National Law Enforcement Museum Washington, D.C.

Architectural Engineering Senior Thesis

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Mechanical Option

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The Pennsylvania State University

National Law Enforcement Museum

Washington DC

Anya Godigamuwe | Mechanical | www.tinyurl.com/NLEM2015 | Dr. Stephen Treado, Advisor

Project Team

Owner: National Law Enforcement Officers' Memorial Fund
Architect: Davis Buckley Architects & Planners
MEP: Loring Consulting Engineers
Civil: A. Morton Thomas & Associates
Structural: Spiegel, Zamecnik & Shah
Construction Manager: Clark Construction
Acoustic Consultant: Shen Milsom Wake
Lighting Consultant: Claude R. Engle
Landscape: Urban Tree + Soils
Delivery: Design-Bid-Build
Cost: $50 Million
Schedule: 28 Months
Construction: June 2014-September 2016

Mechanical

System: Chilled Water Cooling with Electric Heat; Air Handling Units per Zone with Plenum Return; Auxiliary Fan-Coil Units for Supplementary Spaces like Café and Research Center
Cooling: Three Modular Chillers with VFDs in Central Plant, Two Cooling Towers at East Mechanical Room, Free Cooling with Heat Exchanger when applicable
Heating: Electric Heat at Air Handling Units and Variable Air Volume Boxes

Architecture

Façade: Glass and Steel Curtain Wall with Aluminum Metal Panels
Building: 54,000 GSF including Entry Pavilions, Two Floors Below Grade of Museum Space including Exhibit Space, Theater, Offices, Café, Gift Shop, and Research Center and Another Floor for the Central Plant
Energy Efficiency: Use of Daylighting, Heat Recovery, Free Cooling

Lighting/Electrical

Electrical: The Central Plant Contains Two 13.2 kV Feeders to Two 1500kVA Dry Type Transformers; 480/277V to Lighting, 208/120V to Others;
Controls: Power Monitoring System (PMS) used for General Illumination, Display Lighting, Plug Loads and HVAC Components
Lighting: Exhibit Spaces use LEDs & PAR Lamps, Theater uses LEDs, PAR Lamps, and Halogen Lamps; Other Spaces use LEDs and Fluorescents

Structural

Mechanical Level: 8" Reinforced Concrete Slabs, Concrete Columns & Beams
Pavilion: Glass and Tube Steel Façade with Curved Roof of the Same Material
Below Grade: 8" One Way Slabs with 18-24" Walls also Functioning as Retaining Walls
Central Plant: Minimum 4'-0" Reinforced Slab on Grade with 24" Walls

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4 EXECUTIVE SUMMARY

The National Law Enforcement Museum, a new museum to be completed by summer 2016, is an effort funded by the National Law Enforcement Officers' Memorial Fund. This structure will be situated in the Judiciary Square complex a few blocks from the United States Capitol. Highlighted by two glass pavilions in between the wings of the District of Columbia Court of Appeals, the museum will be an underground space with a research area, exhibit space, café, gift shop, hall of remembrance and theater.

The objective of this document is to demonstrate a depth of knowledge in building heating, ventilation and air conditioning design. Throughout the report, two types of modeling software will be used to analyze the existing design as well as proposed changes to the design. The goal of these changes is to reduce energy load, cost, and noise to the museum spaces.

Beginning the document, the mechanical system of the National Law Enforcement Museum is analyzed in depth. In this portion, a full discussion of the variable air volume system's design objectives, site conditions, system operation, code compliance and modeling approach occurs. Heating load, cooling load, ventilation requirements, airflow and annual energy use are all demonstrated in relation to the mechanical system.

The first analysis proposes a change to the museum's glass pavilions. With the current design, the 42% of the building's cooling load is in response to the immediate solar gain from the pavilions. It is proposed that the glass be improved to a higher U-value, shading coefficient and less transmissivity. Another part of this proposal is to take away the sky lighting roof and replace it with opaque materials similar to those used on the exterior walls of the pavilions. The results of these changes are examined using Trane Trace 700. A comparison of the cooling load, heating load and energy use shows that these adjustments would reduce cost over the life of the structure.

Secondly, a variable refrigerant flow system is proposed as a redesign of the NLEM mechanical system. This type of system is predicted to reduce building energy loads and costs. In the same way as the original system, the VRF structure is analyzed using Trane Trace 700 to determine its energy loads, costs, and building heating and cooling loads. These criteria are then compared to the results from the original system's analysis. Through these evaluations, it is determined that using a VRF system would be beneficial to the building because of its reduced energy cost even though the investment is $40,000 more than the conventional variable air volume system.

The final components of this document displays a range of knowledge in building engineering. Room acoustics is the first topic. The origin and importance of reverberation time are discussed, particularly in its applicability to the Hall of Remembrance. The RT of the room is analyzed and determined to be adequate for the task at hand.

Extensive use of glass on the grand entrances to the museum lead directly to a daylighting analysis. The program IES Virtual Environment is used to determine how much daylight infiltrates into the building spaces and whether this will be beneficial to reducing energy costs with daylighting sensors. The results from the modeling show that there is such a large amount of light illuminating the space that utilization of light sensors will be highly beneficial.

5 Building Overview

The National Law Enforcement Museum will be a 5,400 square foot structure, mostly below ground, that will be a testament to the men and women of the United States' law enforcement. This structure will contain a variety of spaces and collections commemorating this part of America's history.

NLEM has a variety of programming spaces to excite any visitor or scholar. The museum is composed of a permanent exhibit space, changing exhibit, a judgement simulator, an auditorium, and hall of remembrance for fallen officers. Other spaces include a gift shop, café, coat room, ticketing area, and a research center housing a portion of J. Edgar Hoover's estate.

The structure is located on E Street NW between 4th and 5th Street in Washington, D.C. This location is within the courthouse complex known as Judiciary Square and across the street from the existing Law Enforcement Officer's Memorial. It will be highlighted with two glass pavilions for entering and exiting the museum. Upon entering through the east pavilion, visitors will descend into the lower ticketing area, following down again to the museum and theater levels.

Because of the historically significant location of the project, a variety of zoning and historical organizations were required to cooperate. These include the DC Preservation Review Board, the US commission for Fine Arts, and the National Capitol Planning Commission. The design is also attempting to reach a LEED Silver status.

The mechanical equipment such as the cooling towers and air intake will be located within the pavilions. Each pavilion will have a roof opening for this purpose. The central plant for the structure containing the chillers and the PEPCO substation for the area are located on the third floor below grade. Other pieces of equipment such as the air handling units are located in mechanical spaces on each floor. Certain areas are heated and cooled with fan coil units such as the café, gift shop and food service area.

5.1 Existing Mechanical System

This section will discuss and analyze the existing mechanical system design of the National Law Enforcement Museum. First, the design conditions and objectives of the clients, designers, and architects will be discussed. Next, the actual mechanical system is detailed, disclosing equipment, sequences of operation and a system schematic. The final parts of this section describe the energy sources for the design, its heating and cooling loads, and ventilation requirements.

5.1.1 Design Objective

The main goals of the National Law Enforcement Museum's mechanical system design are to be energy efficient, generate minimum amounts of noise, and help the building meet its goal of LEED Silver status. This system will utilize high efficiency equipment to best condition the structure. Following code requirements is also relevant to the design. The regulations referenced in the design include, but are not limited to, International Energy Conservation Code 2006, International Building Code 2006, International Mechanical Code 2006, 2008 amendments by the District of Columbia Department of Consumer and Regulatory Affairs, the United States Green Building Council Version 2.2, and ASHRAE Standards 2004 Sections 55, 62.1, and 90.1. By achieving these goals, the building will meet the high standard set by the client and required for a construction of this nature.

5.1.2 Design Conditions

Along with the design objective, various other elements are required for a complete, efficient, and viable mechanical system. The criteria may include the building's location, its site, and cost of construction, weather data, local energy rates and incentives for green building design.

The National Law Enforcement Museum is located in downtown Washington, D.C. It is located within the courtyard of the District of Columbia Court of Appeals, surrounded on the east, west, and south side by the three-building structure. The climate in the area has hot, humid summers and cold winters, therefore cooling design will be the most important challenge. While modeling the loads, the 0.4% ASHRAE Summer design cooling data was used, the winter design heating temperature was 17F and the dehumidification weather was also 0.4% during the cooling months.

The bidding documents for the museum were not released during the study for this thesis, however, the construction management firm, Clark Construction, stated that the cost for the HVAC and plumbing components for the structure came to approximately $4.5 million. This cost is 9% of the total building cost, $50 million. An increase in this value because of redesign would likely be disliked or lead to other elements of the design being taken out by value engineering.

As mentioned in Section 5.1.1, several zoning and design codes were referenced during the progress of the National Law Enforcement Museum. The major referenced building codes are those defined by the District of Columbia Department of Consumer and Regulatory Affairs: 2006 International Building, Mechanical, Plumbing and Fire codes, 2006 ICC Electric code, ANSI A117.1 for Accessible and Usable Buildings and Facilities, and the ADA Accessibility Guidelines for Buildings. Zoning and historic preservation organizations also were involved in the structure's development: US Commission of Fine Arts, the Advisory Commission on Historic Preservation, the National Capitol Planning Commission, the State Historic Preservation office and the DC Preservation Review Board. Further environmental and energy evaluations will be completed in pursuit of a LEED® Silver certification and a Section 106 compliance in Environmental Assessment.

Energy sources available to NLEM are the five utility components of electric demand, electric consumption, gas, water and fuel oil. However, no equipment within the structure utilize fuel oil or gas, only relying on electricity and water for all its heating and cooling requirements. The reasoning for this is because of the tight physical constrains on the building site. As stated earlier, the construction will occur in close proximity to the D.C. Court of Appeals in a very busy and highly trafficked portion of downtown Washington, D.C. Fortunately, the electric supply company, PEPCO, has a major line traveling underneath E Street NW directly adjacent to the construction. This is also why a full substation will be a part of the museum's central plant area. Water will be supplied by the District of Columbia Water & Sewer Authority. The rates for these two companies are show in Table 1 - Table of Utility Costs for the National Law Enforcement Museum and applied within the Trace 700 Energy model.

Table 1 - Table of Utility Costs for the National Law Enforcement Museum

NLEM Utility Costs		
Electric Demand	$/kw	5.4
Electric Consumption	$/kwh	0.09
Electric Demand Off Peak	$/kw	5.87
Electric Consumption Off Peak	$/kwh	0.08
Gas	$/therm	0.466
Water	$/1000 gal.	5.19
Oil	$/therm	0.4776

Because of the varied programing in the space, there is a variety of lighting types from daylighting in the entry lobby and fluorescents in the office areas to LEDs in the museum space and PAR lamps for spot lighting exhibits. For simplifying the modeling process, the mechanical engineers used per square foot lighting and power loads, detailed in Table 2 & Table 3. The envelope, ventilation and occupancy of the building was also specifically outlined by the engineers. This data follows the ASHRAE 90.1 and 62.1 standards and are available in Technical Report Two.

Table 2 - Engineer Specified Lighting Loads for HVAC Calculations

Lighting Loads	**Watts/SF**
General Office Area	1.0
Auditorium	1.0
Hall of Remembrance	1.0
Atrium	1.0
Exhibits	1.0

Table 3 - Table of Power Loads as Used by the MEP Engineers

Power Loads	**Watts/SF**
General Office Area	2.0
Exhibits - Process Lights	10.0
Other areas	Per 90.1

5.1.3 Existing System Overview

The museum is designed to be supplied by six air handling units (AHUs) located in various areas and supplying the multiple spaces in the building. Two 5,000 CFM AHUs are specifically assigned to the East and West pavilions, another two 33,000 CFM air handling units are situated to serve the exhibit area. Two 4,000 CFM units serve the theater and the central plant area. The building is cooled using a combination of a chiller and two cooling towers. The water cooled system is the heat sink for the air handling units. A heat exchanger is also part of the system to support partial or complete free-cooling should the building conditions meet certain criteria.

Air is supplied from the air handling units at a temperature ranging from 50-56 degrees Fahrenheit and then ducted to variable air volume units. The air supply system is separated into three major components: the East & West pavilions, the exhibit areas, and the theater. The theater air handling unit varies its supply to the space with a variable frequency drive at the AHU. Heating in the building is supplied with electric heat at the air handling units and electric reheat at the VAV boxes. Air is returned using a return air plenum for each area and then ducted to be mixed with outside air intakes. Fifteen fan coil units are also used to supplement minor areas such as the café, gift shop and research center.

The entire system is controlled by a direct digital control (DDC) building automation system (BAS). The entry pavilions, theater, and exhibit space each have different control algorithms within the BAS. This control system will use the inputs from various carbon dioxide, oxygen and occupancy sensors. The occupancy schedule is set by the owner with the engineers confirming this with site visits in the one year after construction. Temperature sensors are located within the space and input information to the variable air volume boxes to supply adequate heating or cooling to the spaces. Humidity is maintained at the air handling units from information received by humidity sensors within the return ductwork.

5.1.4 System Operation

This next portion will go through the various components and their control systems from the chiller to the variable air volume units. It will discuss the type of equipment and their controls. An important factor for all this is the temperatures at which each unit functions in its various modes.

The figure in Section 5.1.5 - System Schematic shows the general sequence of the building mechanical system. On the airside, conditioned air is supplied from the air handling units to the VAVs and then the spaces and fan coil units directly to its spaces. Return air is transferred through the plenum into the mechanical rooms where the air handling units take the air after it's mixed with outdoor air and reprocesses it through the building. Harmful exhaust is specifically ducted out, but other exhaust air is released through louvres located on the sides of the buildings at the penthouses.

For the water-side, the components are the cooling towers, chiller, heat exchanger, air handling units and fan coil units. The cooling tower takes the water from the chiller and reduces its temperature. The water is then sent back to the chiller and energy is exchanged. This follows through to the heat exchanger, AHUs and FCUs.

The chillers are four modular units that containing the chilled water and condenser water. The chiller supplies the mechanical cooling and are connected to the cooling towers. This equipment is capable of functioning at partial capacity and is function is controlled by building automation system via its variable frequency drive. Chiller use is very limited when the outdoor air temperature decreases to 45F. This is when the ambient free cooling will be used. However, should the building humidity reach 55%, the chiller will be brought back into use.

The cooling towers work in conjunction with the chillers, operating with variable drives to match the required loads of the building. The overall sequence of this equipment rotates every seven days and the cooling towers are required to have a minimum of 5 minutes off period every day. This equalizes the run time of both fans in the cooling towers. To prevent freezing, when outside temperatures are below 35F a heat tap will be enabled. If temperatures are below 40F, a sump heater is brought in but disabled if temperatures are above 42F.

The settings of the cooling towers and chillers is pressure controlled via a valve. Both pieces of equipment are fully loaded when wet bulb temperature is 78F and above, 75% at 74F, 50% at 70-60F depending on humidity, and 25% at 66F. The plant control system will dedicate at which rate the equipment run. This is from taking the input of the outside wet bulb temperature, the incoming water temperature, chilled water and condenser water flow rate and the efficiency of the chiller. A more precise narrative will be provided to the building maintenance people.

Air handling units take a large amount of input to send out conditioned air. These are space sensors, fan status, filter status, smoke detectors, low temperature sensors, occupancy sensors, other temperature sensors within the ducts, and pressure sensors. All these data points go into the building automation system. All air handling units are directly wired to the occupancy, CO_2 and temperature sensors. Each has a heating coil for pre-heat. Technical Report Three has a specific list of the AHUs and the areas they service. All the

AHUs supply VAV boxes for various zones in the building. The variable air volume units have another heating coil to bring the supply air to the zone required temperature.

The National Law Enforcement Museum utilizes a building automation system to control its mechanical system. At the beginning of the day, the system will wait as long as possible before beginning operation so as to reach the optimum temperature just at the start of building occupancy. Therefore, it will not begin any more than 120 minutes prior to occupation. During the cooling period, the BAS determines when to turn on depending upon the modes zone's VAV units. During the heating season, the local preheat elements in the zones will change the supply the temperatures as required. The BAS will shut down that zone for 120 minutes should the building operator require a time override.

In the night mode, the building shall function as if unoccupied. The ventilation functions will be disabled and the outdoor air supply will not be used. If cooling, the building will be night cooled and prevent the building from reaching temperatures above 85F. The air flow will remain to maintain the pressure in the duct system. For the heating night mode, the building automation system will utilize AHU to maintain the building temperature at a minimum of 60F. The VAVs will also help maintain the temperature. The airflow will not halt in this situation either.

Building humidity needs to be controlled because the structure is a museum. A humidity sensor is located near the fan discharges to modulate the humidifier. Each space also has a humidity sensor that will send the information back to the BAS. Ventilation is controlled directly at the air handling units which maintain the required amount of outdoor air supplied to its zones.

There are special instructions for AHU-5, the air handling unit supplies the theater in a single zone capacity. Normal conditions apply to this equipment during occupied hours. However, for the morning warm up or cool down period, the system will only operate in cooling or heating mode (as required) if the space temperature is 2 degrees or more away from the space set point.

