# Architectural Engineering Senior Thesis:
## Centralized Plant Design of Direct Fired Absorption Chiller-Heaters in a Low-Rise Office Building

HITT Contracting Headquarters
2900 Fairview Park Drive, Falls Church, VA

Prepared By:
Charles Haack
Mechanical Option
April 9, 2009

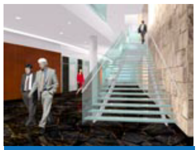
Prepared For:
Dr. William P. Bahnfleth, Ph.D., P.E., Professor
Department of Architectural Engineering
The Pennsylvania State University

# HITT CONTRACTING HEADQUARTERS

## 2900 Fairview Park Drive Falls Church, VA

## Project Overview

Number of Stories -
3 above grade/4 total levels
Size - 135,000 Square Feet
Delivery Method - Design-Bid-Build
Cost - $30 Million
Building Use - Office, Fitness Center, Parking Garage, & Conference Space
Construction Dates -
Start - May 2008
Completion - September 2009



## Project Team

Owner - HITT Contracting Fairfax, VA
CM - Urban, Ltd. Annandale, VA
Landscape Architect - Rhodeside & Harwell Inc. Alexandria, VA
Structural - Fernandez & Associates Structural Engineers, P.C. Falls Church, VA
MEP - KTA Group Herndon, VA
Architect - Noritake Associates Alexandria, VA

## Mechanical

(7) VAV Roof Top Units with Heat Exchangers providing 148,500 CFM
(3) Split-System AC Units supplement cooling loads for the Café & Fitness Center
VAV Terminal boxes distribute air to space

## Structural

Slab on grade foundation with footings
10” 2-way concrete slab for floors 1-3
Flat roof comprised of 10” 2-way concrete slab

## Electrical

4000A 277/480v 3 phase 4 wire utility service
2-75kVA Transformers per floor (6 Total)
125kW 277/480v Stand-by Generator
277v T5 fluorescent lighting

## Architectural

Precast concrete panel envelope with punched out glazing
Covered parking deck
Fitness center and cafe
Signature glazing spine divides building

## Charles Haack

Mechanical Option
http://www.engr.psu.edu/ae/thesis/portfolios/2009/cjh5004/

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## Acknowledgements

Thesis Advisor – William Bahnfleth, Ph. D, P.E., Professor

Ross Rebraca from HITT Contracting

KTA Group

David Noland LEED AP EIT from KTA Group

Brain Kopp from HC Nye

Matt Haapala

Dan Hanley

## Master's Thesis Integration

The topic of the absorption chillers was studied in AE 557 – Central Cooling Systems instructed by Professor Bahnfleth and is included in the mechanical system redesign described in this report.

## Executive Summary

HITT Contracting Headquarters is a four story, 135,000 square foot office building located next to the Capital Beltway in Falls Church, Virginia. The building consists of a variety of spaces including office, conference rooms, server space, café, fitness center and covered, under-building parking. The current mechanical system was designed to achieve a LEED silver rating and utilizes unitary rooftop units with DX cooling and electric resistance heating. The existing system is environmentally conscious and relatively efficient, but improvements could be made through a system redesign. It should be noted that economic and design constraints that were placed upon the design team were not taken into account in this report, as this report is not meant to discredit the existing system.

Three main studies were conducted for this report:

- Centralized redesign of mechanical system
- Sustainability study involving rainfall capturing
- Structural impact analysis studying the effects of the new systems

Before describing the new centralized system, this report overviews the existing system. This new centralized plant was designed with efficient systems including: absorption refrigeration and heating through the use of a chiller-heater, waterside free cooling, primary-secondary pumping, and cooling towers for heat rejection. The primary goal of the redesign was to improve efficiency of the system with a lesser focus on economic first costs. It was found that the new system had a simple payback of seventeen years when compared to the existing system and reduced annual energy usage by approximately ten percent. The new system also diversifies the building energy sources by using both natural gas and electricity; the existing system only uses electricity.

The sustainability study described in this report was implemented to provide additional water for non-potable uses from rainwater that would normally be treated as a waste and expelled from the building. A tank was sized to capture rainwater from the roof and to provide the full amount of water for the toilet systems 25 percent of the time, with supplemental volumes the rest of the year. An economic analysis concluded that the new rainwater capturing system would have a simple payback of approximately 20 years. As in the mechanical redesign, economic payback was not the primary concern of the study. Offsetting of potable water use was the main goal of the study.

A structural impact analysis was also performed to account for the new loads that the mechanical redesign and sustainability study created. The study achieved its goals of redesigning the structural system to the new loads and calculating the cost difference. Cooling towers were added and unitary rooftop units were replaced with air handling units. Minor changes to the roof structure were observed, including a net reduction in the amount of reinforcing steel. The cost change between the existing and new was a minimal savings of $614.51.

The redesign of HITT Contracting Headquarters increases the overall system first cost while reducing the annual operating costs of the building from $2.52 per square foot to $2.38 per square foot. The overall energy usage and amount of potable water consumed by the toilet system were also reduced greatly by the new system. These modifications would be best for long term solutions for the building when considering a life cycle of over 20 years.

## Building Design Background

HITT Contracting Headquarters is a four story, 135,000 square foot office building located next to the Capital Beltway in Falls Church, Virginia. The building consists of a variety of spaces including office, conference rooms, server space, café, fitness center and covered, under-building parking. HITT Contracting is a general contractor based in Northern Virginia and their current headquarters is located in Fairfax, Virginia.

### Existing Design Objectives

The design team was given with the task to devise a building that included office, conference, storage, plotting and printing, and fitness spaces, all while aiming for LEED silver certification. The design of the mechanical systems for HITT Contracting Headquarters had the following requirements:

- Occupant controllability of the system
- Minimal use of usable square footage for mechanical systems
- Energy efficiency (LEED requires improvement upon baseline case)
- Meeting ASHRAE 62.1-2004 (LEED credit EQ 1 Minimum IAQ Performance)
- Meeting ASHRAE 90.1-2004 (Minimum Energy Efficiency Standards)

### Structural System Background

The structural system of HITT Contracting Headquarters is of reinforced concrete design. The foundation system consists of a slab on grade 5” thick reinforced with W/ 6x6 W2.1xW2.1 WWF centered in slab depth that is placed upon 4” of VA DOT #56 Gravel . Floors one to three are comprised of 10” thick 2-way reinforced concrete slabs with 4 ½” deep drop panels around concrete columns. The columns are spaced in approximately a 16’ by 16’ grid. The roof system consists of a 10” thick 2-way concrete slab that forms a flat roof for the structure. The building façade is a curtain wall structure comprised of precast concrete panels with punched out fenestration hung from each floor.

# Mechanical System Existing Conditions

## Design Conditions & Assumptions

Since the building is currently under construction, no usage data could be obtained. As this was the case, Trane Trace 700 was used model the building heating and cooling loads and energy consumption rates. Listed in Tables 1, 2 and 3 below are the design condition and load assumptions used to create the energy model of HITT Contracting Headquarters.

**Table 1** – ASHRAE Design Conditions

| ASHRAE Outdoor Air Conditions (99.6% and 0.4%) | |
|---|---|
| Washington, DC | Temperature °F |
| Winter Dry Bulb | 15 |
| Summer Dry Bulb | 95 |
| Summer Wet Bulb | 78 |

**Table 2** – ASHRAE Indoor Design Conditions

| Indoor Design | Temperature °F |
|---|---|
| Cooling Supply Dry Bulb | 78F |
| Cooling Drift point | 90F |
| Heating Supply Dry Bulb | 72F |
| Heating Drift point | 55F |
| Relative Humidity | 50% |

**Table 3** – Load Calculation Assumptions

| Load Calculation Assumptions | | |
|---|---|---|
| Load Type | Loads | |
| Lighting | 1.1 | Watts/SF |
| Misc. Loads | 3.46 | Watts/SF |
| People | 250 | Btu/Person Sensible |
| | 250 | Btu/Person Latent |
| Occupancy Density | 114 | SF/Person (Office) |
| | 50 | SF/Person (Conference) |
| | 20 | SF/Person (Fitness) |
| | 50 | SF/Person (Cafe) |

## Airside Systems

HITT Contracting Headquarters has seven 50 Ton AAON air-cooled packaged rooftop units with energy recovery wheels serving the four occupied floors; three above ground and one below grade. Each above ground floor has at total of two units that serve the North and South sections respectively. Parallel, series, and shut-off fan-powered Variable-Air-Volume (VAV) terminal units control the final supply temperature and flow to individual zones throughout the building. Three split-system air-conditioning units provide air for loads in fitness and café spaces. See Figure 1 for a schematic of a typical existing rooftop unit.

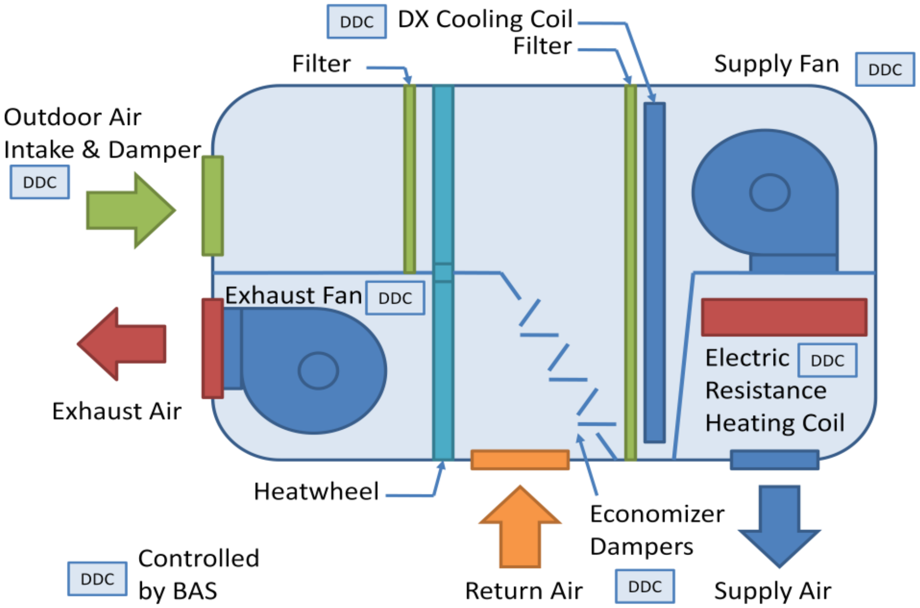

**Figure 1** – Schematic of Typical Existing Rooftop Unit

Powered Roof Ventilators (PRV) provide exhaust for restroom and locker spaces throughout the building. Additional exhaust for storage and trash rooms is provided by ceiling mounted exhaust fans. Exhaust fans also exist in entry rooms from the parking garage to expel harmful vapors that enter from the parking area. See Figure 2 for a schematic of the entire existing airside system. Figure 3 is a rendering of the existing rooftop with rooftop units and screening.

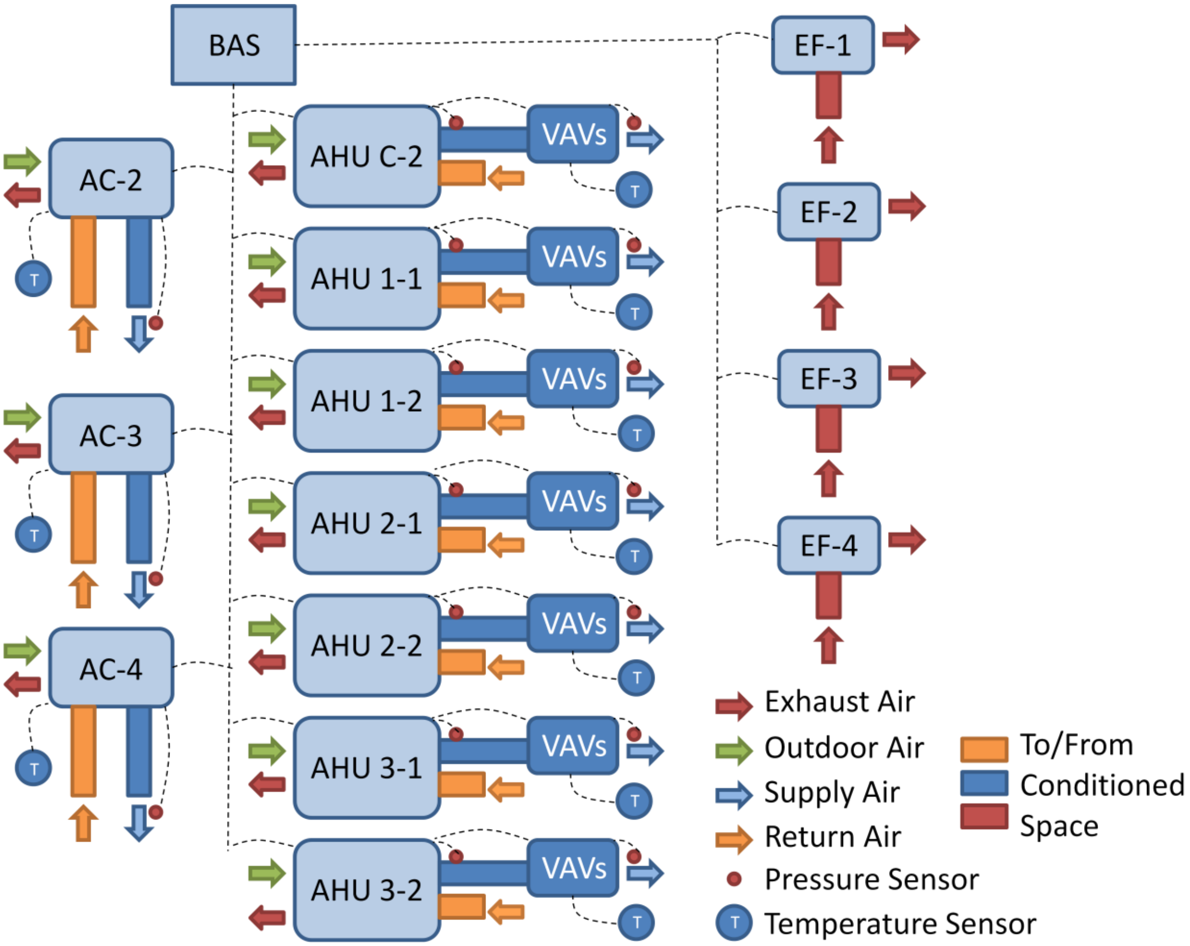

**Figure 2** – Schematic of existing airside system

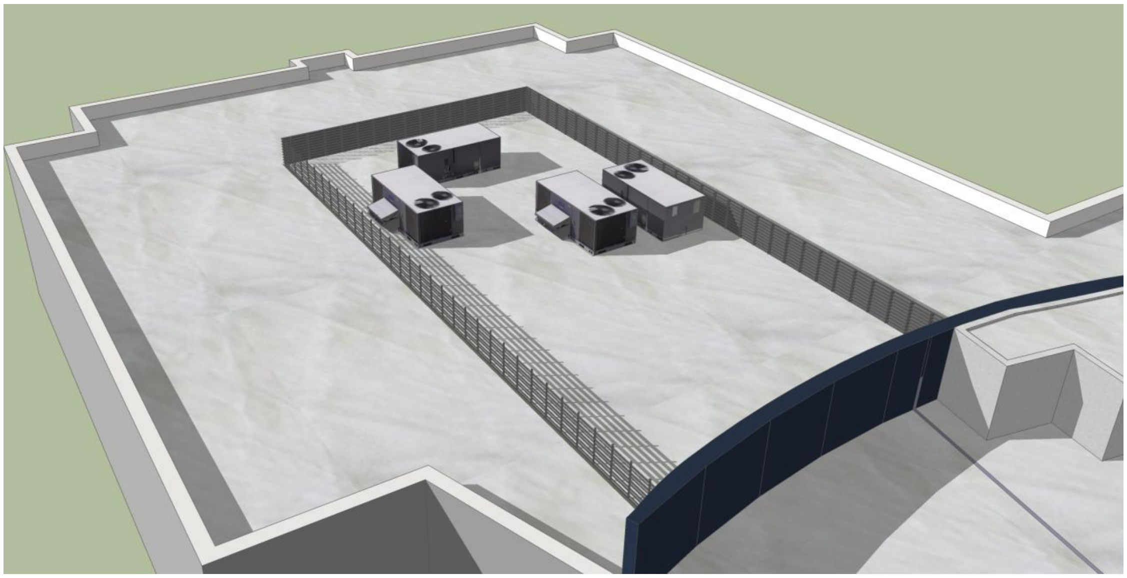

**Figure 3** – Rendering of Existing Rooftop

## Heating & Cooling Requirements

The peak Heating and cooling loads were calculated by Trane Trace 700 and are listed in Table 4 below for each of the rooftop air handling units and the supplemental air handlers for the café and fitness areas.

**Table 4 –** Cooling and Heating Loads

| Cooling and Heating Loads | | |
|---|---|---|
| | Cooling (tons) | Heating (MBH) |
| AHU 1-1 | 52.1 | 309.7 |
| AHU 1-2 | 42.5 | 262.8 |
| AHU 2-1 | 52.1 | 309.7 |
| AHU 2-2 | 39.3 | 259.8 |
| AHU 3-1 | 50.6 | 307.9 |
| AHU 3-2 | 42 | 292.4 |
| AHU C-2 | 63.3 | 264.1 |
| Café | 11.9 | 91.3 |
| Fitness | 10.6 | 129 |

## Existing Building Energy Usage Summary

The monthly energy consumption as calculated by Trace 700 is displayed in Figure 4 below. The schedules noted in Appendix B were used for the energy consumption modeling. On peak demand was set to occur between the hours of 10am – 10pm from June to September and 7am-10pm from October to May. This, along with increased demand to satisfy the cooling loads, accounts for the spike in the off-peak demand during the summer months. The existing annual electricity consumption of HITT Contracting Headquarters was modeled to be 3,769,755 kWh or 27.9 kWh/ft$^2$. This usage leads to an annual energy cost of $340,748 or $2.52 per square foot with a cooling cost of $0.50 per square foot. Figure 5 below describes how the total energy usage is broken down by type.

