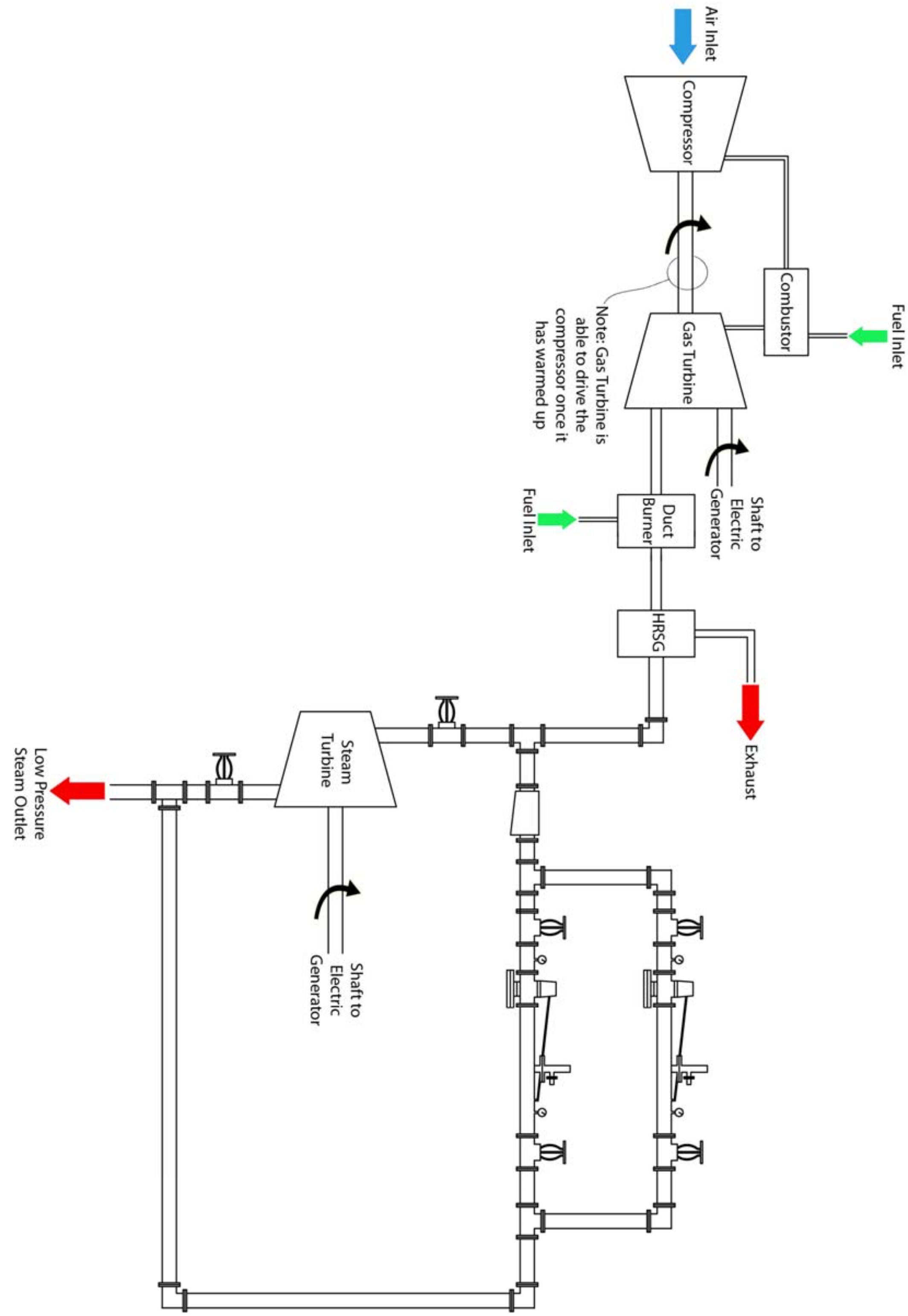


Figure 12 - Combined Cycle Power Generation

The fuel choice that is most commonly used for gas turbines is natural gas. A downfall to the fuel input for gas turbines is that it needs to be increased to such a large pressure. To increase the supply pressure of this fuel a supplemental compressor must be added to the system. Having a high pressure fuel input requires special considerations and design techniques for piping and safety requirements. The acoustical properties of gas turbines are generally a high frequency sound at a moderate decibel level. Gas turbines have a high speed rotational motion that must be isolated from the ground and supporting structure utilizing vibration isolation and housekeeping pads.

7.2.2 Internal Combustion Engines

Internal combustion engines are able to produce electricity at the highest efficiency with some engines approaching 40% efficient. IC engines do not have the large generation capacity when compared to gas turbines. An IC engine with the same MW generation as a gas turbine will have a much larger footprint and is one of the limiting factors to their total MW rating. Internal combustion engines are able to track loads fairly well with part load efficiencies not dropping off significantly from their rated full load efficiency.

The thermal output of IC engines is much less than when compared to a gas turbine. The reason is that when you increase the electric output of a device you are using more of the available enthalpy within the system. With more of this enthalpy being used for electricity generation there is less enthalpy left to use for thermal generation. IC engines also spread out their available thermal enthalpy in many different places such as the exhaust, water jacket, and oil cooler. A diagram of the typical distribution of how the thermal energy is spread out within an IC engine is shown below in Figure 13.

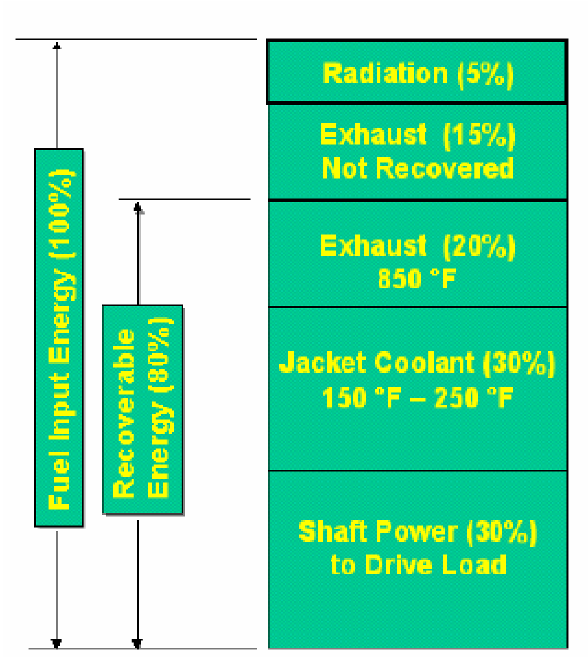


Figure 13 - IC Engine Heat Recovery

As shown in Figure 13 above the recoverable energy is distributed throughout the engine and is not all at a very high temperature. With both of these factors considered it is hard to generate a comparable amount of high quality steam when compared to a gas turbine. IC engines are also able to use a wide variety of fuels and do not necessarily need supplemental pressurization depending on the supply pressure from the utility company.

7.2.3 Fuel Cells

Fuel cells are a technology that creates electricity from a fossil fuel without the use of a combustion process. A fuel cell operates by having hydrogen passing through the anode side of the fuel cell and then it comes in contact with a catalyst. After it comes into contact with the catalyst, the hydrogen splits into two positively charged hydrogen atoms along with two electrons. The electrons are then routed through an external circuit and then are joined with the positively charged hydrogen atoms and oxygen in the cathode which produces water.

Due to the inherent properties of how a fuel cell works it is able to generate electricity the most efficiently when compared to the other two prime movers. The quality of the thermal output in a fuel cell is the lowest of all the fuel cells. The best application for the use of a fuel cell is for generally small applications, such as a residential home, with large electric to thermal ratios.

7.2.4 Prime Mover Summary

After extensive study on the various prime movers that are available for use at Walter Reed it was realized that he best selection available was an internal combustion engine. The IC engine is able to generate the electric demand that is needed without generating an excess amount of steam that is unable to be used at the site. The gas turbine is also a selection that would suit this site except for the large amount of thermal energy needs to be wasted when there is no heating demand for it. One way to use this thermal demand would be through the use of absorption chillers but this would then cut down on the total amount of electricity that the building is calling for. With the amount of electricity utilized being reduced with the use of absorption chillers the turbine would most likely have to sell back more electricity at a discounted price to the grid.

7.3 Analysis Procedure

The results from the hourly simulation were analyzed in a spreadsheet to determine the amount of electricity generation and steam demand savings. A sample of this spreadsheet is shown in Appendix E and F. A 3 MW Internal combustion engine was selected to be used for this analysis. 3 MW was selected due to it covering the total electric demand 80% of the time. In order to avoid some of the losses that are associated with running an IC engine at part load it was determined to run the engine at full load during all hours of the year. Running the engine at full load will maximize the electric generation efficiency and generate a significant portion of the steam which can be supplemented for the building use instead of the campus steam.

The internal combustion engine is a fairly large piece of equipment that is 35 feet long, 7.5 feet wide, and 9 feet tall. It was decided to locate the engine in the basement of Building A due to there being more room in the mechanical space. Figure 14 below shows an outline of how the internal combustion engine will be placed within the mechanical space of Building A. As seen in this figure the engine is placed in the Northeast corner of the mechanical space. This space is well suited to fit the internal combustion engine due to the long and narrow shape of the space. The IC engine fits well when centered in the space as shown and allows for adequate room around the engine for maintenance and all of the necessary piping connections.

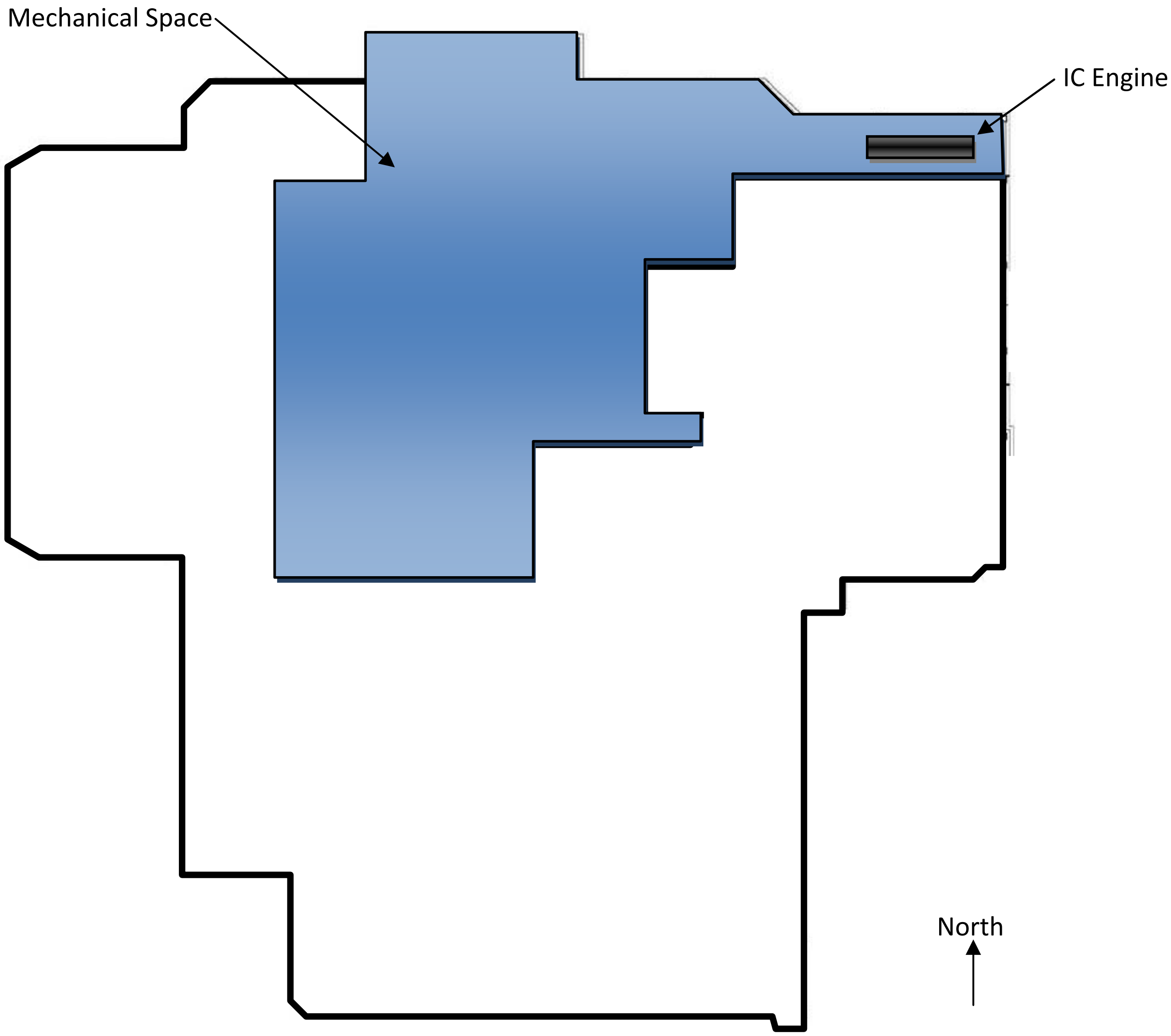


Figure 14 - IC Engine Placement within Building A Basement

Two configurations of the combined heat and power plant were analyzed to determine which configuration provided the best payback period. The two configurations of the plant are outlined below in Figure 15 and Figure 16. Figure 15 was the first alternative to be analyzed which is using the internal combustion engine to produce low pressure steam directly. Producing low pressure steam directly is typically done when an internal combustion engine is used due to the low quality of thermal output for the reasons stated earlier.