The variable air volume units are the last step in control before air enters a space. The space temperature dictates whether the unit functions in heating or cooling mode. Cooling supply set point minimum is 40F and maximum is 110F. Heating supply set point minimum is 40F, also, and maximum is 105F. When in cooling mode, the unit will reference the normal set points for all building equipment: occupied cooling set point – 74F, unoccupied cooling set point – 85F, and occupied standby cooling set point – 78F. In heating mode, the set points change to 71F, 60F and 67F, respectively. All VAV units are equipped with reheat which activates when the space temperature is below the cooling set point and the airflow is at the minimum cooling flow. This adds a redundancy and prevents the use of the reheat coil unless necessary.

Generally speaking, the building automation system controls five aspects of the VAVs. These are space temperature set points, occupied status, unoccupied status, heat or cool mode, and priority shut down. With these elements controlled, the equipment is adequately controlled and waste energy is eliminated.

The various fan coil units in the building follow the same operation as the air handling units. They have the same function for occupied and unoccupied time, morning warm up and cool down, and heating and cooling set points. However, in addition to the BAS controlling the regular occupied, unoccupied, heat/cool mode and priority shutdown, it also has the capability of enabling the economizer that is a part of the FCU.

Finally, the building automation system also manages smoke control in the event of a fire. When the fire alarm system signals the BAS of the presence of smoke, all automatic dampers of each fan will open. AHU-5, supplying the theater, will allow the supply and return air fans to operate at full speed. It will also close the return air damper completely and completely open the relief and outside air damper. For the other AHUs, the supply fans will operate at full speed while the outside air damper opens and the return air damper closes.

Following these immediate reactions, all the exhaust fans will begin or maintain function and the smoke isolation dampers will become fully open or fully closed, depending upon their designation as specified in the mechanical drawings. Also, all the cooling coil control valves will be opened fully and the chiller turned off. However, the chilled water pump will continue to run the fluid at full speed to prevent it freezing. Only when the smoke is completely cleared will the building be manually reset into operation.

5.1.5 System Schematic

A schematic drawing of the existing mechanical system is available in Appendix A – Mechanical System Schematic. This figure shows the interaction between the chilled water system composed of the cooling towers, free-cooling heat exchanger, chiller, air handling units and fan foil units, and the air side of the system composed of the AHUs, FCUs and variable air volume units.

5.1.6 Heating & Cooling Loads

The original load calculation completed by the mechanical engineers for the National Law Enforcement Museum was in Trane Trace 700©, a commonly used building load and energy modeling software. It took in the various inputs concerning the structure such as U-values of walls and partitions, position of the building, occupancy types, dimensions and other criteria to yield the heating and cooling loads that must be met to condition the building. Later, in Section 5.1.8 - Annual Energy Use, the expected energy use for the building based on equipment and load will be discussed.

The engineer's calculation process yielded a total cooling load of 246 tons and a total heating load of 673 MBH. These values and the individual values of the rooms and zones are then used to size the equipment required to condition the museum. A space by space results table from the thesis calculations can be found in Appendix B - Table of Building Heating & Cooling Load for Existing Mechanical System.

5.1.7 Ventilation Requirements

A certain percentage of air supplied to spaces within a structure must be conditioned outdoor air. This is according to ASHRAE Standards 55 and 62.1 put forth to maintain indoor air quality and to remove sick building syndrome. Space type and occupancy determine its required amount of outdoor air whose value is calculated using a series of equations for defining the Breathing Zone Outdoor Airflow. This calculation is necessary because the mechanical system mixes return air and outdoor air to supply to the air handling units and fan coil units. This method allows the outdoor air to be preconditioned in such a way as to reduce the energy load to the building. Therefore, the calculation is used to determine the minimum amount of outdoor air that can be put into the building to meet the ventilation requirements while maintaining low energy cost.

The results of the engineers' calculation can be seen in Table 4 - Table of Ventilation Calculation Comparison to Design. This table shows that most of the system complies with the standard except for three particular pieces: FCH-04, FCH-05 and FCH-07. These units supply the ticketing level café, gift shop area and the exhibit level audio-visual rooms, respectively. However, these components do not need to be increased in size for a variety of reasons.

Table 4 - Table of Ventilation Calculation Comparison to Design

System Summary			
System Summary	**Design V(ot)**	**Calculated V(ot)**	**Compliant?**
AHU-1	500	500	Yes
AHU-2	500	500	Yes
AHU-3	7000	1560	Yes
AHU-4	7000	1370	Yes
AHU-5	980	310	Yes
AHU-6	0	0	Yes
FCH-01	500	220	Yes
FCH-02	0	0	Yes
FCH-03	20	0	Yes
FCH-04	210	310	No
FCH-05	640	1100	No
FCH-06	640	270	Yes
FCH-07	0	20	No
FCH-08	40	40	Yes
FCH-09	0	0	Yes
FCH-10	0	0	Yes
FCH-11	0	0	Yes

First, the café area has a high exhaust rate from the food service area located directly adjacent. This room and the adjacent west elevator lobby have been oversized to meet the needs of all three spaces. Secondly, the gift shop area has its own fan coil unit and FCH-05 is located in the lobby directly adjacent to it. This will allow both areas to be sufficiently ventilated. Finally, the audio visual rooms are mostly unoccupied throughout the day and only store the control elements for the exhibits visuals such as servers and computers.

5.1.8 Annual Energy Use

An energy analysis was completed for this thesis using Trace 700. This utilized the load calculations, equipment designations and energy cost values inputted into the program to yield a yearly cost estimate. Table 5 - Table of Building Energy Use details the output values in kilowatts per year while the following Figure 1 - Pie Chart of Building Energy Use shows the percent distribution of energy used in the building.

Table 5 - Table of Building Energy Use

Energy Costs	KWH	KBTU/YR
Heating	142345	485825
Cooling	186857	637742
Auxiliary Mechanical Equipment	3954	13496
Lighting	280914	958760
Receptacle Load	559656	1910107

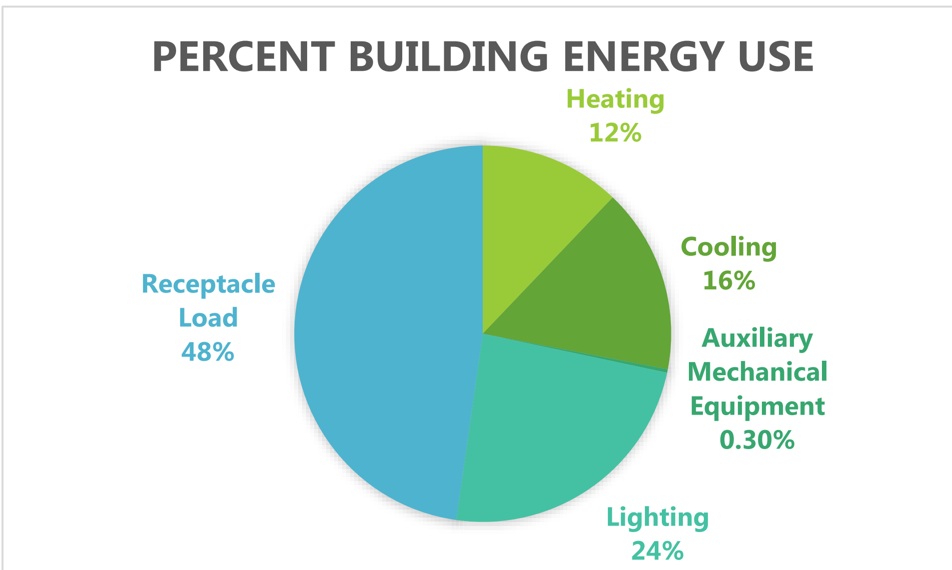


Figure 1 - Pie Chart of Building Energy Use

The large lighting load can be attributed to the majority of the occupied space being below ground. This brings forward the requirement for artificial light as the daylight from the pavilions are unable to filter down into the exhibit or much of the ticketing levels. This is demonstrated and analyzed later in Section 10 which discusses the daylighting aspect of the building design.

Even greater is the receptacle load within the building. This is because the specific exhibit lighting and other technology are placed within the model as a receptacle load. Exhibit lights include PAR lamps and spotlighting LEDs which result in a high energy load. Further discussion of the energy model, its inputs and reasoning are in Section 5.2 - Energy Model.

5.2 Energy Model

Below, the Trace 700 energy model will be discussed. First the inputs and sources for the modeling will be detailed as well as the goals and results from the model. The next two parts of this section detail the cost estimate from the modeling program and the estimated emissions. The final portions discuss validating compliance with ASHRAE Standards 62.1 and 90.1.

5.2.1 Modeling Approach

The majority of the sources for the energy model came from the Mechanical Design Narrative from Loring Engineers. This data included lighting loads, CFM per person ventilation loads, building schedule, expected maximum occupancy, and filtration requirements. All these inputs were placed inside the thesis energy model in an attempt to yield results similar to those of the building's engineers. Section 5.1.1 - Design Objective and Section 5.1.2 - Design Conditions describe further inputs from the mechanical design narrative that were input into the model.

Trace 700 is a very capable program that yields multiple types of results for comparison and analysis. These include building energy loads, heating and cooling requirements, space temperatures & humidity, energy use and cost. It also has the ability to keep up to four alternatives within the program for evaluation. This is very efficient so that data does not have to be transferred between programs or files to do an accurate cost comparison. From running the model, the main outputs analyzed for comparison in this document are building heating and cooling loads, building energy, system type, cost and emissions.

5.2.2 Estimated Energy Costs

Because the mechanical system for the National Law Enforcement Museum does not use a boiler for its heating purposes, but rather electric resistant heat at the variable air volume units, only the electrical energy cost needs to be analyzed for cost and energy comparison purposes. The rate structure for the electricity supplied by PEPCO was detailed in the earlier Section 5.1.2 - Design Conditions in Table 1. The electrical energy monthly and total estimated yearly cost are shown in Table 6 - Table of Monthly and Total Electrical Cost of Mechanical System. The evaluation showed that the designed mechanical system would incur $87,951 per year in utility costs.

The distinct monthly energy use for the building's mechanical system can be found in Appendix C – Tables of Monthly Building Energy Use. The total building energy use per year is 4,005,929 kBtu/year, so the energy utilization index, EUI, for the National Law Enforcement Museum is 74.18 kBtu per year per square foot. According to the Unites States Department of Energy's Commercial Building Benchmarks from October 2009, this value is within the expected EUI for stand-alone retail establishment in climate zone 4A. This is an acceptable category for comparison because the load profile of a museum is similar to that of a retail establishment.

Table 6 - Table of Monthly and Total Electrical Cost of Mechanical System

Month	On Peak Consumption ($)	Off Peak Consumption ($)	On Peak Demand ($)	Off Peak Demand ($)
January	5181	3096	26	14
February	4447	2545	24	12
March	4365	2267	22	11
April	4248	2047	23	13
May	5573	2339	30	17
June	5779	2597	34	19
July	6408	2833	36	20
August	6015	2604	34	18
September	5301	2322	31	17
October	456	2192	23	13
November	4331	2480	23	13
December	4971	3042	25	14
TOTAL	**57075**	**30364**	**331**	**181**

5.3 ASHRAE 62.1 System Compliance

Technical Report One is composed of a full analysis of ASHRAE 62.1 compliance for the designed mechanical system. The results of that examination showed that only a few components of the system could benefit from further improvement. These were the process of dehumidification, building envelope and outdoor air ventilation rate to the fan coil units mentioned in Section 5.1.7 - Ventilation Requirements. The dehumidification concerns are from the humid climate in Washington, D.C. combined with the heavy latent load from the guests within the building. The building envelope concerns are because of the design of the pavilions. These are all curtain wall with some aluminum pre-fabricated walls that are not very thermally resistant. The final concern of the fan coil units can be addressed by increasing their size and supplied outdoor air.

5.4 ASHRAE 90.1 System Compliance

This standard evaluates energy use and efficiency for building systems. A full evaluation of compliance was completed in Technical Report One showing that there was only two small issues: chiller & fan power equipment efficiency and the low u-value of the pavilion curtain wall. Further examination showed that it was not necessary to bring the non-compliant fans to the required efficiency because they were only to be used on an as needed exhausting only basis. The low u-values of the walls may not adversely affect the building energy loads. This is examined as part of the mechanical depth analysis in Section 7 - Mechanical Depth: Pavilion Façade Redesign. It is also important to note that the profuse use of LEDs in the building lighting design significantly reduces the energy required to light the spaces. This topic is particularly relevant considering most of the building is underground.

6 Proposed Redesign

The architectural engineering thesis process is composed of proposing a redesign for the thesis building based on existing conditions. This requires full use of energy and load modeling technology, planning, and understanding of the other areas building engineering. The second portion of the thesis is an understanding of other building engineering components such as structures, architecture, construction, lighting, or acoustics. Two of these elements must also be analyzed in relation to the project building.

6.1 Alternatives Considered

Four possible mechanical redesigns were considered for the depth portion: chilled beams, variable refrigerant flow, dedicated heat recovery chiller and a pavilion façade redesign. A chilled beam system would be a positive change for the building mechanical design because of its low noise, however this type of system does not work with electric resistant heat and must have a boiler as part of its central plant. Also, this design can become very expensive. Chilled beam systems also require very tight humidification control. This would have been difficult within the moist climate and high latent loads from occupants.

A dedicated heat recovery chiller may reduce the energy loads within the building because of its ability to utilize waste heat from the chiller and other pieces of equipment. However, the utilization of this equipment would take away the benefit of free cooling from the design. The other two options of a pavilion façade redesign and applying a variable refrigerant flow system are more feasible options compared to the chilled beam and dedicated heat recovery chiller.

6.2 Proposed Alternatives

First, a redesign of the building façade is analyzed. This is very relevant because the only façade for the building are the pavilions, the rest of the structure being underground. This fact also means that the majority of the building's environmental load will be from this area. In a later section, we will discuss how this redesign may affect the daylighting capabilities of the National Law Enforcement Museum.

In Section 0, the second part of the mechanical depth exercise is a redesign of the mechanical system as a variable refrigerant flow system. This type of system is generally accepted as a method that uses less energy than conventional variable air volume systems. The two will be compared with the criteria of energy, cost, life cycle cost and emissions

Finally, two breadth topics are used to show a more rounded understanding of building engineering and the National Law Enforcement Museum. Sections 9 & 10 examine the effect of acoustics and daylighting, respectively, on the museum as a whole.

7 Mechanical Depth: Pavilion Façade Redesign

The entrance and exit pavilions of the National Law Enforcement Museum are the landmark pieces of architecture to draw in tourists and guest. Unfortunately, this type of design lends to heavy environmental loads that impact the function of the building. As shown in Figure 2, both the exterior walls and roof are completely made of glass held up by a steel structure. This design allows for full infiltration of solar loads and also makes it difficult to maintain temperature within the space.

Figure 2 - Rendering of West Pavilion Interior, Courtesy of Davis Buckley Architects and Planners

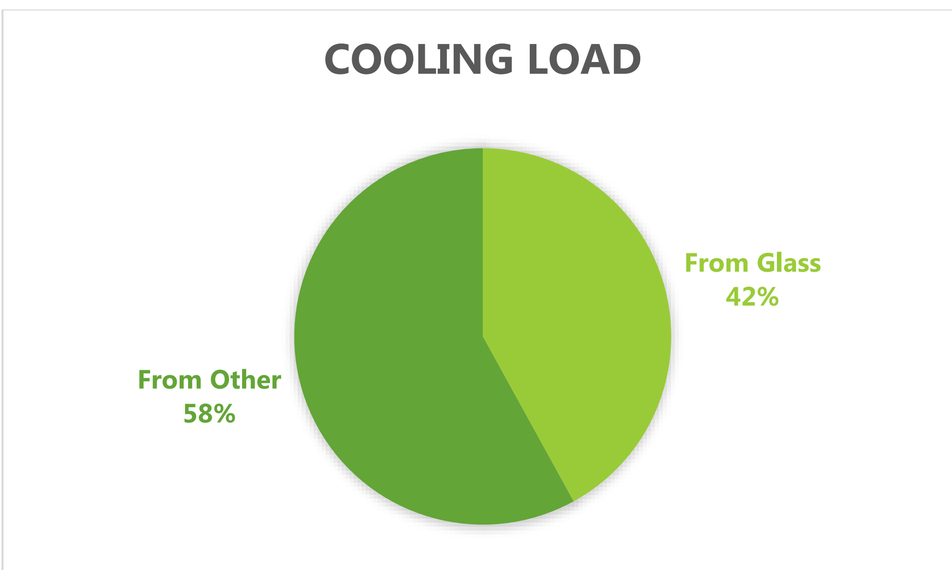
The glass type, as outlined in Section 08900 – Building Enclosure and Assemblies of the NLEM construction specification is composed of 3 layers of glass yielding a U-value of 0.31, as shown in Appendix D – Material Properties. The low U-value leads to a high levels of heat transfer. This glass type also has a shading coefficient of 0.5 and a high visible transmissivity of 90%. The two factors combines also leads to greater solar loads. Fortunately, the structures' south face is shaded by the adjacent DC District Court of appeals, lessening the load from that façade.