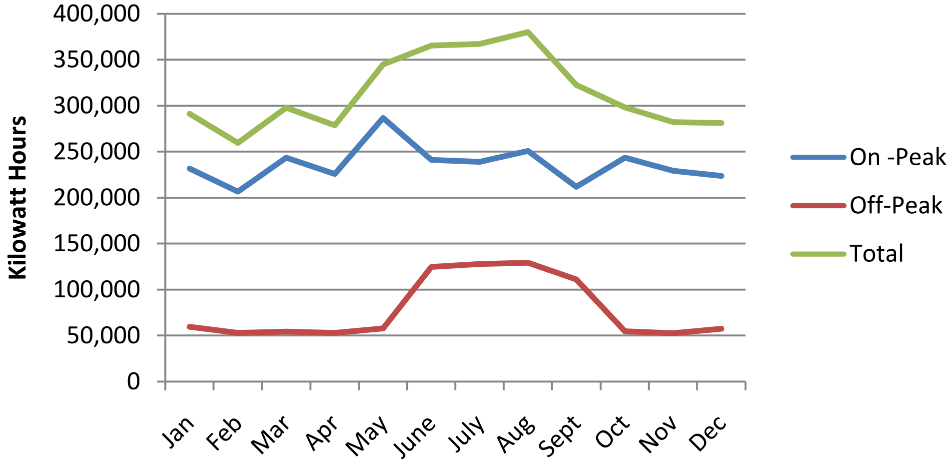

**Figure 4** – Existing Monthly Electricity Usage

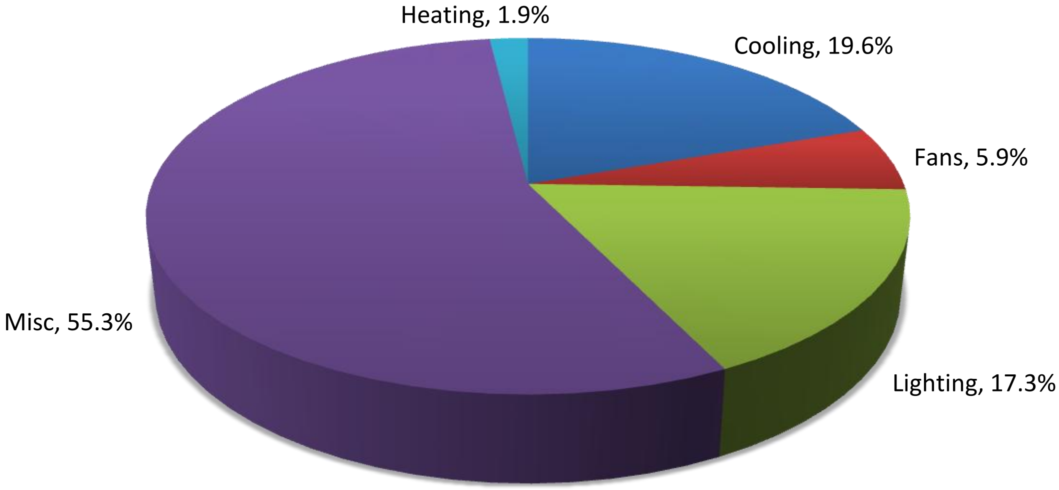

**Figure 5** – Breakdown of Existing Electricity Consumption by Use

## Centralized Plant Design

The change of the heating and cooling systems to a centralized plant design was chosen for this analysis due to the combination of design choices available in a centralized plant system over an all electric direct expansion design. The economic constraints that were placed upon the design team were not considered in this design project and the comparison is for educational reasons only, not to point out flaws in the base building design.

### Centralized Plant Objectives

The objective of the centralized plant design has three main goals:

- Overall reduction in energy consumption over existing system
- Decrease life cycle cost of mechanical systems over existing system
- Educational interest in Absorption chiller & centralized plant design

The discussion of achievements of these goals is discussed in the conclusion section of centralized plant design.

### Design Strategies

The new mechanical system will incorporate a centralized chiller-heater and waterside free cooling. These changes will require the removal of the existing Unitary DX cooling and electric heating rooftop units and the addition of air handlers, cooling towers, heat exchangers, pumps and an absorption chiller-heater. The following sections outline design criteria and selection for this new equipment.

### Absorption Chiller-Heater Design

Chiller-heaters have three operating modes: cooling-only, heating-only, and simultaneous heating and cooling. The direct-fired type of absorption chiller utilizes natural gas or liquid propane to provide heat for the high temperature generator used in the absorption refrigeration cycle. The primary advantage of this system is that there is only one unit that serves in place of the traditional separate boiler and chiller plants.

The cooling-only mode operates as a typical double effect absorption chiller would with a gas-fired high temperature generator and absorber replacing the compressor, see Figure 6 below.

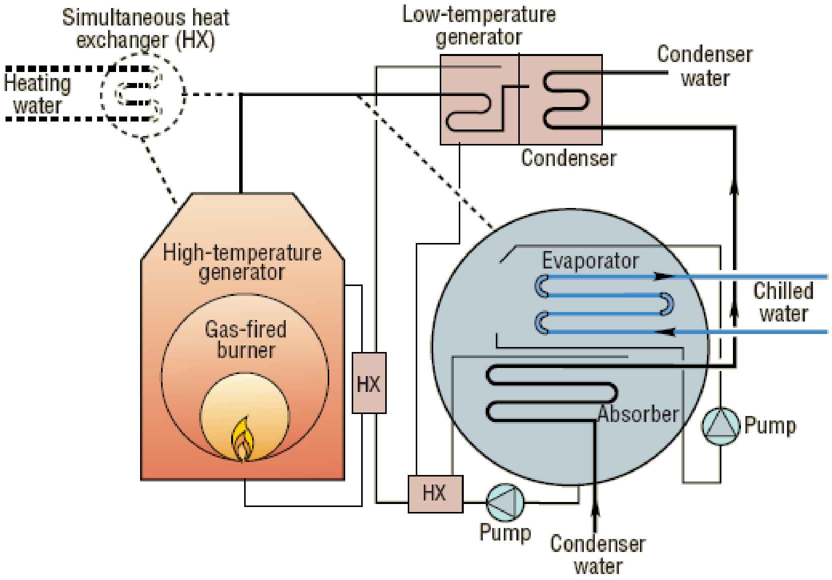

**Figure 6** – Cooling-only mode of a Double Effect Direct-fired Absorption Chiller

The heating-only mode bypasses the condenser used in cooling and utilizes the main evaporator as a condenser. A changeover and downtime is required to switch from cooling-only to heating-only mode because of this. See Figure 7 below for a schematic of the chiller-heater in heating-only.

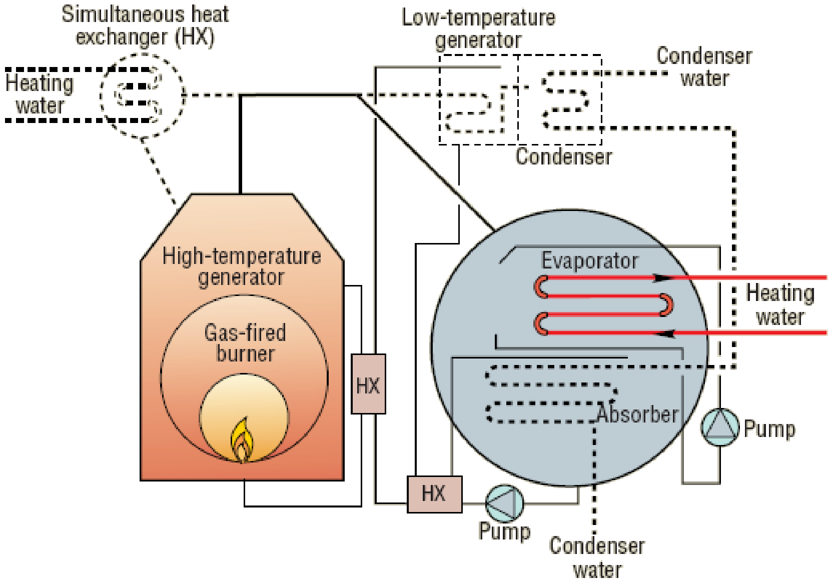

**Figure 7** – Heating-only mode of a Double Effect Direct-fired Absorption Chiller

The simultaneous heating and cooling mode operates as a typical double effect absorption chiller would with a gas-fired high temperature generator, but a heat exchanger is added in parallel between the high and lower temperature generators to produce hot water. See Figure 8 below for a schematic of the simultaneous heating and cooling mode.

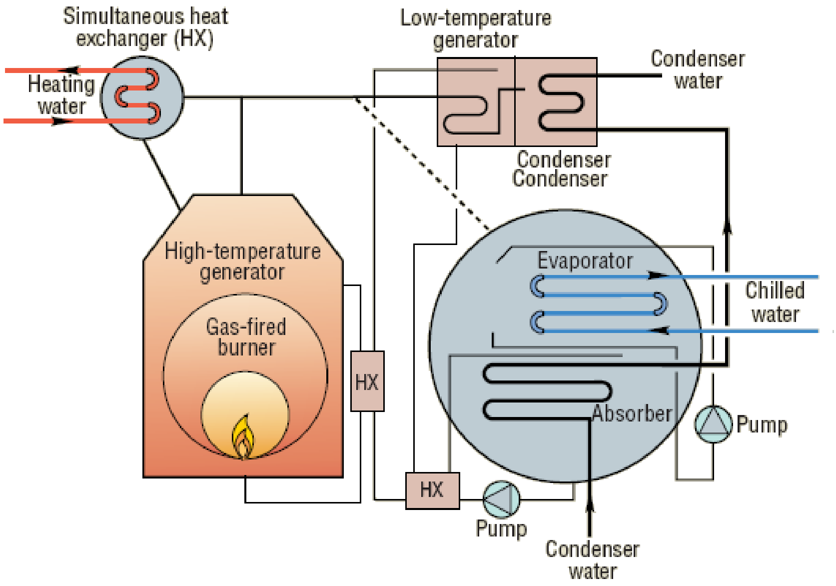

**Figure 8**– Simultaneous heating and cooling mode of a Double Effect Direct-fired Absorption Chiller

Since these systems can provide simultaneous heating and cooling, the chiller-heater cannot be sized based solely upon the peak cooling load. This simultaneous process reduces the effect of both the heating and cooling capabilities since the heat exchanger used to provide hot water reduces the generator heat output in the absorption refrigeration cycle displayed in the Figure 8 above. Because of this combined operation, the chiller-heater should be sized to meet the peak cooling load at approximately 80% of its total capacity to provide excess capacity for producing hot water at part load conditions. See capacity chart in Figure 9 below for an idea of how this tradeoff works.

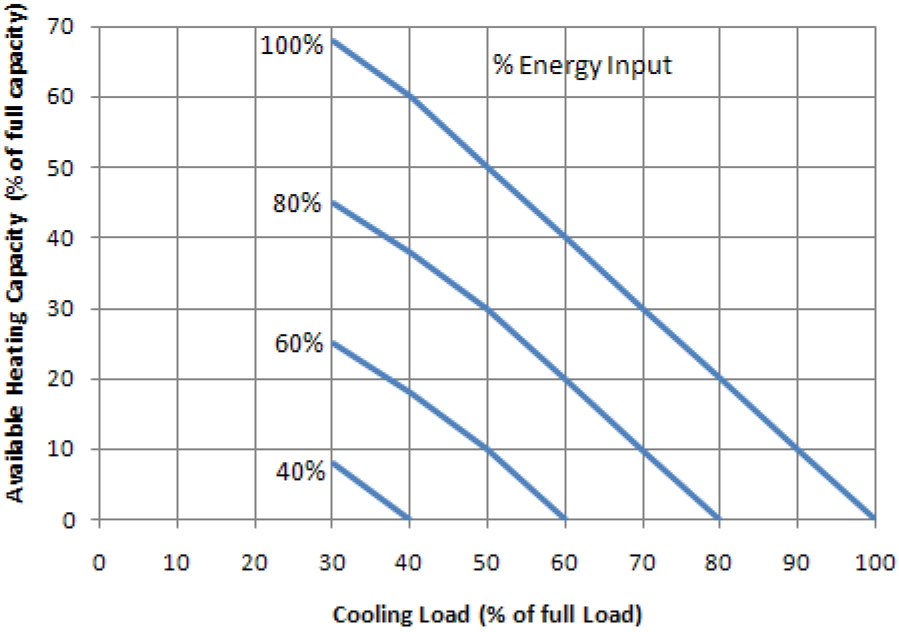

**Figure 9** – Simultaneous Heating and Cooling Capacities Based on Energy Input from Carrier's Absorption Design Guide

### Chiller-Heater Selection

The peak cooling load was calculated to be 367 tons in Trane Trace 700. Based upon this calculation and the method described above, the plant size that would best fit the heating and cooling loads would be a cooling design load of approximately 458 tons. Two 240 ton chiller-heaters (230 tons actual) were used in the new centralized plant for two main reasons:

- System redundancy
- Ability to meet base load with one chiller-heater.

The design day 24 hour cooling demand profile is graphed in Figure 10 below. It is shown that the base load is approximately 60 tons of cooling in summer conditions. One 240 ton chiller can drop down to 30% of its total capacity to meet this base load, whereas if the system consisted of one 480 ton chiller, it would have to drop to 15% of its total capacity. This low capacity is not recommended due to very low efficiencies.

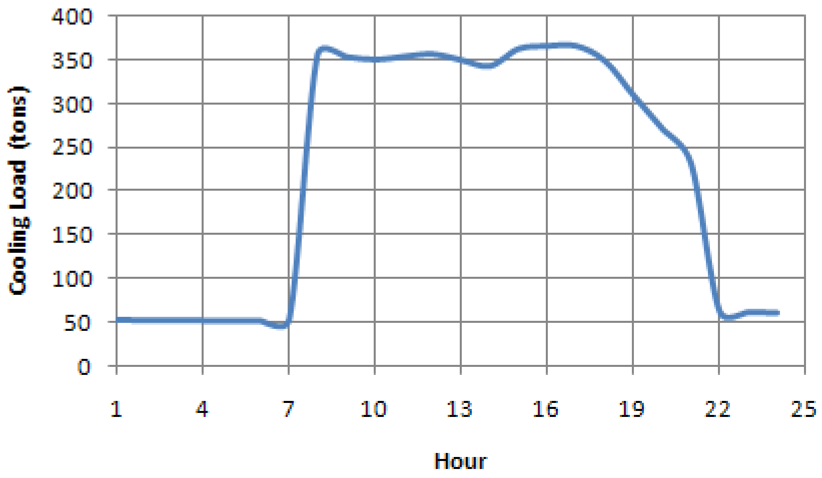

**Figure 10** – Daily Cooling Plant Demand Profile (tons)

### Pumping Selection

Since there are nine heating and cooling coils that the chiller-heaters are supplying, a four-pipe primary/secondary pumping system will be utilized to distribute the hot and chilled water. A variable primary flow system was considered but dismissed due to complications with modeling variable flow rates in the evaporator of a chiller-heater system. So a primary secondary system was chosen. See Figure 13 for a schematic of the centralized plant system.

### Cooling Tower Selection

The cooling towers were selected using Marley UPDATE cooling tower selection software. Table 5 displays the numbers used in selecting each of the cooling towers. See Appendix C for data sheets on the cooling tower selection. The towers were set to have two speed fans to achieve performances similar to variable speed fans, with less cost.

**Table 5** – Cooling Tower Selection Criteria

| Cooling Tower Selection Criteria | | | |
|---|---|---|---|
| # of Towers | GPM | Range | Fan Type |
| 2 | 450 | 10°F | 50/50 2 speed |

## Air Handler Selection

The air handlers for the centralized system serve the same zones as the existing unitary system to provide necessary heating and cooling. This was unchanged due to the variability in peak load between the zones, as they are on different ends of the building. This design makes the first cost of the equipment smaller and can reduce the amount of energy used by the system. The zones are divided into two zones per floor for floors one to three and one zone for the cellar level. See Figure 11 for a graphic displaying the zones and levels described.

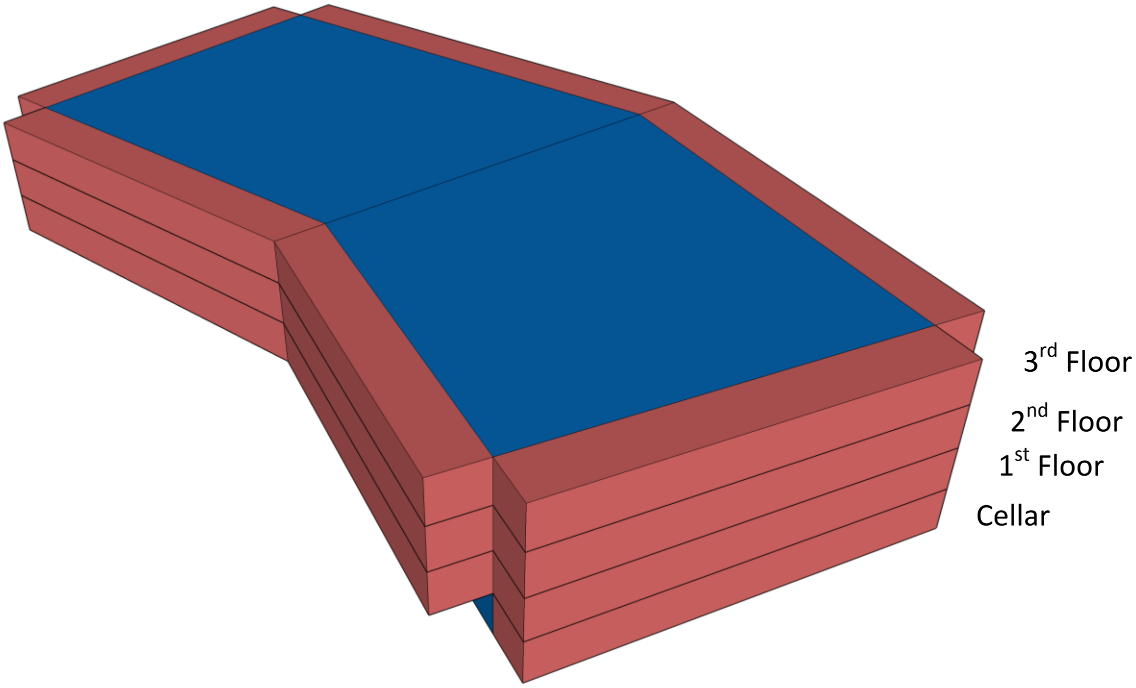

**Figure 11** – Zone Layout Schematic – All Floors

The air handlers replace the existing DX unitary rooftop units and provide a reduction in weight and cost. The new air handlers are VAV rooftop air handlers with total enthalpy wheels and powered exhaust. The basis of design is an AAON RN 40 Air handler. See Table 6 for an overview of the air handler specifications.

