James Lee
Sorenson Language and Communication Center

Sustainable Solutions for Energy Efficiency and Acoustic Performance

AE Senior Thesis Final Report

Prepared by:

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Mechanical Option

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Special Thanks To:

PennState Architectural Engineering

SmithGroup architecture engineering interiors planning

Gallaudet University est. 1864

James Lee Sorenson Language and Communication Center

Future home of
ASL and Deaf Studies
Communication Studies
Government and History
Hearing, Speech, and Language Sciences
Linguistics
Sociology

Image courtesy of Gallaudet University

PROJECT INFORMATION

Building: 3 story office and research wing with mechanical basement and 2 story classroom wing emanate from central atrium
Size: 87,000 SF
Cost: $24,054,000 (estimated)
Completion: Late Summer 2008

ARCHITECTURAL DESIGN

- Adapts to the 'visu-centric' way of being in deaf culture
- Atrium serves as functional and symbolic heart of facility
- Enclosure primarily masonry and glass curtain walls
- Attempting to garner LEED v2.1 Certified Rating
- Colonnaded classroom wing reflects repetition of columns at historic Chapel Hall across campus green
- Features several acoustically sensitive audiology labs

MECHANICAL SYSTEM

- 6 AHUs serve distinct functional zones for indep. operation
- Each space served with a VAV terminal unit
- Steam and Chilled Water supplied from campus utilities
- VFDs and Air-side economizers reduce energy use
- Sound attenuators used on AHUs and VAVs for sensitive acoustical spaces

ELECTRICAL SYSTEM

- 2000A switchboard serves 480/277V, 3-phase, 4-wire system
- 300 kW diesel emergency generator
- Increased ambient lighting in the many video conf. rooms
- Occupancy sensors in single offices, restrooms, and storage

STRUCTURAL SYSTEM

- Concrete caissons support cast-in-place concrete grade beams and foundation walls
- Structural steel skeleton supports upper floors
- Composite floor system supported by open web trusses

PROJECT TEAM

Architects: SmithGroup (primary)
Kuhn Riddle Architects

Engineers:
MEP: SmithGroup
Structural: McMullan & Assoc.
Civil: Edwards & Kelcey
Acoustics: Cavanauch Tocci Assoc.
A/V: Technology Design Resources LLC

Construction Manager: Heery Int'l.

Specifications: Heller and Metzger, PC

Code Compliance: The Protection Engineering Group

Renderings courtesy of SmithGroup

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1. ACKNOWLEDGEMENTS

I would like to take the opportunity to thank all of those who helped me develop this thesis. Their support was instrumental in the successful completion of this learning process.

First, I thank my family and especially my parents for their support in my pursuit of a degree in Architectural Engineering. They have always supported my interests and encouraged me to be at my best. Without their help I would not have been able to come to Penn State to achieve my goals.

All of my teachers in life have helped me develop in some way towards being able to complete this work. My professors at Penn State in the Architectural Engineering Department have always shared their knowledge in order for me to become a better student and future engineer. I especially thank Dr. Jim Freihaut, Dr. Stan Mumma, and Dr. Courtney Burroughs for their time and energy to help me produce this thesis. I also thank Andreas Phelps and Paulo Cesar Tabares for sharing their expertise.

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Finally, I especially want to thank the professionals who have provided me with this thesis building. Cindy Cogil and Greg Mella at SmithGroup were tremendously helpful and graciously provided me with everything I needed to know about the Gallaudet Project. I also thank Gallaudet University for their permission to study the SLCC.

2. EXECUTIVE SUMMARY

The James Lee Sorenson Language and Communication Center (SLCC) is designed to be a one-of-a-kind facility catering to the deaf and hearing impaired community of Gallaudet University and Washington, DC. The facility is home to several departments at the university and allows collaboration and research across these disciplines. The facility is also designed with sustainability in mind as the project is pursuing a LEED Certified Rating.

This thesis analyzes the current design of the SLCC and aims to improve its energy efficiency and acoustic conditions. The proposed redesign of the facility includes replacing the current variable-air volume (VAV) mechanical system with a dedicated outdoor air system (DOAS) with passive chilled beams and installing an extensive green roof in order to achieve these goals.

The following report summarizes the analysis of the original building design and the proposed design. These analyses include an acoustic conditions report, a structural evaluation, an energy use analysis, stormwater management calculations, LEED Rating re-evaluation, and cost analysis.

The findings suggest that an extensive green roof design may be applied to the majority of the roof area of the SLCC. The roof dramatically improves acoustic insulation during peak traffic times and also reduces stormwater runoff significantly. While the green roof does not improve energy efficiency significantly compared to the original "cool roof" design, the green roof reduces building cooling loads on the top floor spaces enough to significantly reduce the number of chilled beams necessary in these spaces. The additional dead load of the saturated soil and plant material would not require any increase in structural support.

The replacement of the original variable-air volume mechanical system with a dedicated outdoor air system saves up to $25,000/yr in energy costs. This figure is increased to about $31,000/yr with the addition of the green roof. This proposed supplies 30% more outdoor air than is required by ASHRAE Standard 62.1 but does not use the air as a primary thermal transport medium. Instead, chilled water is supplied through the building to passive chilled beams which cool plenum air and carry space sensible loads. As a result, air handlers, fans, and ducts are significantly downsized and pumps and chilled water piping are significantly increased in size and number.

The final recommendation is that both the DOAS system and green roof be installed for several reasons. While there is an increased first cost of about $1.83M, the payback period is expected to be just over 4 years. Also, the proposed design does meet the intended goals for energy efficiency and acoustics. Also, the proposed design could improve the LEED Rating from "Certified" to "Silver."

3. PROJECT BACKGROUND

Gallaudet University is a prominent place of higher learning that caters to the deaf and hearing impaired. This university has served the deaf community since Congress and President Abraham Lincoln founded the college in 1864 in Northeast Washington DC. Despite its history, construction of the James Lee Sorenson Language and Communication Center (SLCC) is arguably most important building project for Gallaudet University to move into the 21st Century.

For the first time the Departments of ASL and Deaf Studies; Communication Studies; Government and History; Hearing, Speech, and Language Sciences; Linguistics; and Sociology will be housed under one roof. Research, therapy, hearing aid services, and classes within the SLCC will serve the deaf community for years to come.

Dr. I. King Jordan, President of Gallaudet University from 1988 until 2006, expressed the importance of this collaboration. He said “The idea of the building is fantastic, because that building will pull together all of the different disciplines that study deafness from all of the different points of view. We'll now be meeting each other in the hallways and the faculty lounges doing collaborative research. Nothing like that is happening anywhere in the world. And it can only happen at Gallaudet. So it's really going to change the way we do research and study deafness and understand deaf people.” (Jordan)

Dr. Jane Fernandez, chair of the building committee, expressed the design and function of the facility as “the first of its kind really in the world. It’s visu-centric architecture, which will fit the visual needs of deaf people. Also we have a variety of technology that will be incorporated into this building such as video…technology videoconferencing technology, which comes from the Sorenson Company, as well as technology in the classrooms that allow us to use videoconferencing from distant locations. Also, we have systems in place for people who use hearing aids. We also have visual media that allow deaf people to feel very comfortable in their surroundings in the new building. So we're looking forward so much to the completion of that building.” (Fernandez)

3.1. ARCHITECTURE

SmithGroup has designed the SLCC to be a postmodernist addition to the Gallaudet University Campus. Drawing on elements from the surrounding historic buildings – particularly the university's hallmark Chapel Hall – the SLCC reflects the campus in its own modern language with a two-story, colonnaded classroom wing. A prominent atrium with two main entrances serves as a beacon, gathering space, and circulation space for occupants and visitors (Figure 3.1, Figure 3.2).

Figure 3.1: Rendering of SLCC North Entrance (SmithGroup).

Figure 3.2: Rendering of SLCC Atrium (SmithGroup).

The design adapts to the "visu-centric" way of being within the deaf culture. Vibrant colors and bold text and signage direct occupants throughout the building. Perimeter walls of the atrium are configured to maximize transparency, visually connecting the atrium with the surrounding spaces. A Deaf History Time Line features prominently in the atrium exhibiting milestones within the history of deaf culture. Other elements of this "visu-centric" design include glass elevators, seating in circles, doors with transparent windows, and visual doorbells.

The facility is configured in an articulated rectangular plan arranged around a central enclosed atrium. The south and east corners of the rectangle form a three-story 'L' shaped structure housing faculty offices, computer labs, acoustically sensitive research spaces, and support spaces. The western side of the atrium features a two-story wing extending north. This portion of the SLCC houses classrooms, a media studio, conference rooms and multi-purpose spaces.

3.2. BUILDING SYSTEMS

The SLCC relies on the effective operation of its building systems to efficiently shelter occupants and allow them to function in a comfortable environment. These systems include:

3.2.1. STRUCTURAL SYSTEM

The structural system of the SLCC above grade is primarily composed of W-shape structural steel columns and beams with open web trusses. Floors above grade are constructed of composite light weight concrete floor slabs on a composite metal decking and are supported by the open web trusses. The lateral force resisting system of the SLCC is a combination of braced frames and moment connections.

The foundation system of the SLCC consists of 30 in. to 72 in. diameter concrete caissons that support perimeter grade beams. The basement floor is composed of a 6 in. reinforced concrete slab on grade, while above slabs on grade are 5 in. reinforced concrete. Foundation walls are typically 12 in. reinforced concrete walls.

3.2.2. ELECTRICAL SYSTEM

Electrical service is distributed from the utility throughout campus via the Central Utilities Building. Power for the SLCC is tapped from under the street behind the facility and directed to a 15KV-480/277V, 3 phase, 4 wire pad mounted transformer located adjacent to the new building. From here, a ductbank leads to the main electrical room in the basement and feeds a 480/277V, 3 phase, 4 wire, 2000A switchboard. Closets on each floor contain a 480V panelboard for lighting and mechanical loads, a 480-120/208V transformer, and 120/208V panelboards for receptacle loads.

Emergency power is provided by a 300KW diesel generator. 480/277V, 3 phase, 4 wire emergency power is directed to three automatic switches; one switch is for life safety loads such as fire alarms and egress lighting, one for elevator power, and one for miscellaneous emergency loads.

3.2.3. LIGHTING

The deaf community relies on visual communication much more than the hearing population. Therefore the SLCC design adapts to this "visu-centric" way of being. Lighting is notably important in this goal and the lighting design of the SLCC includes unique features to address it. For instance, all spaces without portal windows in the doors will be equipped with visual doorbells. These devices turn off lights above doorways when the doorbell is pressed to alert a deaf occupant.

Exterior lighting is intended to draw visitors towards the central atrium and to highlight the varying textures of the façade. The frequency and brightness of the lighting – from both exterior and interior illumination – increase closer to the main atrium entrances. Also, the brightest space in the SLCC is the focal atrium. Metal halide downlights illuminate the pathways leading to the entrances and metal halide in-grade grazing uplights feature the texture of the brick façade and reflectance of the zinc siding.

3.2.4. PLUMBING

One major design goal of the SLCC is to reduce water use by 30%. In order to do this, design elements include waterless urinals, dual-flush toilets, and automatic sensors on sinks. Domestic water service is provided from a street main with a backflow protection device and booster pump. A dual coil steam/electric water heater with a 225 gal capacity produces domestic hot water. All graywater drains to street sanitary sewer systems. Storm water drains directly from the roof through rain leaders inside the building and is directed to street storm drains.

3.2.5. FIRE PROTECTION

A wet pipe sprinkler system serves the occupied portions of the building. Fire alarms consist of audio horns, strobes and combination devices. An annunciator panel with building graphics and an LED screen is located at the ground level east entrance to the atrium.

Finally, three (3) 15,000 CFM atrium smoke exhaust fans are linked to the fire alarm system and evacuate smoke from the large atrium space. A negative pressure within the atrium draws air from the exterior and adjacent spaces, thus limiting a fire and smoke from spreading outside the atrium.

3.2.6. CONSTRUCTION

The SLCC will be delivered to the owners at Gallaudet University with a design-bid-build method. The project was put out for bid in September 2006 following completion of the contract documents. Protests at the campus in the Fall 2006 Semester delayed the committee’s selection of a general contractor. A contactor was selected by the end of November 2006 and the planned project completion date is now August 2008. Heery International will serve as the construction manager.

4. OVERVIEW OF MECHANICAL SYSTEM

The 87,000 SF SLCC is served by six (6) Trane M-Series Climate Changer Air Handing Units (AHUs). Each unit serves a distinct zone within the facility that is unique in use and occupation schedule. VAV terminal units with hot water reheat regulate airflow and supply air temperature to each zone. Thermal energy is delivered via chilled water and high pressure steam from the Central Utilities Building on campus.

4.1. DESIGN OBJECTIVES

The design of the SLCC was based on a balance of energy efficiency, cost, and acoustics while meeting ventilation, energy, refrigeration, and fire protection codes and standards. The mechanical system is tagged with the responsibility to effectively heat and cool the facility while meeting these requirements.

SmithGroup performed the primary architectural and MEP engineering design services for the SLCC. The design only needs to meet DC Codes as of 2006, which refer to ASHRAE Standards 15-1994, 55-1992, 62.1-1989,and 90.1-1989. However, LEED v.2.1 requires compliance with ASHRAE Standards written in 1999 and therefore the SLCC is designed to these criteria instead of DC Codes.

Some of the specific mechanical system design criteria include:

- Efficiently condition the occupied spaces within the SLCC. This includes utilizing air-side economizer, AHU zoning, occupancy sensors, etc.
- Provide adequate acoustics for sensitive spaces such as classrooms, Audiology and Hearing Science Labs, Speech and Language Sciences Labs, the Hearing Aid Fitting Room, and therapy rooms. These spaces are intended to be at or below NC-25.
- Provide adequate indoor air quality by complying with the IMC-2000 and ASHRAE Std. 62.1-1999; exhausting toilet rooms, rooms with large-format copiers and kitchens; effectively filtering outdoor air and mixed air; and maintaining positive pressurization inside the building.
- Utilize central utilities from the campus Central Utilities Building including chilled water (43°F) and steam (100 psig) to eliminate the need for redundant systems.
- Reduce power use by the equipment with the application of variable frequency drives on fan and pump motors.
- Minimize rooftop equipment for aesthetic and service-life purposes. This exposed equipment is limited to several exhaust fans on the third floor roof. All equipment is particularly restricted from installation on the second floor roof because of sightlines from the third floor atrium balcony to this area.
- Distinct zones for scheduling control of the system to isolate high density spaces and reduce overall building ventilation. This avoids a penalty required to properly ventilate the low density spaces due to the primary outdoor air fraction (Z_p).