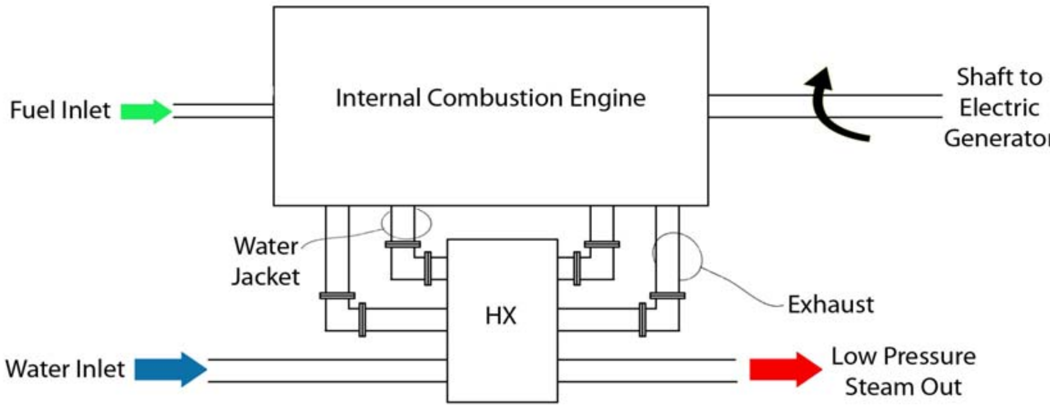


Figure 15 - CHP with Internal Combustion Engine

Figure 16 was next to be analyzed which is the use of the IC engine to generate high pressure steam and then routing this high pressure steam through a backpressure steam turbine to create low pressure steam. The benefit of a system configuration like this is that the backpressure steam turbine will be able to generate additional electricity to either reduce the consumption or to sell back to the grid. High pressure steam from the campus will still need to be purchased during certain times of the year due to the fact that less high pressure steam is able to be generated through the heat exchanger. The cost of purchasing this steam may not be offset by the electric savings with the backpressure steam turbine.

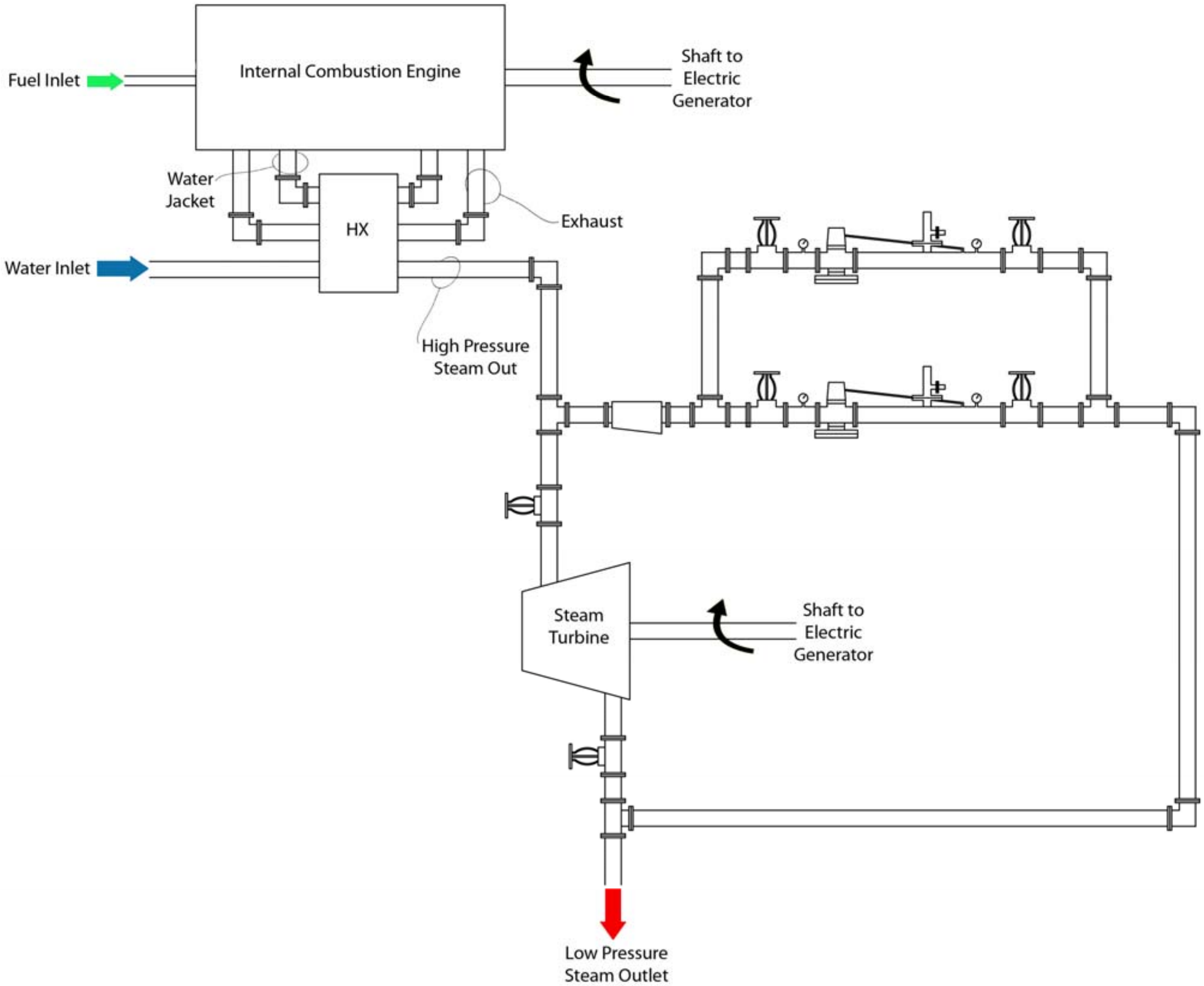


Figure 16 - Internal Combustion Engine with Backpressure Steam Turbine

Utilities are required to purchase back electricity but can do so at significantly reduced rates over the rate schedule that applies to that building type. The electric utility is also able to charge a standby fee in order to have capacity reserved at any time in the case that the CHP plant fails and electricity must be drawn from the grid. This fee is on a case by case basis and can be negotiated with the utility but usually tends to be a fairly significant monthly fee. This fee was not added into this analysis but would need to be investigated before any combined heat and power system was installed. Baltimore Gas and Electric (BGE) has a specific rate schedule for combine heat and power which specifies that the seller will be paid the PJM locational marginal price (LMP).

PJM is the regional transmission organization that is in charge of the wholesale of electricity for the eastern interconnection. The LMP varies with what utility is providing service to the building. The current weighted average LMP is $0.03/kWh. This LMP was assumed to be constant throughout the year when in reality it can be obtained in real time. The LMP will vary with the electric demand, the current price of fuel, and many global factors.

7.4 Combined Heat and Power Results

The results of both alternative CHP designs for WRNMMC are shown in Table 18 below. The configuration that is equipped with the backpressure steam turbine is able to offset a greater portion of electricity due to the additional generation of the turbine. This configuration is also able to sell back more electricity for this same reason. However, when the IC Engine is used to produce high pressure steam it is not able to generate a large quantity of steam and campus steam then must be purchased from the steam plant. The configuration with the steam turbine must purchase over $300,000 of steam which is not able to be offset by the additional sale of electricity to the grid.

The electricity savings with the use of a backpressure steam turbine is $72,627 while it uses an additional $335,166 of steam a year. Both the electricity rates and PJM LMP were changed to determine when the electricity savings will offset the additional steam that needs to be purchased. If the LMP increased to $0.05/kWh the electricity savings from the addition of the backpressure steam turbine would be $121,044 which would be able to reduce the simple payback period to 11 years. With the costs of electricity tending to increase every year this LMP price may not be unreasonable within the upcoming years. If an engineer was interested in designing this type of system their energy information must be highly accurate and their predicted trends of the electricity price in the future will be the determining factor for the feasibility of the system

However, with the electrical rates given by Baltimore Gas and Electric along with the current PJM LMP, utilizing an internal combustion engine to produce low pressure steam directly provides the lowest payback period. Being able to eliminate the backpressure steam turbine also reduces the operation and maintenance costs and well as reducing the amount of specialized operator knowledge required for the facility maintenance staff.

	IC Engine without Steam Turbine	IC Engine with Steam Turbine
Electricity Offset	$1,769,083	$1,769,083
Electricity Sold Back	$323,815	$396,442
Electricity Demand Savings	$186,799	$186,799
Steam Savings	$822,277	$487,110
Electricity Purchased	$67,376	$67,376
Steam Purchased	$21,696	$356,862
Fuel Cost	$2,012,361	$2,012,361
Yearly Savings	**$902,815**	**$640,275**
First Cost	$4,208,599	$4,457,555
O/M Cost per year	$279,322	$292,407
Simple Payback (Years)	**7**	**13**

Table 18 - Combined Heat and Power Results

8.0 Acoustical Analysis

8.1 Analysis Procedure

Due to the addition of an internal combustion engine in the basement mechanical space of Building A an acoustical analysis must be performed to verify that the adjacent rooms will still be able to meet their noise criteria levels. The rooms that are both adjacent to the location of the internal combustion engine as well as directly above the engine are listed in Table 19 below.

Room Number	Room Name	Location	In Room Noise Level		
			Min NC	Max NC	STC
B330	FATS Lab	Adjacent	35	40	40
B328	Care Lab	Adjacent	35	40	40
B314	Gait Lab	Adjacent	35	40	40
1232	Conference	Above	25	30	40
1230	Recovery Room	Above	30	35	40
1228	Rad Procedure	Above	35	40	40
1226	Office	Above	30	35	40
1224	Office	Above	30	35	40
1222	Waiting Room	Above	30	35	40
1220	Office	Above	30	35	40
1209	Staff Lounge	Above	35	40	45
1212	Office	Above	30	35	40
1210	Office	Above	30	35	40

Table 19 - Rooms Adjacent to IC Engine

The acoustic data for the GE Jenbacher Type 620 internal combustion engine was obtained in order to determine the amount of sound isolation needed. The acoustical data for both the engine and exhaust are given in Table 20 and Table 21 below. The engine acoustic values that are given below are measured values for both the engine and generator combined. These values were also measured at a distance of 1 meter away from the engine. The exhaust measurements are given for the exhaust directly after it leaves the engine. These values do not take into account any exhaust silencers or the sound attenuation provided by an external heat exchanger. With the exhaust values not taking into account a silencer or heat exchanger it is assumed for this analysis that the noise due to the engine will be much greater than the exhaust noise and cancel it out due to decibel addition.

Engine	31.5 Hz	63 Hz	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz	8000 Hz
dBA re 20µPa	88	95	101	99	94	93	92	94	95

Table 20 - GE Jenbacher Type 620 Engine Acoustics

Exhaust	31.5 Hz	63 Hz	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz	8000 Hz
dBA re 20µPa	112	121	131	119	117	118	117	112	98

Table 21 - GE Jenbacher Type 620 Exhaust Acoustics

The sound absorbing properties of the walls and floor construction which separate the occupied spaces from the engine noise was obtained for each octave band. These transmission loss values are shown in below in Table 22. As seen from this table the wall which separates the spaces adjacent to the engine attenuates a greater level of the sound coming off of the engine. This provides a challenge in the design due to the fact that the room with the most stringent noise criteria levels to meet is located directly above the IC engine.

Construction	63 Hz	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz	8000 Hz
Wall	42	42	45	53	61	67	70	70
Floor	38	41	43	52	59	67	72	72

Table 22 - Construction Transmission Loss Values

When a design engineer is looking to increase the sound absorption characteristics of a particular space they have a few options in which to do so. They are able to increase the sound absorption material thickness, add distance between the source and receiver, or use multiple material types in wall or floor construction series. The material properties that make a good absorber are a very fibrous material that will allow the impinging sound energy to strike the fibers and cause them to vibrate. These small vibrations transform the sound energy into heat. With respect to this analysis, adding distance between the source and receiver was not considered due to the amount of architectural redesign that would need to take place.

The first technique that was examined was adding a highly absorptive material within the wall construction in order to raise the transmission loss values for the wall assembly. Adding only one layer of material to the assemblies worked well for the higher frequencies but was not able to reduce the sound level enough for the lower frequencies where the bulk of the sound is concentrated for this particular engine. The next sound absorption technique that was analyzed was to keep the same sound absorbing material on the surrounding surfaces as well as add an acoustic enclosure specifically design for internal combustion engines and electric generators. Adding absorption in this way will reduce the sound level within a very short distance of the engine and then the sound will have to travel through a fairly large air space before reaching the wall or roof. Table 23 shows the values that were used for the conference room acoustical analysis. The rest of the rooms were analyzed in a similar fashion and are shown in Appendix G.

Conference									
NC Max 30		63 Hz	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz	8000 Hz
	Engine dBA re 20µPa	95	101	99	94	93	92	94	95
	A weighting	-26	-16	-9	-3	0	1	1	-1
	Engine dB re 20µPa	121	117	108	97	93	91	93	96
	IC Engine Enclosure TL	22	22	29	40	48	54	60	60
	Wall TL	38	41	43	52	59	67	72	72
	Added Absorption TL	21	21	27	29	37	49	53	53
	dB in Receiving Room	40	33	9	0	0	0	0	0
	NC Curve Limits	56	47	41	35	31	29	28	26

Table 23 - Conference Room Acoustical Analysis

It must also be considered that adding an enclosure around the IC engine will not allow the heat to dissipate at the same rate as when it is placed in a larger area. In order to allow the engine to run at a high efficiency it must be kept reasonably cool so that it does not overheat. Also, the engine has certain airflow requirements that need to be maintained both in the intake section and around the engine itself. Both of these also need to be considered by the design engineer before the implementation of such a large system takes place. All of the room NC levels throughout the octave bands are plotted below in Figure 17. This figure shows that all of the occupied spaces are reduced to a NC level that is below the maximum NC permitted in that space as stated in the RFP. Most of the NC curves within the spaces overlap due to either the same wall or ceiling transmission losses being utilized for the calculations. These would not completely overlap when actual measurements were taken due to the fact that they are various distances away from the noise source. This analysis assumed that the transmission loss through the air is negligible which is a reasonable assumption for such high levels at low frequencies.