**Table 6** – Air Handler Requirements

| Air Handler Requirements | | | |
|---|---|---|---|
| Air Handlers | CFM | Cooling (tons) | Heating (MBH) |
| AHU-1-1 | 22005 | 52.1 | 309.7 |
| AHU-1-2 | 21260 | 42.5 | 262.8 |
| AHU-2-1 | 21230 | 52.1 | 309.7 |
| AHU-2-2 | 22755 | 39.3 | 259.8 |
| AHU-3-1 | 22000 | 50.6 | 307.9 |
| AHU-3-2 | 22000 | 42 | 292.4 |
| AHU-C-2 | 27087 | 63.3 | 264.1 |
| Café 1 & 2 | 3630 | 11.9 | 91.3 |
| Fitness | 3920 | 10.6 | 129 |

## Free Waterside Cooling Design

During cool weather, the outside ambient wet bulb temperature can help save energy in systems that utilize cooling towers. The temperature of water coming from the cooling tower can be used with a heat exchanger to provide cooling for the chilled water returning to the chilled water plant without running the thermal compressor of the absorption chiller. Free cooling can be used to save energy whenever the outside wet-bulb temperature drops below the required chilled water set-point of approximately 46 degrees Fahrenheit. The heat exchanger specifications are listed in Table 7. Figure 12 is an example of a plate and frame heat exchanger.

**Table 7 –** Free Waterside Heat Exchanger Requirements

| LMTD Calculation | | | |
|---|---|---|---|
| $T_{hotin}$ | = | 85 | °F |
| $T_{hotout}$ | = | 95 | °F |
| $T_{coldin}$ | = | 65 | °F |
| $T_{coldout}$ | = | 46 | °F |
| LMTD | = | **34.3** | °F |
| $NTU_{hot}$ | = | 0.29 | |
| $NTU_{cold}$ | = | 0.55 | |
| $h_{hot}$ | = | 750 | |
| $h_{cold}$ | = | 750 | |
| ΔP | = | 15 | psig |
| U | = | **219.5** | btuh/ft$^2$ |

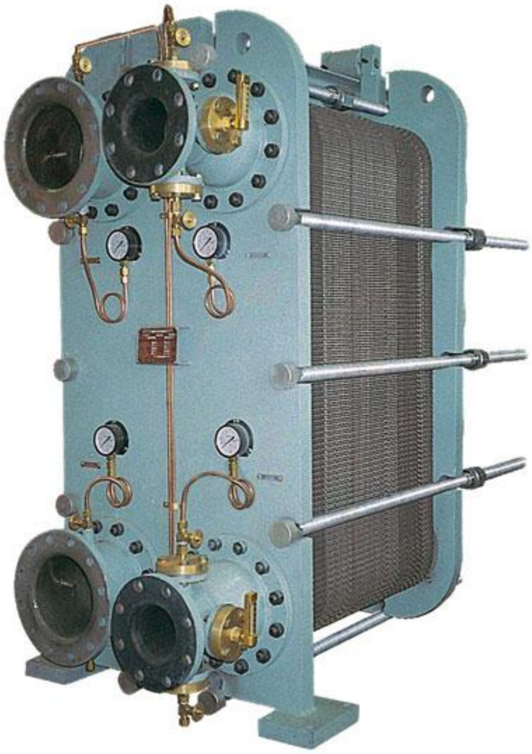

**Figure 12** – Plate and Frame Heat Exchanger

## Centralized Plant Analysis

The new centralized plant will require a new piping system to deliver hydronic heating and cooling to the rooftop air handling unit along with condenser water to the cooling towers on the rooftop. Space for the absorption chiller heater and plate and frame heat exchanger for free cooling will also have to be made inside the building. See Figure 13 below for a schematic of both heating and cooling systems in the central plant. Only the secondary pumps are shown on the schematic for clarity.

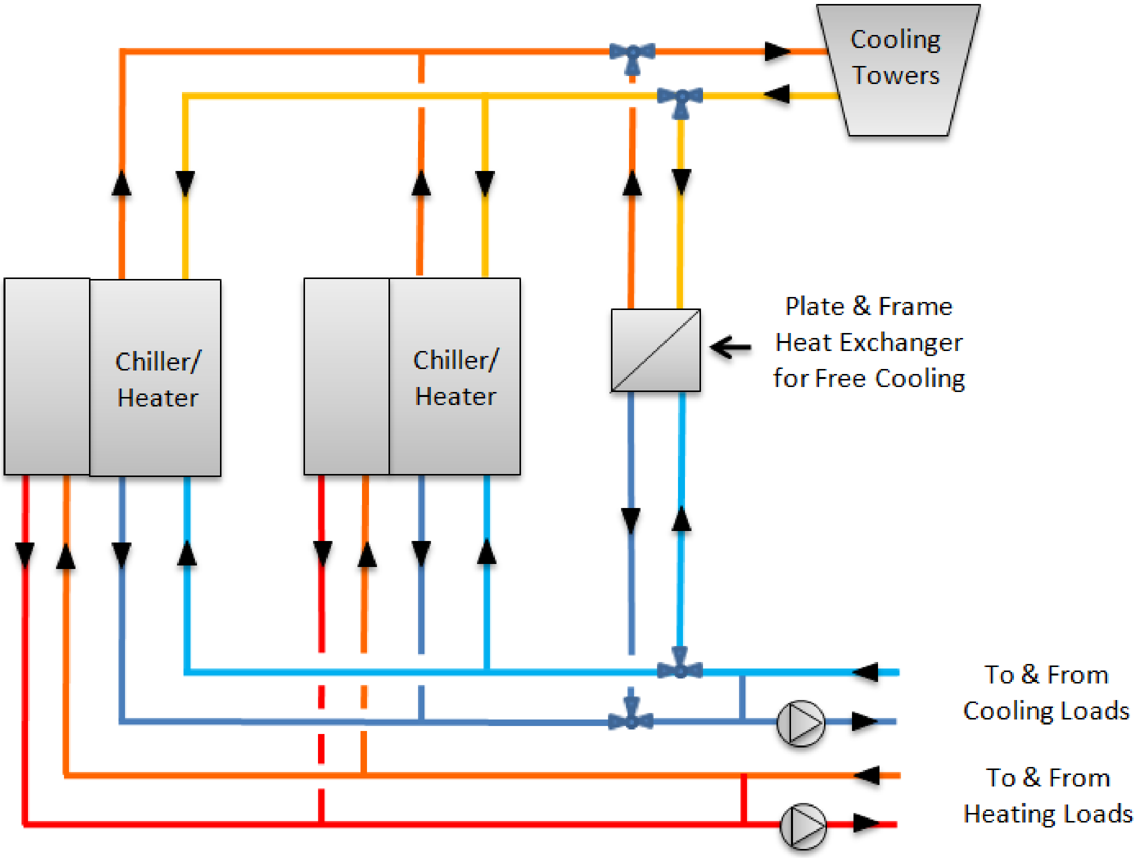

**Figure 13** – Centralized Plant Schematic

The long term flexibility of the central plant system is also a benefit to the building owner; when technologies become more efficient and available the building can be easily retrofitted for a new system after the life cycle of the current system. The centralized chiller-heater with cooling tower was chosen for its anticipated improvement in energy efficiency, smaller shaft space requirements, diversification of primary energy sources and for educational purposes. The system will maintain its ability to simultaneously heat and cool in different parts of the building, provide adequate thermal comfort to building occupants, and provide minimum ventilation.

## ASHRAE 90.1 Compliance

ASHRAE 90.1-2007 prescribes minimum requirements for the building envelope, HVAC systems, service water heating, power, lighting and electric motor efficiency. The compliance calculations below are applied to the equipment in the newly design chiller-heater plant. The location of the building falls into climate zone 5A. Tables 8, 9 and 10 test these requirements.

**Table 8 –** Equipment Compliance

| Minimum Efficiencies - AHSRAE 90.1 Section 6 | | | | | | |
|---|---|---|---|---|---|---|
| | Actual IPLV | Actual COP | Minimum IPLV | Minimum COP | Pass/Fail | System Type |
| AB-1 | 1.09 | 1.14 | 1.00 | 1.00 | Pass | Absorption double effect, Direct-fired |

**Table 9 –** Fan Power Compliance

| Fan Power Limitation - ASHRAE 90.1 Section 6 | | | | | |
|---|---|---|---|---|---|
| Fan Name | Fan Type | [CFM] | HP | $CFM_s \cdot x$ | Pass/Fail |
| AHU-C-2 | Variable | 27087 | 25 | 39.60 | Pass |
| AHU-1-1 | Variable | 22005 | 20 | 29.78 | Pass |
| AHU-1-2 | Variable | 21260 | 25 | 33.00 | Pass |
| AHU-2-1 | Variable | 21230 | 20 | 29.78 | Pass |
| AHU-2-2 | Variable | 22755 | 25 | 33.00 | Pass |
| AHU-3-1 | Variable | 21230 | 20 | 27.45 | Pass |
| AHU-3-2 | Variable | 22755 | 20 | 30.00 | Pass |
| AC-2 | Variable | 4200 | 3 | 6.30 | Pass |
| AC-3 | Variable | 2500 | 2 | 3.75 | Pass |
| AC-4 | Variable | 2500 | 2 | 3.75 | Pass |
| ERV-1 | Variable | 3400 | 5 | 5.10 | Pass |
| EF-C-1 | Constant | 1085 | 0.33 | 1.19 | Pass |
| EF-C-2 | Constant | 150 | 0.15 | 0.17 | Pass |
| EF-C-3 | Constant | 150 | 0.15 | 0.17 | Pass |
| EF-C-4 | Constant | 350 | 0.18 | 0.39 | Pass |
| EF-C-5 | Constant | 150 | 0.15 | 0.17 | Pass |
| EF-C-6 | Constant | 450 | 0.23 | 0.50 | Pass |
| EF-C-7 | Constant | 200 | 0.21 | 0.22 | Pass |
| EF-C-8 | Constant | 350 | 0.18 | 0.39 | Pass |
| EF-C-9 | Constant | 350 | 0.18 | 0.39 | Pass |
| EF-1-1 | Constant | 465 | 0.42 | 0.51 | Pass |
| EF-1-2 | Constant | 465 | 0.42 | 0.51 | Pass |
| EF-2-1 | Constant | 465 | 0.42 | 0.51 | Pass |
| EF-2-2 | Constant | 465 | 0.42 | 0.51 | Pass |
| EF-3-1 | Constant | 465 | 0.42 | 0.51 | Pass |
| EF-3-2 | Constant | 465 | 0.42 | 0.51 | Pass |
| EF-1 | Constant | 2600 | 0.5 | 2.86 | Pass |
| EF-2 | Constant | 3000 | 0.75 | 3.30 | Pass |
| EF-3 | Constant | 1400 | 0.33 | 1.54 | Pass |
| EF-4 | Constant | 700 | 0.25 | 0.77 | Pass |

**Table 10 –** Building Envelope Compliance

<table>
<tr><th colspan="3">Section 5.2 - Building Envelope<br>Opaque Elements</th><th>Area</th><th>U-Factor</th><th>Required U-Factor</th><th>Pass/Fail</th></tr>
<tr><td colspan="3">Roof - Insulation Entirely Above Deck</td><td>41,500</td><td>0.046</td><td>0.048</td><td>Pass</td></tr>
<tr><td colspan="3">Walls - Above-grade</td><td>31,136</td><td>0.05</td><td>0.09</td><td>Pass</td></tr>
<tr><td colspan="3">Walls - Below-grade</td><td>6,845</td><td>0.1</td><td>0.119</td><td>Pass</td></tr>
<tr><td colspan="3">Floors - Slab-on-Grade Floors</td><td>1,010</td><td>0.7</td><td>0.86</td><td>Pass</td></tr>
<tr><th>Fenestration Vertical Glazing</th><th>Area</th><th>U-Factor</th><th>SGHC</th><th>Required U-Factor</th><th>Required SGHC</th><th>Pass/Fail</th></tr>
<tr><td>Cellar level</td><td>16432</td><td>0.046</td><td>0.249</td><td>0.55</td><td>0.4</td><td>Pass</td></tr>
<tr><td>Floors 1-3</td><td>1535</td><td>0.49</td><td>0.697</td><td>0.55</td><td>0.4</td><td>Pass</td></tr>
<tr><td>Doors</td><td>402</td><td>0.49</td><td>0.697</td><td>0.8</td><td>0.4</td><td>Pass</td></tr>
</table>

## ASHRAE 62.1 Compliance

An analysis using ASHRAE 62.1-2007 is shown in Table 11 below. ASHRAE 62.1-2007 prescribes the minimum amount of outdoor air to be supplied to building spaces. As noted, the system as designed exceeds the minimum outdoor air requirements in all of the building air systems by a minimum of 30%, earning LEED-NC 2.2 EQ Credit 2 - Increased Ventilation.

**Table 11 –** Ventilation Calculation

| ASHRAE 62.1 Ventilation Calculation | | | | | | | |
|---|---|---|---|---|---|---|---|
| | Area $ft^2$ | ∑Voz CFM | Vpz Total CFM | Vot Total CFM | Voa Actual CFM | Pass/Fail | % Increase |
| AHU-C-2 | 18095 | 1615 | 27087 | 1794 | 2400 | Pass | 34% |
| AHU-1-1 | 17520 | 1851 | 22005 | 2058 | 2700 | Pass | 31% |
| AHU-1-2 | 18125 | 1999 | 21260 | 2221 | 2900 | Pass | 31% |
| AHU-2-1 | 18665 | 1853 | 21230 | 2059 | 2700 | Pass | 31% |
| AHU-2-2 | 19305 | 2384 | 22755 | 2649 | 3500 | Pass | 32% |
| AHU-3-1 | 18665 | 1853 | 22000 | 2059 | 2700 | Pass | 31% |
| AHU-3-2 | 19305 | 2384 | 22000 | 2649 | 3500 | Pass | 32% |
| Café | 1957 | 595 | 3630 | 595 | 800 | Pass | 34% |
| Fitness | 2150 | 521 | 3920 | 522 | 700 | Pass | 34% |

## Usable Space Breakdown

The required space for new mechanical equipment in HITT Contracting Headquarters had little impact on the usable building square footage. 1.44% of the total building usable square footage is allotted to mechanical systems. The large air handling units that the system uses are located on the roof, freeing up space on the usable floors below. The bulk of the square footage that is taken up by the system is from the new mechanical room created in the cellar. This, along with a dropped acoustical tile ceiling and shafts descending from the rooftop air handling units, provides ample space on floors one to three. See Table 12 below for a total breakdown of the lost usable square footage and per floor. Figure 17 below displays a typical floor with the mechanical shaft areas highlighted in blue.

**Table 12** - Lost Usable Square Footage

| | Total ft$^2$ | Mech ft$^2$ | % Lost Usable Space |
|---|---|---|---|
| Cellar | 20245 | 1329 | 6.56% |
| 1st Floor | 37500 | 93 | 0.25% |
| 2nd Floor | 37500 | 197 | 0.53% |
| 3rd Floor | 37500 | 288 | 0.77% |
| Total | 132745 | 1907 | 1.44% |

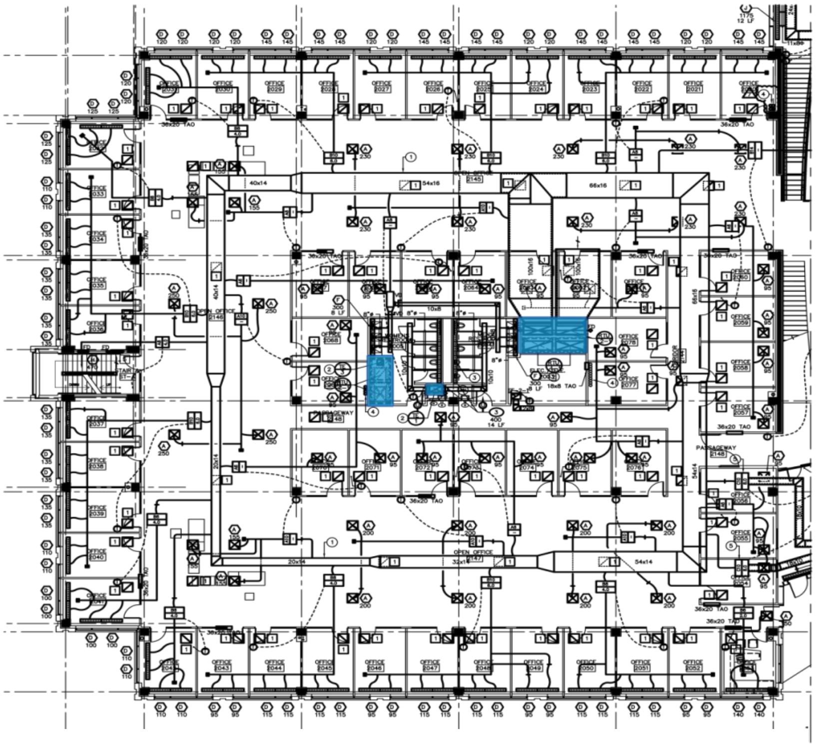

**Figure 17** - Typical Floor Mechanical Spaces

## Energy Analysis

The results from Trane Trace 700 of the new monthly consumption of electricity and natural gas are displayed Figures 14 and 15. The natural gas usage for the building peaks in the summer months when natural gas prices are at a minimum. The natural gas also helps to alleviate increases in on peak consumption of electricity during the months of June, July, August and September and levels out the annual electricity consumption from month to month as shown in Figure 14 below. Figure 16 displays the breakdown of the energy usage by type in the new centralized system. See Appendix A for a breakdown of the energy usage by month.