The above stated criteria make selecting and redesigning the façade and curtain wall system of the National Law Enforcement Museum an ideal solution to reducing energy use within the building. This assessment is validated further because 42% of the cooling load to the building mechanical system stems from solar gain from the skylight and curtain wall (Figure 3.) A positive change can be done in two steps. First, by specifying a more effective glass type and further shading to the space with the use of fritting. And secondly, by specifying actual roofing material to reduce heat loss and solar gain from the roof above.

Table 7 - Table of Properties of Vertical Fenestration

Vertical Insulating Laminated Glass		
Material	Description	Thickness (in.)
Outboard Lite	clear (low iron) heat tempered, heat soaked glass with Low Emissivity Coating on Number 2 Surface, and with flat ground and polished edges	0.31
Air Space	Air	0.5
Inboard Lite x2	Clear (low iron) heat soaked glass laminated with 0.060" DuPont SentryGlass Plus structural interlayer with flat ground and polished edges	0.625
Thickness		1.50
Approximate U-Value		0.31
Shading Coefficient		0.50
Visible Transmissivity		0.90

Figure 3 - Percent of Cooling Load from Glass



A better glass type for the curtain wall is Viracon Insulating Low-E Silk-screened glass, VE1-2M-V175. This is a double paned glass type with a white or gray ceramic frit on the exterior face and a low-E coating applied to the exterior face of the inner unit. The silk screen technology can come in a variety of patterns from 1/8" diameter dots or ½" stripes covering between 20 and 60 percent of the glass. Table 8 - Table of Properties of Proposed Viracon Glass describes the glass in more detail.

The roof of the pavilions can remain curved and aesthetically pleasing but with a different construction material. An aluminum based roof would match the structures aluminum-type exterior walls currently used by the pavilions. This would have a better u-value of 0.12. Also, the solar gain factor from the roof would completely be removed.

Table 8 - Table of Properties of Proposed Viracon Glass

Vertical Insulating Laminated Glass		
Material	Description	Thickness (in.)
Outer Layer	Insulating tempered glass with 30% silk screen coverage	0.25
Air Space	Air	0.5
Inner Layer	Tempered glass with low-E coating	.25
Thickness		1.00
Approximate U-Value		0.26
Shading Coefficient		0.35
Visible Transmissivity		0.55

7.1 Energy Model

Trane Trace 700 is used to evaluate the change in building and energy loads by specifying the new glass and roof type. An alternative is created in the program with the same system, room configuration and all other data. Only the roof type and curtain wall are changed on the ground level to effect the construction of the pavilions. The model is then calculated again so that comparisons can be made between the two systems.

7.1.1 Solar Heat Gain

There is a significant drop in solar gain from the skylight as the roof is no longer composed of glass and another decrease in solar gain from the vertical fenestration because of the improved quality of the Viracon glass. The data also showed that the cooling load from the glass reduced to only 7% of the total building cooling load, a significant change from the previous 42% (Figure 5 - Percent of Cooling Load from Glass with New facade.) Based purely on the reduction of heat gain from the sun, changing the façade of the pavilion to a fritted glass type and removing the skylights completely has a positive effect on the energy load to the building.

Figure 4 - Change in Cooling Load for Solar Gain

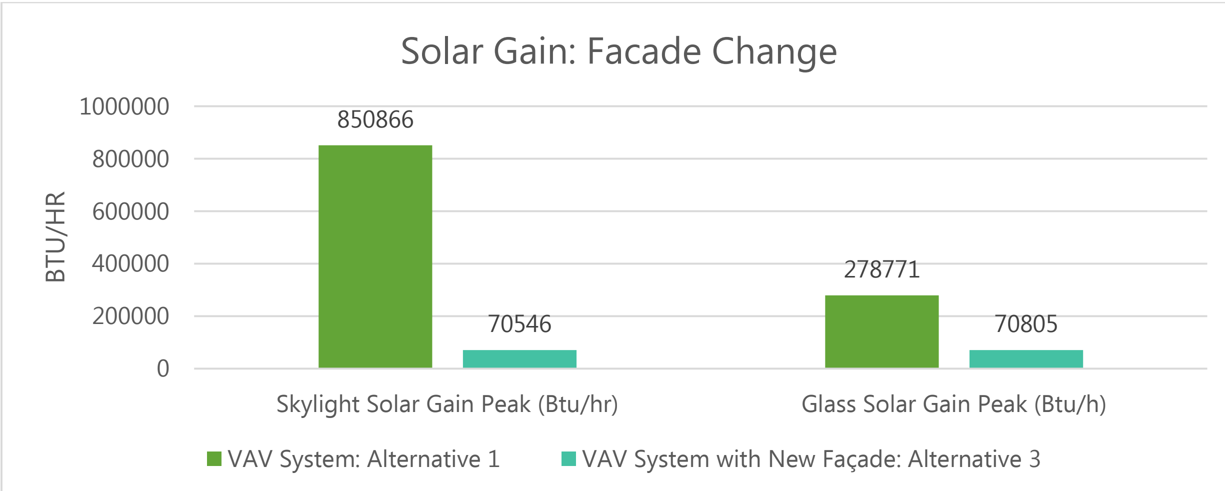
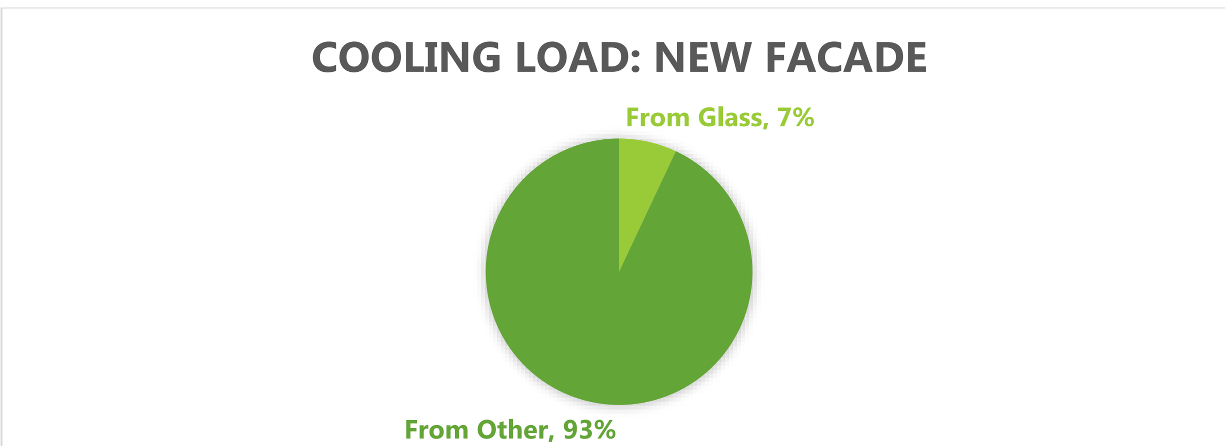


Figure 5 - Percent of Cooling Load from Glass with New facade



7.1.2 Heating & Cooling Loads

Appendix E – Cooling & Heating Load for Alternatives displays the results of the Trace energy model per alternative. Alternative 1 is the existing designed variable air volume system, Alternative 2 is the model for Section 8, and Alternative 3 is for the façade redesign only. These results show there is approximately 32% decrease in cooling energy by changing the façade, as shown in Figure 7. The energy cost is also decreased, particularly in the summer months. A yearly difference of $3,490 in utility costs is apparent between the existing design and the reduction and specification of glass. A month to month comparison of the two alternatives is shown in Figure 6 - Monthly Utility Cost, Alternatives 1 & 3.

Figure 7 - Cooling Load Comparison for Alternatives 1 & 3

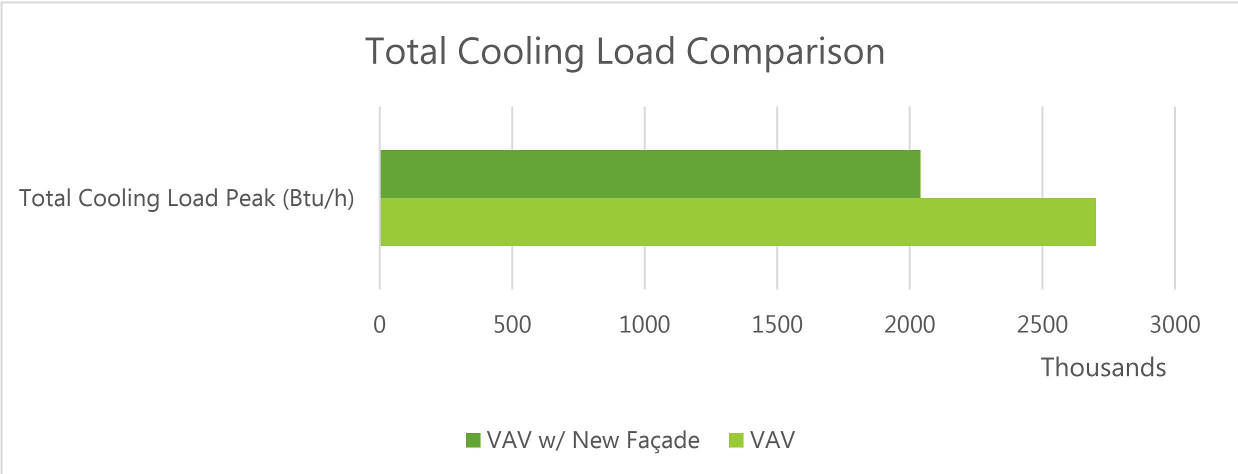
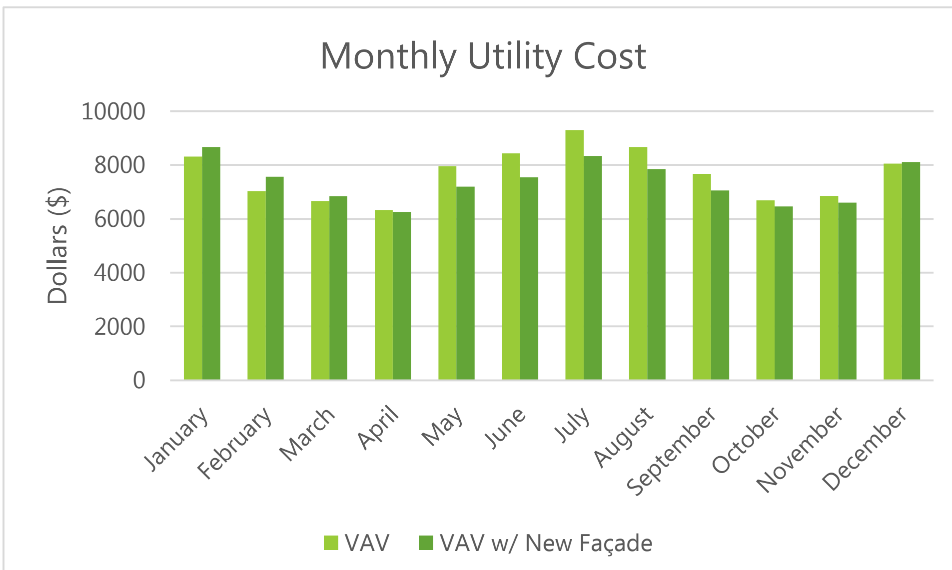


Figure 6 - Monthly Utility Cost, Alternatives 1 & 3



7.2 Recommendation

After completing the analysis of the existing glazing system and its effects on the cooling load and energy cost for the National Law Enforcement Museum, it can be concluded that a reduction in the glass of the pavilions will be beneficial to the energy use of the building. The analysis yielded a variety of options for improving the building energy load by changing the façade. First, the glazing type can be changed to a material with a better U-value, shading capability, and transmissivity. The roof, currently 100% glass, can be reduced or replaced with a more thermally resistive system. Both these elements can be executed fully or partially to improve the building energy use. Ideally, specifying a different glass type would be the most effective way to reduce energy while maintaining aesthetic.

8 Mechanical Depth: System Redesign

8.1 Variable Refrigerant Flow System

A variable refrigerant flow system is a building heating and cooling system that relies on changing the amount of coolant entering a VRF unit and using it as either a heat source or heat sink. Generally, an air handling unit or a dedicated outdoor air system supplies a predetermined amount of conditioned air to each unit. There, the air is further manipulated to reach a temperature best suiting its supplied zone.

To function at its best, a VRF system must be strictly controlled, having many inputs and outputs to the building automation system and continuously correcting the fluid flow. The three main manufacturers of variable refrigerant flow systems are Daikin, Mitsubishi and LG, the basis of design for this analysis. This system type is also beneficial to mechanical designs because it reduces duct size because of the lessening of supplied air to equipment. It would also remove the excess fan noise that is apparent in the existing design.

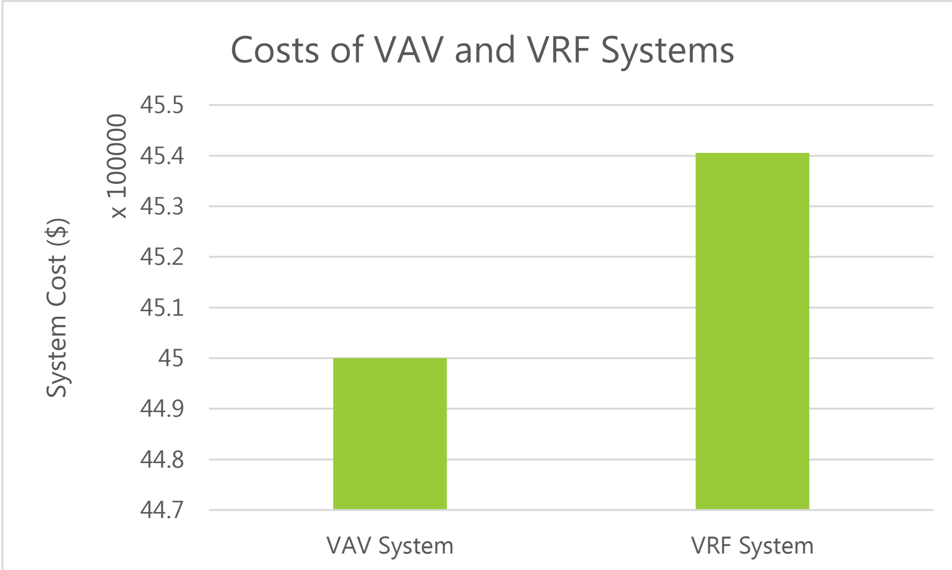
In the following sections, a description of the equipment required for a VRF system will be discussed, followed by a definition of the system operation. Next, a system schematic will be presented to enhance the understanding of the VRF layout. Then, the results from the load and energy model are shown and analyzed in the Modeling & Energy Comparison sections. Finally, to further evaluate the merits of the variable refrigerant flow system to that of the variable air volume system, a life cycle cost analysis will compare the payback period, benefit to cost ratio and internal rate of return.

8.2 Equipment

The only major change in the equipment required for the variable refrigerant flow system for the National Law Enforcement Museum is the inclusion of VRF units and the installation of the DOAS system. The chiller and cooling towers remain a similar. VRF units are sized based on the zones they supply and range from 100 to 8,500 CFM. The larger units are for the heavy load spaces such as the theater, entry lobby and exit lobby. There will be two dedicated outdoor air units (DOAS) supplying air to the building at the minimum required amount. This will overall reduce the energy use of the building by combining the fresh air with return air.

Sources from the construction management firm, Clark Building Group, approximated the full cost of the mechanical system including all fixtures, ducts and plumbing to be $4.5 million. By referencing RS Means 2014, the same year as that of the cost estimate, an equipment cost of $291,665 is determined for the VAV system and $332,220 for the VRF system. There is a $40,555 difference in first cost between the two systems. A graphical representation of the difference in cost of the two systems is show in Figure 8. Further analysis of cost can be found in Section 8.7 - Cost Comparison & Life Cycle Cost Analysis.

Figure 8 - Bar Graph of System First Cost for VAV and VRF Systems



8.3 System Operation

By definition, the variable refrigerant flow system works differently than the conventional variable air volume system. As depicted in the graphic of Figure 15 - Schematic Diagram of VRF System found in Appendix A – Mechanical System Schematic, the coolant travels not only to the DOAS units to condition the air but also to each VRF to further condition air to meet the space requirements. With this two fold system, the chilled water does not have to be as cold as in a VAV system, reducing the amount of energy required to attain the optimal temperature.

Another component in this design that differs from the VAV is the function of recirculated plenum air. In a VAV system, the return air is mixed with outside air to precondition it and make it simpler for the air handling unit to process it. Conversely, in this system design, the plenum air directly funnels through the VRF units at the location. This reduces the amount of duct but also guarantees the infiltration of required fresh air for ventilation purposes. A certain amount of air, however, must be exhausted to both maintain the pressure of the building but also to take away unwanted particulates, smells, and humidity. The chiller and cooling towers work in the same fashion as described in the variable air volume sequence of operation in Section 5.1.4.