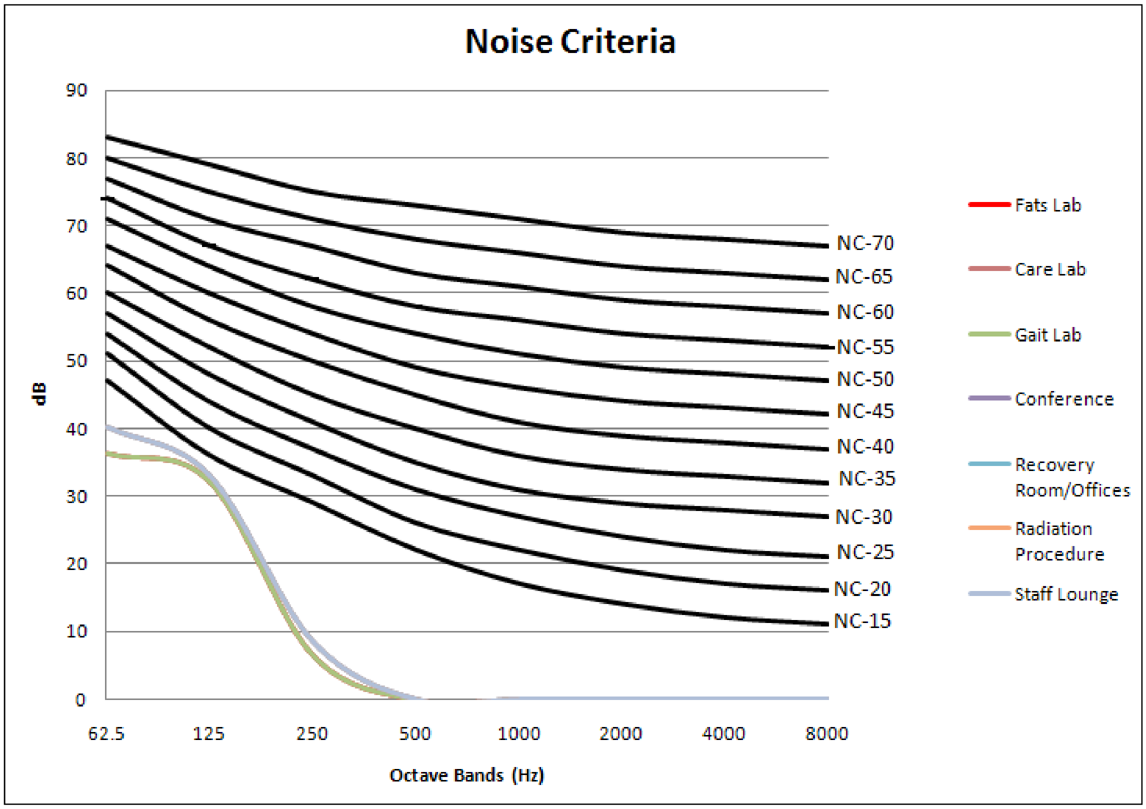


Figure 17 - Noise Criteria within the Occupied Spaces

8.2 Acoustical Analysis Results

Having two separate levels of sound absorption proved to be enough to reduce the noise levels in the surrounding rooms to acceptable limits for the upper NC value. Both levels of sound absorption were needed in order to stay below the NC level curves for each room. When one sound absorbing piece was removed the NC levels increased dramatically and these new values exceeded the limits stated above. Acoustics plays a significant role in most buildings, especially hospitals, and must be considered early in the design process in order to mitigate any potential problems.

Adding in such a large piece of equipment without being able to consider it during the early parts of the design phase, as in this report, is not the best way to do so. Being able to consider the acoustical characteristics of the engine during the early stages of design and using integrated design techniques with the architect and other trades may have been able to reduce or eliminate this acoustical problem completely. Being able to see how greatly the decisions of one trade effect another trade shows why utilizing techniques such as Building Information Modeling (BIM) and Integrated Project Delivery (IPD) can improve the construction process for all parties involved.

9.0 Solar Shading and Day Lighting Analysis

9.1 Analysis Procedure

Electronically controlled external solar shading was added to all of the South and Westward facing windows. The solar shading was added in order to reduce some of the solar thermal gain within all of the perimeter spaces which would in turn reduce the cooling load. The solar shading would also be able to reduce the amount of direct sunlight passing through the glazing and in turn make the light that passes through to the interior spaces a diffuse beam and not direct beam. Being able to change the sunlight characteristics from direct to diffuse would make it more tolerable for a bedridden patient who was subjected to direct beam light hitting them within their room.

The solar shading is electronically controlled to cover the windows when the sun is on that particular side of the building. In order to model the savings from this control scheme, the solar position of the sun was going to have to be calculated throughout the entire year. To get the solar azimuth angle, Engineering Equation Solver (EES) was used to model this for the entire year. Hourly results were obtained and inserted into an excel spreadsheet. In order to limit the number of shading schedules the monthly average solar position was used and one solar shading schedule was created for each month. If this technique were implemented on a building the design engineer may want to optimize the control system by having a different solar shading schedule for each day. But for this report the monthly average solar position will provide a very reasonable savings that can potentially be obtained. A sample monthly schedule is shown below in Table 24; the other monthly values can be seen in Appendix H. The value of zero represents that the solar shade will be up during that hour and a value of 100 means the shade will be all the way down during that hour.

Solar shading had to be approached carefully due to the amount of time and effort that were spent on the architecture of the new buildings to match it to that of the historic buildings surrounding it. That is why electronically controlled solar shading was selected to be modeled and not any horizontal or vertical fixed shading. These shades when not in use are automatically rolled up and hidden behind covers which can be painted to match the exterior façade. Careful consideration of fabric color would also need to be coordinated with the architect and approval would need to be granted by the State Historic Planning Commission as well. For this analysis it was assumed that permission for solar shading could be obtained from all of the necessary parties.

January				
Time	Azimuth	Altitude	South	West
1	-166.01	0.00	0	0
2	-152.15	0.00	0	0
3	-138.65	0.00	0	0
4	-102.19	0.00	0	0
5	-64.50	0.00	0	0
6	-69.15	0.00	0	0
7	-64.50	0.00	0	0
8	-54.82	8.01	0	0
9	-43.67	16.84	100	0
10	-30.75	23.91	100	0
11	-15.99	28.54	100	0
12	0.00	30.17	100	0
13	15.99	28.54	100	0
14	30.75	23.91	100	0
15	43.67	16.84	0	100
16	54.82	8.01	0	100
17	64.50	0.00	0	0
18	69.15	0.00	0	0
19	64.50	0.00	0	0
20	102.19	0.00	0	0
21	138.65	0.00	0	0
22	152.15	0.00	0	0
23	166.01	0.00	0	0
24	180.00	0.00	0	0

Table 24 - Solar Shading Sun Angles and Shade Position

The base case cooling coil load and the cooling coil load after the solar shading schedules were extracted from Trane TRACE after yearly simulations have been completed. Due to software limitations the only way to model a blind type of solar shading was to model it in the interior of the space. The only exterior solar shading that is able to be modeled is shading from other buildings, fixed horizontal shading, and fixed vertical shading. The results that were obtained by modeling the proposed shading as interior solar shading are shown below in Table 25 . These results will be conservative due to the solar energy that is absorbed by the shade will transmit that energy in the form of heat directly to the space. But the results should provide a good approximation of what is likely to happen when the shades are installed on the exterior of the building.

Initial Cost ($)	$604,333.00
O/M Cost ($/year)	$5,000.00
Total Savings ($/year)	$38,531.99
Simple Payback (years)	18

Table 25 - Solar Shading Results

The simple payback period for the addition of electronically controlled external solar shading system is higher than what is easily justifiable to most owners. The large upfront cost of the system is the prohibiting factor to making this a more feasible option in terms of cost. This high initial cost is due to the costs associated with being able to add this interface in with the existing building management system. This upfront cost is also significant due to the amount of time in analysis and programming within the control system that must be done to ensure this system operates correctly. There also must be additional time added into the construction schedule for both installation and testing of the shading system.

The quantity of daylight that was able to be reduced by the use of solar shading was analyzed utilizing AGI32. A model was created utilizing 3D AutoCAD and imported into this program. The space that was chosen to be modeled was a South facing patient bedroom in Building B. Lighting requirements were obtained from the Illuminating Engineering Society (IES) handbook to determine the required foot-candles within the space. Two values for the minimum foot-candles were given within the text for general space requirements and observation requirements. The general space requirements are for day to day tasks while the observation requirements are for when a doctor is within the room performing a check up on the patients and will most likely be obtained through task lighting.

A grid was created within AGI32 at a level of three feet above the floor in order to take day lighting intensity measurements. The height of three feet was determined due to the patient's bed being located at that level and any desks or tables will be located at a height close to that level. The grid is shown in Figure 18 before solar shading and Figure 19 after solar shading. As seen from these figures the solar shading is able to reduce the level of foot-candles at the three foot work plane height designated. Being able to reduce the day lighting levels this much in the rooms will reduce the heat gain within the space but will increase the task lighting that may need to be turned on. Also, being able to reduce the direct glare from the sun will provide for a more enjoyable space for either patients or doctors to be in.

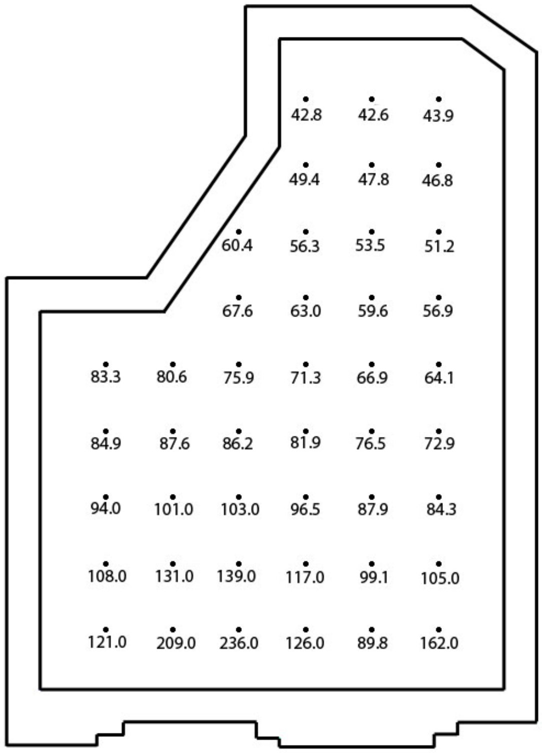


Figure 18 - Patient Bedroom Solar Intensity without Shading

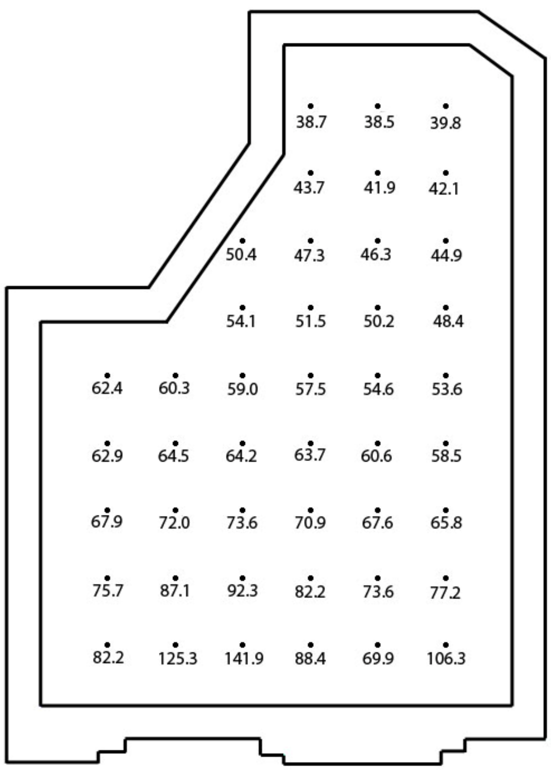


Figure 19 - Patient Bedroom Solar Intensity with Shading

This day lighting analysis within AGI32 was run for three time periods for one day each month until June where it is assumed the calculations for the rest of the year will be the same after the summer solstice. Two sample images are shown below in Figure 20 and Figure 21 for January 1st. As seen in these figures the direct beam solar intensity has been greatly reduced due to the addition of solar shading. This will be able to provide a better atmosphere for the patient within the room due to the sun not shining directly on their bed. More interior renderings for additional times throughout the year are shown in Appendix I. The interior lighting levels after the shading has been applied are still greater than the requirements that were stated within the IES handbook.