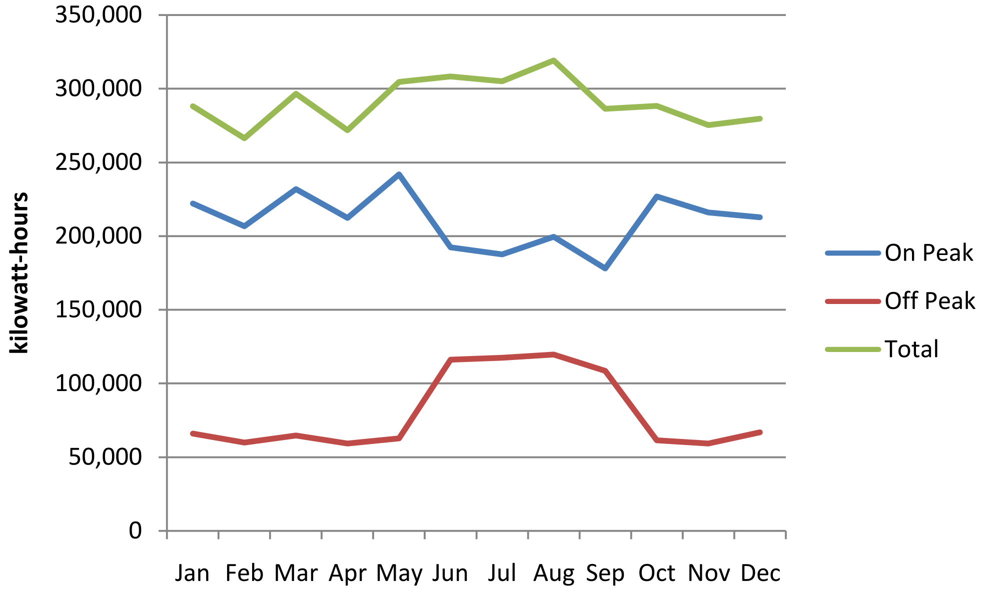

**Figure 14 –** New Monthly Electricity Consumption

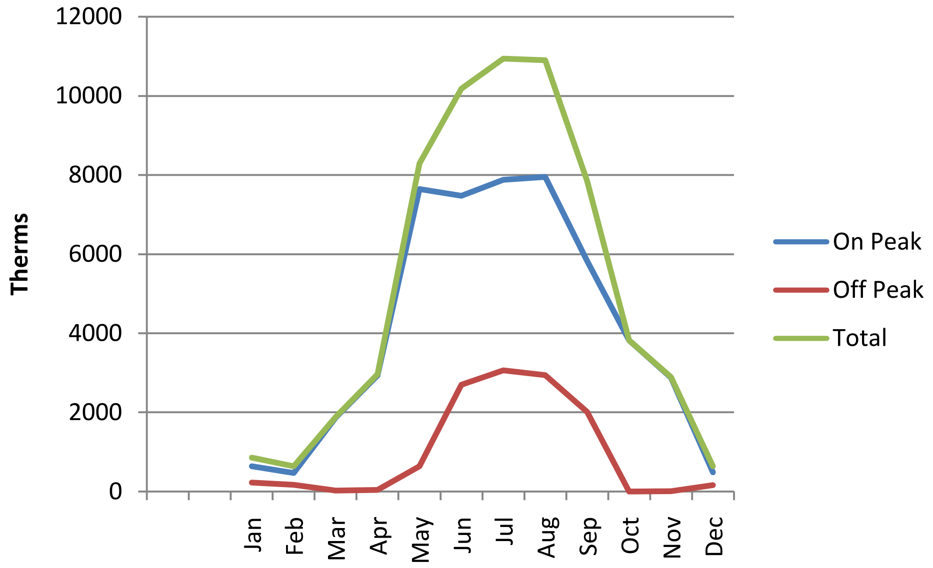

**Figure 15 –** New Monthly Natural Gas Consumption

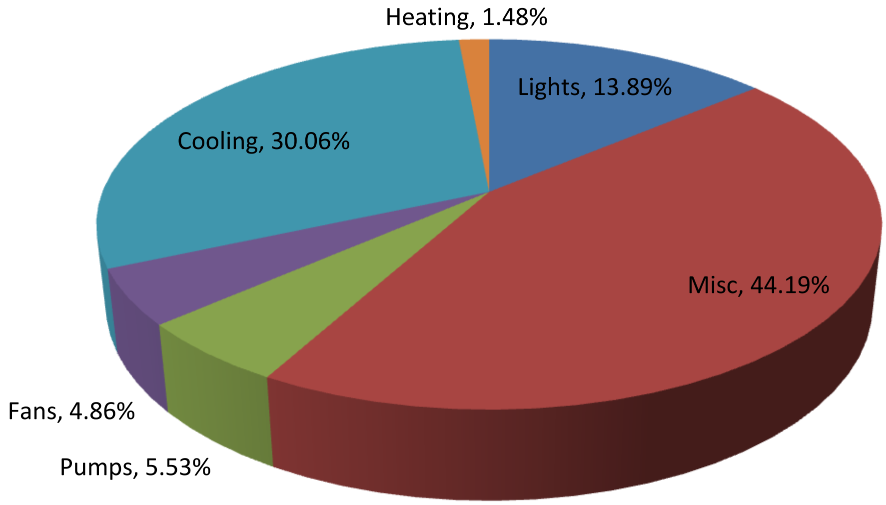

**Figure 16 –** Breakdown of New Energy Consumption by Type

## Economic Analysis

This section displays the calculations associated with the comparison of the first costs, operating costs, and life cycle costs of the existing system with the new centralized system. The life cycle cost analysis was performed for both systems with a simple interest rate of 6% over 20 years. The results show that the simple payback period for the system is approximately 17 years. Maintenance for this system was assumed to be similar to that of the existing system for this analysis. Utility rates are also listed below for reference in Tables 13 and 14. The annual energy cost for the new system was calculated to be $322,556 or $2.38 per square foot with a cooling cost of $0.44 per square foot.

**Table 13** – Natural Gas Rates in Dollars per Therm by Month

| Natural Gas Prices | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Jan | Feb | Mar | April | May | Jun | July | Aug | Sep | Oct | Nov | Dec |
| 1.0957 | 1.0957 | 0.9833 | 0.9833 | 0.9833 | 1.0061 | 0.9507 | 0.8579 | 0.9611 | 0.9067 | 0.981 | 1.0542 |

**Table 14** - Dominion Virginia Power Utility Rates

| | | |
|---|---|---|
| On Peak Demand | 14.488 | $/kW Demand |
| Off Peak Demand | 2.926 | $/kW Demand |
| On Peak Consumption | 0.0404 | $/kWh |
| Off Peak Consumption | 0.0272 | $/kWh |
| Customer Charge(Per Month) | 119.8 | $/Month |

**Table 15** – First Cost of Mechanical Equipment

| Mechanical Equipment First Costs | | |
|---|---|---|
| | DX System | Absorption System |
| DX Rooftop Units | $460,280 | n/a |
| Chiller-Heater | n/a | $255,000 |
| Plate & Frame HX | n/a | $19,000 |
| VAV AHU | n/a | $365,910 |
| VAV Boxes w/ Electric Reheat | $56,000 | n/a |
| VAV Boxes w/ Hydronic Reheat | n/a | $45,500 |
| Cooling Towers | n/a | $17,400 |
| Totals | $516,280 | $702,810 |

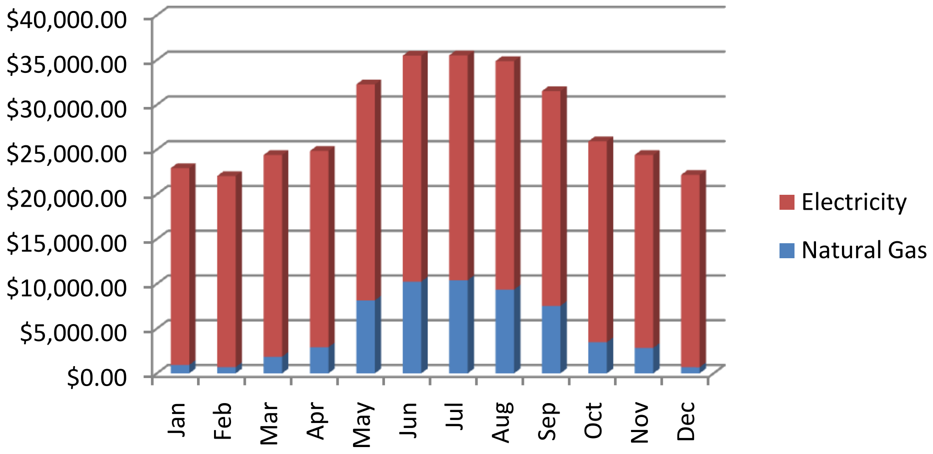

**Figure 18 –** Monthly Energy Costs

**Table 16** – Life Cycle Cost of Mechanical Equipment

| Life Cycle Cost Comparison | | |
|---|---|---|
| i=0.06 | DX System | Absorption System |
| Year 1 | $340,748 | $322,556 |
| Year 2 | $340,748 | $322,556 |
| Year 3 | $340,748 | $322,556 |
| Year 4 | $340,748 | $322,556 |
| Year 5 | $340,748 | $322,556 |
| Year 6 | $340,748 | $322,556 |
| Year 7 | $340,748 | $322,556 |
| Year 8 | $340,748 | $322,556 |
| Year 9 | $340,748 | $322,556 |
| Year 10 | $340,748 | $322,556 |
| Year 11 | $340,748 | $322,556 |
| Year 12 | $340,748 | $322,556 |
| Year 13 | $340,748 | $322,556 |
| Year 14 | $340,748 | $322,556 |
| Year 15 | $340,748 | $322,556 |
| Year 16 | $340,748 | $322,556 |
| Year 17 | $340,748 | $322,556 |
| Year 18 | $340,748 | $322,556 |
| Year 19 | $340,748 | $322,556 |
| Year 20 | $340,748 | $322,556 |
| Net Present Worth | $3,908,353 | $3,699,692 |
| Initial Cost | $516,280 | $702,810 |
| Life Cycle Cost | $4,424,633 | $4,402,502 |

## Central Plant Conclusions

The change to a centralized plant system succeeded in all three of the goals that were set forth in the objectives section. A reduction in energy consumption was achieved as noted in the Energy Analysis section. The goal of decreasing the 20 year life cycle cost was achieved and was done so by $22,131 or 0.5%. The centralized plant system design utilizes more expensive equipment than the existing unitary system and in order to achieve the goal set forth of reducing life cycle cost would have to consume less energy in order to make up the cost difference. The initial cost of the system components were combined with the yearly operating costs calculated in Trane Trace 700. Trane Trace 700 was used to calculate both the existing and new annual energy costs. The system did make profound changes to the roof structure. See Figure 19 for a rendering of the rooftop with the new system.

It was found that the payback period of the system was 17 years, which does not fall into the ideal payback length of 2-4 years. This economic calculation was performed on the basis of current electric and natural gas rates, which are relatively variable. The advantage of the new system is the diversity of energy sources between electric and natural gas as compared to the existing system that depends solely upon electricity rates. Any future increases in electric rates would have a much more profound effect upon the on life cycle cost of the existing system when compared to the new centralized system with an absorption chiller heater.

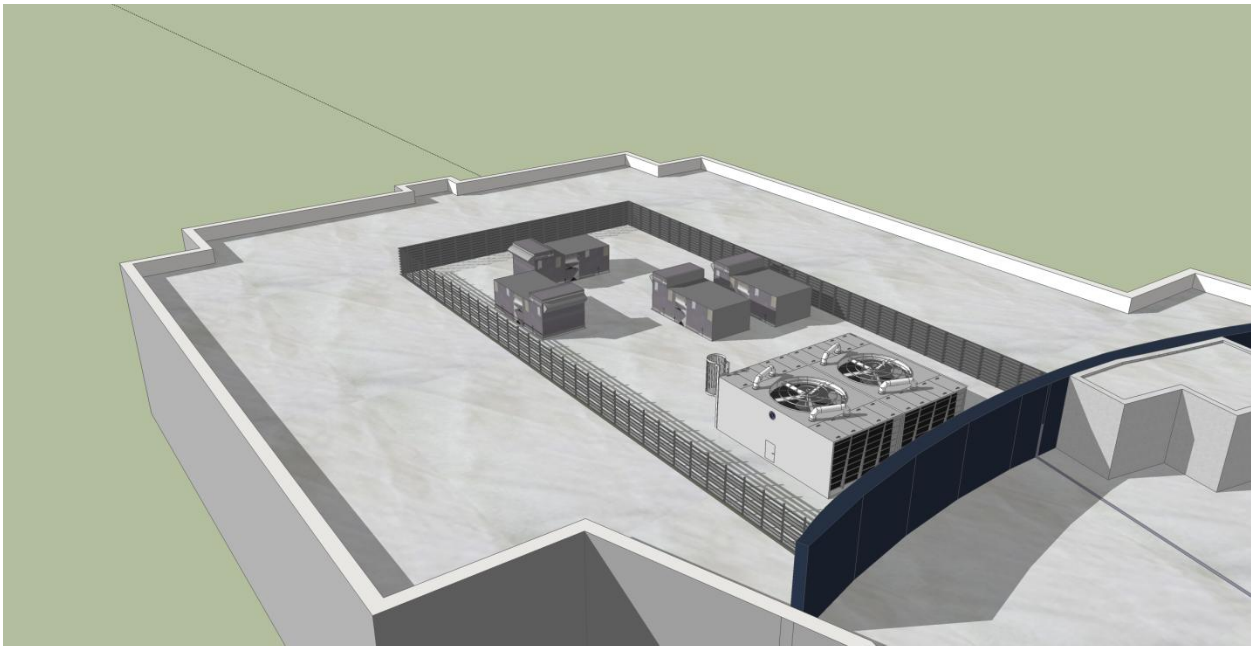

**Figure 19 –** Rendering of New Rooftop

# Sustainability Study: Rainwater Capturing System

## Sustainability Objectives

The objective of this design project is to create a system that captures rainfall that would normally be discharged into the storm water system and put it towards use in a building process that would be using potable water in addition to protecting the building structure from water damage. Due to the many possible applications of the captured rainwater (site irrigation, cooling tower makeup water, and toilet water systems) the decision was made that the harvested rainwater would be used for the toilet water systems in the building.

The decision was also made to provide a roofing system that is non-PVC and does not contribute to degradation of the environment during its disposal. The roofing type will have to be changed from PVC (Polyvinyl Chloride) to a TPO (Thermo Plastic Olefin) or EPDM (ethylene propylene diene M-class rubber).

## Building Background

With all the current focus on energy efficiency of building envelopes and mechanical systems, the availability of clean, potable water has not been stressed enough as an important aspect sustainable design. HITT contracting Headquarters has 42,000 square feet of available flat roof that currently drains its rainwater to storm drain systems. NOAA rainfall data used for this analysis was approximated to be the same as data collected in Vienna, VA from 1971 to 2000 with the average annual rainfall for the site being 45.12 inches. See Figure 20 for a graph of monthly rainfall averages for Falls Church, Virginia as reported by NOAA.

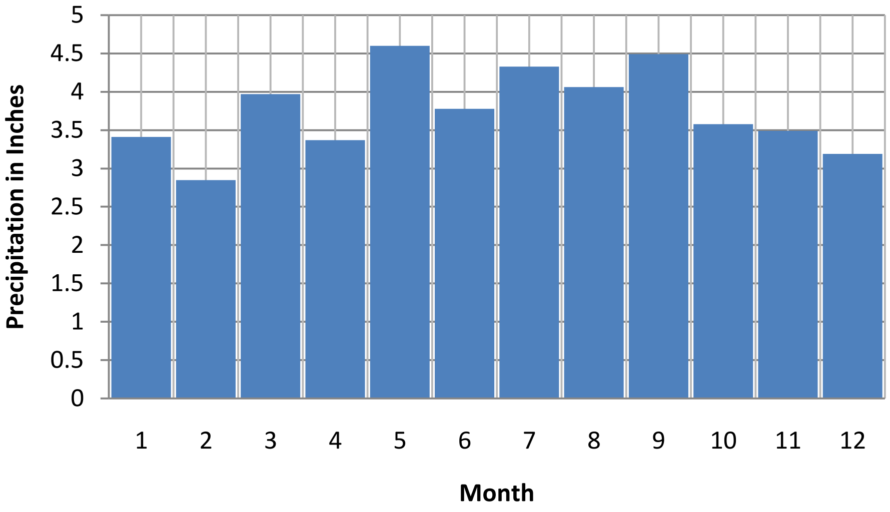

**Figure 20** – Average Monthly Precipitation Totals in Inches from NOAA

## Calculation Process

### Toilet System Water Demand

The amount of water required per day by the toilet system was calculated as per the LEED NC v2.2 WE Credit 2 – Innovative Wastewater Technologies. The credit requires a 50% increase in performance over a baseline case that uses FTE (Full Time Equivalent) occupancy and usage rates. The typical occupant utilizes the restrooms three times per day, with the typical male having one water closet and two urinal usages. The FTE of the building was calculated to be approximately 200 by utilizing basic furniture and office space counting methods. For this calculation, it is assumed that half of the full time equivalent occupants are male and the other half female. See Tables 18 and 19 below for calculations involving the baseline and new design cases.

**Table 18 –** LEED Calculation: Baseline Case

| Baseline Case | | | | |
|---|---|---|---|---|
| Fixture Type | Daily Uses | Flowrate (GPF) | Occupants | Water Utilized (Gal/Day) |
| Water Closet (Male) | 1 | 1.6 | 100.00 | 160.00 |
| Water Closet (Female) | 3 | 1.6 | 100.00 | 480.00 |
| Urinal (Male) | 2 | 1 | 100.00 | 200.00 |
| | | | | 840.00 |

**Table 19 –** LEED Calculation: New Case without Rainwater Capturing

| New Case without Rainwater Capturing | | | | |
|---|---|---|---|---|
| Fixture Type | Daily Uses | Flowrate (GPF) | Occupants | Water Utilized (Gal/Day) |
| Low-Flow Water Closet (Male) | 1 | 1.1 | 100.00 | 110.00 |
| Low-Flow Water Closet (Female) | 3 | 1.1 | 100.00 | 330.00 |
| Waterless Urinal (Male) | 2 | 0 | 100.00 | 0.00 |
| Low-Flow Water Closet (Female) | 0 | 0.8 | 100.00 | 0.00 |
| | | | | 440.00 |

Since the new design case only reduces the usage to 440 gallons per day, this cannot be done by utilizing low-flow fixtures alone, supplemental rainwater is required to achieve the credit. This supplemental water will be provided by rainwater collected from the 42,000 square foot roof.

## Tank Sizing Procedure

In order to size the rainwater storage tank, the monthly precipitation totals for the site, representative rainfall values for the Mid-Atlantic region and the usage rates of the toilet system calculated above must be used. Using the methods described in Baetz (2007), an equation can be derived that relates the required gallons per day of usage, the reliability of supply for that usage and the size of the tank required to provide that reliability.

The daily water demand found above to be 440 gallons per day. Utilizing the equations set forth in Baetz with the assumptions of 5% runoff and a first flush of 0.1 inches, the formula was put into EES (Engineering Equation Solver) and calculated for a range of reliabilities. A graph that displays the percentage of the time that the full 440 gallons would be able to be supplied to the toilet water system was produced by EES. See Figure 21 below for a graph of the tank size vs. reliability. The maximum reliability achievable would be approximately 35% of the year. This means that for 35% of the year, the toilet water can be entirely supplied by captured rainwater. This statistic does not include days in which the captured rainwater provides a fraction of the toilet water.