8.4 System Schematic

A schematic drawing of the existing mechanical system is available in Appendix A – Mechanical System Schematics, Figure 14 - Schematic Diagram of VAV System. This figure shows the interaction between the chilled water system composed of the cooling towers, chiller, and dedicated outdoor air units, and the air side of the system composed of the DOAS units and variable air volume units.

8.5 Modeling

The program Trane Trace 700 was used again to model the building and energy loads for this mechanical system redesign. By using the same program, this alternative, Alternative 2, could be compared to the original variable air volume system, Alternative 1. Most of the design inputs remained the same for this model as the redesign of the mechanical system did not change the building's construction, occupancy, schedule or other functional aspects.

New systems had to be defined within the model using the LG VRFs as the basis of design. Each VRF had the building's schedule and design set points input into them. The program was also set to show a dedicated outdoor air supply system. A special use of a sensible wheel helped to precondition the air and reduce the load on the DOAS units. The equipment data itself had to be imported into the Trace 700 library. Fortunately, LG provides a compressed file on their website containing all their VRF unit information. This was loaded in and specified to the system.

A major component for designing VRF systems is grouping rooms for zoning. Appendix F – Zoning for VRF Design contains graphics depicting the zoning used for the mechanical system redesign. Spaces are grouped by function and occupancy. This means that they have similar loads and schedules allowing for more control in the conditioning process. Certain spaces such as restrooms, corridors, and stairwells are designated separately. These areas will be either supplied with secondary air or exhausted; they do not affect the load on the VRF units.

8.6 Energy Comparison

Utilizing a variable refrigerant volume system is a more streamlined heating and cooling method because of the overall reduction in energy presented by varying the fluid, a smaller volumetric rate, than by varying air volume. Also, this system type makes more use of pumps rather than fans, another reduction of energy use. Figure 9 - Comparison of Cooling and Heating Loads, Alternatives 1 & 2 graphically shows the difference in cooling and heating load between systems. This results in an approximate 25% decrease in building heating and cooling load solely because of the change in system type.

Other criteria to consider when evaluating the energy use of a system are total required airflow in cubic feet per minute, the total energy use per year, energy use per month and environmental emissions. Table 9 - Comparison of VAV and VRF Systems compares a variety of elements between the VAV and VRF systems. Though the airflow, emissions, and energy use are overall less for the variable refrigerant flow system, there is only a small discernable difference. Even though the building loads were reduced greatly, the overall energy used is too similar to positively select one system over another. This is tactic is further verified when looking at the monthly utility cost comparison between the two systems as shown in Figure 10. Though the VRF system uses less energy in the winter months between November and February, the dehumidification requirements increase the energy use in the summer causing both systems to be relatively equal with only a 6.23% difference. By referencing Appendix C, the EUI for the VRF system is 70.22, four points less than the VAV system.

Figure 9 - Comparison of Cooling and Heating Loads, Alternatives 1 & 2

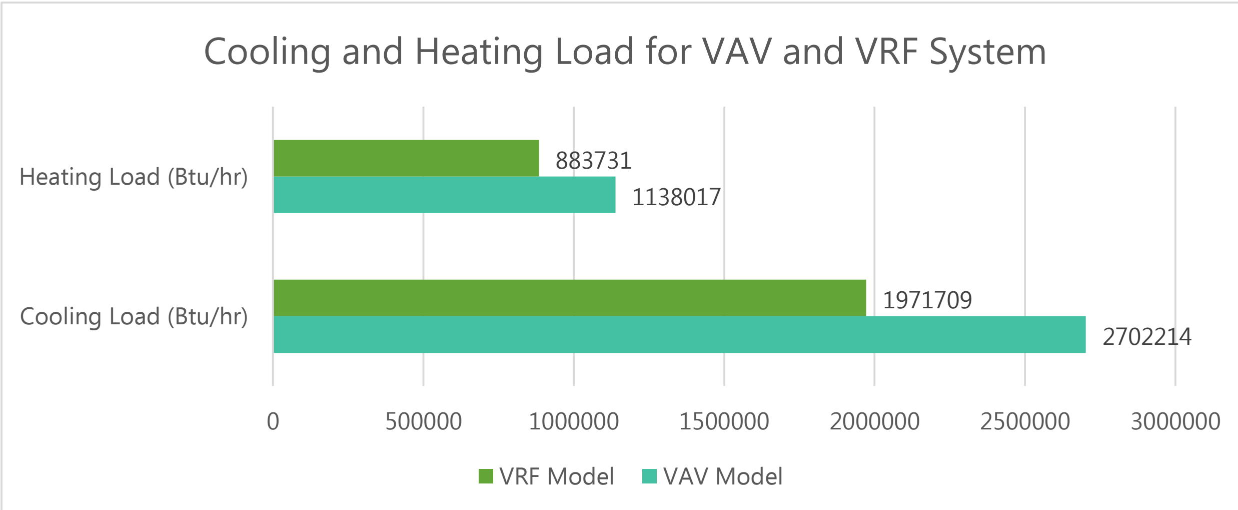
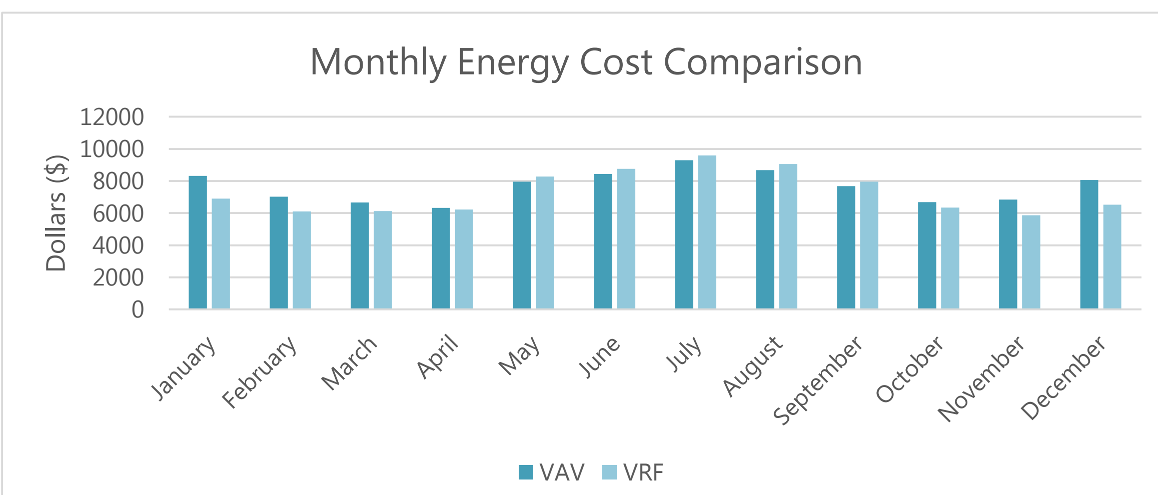


Table 9 - Comparison of VAV and VRF Systems

Alternative 1 & 2 Comparison			
	VAV	**VRF**	**%Difference**
CFM	109761	106867	2.64%
KW	1181926	1108271	6.23%
CO2 (lbm/yr)	3265014	3090651	5.34%
SO2 (gm/yr)	11672	11049	5.34%
NOX (gm/yr)	4982	4716	5.34%

Figure 10 - Monthly Energy Cost Comparison, Alternatives 1 & 2



8.7 Cost Comparison & Life Cycle Cost Analysis

In this portion, the variable air volume and variable refrigerant flow systems will be analyzed for first cost and life cycle cost. Evaluating the life cycle cost requires determining the simple payback period, benefit to cost ratio and internal rate of return. Completing the lifecycle cost analysis requires a decision about the length of the system's life and its discount rate. The Mitsubishi Company states that life cycle of their VRF systems at 20 years, therefore this value will be used. A commonly accepted discount rate for HVAC systems is 3% and inflation will be disregarded for this exercise.

As mentioned earlier in Section 8.2 - Equipment, the first cost for the VAV system was stated as $291,665 and for the VRF system as $332,220. These values were calculated using RS Means Mechanical Cost Data 2014. No inflation rate need be applied to this calculation because the estimates for the cost are also from the same year. From the energy cost evaluations, the difference in yearly operating cost is $4,168. The maintenance cost was not considered in this evaluation and is assumed to be the same for both system types. From this evaluation, the simple payback period for the VRF system will be 10 years, as shown below.

$$Simple\ Payback\ Period = \frac{\Delta\, First\ Cost}{\Delta\, Annual\ Operating\ Cost} = \frac{\$40555.00}{\$4168.00} = 9.73\ \approx 10\ years$$

$$Benefit\ to\ Cost\ Ratio = \frac{Savings\ over\ Life, 20\ years\ at\ 3\%}{\Delta\, First\ Cost}$$

$$BCR = \frac{\$4168\ (^{P}/_{A}, 3, 20)}{\$40555} = \frac{\$62009.29}{\$40555} = 1.529$$

The above calculation for benefit to cost ratio shows a result of 1.529. Since this value is greater than 1, the investment in a VRF system can be determined to be cost effective. The final calculation for life cycle cost analysis is the internal rate of return. This value is the rate at which the full change in first cost will be regained over the twenty year course of the system's life.

$$\Delta\, First\ Cost = \ \Delta\, Annual\ Operating\ Cost\ (^{P}/_{A}, i, 20)$$

$$\frac{\Delta\, First\ Cost}{\Delta\, Annual\ Operating\ Cost} = (^{P}/_{A}, i, 20) = \frac{\$40555}{\$4168} = 9.73$$

This value falls between 8% and 9% rate of return. By interpolation, the internal rate of return is 8.13%. This value is higher than the discount rate which means that investing in the VRF system in the long run is a more beneficial than the conventional variable air volume system. Table 10 displays a summary of the life cycle cost estimate and all relevant data from the calculations.

Table 10 - Summary of Life Cycle Cost Estimate

Life Cycle Cost Estimate	
Delta First Cost	$ 40,555.00
Net change in annual operating cost	$ 4,168.00
Simple Payback Period	9.73
Length of life	20 years
Discount Rate	3%
Savings over life (20yrs @ 3%)	$ 62,009.29
Benefit to Cost Ratio	1.53
Is BCR Cost effective?	1.53
Internal Rate of Return	8.13%

8.8 Recommendation

A VRF system for the National Law Enforcement Museum may be beneficial in many ways. The system's operation is similar to a variable air volume system. Its cooling energy is much less than the existing mechanical system, but the total energy and utility costs differ only by 6%. The installation of the system is $40,000 more than the existing design with a payback period of nearly ten years. Positively, a variable refrigerant flow system would reduce carbon emissions by 5% and decrease the energy utilization index of the structure. While both these points would be beneficial in the long run, the extra cost for this system type is not a viable option for redesign.

9 Acoustic Breadth: Hall of Remembrance

The breadth section of the Architectural Engineering Senior Thesis is designed to show the proficiency of the student in areas outside of their designated option. This section will discuss room acoustics and how it is very important in the Hall of Remembrance.

9.1 Acoustic Design Objectives

When in a space as reverent as the Hall of Remembrance in the National Law Enforcement Museum, it is imperative to be able to hear and understand one's family member or tour guide, yet the sound cannot linger and disturb the other guests within the space. Reverberation time, a quality affecting sound and speech intelligibility, must be controlled in this space. Reverberation time (RT) is defined as "the time it takes for sound to decay to 60 dB." It is a function of the sound absorptive quality of the room, its volume and a constant related to the speed of sound.

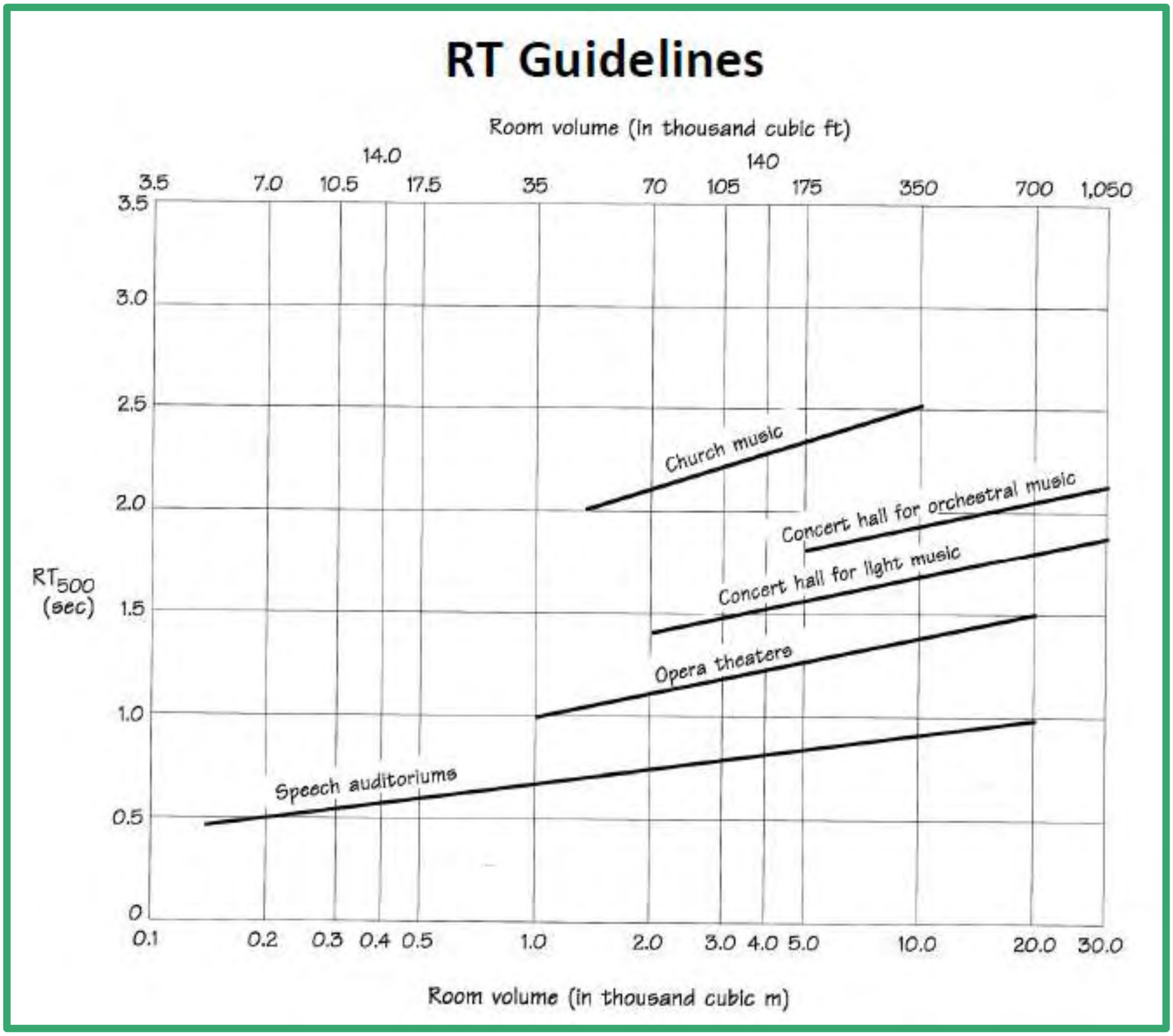
The concept of reverberation time was first discovered by Wallace Clement Sabine in the late nineteenth century at Harvard University. His equation for calculating RT, the Sabine Equation, is most accurate when the average absorption value of a space is less than 0.2. Another equation, the Norris-Eyring Equation, is better suited for absorption values greater than or equal to 0.2. Reverberation time varies from frequency to frequency and therefore the calculations to get a result must be done for each band from 125-4000 hertz. The equations for imperial units are as follows:

$$Sabine\ Equation: RT = \frac{0.049V}{S_{tot}\bar{\alpha}\ + 4mV}$$

$$Norris - Eyring\ Equation: RT = \frac{0.049V}{-S_{tot}\ ln(1-\bar{\alpha}) + 4mV}$$

The ideal reverberation time for spaces are arbitrary but guidelines have been created by professionals in the industry after years of experience. The baseline is from the reverberation time for sounds in the 500 hertz band. A sample of reverberation time guidelines is shown in Figure 11. This aspect of the interior design is important to the Hall of Remembrance in particular because it combines the display of a memorial wall of fallen officers with other audio and visual media. Every aspect of the space must be able to be enjoyed without interference from other noise sources.