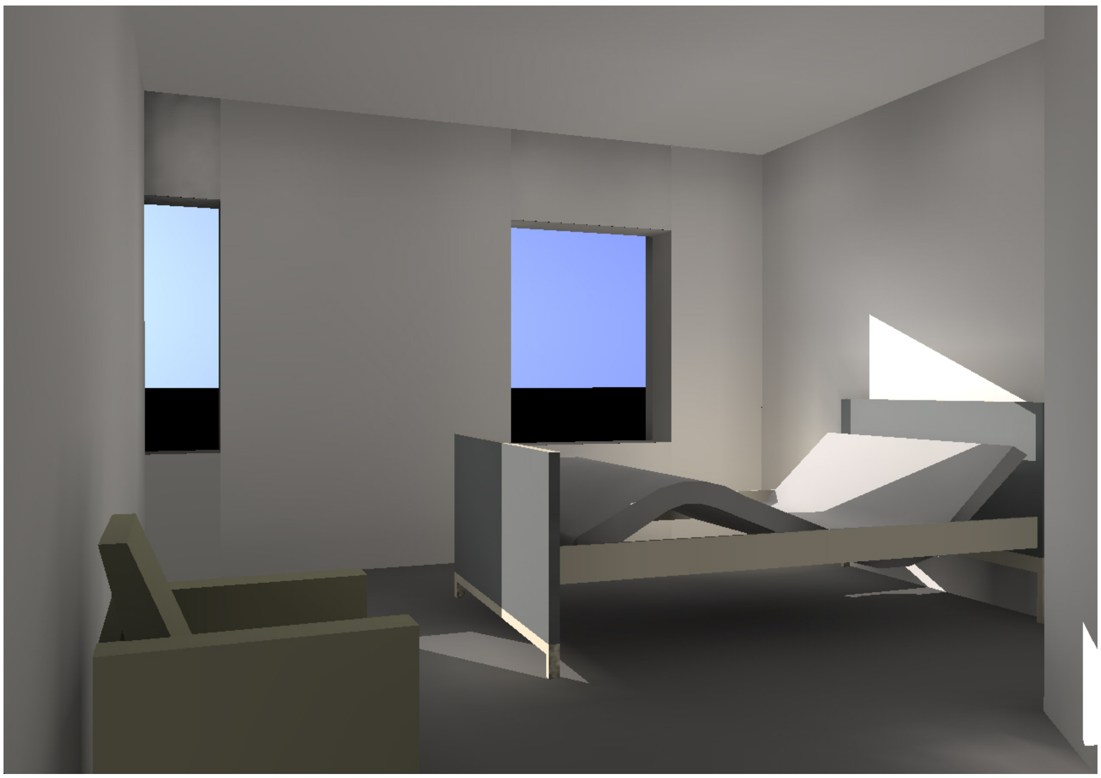


Figure 20 - January 1st at 10:00 AM with no Solar Shading

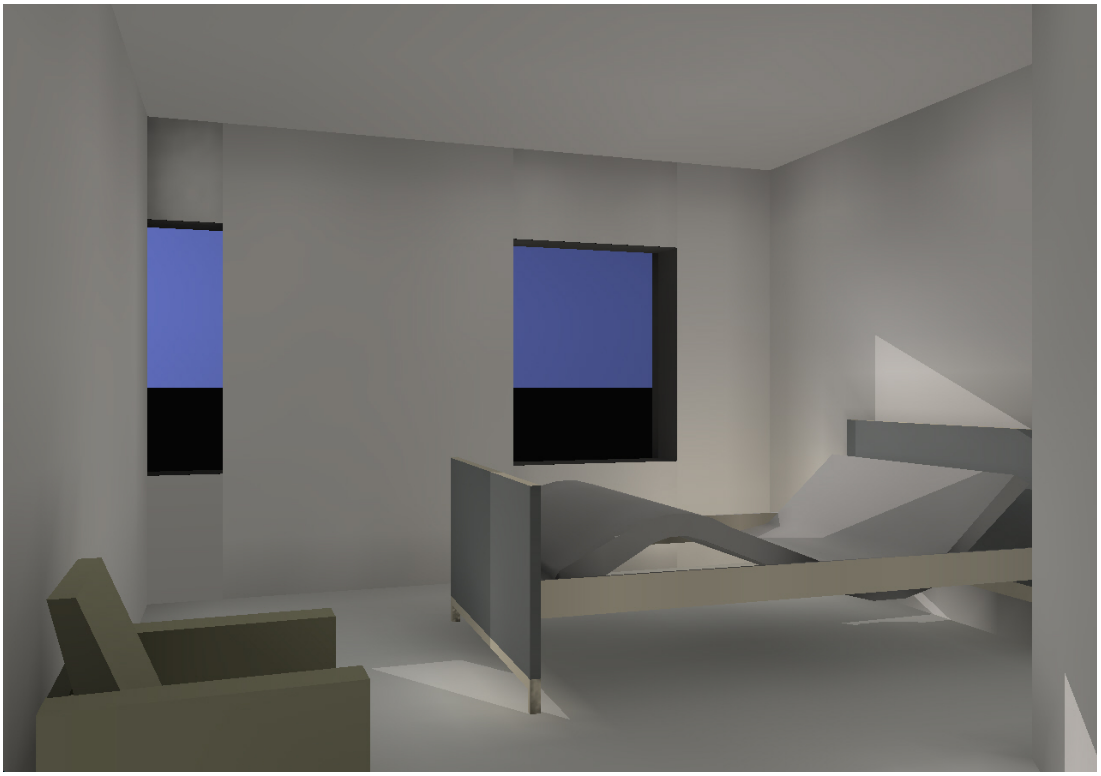


Figure 21 - January 1st at 10:00 AM with Solar Shading

10.0 Conclusion and Recommendations

10.1 Initial and Lifecycle Cost

When presenting potential savings to an owner, the design engineer must always present the initial and lifecycle costs for the system alternatives. The initial costs are important in an owners mind because this represents the amount of initial capital that they will have to invest into the building. This initial capital investment is important to an owner because they usually have a fixed budget and investing more in another system takes away from other additions that they may want to invest in. To calculate the lifecycle cost of the options analyzed within this report, the following equation was used to determine the present value worth for each alternative.

$$PV = A \times \frac{\left[(1+i)^n - 1\right]}{i \times (1+i)^n}$$

Where:
PV=Present Value
A= Annual Payment
i= Discount Rate
n= Number of Years

The lifecycle cost data is shown below in Table 26 for all of the mechanical system alternatives discussed earlier and the system as it is currently designed. The two combined heat and power options have the lowest lifecycle costs when compared to all of the system alternatives examined. This savings when utilizing combined heat and power comes from the amount of money being spent on fuel costs each year. Utilizing CHP without a steam turbine is able to save close to 5% in the 20 year lifecycle that was assumed in the analysis above. This table is a primary example on why the design engineer must always consider lifecycle cost information on not only simple payback. The simple paybacks of changes can be relatively short but when looked at in the long term do not save a great deal of money when compared to the total mechanical and plumbing scope of the project.

System	System As Designed	Decentralized Supply Fans	Backpressure Steam Turbine	CHP without Steam Turbine	CHP with Steam Turbine
Initial Cost	$109,500,000	$109,797,896	$109,660,000	$113,708,598	$113,957,555
Discount Rate	5%	5%	5%	5%	5%
Lifecycle (years)	20	20	20	20	20
Electric Cost	$1,836,459	$1,783,890	$1,798,320	$67,376	$67,376
Electric Sold to Utility	$0	$0	$0	$323,815	$396,441
Purchased Steam Cost	$843,972	$843,972	$843,972	$21,695	$356,861
Natural Gas Cost	$0	$0	$0	$2,012,360	$2,012,360
Total O/M Cost	$500,000	$521,600	$515,240	$779,322	$792,407
20 Year Lifecycle Cost	$142,898,168	$142,541,054	$142,582,956	$135,857,693	$139,377,899
Rank	5	3	4	1	2

Table 26 - Lifecycle Cost Information

10.2 System Recommendation

If the owner is able and willing to increase their total mechanical budget of the project then the implementation of the combined heat and power alternative without the steam turbine is the most favorable in terms of lifecycle cost. However, the owner would have to be aware of the increased technical expertise required in their facilities maintenance staff in order to properly run such a complex system. The owner would also need to express interest in this alternative very early in the design process due to the extensive coordination required between all of the trades to make this a successful and feasible opportunity.

If the owner is unable to expand their budget to the levels required to implement a combined heat and power system then installing only a backpressure steam turbine within the system will be a good alternative. The steam turbine is a very robust piece of equipment that will be able to last the owner well over the twenty years assumed in the lifecycle cost analysis. A backpressure steam turbine can easily be piped in parallel with the pressure reducing station that is in the current mechanical system design. The fan decentralization was not recommended above the backpressure steam turbine due to the changes required in the architectural design of the system. Also the backpressure steam turbine will be able to have a longer lifecycle than a supply fan which would better suit the owner assuming that the building is going to be occupied well after twenty years. This assumption is likely valid due to the fact that the current Walter Reed Army Medical center has been in operation since the early 1900's

Depending on the initial funding the owner is able to provide for the mechanical system the two options stated above suit either case well. Both of these options will be able to provide lifecycle cost savings well after the twenty year analysis period as long as the required and recommended maintenance procedures are followed for each piece of equipment installed on the project.

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Appendix A – MAE Course Work

As part of the MAE requirements for the senior thesis report, a discussion of how Masters level courses were utilized within the report is required. Outlined below are the Masters courses that I have utilized during the analysis and creation of this report.

AE 551 - Combined Heat and Power System Design for Buildings

Information presented within AE 551 was used significantly for both combined heat and power options discussed as well as the backpressure steam turbine analysis. The knowledge gained within this class helped enable the creation of the spreadsheets required for such an extensive analysis.

AE 558 - Centralized Heating Production and Distribution Systems

Within AE 558 was a section that was presented on lifecycle cost analysis procedures. This was utilized within the report to generate the twenty year lifecycle cost calculation to compare all of the design alternatives. Life cycle cost information was an important part in the report process because it was able to determine the twenty year present value of the savings for each system alternative.

AE 552 – Indoor Air Quality

While no studies have been quantified within this report regarding indoor air quality it has been discussed in previous sections relating to the spreading of infectious disease throughout the building. Indoor air quality plays a key role in facilities such as a hospital due to the occupant type.

Appendix B – Design Load Schedules

Library Members

Schedules

Lights - WR Hospital — **Simulation type: Reduced year**

		Start time	End time	Percentage	Utilization
January - December	Saturday	Midnight	7 a.m.	30.0	
		7 a.m.	8 a.m.	40.0	
		8 a.m.	6 p.m.	70.0	
		6 p.m.	9 p.m.	50.0	
		9 p.m.	Midnight	30.0	

Heating Design		Start time	End time	Percentage	Utilization
		Midnight	Midnight	0.0	

		Start time	End time	Percentage	Utilization
January - December	Weekday	Midnight	7 a.m.	30.0	
		7 a.m.	8 a.m.	50.0	
		8 a.m.	4 p.m.	90.0	
		4 p.m.	11 p.m.	50.0	
		11 p.m.	Midnight	30.0	

		Start time	End time	Percentage	Utilization
January - December	Cooling design	Midnight	Midnight	100.0	

		Start time	End time	Percentage	Utilization
January - December	Sunday	Midnight	8 a.m.	30.0	
		8 a.m.	4 p.m.	70.0	
		4 p.m.	Midnight	30.0	

Library Members

Schedules

LIGHTS- WR OFFICE — Simulation type: Reduced year

		Start time	End time	Percentage	
January - December	Weekday	Midnight	5 a.m.	10.0	Utilization
		5 a.m.	7 a.m.	20.0	
		7 a.m.	8 a.m.	30.0	
		8 a.m.	noon	90.0	
		noon	1 p.m.	80.0	
		1 p.m.	5 p.m.	90.0	
		5 p.m.	6 p.m.	50.0	
		6 p.m.	8 p.m.	30.0	
		8 p.m.	10 p.m.	20.0	
		10 p.m.	11 p.m.	10.0	
		11 p.m.	Midnight	5.0	
January - December	Saturday	**Start time**	**End time**	**Percentage**	Utilization
		Midnight	6 a.m.	10.0	
		6 a.m.	8 a.m.	20.0	
		8 a.m.	noon	30.0	
		noon	5 p.m.	20.0	
		5 p.m.	Midnight	10.0	
Heating Design		**Start time**	**End time**	**Percentage**	Utilization
		Midnight	Midnight	0.0	
January - December	Cooling design	**Start time**	**End time**	**Percentage**	Utilization
		Midnight	Midnight	100.0	
January - December	Sunday	**Start time**	**End time**	**Percentage**	Utilization
		Midnight	6 a.m.	10.0	
		6 a.m.	5 p.m.	20.0	
		5 p.m.	Midnight	10.0	

Library Members

Schedules

People - WR Hospital — **Simulation type: Reduced year**

	Start time	End time	Percentage	
January - December Sunday	**Start time**	**End time**	**Percentage**	Utilization
	Midnight	8 a.m.	30.0	
	8 a.m.	4 p.m.	70.0	
	4 p.m.	Midnight	30.0	
January - December Saturday	**Start time**	**End time**	**Percentage**	Utilization
	Midnight	7 a.m.	30.0	
	7 a.m.	8 a.m.	35.0	
	8 a.m.	9 a.m.	40.0	
	9 a.m.	5 p.m.	70.0	
	5 p.m.	7 p.m.	40.0	
	7 p.m.	Midnight	30.0	
Heating Design	**Start time**	**End time**	**Percentage**	Utilization
	Midnight	Midnight	0.0	
January - December Weekday	**Start time**	**End time**	**Percentage**	Utilization
	Midnight	7 a.m.	30.0	
	7 a.m.	8 a.m.	40.0	
	8 a.m.	9 a.m.	50.0	
	9 a.m.	5 p.m.	80.0	
	5 p.m.	6 p.m.	50.0	
	6 p.m.	8 p.m.	40.0	
	8 p.m.	10 p.m.	35.0	
	10 p.m.	Midnight	30.0	
January - December Cooling design	**Start time**	**End time**	**Percentage**	Utilization
	Midnight	Midnight	100.0	

Library Members

Schedules

People - WR Office — Simulation type: Reduced year

Schedule	Start time	End time	Percentage	
Heating Design	Start time	End time	Percentage	Utilization
	Midnight	Midnight	0.0	
January - December Sunday	Start time	End time	Percentage	Utilization
	Midnight	4 a.m.	0.0	
	4 a.m.	8 a.m.	5.0	
	8 a.m.	Midnight	0.0	
January - December Cooling design	Start time	End time	Percentage	Utilization
	Midnight	Midnight	100.0	
January - December Saturday	Start time	End time	Percentage	Utilization
	Midnight	6 a.m.	0.0	
	6 a.m.	8 a.m.	10.0	
	8 a.m.	noon	30.0	
	noon	5 p.m.	10.0	
	5 p.m.	7 p.m.	5.0	
	7 p.m.	Midnight	0.0	
January - December Weekday	Start time	End time	Percentage	Utilization
	Midnight	6 a.m.	0.0	
	6 a.m.	7 a.m.	10.0	
	7 a.m.	8 a.m.	20.0	
	8 a.m.	noon	95.0	
	noon	1 p.m.	50.0	
	1 p.m.	5 p.m.	95.0	
	5 p.m.	6 p.m.	30.0	
	6 p.m.	10 p.m.	10.0	
	10 p.m.	Midnight	5.0	

Misc - Low rise office — **Simulation type: Reduced year**

January - December **Cooling design to Weekday** — Utilization

Start time	End time	Percentage
Midnight	7 a.m.	5.0
7 a.m.	8 a.m.	80.0
8 a.m.	10 a.m.	90.0
10 a.m.	noon	95.0
noon	2 p.m.	80.0
2 p.m.	4 p.m.	90.0
4 p.m.	5 p.m.	95.0
5 p.m.	6 p.m.	80.0
6 p.m.	7 p.m.	70.0
7 p.m.	8 p.m.	60.0
8 p.m.	9 p.m.	40.0
9 p.m.	10 p.m.	30.0
10 p.m.	Midnight	20.0

Heating Design — Utilization

Start time	End time	Percentage
Midnight	Midnight	0.0

January - December **Saturday to Sunday** — Utilization

Start time	End time	Percentage
Midnight	Midnight	5.0

Misc - Hospital

Simulation type: Reduced year

January - December

Cooling design to Sunday

Start time	End time	Percentage
Midnight	7 a.m.	70.0
7 a.m.	noon	100.0
noon	1 p.m.	90.0
1 p.m.	5 p.m.	100.0
5 p.m.	10 p.m.	90.0
10 p.m.	Midnight	70.0