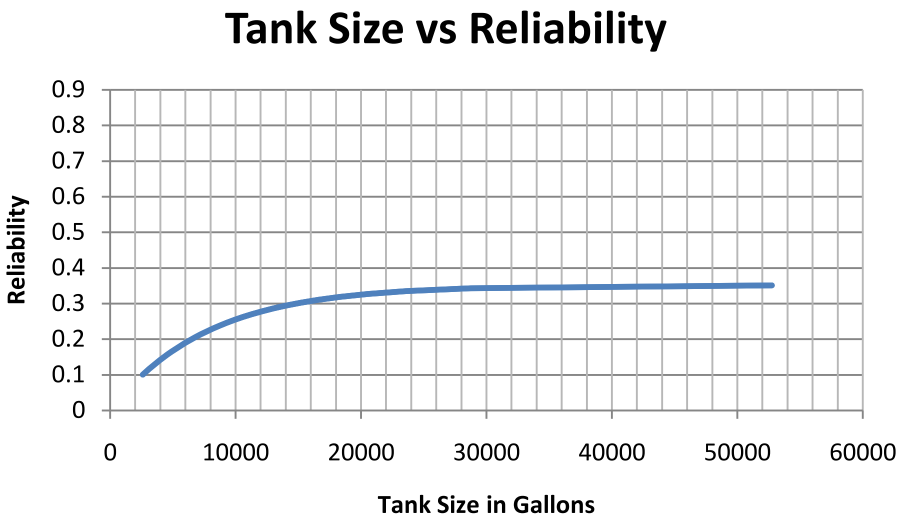

**Figure 21 –** Tank Size vs Reliability for a rate of 440 gallons/day

The maximum of 35% availability would be impractical because of the massive tank size greater than 40,000 gallons when compared to a tank of 15,000 gallons that would provide 30% availability. So a 10,750 gallon tank was selected because it is near the pivot point in the reliability graph of the tradeoff of availability to tank size. It was also chosen for economic reasons, the cost to upsize a 10,750 gallon tank and get 5% more availability throughout the year would have been in increase of $3700 or 43%. See Appendix D for further in depth calculations. Table 20 displays the LEED calculation with the additional rainwater incorporated.

This calculation is on the conservative side due to the fact that it only takes into account the days in which the rainwater capturing system provides all of the water to the toilet system and does not include days in which partial amounts are supplied

**Table 20 –** LEED Calculation: New Case with Rainwater Capturing

| New Case with Rainwater Capturing | | | | |
|---|---|---|---|---|
| Fixture Type | Daily Uses | Flowrate (GPF) | Occupants | Water Utilized (Gal/Day) |
| Low-Flow Water Closet (Male) | 1 | 1.1 | 100.00 | 110.00 |
| Low-Flow Water Closet (Female) | 3 | 1.1 | 100.00 | 330.00 |
| Waterless Urinal (Male) | 2 | 0 | 100.00 | 0.00 |
| Low-Flow Water Closet (Female) | 0 | 0.8 | 100.00 | 0.00 |
| Water From Capturing System | n/a | n/a | n/a | -110.00 |
| | | | | 330.00 |

## Equipment requirements

The existing roof of the structure of HITT Contracting Headquarters consists of a flat built up roof with rigid insulation and a 65 mill PVC (Polyvinyl-Chloride) fully adhered membrane. The roof drainage system is typical for this type of flat roof with penetrations for both regular roof drains and overflow drains used in the event of a failure of one or more of the regular drains. The regular storm drains guide the water to cellar level where it is connected with the building storm water rejection system. The overflow drains do not bring the water to together in the cellar, but release the water through downspouts along the building parameter.

The success of a rainwater capturing system depends upon the current roof drain system described above. A basic filtration system will have to be installed at the cellar level to separate the first flush debris from the rest of the harvested rainwater. A vortex filtration system was chosen to separate roof debris and dirt from being directed into the rainwater storage tank. See Figure 22 below for a diagram of the vortex filter.

TPO (Thermoplastic Polyolefin) Roofing was chosen to replace the existing PVC roofing as stated in the objectives for the rainwater system. The TPO roofing membrane will be fully adhered just as the existing PVC membrane was. TPO membranes are environmentally friendly and combine the advantages of both EPDM and PVC roofing materials.

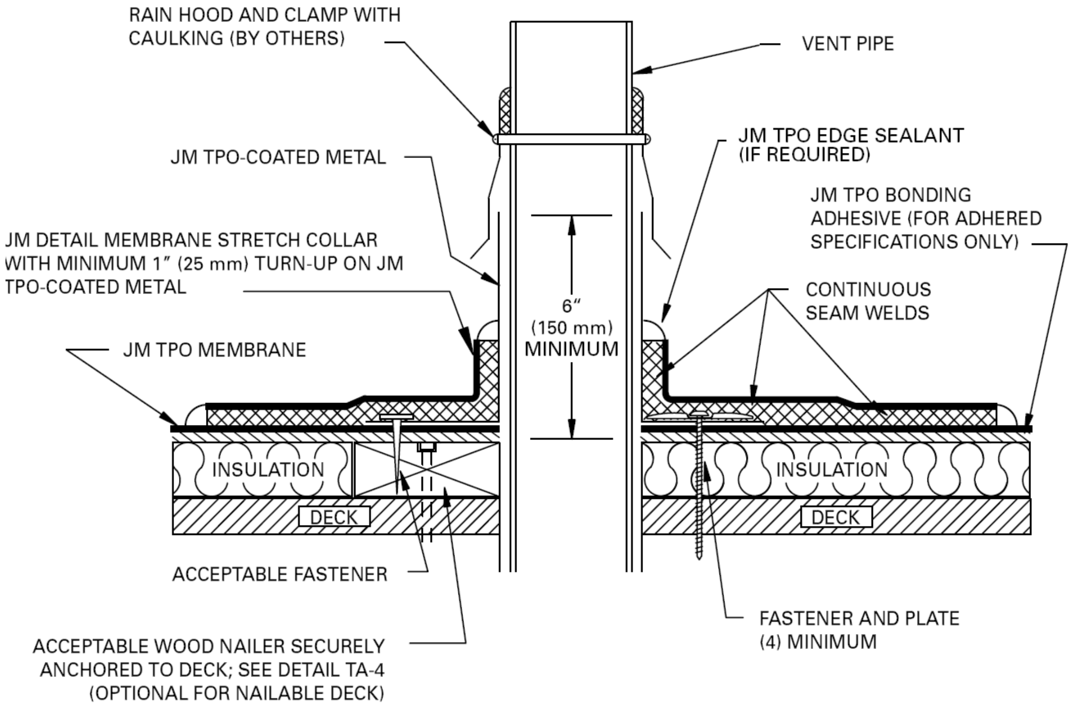

**Figure 23**– TPO Vent Penetration Detail

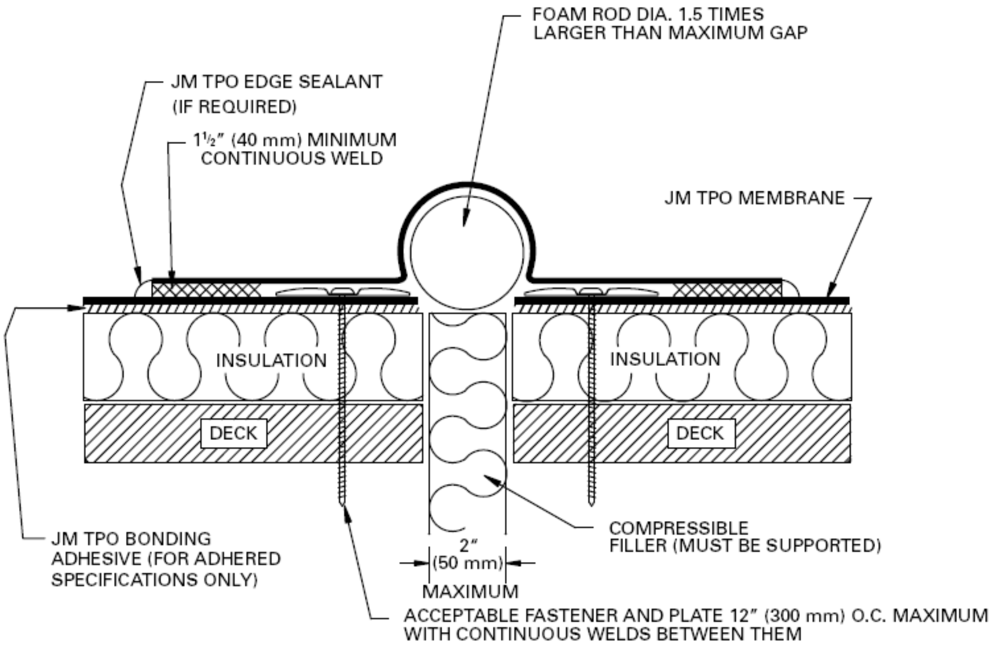

**Figure 24 –** TPO Expansion Joint Detail

## Economic Analysis

This section includes the calculations involving the first cost of the rainwater system and roofing system along with the life cycle cost of the entire system. The life cycle cost analysis was performed with a simple interest rate of 6% over 20 years and concluded that the simple payback period for the system is 20 years. Maintenance for this system was assumed to be similar to that of the existing system for this analysis. Table 21 lists the water costs and first costs of the rainwater equipment require. Table 22 displays the first cost analysis of the new roofing system. The life cycle cost of the entire system is calculated in Table 23.

**Table 21 –** Rainwater System Economic Analysis

| Economic Analysis - Rainwater System | |
|---|---|
| $3.03 | per 1,000 gallons supplied |
| $5.91 | per 1,000 gallons sewer |
| $47.60 | Per month |
| 160,600 | Gallons supplied per Year Old |
| 120,450 | Gallons supplied per Year New |
| 160,600 | Gallons sewer per Year |
| $9,800 | Filter First costs |
| $8,649 | Storage Tank First Cost |
| $2,006.96 | Cost per Year Old |
| $1,361.71 | Cost per Year New |
| $645.25 | Cost Savings per Year |
| 40,150 | Gallons of Water Savings per Year |

**Table 22 –** Roofing System Economic Analysis

| Economic Analysis - Roofing System | |
|---|---|
| $205.69 | Cost per 100 $ft^2$ of TPO Roofing |
| $233.70 | Cost per 100 $ft^2$ of PVC Roofing |
| 42,000 | Square feet of Roofing |
| $86,390 | OPM Roofing First Cost |
| $98,154 | PVC Roofing First Cost |

**Table 23 –** Rainwater System Life Cycle Economic Analysis

| Life Cycle Cost Comparison | | |
|---|---|---|
| i=0.06 | New with TPO | Old with PVC |
| Year 1 | $1,362 | $2,007 |
| Year 2 | $1,362 | $2,007 |
| Year 3 | $1,362 | $2,007 |
| Year 4 | $1,362 | $2,007 |
| Year 5 | $1,362 | $2,007 |
| Year 6 | $1,362 | $2,007 |
| Year 7 | $1,362 | $2,007 |
| Year 8 | $1,362 | $2,007 |
| Year 9 | $1,362 | $2,007 |
| Year 10 | $1,362 | $2,007 |
| Year 11 | $1,362 | $2,007 |
| Year 12 | $1,362 | $2,007 |
| Year 13 | $1,362 | $2,007 |
| Year 14 | $1,362 | $2,007 |
| Year 15 | $1,362 | $2,007 |
| Year 16 | $1,362 | $2,007 |
| Year 17 | $1,362 | $2,007 |
| Year 18 | $1,362 | $2,007 |
| Year 19 | $1,362 | $2,007 |
| Year 20 | $1,362 | $2,007 |
| Net Present Worth | $15,619 | $23,020 |
| Initial Cost | $104,839 | $98,154 |
| Life Cycle Cost | $120,457 | $121,174 |

## Conclusions

Both of the objectives for the study were completed. The effective reduction in daily water usage provided by the rainwater capturing system drops the daily usage to a conservative 330 gallons per day, which is less than half of the 880 gallon per day baseline case. This reduction passes the LEED WE Credit 2 requirement of a 50% reduction in potable water usage through innovative technologies and achieves one LEED point.

Using methods described in “Sizing of Rainwater Storage Units for Green Building Applications” the total annual volume of rainwater that the roof could capture was calculated to be 1,033,529 gallons. It was also found that the reliability of enough rainwater being available for the usage of these systems was not anywhere near 100% as the annual usage is 3,212,000 gallons. As shown in the reliability graph in Figure 21 the maximum reliability for the amount of water required by the toilet water system when applied to the amount of rainwater collected throughout the year is 35%, but this would require a storage tank in excess of 40,000 gallons. The more reasonable tank size of 10,750 gallons was selected and has a reliability of 25%.

The rainwater system has a payback period of 20 years, which is not typically thought of as a very good payback length when compared to a typical 2-4 year payback. The goal of the analysis was to achieve LEED-NC v2.2 WE Credit 2 – Innovative Wastewater Technologies through the reduction of potable water usage and these requirements were more important than the economic effects in guiding the analysis.

## Structural Impact Study

### Structural Objectives

The roof structure will receive different loads and new loads with the implementation of the new centralized system. The goals of the structural impacts analysis are to:

- Calculate the new structural design that takes into account the modified loading
- Calculate cost savings or increases of the new structural system compared to the existing system

### Existing Design

The current roofing system is comprised of a 10" two way reinforced slab. The redesigned mechanical system requires additional mechanical equipment on the roof level along with a reduction in load of currently placed rooftop mechanical equipment. See Table 24 for a table describing the load changes from the existing to new design.

**Table 24 –** New & Existing Roofing Loads

| Roofing Loads | | |
|---|---|---|
| lbs or lb/ft$^2$ | Existing | New |
| Live Load | 15 | 15 |
| Air handlers (each) | 10000 | 8200 |
| Cooling Towers (each) | n/a | 8500 |

## Structural Analysis

This report analyzes two of the changes to the roof loading, a typical change in air handler weight to a span and the addition of a cooling tower to a span. The two way slab structure was analyzed using the PCA Slab software. PCA Slab is a part of the PCA (Portland Cement Association) software suite and is specifically designed for analyzing concrete slab systems. The software analyzes one column line at a time, so two simple procedures were required to obtain slab thicknesses and the size and location of reinforcing steel; one that sizes the slab and steel in one direction and a second that sizes column line perpendicular to the first column line. These results are combined and are used in the design of the reinforced concrete.

## Existing System Analysis

The existing system consists of the 10” slab noted in the existing design section along with the existing AHU loads acting on the members. Tables 25 and 26 below display the takeoff values for the existing design for both steel and concrete. Appendix E graphically describes the width and length moment, shear, deflection diagrams.

**Table 25 –** Existing Column Line Analysis: Length

| Existing Length Results | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Top Bars: | 6120.1 | lb | <=> | 38.5 | lb/ft | <=> | 0.7855 | lb/ft^2 |
| Bottom Bars: | 6821.2 | lb | <=> | 42.9 | lb/ft | <=> | 0.8755 | lb/ft^2 |
| Stirrups: | 0 | lb | <=> | 0 | lb/ft | <=> | 0 | lb/ft^2 |
| Total Steel: | 12941 | lb | <=> | 84 | lb/ft | <=> | 1.681 | lb/ft^2 |
| Concrete: | 6472.9 | ft^3 | <=> | 42 | ft^3/ft | <=> | 0.841 | ft^3/ft^2 |

**Table 26 –** Existing Column Line Analysis: Width

| Existing Width Results | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Top Bars: | 3852.8 | lb | <=> | 27.92 | lb/ft | <=> | 0.931 | lb/ft^2 |
| Bottom Bars: | 3264.6 | lb | <=> | 23.66 | lb/ft | <=> | 0.789 | lb/ft^2 |
| Stirrups: | 0 | lb | <=> | 0 | lb/ft | <=> | 0 | lb/ft^2 |
| Total Steel: | 7117.4 | lb | <=> | 51.57 | lb/ft | <=> | 1.719 | lb/ft^2 |
| Concrete: | 4196.3 | ft^3 | <=> | 30.41 | ft^3/ft | <=> | 1.014 | ft^3/ft^2 |

## Air Handler Analysis

The air handler analysis consists of the same 10” slab noted in the existing design section but includes the new AHU loads acting on the members. Slab depth did not have to be increased due to the new loading scheme. Tables 27 and 28 below display the takeoff values for the existing design for both steel and concrete. Appendix E graphically describes the width and length moment, shear, deflection diagrams for the air handler.

**Table 27 –** Air Handler Column Line Analysis: Length

| New AHU Length Results | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Top Bars: | 5860.3 | lb | <=> | 38.05 | lb/ft | <=> | 0.761 | lb/ft^2 |
| Bottom Bars: | 6737.8 | lb | <=> | 43.75 | lb/ft | <=> | 0.875 | lb/ft^2 |
| Stirrups: | 0 | lb | <=> | 0 | lb/ft | <=> | 0 | lb/ft^2 |
| Total Steel: | 12598 | lb | <=> | 81.81 | lb/ft | <=> | 1.636 | lb/ft^2 |
| Concrete: | 6472.9 | ft^3 | <=> | 42.03 | ft^3/ft | <=> | 0.841 | ft^3/ft^2 |

**Table 28 –** Air Handler Column Line Analysis: Width

| New AHU Width Results | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Top Bars: | 3930.5 | lb | <=> | 28.48 | lb/ft | <=> | 0.949 | lb/ft^2 |
| Bottom Bars: | 3295.9 | lb | <=> | 23.88 | lb/ft | <=> | 0.796 | lb/ft^2 |
| Stirrups: | 0 | lb | <=> | 0 | lb/ft | <=> | 0 | lb/ft^2 |
| Total Steel: | 7226.4 | lb | <=> | 52.37 | lb/ft | <=> | 1.746 | lb/ft^2 |
| Concrete: | 4196.3 | ft^3 | <=> | 30.41 | ft^3/ft | <=> | 1.014 | ft^3/ft^2 |

## Cooling Tower Analysis

The cooling tower analysis consists of the same 10” slab noted in the existing design section but includes the new cooling tower loads acting on the span. Slab depth did not have to be increased loading scheme. Tables 29 and 30 below display the takeoff values for the existing design for both steel and concrete. Appendix E graphically describes the width and length moment, shear, deflection diagrams for the cooling tower.