4.2. SYSTEM ORIENTATION

The six AHUs serve distinct zones within the SLCC (Figure 4.1). The loads, occupancy schedules, and size of spaces dictated the division of zones. For instance, the Student Media Studio (AHU-2, yellow) is not occupied as often as the classrooms. When the studio is in use, though, the cooling loads required to condition a space with a high density of theatrical lighting and video equipment are much greater than those for a classroom or office. The volume of the atrium and fire codes for smoke evacuation makes isolating the atrium to its own zone (AHU-3, light blue) logical. The Hearing Clinic on the second floor operates for extended hours in relation to the offices and labs that surround it on the first and third floors. Therefore the second floor is separated into its own zone (AHU-5, red).

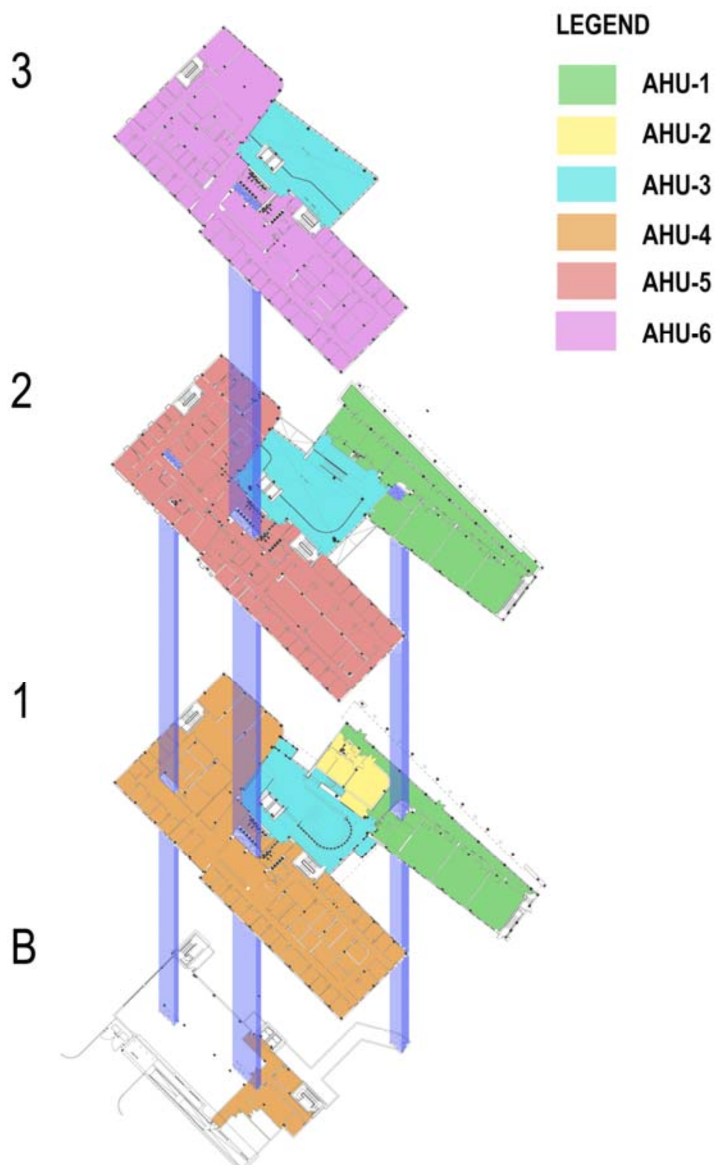


Figure 4.1: Mechanical system zones within the SLCC.

4.3. SYSTEM DESIGN & OPERATION

The mechanical system is designed to meet ASHRAE Standards 62.1-1999 and 90.1-1999 among others, supply air at the conditions described in Table 4.1, and maintain the temperature and humidity conditions described in Table 4.2. A summary of the outdoor and supply airflows for each AHU can be found in Table 4.3.

	Supply Air Conditions					
	AHU-1	AHU-2	AHU-3	AHU-4	AHU-5	AHU-6
$T_{SA, Summer}$ [°F]	55	55	55	55	55	55
$T_{SA, Winter}$ [°F]	60	55	70	55	55	60

Table 4.1: Design Supply Air Temperatures.

zone →	Design Conditions*					
	Outdoor		AHU (all)	CRAC	FCU (all)	UH (all)
	T_{DB} [°F]	T_{MCWB} [°F]	T_{RA} [°F]	T_{DB} [°F]	T_{DB} [°F]	T_{DB} [°F]
Cooling (1%)	91.9	75.3	78	72	85	-
Heating (99%)	20.2	-	72	72	85	55

* Relative humidity maintained at 50%.

Table 4.2: Design Room Air Temperature Setpoints

AHU Summary						
AHU	**# Zones / VAVs**	**Area Served [SF]**	**Design OA [CFM]**	**Design SA [CFM]**	**Capacity [CFM]**	**Unit Size***
1	19	13185	4130	17400	17700	40
2	3	1311	360	2230	2500	6
3	0	7990	2890	13070	13800	35
4	44	15285	4650	14080	13300	30
5	37	15061	4550	11965	11200	30
6	39	15146	5050	14130	13400	30
TOTALS	**142**	**67978**	**21630**	**72875**	**71900**	

* Unit Size for TRANE M-Series Climate Changer AHU

Table 4.3: AHU Summary.

4.3.1. AIRSIDE SYSTEM

The air side mechanical system of the SLCC is a traditional VAV system with reheat. Figure 4.2 includes a full schematic of the airside system. Outside air is introduced to the system through louvers at the basement level of the west façade and delivered to each of the six AHUs where it is mixed with return air. Full side economizer mode is employed in AHUs 1 and 4-6 when the outside air enthalpy is less than the return air enthalpy. Temperature, humidity, and airflow sensor inputs coordinate dampers and fans via direct digital control (DDC) panels. All AHUs use heating hot water and chilled water coils to condition the air stream to design supply conditions (Table 4.1). Each air handler also includes a pre-filter, supply fan, and primary filter.

Supply air is then distributed throughout the building through three shaft spaces (Figure 4.1, dark blue). VAV terminal units – most with hot water reheat or electric reheat – deliver the supply air to each zone via flexibly ducted ceiling diffusers. Room temperature sensors feed data to the DDC panel which modulates the VAV airflow damper. Return air is drawn into the plenum and transferred to the corridors via transfer ducts, and then drawn back to the AHU mixing boxes or exhausted by a return fan. Some spaces including toilet rooms, kitchens, and rooms with large format copiers have direct ducted exhaust to the outside to meet codes. Three 15,000 CFM exhaust fans serve the atrium space in case of a fire emergency.

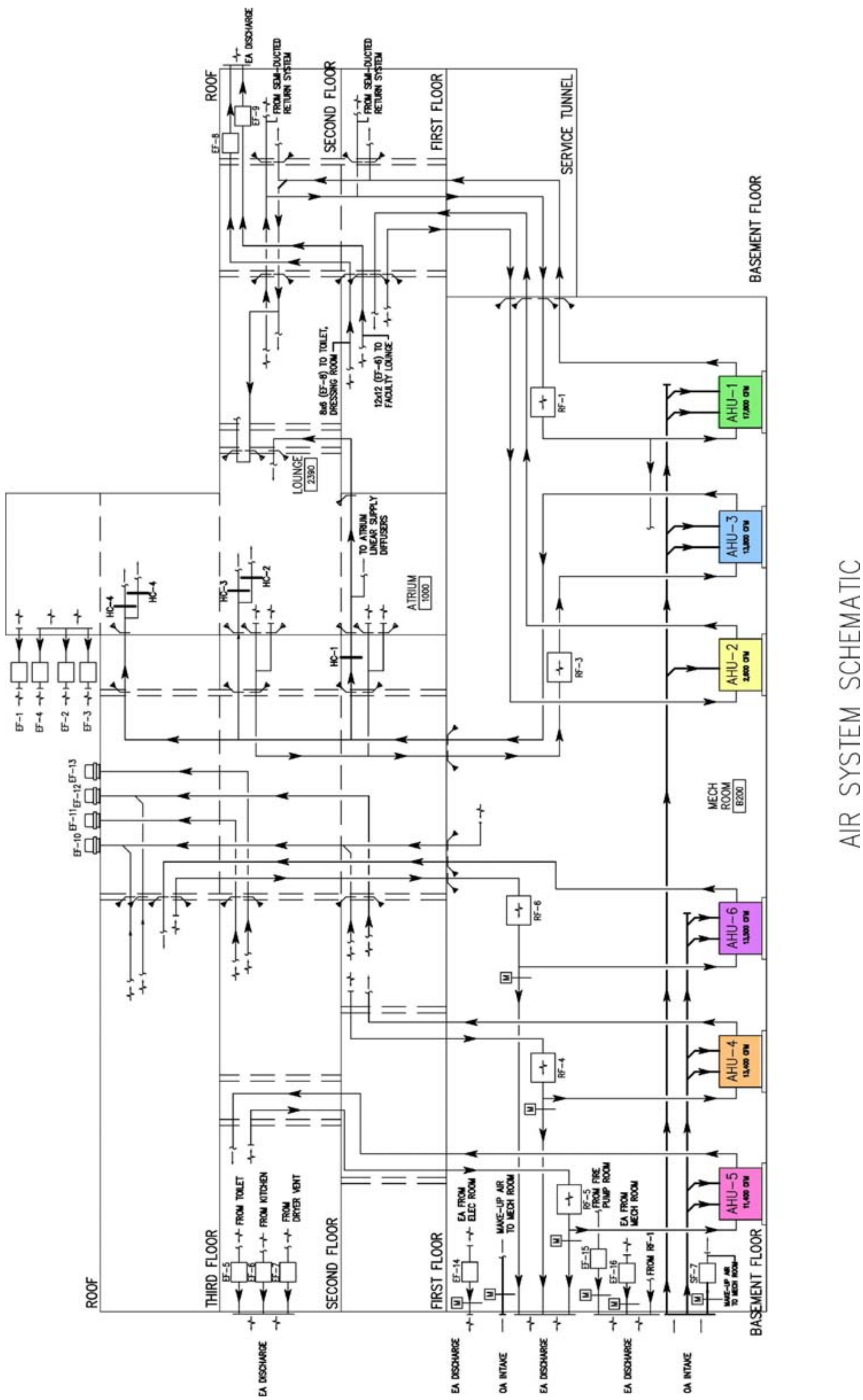


Figure 4.2: Airside System Schematic.

4.3.2. WATERSIDE SYSTEM

The Central Utilities Building at Gallaudet University serves the SLCC with chilled water at 43°F on a 10°F ΔT loop. These service lines enter and leave the facility under the east entrance and are directed to/from the mechanical equipment room (MER). Most of the mechanical piping is confined to the MER, the organization of which can be viewed in the Chilled Water Schematic (Figure 4.3).

The chilled water supply directly serves the loads in the SLCC. After passing through an air separator and expansion tank the chilled water is directed to two parallel 730 gpm pumps (one standby) each capable of producing 93 ft. w.g. of head. These pumps are enabled either manually or automatically by the DDC panel when a cooling coil needs to be used. The pumps are modulated by variable frequency drives controlled by adjustable frequency motor controller (AFMC) with input from a pressure differential sensor between the supply and return flows. The vast majority of chilled water directly serves the cooling coils in the AHUs. Less than four percent of the total flow is directed to the eight fan coil units (FCU) and computer room air conditioning (CRAC) unit. Return chilled water is directly sent back to the Central Utilities Building at 53°F.

The heating hot water (HHW) system of the SLCC is served by 100 psig high pressure steam (HPS) from the Central Utilities Building and enters and leaves the facility under the east entrance. HPS is directed to the PRV Station where the pressure is reduced from to 15 psig. This PRV Station has a capacity of 2800 lbs/hr and two valves controlling 1/3 and 2/3 of the flow each. The low pressure steam (LPS) is then directed to both the steam-to-water heat exchanger and the domestic hot water heater. These devices transfer thermal energy from the steam to the water in the system. The organization of these systems can be viewed in the Heating Hot Water Schematics 1 and 2 (Figure 4.4, Figure 4.5, respectively).

The majority of the LPS is directed to the heating hot water plate and frame heat exchanger. This heat exchanger has a capacity of 2800 MBH and serves the heating hot water coils in all AHUs, VAV HW reheat coils, HW Unit Heaters, and the CRAC unit. One of two 280 gpm pumps (one standby) is activated whenever a heating coil is in use and controlled with AFMCs. Return HHW is directed to an air separator and expansion tank because the pressure on the water is lower here. Return water is then reheated in the heat exchanger and recirculated throughout the system. Condensate from the steam side of the system is collected and pumped back to the Central Utilities Building with a condensate receiver and pump.

The domestic hot water heater uses an indirect steam-to-hot-water heat exchanger and has an auxiliary electric heater for when steam service is down for maintenance. Water stored in the tank is maintained at 140°F.