Utilization

Heating Design

Start time	End time	Percentage
Midnight	Midnight	0.0

Utilization

Appendix C – Decentralized Fan Analysis

Date	Hour	Building A Base Case (kW)	Building A Decentralized Fans (kW)	Building A Electric Savings (kW)	Building B Base Case (kW)	Building B Decentralized Fans (kW)	Building B Electric Savings (kW)	Total Electric Savings (kW)	Electric Rates ($/kWh)	Electric Consumption Savings	Electric Demand Before (kW)	Electric Demand After (kW)	Max Electric Demand Before (kW)	Max Electric Demand After (kW)	Electric Demand Savings (kW)
	1	24.3	22.6	1.7	128.4	124.1	4.4	6.1	0.1	0.7	152.7	136.4			
	2	24.5	22.4	2.1	128.3	123.8	4.6	6.7	0.1	0.8	152.8	135.9			
	3	25.4	22.2	3.2	129.2	123.9	5.3	8.5	0.1	1.0	154.6	135.8			
	4	26.1	24.1	2.0	136.1	144.3	-8.2	-6.2	0.1	-0.8	162.2	156.5			
	5	19.7	35.8	-16.1	131.7	140.1	-8.5	-24.6	0.1	-3.0	151.4	163.9			
	6	573.1	501.1	72.0	167.6	161.5	6.1	78.1	0.1	9.5	740.6	626.7			
	7	573.1	501.1	72.0	149.6	150.5	-0.9	71.1	0.1	8.7	722.7	616.6			
	8	573.9	502.0	71.9	174.5	153.5	21.0	92.9	0.1	11.5	748.4	620.2			
	9	573.9	502.0	71.9	171.0	145.6	25.4	97.3	0.1	12.1	744.9	612.9			
	10	574.8	503.0	71.8	133.9	148.9	-15.0	56.8	0.1	7.0	708.7	616.9			
	11	573.9	502.0	71.9	159.7	135.2	24.5	96.4	0.1	12.0	733.6	603.3			
11-Aug	12	573.9	502.0	71.9	171.0	129.3	41.7	113.6	0.1	14.8	744.9	597.8	748.4	626.7	121.7
	13	573.1	501.1	72.0	133.6	151.3	-17.7	54.3	0.1	7.1	706.6	617.3			
	14	573.9	502.0	71.9	135.0	135.2	-0.3	71.6	0.1	9.3	708.8	603.3			
	15	574.8	503.0	71.8	162.2	129.4	32.7	104.6	0.1	13.6	736.9	598.9			
	16	575.7	504.0	71.7	134.1	135.7	-1.6	70.1	0.1	9.1	709.8	605.7			
	17	574.8	503.0	71.8	133.6	130.0	3.6	75.4	0.1	9.8	708.3	599.4			
	18	574.8	503.0	71.8	163.8	148.4	15.3	87.1	0.1	10.8	738.6	616.5			
	19	573.9	502.0	71.9	149.7	140.7	8.9	80.9	0.1	10.0	723.6	608.4			
	20	572.3	500.2	72.1	133.5	130.7	2.8	74.9	0.1	9.3	705.8	597.4			
	21	571.6	499.5	72.1	146.5	144.1	2.4	74.5	0.1	9.2	718.1	609.1			
	22	22.9	25.8	-2.9	127.5	123.1	4.4	1.4	0.1	0.2	150.3	138.6			
	23	19.8	22.5	-2.7	127.9	125.7	2.2	-0.4	0.1	-0.1	147.7	137.8			
	24	19.5	22.3	-2.8	134.7	136.7	-2.0	-4.7	0.1	-0.6	154.3	147.8			
	1	28.5	21.7	6.8	167.4	158.4	9.0	15.8	0.1	1.9	195.9	167.3			
	2	36.5	21.6	14.8	168.5	157.5	11.0	25.9	0.1	3.1	205.0	166.4			
	3	36.8	21.6	15.2	167.4	158.4	9.0	24.3	0.1	3.0	204.3	167.2			
	4	38.0	21.5	16.5	168.5	158.4	10.1	26.6	0.1	3.2	206.5	167.1			
	5	18.9	25.3	-6.4	158.9	148.0	10.9	4.5	0.1	0.5	177.8	161.1			
	6	570.6	498.4	72.2	174.7	165.0	9.7	81.9	0.1	10.0	745.3	627.5			
	7	570.6	498.4	72.2	162.7	158.1	4.7	76.9	0.1	9.4	733.3	621.0			
	8	571.6	499.5	72.1	164.7	159.3	5.4	77.5	0.1	9.6	736.3	623.2			
	9	572.3	500.2	72.1	146.2	139.3	6.9	79.0	0.1	9.8	718.5	605.4			
	10	573.9	502.0	71.9	166.4	153.0	13.4	85.3	0.1	10.6	740.3	619.7			
	11	573.9	502.0	71.9	146.8	132.6	14.2	86.1	0.1	10.7	720.7	600.9			
12-Aug	12	574.8	503.0	71.8	138.6	153.1	-14.6	57.3	0.1	7.5	713.4	620.8	745.3	627.5	117.9
	13	574.8	503.0	71.8	160.4	132.8	27.6	99.4	0.1	13.0	735.2	601.9			
	14	575.7	504.0	71.7	138.8	132.4	6.3	78.1	0.1	10.2	714.5	602.6			
	15	576.7	505.1	71.6	163.4	135.3	28.1	99.7	0.1	13.0	740.1	606.3			
	16	577.7	506.2	71.5	139.0	132.7	6.3	77.8	0.1	10.1	716.7	605.0			
	17	26.4	29.4	-2.9	158.0	148.4	9.5	6.6	0.1	0.9	184.4	165.4			
	18	20.3	22.9	-2.6	151.2	146.6	4.6	2.0	0.1	0.2	171.5	157.6			
	19	21.9	22.7	-0.8	150.9	146.1	4.8	4.0	0.1	0.5	172.8	157.0			
	20	22.0	22.5	-0.5	150.6	146.0	4.6	4.1	0.1	0.5	172.6	156.6			
	21	22.4	22.3	0.1	150.4	145.7	4.6	4.7	0.1	0.6	172.8	156.2			
	22	22.4	22.1	0.2	149.9	145.3	4.6	4.9	0.1	0.6	172.3	155.6			
	23	20.6	22.0	-1.4	149.8	145.2	4.7	3.2	0.1	0.4	170.4	155.4			
	24	19.2	21.9	-2.7	149.8	145.0	4.8	2.2	0.1	0.3	169.0	155.1			

Appendix D – Backpressure Steam Turbine Analysis

Day	Hour	Thermal Usage	Thermal Usage	Steam Usage	BPST Output	Electricity Produced	Total Electric Demand	Electric Demand After BPST	Electric Rates	Savings			
		Mbh	Btuh	Mlb/hr	kWh/Mlb	kWh	kW	kw	$/kWh	Consumption Savings ($)	Demand Charge Before ($)	Demand Charge After ($)	Demand Savings ($)
	1	-206.38	206380	0.2	15.0	2.1	574.1	572.0	0.122	0.26			
	2	-660	660000	0.6	15.0	6.8	593.4	586.6	0.122	0.83			
	3	-151.1	151100	0.1	15.0	1.6	534.7	533.2	0.122	0.19			
	4	-259.55	259550	0.2	15.0	2.7	584.3	581.6	0.122	0.33			
	5	-162.31	162310	0.1	15.0	1.7	543.5	541.8	0.122	0.20			
	6	-2136.25	2136250	1.8	15.0	22.0	1419.9	1397.9	0.122	2.68			
	7	-1090.72	1090720	0.9	15.0	11.2	2175.5	2164.3	0.122	1.37			
	8	-1838.26	1838260	1.6	15.0	18.9	2632.6	2613.7	0.124	2.35			
	9	-4775.11	4775110	4.1	15.0	55.4	3195.8	3140.4	0.124	6.87			
	10	-1170.7	1170700	1.0	15.0	12.1	2880.1	2868.0	0.124	1.50			
	11	-4754.57	4754570	4.1	15.0	55.1	3023.8	2968.7	0.124	6.84			
11-Aug	12	-1761.5	1761500	1.5	15.0	18.2	2692.2	2674.1	0.130	2.37	19,653.86	19,313.30	340.57
	13	-4044.01	4044010	3.5	15.0	46.9	2735.6	2688.7	0.130	6.11			
	14	-4786	4786000	4.1	15.0	55.5	3088.6	3033.1	0.130	7.23			
	15	-2437.73	2437730	2.1	15.0	25.1	2971.5	2946.3	0.130	3.27			
	16	-4586.19	4586190	3.9	15.0	53.2	3017.9	2964.7	0.130	6.93			
	17	-1507.31	1507310	1.3	15.0	15.5	2372.0	2356.4	0.130	2.02			
	18	-1842.34	1842340	1.6	15.0	19.0	2375.9	2356.9	0.124	2.36			
	19	-1872.4	1872400	1.6	15.0	19.3	2058.2	2038.9	0.124	2.39			
	20	-460.98	460980	0.4	15.0	4.8	1801.3	1796.5	0.124	0.59			
	21	-1044.02	1044020	0.9	15.0	10.8	1589.1	1578.3	0.124	1.33			
	22	-329.49	329490	0.3	15.0	3.4	810.2	806.8	0.122	0.41			
	23	-347.5	347500	0.3	15.0	3.6	655.5	651.9	0.122	0.44			
	24	-330.81	330810	0.3	15.0	3.4	509.9	506.5	0.122	0.42			
	1	-553.83	553830	0.5	15.0	5.7	501.5	495.8	0.122	0.69			
	2	-682.82	682820	0.6	15.0	7.0	514.6	507.5	0.122	0.86			
	3	-841.46	841460	0.7	15.0	8.7	500.4	491.7	0.122	1.06			
	4	-821.13	821130	0.7	15.0	8.5	567.4	558.9	0.122	1.03			
	5	-882.37	882370	0.8	15.0	9.1	597.1	588.0	0.122	1.11			
	6	-2879.95	2879950	2.5	15.0	29.7	1221.5	1191.8	0.122	3.61			
	7	-2258.28	2258280	1.9	15.0	23.3	1303.1	1279.8	0.122	2.83			
	8	-790.88	790880	0.7	15.0	8.2	1452.3	1444.1	0.124	1.01			
	9	-613.84	613840	0.5	15.0	6.3	1699.7	1693.3	0.124	0.78			
	10	-840.25	840250	0.7	15.0	8.7	1615.8	1607.1	0.124	1.07			
	11	-1151.17	1151170	1.0	15.0	11.9	1671.5	1659.6	0.124	1.47			
12-Aug	12	-669.15	669150	0.6	15.0	6.9	1551.7	1544.8	0.130	0.90	10,452.97	10,414.06	38.92
	13	-1034.74	1034740	0.9	15.0	10.7	1595.2	1584.6	0.130	1.39			
	14	-1259.06	1259060	1.1	15.0	13.0	1640.0	1627.0	0.130	1.69			
	15	-692.04	692040	0.6	15.0	7.1	1596.8	1589.7	0.130	0.93			
	16	-1105.1	1105100	0.9	15.0	11.4	1616.2	1604.8	0.130	1.48			
	17	-940.61	940610	0.8	15.0	9.7	936.1	926.4	0.130	1.26			
	18	-252.33	252330	0.2	15.0	2.6	830.8	828.2	0.124	0.32			
	19	-684.97	684970	0.6	15.0	7.1	840.2	833.2	0.124	0.88			
	20	-238.31	238310	0.2	15.0	2.5	843.3	840.9	0.124	0.30			
	21	-668.94	668940	0.6	15.0	6.9	867.7	860.8	0.124	0.86			
	22	-164.79	164790	0.1	15.0	1.7	690.1	688.4	0.122	0.21			
	23	-209.63	209630	0.2	15.0	2.2	782.0	779.9	0.122	0.26			
	24	-688.5	688500	0.6	15.0	7.1	755.5	748.4	0.122	0.86			