**Table 29 –** Cooling Tower Column Line Analysis: Length

| New Cooling Tower Length Results | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Top Bars: | 6245.6 | lb | <=> | 40.56 | lb/ft | <=> | 0.811 | lb/ft^2 |
| Bottom Bars: | 6769.1 | lb | <=> | 43.95 | lb/ft | <=> | 0.879 | lb/ft^2 |
| Stirrups: | 0 | lb | <=> | 0 | lb/ft | <=> | 0 | lb/ft^2 |
| Total Steel: | 13014.6 | lb | <=> | 84.51 | lb/ft | <=> | 1.69 | lb/ft^2 |
| Concrete: | 6472.9 | ft^3 | <=> | 42.03 | ft^3/ft | <=> | 0.841 | ft^3/ft^2 |

**Table 30 –** Cooling Tower Column Line Analysis: Width

| New Cooling Tower Width Results | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Top Bars: | 3952.3 | lb | <=> | 28.64 | lb/ft | <=> | 0.955 | lb/ft^2 |
| Bottom Bars: | 3295.9 | lb | <=> | 23.88 | lb/ft | <=> | 0.796 | lb/ft^2 |
| Stirrups: | 0 | lb | <=> | 0 | lb/ft | <=> | 0 | lb/ft^2 |
| Total Steel: | 7248.2 | lb | <=> | 52.52 | lb/ft | <=> | 1.751 | lb/ft^2 |
| Concrete: | 4196.3 | ft^3 | <=> | 30.41 | ft^3/ft | <=> | 1.014 | ft^3/ft^2 |

## Economic Analysis

Table 31 displays the costs of the reinforcing steel and the total amounts of steel for each of the column line width and length cases combined: existing, new AHUs, and new cooling towers. The total amount of money saved was calculated to be $614.51 with a reduction of approximately 1232 pounds of steel. This calculation was performed on a solely material cost basis as the labor required to install the reinforcing steel is approximately the same, but the size of the members are slightly larger or smaller.

**Table 31 –** Structural Economic Analysis

| Structural Economic Analysis | | | | |
|---|---|---|---|---|
| | lbs | $/ton | $/lb | Cost |
| Existing Spans | 20059 | $998 | $0.50 | $10,009 |
| New AHU Spans | 19824 | $998 | $0.50 | $9,892 |
| New Cooling Tower Spans | 20263 | $999 | $0.50 | $10,121 |
| **Cost Differences** | | | | |
| | lbs Difference | | Cost Difference | |
| 7 New AHU Spans | -1640 | | -$818.41 | |
| 2 New Cooling Tower Spans | 408 | | $203.90 | |
| Total | -1232 | | **-$614.51** | |

### Structural Impact Conclusions

Both of the goals for the structural impact section were met; the new structural system was calculated and the costs associated with it were found with no requirement as to whether it was a reduction or increase in cost. This was decided in the objectives section because of the addition of weight of the new cooling towers along with the reduction in weight of the new air handlers. The changes saved approximately $614.51 in materials cost or 6% over the existing system.

## Report Conclusions

The three primary sections of this report each achieved their stated goals. These goals included: improvements to energy efficiency of the system through the design of a centralized plant, water conservation and LEED, an assessment of the impacts of the new roof loads on the roof structure and redesign, and finally the overall educational experience from the research and calculations performed for this report.

The centralized plant redesign successfully reduced annual energy costs, while providing a payback period of 17 years. This is not the best of payback periods due to the high first cost of the new system but it should still be noted that the system does pay for itself over a reasonable life cycle length of 20 years. Waterside free cooling was also explored in the redesign, allowing for the absorption chiller-heater to be bypassed for cooling and used for heating alone when outdoor wet bulb conditions are favorable.

The sustainability study was implemented to provide additional water for non-potable uses from rainwater that would have been simply expelled before. A tank was sized to capture rainwater from the roof and to provide water for the toilet systems with an availability of 25% of the time. The economic analysis concluded that the new rainwater capturing system would have a simple payback of approximately 20 years. Economic payback was not the primary concern of the study as it was the offsetting of potable water use.

The structural impact study achieved its goals of redesigning the structural system to the new loads and calculating the cost difference. The cost change between the existing and new was a minimal savings of $614.51.

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# Appendices

## Appendix A – Breakdown of Monthly Energy Consumption & Costs

**Table 32 –** New Energy Consumption by Month

| Energy Analysis | | | | | | |
|---|---|---|---|---|---|---|
| Electric | Jan | Feb | Mar | Apr | May | Jun |
| On Peak Consumption (kWh) | 222,030 | 206,577 | 231,893 | 212,386 | 241,873 | 192,257 |
| Off Peak Consumption (kWh) | 66,069 | 59,819 | 64,721 | 59,351 | 62,752 | 116,103 |
| Natural Gas | | | | | | |
| On Peak Consumption (Therms) | 636 | 469 | 1,864 | 2,930 | 7,647 | 7,478 |
| Off Peak Consumption (Therms) | 228 | 175 | 25 | 41 | 646 | 2705 |

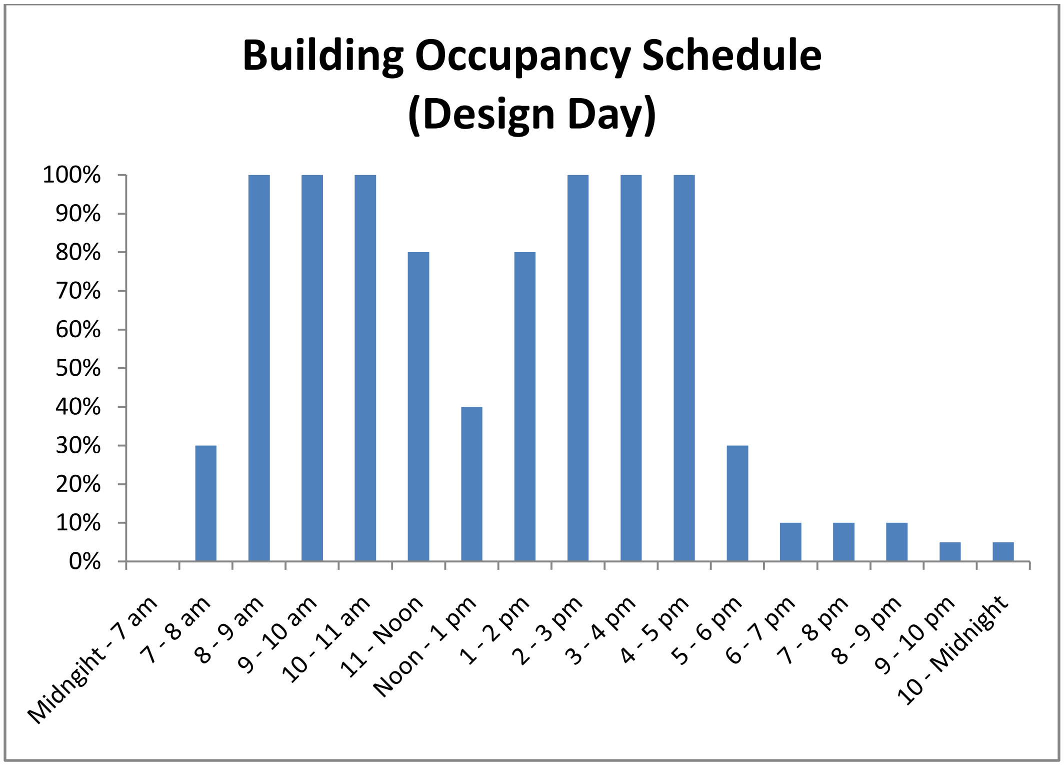
| Energy Analysis | | | | | | | |
|---|---|---|---|---|---|---|---|
| Electric | Jul | Aug | Sep | Oct | Nov | Dec | Total |
| On Peak Consumption (kWh) | 187,542 | 199,534 | 177,926 | 226,827 | 216,030 | 212,822 | 2,527,697 |
| Off Peak Consumption (kWh) | 117,413 | 119,598 | 108,422 | 61,485 | 59,258 | 66,874 | 961,864 |
| Natural Gas | | | | | | | |
| On Peak Consumption (Therms) | 7,877 | 7,951 | 5,828 | 3,824 | 2,879 | 482 | 49,866 |
| Off Peak Consumption (Therms) | 3065 | 2947 | 2017 | 4 | 16 | 164 | 12,032 |

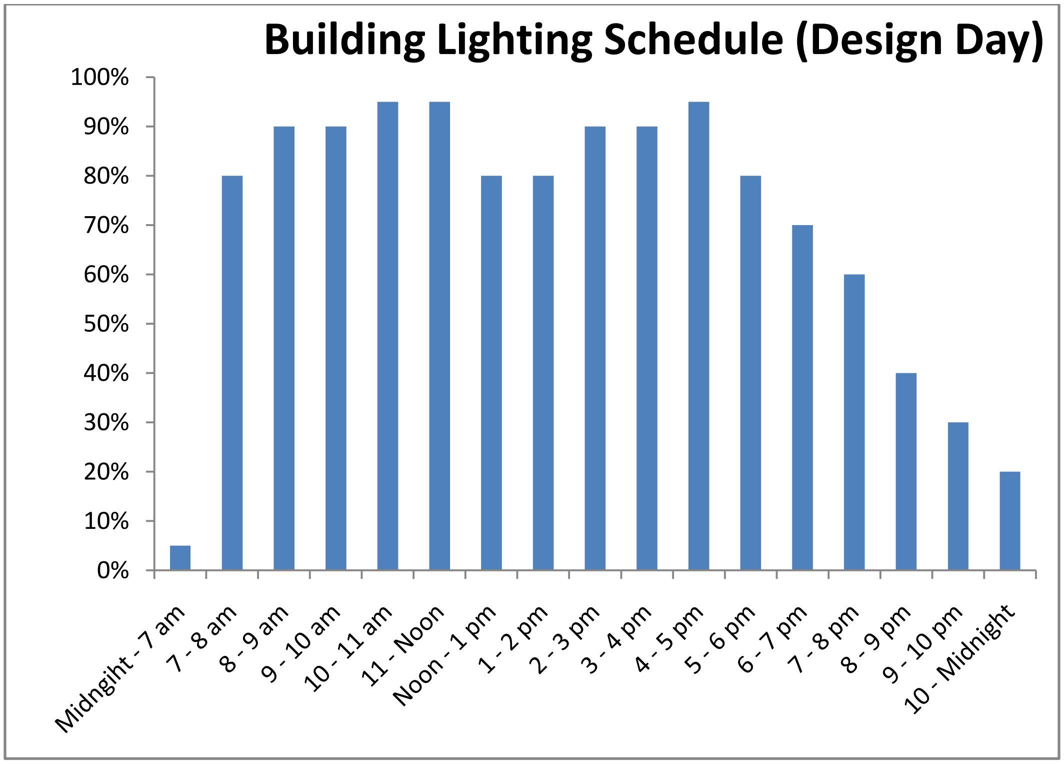
**Tables 33 –** New Energy Cost by Month

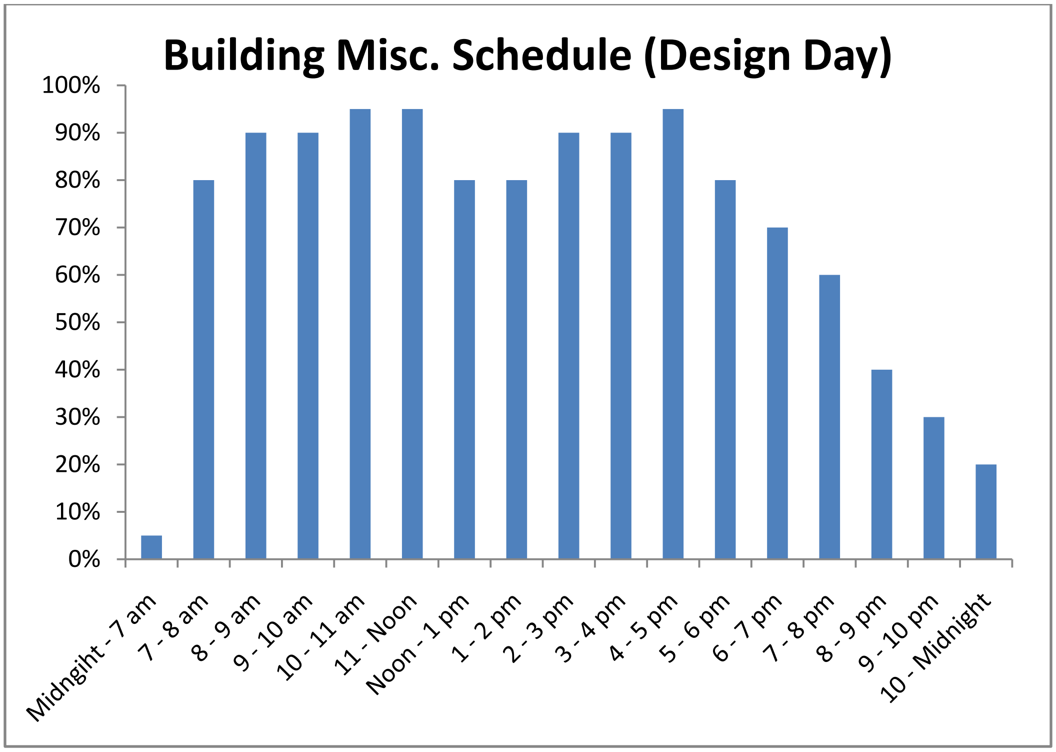
| Monthly Energy Costs | | | | | | | |
|---|---|---|---|---|---|---|---|
| | Jan | Feb | Mar | Apr | May | Jun | Total |
| Natural Gas | $946.68 | $705.63 | $1,857.45 | $2,921.38 | $8,154.51 | $10,245.12 | $59,114.42 |
| Electricity | $21,970.23 | $21,335.30 | $22,525.52 | $21,915.96 | $24,118.48 | $25,236.26 | $277,181.20 |
| | Jul | Aug | Sep | Oct | Nov | Dec | **$336,295.62** |
| Natural Gas | $10,402.56 | $9,349.39 | $7,539.83 | $3,470.85 | $2,840.00 | $681.01 | |
| Electricity | $25,101.89 | $25,526.54 | $23,977.90 | $22,441.52 | $21,547.72 | $21,483.88 | |

## Appendix B – Building Usage Schedules

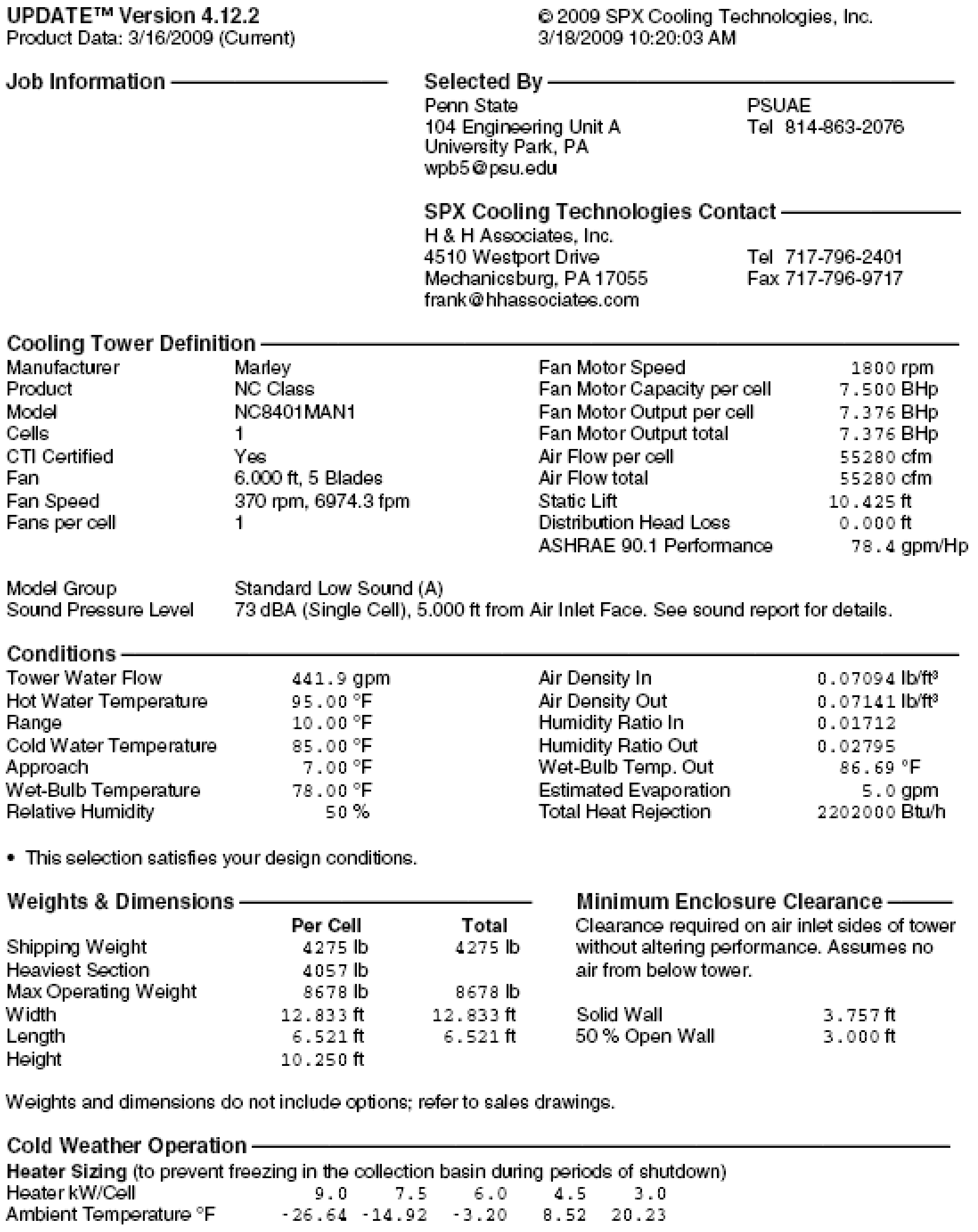
All schedules reflect a typical Monday to Friday schedule for the respective system. During weekends, the building is assumed to be unoccupied.