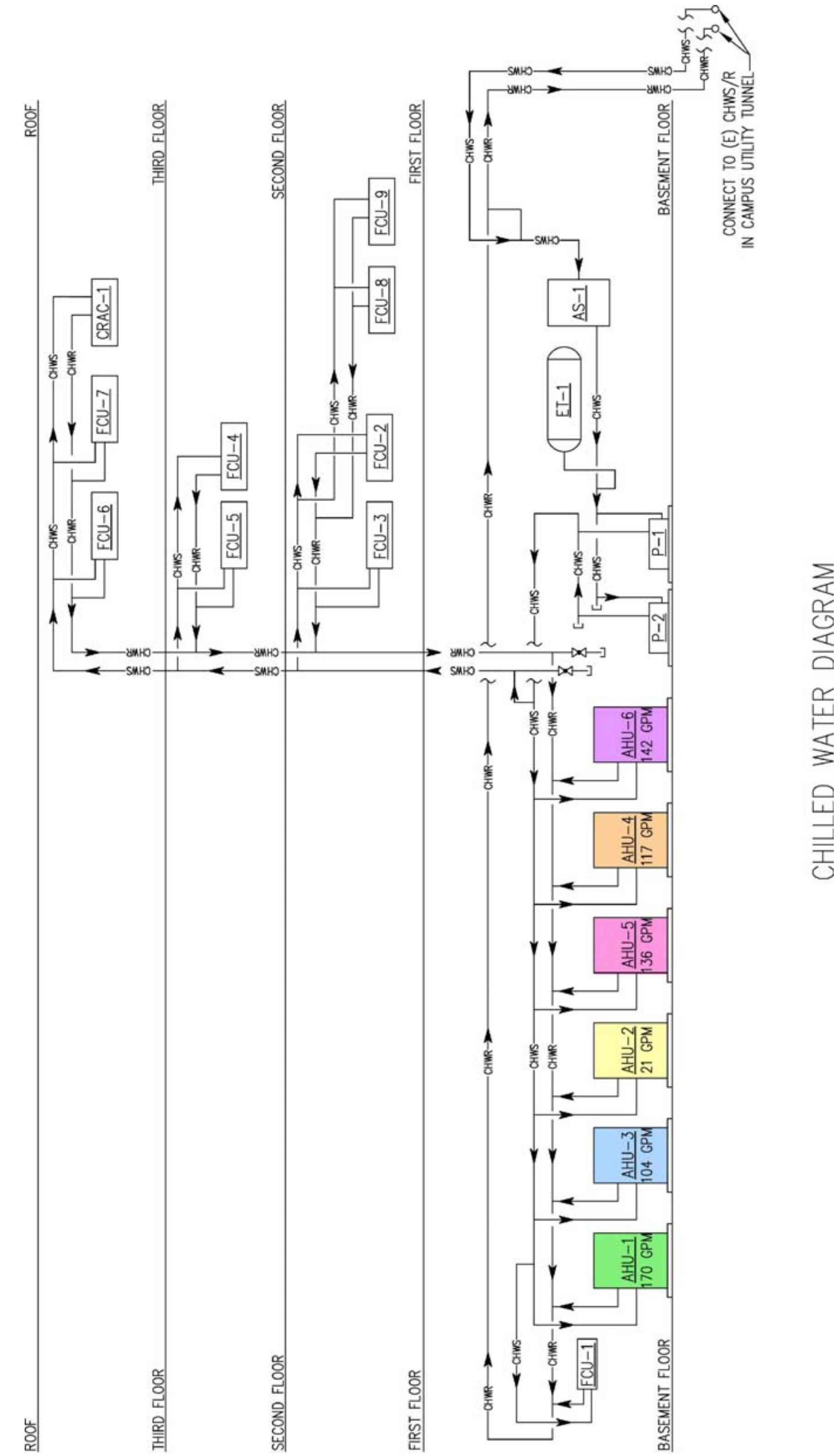


Figure 4.3: Chilled Water System Schematic

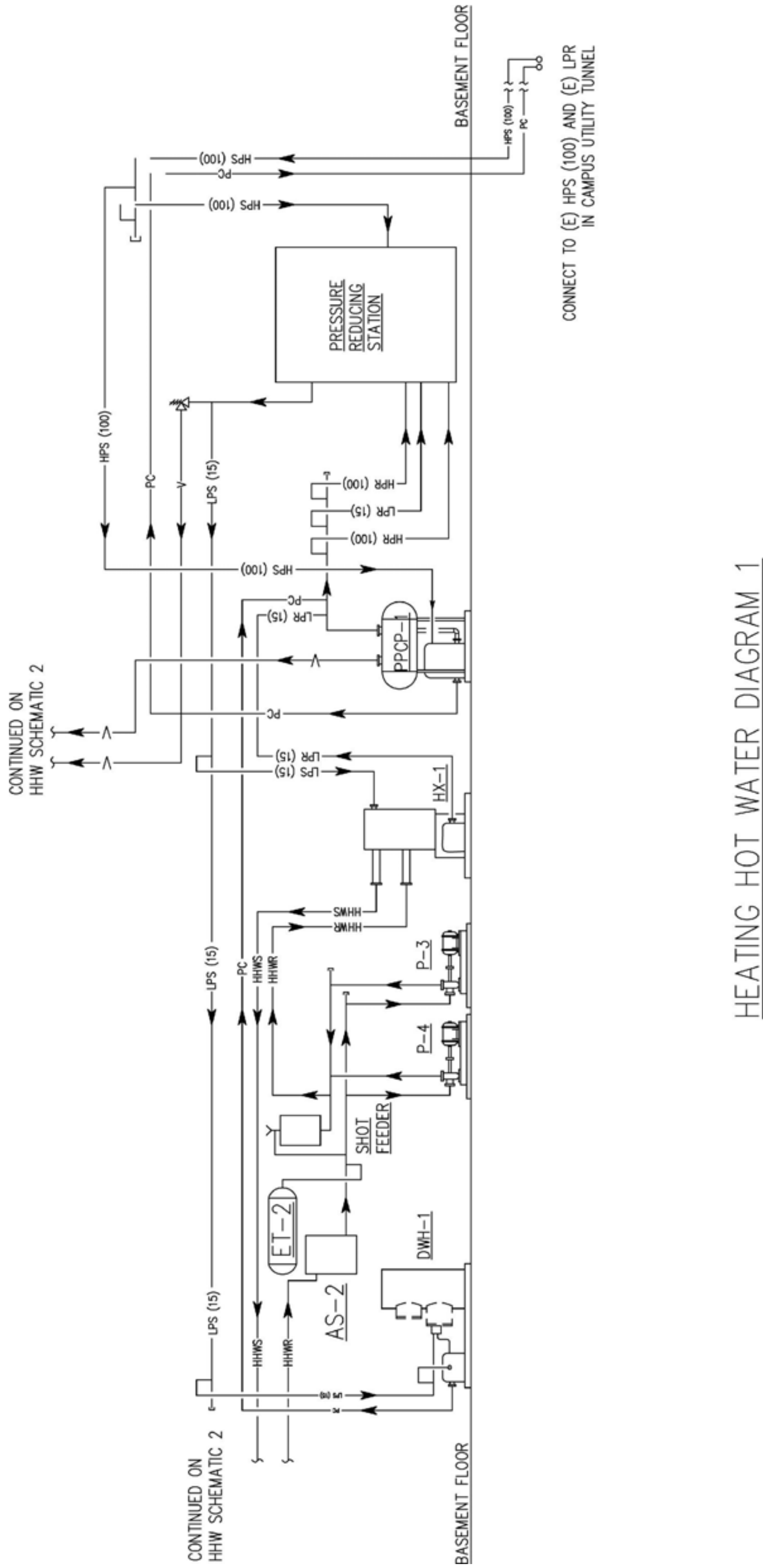


Figure 4.4: Heating Hot Water System Schematic (PRV, HX, Pumps).

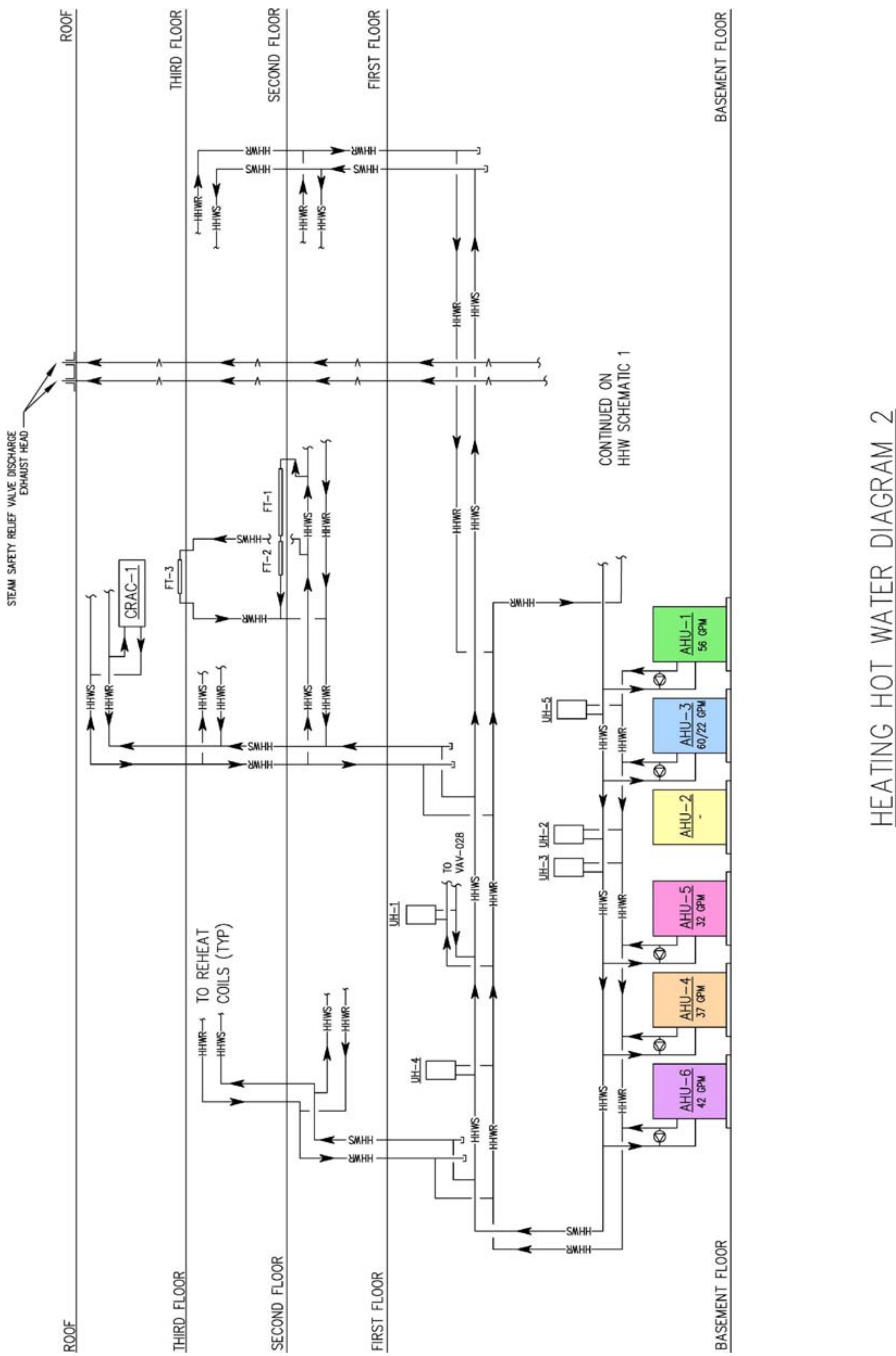


Figure 4.5: Heating Hot Water System Schematic (Distribution).

5. THESIS DESIGN PROPOSAL

The primary goals of this thesis are to improve energy efficiency and acoustic conditions for the Sorenson Language and Communication Center. In the spirit of sustainability thesis proposes designs that also reduce the impact of the facility on its surroundings. Success is defined as achieving the stated goals at a similar or reduced life cycle cost. Since the building has been designed to LEED-NC v2.1 Standards the proposed designs are be justified by improvement in the LEED Rating of the facility. Two design elements are proposed: a green roof and a dedicated outdoor air system (DOAS) with a parallel sensible cooling system.

5.1. GREEN ROOF

The first design this thesis investigates is the application of a "green roof" or garden roof. The expected benefits are building heating and cooling load reductions, increased acoustic transmission loss, and improved stormwater management. However, there may be implications on the structural support system due to the additional weight of the saturated soil and plant matter.

5.2. MECHANICAL SYSTEM

The second design proposed in this thesis is a dedicated outdoor air system (DOAS). The objective of this system is to provide each space with an appropriate supply of outdoor air to meet ASHRAE Std. 62.1 and to meet latent loads. Instead of using air as a thermal transport medium a parallel sensible cooling system in each space uses chilled water. Water has a much higher specific heat capacity and density than air so the volume of the energy transport medium is much lower.

Fan energy is expected to decrease for a DOAS system relative to a traditional VAV system, but pumping energy should increase. Airside equipment could be downsized because of reduced air flow and cooling loads. However, waterside equipment would need to be enlarged because of the increase in chilled water flow throughout the building. Radiant panels or chilled beams carry the sensible load in each space. The reduced airflow, smaller equipment, and elimination of VAV boxes could reduce mechanical noise and improve acoustic conditions in the building.

6. GREEN ROOF DESIGN

The first primary topic of this thesis is to investigate the application of a green roof to the SLCC. SmithGroup's original schematic design includes a roof terrace and garden on the second story roof; it features views of campus and the Washington city skyline beyond (Figure 6.1). Access to this space requires an extended balcony in the atrium and egress stairway at the far end of the terrace. Instead of pursuing this design, the value engineering process eliminated the roof garden; the costs of the additional structure, access, and green roofing were deemed to great for the value of this design feature. The final SLCC design includes a highly reflective "cool roof" instead (Figure 6.2).

This section investigates and compares the thermal properties of the original "cool roof" and the proposed green roof. Implications on stormwater retention and the urban heat island effect are also addressed in this section. Structural and acoustic implications are studied as breadth topics in Sections 8 and 9, respectively.

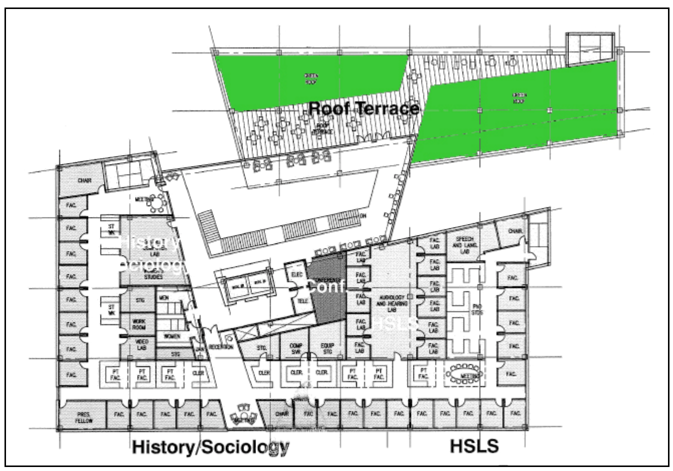


Figure 6.1: Schematic Design Phase proposal for green roof (SmithGroup).

Figure 6.2: Example of a cool roof (fypower.org).