Figure 11 - Reverberation Time Guidelines from *Architectural Acoustics: Principles & Design*



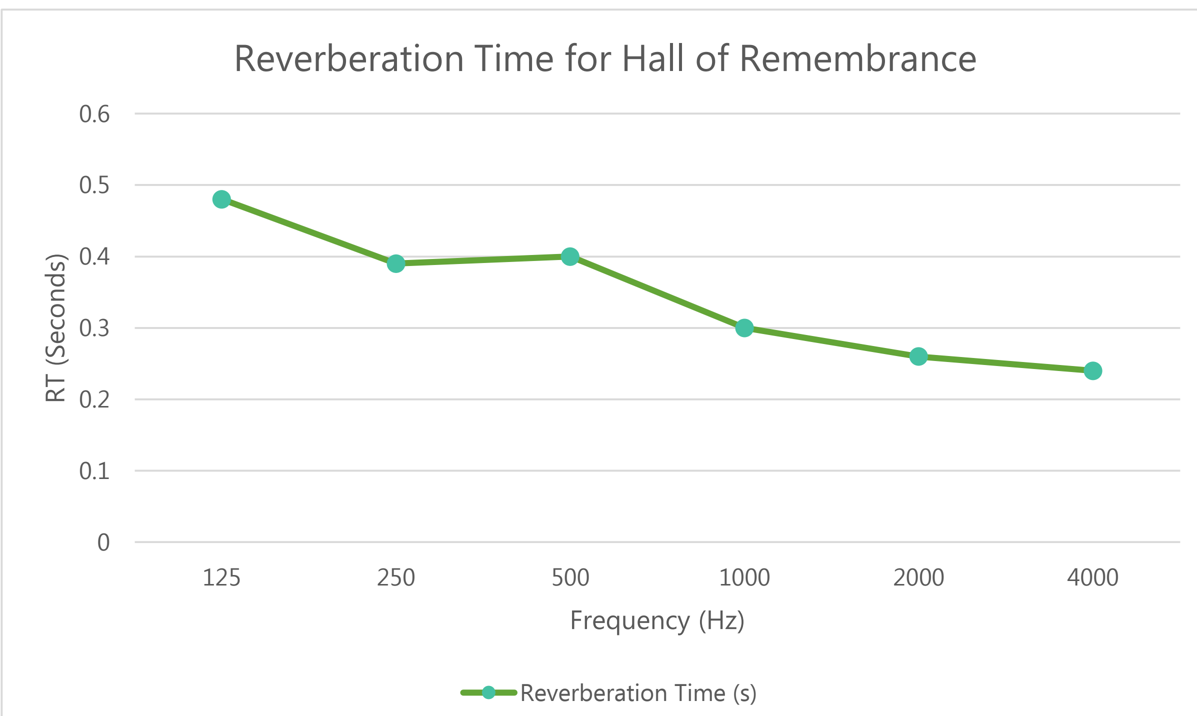
9.2 Calculating Reverberation Time

The first step to calculating reverberation time is gathering the absorption data for the space. This involves determining material types, their absorption coefficients, and what their surface area is. These values are then put into a table and their reverberation times calculated depending upon the average absorption of each frequency. The calculation table can be seen in Appendix G – Acoustic Reverberation Time Calculation. The results show that the RT at 500 hertz is 0.4 seconds. Figure 12 displays the RT at each octave band. It shows that the longest reverberation time to occur at the lowest frequencies.

9.3 Recommendation

Analysis of the figures and calculations represented in Section 9.2 show that the reverberation time in the Hall of Remembrance falls within the guideline requirements for a space where speech is very important. From this, it can be concluded that the existing interior design for the space is more than adequate for the task at hand. Should the National Law Enforcement Museum wish to reduce the reverberation time in the lower frequencies, the application of a thicker carpet flooring is recommended. Footfalls are the most prominent form of low frequency noise in buildings. The addition of more plush carpet will reduce the noise there and lower that frequency's reverberation time.

Figure 12 - Acoustic Breadth, Reverberation Time per Octave Band



10 Daylighting Breadth: Pavilion Façade Redesign

10.1 Daylighting Design Objectives

According to the architects at Davis Buckley Architects & Planners, the goal of the National Law Enforcement Museum is to "minimize intrusion into the square" by putting the museum underground. The two glass entrance pavilions are "strong and elegant" objects that "respectfully respond to the heavier mass of the historic streetscape". This design ultimately creates a "strong, contemporary image for the museum."

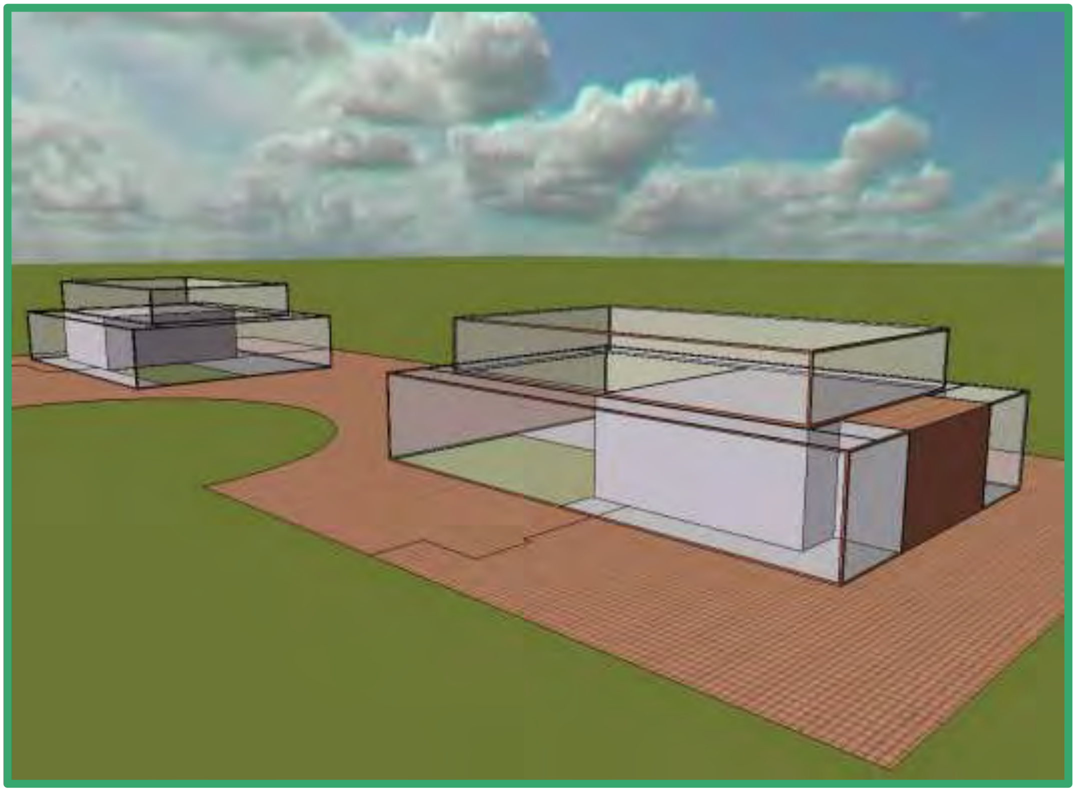
Unfortunately, this large amount of glass puts a strain on the building environmental control system. Per the energy model analyzed in Section 0, 42% of the cooling load is directly solar gain from the pavilions. However, these glass pavilions may be helpful for daylighting spaces. In this section, the existing design for the pavilions will be analyzed to whether the structure positively affects the lighting load of the building. The daylight must reach 100 lux on the horizontal surfaces within the space to meet the guidelines for building entry lobbies as outlined in the Lighting Handbook published by the I Illuminating Engineering Society of North America.

10.2 Modeling with IES Virtual Environment

Daylighting will be analyzed using the program IES Virtual Environment. This software has multiple capabilities from creating a model of the building, specifying construction properties, calculating cooling load, natural ventilation and mapping daylight infiltration. The final task can be completed using the subprogram RadienceIES. The base date for the analysis will be fall equinox, September 21 at noon.

First the model was created in the ModelIT subprogram. However only the glass pavilions and the ticketing level were modeled. This is because the daylight infiltration to the exhibit level is assumed to be very low and therefore outside this analysis. The program is unable to create the curved structure of the pavilions so the upper area had to be approximated. Figure 13 shows what the program is using to analyze the daylight. The green spaces within the structure are holes to the level below. This model is very rudimentary but is adequate for the simple analysis being conducted.

Figure 13 - Image of Model from IES VE



10.3 Daylighting Analysis & Recommendation

The results of the daylighting analysis are shown in Figure 27 - Daylight Gradient on Ground Level and Figure 28 - Daylight Gradient on Ticketing Level located in Appendix H – Daylighting Analysis Results. On the ground level, most of the spaces are very bright, upwards of 400 lux in the main entry areas. The Eisenhower Research Center is the only not lobby area with daylight infiltration on the ground floor. Because the window in the space faces the west, some daylight infiltrates but not enough to validate daylight sensors. Daylight form the level above infiltrates into the lower area and spreads very widely into the ticketing space. The lower areas have daylight infiltration ranging from 0-425 lux. However, this only affects a small portion of the floor.

From the analysis above, the entry lobby, exit lobby, ticketing area, and the area around the gift show will benefit from having daylight controls. This will likely reduce the lighting load from those areas throughout the day, particularly in the summer when there is more light.

11 CONCLUSION

This document discussed the mechanical system of the National Law Enforcement Museum, to be constructed in Washington, DC. The beginning of the document discussed the building, its architecture and mechanical system. These sections particularly analyze the existing system in depth discussing the modeling process, energy results and other elements. The final portion details a proposed redesign for the building and leads into the mechanical depth of the thesis.

The first depth topic is modifying the façade to reduce the loads to the building. The analysis suggested that changing the existing glass type to a model that has a higher U-value and fritted to reduce the load on the building would be beneficial to the design. The second depth topic was a redesign of the mechanical system as a variable fluid flow system. Energy models and cost analyses show a significant difference between the existing variable air volume system and the proposed VRF system. The reduced energy with the benefits of reduced cost over the life of the equipment is beneficial, however because of the extra cost of the VRF system it is not recommended to change the mechanical system to a variable fluid flow system.

The final portion of this thesis are breadth topics demonstrating a width of knowledge. First, the room acoustics of the Hall of Remembrance is analyzed to determine whether the space has good reverberation time. This acoustic criteria is paramount for good speech intelligibility and communication. Daylighting is the second breadth topic. IES Virtual Environment, a multi-talented building energy modeling program, is used to determine daylight infiltration. This model showed that upwards of 400 lux permeates into the lobby areas and the ticketing level. It can be concluded that the building could benefit from daylighting and the utilization of sensors to reduce the overall lighting load from the fixtures.

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14 Appendix A – Mechanical System Schematics

Figure 14 - Schematic Diagram of VAV System

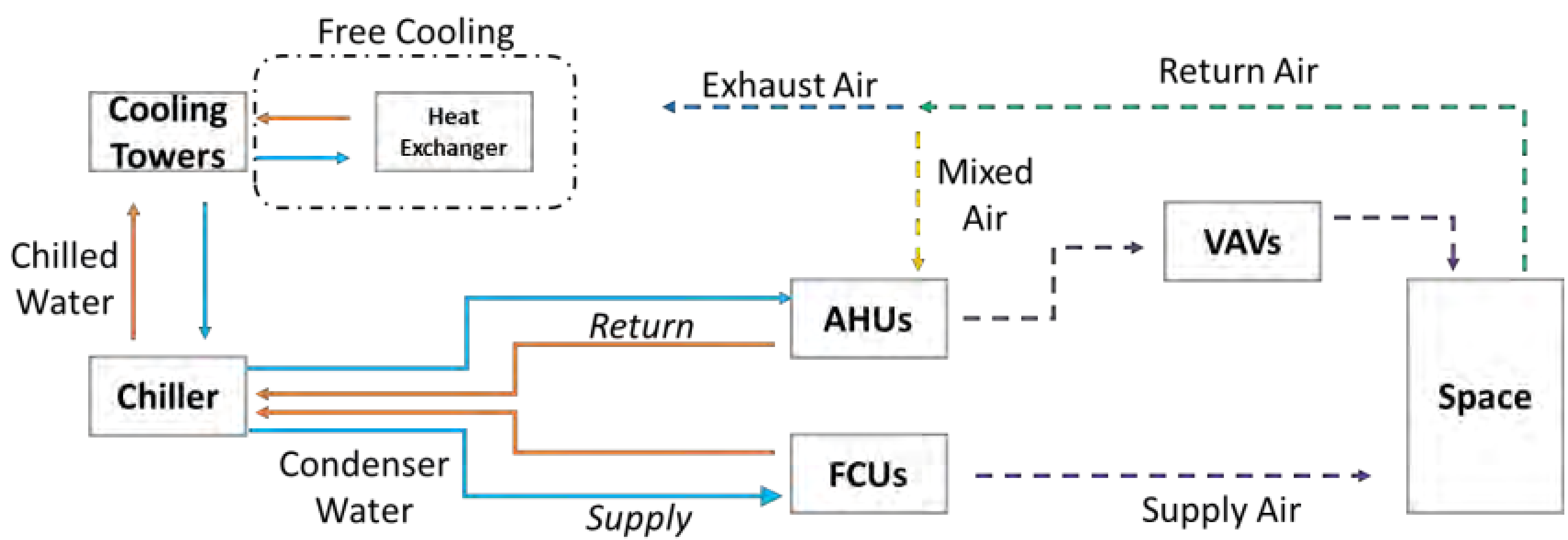
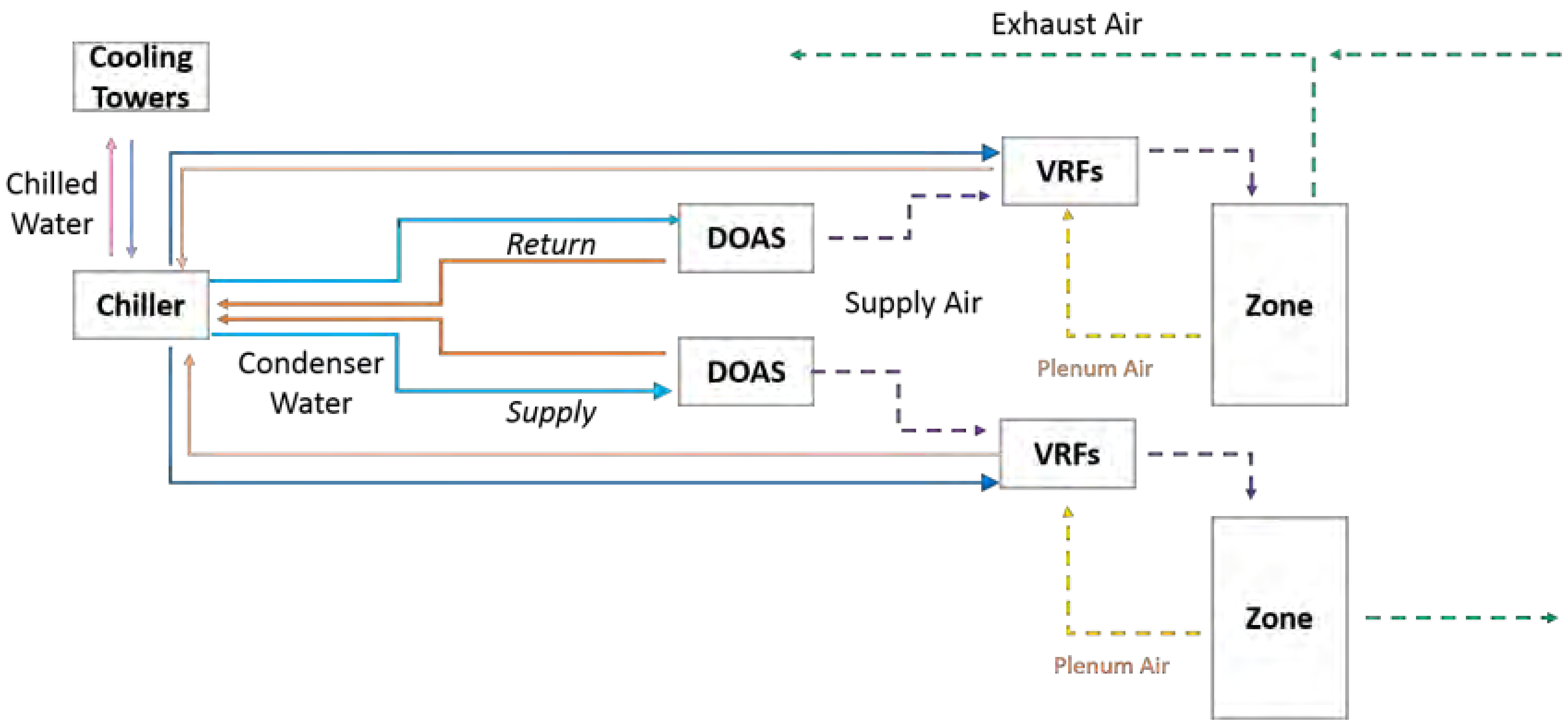