Building Occupancy Schedule (Design Day)
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Midngiht - 7 am
7 - 8 am
8 - 9 am
9 - 10 am
10 - 11 am
11 - Noon
Noon - 1 pm
1 - 2 pm
2 - 3 pm
3 - 4 pm
4 - 5 pm
5 - 6 pm
6 - 7 pm
7 - 8 pm
8 - 9 pm
9 - 10 pm
10 - Midnight


Building Lighting Schedule (Design Day)
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Midngiht - 7 am
7 - 8 am
8 - 9 am
9 - 10 am
10 - 11 am
11 - Noon
Noon - 1 pm
1 - 2 pm
2 - 3 pm
3 - 4 pm
4 - 5 pm
5 - 6 pm
6 - 7 pm
7 - 8 pm
8 - 9 pm
9 - 10 pm
10 - Midnight


Building Misc. Schedule (Design Day)
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Midngiht - 7 am
7 - 8 am
8 - 9 am
9 - 10 am
10 - 11 am
11 - Noon
Noon - 1 pm
1 - 2 pm
2 - 3 pm
3 - 4 pm
4 - 5 pm
5 - 6 pm
6 - 7 pm
7 - 8 pm
8 - 9 pm
9 - 10 pm
10 - Midnight

## Appendix C – Cooling Tower Design Sheets



**UPDATE™ Version 4.12.2**
Product Data: 3/16/2009 (Current)

© 2009 SPX Cooling Technologies, Inc.
3/18/2009 10:20:03 AM

**Job Information**

**Selected By**

Penn State
104 Engineering Unit A
University Park, PA
wpb5@psu.edu

PSUAE
Tel 814-863-2076

**SPX Cooling Technologies Contact**

H & H Associates, Inc.
4510 Westport Drive
Mechanicsburg, PA 17055
frank@hhassociates.com

Tel 717-796-2401
Fax 717-796-9717

**Cooling Tower Definition**

| | | | |
|---|---|---|---|
| Manufacturer | Marley | Fan Motor Speed | 1800 rpm |
| Product | NC Class | Fan Motor Capacity per cell | 7.500 BHp |
| Model | NC8401MAN1 | Fan Motor Output per cell | 7.376 BHp |
| Cells | 1 | Fan Motor Output total | 7.376 BHp |
| CTI Certified | Yes | Air Flow per cell | 55280 cfm |
| Fan | 6.000 ft, 5 Blades | Air Flow total | 55280 cfm |
| Fan Speed | 370 rpm, 6974.3 fpm | Static Lift | 10.425 ft |
| Fans per cell | 1 | Distribution Head Loss | 0.000 ft |
| | | ASHRAE 90.1 Performance | 78.4 gpm/Hp |

| | |
|---|---|
| Model Group | Standard Low Sound (A) |
| Sound Pressure Level | 73 dBA (Single Cell), 5.000 ft from Air Inlet Face. See sound report for details. |

**Conditions**

| | | | |
|---|---|---|---|
| Tower Water Flow | 441.9 gpm | Air Density In | 0.07094 lb/ft³ |
| Hot Water Temperature | 95.00 °F | Air Density Out | 0.07141 lb/ft³ |
| Range | 10.00 °F | Humidity Ratio In | 0.01712 |
| Cold Water Temperature | 85.00 °F | Humidity Ratio Out | 0.02795 |
| Approach | 7.00 °F | Wet-Bulb Temp. Out | 86.69 °F |
| Wet-Bulb Temperature | 78.00 °F | Estimated Evaporation | 5.0 gpm |
| Relative Humidity | 50 % | Total Heat Rejection | 2202000 Btu/h |

- This selection satisfies your design conditions.

**Weights & Dimensions**

| | Per Cell | Total |
|---|---|---|
| Shipping Weight | 4275 lb | 4275 lb |
| Heaviest Section | 4057 lb | |
| Max Operating Weight | 8678 lb | 8678 lb |
| Width | 12.833 ft | 12.833 ft |
| Length | 6.521 ft | 6.521 ft |
| Height | 10.250 ft | |

**Minimum Enclosure Clearance**

Clearance required on air inlet sides of tower without altering performance. Assumes no air from below tower.

| | |
|---|---|
| Solid Wall | 3.757 ft |
| 50 % Open Wall | 3.000 ft |

Weights and dimensions do not include options; refer to sales drawings.

**Cold Weather Operation**

**Heater Sizing** (to prevent freezing in the collection basin during periods of shutdown)

| | | | | | |
|---|---|---|---|---|---|
| Heater kW/Cell | 9.0 | 7.5 | 6.0 | 4.5 | 3.0 |
| Ambient Temperature °F | -26.64 | -14.92 | -3.20 | 8.52 | 20.23 |

**UPDATE™ Version 4.12.2**
Product Data: 3/16/2009 (Current)

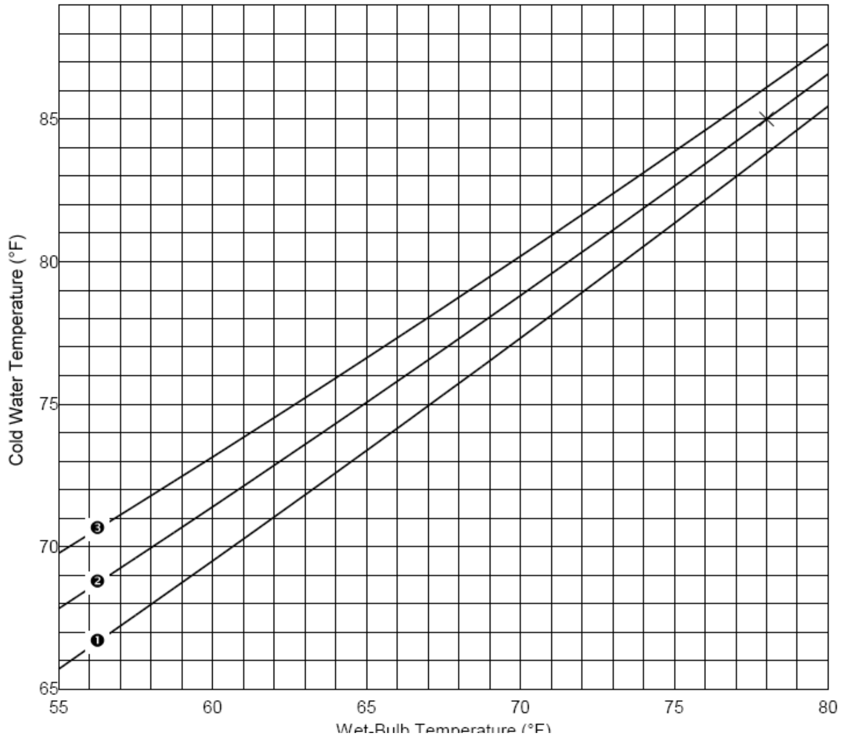
3/18/2009 10:22:12 AM

**Job Information**

**Selected by**
Penn State
104 Engineering Unit A
University Park, PA
wpb5@psu.edu
PSUAE
Tel 814-863-2076
Fax

**Cooling Tower Definition**

| | |
|---|---|
| Manufacturer | Marley |
| Product | NC Class |
| Model | NC8401MAN1 |
| Cells | 1 |
| Fan | 6.000 ft, 5 Blades |
| Fans per cell | 1 |
| Fan Motor Capacity per cell | 7.500 BHp |



**Design Conditions**

| | |
|---|---|
| Tower Water Flow | 441.9 gpm |
| Hot Water Temperature | 95.00 °F |
| Cold Water Temperature | 85.00 °F |
| Wet-Bulb Temperature | 78.00 °F |

**Curve Conditions**

| | |
|---|---|
| Tower Water Flow (100.0 %) | 441.9 gpm |
| Fan Speed (100.0 %) | 370 rpm |
| Fan Motor Speed (100.0 %) | 1800 rpm |
| Fan Motor Output per cell | 7.376 BHp |
| Fan Motor Output total | 7.376 BHp |

**Legend**
❶ 8 °F Range
❷ 10 °F Range
❸ 12 °F Range
× Design Point

## Appendix D – Rainwater Tank Sizing Calculations

| Rainfall Storage Tank Calculation<br>Region 2 - Mid Atlantic region | | | | | |
|---|---|---|---|---|---|
| Event | mm | | 11.53 | Values Taken from NOAA | |
| Mean | mm/hr | | 2.6235 | | |
| Mean duration | hr | | 4.4 | | |
| Mean interval | hr | | 70 | | |
| | | | | | |
| Area of roof | $m^2$ | A | 3902 | 42001 | $ft^2$ |
| Runoff Coefficient | | $\phi$ | 1 | | |
| Avg # of rainfall events | # | $\theta$ | 86.96 | | |
| Depth Parameter | 1/mm | $\zeta$ | 0.086730269 | | |
| Duration Parameter | 1/hr | $\lambda$ | 0.227272727 | | |
| Time Parameter | 1/hr | $\psi$ | 0.014285714 | | |
| Designed first flush depth | mm | $v_{ff}$ | 0 | | |
| Annual total water collected | L | $R_a$ | 3912336 | 1033529.7 | gallons |
| Reliability of supply of water | | $R_e$ | 0.3 | | |
| Max reliability of supply of water | | $R_{emax}$ | 0.35088 | | |
| Annual discharge time | hr | $T_d$ | 6087.2 | | |
| Maximum use per reliability $R_e$ | L/day | $G_{max}$ | 1499.67 | 396.17055 | gallons |
| Actual Water use | L/day | G | 1189 | 314.10057 | gallons |
| Required Storage Volume | L | B | 60811 | 16064.675 | gallons |
| Probabilty of Spillage | % | G(0) | 0.3509 | | |
| Estimated Spill Volume | L | S | 15786.18 | 4170.2687 | gallons |

## Appendix E – Structural Calculations

The following appendix is a compilation of PCA Slab outputs and is divided into both the width and length column line calculations for a typical new air handling unit and a new cooling tower. Shear, Moment, and Deflection diagrams are shown along with a graphics showing the placement and size of the reinforcing steel for each of the cases.