Appendix E – Combined Heat and Power Analysis with Backpressure Steam Turbine

Day	Hour	Electric Consumption Building A	Electric Consumption Building B	Total Consumption	Total Engine Output	Electric Required From Grid	Excess Generation	Electricity Rates	Electricity Consumption Offset	PJM LMP Electric Resale Value	Excess Generation Sold Back	Electricity Purchased	Backpressure Steam Turbine	Steam Usage (15 psi, 300F)			Thermal Enthalpy From IC Engine	High Pressure Steam (125 psi, 300F)	Low Pressure Steam (15 psi)	Excess Steam Produced	Purchased Steam Rate	Steam Savings	Amount of Steam Purchased	IC Engine Natural Gas Input				
		kWh	kWh	kWh	kWh	kWh	kWh	$/kWh	$	$/kWh	$	$	kWh	Btu/hr	lb/hr	Therm/hr	Btu/hr	Btu/hr	Btu/hr	Btu/hr	$/therm	$	$	btu/hr	therm/hr	$/ first 10,000 therms	$/over 10,000 therms	$
11-Aug	1	341.47	655.32	996.79	2994.00	0.00	2308.41	0.122	$121.33	$0.03	$69.25	$0.00	311.20	206380	173	2.1	10618000	5309000	2654500	2448120	2.985	6.16	0.00	24,556,558	246	1.03	0.93	$228
	2	340.00	650.90	990.90	2994.00	0.00	2314.30	0.122	$120.61	$0.03	$69.43	$0.00	311.20	660000	554	6.6	10618000	5309000	2654500	1994500	2.985	19.70	0.00	24,556,558	246	1.03	0.93	$228
	3	339.66	607.59	947.25	2994.00	0.00	2357.95	0.122	$115.30	$0.03	$70.74	$0.00	311.20	151100	127	1.5	10618000	5309000	2654500	2503400	2.985	4.51	0.00	24,556,558	246	1.03	0.93	$228
	4	339.77	608.05	947.82	2994.00	0.00	2357.38	0.122	$115.37	$0.03	$70.72	$0.00	311.20	259550	218	2.6	10618000	5309000	2654500	2394950	2.985	7.75	0.00	24,556,558	246	1.03	0.93	$228
	5	389.52	611.82	1001.34	2994.00	0.00	2303.86	0.122	$121.88	$0.03	$69.12	$0.00	311.20	162310	136	1.6	10618000	5309000	2654500	2492190	2.985	4.84	0.00	24,556,558	246	1.03	0.93	$228
	6	1351.35	690.04	2041.39	2994.00	0.00	1263.81	0.122	$248.48	$0.03	$37.91	$0.00	311.20	2136250	1792	21.4	10618000	5309000	2654500	518250	2.985	63.77	0.00	24,556,558	246	1.03	0.93	$228
	7	1597.98	737.26	2335.24	2994.00	0.00	969.96	0.122	$284.24	$0.03	$29.10	$0.00	311.20	1090720	915	10.9	10618000	5309000	2654500	1563780	2.985	32.56	0.00	24,556,558	246	1.03	0.93	$228
	8	2455.31	1238.81	3694.12	2994.00	700.12	0.00	0.124	$409.94	$0.03	$0.00	$86.84	311.20	1838260	1542	18.4	10618000	5309000	2654500	816240	2.985	54.87	0.00	24,556,558	246	1.03	0.93	$228
	9	2354.34	1157.31	3511.65	2994.00	517.65	0.00	0.124	$409.94	$0.03	$0.00	$64.20	311.20	4775110	4006	47.8	10618000	5309000	2654500	-2120610	2.985	79.24	63.30	24,556,558	246	1.03	0.93	$228
	10	2362.89	1110.70	3473.59	2994.00	479.59	0.00	0.124	$409.94	$0.03	$0.00	$59.48	311.20	1170700	982	11.7	10618000	5309000	2654500	1483800	2.985	34.95	0.00	24,556,558	246	1.03	0.93	$228
	11	2291.65	1247.37	3539.02	2994.00	545.02	0.00	0.124	$409.94	$0.03	$0.00	$67.60	311.20	4754570	3989	47.5	10618000	5309000	2654500	-2100070	2.985	79.24	62.69	24,556,558	246	1.03	0.93	$228
	12	2305.20	1242.59	3547.79	2994.00	553.79	0.00	0.130	$430.70	$0.03	$0.00	$72.16	311.20	1761500	1478	17.6	10618000	5309000	2654500	893000	2.985	52.58	0.00	24,556,558	246	1.03	0.93	$228
	13	2376.61	1137.92	3514.53	2994.00	520.53	0.00	0.130	$430.70	$0.03	$0.00	$67.83	311.20	4044010	3393	40.4	10618000	5309000	2654500	-1389510	2.985	79.24	41.48	24,556,558	246	1.03	0.93	$228
	14	2348.04	1216.97	3565.01	2994.00	571.01	0.00	0.130	$430.70	$0.03	$0.00	$74.41	311.20	4786000	4015	47.9	10618000	5309000	2654500	-2131500	2.985	79.24	63.63	24,556,558	246	1.03	0.93	$228
	15	2348.34	1234.60	3582.94	2994.00	588.94	0.00	0.130	$430.70	$0.03	$0.00	$76.74	311.20	2437730	2045	24.4	10618000	5309000	2654500	216770	2.985	72.77	0.00	24,556,558	246	1.03	0.93	$228
	16	2218.89	904.85	3123.74	2994.00	129.74	181.46	0.130	$407.05	$0.03	$5.44	$16.91	311.20	4586190	3847	45.9	10618000	5309000	2654500	-1931690	2.985	79.24	57.66	24,556,558	246	1.03	0.93	$228
	17	1834.66	872.83	2707.49	2994.00	0.00	597.71	0.130	$352.81	$0.03	$17.93	$0.00	311.20	1507310	1265	15.1	10618000	5309000	2654500	1147190	2.985	44.99	0.00	24,556,558	246	1.03	0.93	$228
	18	1569.61	900.88	2470.49	2994.00	0.00	834.71	0.124	$306.41	$0.03	$25.04	$0.00	311.20	1842340	1546	18.4	10618000	5309000	2654500	812160	2.985	54.99	0.00	24,556,558	246	1.03	0.93	$228
	19	1488.58	791.86	2280.44	2994.00	0.00	1024.76	0.124	$282.84	$0.03	$30.74	$0.00	311.20	1872400	1571	18.7	10618000	5309000	2654500	782100	2.985	55.89	0.00	24,556,558	246	1.03	0.93	$228
	20	1357.07	755.42	2112.49	2994.00	0.00	1192.71	0.124	$262.01	$0.03	$35.78	$0.00	311.20	460980	387	4.6	10618000	5309000	2654500	2193520	2.985	13.76	0.00	24,556,558	246	1.03	0.93	$228
	21	1370.73	754.65	2125.38	2994.00	0.00	1179.82	0.124	$263.61	$0.03	$35.39	$0.00	311.20	1044020	876	10.4	10618000	5309000	2654500	1610480	2.985	31.16	0.00	24,556,558	246	1.03	0.93	$228
	22	430.17	659.58	1089.75	2994.00	0.00	2215.45	0.122	$132.64	$0.03	$66.46	$0.00	311.20	329490	276	3.3	10618000	5309000	2654500	2325010	2.985	9.84	0.00	24,556,558	246	1.03	0.93	$228
	23	318.75	548.66	867.41	2994.00	0.00	2437.79	0.122	$105.58	$0.03	$73.13	$0.00	311.20	347500	292	3.5	10618000	5309000	2654500	2307000	2.985	10.37	0.00	24,556,558	246	1.03	0.93	$228
	24	332.31	531.86	864.17	2994.00	0.00	2441.03	0.122	$105.19	$0.03	$73.23	$0.00	311.20	330810	278	3.3	10618000	5309000	2654500	2323690	2.985	9.87	0.00	24,556,558	246	1.03	0.93	$228
12-Aug	1	340.16	536.08	876.24	2994.00	0.00	2428.96	0.122	$106.66	$0.03	$72.87	$0.00	311.20	553830	465	5.5	10618000	5309000	2654500	2100670	2.985	16.53	0.00	24,556,558	246	1.03	0.93	$228
	2	346.49	515.30	861.79	2994.00	0.00	2443.41	0.122	$104.90	$0.03	$73.30	$0.00	311.20	682820	573	6.8	10618000	5309000	2654500	1971680	2.985	20.38	0.00	24,556,558	246	1.03	0.93	$228
	3	346.14	498.54	844.68	2994.00	0.00	2460.52	0.122	$102.81	$0.03	$73.82	$0.00	311.20	841460	706	8.4	10618000	5309000	2654500	1813040	2.985	25.12	0.00	24,556,558	246	1.03	0.93	$228
	4	346.97	492.71	839.68	2994.00	0.00	2465.52	0.122	$102.21	$0.03	$73.97	$0.00	311.20	821130	689	8.2	10618000	5309000	2654500	1833370	2.985	24.51	0.00	24,556,558	246	1.03	0.93	$228
	5	328.18	489.77	817.95	2994.00	0.00	2487.25	0.122	$99.56	$0.03	$74.62	$0.00	311.20	882370	740	8.8	10618000	5309000	2654500	1772130	2.985	26.34	0.00	24,556,558	246	1.03	0.93	$228
	6	1160.26	544.82	1705.08	2994.00	0.00	1600.12	0.122	$207.54	$0.03	$48.00	$0.00	311.20	2879950	2416	28.8	10618000	5309000	2654500	-225450	2.985	79.24	6.73	24,556,558	246	1.03	0.93	$228
	7	1327.58	647.15	1974.73	2994.00	0.00	1330.47	0.122	$240.36	$0.03	$39.91	$0.00	311.20	2258280	1895	22.6	10618000	5309000	2654500	396220	2.985	67.41	0.00	24,556,558	246	1.03	0.93	$228
	8	1513.58	836.68	2350.26	2994.00	0.00	954.94	0.124	$291.50	$0.03	$28.65	$0.00	311.20	790880	663	7.9	10618000	5309000	2654500	1863620	2.985	23.61	0.00	24,556,558	246	1.03	0.93	$228
	9	1523.51	884.01	2407.52	2994.00	0.00	897.68	0.124	$298.60	$0.03	$26.93	$0.00	311.20	613840	515	6.1	10618000	5309000	2654500	2040660	2.985	18.32	0.00	24,556,558	246	1.03	0.93	$228
	10	1547.23	1053.37	2600.60	2994.00	0.00	704.60	0.124	$322.55	$0.03	$21.14	$0.00	311.20	840250	705	8.4	10618000	5309000	2654500	1814250	2.985	25.08	0.00	24,556,558	246	1.03	0.93	$228
	11	1545.72	917.25	2462.97	2994.00	0.00	842.23	0.124	$305.48	$0.03	$25.27	$0.00	311.20	1151170	966	11.5	10618000	5309000	2654500	1503330	2.985	34.36	0.00	24,556,558	246	1.03	0.93	$228
	12	1410.95	912.57	2323.52	2994.00	0.00	981.68	0.130	$302.78	$0.03	$29.45	$0.00	311.20	669150	561	6.7	10618000	5309000	2654500	1985350	2.985	19.97	0.00	24,556,558	246	1.03	0.93	$228
	13	1401.24	1033.17	2434.41	2994.00	0.00	870.79	0.130	$317.23	$0.03	$26.12	$0.00	311.20	1034740	868	10.3	10618000	5309000	2654500	1619760	2.985	30.89	0.00	24,556,558	246	1.03	0.93	$228
	14	1430.45	925.53	2355.98	2994.00	0.00	949.22	0.130	$307.01	$0.03	$28.48	$0.00	311.20	1259060	1056	12.6	10618000	5309000	2654500	1395440	2.985	37.58	0.00	24,556,558	246	1.03	0.93	$228
	15	1400.76	1042.07	2442.83	2994.00	0.00	862.37	0.130	$318.32	$0.03	$25.87	$0.00	311.20	692040	581	6.9	10618000	5309000	2654500	1962460	2.985	20.66	0.00	24,556,558	246	1.03	0.93	$228
	16	1410.27	935.54	2345.81	2994.00	0.00	959.39	0.130	$305.68	$0.03	$28.78	$0.00	311.20	1105100	927	11.1	10618000	5309000	2654500	1549400	2.985	32.99	0.00	24,556,558	246	1.03	0.93	$228
	17	476.09	1036.60	1512.69	2994.00	0.00	1792.51	0.130	$197.12	$0.03	$53.78	$0.00	311.20	940610	789	9.4	10618000	5309000	2654500	1713890	2.985	28.08	0.00	24,556,558	246	1.03	0.93	$228
	18	341.91	752.65	1094.56	2994.00	0.00	2210.64	0.124	$135.76	$0.03	$66.32	$0.00	311.20	252330	212	2.5	10618000	5309000	2654500	2402170	2.985	7.53	0.00	24,556,558	246	1.03	0.93	$228
	19	342.86	735.84	1078.70	2994.00	0.00	2226.50	0.124	$133.79	$0.03	$66.79	$0.00	311.20	684970	575	6.8	10618000	5309000	2654500	1969530	2.985	20.45	0.00	24,556,558	246	1.03	0.93	$228
	20	341.90	723.53	1065.43	2994.00	0.00	2239.77	0.124	$132.14	$0.03	$67.19	$0.00	311.20	238310	200	2.4	10618000	5309000	2654500	2416190	2.985	7.11	0.00	24,556,558	246	1.03	0.93	$228
	21	341.61	689.22	1030.83	2994.00	0.00	2274.37	0.124	$127.85	$0.03	$68.23	$0.00	311.20	668940	561	6.7	10618000	5309000	2654500	1985560	2.985	19.97	0.00	24,556,558	246	1.03	0.93	$228
	22	340.59	649.12	989.71	2994.00	0.00	2315.49	0.122	$120.47	$0.03	$69.46	$0.00	311.20	164790	138	1.6	10618000	5309000	2654500	2489710	2.985	4.92	0.00	24,556,558	246	1.03	0.93	$228
	23	337.18	687.39	1024.57	2994.00	0.00	2280.63	0.122	$124.71	$0.03	$68.42	$0.00	311.20	209630	176	2.1	10618000	5309000	2654500	2444870	2.985	6.26	0.00	24,556,558	246	1.03	0.93	$228
	24	334.66	715.22	1049.88	2994.00	0.00	2255.32	0.122	$127.79	$0.03	$67.66	$0.00	311.20	688500	578	6.9	10618000	5309000	2654500	1966000	2.985	20.55	0.00	24,556,558	246	1.03	0.93	$228