6.1. EXISTING ROOF DESIGN

The existing roof is designed as a “cool roof” or highly reflective roof. This selection is based on reducing the heat gain through the roof and to earn a LEED point for reducing the urban heat island effect. A cool roof is essentially a typical roof with a highly reflective (white) membrane that reflects approximately 80% of incoming solar radiation. A typical roof by contrast absorbs approximately 80% of incoming solar radiation. Both roofs re-emit approximately 90%-95% of incoming infrared radiation. The net heat gain for a cool roof is thus much less with a highly reflective roof than with a traditional roof (Gaffin, et al.). See Figure 6.3 for typical material solar absorptivity and emissivity ratios. Note that the approximation for a green roof solar reflectance includes the effect of evapotranspiration.

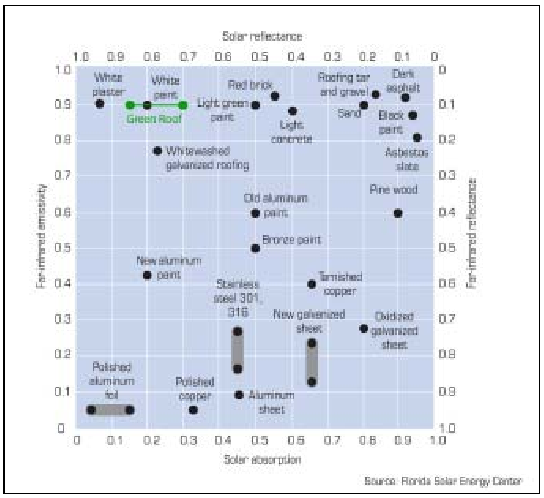


Figure 6.3: Typical material solar absorptivity and emissivity ratios (Gaffin, et al.).

The existing roof is composed of either 18GA or 20GA 1-½ in. steel roof deck, eternal gypsum board, 3in rigid insulation, cover board, and a modified bituman roof membrane with a high albedo coating (Figure 6.4).

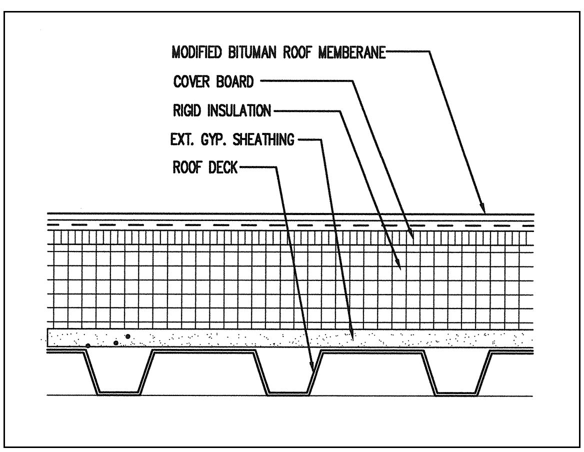


Figure 6.4: Existing roof construction (SmithGroup).

6.2. PROPOSED ROOF DESIGN

There are two fundamental forms of green roofs: intensive and extensive. Intensive green roofs typically have soil beds greater than 4in deep and larger plants that require deep root structures. Some intensive roofs even include trees, though many are only designed for grasses, flowers and small shrubs. These roofs typically require the structure to carry gravity loads of 50psf or more. Intensive green roofs also require more sophisticated drainage and irrigation systems and more frequent maintenance in comparison to extensive green roofs (United States Environmental Protection Agency).

Extensive green roofs, instead, are more utilitarian in nature. The soil on an extensive green roof is usually less than 4in deep and the plantings are typically sedums, mosses, and other plants that require shallow roof structures. These plants also need to be drought resistant in order to function all year. Extensive green roofs can sometimes be retrofitted on existing roof structures because the structure may be oversized (Gifford).

This thesis investigates the application of an extensive green roof for several reasons. The extensive green roof has positive influences on the building cooling load, stormwater management, urban heat island effect, aesthetics, and acoustics without as negative an impact on the structure and first cost.

The construction of a green roof is similar to a typical roof with the addition of drainage layer and root barrier, soil substrate, and plantings (Figure 6.5).

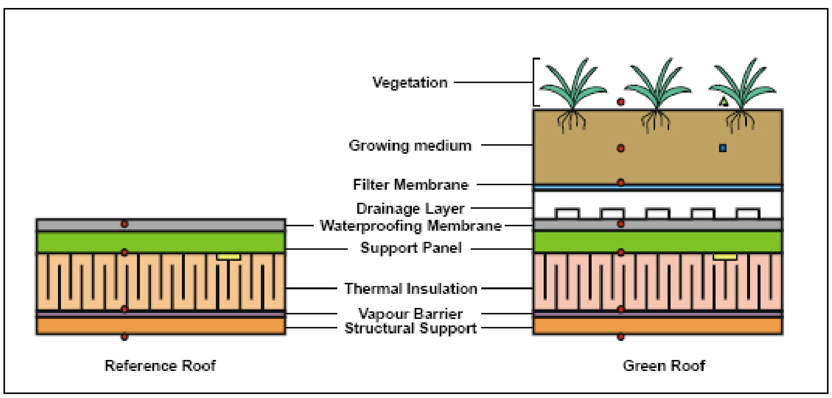


Figure 6.5: Construction of original roof and green roof.

The scope of the proposed extensive green roof includes the entire roof except for areas with access hatches and mechanical equipment (Figure 6.6). Unlike the schematic design for a roof terrace, this 24,000SF area is mostly unoccupied except for routine maintenance.

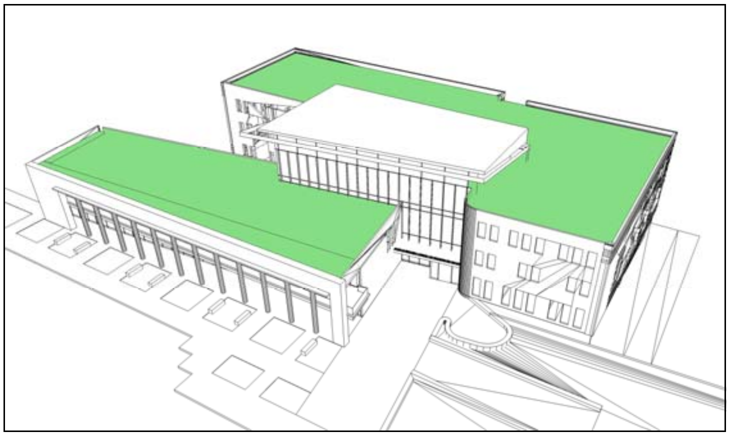


Figure 6.6: Scope of proposed green roof.

DC Greenworks is a full-service green roof design, installation, and consulting company in Washington, DC. According to their website (dcgreenworks.org) and Dawn Gifford, Executive Director of DC Greenworks, the preferred plant types for green roofs in Washington are from the *sedum* genus. These plants typically have high water retention to resist drought and require minimal maintenance.

The proposed green roof design for the SLCC consists of a 4in thick soil substrate and allows several types of plants such as the sedum kamtschaticum (Figure 6.7) – a fleshy 6in. tall plant with a midsummer bloom and high drought tolerance – to grow throughout the year (greenroofplants.com).

Figure 6.7: Sedum kamtschaticum applied to a green roof project (greenroofplants.com).

6.3. THERMAL PERFORMANCE

A green roof can have a positive influence on the thermal performance of a building. A common misconception is that the soil and plant material act as additional thermal insulation. Instead, green roofs perform a complex energy balance throughout the day. Incident and reflected solar radiation, incident and emitted infrared radiation, convective heat losses, latent heat losses (evapotranspiration), and conductive heat losses vary somewhat independently throughout the day (Figure 6.8) (Gaffin, et al.).

The evapotranspiration is what truly makes a green roof unique from other roofing options. Also, the green roof acts as a thermal mass by storing thermal energy from the day and releasing it at night.

A mathematical analysis of this energy balance finds the conductive heat gain (i.e. cooling load) on the building. The methodology and calculations for this energy balance may be found in sections 6.4 and 6.4.1.

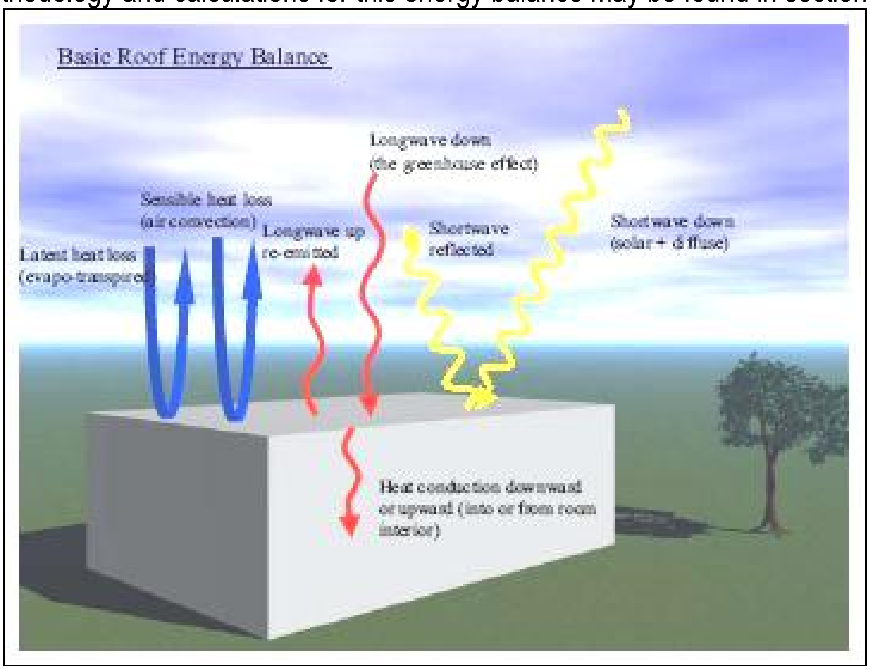


Figure 6.8: Energy balance of a green roof (Gaffin, et al.).

6.4. METHODOLOGY

An energy balance of shortwave radiation, longwave radiation, convection, latent heat loss, and conduction approximates the heat gain through the roof. This heat gain is assumed to be equal to the additional cooling load on the building mechanical system.

In order to form a more accurate model one month bins are analyzed for this energy balance per square foot of green roof space. Incident solar radiation is calculated using the clear sky model. From this, annual averages are calculated using various average weather data for each month. Then annual heat gain for the entire building is calculated using the annual average heat gain per square foot of roof area. The process is repeated for the original cool roof and for a typical roof. The following governing equations apply (Gaffin, et al.):

Solve for:	Equation	[Units]
Heat Gain (conductive)	$Q_{cond} = Q_{SW,in} - Q_{SW,out} + Q_{LW,in} - Q_{LW,out} - Q_{conv} - Q_{lat}$	$[W/m^2]$
Incident Shortwave Radiation	$Q_{SW,in} = G_b + G_d$	$[W/m^2]$
Beam Solar Radiation	$G_b = G_{on}\, \tau_b \cos(\Theta_z)$	$[W/m^2]$
Diffuse Solar Radiation	$G_d = G_{on}\, \tau_d \cos(\Theta_z)$	$[W/m^2]$
Direct Solar Radiation	$G_{on} = Gsc\, [\, 1 + 0.033 \cos(360n/365)\,]$	$[W/m^2]$
Beam Solar Transmittance	$\tau_b = a_0 + a_1 \exp[\, -k / \cos(\Theta_z)\,]$	[-]
Diffuse Solar Transmittance	$\tau_d = 0.271 - 0.294\, \tau_b$	[-]
Transmittance Coefficients	$a_0 = r_0\, [\, 0.4237 - 0.00821(6-A)^2\,]$	[-]
	$a_1 = r_1\, [\, 0.5055 - 0.00595(6.5-A)^2\,]$	[-]
	$k = r_k\, [\, 0.2711 - 0.01858(2.5-A)^2\,]$	[-]
Reflected Shortwave Radiation	$Q_{SW,in} = \alpha\, Q_{SW,in}$	$[W/m^2]$
Incident Longwave Radiation	$Q_{LW,in} = (\, 0.605 + 0.048\, e^{0.5}\,)\, \sigma\, T_{air}^4$	$[W/m^2]$
Emitted Longwave Radiation	$Q_{LW,out} = \varepsilon\, \sigma\, T_{roof}^4$	$[W/m^2]$
Convective Heat Loss (u > 1.75)	$Q_{conv} = \gamma_1\, u^{0.8} (T_{roof} - T_{air})$	$[W/m^2]$
Convective Heat Loss (u ≤ 1.75)	$Q_{conv} = \gamma_2 (T_{roof} - T_{air})$	$[W/m^2]$
Latent Heat Loss (Evapotranspiration)	$Q_{lat} = Q_{conv} / B$	$[W/m^2]$

Variable/Constant	Symbol	Value	[Units]
Zenith Angle	Θ_z	varies	[°]
Solar Constant Shortwave Radiation	Gsc	1367	[W/m^2]
Altitude above sea level	A	0.125	[km]
Albedo	α	varies	[-]
Water Vapor Pressure	e	varies	[millibars]
Stefan-Boltzman Constant	σ	5.67×10^{-8}	[W/m^2-K^4]
Emissivity	ε	varies	[-]
Convective Heat Transfer Coefficient	γ	varies	[W/m^2-K]
Average Wind Speed	u	varies	[m/s]
Bowen Ratio	B	varies	[-]

ASSUMPTIONS

- The maximum and minimum heat transfer equal the peak daily and base nightly heat gain through the roof, respectively.
- The daily profile of the net heat transfer is a sinusoidal curve between these peak and base values.
- The peak and base values are assumed to be twelve (12) hours apart, with the peak at 2:00pm for the typical and cool roof, and 4:30pm for the green roof (to account for thermal mass).
- The total conductive heat transfer through the roof is equal to the heating/cooling load on the mechanical system.
- Because the clear sky model is used, all days are assumed to have clear skies and there is no shade on the roof.
- Shortwave solar radiation at night is assumed to be 0 W/m^2.
- The roof temperatures are approximated from research results at the Penn State Center for Green Roof Research (Gaffin, et al.).
- The albedo of the green roof is assumed to be 0.25, 0.78 for the cool roof, and 0.2 for a typical roof (Nobel).
- The emissivity of all roofs is assumed to equal 0.9 (Gaffin, et al.).
- The Bowen Ratio is approximated as 0.17 (Gaffin).
- Weather data is provided from the Department of Meteorology at the University of Utah.

6.4.1. CALCULATIONS

Beam (G_b) and diffuse (G_d) incident solar shortwave radiation calculated using the clear sky model for each month can be seen in Table 6.1. The energy balance of the green roof required input data for the site conditions throughout the year. This data may be found in Table 6.2. Finally, the hourly annual average heat transfer and net heat gain per square meter may be seen in Table 6.3 and Figure 6.9. Breakdowns of average heat gain for each month and roof type for day and night conditions can be found in Appendix A.