Figure 15 - Schematic Diagram of VRF System



15 Appendix B - Table of Building Heating & Cooling Load for Existing Mechanical System

Table 11 - Heating and cooling load, BTU/hr., by space

Room Name2	Cooling (Btu/hr)2	Heating (Btu/hr)3
East Mechanical Penthouse	177847	40745
West Mechanical Penthouse	177010	39454
Entry Lobby	193069	62217
Corridor	47357	18889
E. Elevator Lobby - Plaza	2749	639
Fire Control Room	2263	902
Corridor	60680	23435
Exit Lobby	195414	71452
Corridor	70885	24884
W. Elevator Lobby - Plaza	2043	475
J. Edgar Hoover Research Center	16298	9710
Mechanical	2244	512
Corridor	46767	16739
Ticket/Information Area	340900	109134
E. Elevator Lobby - Ticket	4566	2225
East Mechanical	15511	14536
Fire Pump	3405	5600
Electrical	1764	548
Emergency Generator	3336	5350
Service Elevator Lobby	6478	3156
Corridor	16051	4669
Warming Pantry	19396	1161
Janitor's Closet	587	257
Gift Shop Storage	684	2822
Mail Room	1828	532
Security Control Room	1744	507
Bridge	27279	16376
W. Elevator Lobby - Tickets	5877	2884
Corridor	8873	4354
W. TVS Lobby	22424	11675
Gift Shop	35672	33101
Gift Office	1610	460
Women's Public Restroom	2239	4714
Janitor's Closet	174	76

Room Name2	Cooling (Btu/hr)2	Heating (Btu/hr)3
Public Coats/Lockers	1297	2580
Men's Public Restroom	1348	2832
Café	35837	2439
Food Service Area	12293	2423
Admin Offices	12031	9245
West Mechanical	7847	8959
Multi-purpose	6334	4858
Closet	398	930
Staff Locker Room	705	388
Restroom	611	337
Green Room	5327	2055
Office	11866	3065
IT Closet	3012	747
Electrical Room	1695	616
Corridor	6786	1683
Corridor	5495	1363
Exhibit Support	11274	11016
Storage	543	299
Hall of Remembrance	28504	8518
AV Hall of Remembrance	1969	2474
Changing Exhibit	106913	46246
IDF-2E	349	85
Storage	204	65
W. Elev. Lobby	3391	1421
Men's Public Restroom	2039	648
Women's Public Restroom	2634	838
Janitor's Closet	174	76
Office	2319	2121
Electrical Room	1623	1221
Exhibit AV	3148	2305
Corridor	3525	859
Theater	200360	122967
Projection Room	1178	374
Storage	532	179
Theater Vestibule	3740	1941
Theater Vestibule	2312	1200
Exhibit Hall	591997	235781
E. Elev. Lobby	2850	1194
AV Room	2007	2928
Judgement Simulator	21633	13364

Room Name2	Cooling (Btu/hr)2	Heating (Btu/hr)3
Interrogation	13286	8821
Electrical Closet	1364	344
Pepco Substation	11224	13471
Low Voltage Switchgear Room	5097	7104
Building Management Controls	4254	5091
Central Plant	18506	20970
Elev 3 Control	2033	612
Elev 1 Control	1226	119
Stair 1 Plaza	2298	1007
Stair 2 Plaza	7561	6560
Stair 3 Plaza	32534	12141
Stair 4 Plaza	1021	447
Stair 5 Plaza	981	149
Stair 6 Plaza	10821	9168
Stair 7 Plaza	485	212
Stair 8 Plaza	7463	6411
Stair 9 Plaza	638	279
Stair 10 Plaza	1398	212
Stair 3 Ticket	1600	701
Stair 4 Ticket	1600	701
Stair 6 Ticket	1225	535
Stair 7 Ticket	1225	353
Stair 11 Ticket	425	186
Stair 13 Ticket	885	386
Stair 3 Exhibit	637	351
Stair 4 Exhibit	1316	725
Stair 6 Exhibit	1826	581
Stair 7 Exhibit	1181	376
Stair 12 Exhibit	1829	581
Stair 3 Plant	812	516

16 Appendix C – Tables of Monthly Building Energy Use

Figure 16 - Existing Mechanical System Monthly Energy Use, VAV System

Month	On Peak Consumption (kWh)	Off Peak Consumption (kWh)	Mid Peak Consumption (kWh)	On Peak Demand (kWh)	Off Peak Demand (kWh)	Midpeak Demand (kWh)
January	57565	38698	10180	291	174	245
February	49407	31816	8797	262	152	197
March	48504	28340	8512	243	134	147
April	47195	25588	8197	261	163	174
May	61926	29232	9773	37	214	239
June	64209	32468	10776	374	236	263
July	71205	35409	12193	395	247	278
August	66834	32548	11068	377	231	262
September	58898	29026	9375	339	208	233
October	49513	27406	8257	255	162	169
November	48123	30997	8575	255	162	177
December	55231	38027	9861	274	174	193
TOTAL	**678610**	**379555**	**115564**	**3363**	**2257**	**2577**
						1181926

Figure 17 - Redesigned Mechanical System Monthly Energy Use, VRF System

Name	On Peak Consumption (kWh)	Off Peak Consumption (kWh)	Mid Peak Consumption (kWh)	On Peak Demand (kWh)	Off Peak Demand (kWh)	Midpeak Demand (kWh)
January	49910	29822	8217	242	140	166
February	44385	26038	7256	240	139	147
March	45940	24558	7184	247	131	139
April	47320	24438	7381	278	163	181
May	64846	29761	9917	349	226	250
June	66827	33160	10804	378	246	270
July	74124	35398	1258	395	256	283
August	70124	33209	10956	379	241	269
September	61997	28914	9255	347	218	242
October	49532	23233	7131	265	160	173
November	44289	23198	6830	253	130	168
December	47813	27437	7584	234	136	144
TOTAL	**667107**	**339166**	**93773**	**3607**	**2186**	**2432**
						1108271

17 Appendix D – Material Properties

Figure 18 - Properties of Sloped or Curved Glass

Sloped/Curved Insulating Laminated Glass		
Material	Description	Thickness (in.)
Outboard Lite	clear (low iron) heat tempered, heat soaked glass with Low Emissivity Coating on Number 2 Surface, and with flat ground and polished edges	0.38
Air Space	Air	0.5
Inboard Lite x2	Clear (low iron) heat soaked glass laminated with 0.060" DuPont SentryGlass Plus structural interlayer with flat ground and polished edges	0.75
Thickness		1.69
Approximate U-Value		0.33

Figure 19 - Properties of Skylight Glass

Skylight Insulating Laminated Glass		
Material	Description	Thickness (in.)
Laminated Glass x9	clear (low iron) heat tempered, heat soaked, glass laminated with 0.060" DuPont SentryGlas Plus Edge Stability structural interlayer, flat ground edges	4.50
Thickness		1.69
Approximate U-Value		0.27

18 Appendix E – Cooling & Heating Load for Alternatives

Table 12 - Solar Gain to Cooling and Heating Load for Alternative 1, VAV System

VAV System: Alternative 1											
Name	Skylight Solar Gain Peak (Btu/hr)	Glass Solar Gain Peak (Btu/h)	Total Solar Gain Peak (Btu/h)	Total Cooling Load Peak (Btu/h)	% Cooling Load from Solar Gain	Skylight Heating Load Peak (Btu/h)	Glass Heating Load Peak (Btu/h)	Total Glass Heating Load Peak (Btu/h)	Total Heating Load Peak (Btu/h)	% Heating Load from Glass Area	CFM
AHU 1	324290	104675	428965	541747	79%	35082	52899	87981	207545	42%	31371
AHU 2	526576	174096	700672	911474	77%	61396	73022	134418	333343	40%	48414
AHU 3	0	0	0	759745	0%	0	0	0	314803	0%	21437
AHU 4	0	0	0	74911	0%	0	0	0	36360	0%	1445
AHU 5	0	0	0	209982	0%	0	0	0	128376	0%	3050
AHU 6	0	0	0	35638	0%	0	0	0	0	0%	672
FCU 1	0	0	0	16298	0%	0	0	0	9710	0%	590
FCU 3	0	0	0	2263	0%	0	0	0	902	0%	66
FCU 4	0	0	0	35837	0%	0	0	0	2439	0%	575
FCU 5	0	0	0	22424	0%	0	0	0	11675	0%	399
FCU 6	0	0	0	35672	0%	0	0	0	33101	0%	406
FCU 7	0	0	0	2007	0%	0	0	0	2928	0%	65
FCU 8	0	0	0	3148	0%	0	0	0	2305	0%	104
FCU 9	0	0	0	1226	0%	0	0	0	0	0%	49
FCU 10	0	0	0	2033	0%	0	0	0	612	0%	62
FCU 11	0	0	0	4254	0%	0	0	0	5090	0%	97
FCU 12	0	0	0	12293	0%	0	0	0	2423	0%	142
FCU 13	0	0	0	19396	0%	0	0	0	1161	0%	339
FCU 14	0	0	0	11866	0%	0	0	0	3065	0%	478
TOTAL	**850866**	**278771**	**1129637**	**2702214**	42%			**222399**	**1095838**	20%	**109761**

Table 13 - Solar Gain to Cooling and Heating Load for Alternative 2, VRF System

VRF System: Alternative 2											
Name	Skylight Solar Gain Peak (Btu/hr)	Glass Solar Gain Peak (Btu/h)	Total Solar Gain Peak (Btu/h)	Total Cooling Load Peak (Btu/h)	% Cooling Load from Solar Gain	Skylight Heating Load Peak (Btu/h)	Glass Heating Load Peak (Btu/h)	Total Glass Heating Load Peak (Btu/h)	Total Heating Load Peak (Btu/h)	% Heating Load from Glass Area	CFM
VRF 01	274830	52914	327744	349960	94%	29665	25855	55520	69153	80%	20368
VRF 02	216990	58815	275805	311922	88%	23638	27044	50682	71226	71%	14301
VRF 03	155172	104333	259505	293144	89%	17466	47035	64501	74838	86%	14754
VRF 04	0	0	0	9873	0%	0	0	0	22319	0%	443
VRF 05	0	0	0	1863	0%	0	0	0	5363	0%	84
VRF 06	0	0	0	11895	0%	0	0	0	7578	0%	736
VRF 07	0	0	0	12361	0%	0	0	0	1406	0%	350
VRF 08	209307	78567	287874	322414	89%	27713	25987	53700	74671	72%	21968
VRF 09	0	0	0	10274	0%	0	0	0	13989	0%	234
VRF 10	0	0	0	19600	0%	0	0	0	66194	0%	1311
VRF 11	0	0	0	29031	0%	0	0	0	4572	0%	716
VRF 12	0	0	0	8307	0%	0	0	0	7014	0%	443
VRF 13	0	0	0	3638	0%	0	0	0	9632	0%	163
VRF 14	0	0	0	2507	0%	0	0	0	433	0%	132
VRF 15	0	0	0	367619	0%	0	0	0	181350	0%	18904
VRF 16	0	0	0	68266	0%	0	0	0	36420	0%	3543
VRF 17	0	0	0	11763	0%	0	0	0	11780	0%	592
VRF 18	0	0	0	21565	0%	0	0	0	19017	0%	1105
VRF 19	0	0	0	10845	0%	0	0	0	7069	0%	584
VRF 20	0	0	0	15761	0%	0	0	0	4309	0%	668

VRF System: Alternative 2											
Name	Skylight Solar Gain Peak (Btu/hr)	Glass Solar Gain Peak (Btu/h)	Total Solar Gain Peak (Btu/h)	Total Cooling Load Peak (Btu/h)	% Cooling Load from Solar Gain	Skylight Heating Load Peak (Btu/h)	Glass Heating Load Peak (Btu/h)	Total Glass Heating Load Peak (Btu/h)	Total Heating Load Peak (Btu/h)	% Heating Load from Glass Area	CFM
VRF 21	0	0	0	19581	0%	0	0	0	25495	0%	772
VRF 22	0	0	0	48510	0%	0	0	0	118226	0%	3786
VRF 23	0	0	0	5688	0%	0	0	0	11858	0%	255
VRF 24	0	0	0	4765	0%	0	0	0	12844	0%	214
VRF 25	0	0	0	9835	0%	0	0	0	21975	0%	441
TOTAL	856299	294629	1150928	1971709	58%			224403	883731	26%	106867

Table 14 - Solar Gain to Cooling and Heating Load for Alternative 3, New Facade

VAV System with New Façade: Alternative 3											
Name	Skylight Solar Gain Peak (Btu/hr)	Glass Solar Gain Peak (Btu/h)	Total Solar Gain Peak (Btu/h)	Total Cooling Load Peak (Btu/h)	% Cooling Load from Solar Gain	Skylight Heating Load Peak (Btu/h)	Glass Heating Load Peak (Btu/h)	Total Glass Heating Load Peak (Btu/h)	Total Heating Load Peak (Btu/h)	% Heating Load from Glass Area	Total CFM
AHU 1	35273	56226	91499	299722	31%	5167	42889	48056	173129	28%	8695
AHU 2	35273	14579	49852	491890	10%	5050	59204	64254	283536	23%	12749
AHU 3	0	0	0	759745	0%	0	0	0	314803	0%	21437
AHU 4	0	0	0	74911	0%	0	0	0	36360	0%	1445
AHU 5	0	0	0	209982	0%	0	0	0	128376	0%	3050
AHU 6	0	0	0	35638	0%	0	0	0	0	0%	672
FCU 1	0	0	0	16298	0%	0	0	0	9710	0%	796
FCU 3	0	0	0	2263	0%	0	0	0	902	0%	91

VAV System with New Façade: Alternative 3											
Name	Skylight Solar Gain Peak (Btu/hr)	Glass Solar Gain Peak (Btu/h)	Total Solar Gain Peak (Btu/h)	Total Cooling Load Peak (Btu/h)	% Cooling Load from Solar Gain	Skylight Heating Load Peak (Btu/h)	Glass Heating Load Peak (Btu/h)	Total Glass Heating Load Peak (Btu/h)	Total Heating Load Peak (Btu/h)	% Heating Load from Glass Area	Total CFM
FCU 4	0	0	0	35837	0%	0	0	0	2439	0%	575
FCU 5	0	0	0	22424	0%	0	0	0	11675	0%	399
FCU 6	0	0	0	35672	0%	0	0	0	33101	0%	406
FCU 7	0	0	0	2007	0%	0	0	0	2928	0%	65
FCU 8	0	0	0	3148	0%	0	0	0	2305	0%	104
FCU 9	0	0	0	1226	0%	0	0	0	0	0%	49
FCU 10	0	0	0	2033	0%	0	0	0	612	0%	62
FCU 11	0	0	0	4254	0%	0	0	0	5090	0%	97
FCU 12	0	0	0	12293	0%	0	0	0	2423	0%	142
FCU 13	0	0	0	19396	0%	0	0	0	1161	0%	339
FCU 14	0	0	0	11866	0%	0	0	0	3065	0%	478
TOTAL	70546	70805	141351	2040605	7%			112310	1011615	11%	51651