Appendix F – Combined Heat and Power Analysis without Backpressure Steam Turbine

Day	Hour	Electric Consumption Building A	Electric Consumption Building B	Total Consumption	Total Engine Output	Electric Required From Grid	Excess Generation	Electricity Rates	Electricity Consumption Offset	PJM LMP Electric Resale Value	Excess Generation Sold Back	Electricity Purchased	Steam Usage (15 psi, 300F)			Thermal Enthalpy	Thermal Enthalpy From IC Engine	Excess Steam Produced	Purchased Steam Rate	Steam Savings	Amount of Steam Purchased	IC Engine Natural Gas Input				
		kWh	kWh	kWh	kWh		kWh	$/kWh	$	$/kWh	$	$	Btu/hr	lb/hr	Therm/hr	Btu/hr	Btu/hr	Btu/hr	$/therm	$	$	btu/hr	therm/hr	$/ first 10,000 therms	$/over 10,000 therms	$
11-Aug	1	341.47	655.32	996.79	2994.00	0.00	1997.21	0.122	$121.33	$0.03	$59.92	$0.00	206380	173	2.1	10618000	8282040	8075660	2.985	6.16	0.00	24,556,558	246	1.03	0.93	$228
	2	340.00	650.90	990.90	2994.00	0.00	2003.10	0.122	$120.61	$0.03	$60.09	$0.00	660000	554	6.6	10618000	8282040	7622040	2.985	19.70	0.00	24,556,558	246	1.03	0.93	$228
	3	339.66	607.59	947.25	2994.00	0.00	2046.75	0.122	$115.30	$0.03	$61.40	$0.00	151100	127	1.5	10618000	8282040	8130940	2.985	4.51	0.00	24,556,558	246	1.03	0.93	$228
	4	339.77	608.05	947.82	2994.00	0.00	2046.18	0.122	$115.37	$0.03	$61.39	$0.00	259550	218	2.6	10618000	8282040	8022490	2.985	7.75	0.00	24,556,558	246	1.03	0.93	$228
	5	389.52	611.82	1001.34	2994.00	0.00	1992.66	0.122	$121.88	$0.03	$59.78	$0.00	162310	136	1.6	10618000	8282040	8119730	2.985	4.84	0.00	24,556,558	246	1.03	0.93	$228
	6	1351.35	690.04	2041.39	2994.00	0.00	952.61	0.122	$248.48	$0.03	$28.58	$0.00	2136250	1792	21.4	10618000	8282040	6145790	2.985	63.77	0.00	24,556,558	246	1.03	0.93	$228
	7	1597.98	737.26	2335.24	2994.00	0.00	658.76	0.122	$284.24	$0.03	$19.76	$0.00	1090720	915	10.9	10618000	8282040	7191320	2.985	32.56	0.00	24,556,558	246	1.03	0.93	$228
	8	2455.31	1238.81	3694.12	2994.00	700.12	0.00	0.124	$371.34	$0.03	$0.00	$86.84	1838260	1542	18.4	10618000	8282040	6443780	2.985	54.87	0.00	24,556,558	246	1.03	0.93	$228
	9	2354.34	1157.31	3511.65	2994.00	517.65	0.00	0.124	$371.34	$0.03	$0.00	$64.20	4775110	4006	47.8	10618000	8282040	3506930	2.985	142.54	0.00	24,556,558	246	1.03	0.93	$228
	10	2362.89	1110.70	3473.59	2994.00	479.59	0.00	0.124	$371.34	$0.03	$0.00	$59.48	1170700	982	11.7	10618000	8282040	7111340	2.985	34.95	0.00	24,556,558	246	1.03	0.93	$228
	11	2291.65	1247.37	3539.02	2994.00	545.02	0.00	0.124	$371.34	$0.03	$0.00	$67.60	4754570	3989	47.5	10618000	8282040	3527470	2.985	141.92	0.00	24,556,558	246	1.03	0.93	$228
	12	2305.20	1242.59	3547.79	2994.00	553.79	0.00	0.130	$390.15	$0.03	$0.00	$72.16	1761500	1478	17.6	10618000	8282040	6520540	2.985	52.58	0.00	24,556,558	246	1.03	0.93	$228
	13	2376.61	1137.92	3514.53	2994.00	520.53	0.00	0.130	$390.15	$0.03	$0.00	$67.83	4044010	3393	40.4	10618000	8282040	4238030	2.985	120.71	0.00	24,556,558	246	1.03	0.93	$228
	14	2348.04	1216.97	3565.01	2994.00	571.01	0.00	0.130	$390.15	$0.03	$0.00	$74.41	4786000	4015	47.9	10618000	8282040	3496040	2.985	142.86	0.00	24,556,558	246	1.03	0.93	$228
	15	2348.34	1234.60	3582.94	2994.00	588.94	0.00	0.130	$390.15	$0.03	$0.00	$76.74	2437730	2045	24.4	10618000	8282040	5844310	2.985	72.77	0.00	24,556,558	246	1.03	0.93	$228
	16	2218.89	904.85	3123.74	2994.00	129.74	0.00	0.130	$390.15	$0.03	$0.00	$16.91	4586190	3847	45.9	10618000	8282040	3695850	2.985	136.90	0.00	24,556,558	246	1.03	0.93	$228
	17	1834.66	872.83	2707.49	2994.00	0.00	286.51	0.130	$352.81	$0.03	$8.60	$0.00	1507310	1265	15.1	10618000	8282040	6774730	2.985	44.99	0.00	24,556,558	246	1.03	0.93	$228
	18	1569.61	900.88	2470.49	2994.00	0.00	523.51	0.124	$306.41	$0.03	$15.71	$0.00	1842340	1546	18.4	10618000	8282040	6439700	2.985	54.99	0.00	24,556,558	246	1.03	0.93	$228
	19	1488.58	791.86	2280.44	2994.00	0.00	713.56	0.124	$282.84	$0.03	$21.41	$0.00	1872400	1571	18.7	10618000	8282040	6409640	2.985	55.89	0.00	24,556,558	246	1.03	0.93	$228
	20	1357.07	755.42	2112.49	2994.00	0.00	881.51	0.124	$262.01	$0.03	$26.45	$0.00	460980	387	4.6	10618000	8282040	7821060	2.985	13.76	0.00	24,556,558	246	1.03	0.93	$228
	21	1370.73	754.65	2125.38	2994.00	0.00	868.62	0.124	$263.61	$0.03	$26.06	$0.00	1044020	876	10.4	10618000	8282040	7238020	2.985	31.16	0.00	24,556,558	246	1.03	0.93	$228
	22	430.17	659.58	1089.75	2994.00	0.00	1904.25	0.122	$132.64	$0.03	$57.13	$0.00	329490	276	3.3	10618000	8282040	7952550	2.985	9.84	0.00	24,556,558	246	1.03	0.93	$228
	23	318.75	548.66	867.41	2994.00	0.00	2126.59	0.122	$105.58	$0.03	$63.80	$0.00	347500	292	3.5	10618000	8282040	7934540	2.985	10.37	0.00	24,556,558	246	1.03	0.93	$228
	24	332.31	531.86	864.17	2994.00	0.00	2129.83	0.122	$105.19	$0.03	$63.89	$0.00	330810	278	3.3	10618000	8282040	7951230	2.985	9.87	0.00	24,556,558	246	1.03	0.93	$228
12-Aug	1	340.16	536.08	876.24	2994.00	0.00	2117.76	0.122	$106.66	$0.03	$63.53	$0.00	553830	465	5.5	10618000	8282040	7728210	2.985	16.53	0.00	24,556,558	246	1.03	0.93	$228
	2	346.49	515.30	861.79	2994.00	0.00	2132.21	0.122	$104.90	$0.03	$63.97	$0.00	682820	573	6.8	10618000	8282040	7599220	2.985	20.38	0.00	24,556,558	246	1.03	0.93	$228
	3	346.14	498.54	844.68	2994.00	0.00	2149.32	0.122	$102.81	$0.03	$64.48	$0.00	841460	706	8.4	10618000	8282040	7440580	2.985	25.12	0.00	24,556,558	246	1.03	0.93	$228
	4	346.97	492.71	839.68	2994.00	0.00	2154.32	0.122	$102.21	$0.03	$64.63	$0.00	821130	689	8.2	10618000	8282040	7460910	2.985	24.51	0.00	24,556,558	246	1.03	0.93	$228
	5	328.18	489.77	817.95	2994.00	0.00	2176.05	0.122	$99.56	$0.03	$65.28	$0.00	882370	740	8.8	10618000	8282040	7399670	2.985	26.34	0.00	24,556,558	246	1.03	0.93	$228
	6	1160.26	544.82	1705.08	2994.00	0.00	1288.92	0.122	$207.54	$0.03	$38.67	$0.00	2879950	2416	28.8	10618000	8282040	5402090	2.985	85.97	0.00	24,556,558	246	1.03	0.93	$228
	7	1327.58	647.15	1974.73	2994.00	0.00	1019.27	0.122	$240.36	$0.03	$30.58	$0.00	2258280	1895	22.6	10618000	8282040	6023760	2.985	67.41	0.00	24,556,558	246	1.03	0.93	$228
	8	1513.58	836.68	2350.26	2994.00	0.00	643.74	0.124	$291.50	$0.03	$19.31	$0.00	790880	663	7.9	10618000	8282040	7491160	2.985	23.61	0.00	24,556,558	246	1.03	0.93	$228
	9	1523.51	884.01	2407.52	2994.00	0.00	586.48	0.124	$298.60	$0.03	$17.59	$0.00	613840	515	6.1	10618000	8282040	7668200	2.985	18.32	0.00	24,556,558	246	1.03	0.93	$228
	10	1547.23	1053.37	2600.60	2994.00	0.00	393.40	0.124	$322.55	$0.03	$11.80	$0.00	840250	705	8.4	10618000	8282040	7441790	2.985	25.08	0.00	24,556,558	246	1.03	0.93	$228
	11	1545.72	917.25	2462.97	2994.00	0.00	531.03	0.124	$305.48	$0.03	$15.93	$0.00	1151170	966	11.5	10618000	8282040	7130870	2.985	34.36	0.00	24,556,558	246	1.03	0.93	$228
	12	1410.95	912.57	2323.52	2994.00	0.00	670.48	0.130	$302.78	$0.03	$20.11	$0.00	669150	561	6.7	10618000	8282040	7612890	2.985	19.97	0.00	24,556,558	246	1.03	0.93	$228
	13	1401.24	1033.17	2434.41	2994.00	0.00	559.59	0.130	$317.23	$0.03	$16.79	$0.00	1034740	868	10.3	10618000	8282040	7247300	2.985	30.89	0.00	24,556,558	246	1.03	0.93	$228
	14	1430.45	925.53	2355.98	2994.00	0.00	638.02	0.130	$307.01	$0.03	$19.14	$0.00	1259060	1056	12.6	10618000	8282040	7022980	2.985	37.58	0.00	24,556,558	246	1.03	0.93	$228
	15	1400.76	1042.07	2442.83	2994.00	0.00	551.17	0.130	$318.32	$0.03	$16.54	$0.00	692040	581	6.9	10618000	8282040	7590000	2.985	20.66	0.00	24,556,558	246	1.03	0.93	$228
	16	1410.27	935.54	2345.81	2994.00	0.00	648.19	0.130	$305.68	$0.03	$19.45	$0.00	1105100	927	11.1	10618000	8282040	7176940	2.985	32.99	0.00	24,556,558	246	1.03	0.93	$228
	17	476.09	1036.60	1512.69	2994.00	0.00	1481.31	0.130	$197.12	$0.03	$44.44	$0.00	940610	789	9.4	10618000	8282040	7341430	2.985	28.08	0.00	24,556,558	246	1.03	0.93	$228
	18	341.91	752.65	1094.56	2994.00	0.00	1899.44	0.124	$135.76	$0.03	$56.98	$0.00	252330	212	2.5	10618000	8282040	8029710	2.985	7.53	0.00	24,556,558	246	1.03	0.93	$228
	19	342.86	735.84	1078.70	2994.00	0.00	1915.30	0.124	$133.79	$0.03	$57.46	$0.00	684970	575	6.8	10618000	8282040	7597070	2.985	20.45	0.00	24,556,558	246	1.03	0.93	$228
	20	341.90	723.53	1065.43	2994.00	0.00	1928.57	0.124	$132.14	$0.03	$57.86	$0.00	238310	200	2.4	10618000	8282040	8043730	2.985	7.11	0.00	24,556,558	246	1.03	0.93	$228
	21	341.61	689.22	1030.83	2994.00	0.00	1963.17	0.124	$127.85	$0.03	$58.90	$0.00	668940	561	6.7	10618000	8282040	7613100	2.985	19.97	0.00	24,556,558	246	1.03	0.93	$228
	22	340.59	649.12	989.71	2994.00	0.00	2004.29	0.122	$120.47	$0.03	$60.13	$0.00	164790	138	1.6	10618000	8282040	8117250	2.985	4.92	0.00	24,556,558	246	1.03	0.93	$228
	23	337.18	687.39	1024.57	2994.00	0.00	1969.43	0.122	$124.71	$0.03	$59.08	$0.00	209630	176	2.1	10618000	8282040	8072410	2.985	6.26	0.00	24,556,558	246	1.03	0.93	$228
	24	334.66	715.22	1049.88	2994.00	0.00	1944.12	0.122	$127.79	$0.03	$58.32	$0.00	688500	578	6.9	10618000	8282040	7593540	2.985	20.55	0.00	24,556,558	246	1.03	0.93	$228

Appendix G – Acoustical Calculations

Fats Lab									
NC Max 40		63 Hz	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz	8000 Hz
	Engine dBA re 20µPa	95	101	99	94	93	92	94	95
	A weighting	-26	-16	-9	-3	0	1	1	-1
	Engine dB re 20µPa	121	117	108	97	93	91	93	96
	IC Engine Enclosure TL	22	22	29	40	48	54	60	60
	Wall TL	42	42	45	53	61	67	70	70
	Added Absorption TL	21	21	27	29	37	49	53	53
	dB in Receiving Room	36	32	7	0	0	0	0	0
	NC Curve Limits	63	55	50	45	41	39	37	36

Care Lab									
NC Max 40		63 Hz	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz	8000 Hz
	Engine dBA re 20µPa	95	101	99	94	93	92	94	95
	A weighting	-26	-16	-9	-3	0	1	1	-1
	Engine dB re 20µPa	121	117	108	97	93	91	93	96
	IC Engine Enclosure TL	22	22	29	40	48	54	60	60
	Wall TL	42	42	45	53	61	67	70	70
	Added Absorption TL	21	21	27	29	37	49	53	53
	dB in Receiving Room	36	32	7	0	0	0	0	0
	NC Curve Limits	63	55	50	45	41	39	37	36

Gait Lab									
NC Max 40		63 Hz	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz	8000 Hz
	Engine dBA re 20µPa	95	101	99	94	93	92	94	95
	A weighting	-26	-16	-9	-3	0	1	1	-1
	Engine dB re 20µPa	121	117	108	97	93	91	93	96
	IC Engine Enclosure TL	22	22	29	40	48	54	60	60
	Wall TL	42	42	45	53	61	67	70	70
	Added Absorption TL	21	21	27	29	37	49	53	53
	dB in Receiving Room	36	32	7	0	0	0	0	0
	NC Curve Limits	63	55	50	45	41	39	37	36

Conference									
NC Max 30		63 Hz	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz	8000 Hz
	Engine dBA re 20µPa	95	101	99	94	93	92	94	95
	A weighting	-26	-16	-9	-3	0	1	1	-1
	Engine dB re 20µPa	121	117	108	97	93	91	93	96
	IC Engine Enclosure TL	22	22	29	40	48	54	60	60
	Wall TL	38	41	43	52	59	67	72	72
	Added Absorption TL	21	21	27	29	37	49	53	53
	dB in Receiving Room	40	33	9	0	0	0	0	0
	NC Curve Limits	56	47	41	35	31	29	28	26

Recovery Room/Offices									
		63 Hz	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz	8000 Hz
NC Max 35	Engine dBA re 20µPa	95	101	99	94	93	92	94	95
	A weighting	-26	-16	-9	-3	0	1	1	-1
	Engine dB re 20µPa	121	117	108	97	93	91	93	96
	IC Engine Enclosure TL	22	22	29	40	48	54	60	60
	Wall TL	38	41	43	52	59	67	72	72
	Added Absorption TL	21	21	27	29	37	49	53	53
	dB in Receiving Room	40	33	9	0	0	0	0	0
	NC Curve Limits	60	52	45	40	36	34	33	32

Radiation Procedure									
		63 Hz	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz	8000 Hz
NC Max 40	Engine dBA re 20µPa	95	101	99	94	93	92	94	95
	A weighting	-26	-16	-9	-3	0	1	1	-1
	Engine dB re 20µPa	121	117	108	97	93	91	93	96
	IC Engine Enclosure TL	22	22	29	40	48	54	60	60
	Wall TL	38	41	43	52	59	67	72	72
	Added Absorption TL	21	21	27	29	37	49	53	53
	dB in Receiving Room	40	33	9	0	0	0	0	0
	NC Curve Limits	63	55	50	45	41	39	37	36