Average Peak Instantaneous Solar Radiation

MONTH	n	δ	Θz	G_{on} [W/m²]	G_b [W/m²]	G_d [W/m²]	G_{total} [W/m²]
JANUARY	17	-20.92	59.80	1410.19	417.29	69.57	486.86
FEBRUARY	47	-12.95	51.83	1398.13	508.19	84.72	592.91
MARCH	75	-2.42	41.30	1379.46	609.61	101.63	711.24
APRIL	105	9.41	29.47	1356.42	694.67	115.81	810.48
MAY	135	18.79	20.09	1336.15	738.13	123.06	861.19
JUNE	162	23.09	15.79	1324.67	749.77	125.00	874.77
JULY	198	21.18	17.70	1323.49	741.65	123.65	865.30
AUGUST	228	13.45	25.43	1335.03	709.23	118.24	827.47
SEPTEMBER	248	6.18	32.70	1347.65	667.09	111.22	778.31
OCTOBER	288	-9.60	48.48	1377.96	537.29	89.58	626.87
NOVEMBER	318	-18.91	57.79	1398.13	438.34	73.08	511.41
DECEMBER	344	-23.05	61.93	1409.20	390.05	65.03	455.07

Location: Washington, DC

A [km] = 0.125 φ = 38.88 ω = 0

τ_b = 0.588 a_0^* = 0.14033 r_0 = 0.97 a_0 = 0.13612

τ_d = 0.098 a_1^* = 0.74731 r_1 = 0.99 a_1 = 0.73984

G_{sc} [W/m²] = 1367.0 k^* = 0.37590 r_k = 1.02 k = 0.38342

Table 6.1: Monthly average peak instantaneous solar radiation.

Monthly Average Ambient Conditions for Washington, DC

Month → Energy Flux Mode↓	J	F	M	A	M	J	J	A	S	O	N	D	ANNUAL
T_{OA} [K]:	278.9	280.9	286.8	292.4	297.7	302.4	304.5	303.7	299.9	293.8	287.8	281.5	292.6
T_{OA} [°F]:	42.3	45.9	56.5	66.7	76.2	84.7	88.5	86.9	80.1	69.1	58.3	47	66.9
T_{roof} [K]:	283.2	285.2	291.0	296.7	302.0	306.7	308.8	307.9	304.2	298.0	292.0	285.8	296.8
T_{roof} [°F]:	50	53.6	64.2	74.4	83.9	92.4	96.2	94.6	87.8	76.8	66	54.7	74.6
T_{RA} [K]:	295.4	295.4	295.4	298.7	298.7	298.7	298.7	298.7	298.7	298.7	295.4	295.4	297.3
T_{RA} [°F]:	72	72	72	78	78	78	78	78	78	78	72	72	75.5
P_{vapor} [millibars]:	0.0089	0.0101	0.0151	0.0218	0.0298	0.0384	0.0426	0.0408	0.0336	0.0237	0.0161	0.0106	0.0244
U_{wind} [m/s]:	4.5	4.6	4.9	4.7	4.2	4.0	3.7	3.6	3.8	3.9	4.2	4.3	4.2
Direct Solar (G_b):	417.29	508.19	609.61	694.67	738.13	749.77	741.65	709.23	667.09	537.29	438.34	390.05	600.4
Diffuse Solar (G_d):	69.57	84.72	101.63	115.81	123.06	125	123.65	118.24	111.22	89.58	73.08	65.03	100.1
Avg. Precipitation [in]:	2.72	2.71	3.17	2.71	3.66	3.38	3.80	3.91	3.31	3.02	3.12	3.12	38.63

Table 6.2: Monthly average ambient conditions for Washington, DC.

Average Daily Net Roof Heat Flux [BTU/hr-ft^2]

	Green Roof	Cool Roof	Typical Roof
Peak (Day)	-54.45	-21.87	106.92
Average 24hr	**-79.09**	**-49.83**	**14.57**
Base (Night)	-103.72	-77.78	-77.78
Δ Heat Flux	49.27	55.91	184.70

Hour of Day	Green Roof	Cool Roof	Typical Roof
0	-88.52	-74.04	-65.41
1	-94.09	-76.83	-74.64
2	-98.63	-77.78	-77.78
3	-101.85	-76.83	-74.64
4	-103.51	-74.04	-65.41
5	-103.51	-69.59	-50.73
6	-101.85	-63.80	-31.61
7	-98.63	-57.06	-9.33
8	-94.09	-49.83	14.57
9	-88.52	-42.59	38.47
10	-82.30	-35.85	60.74
11	-75.87	-30.06	79.87
12	-69.66	-25.61	94.54
13	-64.09	-22.82	103.77
14	-59.54	-21.87	106.92
15	-56.33	-22.82	103.77
16	-54.66	-25.61	94.54
17	-54.66	-30.06	79.87
18	-56.33	-35.85	60.74
19	-59.54	-42.59	38.47
20	-64.09	-49.83	14.57
21	-69.66	-57.06	-9.33
22	-75.87	-63.80	-31.61
23	-82.30	-69.59	-50.73
24	-88.52	-74.04	-65.41

Figure 6.9: Average net heat flux into SLCC per hour.

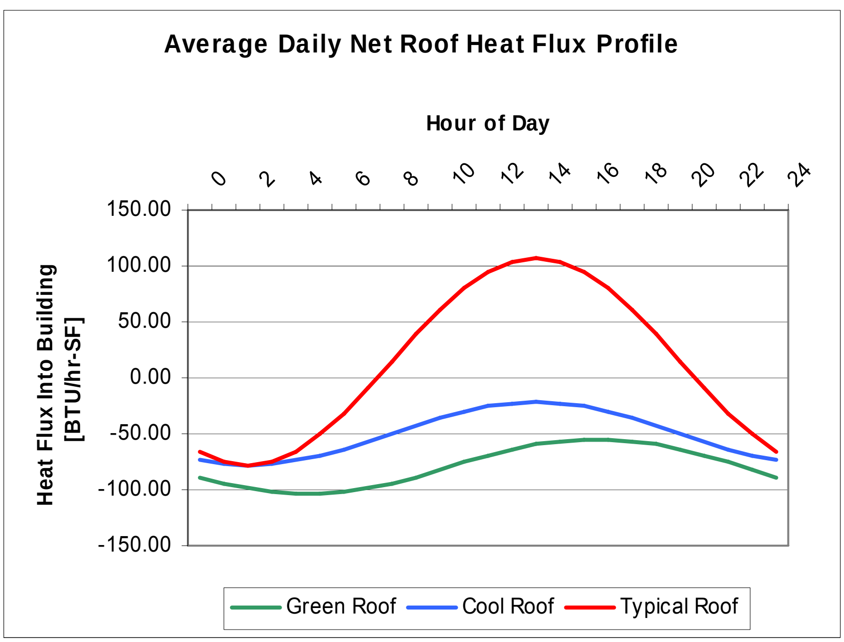


Figure 6.10: Average net heat gain histogram through different roof types.

6.4.2. CONCLUSIONS

The annual average net heat gains and associated cooling costs/savings for each roof type are described in Table 6.3. Based on the cost of remote chilled water production for the facility ($0.026495/MBH). the green roof produces significant savings in annual energy use over the budget model. However, compared to the actual design of the SLCC cool roof, the green roof does not produce significant savings (Table 6.3). This, of course, is for the ideal conditions of each roof. Given that the cool roof is likely to lose some of its reflectivity over its life (let's assume α = 0.5 sometime in the future), green roof energy savings over the cool roof may double to over $14,000/yr.

Total Energy Savings for Green Roof Design

	Green Roof			Cool Roof	Typical Roof
	Cooling Load [BTU/hr-ft^2]	Savings [MBH/hr]	Savings [$]	Cooling Load [BTU/hr]	Cooling Load [BTU/hr]
Average 24hr	79.09	723	$0.02	49.83	
		4,236	$0.11		92.35
Annual	28,887	264,110	**$6,997.60**	18,199	
		1,547,283	**$40,995.27**		33,730

Green Roof Area: 24710ft^2

Table 6.3: Total energy costs savings for green roof compared to cool roof, typical roof.

6.5. STORMWATER RETENTION

A primary benefit of green roofs is their ability to manage stormwater. Precipitation is captured and stored rather than being shed. An extensive green roof has the capability of retaining about 70% of precipitation and acts as a natural filter. Also, a green roof acts as a capacitor in that it holds water back from the storm sewer system and discharges it at a later time and at a slower rate. A traditional roof, however, immediately sheds approximately 95% of precipitation upon it. As a result, the load on the storm sewer infrastructure is reduced which has a direct impact on flash flooding (LEED).

Also, the runoff of pollution and sediment is minimized. Water that is filtered through the soil substrate experiences bioremediation and photoremediation which remove pollution. This is critical for the health of the waterways downstream. The SLCC is located within the Anacostia Watershed (
Figure 6.11). This river has a history of pollution and is a part of the sensitive Chesapeake Bay Watershed. Controlling stormwater runoff and along with it pollution and sediment is critical to the survival of these habitats (Anacostia Watershed Society).

Figure 6.11: The SLCC (red dot) is located in the Anacostia Watershed (yellow).

An analysis of impervious area and stormwater runoff is included in the LEED Sustainable Sites Credits. The goal is to reduce the amount of impervious area on the building site from pre-construction to post-construction. The site of the SLCC originally consisted of an asphalt parking lot and grass/dirt lawn. The current design for the site (
Figure 6.12) increases the amount of impervious surface area because of the impervious footprint of the building.

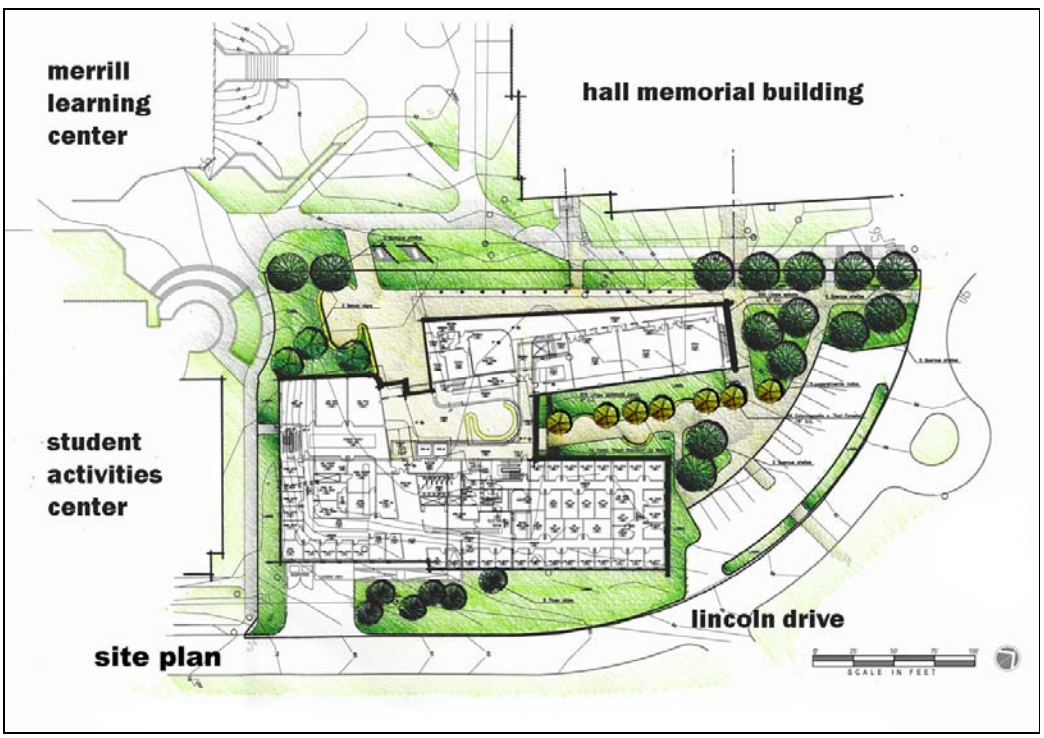


Figure 6.12: Site plan for the SLCC.

The addition of a green roof, however, greatly reduces this impervious area.

Table 6.4 shows a comparison of the amount of impervious area on the site before and after construction for each design. The proposed green roof alone reduces stormwater runoff by 5% compared to the pre-construction site and reduces runoff by 25% compared to the actual site design. The amount of runoff from the actual SLCC site design per year is equivalent to 75% of the atrium volume.

Annual Site Stormwater Runoff

	Runoff Coefficient	Original Site			Actual Design			Proposed Green Roof Design		
		Area [SF]	% of Site	Runoff [CF]	Area [SF]	% of Site	Runoff [CF]	Area [SF]	% of Total	Runoff [CF]
Asphalt/Concrete:	0.95	42550	54.8%	130127	30360	39.1%	92847	30360	39.1%	92847
Building (roof):	0.95	0	0.0%	0	33840	43.6%	103490	9130	11.8%	27921
Grass:	0.25	28050	36.1%	22574	13400	17.3%	10784	13400	17.3%	10784
Green Roof:	0.30	0	0.0%	0	0	0.0%	0	24710	31.8%	23864
Other:	0.50	7000	9.0%	11267	0	0.0%	0	0	0.0%	0
Total Pervious:	0.00	26665	34.4%	0	13260	17.1%	0	29322	37.8%	0
Total Impervious:	1.00	50935	**65.6%**	163968	64340	**82.9%**	207121	48279	**62.2%**	155417
TOTAL		77600		**163968**	77600		**207121**	77600		**155417**

Site Area [SF]: 77600
Annual Precip. [in]: 38.63

Table 6.4: Annual site stormwater runoff.

If pervious pavement is used in the parking lot rather than asphalt another 33,000CF of rain water is retained on the site (Table 6.5). The impervious area of the new site would be 25.3% less than the undeveloped site.