19 Appendix F – Zoning for VRF Design

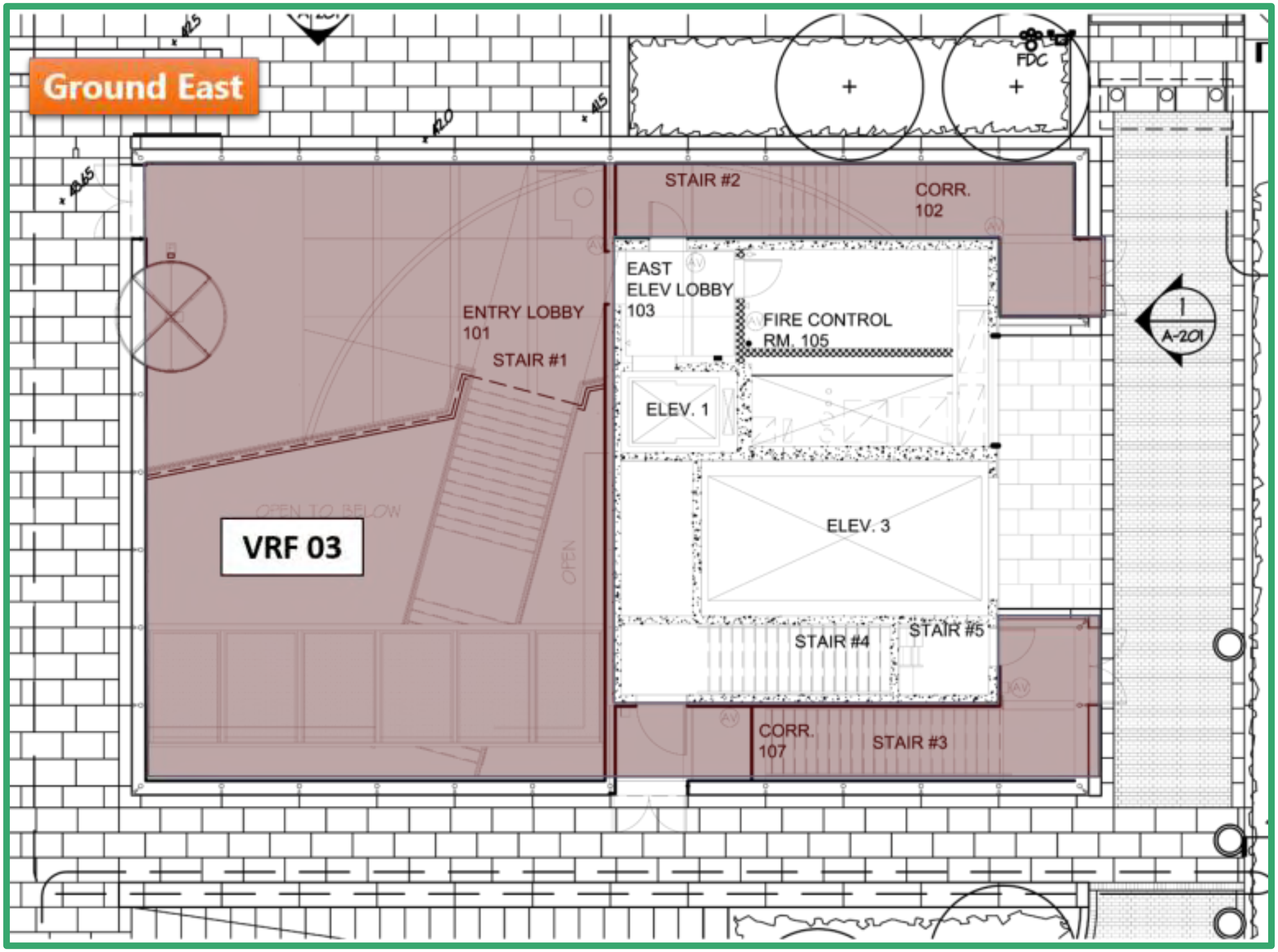


Figure 20 - VRF Zoning, Ground Level East

Figure 21- VRF Zoning, Ground Level West

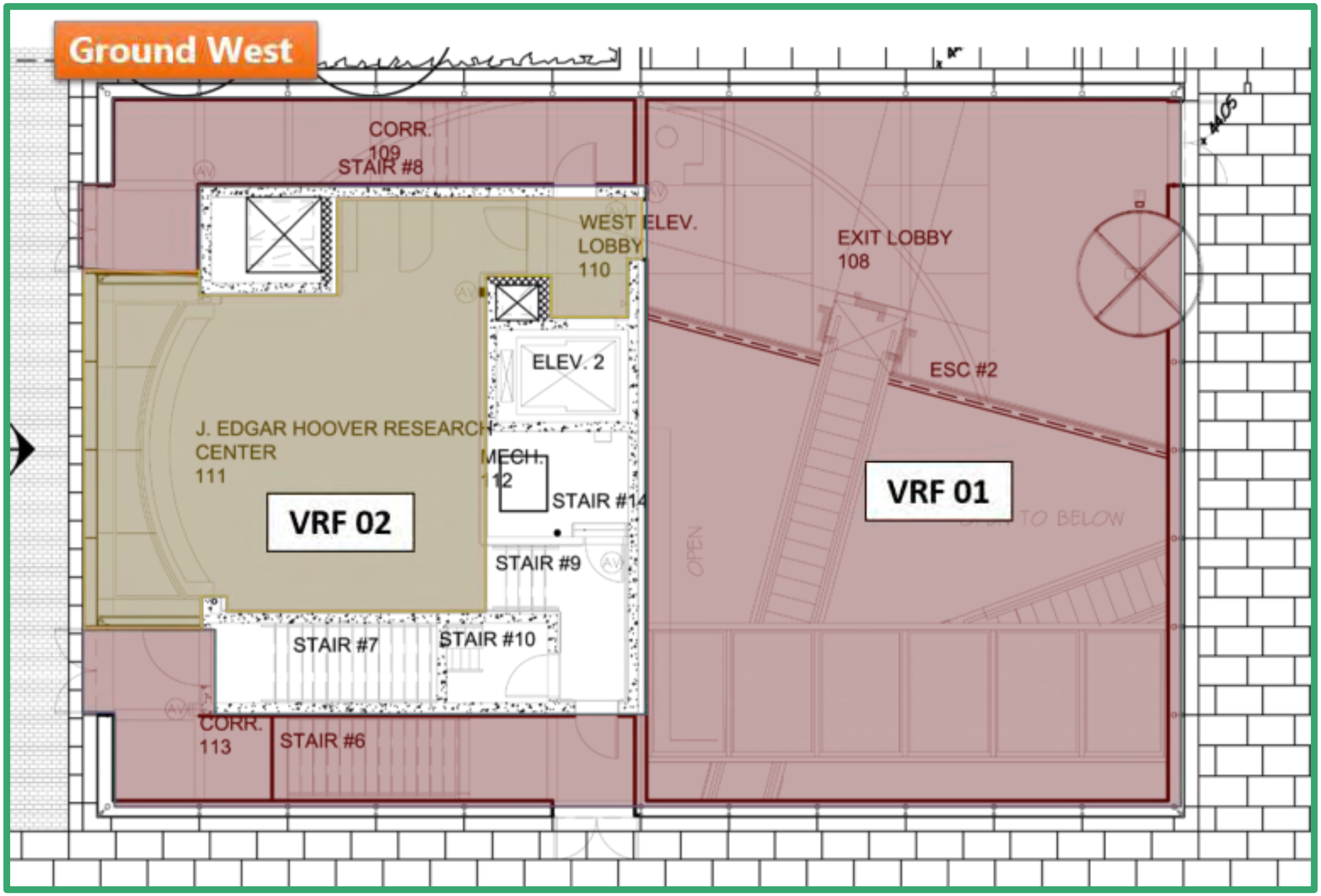


Figure 22 - VRF Zoning, Ticket Level East

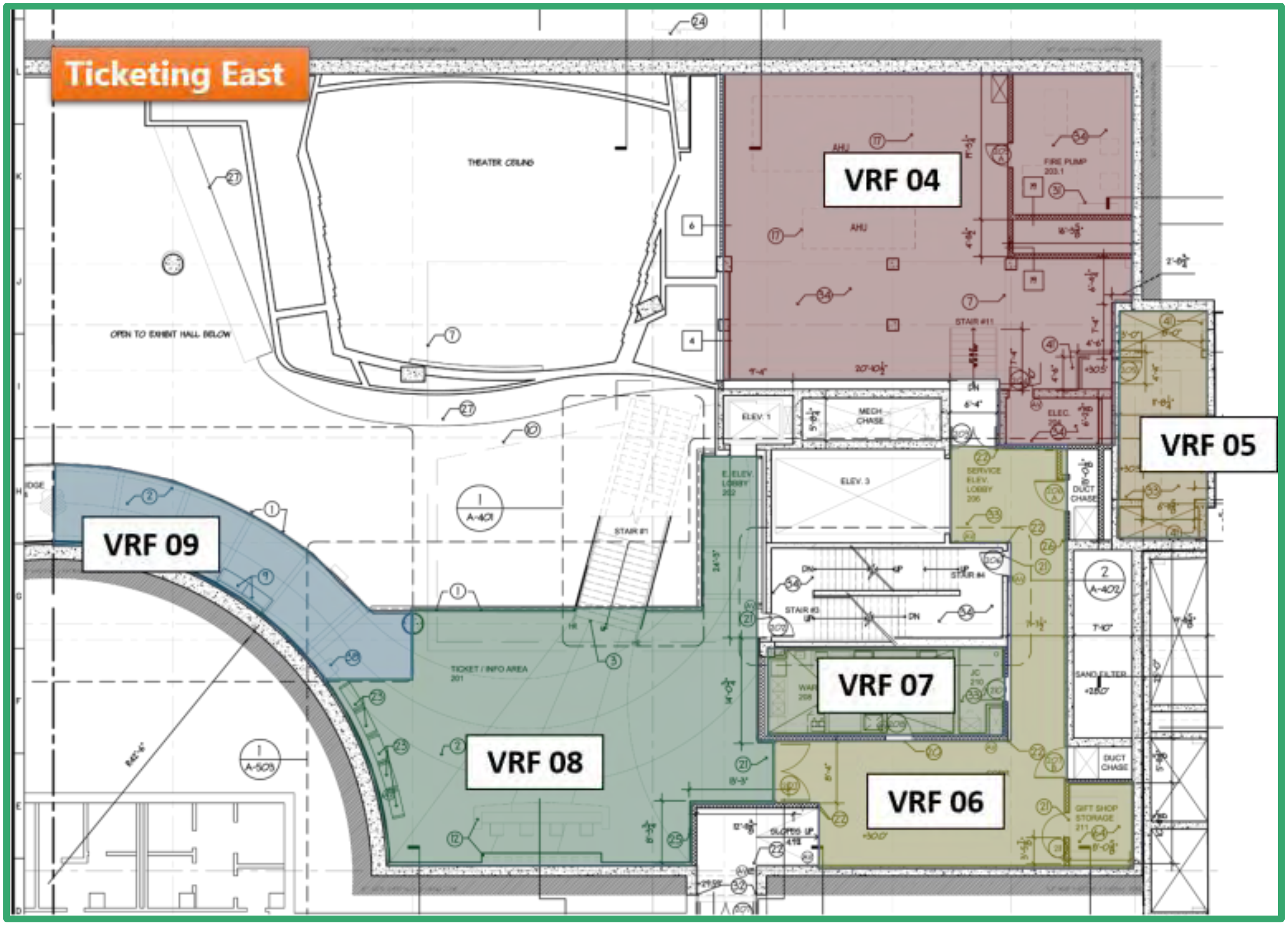


Figure 23 - VRF Zoning, Ticket Level West

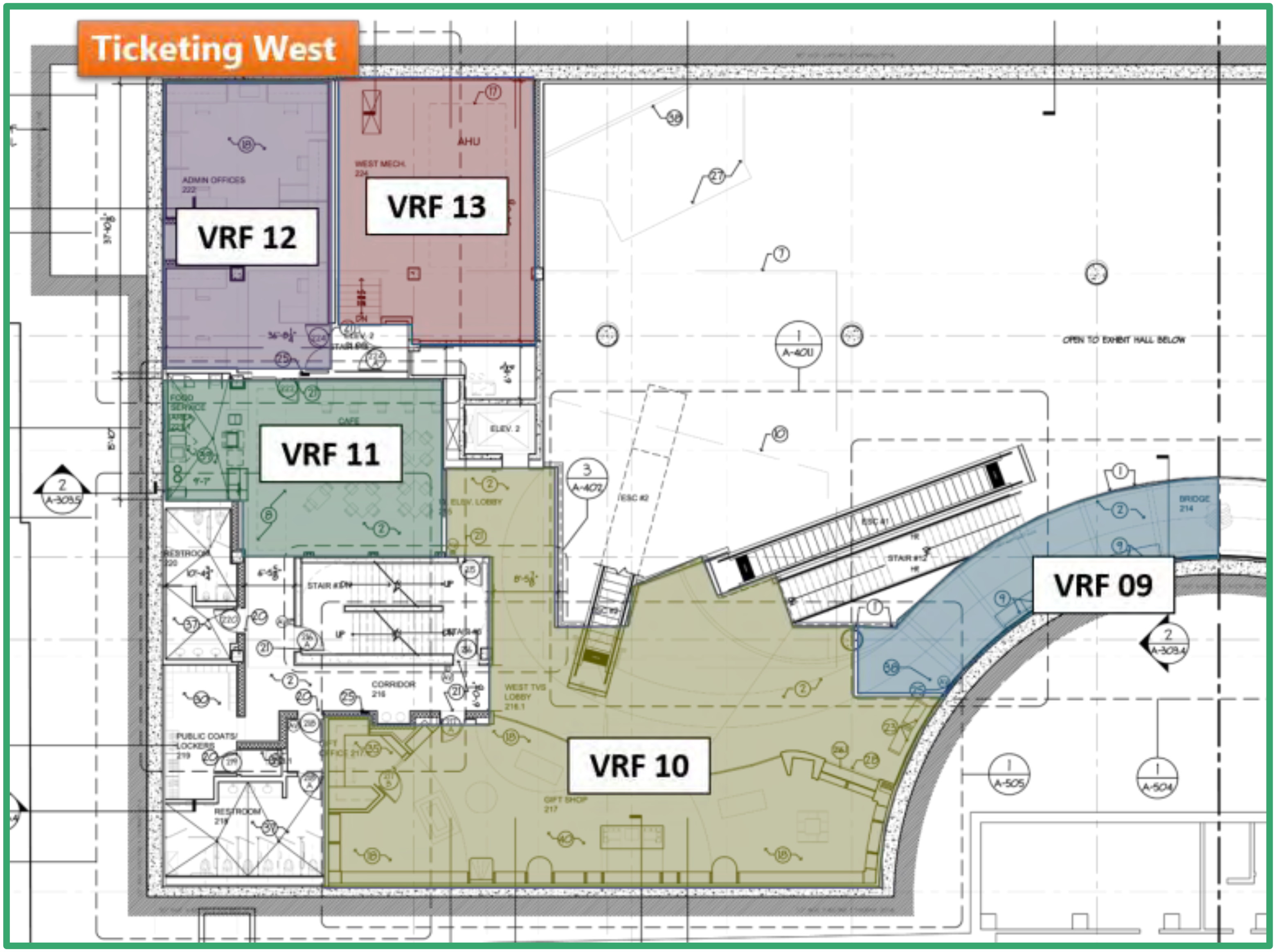


Figure 24 - VRF Zoning, Exhibit Level East

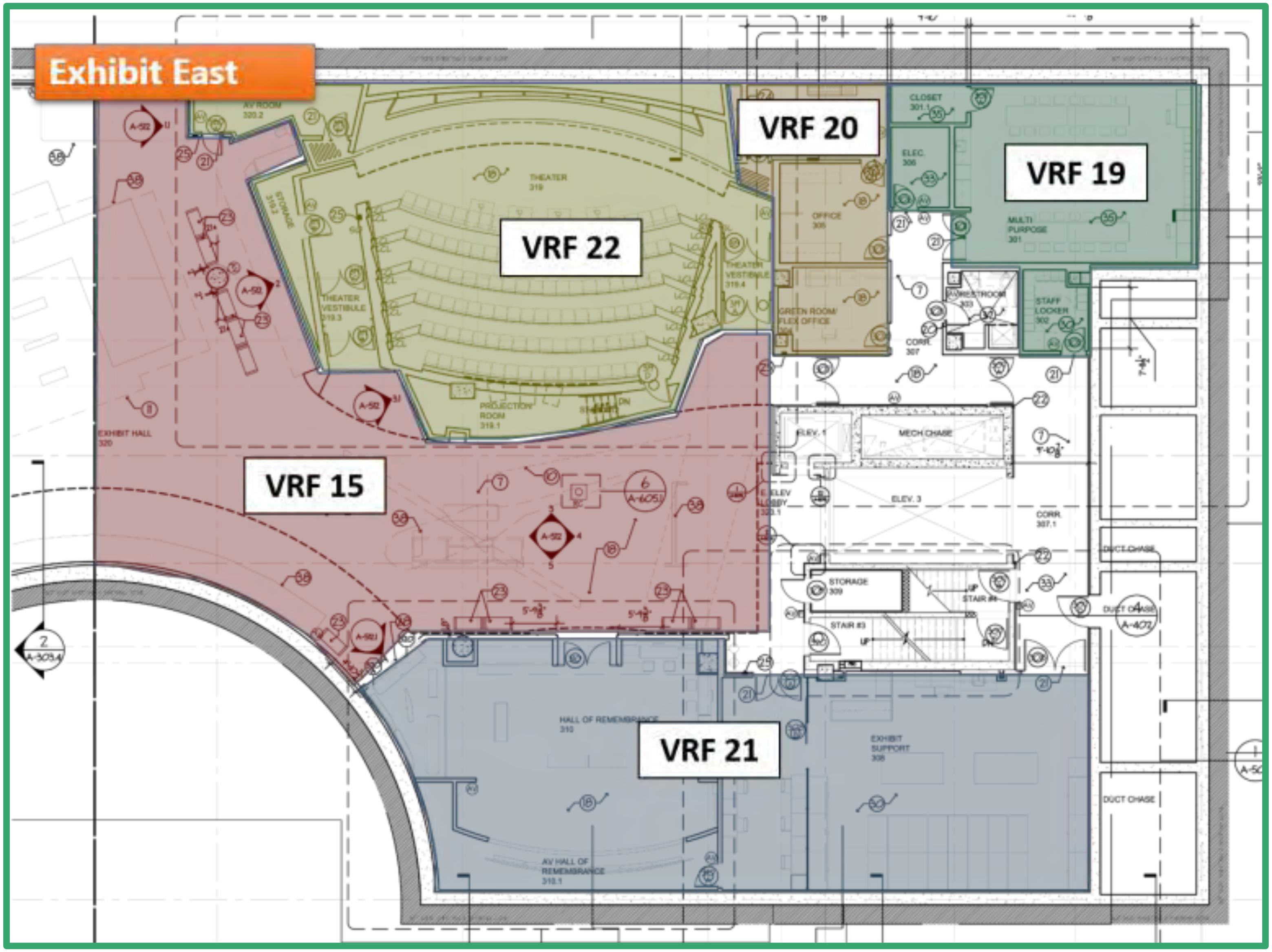


Figure 25 - VRF Zoning, Exhibit Level West

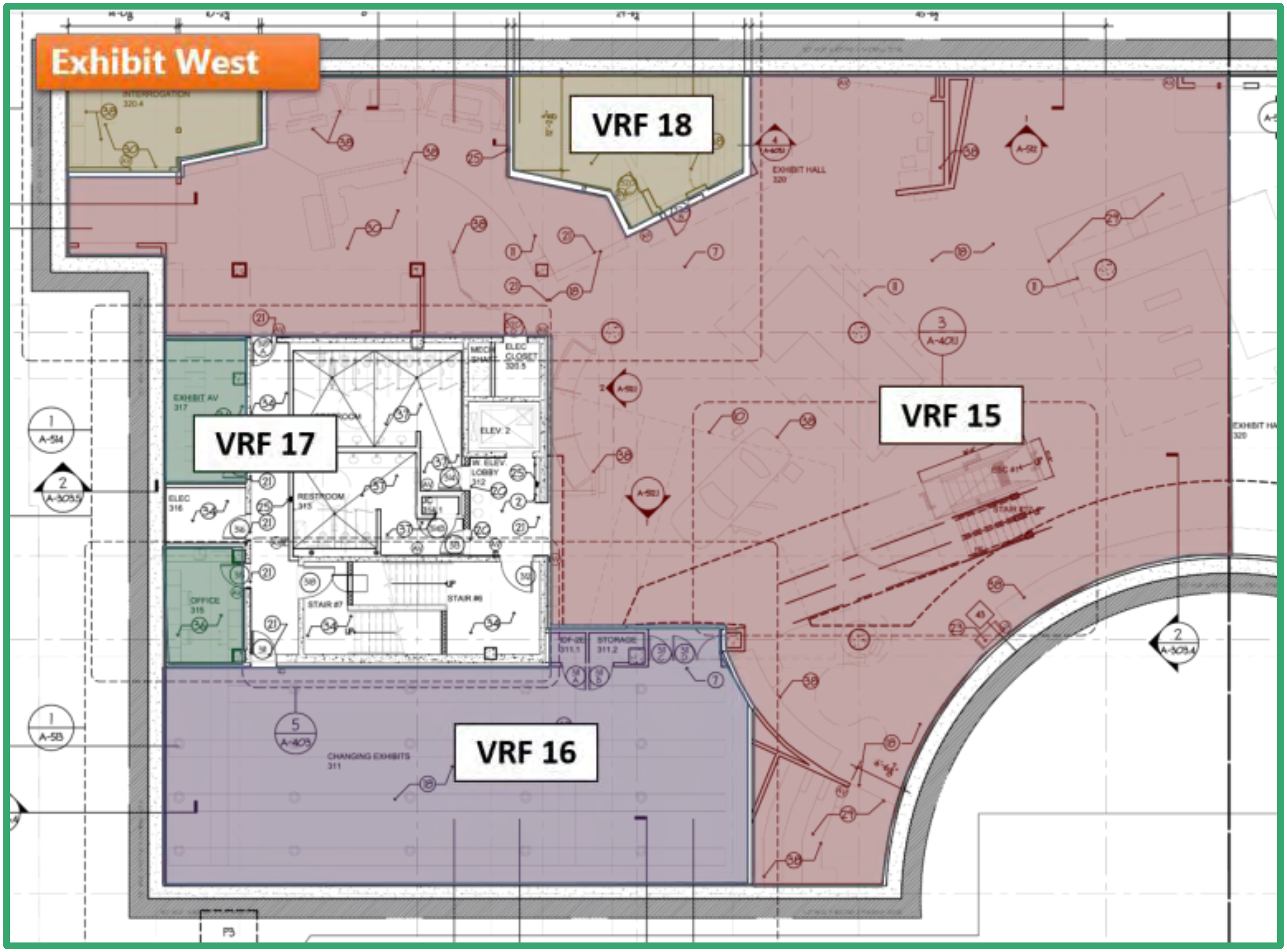
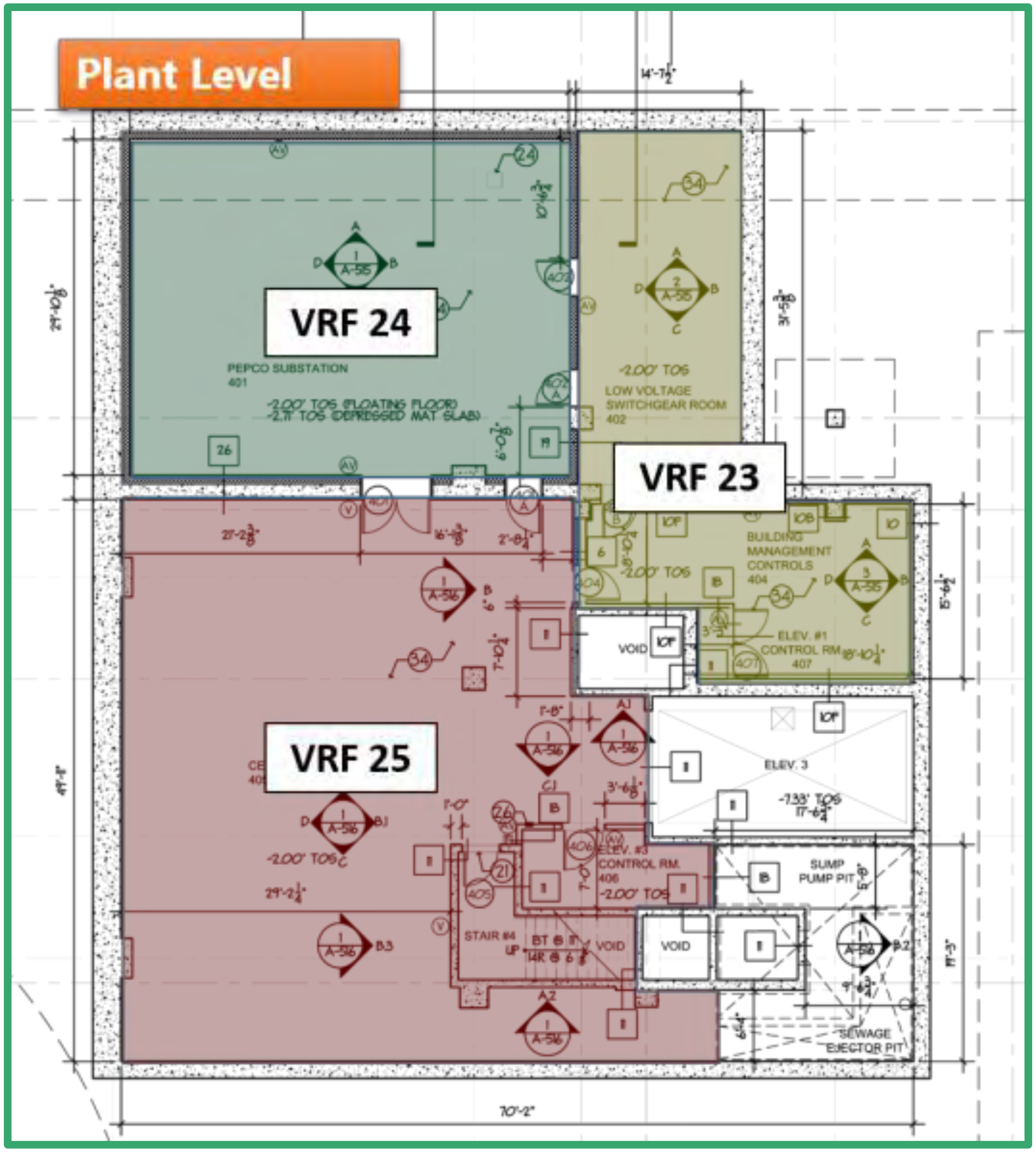


Figure 26 - VRF Zoning, Plant Level



20 Appendix G – Acoustic Reverberation Time Calculation

AE Thesis: Acoustic Breath - Original Reverberation Time Calculations for Hall of Remembrance at NLEM
(English Units)

Volume: (ft^3) V= 14691.74

Toatal Surface Area: (ft^2) S_{tot}= 4086.49

W(ft)	20.9882
L(ft)	50
H(ft)	14

Surface Description	Surface Area, S (ft^2)	Material Description	Sound Absorption Coefficient, α						S*α (sabins)					
			Frequency (Hz)						Frequency (Hz)					
			125	250	500	1000	2000	4000	125	250	500	1000	2000	4000
A	20.8958333	Glass	0.35	0.25	0.18	0.12	0.07	0.04	7.313542	5.223958	3.76125	2.5075	1.462708	0.835833
B	26.67	Type 37 - Metal panel wall system with 5/8" medium density fiberboard, "Z" clips, 2 layers of 5/8" GWB, 3-5/8" metal studs at 16" OC with insulation, 2 layers of 5/8" GWB	0.1	0.07	0.05	0.05	0.04	0.04	2.667	1.8669	1.3335	1.3335	1.0668	1.0668
C	35	Type 38A - Cast in place concrete wall, 3-5/8" metal studs at 16" OC, 2 layers of 5/8" GWB	0.15	0.08	0.06	0.05	0.04	0.04	5.25	2.8	2.1	1.75	1.4	1.4
D	45	Type 38A	0.15	0.08	0.06	0.05	0.04	0.04	6.75	3.6	2.7	2.25	1.8	1.8
E	35	Type 38A	0.15	0.08	0.06	0.05	0.04	0.04	5.25	2.8	2.1	1.75	1.4	1.4
F	98.02	Type 37	0.1	0.07	0.05	0.05	0.04	0.04	9.802	6.8614	4.901	4.901	3.9208	3.9208
G	35	Type 9C - 2 layers of 5/8" GWB, 3-5/8" metal studs at 16" OC with insulation, 1 layer 5/8" GWB, 1-1/2" acoustic blanket, 2x4 wood furring, 5/8" wood veneer sound board	0.19	0.53	0.81	0.91	0.94	0.98	6.65	18.55	28.35	31.85	32.9	34.3
H	42	Glass storefront-type door	0.35	0.25	0.18	0.12	0.07	0.04	14.7	10.5	7.56	5.04	2.94	1.68