## Width Graphical Outputs

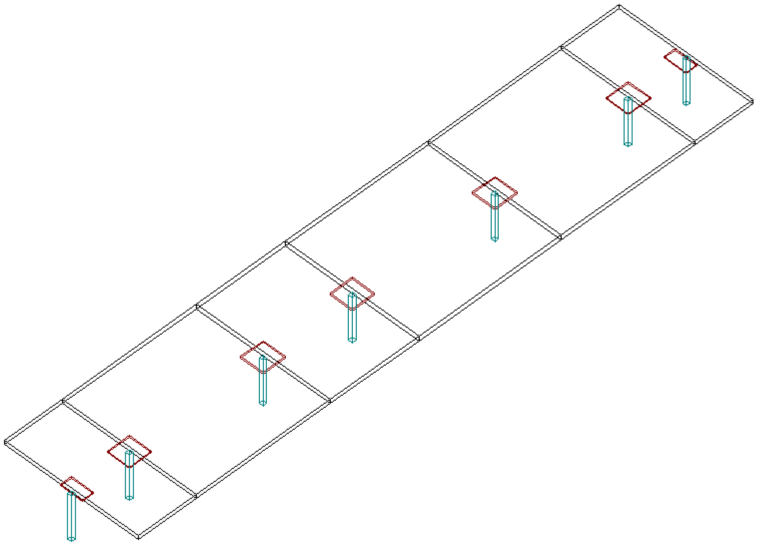


**Figure XX** - Isometric Displaying Tributary Areas for Width Calculation

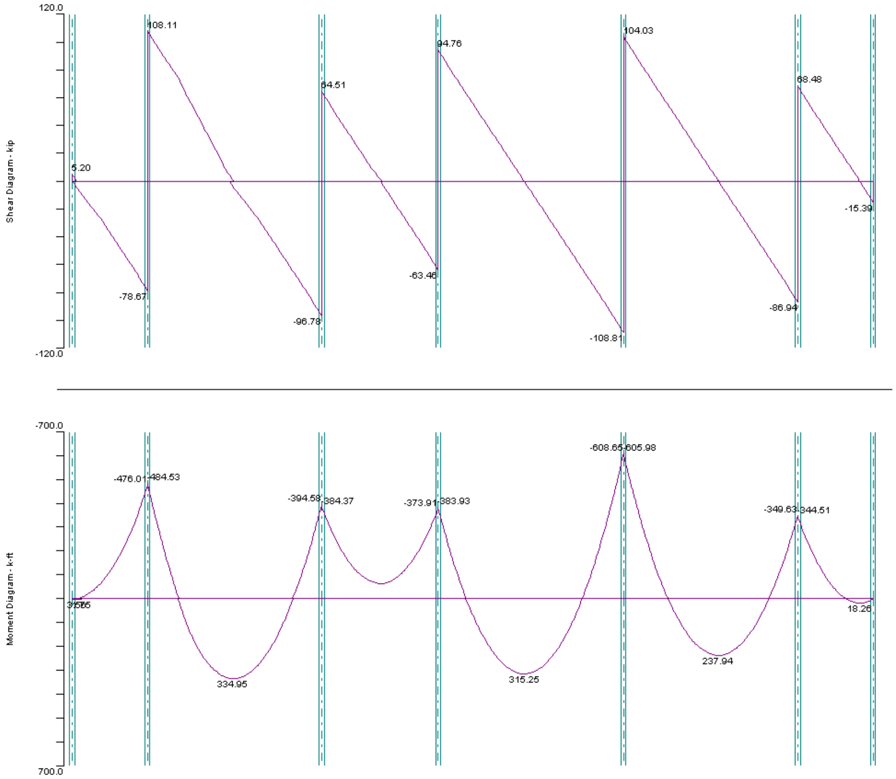


**Figure 25** – Shear and Moment Diagrams for Typical AHU Width

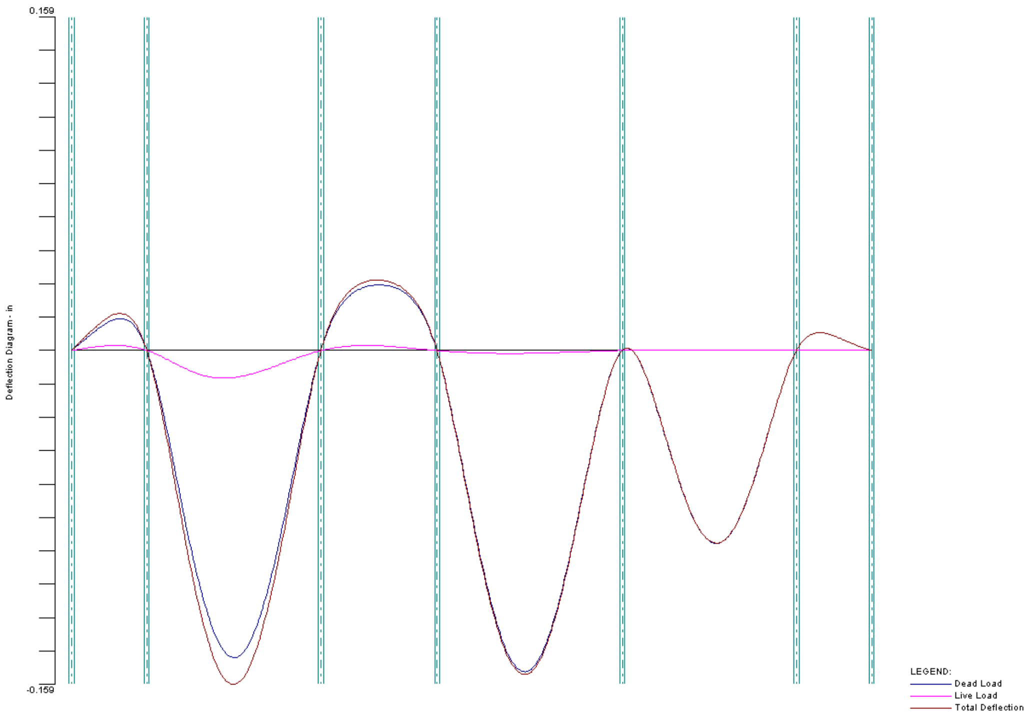


**Figure 26** –Deflection Diagrams for Typical AHU Width

**Figure 27** –Reinforcement for Typical AHU Width

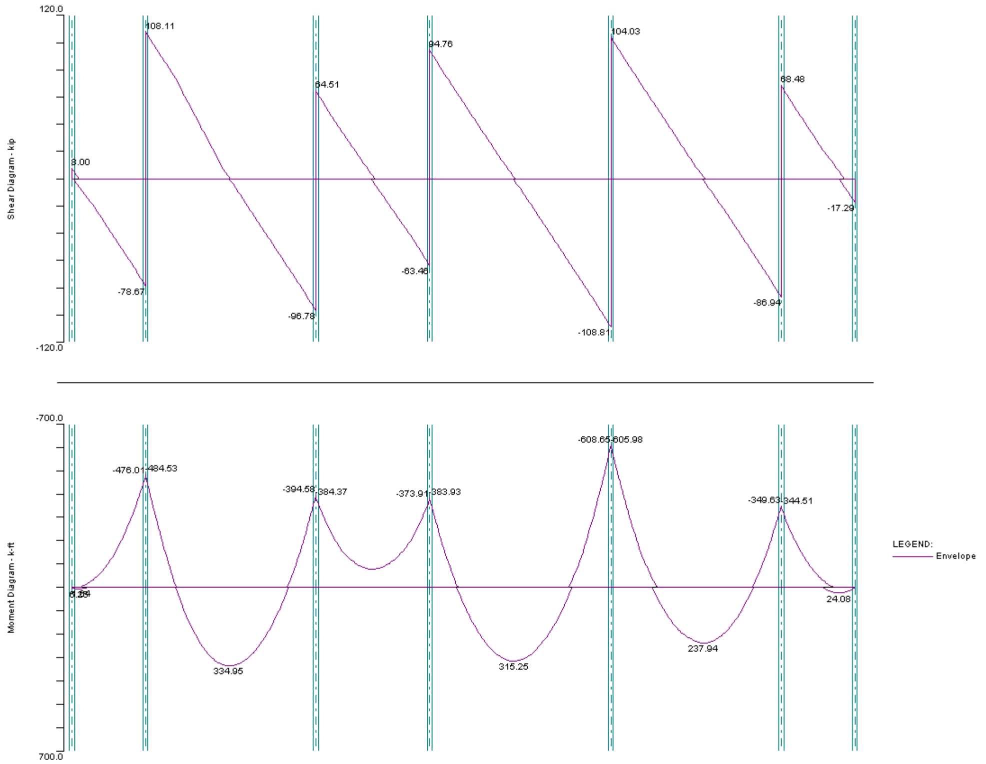


**Figure 28** – Shear and Moment Diagrams for Typical Cooling Tower Width

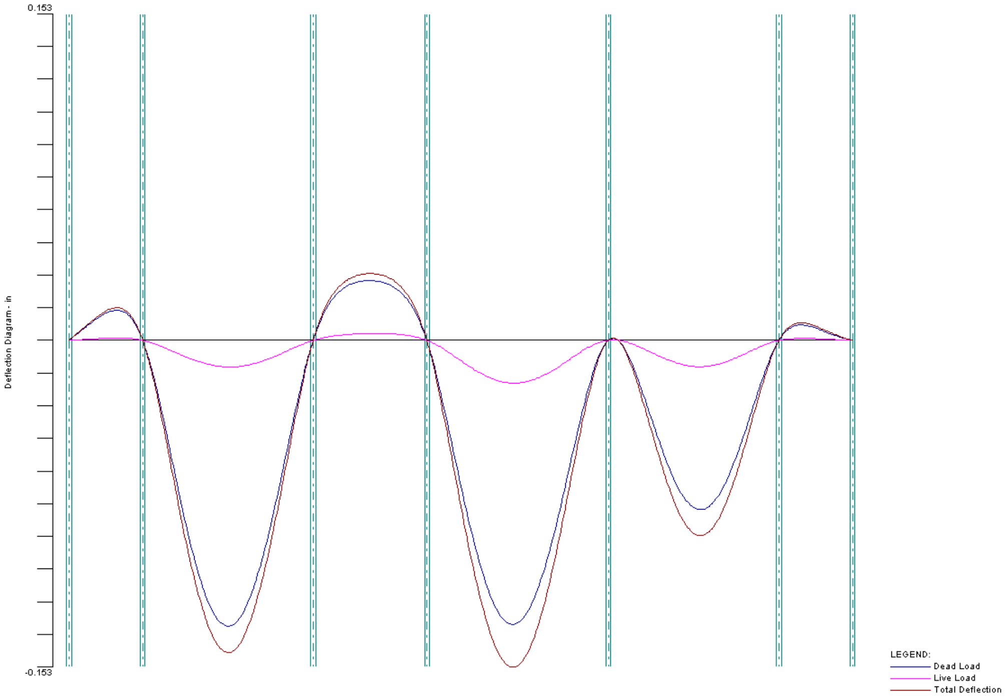


**Figure 29** –Deflection Diagrams for Typical Cooling Tower Width

**Figure 30** –Reinforcement for Typical Cooling Tower Width

## Length Graphical Outputs

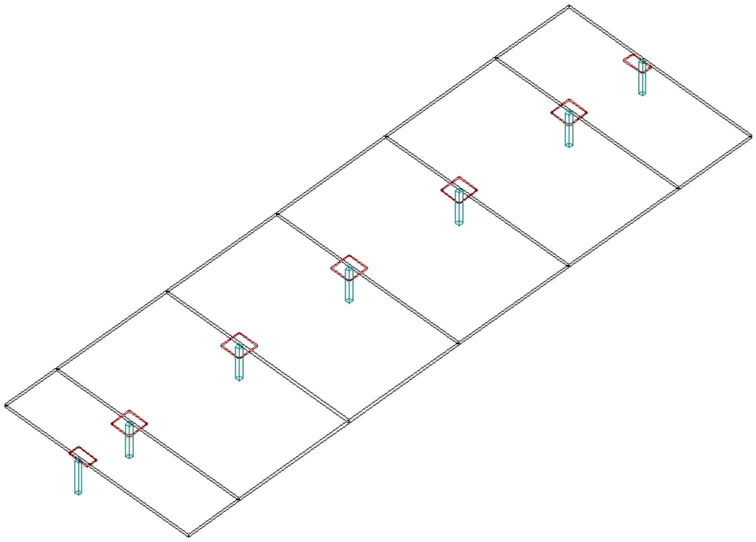


**Figure 31** - Isometric Displaying Tributary Areas for Length Calculation

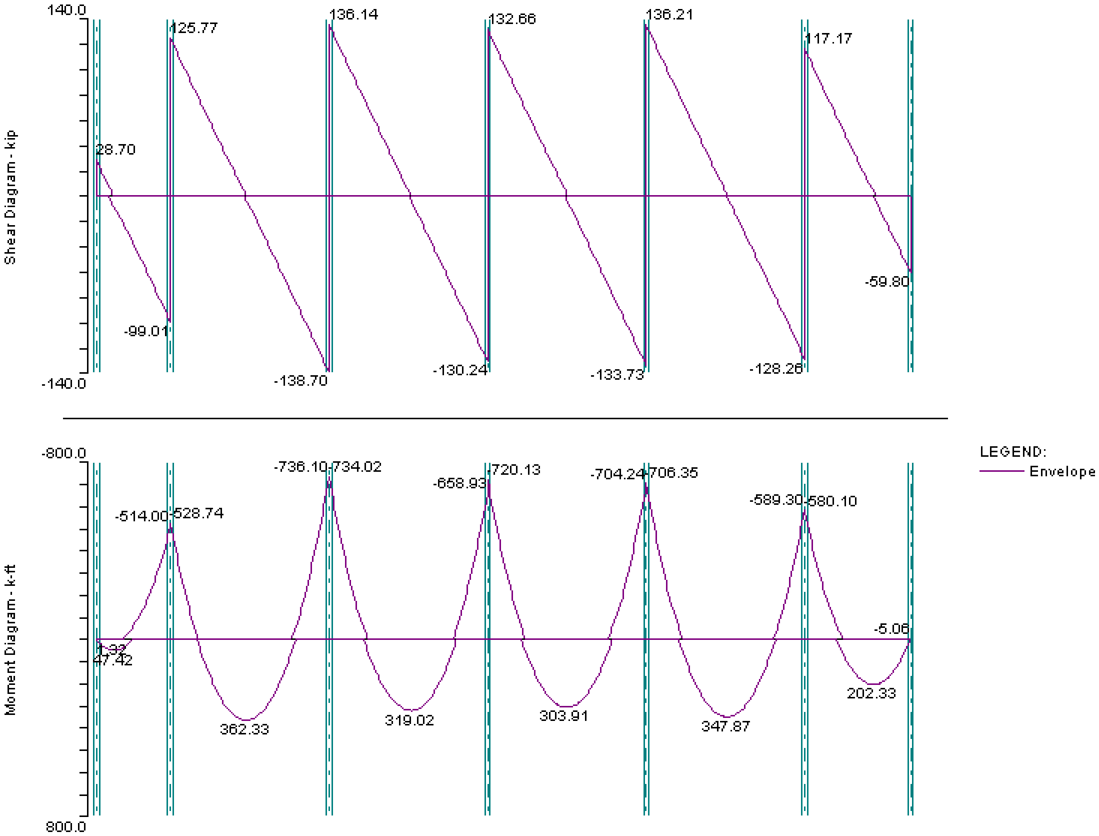


**Figure 32** – Shear and Moment Diagrams for Typical AHU Length

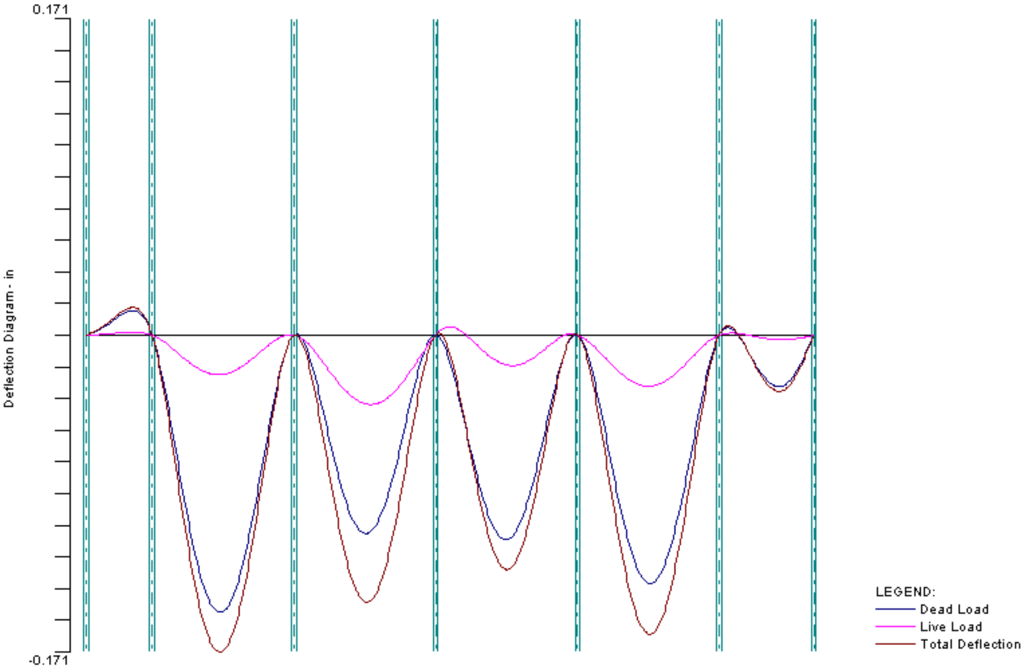
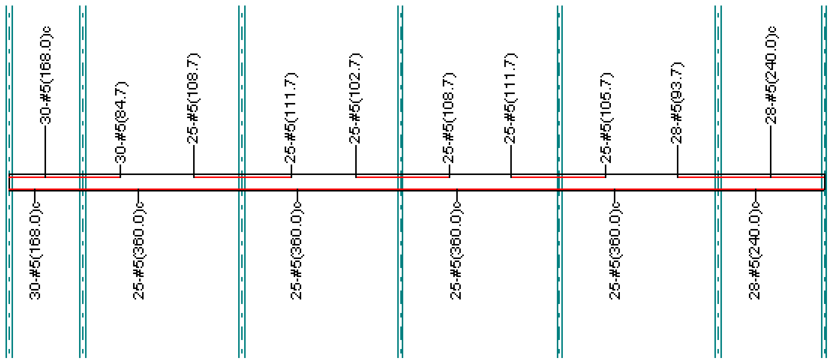
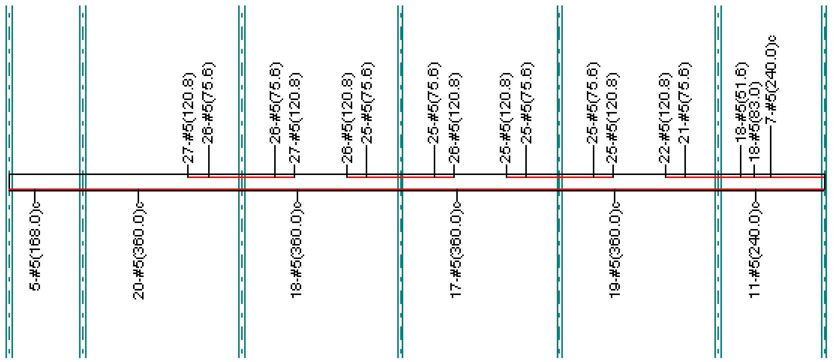


**Figure 33** –Deflection Diagrams for Typical AHU Length



Middle Strip Flexural Reinforcement



Column Strip Flexural Reinforcement

**Figure 34** –Reinforcement for Typical AHU Length

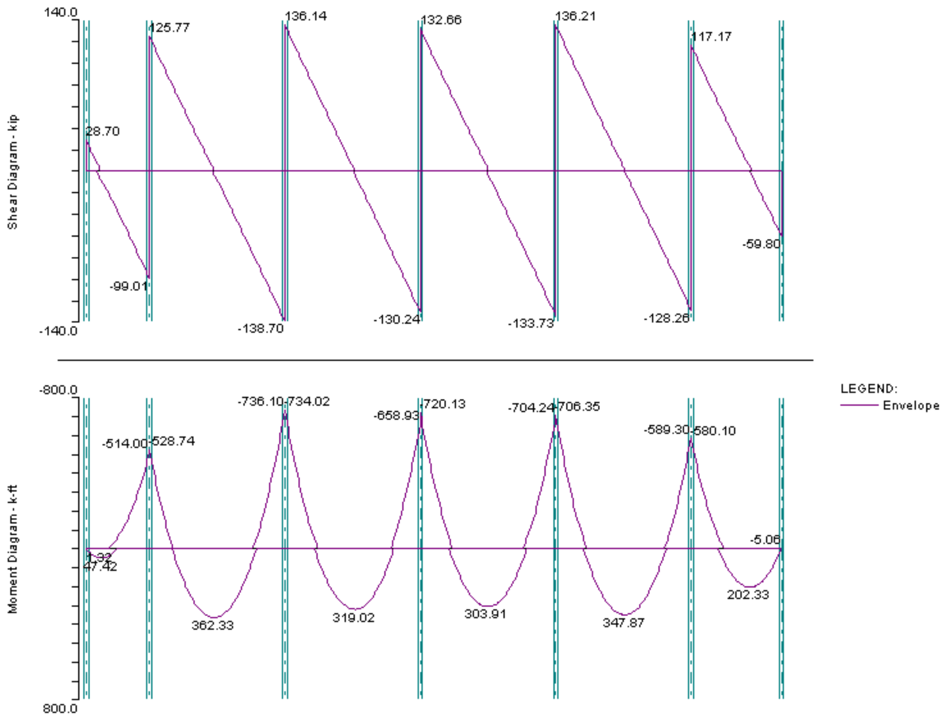


**Figure 35** – Shear and Moment Diagrams for Typical Cooling Tower Length

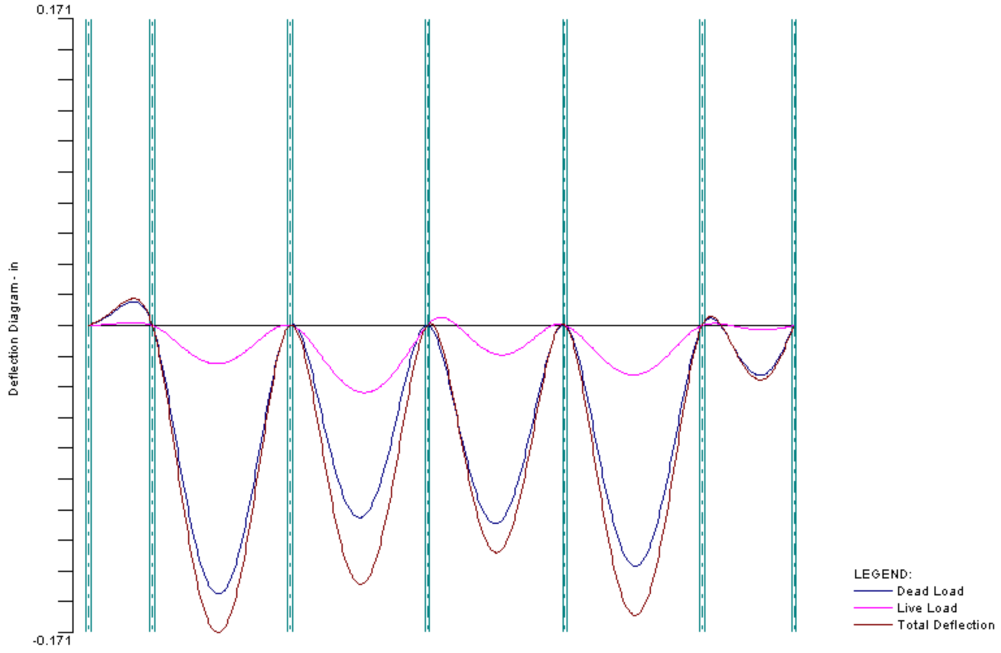
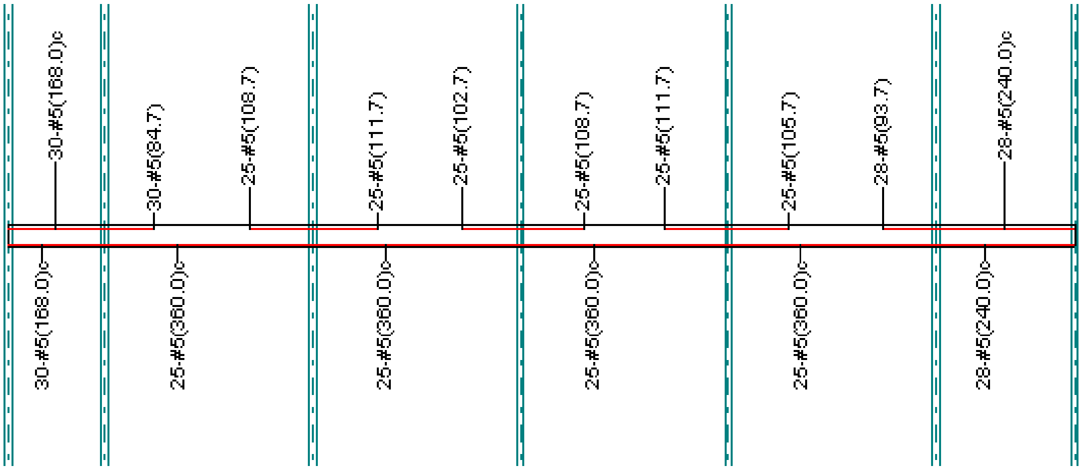
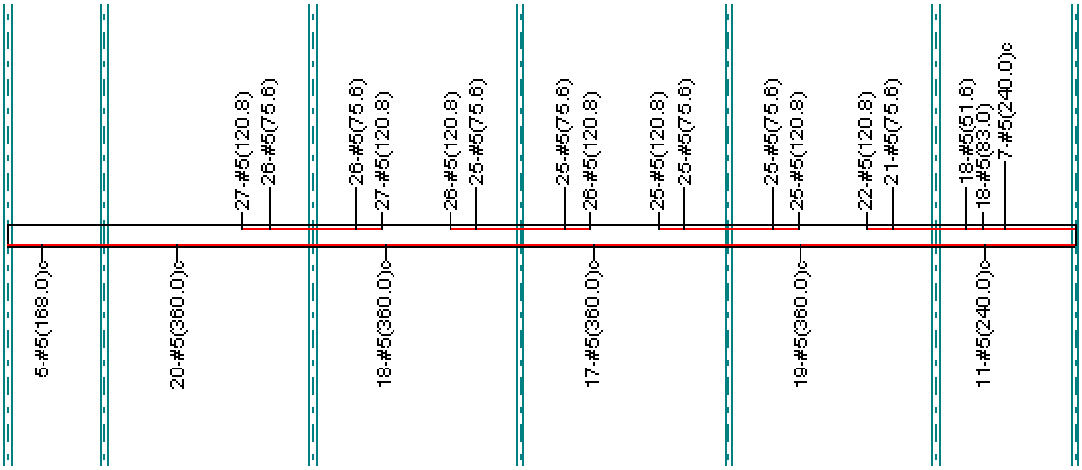


**Figure 36** –Deflection Diagrams for Typical Cooling Tower Length



Middle Strip Flexural Reinforcement



Column Strip Flexural Reinforcement

**Figure 37** –Reinforcement for Typical Cooling Tower Length