Annual Site Stormwater Runoff

	Runoff Coefficient	Original Site		Green Roof, Perv. Parking		
		Area [SF]	Runoff [CF]	Area [SF]	% of Total	Runoff [CF]
Asphalt/Concrete:	0.95	42550	130127	22260	28.7%	68076
Pervious Concrete	0.60	0	0	8100	10.4%	15645
Building (roof):	0.95	0	0	9130	11.8%	27921
Grass:	0.25	28050	22574	13400	17.3%	10784
Green Roof:	0.00	0	0	24710	31.8%	0
Other:	0.50	7000	11267	0	0.0%	0
Total Pervious:	0.00	26665	0	44430	57.3%	0
Total Impervious:	1.00	50935	163968	33171	**42.7%**	106781
TOTAL		77600	**163968**	77600		**122427**

Site Area [SF]: 77600
Annual Precip. [in]: 38.63

Table 6.5: Annual stormwater runoff with green roof and pervious pavement.

Another advantage of the green roof stormwater retention is the ability to downsize roof downspouts. Since the soil and plant material hold back about 70% of rainfall the amount of water drained from the roof is dramatically less. The original roof design uses 6in. downspouts for all roof drainage areas. Some of these are oversized, but all are likely the same size for uniformity. The calculations below show the sizing of the downspouts for two (2) areas of the original roof and green roof (Figure 6.13) based on rainfall of 3.2in./hr. during a one hour storm for a 100 year return period in Washington, DC (MIFAB) (International Plumbing Code Table 1106.6).

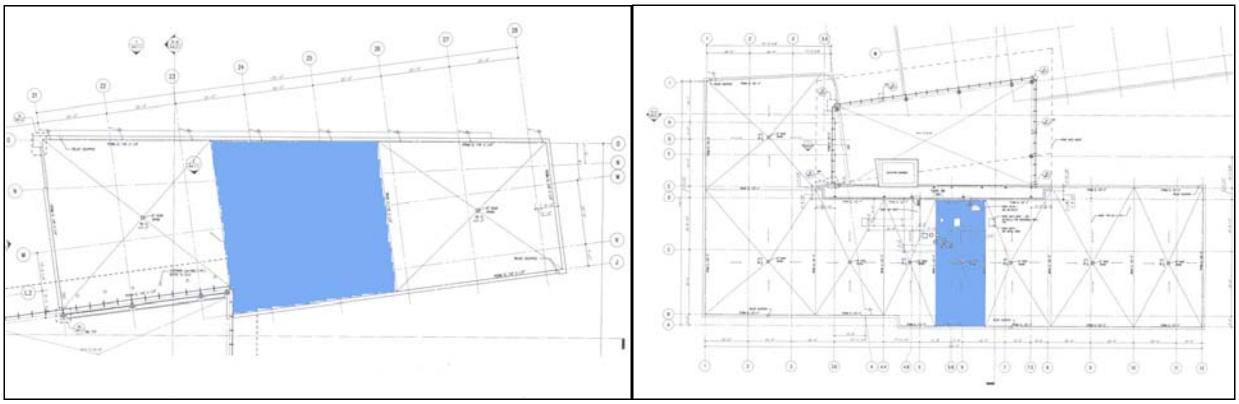


Figure 6.13: Roof drainage areas 1 (left) and 2 (right).

Drainage area of roof:

$A_1 = (58\text{ft})*(66\text{ft}) = 3{,}828\text{ ft}^2$
$A_2 = (20\text{ft})*(60\text{ft}) = 1{,}200\text{ ft}^2$

Runoff per hour:

$V_{1,\text{ original roof}} = (3{,}828\text{ ft}^2)*(3.2\text{in/hr})*(0.0104\text{ gpm/in-ft}^2) = 127.4\text{ gpm/hr}$
$V_{1,\text{green roof}} = (3{,}828\text{ ft}^2)*(3.2\text{in/hr})*(0.3)*(0.0104\text{ gpm/in-ft}^2) = 38.2\text{ gpm/hr}$

$V_{2,\text{ original roof}} = (1{,}200\text{ ft}^2)*(3.2\text{in/hr})*(0.0104\text{ gpm/in-ft}^2) = 40.0\text{ gpm/hr}$
$V_{2,\text{green roof}} = (1{,}200\text{ ft}^2)*(3.2\text{in/hr})*(0.3)*(0.0104\text{ gpm/in-ft}^2) = 12.0\text{ gpm/hr}$

Roof Downspout Sizing

Roof Area	Roof Type	Design DS Size (in. dia.)	Actual DS Size (in. dia.)
1	Original	6	6
	Green	4	4
2	Original	3	6
	Green	2	4

Table 6.6: Roof downspout sizes.

6.6. URBAN HEAT ISLAND EFFECT

Green roofs also have the ability to reduce the urban heat island effect. This phenomenon is defined in the LEED v2.1 Reference Guide as the occurrence of “warmer temperatures in an urban landscape compared to adjacent rural areas as a result of solar energy retention on constructed surfaces” such as parking lots, streets, sidewalks, and buildings. Vegetation tends to cool surrounding areas by shading and evapotranspiration whereas the built environment tends to absorb solar radiation and radiate it back to the surroundings. The result is an increase in urban temperatures of up to 10°F when compared to surrounding areas. This impacts the building cooling loads by increasing heat loss through the envelope and thus requires larger mechanical equipment and energy use.

Washington, DC is subject to this urban heat island effect. Figure 6.14 depicts the range of infrared radiation from surfaces in the metro area of Washington, DC. Blue indicates buildings, streets, parking lots, etc that re-radiate this energy to the surroundings and thus increase ambient temperatures. Red areas show vegetation (the National Mall can easily be seen in the center of the image) that do not radiate as much energy (Baumann). The proposed SLCC green roof (and original cool roof) would act to decrease the “blue” area of the city.

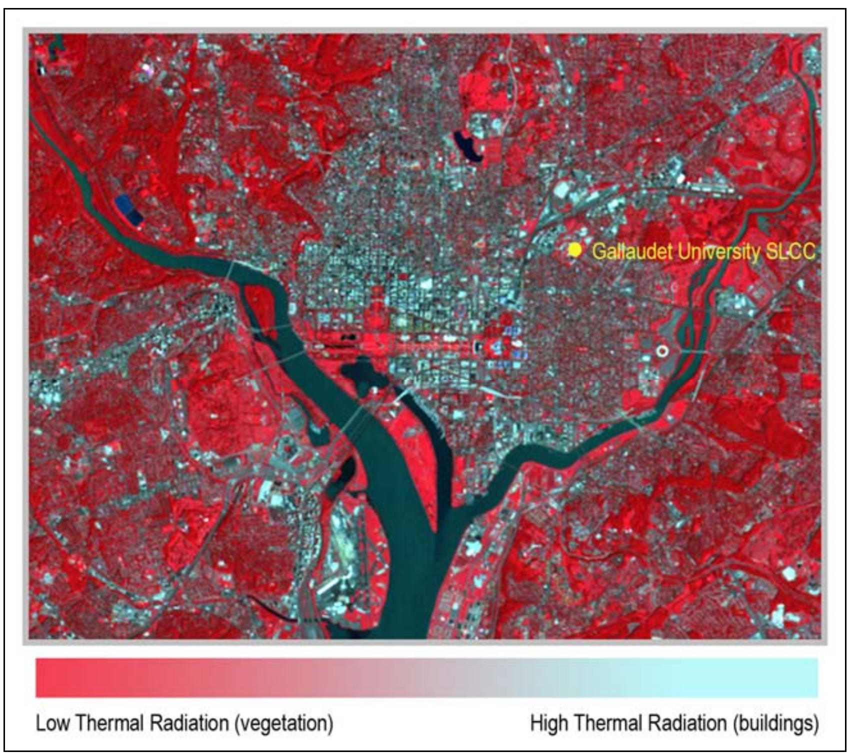


Figure 6.14: Thermal radiation in the urban Washington, DC environment in 1990(Baumann).

7. MECHANICAL SYSTEM DESIGN

The second primary topic of this thesis is to investigate the application of a dedicated outdoor air system (DOAS) to the SLCC. The stated goals for this thesis of improved energy efficiency and acoustic performance are directly related to the design and performance of the mechanical system. A DOAS system is investigated for its ability to save energy and deliver less supply air to the occupied spaces, thus possibly dampening system noise. This section analyzes the energy performance of the DOAS system and compares it to the original VAV design.

7.1. PROPOSED SYSTEM DESIGN

The proposed DOAS design of the system is based on the idea of decoupling how the mechanical system addresses sensible and latent loads. Also, the DOAS system delivers an appropriate amount of outdoor air to each space for ventilation, but does not condition and as much more air as a standard VAV system does.

The outdoor air stream is conditioned to supply enough outdoor air to meet the greater of two requirements: compliance with ASHRAE Standard 62.1 for ventilation, or to compensate for the latent load in the space. The remaining sensible load of the space is cooled using a Halton CPT passive chilled beam parallel system (Halton)(Figure 7.1). The beams will be inserted into the ceiling grid and draw warm air from the plenum down across chilled water coils within the unit and into the space with natural buoyancy forces. Warm air is supplied to the plenum through return grilles. Figure 7.2 shows a potential layout of the beam system in a classroom space.

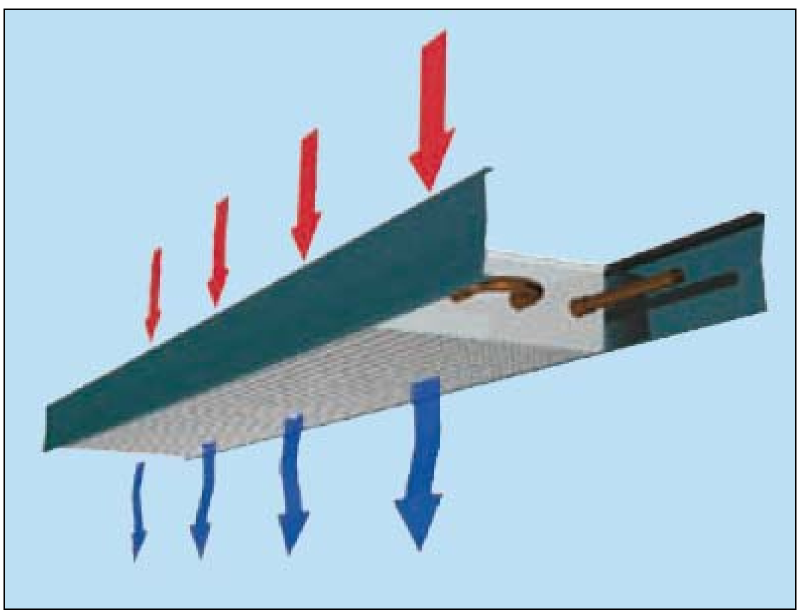


Figure 7.1: Passive chilled beam.

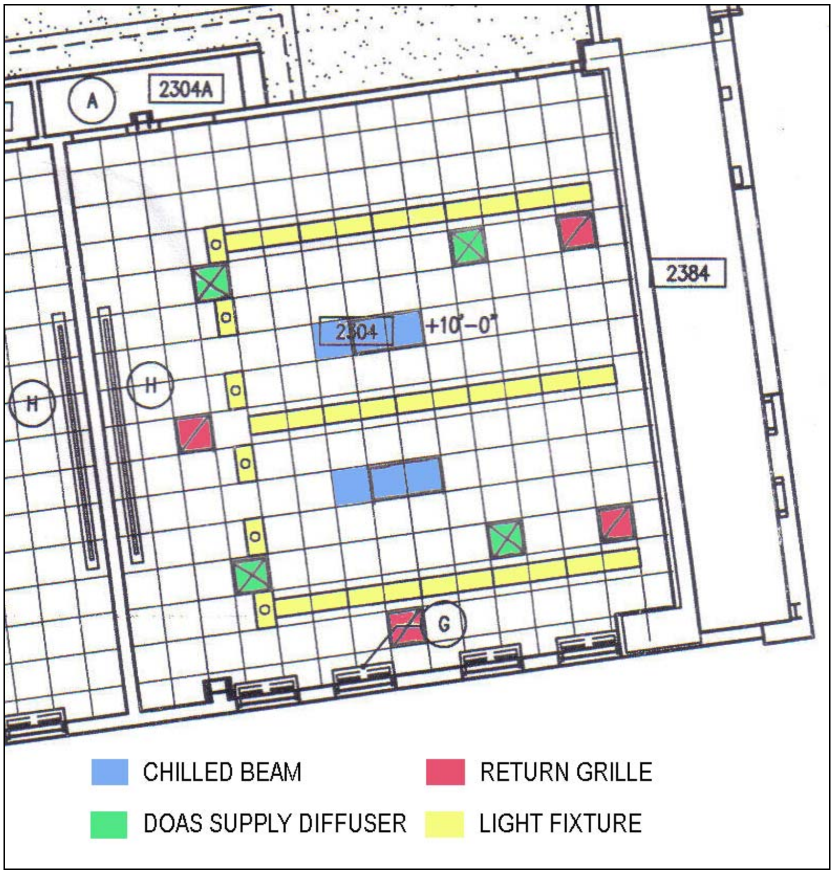


Figure 7.2: Proposed reflected ceiling plan for chilled beam system.

Radiant chilled water ceiling panels do not have the capacity to meet the cooling load within the ceiling area constraints of many spaces. According to the Aero Tech Radiant Panel Engineering Manual, radiant panels only cool about 21 BTU/hr-ft^2 for a 10°F ΔT. In a typical office about 28 2'x2' panels are required to properly cool the room, but only 20 2'x2' ceiling panels are available. Also, the metal panels would reflect sound differently than the acoustic ceiling tiles they replace.

Chilled water is used to exchange thermal energy in each space rather than air because of water's greater specific heat and density. As a result, air ducts may be significantly downsized as more chilled water is pumped throughout the building. The sizes of the pipes for this chilled water supply and return are much smaller than the air ducts. While fan energy decreases pumping energy increases.

The schematic in Figure 7.3 shows that 43°F chilled water from the Central Utilities Building is directed to the AHU cooling coils which experience a ΔT of 10°F. Because the chilled water temperature is below the dew point of the air in each space (57.9°F in summer, 52.4°F in winter), a secondary closed loop of chilled water supplies 60°F chilled water in the summer and 55°F chilled water in the winter to each parallel unit with a ΔT of 16°F. This prevents condensation on the unit and "raining" within the space. A plate heat exchanger transfers thermal energy between each loop. Three parallel CHWS pumps serve the system because of the large pressure drop and volume of flow. A standby pump is included to be turned on when another pump is out of order or receiving maintenance.