I	48	Type 9C	0.19	0.53	0.81	0.91	0.94	0.98	9.12	25.44	38.88	43.68	45.12	47.04
J	35	Type 9C	0.19	0.53	0.81	0.91	0.94	0.98	6.65	18.55	28.35	31.85	32.9	34.3
K	100	Type 37	0.1	0.07	0.05	0.05	0.04	0.04	10	7	5	5	4	4
L	45	Type 10B - Cast in place concrete wall, 7/8" insulation with metal studs at 16" OC, 2 layers 5/8" GWB	0.27	0.01	0.05	0.04	0.03	0.03	12.15	0.45	2.25	1.8	1.35	1.35
M	27.5	Type 10B	0.27	0.01	0.05	0.04	0.03	0.03	7.425	0.275	1.375	1.1	0.825	0.825
N	135	Type 1 - 2 layers of 5/8" GWB, 3-5/8" metal studs at 16" OC with insulation, 2 layer 5/8" GWB	0.15	0.08	0.06	0.05	0.04	0.04	20.25	10.8	8.1	6.75	5.4	5.4
O	50	Type 1	0.15	0.08	0.06	0.05	0.04	0.04	7.5	4	3	2.5	2	2
P	58.958	Type 27A - 2 layers of 5/8" GWB, 3-5/8" metal studs with insulation, 5/8" plywood, 5/8" GWB	0.22	0.08	0.05	0.04	0.03	0.03	12.97076	4.71664	2.9479	2.35832	1.76874	1.76874
Q	46	Type 1	0.15	0.08	0.06	0.05	0.04	0.04	6.9	3.68	2.76	2.3	1.84	1.84
R	512.5	Type 1	0.15	0.08	0.06	0.05	0.04	0.04	76.875	41	30.75	25.625	20.5	20.5
S	45	Type 1	0.15	0.08	0.06	0.05	0.04	0.04	6.75	3.6	2.7	2.25	1.8	1.8
T	58.95833	Type 27A	0.22	0.08	0.05	0.04	0.03	0.03	12.97083	4.716666	2.947917	2.358333	1.76875	1.76875
U	60	Type 1	0.15	0.08	0.06	0.05	0.04	0.04	9	4.8	3.6	3	2.4	2.4
V	135	Type 43	0.19	0.53	0.81	0.91	0.94	0.98	25.65	71.55	109.35	122.85	126.9	132.3
Ceiling	1216.25	Suspended GWB platforms with fiberglass	0.76	0.93	0.83	0.99	0.99	0.94	924.35	1131.113	1009.488	1204.088	1204.088	1143.275
Floor	1050	1/4" pile carpet	0.04	0.10	0.15	0.30	0.50	0.55	42	105	157.5	315	525	577.5
								∑Sα=	1248.944	1488.893	1461.804	1823.891	2024.55	2024.471

always go North, East, South, West, Ceiling, Floor

Avg. α=	0.306	0.364	0.358	0.446	0.495	0.495
Air absorption constant for 20 oC and 40% RH, m	0	0	1.83E-04	3.26E-04	7.86E-14	2.56E-03
Sabine Reverb Time: (s) *RT =*	0.59	0.49	0.5	0.4	0.36	0.34
Norris-Eyring Reverb Time: (s) *RT =*	0.48	0.39	0.4	0.3	0.26	0.24
Calculated *RT* (s)	0.48	0.39	0.4	0.3	0.26	0.24

Table 15 - Reverberation Time Calculation for Hall of Remembrance

21 Appendix H – Daylighting Analysis Results

Figure 27 - Daylight Gradient on Ground Level

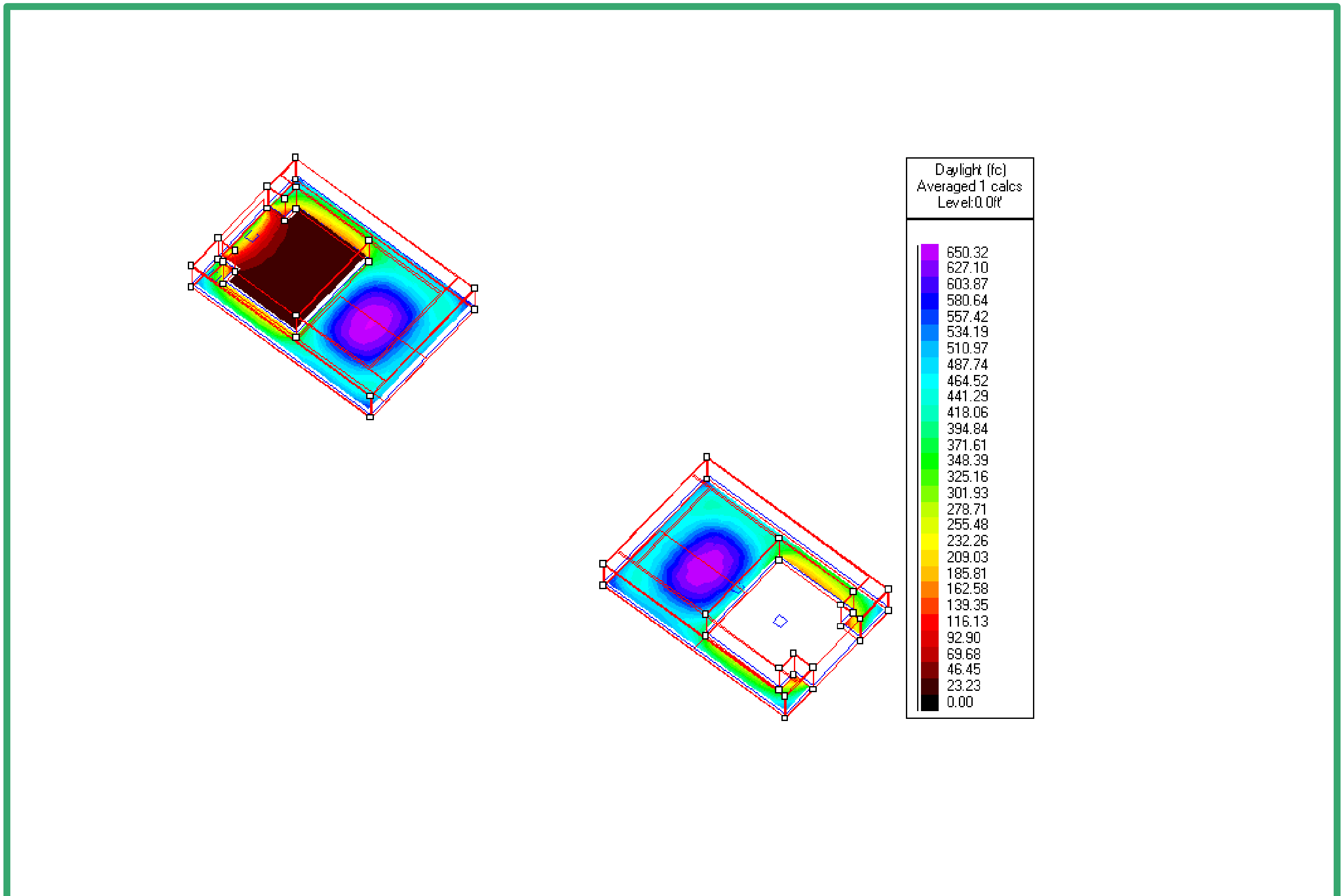


Figure 28 - Daylight Gradient on Ticketing Level