Staff Lounge									
		63 Hz	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz	8000 Hz
NC Max 40	Engine dBA re 20µPa	95	101	99	94	93	92	94	95
	A weighting	-26	-16	-9	-3	0	1	1	-1
	Engine dB re 20µPa	121	117	108	97	93	91	93	96
	IC Engine Enclosure TL	22	22	29	40	48	54	60	60
	Wall TL	38	41	43	52	59	67	72	72
	Added Absorption TL	21	21	27	29	37	49	53	53
	dB in Receiving Room	40	33	9	0	0	0	0	0
	NC Curve Limits	63	55	50	45	41	39	37	36

Appendix H – Solar Shading and Day lighting Solar Angles and Shade Position

January				
Time	Azimuth	Altitude	South	West
1	-166.01	0.00	0	0
2	-152.15	0.00	0	0
3	-138.65	0.00	0	0
4	-102.19	0.00	0	0
5	-64.50	0.00	0	0
6	-69.15	0.00	0	0
7	-64.50	0.00	0	0
8	-54.82	8.01	0	0
9	-43.67	16.84	100	0
10	-30.75	23.91	100	0
11	-15.99	28.54	100	0
12	0.00	30.17	100	0
13	15.99	28.54	100	0
14	30.75	23.91	100	0
15	43.67	16.84	0	100
16	54.82	8.01	0	100
17	64.50	0.00	0	0
18	69.15	0.00	0	0
19	64.50	0.00	0	0
20	102.19	0.00	0	0
21	138.65	0.00	0	0
22	152.15	0.00	0	0
23	166.01	0.00	0	0
24	180.00	0.00	0	0

February				
Time	Azimuth	Altitude	South	West
1	-165.43	0.00	0	0
2	-150.92	0.00	0	0
3	-136.58	0.00	0	0
4	-122.65	0.00	0	0
5	-81.55	0.00	0	0
6	-76.67	0.00	0	0
7	-70.25	2.91	0	0
8	-60.08	13.48	0	0
9	-48.38	22.94	100	0
10	-34.48	30.66	100	0
11	-18.13	35.85	100	0
12	0.00	37.69	100	0
13	18.13	35.85	100	0
14	34.48	30.66	100	0
15	48.38	22.94	0	100
16	60.08	13.48	0	100
17	70.25	2.91	0	0
18	76.67	0.00	0	0
19	81.55	0.00	0	0
20	122.65	0.00	0	0
21	136.58	0.00	0	0
22	150.92	0.00	0	0
23	165.43	0.00	0	0
24	180.00	0.00	0	0

March				
Time	Azimuth	Altitude	South	West
1	-165.04	0.00	0	0
2	-150.09	0.00	0	0
3	-135.16	0.00	0	0
4	-120.27	0.00	0	0
5	-105.57	0.00	0	0
6	-87.48	0.37	0	0
7	-78.59	10.06	0	0
8	-68.21	21.21	0	0
9	-56.06	31.50	0	0
10	-41.01	40.25	100	0
11	-22.11	46.38	100	0
12	0.00	48.63	100	0
13	22.11	46.38	100	0
14	41.01	40.25	100	0
15	56.06	31.50	0	100
16	68.21	21.21	0	100
17	78.59	10.06	0	100
18	87.48	0.37	0	0
19	105.57	0.00	0	0
20	120.27	0.00	0	0
21	135.16	0.00	0	0
22	150.09	0.00	0	0
23	165.04	0.00	0	0
24	180.00	0.00	0	0

April				
Time	Azimuth	Altitude	South	West
1	-165.24	0.00	0	0
2	-150.50	0.00	0	0
3	-135.86	0.00	0	0
4	-121.46	0.00	0	0
5	-107.90	0.00	0	0
6	-97.41	5.95	0	0
7	-88.08	17.57	0	0
8	-78.03	29.12	0	0
9	-66.10	40.19	0	0
10	-50.48	50.11	100	0
11	-28.63	57.58	100	0
12	0.00	60.51	100	0
13	28.63	57.58	100	0
14	50.48	50.11	100	100
15	66.10	40.19	0	100
16	78.03	29.12	0	100
17	88.08	17.57	0	100
18	97.41	5.95	0	100
19	107.90	0.00	0	0
20	121.46	0.00	0	0
21	135.86	0.00	0	0
22	150.50	0.00	0	0
23	165.24	0.00	0	0
24	180.00	0.00	0	0

May				
Time	Azimuth	Altitude	South	West
1	-165.83	0.00	0	0
2	-151.77	0.00	0	0
3	-138.02	0.00	0	0
4	-124.98	0.00	0	0
5	-113.89	1.03	0	0
6	-104.83	11.70	0	0
7	-96.04	23.15	0	0
8	-86.74	34.78	0	0
9	-75.77	46.29	0	0
10	-60.85	57.12	100	0
11	-37.23	65.98	100	0
12	0.00	69.83	100	0
13	37.23	65.98	100	0
14	60.85	57.12	100	100
15	75.77	46.29	0	100
16	86.74	34.78	0	100
17	96.04	23.15	0	100
18	104.83	11.70	0	100
19	113.89	1.03	0	0
20	124.98	0.00	0	0
21	138.02	0.00	0	0
22	151.77	0.00	0	0
23	165.83	0.00	0	0
24	180.00	0.00	0	0

June				
Time	Azimuth	Altitude	South	West
1	-166.23	0.00	0	0
2	-152.62	0.00	0	0
3	-139.42	0.00	0	0
4	-127.19	0.00	0	0
5	-117.09	3.52	0	0
6	-108.33	14.27	0	0
7	-99.89	25.57	0	0
8	-91.10	37.17	0	0
9	-80.87	48.79	0	0
10	-66.87	59.98	100	0
11	-43.13	69.61	100	0
12	0.00	74.10	100	0
13	43.13	69.61	100	0
14	66.87	59.98	100	100
15	80.87	48.79	0	100
16	91.10	37.17	0	100
17	99.89	25.57	0	100
18	108.33	14.27	0	100
19	117.09	3.52	0	0
20	127.19	0.00	0	0
21	139.42	0.00	0	0
22	152.62	0.00	0	0
23	166.23	0.00	0	0
24	180.00	0.00	0	0

July				
Time	Azimuth	Altitude	South	West
1	-166.03	0.00	0	0
2	-152.20	0.00	0	0
3	-138.74	0.00	0	0
4	-126.13	0.00	0	0
5	-115.60	2.22	0	0
6	-106.70	13.09	0	0
7	-98.09	24.46	0	0
8	-89.05	36.08	0	0
9	-78.45	47.66	0	0
10	-63.98	58.69	100	0
11	-40.19	67.96	100	0
12	0.00	72.12	100	0
13	40.19	67.96	100	0
14	63.98	58.69	100	100
15	78.45	47.66	0	100
16	89.05	36.08	0	100
17	98.09	24.46	0	100
18	106.70	13.09	0	100
19	115.60	2.22	0	0
20	126.13	0.00	0	0
21	138.74	0.00	0	0
22	152.20	0.00	0	0
23	166.03	0.00	0	0
24	180.00	0.00	0	0

August				
Time	Azimuth	Altitude	South	West
1	-165.43	0.00	0	0
2	-150.93	0.00	0	0
3	-136.59	0.00	0	0
4	-122.67	0.00	0	0
5	-110.06	0.00	0	0
6	-100.42	8.31	0	0
7	-91.27	19.89	0	0
8	-81.46	31.50	0	0
9	-69.83	42.77	0	0
10	-54.33	53.07	100	0
11	-31.62	61.07	100	0
12	0.00	64.32	100	0
13	31.62	61.07	100	0
14	54.33	53.07	100	100
15	69.83	42.77	0	100
16	81.46	31.50	0	100
17	91.27	19.89	0	100
18	100.42	8.31	0	0
19	110.06	0.00	0	0
20	122.67	0.00	0	0
21	136.59	0.00	0	0
22	150.93	0.00	0	0
23	165.43	0.00	0	0
24	180.00	0.00	0	0

September				
Time	Azimuth	Altitude	South	West
1	-165.03	0.00	0	0
2	-150.07	0.00	0	0
3	-135.14	0.00	0	0
4	-120.23	0.00	0	0
5	-105.51	0.00	0	0
6	-91.40	1.67	0	0
7	-82.02	12.87	0	0
8	-71.69	24.20	0	0
9	-59.51	34.80	0	0
10	-44.13	43.97	100	0
11	-24.15	50.55	100	0
12	0.00	53.01	100	0
13	24.15	50.55	100	0
14	44.13	43.97	100	0
15	59.51	34.80	0	100
16	71.69	24.20	0	100
17	82.02	12.87	0	100
18	91.40	1.67	0	0
19	105.51	0.00	0	0
20	120.23	0.00	0	0
21	135.14	0.00	0	0
22	150.07	0.00	0	0
23	165.03	0.00	0	0
24	180.00	0.00	0	0

October				
Time	Azimuth	Altitude	South	West
1	-165.25	0.00	0	0
2	-150.54	0.00	0	0
3	-135.93	0.00	0	0
4	-121.57	0.00	0	0
5	-95.09	0.00	0	0
6	-80.15	0.00	0	0
7	-72.88	5.20	0	0
8	-62.60	15.97	0	0
9	-50.70	25.70	100	0
10	-36.40	33.74	100	0
11	-19.26	39.21	100	0
12	0.00	41.17	100	0
13	19.26	39.21	100	0
14	36.40	33.74	100	0
15	50.70	25.70	100	100
16	62.60	15.97	0	100
17	72.88	5.20	0	0
18	80.15	0.00	0	0
19	95.09	0.00	0	0
20	121.57	0.00	0	0
21	135.93	0.00	0	0
22	150.54	0.00	0	0
23	165.25	0.00	0	0
24	180.00	0.00	0	0

November				
Time	Azimuth	Altitude	South	West
1	-165.85	0.00	0	0
2	-151.81	0.00	0	0
3	-138.09	0.00	0	0
4	-125.10	0.00	0	0
5	-65.90	0.00	0	0
6	-70.95	0.00	0	0
7	-65.90	0.24	0	0
8	-56.06	9.32	0	0
9	-44.76	18.31	100	0
10	-31.60	25.53	100	0
11	-16.47	30.29	100	0
12	0.00	31.97	100	0
13	16.47	30.29	100	0
14	31.60	25.53	100	0
15	44.76	18.31	100	0
16	56.06	9.32	0	0
17	65.90	0.24	0	0
18	70.95	0.00	0	0
19	65.90	0.00	0	0
20	125.10	0.00	0	0
21	138.09	0.00	0	0
22	151.81	0.00	0	0
23	165.85	0.00	0	0
24	180.00	0.00	0	0

December				
Time	Azimuth	Altitude	South	West
1	-166.24	0.00	0	0
2	-152.63	0.00	0	0
3	-139.42	0.00	0	0
4	-52.81	0.00	0	0
5	-62.69	0.00	0	0
6	-66.91	0.00	0	0
7	-62.69	0.00	0	0
8	-53.28	6.36	0	0
9	-42.33	15.00	100	0
10	-29.71	21.87	100	0
11	-15.41	26.35	100	0
12	0.00	27.92	100	0
13	15.41	26.35	100	0
14	29.71	21.87	100	0
15	42.33	15.00	100	0
16	53.28	6.36	0	0
17	62.69	0.00	0	0
18	66.91	0.00	0	0
19	62.69	0.00	0	0
20	52.81	0.00	0	0
21	139.42	0.00	0	0
22	152.63	0.00	0	0
23	166.24	0.00	0	0
24	180.00	0.00	0	0

Appendix I – Day Lighting Interior Renderings

January 1st - 12:00PM


Before Shading

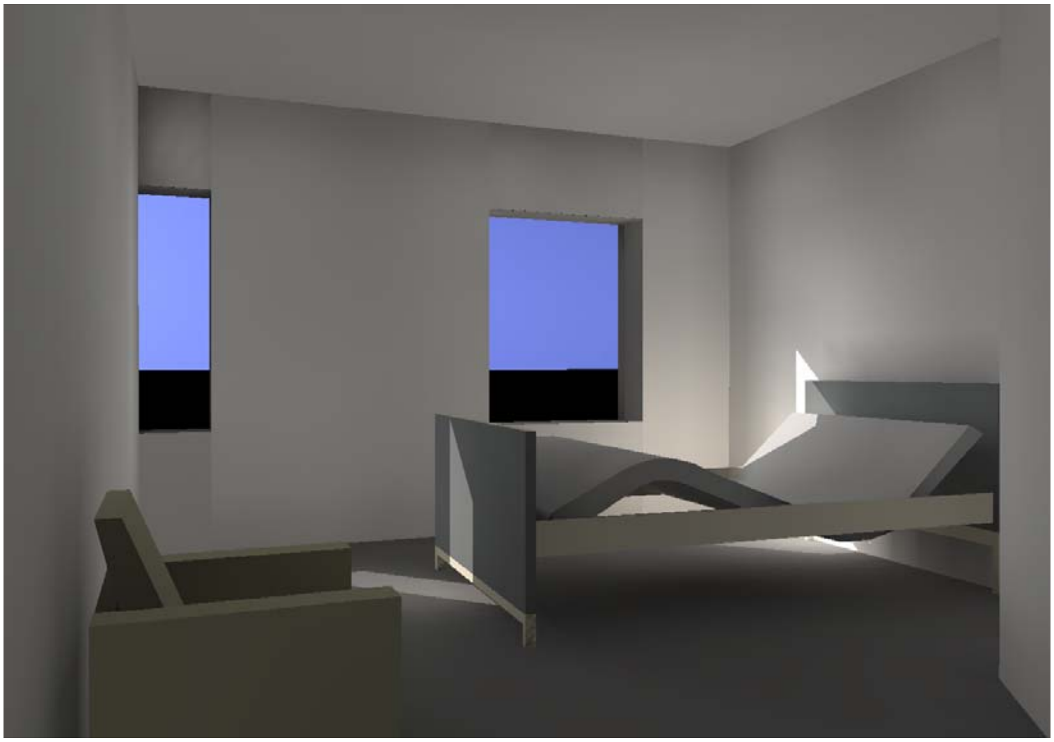

After Shading

January 1st - 2:00PM

Before Shading

After Shading

March 2nd – 10:00AM



Before Shading

After Shading

March 2nd – 12:00PM

Before Shading

After Shading

March 2nd – 2:00PM


Before Shading


After Shading