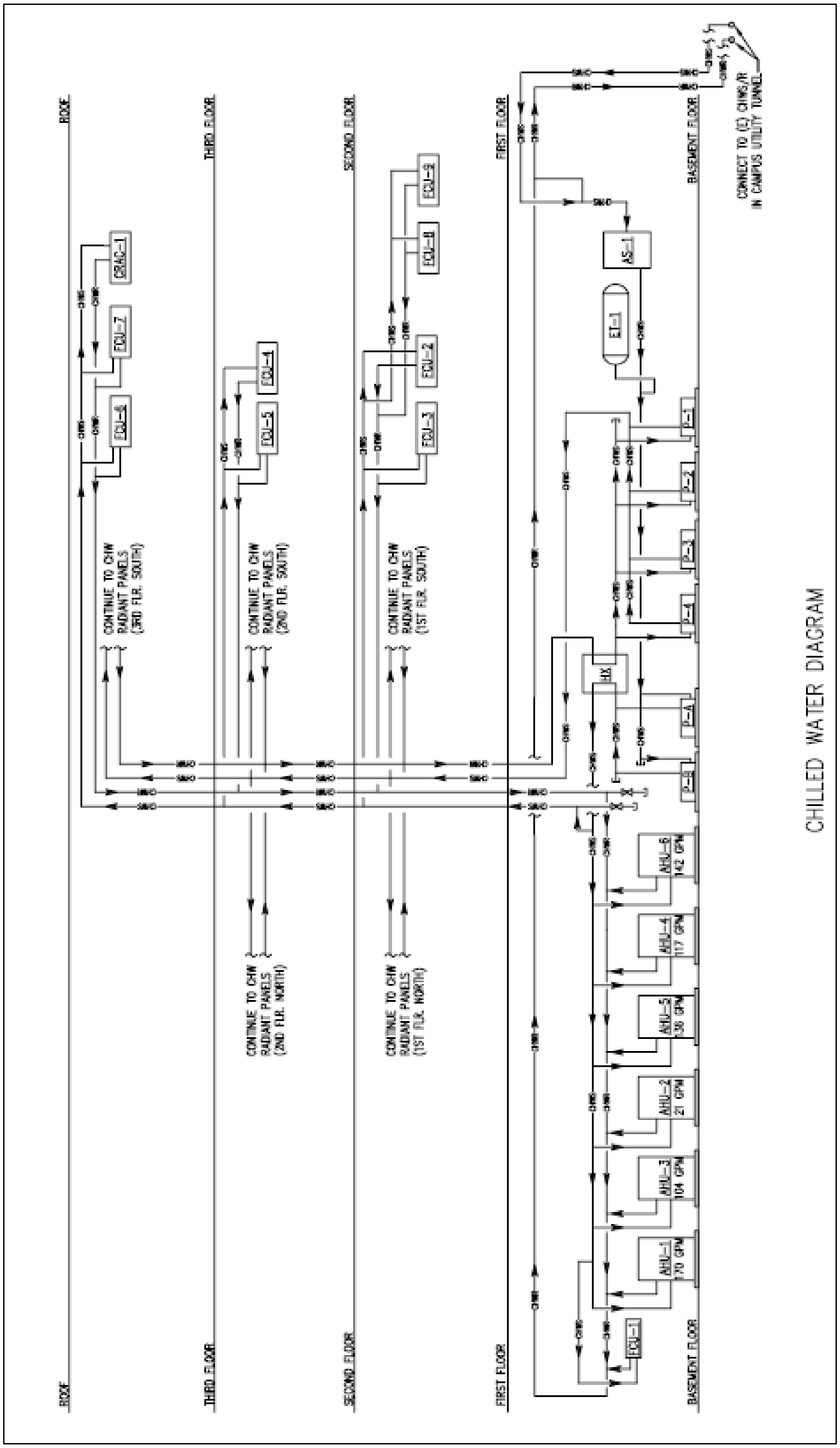


Figure 7.3: Proposed chilled water system schematic with two (2) CHW loops.

Perimeter spaces and those with roof loads would need some sort of parallel heating system. The proposed mechanical system uses baseboard heating because the radiant panels and air supply only cool the spaces. The baseboard heating warms the curtain of air against exterior walls where the heating load is located. Electricity is more expensive per unit of energy than the hot water supply from the Central Utilities Building so the baseboard heating would use hot water. The spark gap is approximately $0.295/MBH. Also, direct thermal energy extracted from a boiler is an approximately 80% efficient use of fossil fuels whereas electricity generation and transmission is an approximately 28% efficient use of fossil fuels (Pletchers).

The original zoning of the airside system generally remains intact because scheduled occupancies for each zone are slightly different from one another. The only exception to this is the merger of AHUs 4 and 6. All units except AHU 3 are dramatically downsized since they are only tasked with conditioning about 35% of the amount of air the original AHUs did. The supply air would continue to be supplied at 55°F. Instead of returning air to recycle it within the building, a DOAS system by definition generally exhausts as much air as it supplies. Rather than wasting the thermal energy in the exhaust air stream a Heat and Energy Recovery Ventilator (HRV/ERV) Enthalpy Exchanger would be used (Figure 7.4). This would exchange sensible and latent loads between the outdoor air intake and exhaust air streams for each AHU. In effect, this pre-heats and humidifies the outdoor air in the winter and pre-cools and dehumidifies it in the summer. Cross contamination of the air streams is not likely to be as much of a problem (Renewaire).

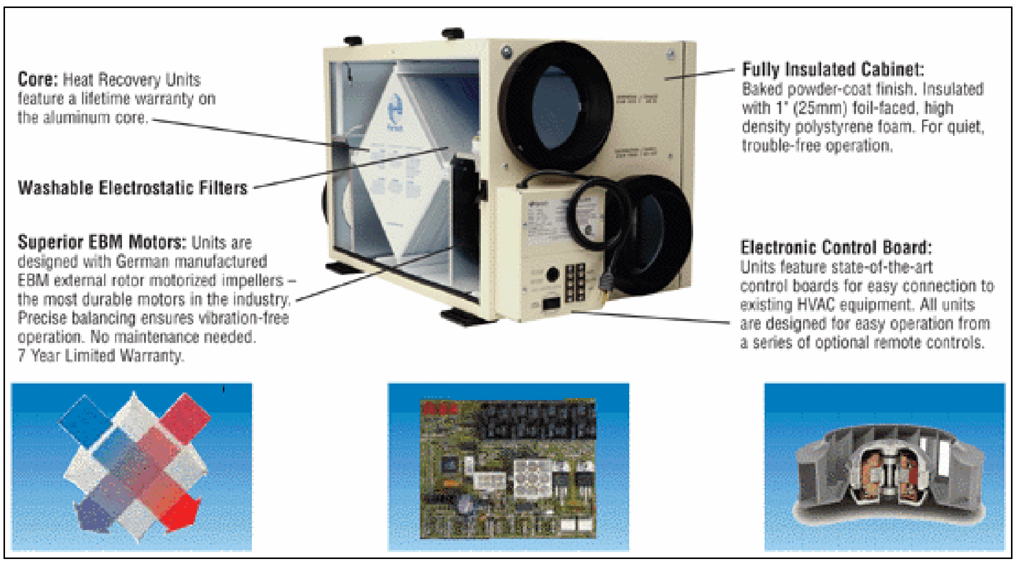


Figure 7.4: Typical Heat and Energy Recovery Ventilator (HRV/ERV) (Fantech).

Energy Recovery Ventilator Schedule

AHU	CFM	Unit*	Effectiveness		
			Sensible	Winter	Summer
1	2650	HE4XINH	74%	64%	50%
2	515	HE1XINH	76%	68%	54%
3	2890	HE4XINH	72%	62%	48%
4	3875	HE6XINH	73%	64%	50%
5	3725	HE6XINH	74%	65%	51%
6	4180	HE6XINH	70%	61%	47%

*Renewaire ERV Model

Figure 7.5: Schedule of selected ERVs

7.2. VENTILATION STRATEGY

The DOAS system only supplies enough conditioned outdoor air to each space to meet either the ASHRAE Standard 62.1 minimum ventilation requirement or the latent load in the space, whichever governs. Instead of meeting the minimum ventilation standards the calculations included an extra 30% outdoor air supply volume. This is to improve the indoor air quality and in keeping with LEED-NC v2.2 which offers a point for exceeding ventilation requirements by at least 30%. While this point can not be earned because the SLCC is designed to LEED-NC v2.1, the principle behind it is still assumed to be good practice for indoor air quality.

The proposed mechanical system delivers about 65% less air than the original VAV system at its peak (Table 7.1). As a result, AHUs, fans, and ducts are significantly downsized. There is actually a 13.5% reduction in the amount of outdoor air flow to the spaces even when the DOAS system supplies 30% extra outdoor air. This is due to the system efficiency (E_z) factor for critical spaces in Standard 62.1.

SUMMARY										
AHU	# Zones / VAVs	Area Served [SF]	ASHRAE Minimum OA [CFM]	DOAS Design OA [CFM]	Original Design OA [CFM]	Reduction in OA Flow [CFM]	DOAS Design SA [CFM]	Original Design SA [CFM]	Reduction in SA Flow [CFM]	Original Unit Capacity [CFM]
1	19	13185	2000	2650	4130	35.8%	2650	17400	84.8%	17700
2	3	1311	390	515	360	-43.1%	515	2230	76.9%	2500
3	0	7990	1240	2890	2890	0.0%	2890	13070	77.9%	13800
4	44	15285	2875	3875	4650	16.7%	3875	14080	72.5%	13300
5	37	15061	2405	3725	4550	18.1%	3725	11965	68.9%	11200
6	39	15146	2990	4180	4050	-3.2%	4180	14130	70.4%	13400
4/ 6	83	30431	5865	8055	8700	7.4%	8055	28210	71.4%	-
TOTALS	**142**	**67978**	**11900**	**17835**	**20630**	**13.5%**	**25890**	**72875**	**64.5%**	

Table 7.1: Comparison of outdoor and supply air flows for each system.

7.3. ENERGY ANALYSIS METHODOLOGY

The technical reports for this thesis conducted in the Fall 2006 Semester required building an energy model of the SLCC. This model was built in Carrier's Hourly Analysis Program (HAP). While HAP has code written to analyze variable-air volume systems there is no simple way to analyze a DOAS system. Instead, the program must be "tricked" to analyze the system properly. As a result, three versions of each space need to be created.

The first space created is used to model the space sensible load. All inputs remain the same as if the space were being analyzed as a VAV system except for the latent load of the occupants and the amount of outdoor air supply. These values are set to zero because the air supply carries these loads. Occupancy and load scheduling remain the same. The sensible cooling capacity of the supply outdoor air is included in "miscellaneous loads" by the equation (Q_{sen} = -1.08 CFM ΔT). The purpose is to model the cooling load on the parallel cooling system.

The second space to be modeled is the daytime latent and outdoor air load. A duplicate of the first space is made and outdoor air flows are reinstated for both occupancy and floor area. Also, all electrical equipment, lighting, walls, windows, and occupant sensible loads are set to zero. The latent load of the occupants is re-input into the program and occupancy is scheduled as normal. This space represents the cooling load of the outdoor air and latent load of the occupants during the occupied hours.

The final space created is the unoccupied outdoor air load. A duplicate of the previous space is made and the occupancy schedule is set to zero. Therefore the only load is the ventilation air per floor area.

The systems created address the unique aspects of each space. All "sensible load" spaces are conditioned with their own fan coil unit to recognize that these spaces are cooled using chilled water. The "daytime outdoor air and latent load" spaces are input into a special AHU whose schedule is to run only during occupied hours. The AHU is duplicated, the spaces are switched to "nighttime outdoor air load," and the schedule of operation is set to the opposite of the previous AHU. The plants remain the same except for which systems they serve, and the building remains the same. The output is an approximation of the heating and cooling loads and lighting, electrical equipment, fan, and pump energy use.

7.4. CASE 1: EXISTING SYSTEM ENERGY ANALYSIS

An energy model of the SLCC was created in Fall 2006 for Technical Report 2. The results below show the annual energy use and cost (Table 7.2).

Annual Energy Use and Cost by End Use

End Use	Energy Type	Electric [kWh]	Oil [MBH]	Energy Use [MBH]	Energy Cost
Lighting	Electricity	223695		763246	$20,222
Space Heating	Remote HW		89314	89314	$1,237
Space Cooling	Remote CW		3403435	3403435	$90,174
Fans	Electricity	83838		286057	$7,579
Pumps	Electricity	115144		392871	$10,409
Receptacles	Electricity	258639		882478	$23,381
TOTAL		681316	3492749	5817400	$153,002

Table 7.2: Existing system annual energy cost and use.

7.5. CASE 2: DOAS SYSTEM ENERGY ANALYSIS

The HAP model created by the methodology described in Section 7.3 above produced the following outputs (Table 7.3):

Annual Energy Use and Cost by End Use

End Use	Energy Type	Electric [kWh]	Oil [MBH]	Energy Use [MBH]	Energy Cost
Lighting	Electricity	223053		761057	$20,164
Space Heating	Remote HW		35668	35668	$494
Space Cooling	Remote CW		2786186	2786186	$73,820
Fans	Electricity	101593		346635	$9,184
Pumps	Electricity	19580		66806	$1,770
Receptacles	Electricity	256925		876627	$23,226
TOTAL		601150	2821854	4872979	$128,658

Table 7.3: Annual energy cost and use for the DOAS system.

7.6. CASE 3: OVERALL IMPACT OF DOAS, GREEN ROOF LOADS

By combining the results of Sections 7.4 and 7.5 the annual energy uses and costs are as follows (Table 7.4):

Annual Energy Use and Cost by End Use

End Use	Energy Type	Electric [kWh]	Oil [MBH]	Energy Use [MBH]	Energy Cost
Lighting	Electricity	223053		761057	$20,164
Space Heating	Remote HW		35668	35668	$494
Space Cooling	Remote CW		2529430	2529430	$67,017
Fans	Electricity	101593		346635	$9,184
Pumps	Electricity	19580		66806	$1,770
Receptacles	Electricity	256925		876627	$23,226
TOTAL		601150	2565098	4616223	$121,855

Table 7.4: Annual energy cost and use for the DOAS system with a green roof.

7.7. ENERGY COST SAVINGS

A comparison of the results of Section 7.6 shows a total energy use and cost reduction of approximately 1.2MMBH and $31,147, respectively, with the proposed DOAS and green roof designs.

8. STRUCTURAL ANALYSIS

The addition of a green roof to the SLCC imposes additional gravity loads on the structure. The conclusion to include an extensive green roof imposes a minimum superimposed dead load of 25 pounds per square foot (DC Greenworks). This section evaluates the current roof deck and support system's capacity to carry this additional gravity load.

8.1. EXISTING CONDITIONS

The SLCC has three roof levels: a two (2) story wing roof; a three (3) story wing roof; and an atrium roof. The proposed green roof will be applied to the first two roof surfaces which cover the majority of the building footprint. These roofs are composed to two typical constructions. The predominant roof surface is designed to be unoccupied and consists of 20 GA wide rib steel roof deck, 3" rigid insulation, and a waterproof membrane (Figure 8.1). This roof is supported by K-shape open-web steel joists and W-shape girders. The other typical roof is located exclusively on the third floor roof around the rooftop mechanical equipment and is intended to carry semi-frequent occupant loads. This roof is constructed with 18GA roof deck rather than 20GA deck. This construction is supported by W-shape steel beams and girders. The load path for both roof types leads from the girders to W-shape steel columns and directly down to the foundation.

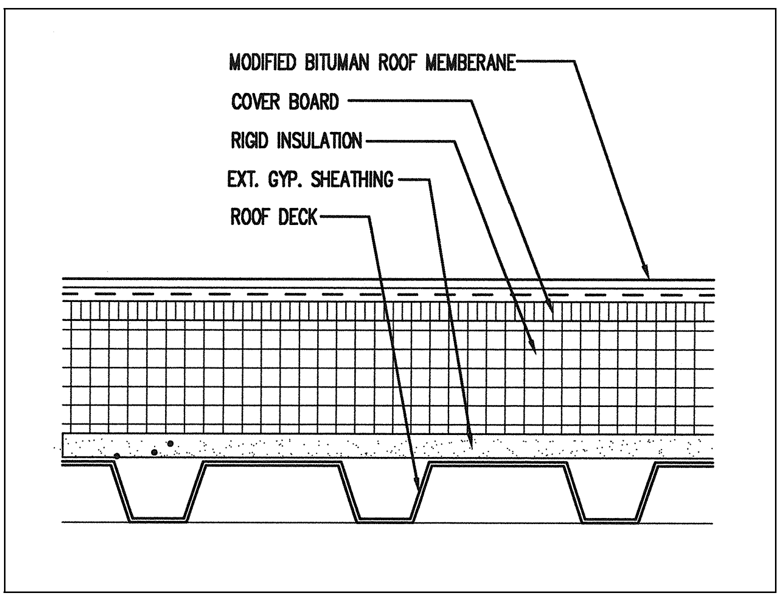


Figure 8.1: Typical roof construction detail.

8.2. STRUCTURAL ANALYSIS METHODOLOGY

Design roof loads are determined using the structural cover sheet of the SLCC Construction Documents and Table C3-1 from ASCE 7-05. The corrected snow load for the roof level is derived from the contract documents. The additional extensive green roof dead load is given by DC Greenworks. These loads are combined to determine the total dead load for each roof design. Dead and live loads were added together to determine total gravity loads. See Table 8.1 for each of these loads.

Structural Roof Loads

Roof Dead Load		
Construction	**Material**	**PSF**
Green Roof	Soil, plants, etc.	25.0
Waterproof Membrane	Smooth, bituminous membrane	1.5
Insulation	Rigid insulation	1.0
Roof Deck	20G - 18G Steel, 1 1/2" deep	3.0
MEP	Mech, Elec. equipment	5.0
Ceiling	Ceiling panels, fasteners	2.0
Collateral		5.0
TOTAL	Original Roof Design	**17.5**
	Green Roof Design	**42.5**

Roof Live Load	
Category	**PSF**
Ground Snow Load	30.0
Flat Roof Snow Load (Governs)	23.0
People	20.0
TOTAL	**23.0**

TOTAL	PSF
Original Roof Design	**35.5**
Green Roof Design	**60.5**

Table 8.1: Expected gravity loads on roof.

Several members are checked for their capacity to carry the new green roof loads with hand calculations. These calculations find the maximum shear force, maximum moment, maximum allowable deflection, moment of inertia, and plastic section modulus. The results are then compared to the W-shape beam properties in AISC Steel Manual Table 3-6. Open-web steel joists are evaluated based on their capacity to carry maximum and total and live shear loads according to Steel Joist Institute Standard Load Tables. Girders are checked by their maximum shear force, maximum moment force, and plastic section modulus. See the sample calculations below for an example of this process.

A RAM Steel Model of the roof structure and top tier of columns include input based on the loads in Table 8.1 and physical dimensions of the actual building. The program computes loads for all joists, girders and columns and produces an output report suggesting sizes for these members.

8.2.1. STRUCTURAL EQUATIONS

Solve for:	Equation	[Units]
Deflection	$\Delta = (5\, w\, \ell^4) / (384\, E\, I_x)$	[in]
Maximum Deflection (total load)	$\Delta_{max,\, total} = \ell / 240$	[in]
Maximum Deflection (live load)	$\Delta_{max,\, live} = \ell / 360$	[in]
Maximum Service Load Moment	$M_{max} = (w\, \ell^2) / 8$	[kip ft]
Maximum Service Load Shear Force	$V_{max} = (w\, \ell) / 2 \leq V_n / \Omega_v$	[kip]
Plastic Section Modulus about x-axis	$Z_x \geq M_{max} / F_y$	[in^3]

Variable	Symbol	[Units]
Uniformly Distributed Load	w	[kips/ft]
Span Length	ℓ	[ft, in]
Modulus of Elasticity of Steel	$E = 29000$	[ksi]
Moment of Inertia of Cross Section	I_x	[in^4]
Maximum Shear Strength	V_n	[kips]
ASD Safety Factor	$\Omega_v = 1.67$	-
Specified Minimum Yield Stress (A992 Steel)	$F_y = 50$	[ksi]

8.2.2. ASSUMPTIONS:

- Member connections are sized based on designed capacity of members and future loads.
- If all members are sufficiently sized for the roof structure and its supporting columns, the supporting columns and caissons are also able to support the additional green roof load.

8.2.3. FREE BODY DIAGRAMS

The figures below depict the typical load patterns for the structural elements analyzed in this thesis with hand calculations. Figure 8.2 shows the plans for the two typical bays, Figure 8.3 is a free body diagram of the loading pattern of a typical girder, and Figure 8.4 presents the loading pattern for a typical joist.

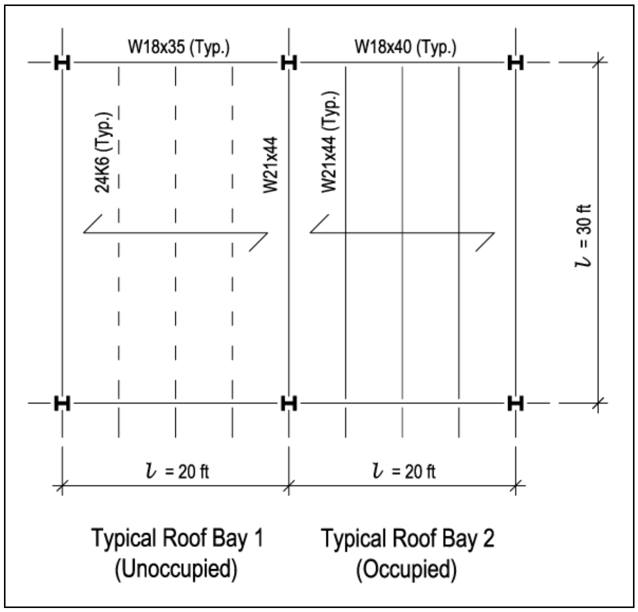
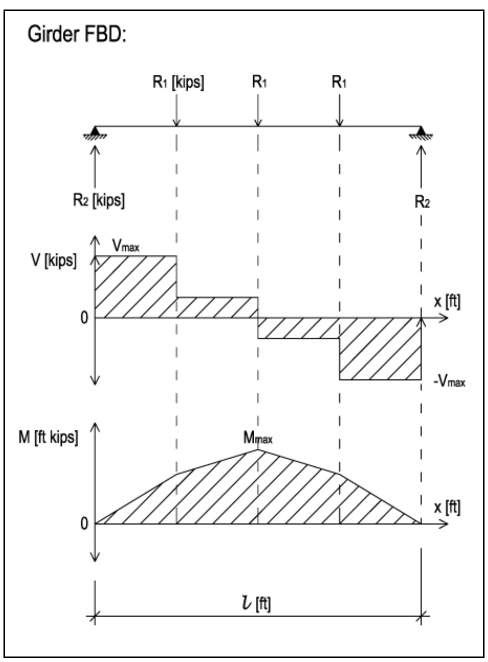


Figure 8.2: Plans of typical structural bays studied.



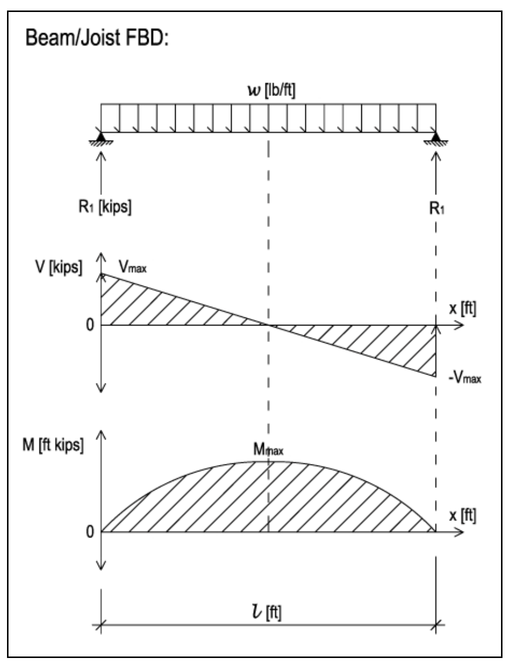


Figure 8.3: Free body diagram of a typical girder.
Figure 8.4: Free body diagram of a typical joist.

8.3. SAMPLE CALCULATIONS

8.3.1. SAMPLE JOIST CALCULATION

This is the calculation for the typical bay 2 (18GA deck) (Figure 8.2) green roof loading case according to the typical joist loading pattern (Figure 8.4).

$\Delta_{total} = (5\,w\,\ell^4)/(384\,E\,I_x)$
$= (5\,(0.3575)(30)^4(12)^3)/(384\,(29000)\,I_x)$
$= 224.67\ in^5/I_x$

$\Delta_{max,\ total} = \ell/240$
$= (30*12)/240$
$= 1.5\ in$

$\Delta_{total} \leq \Delta_{max,\ total}$
$224.67\ in^5/I_x \leq 1.5\ in$

$\longrightarrow$ $\mathbf{I_x \geq 149.78\ in^4}$ (GOVERNS)
(See AISC Steel Const. Manual Table 1-1)

$\Delta_{live} = (5\,(0.215)(30)^4(12)^3)/(384\,(29000)\,I_x)$
$= 135.12\ in^5/I_x$

$\Delta_{max,\ live} = \ell/360$
$= (30*12)/360$
$= 1.0\ in$

$\Delta_{live} \leq \Delta_{max,\ live}$
$135.12\ in^5/I_x \leq 1.0\ in$

$\longrightarrow$ $I_x \geq 135.12\ in^4$
$135.12\ in^4 < 149.78\ in^4$ (DOES NOT GOVERN)

$V_{max} = (w\,\ell)/2$
$= (.3575)(30)/2$
$\mathbf{V_{max} = 5.36\ kips}$ (See AISC Steel Const. Manual Table 3-6)

$M_{max} = (w\,\ell^2)/8$
$= (.3575)(30^2)/8$
$= 40.22\ ft\ kips$

$Z_x \geq M_{max}/F_y$
$\geq (40.22)(12)/50$
$\mathbf{Z_x \geq 9.84\ in^3}$ (See AISC Steel Const. Manual Table 3-6)

$\longrightarrow$ Select a **W12x22** Member ($I_x = 156 in^4$, $V_{max} = 64$ kips, $Z_x = 29.3\ in^3$)

Check: Δ_{live} = 135.12in^5 / 156in^4
= 0.86 in ≤ 1.0 in **OK**

Δ_{total} = 224.67in^5 / 156in^4
= 1.44 in ≤ 1.5 in **OK**

8.3.2. SAMPLE GIRDER CALCULATION

This is the calculation for a girder between typical bay 1 and 2 for the green roof loading case according to the typical girder loading pattern (Figure 8.3).

V_{max} = ∑ R_i ⁄ 2
= (4.01+6.02)(3) ⁄ 2
V_{max} = 15.04 kips + 0.5*Self Weight

M_{max} = ∑ Areas under half of shear curve
= (5)(5.02 + 15.04)
= 100.28 ft kips

$Z_x \geq M_{max} / F_y$
≥ (100.28)(12) ⁄ 50
$Z_x \geq$ 24.07 in^3

→ Select a **W12x19** Member (V_{max} = 57.2 kips, Z_x = 24.7 in^3)

8.4. EXISTING STRUCTURE EVALUATION

The results of the hand calculations in Table 8.2 and Table 8.3 indicate that the selected typical members have the capacity to carry the additional gravity load of the green roof.

Joist/Beam Selections for Typical Bays[1]

Bay	Roof Type	Member Selection [2]	Actual Member	Comments
Typical Bay No. 1	Original	20K4	24K6	3 rows bridging
	Green	20K4	24K6	**Original Design OK**
Typical Bay No. 2	Original	W12x19	W21x44	
	Green	W12x22	W21x44	**Original Design OK**

[1] N.B. Span = 30 ft, 24" deep structural plenum.

[2] Assume L/240 Max. Deflection

Table 8.2: Joist and beam selections for original, green roofs.

Girder Selections for Typical Bays[1]

Bay	Roof Type	Member Selection	Actual Member	Comments
Typical Bay No. 1	Original	W12x16	W18x40	
	Green	W12x19	W18x40	**Original Design OK**
Typical Bay No. 2	Original	W12x16	W24x84	
	Green	W12x19	W24x84	**Original Design OK**

[1] N.B. Span = 20 ft, 24" deep structural plenum.

Table 8.3: Girder selections for original, green roofs.

A model of the roof structure and supporting columns for one floor height below the roof was produced in RAM Steel (Figure 8.5, Figure 8.6). Both the original and green roof loading cases were analyzed and all beams, joists, girders, and columns are found to be sufficient to carry both load cases. A full check of each member can be found in Appendix B and shows that every roof structure member is sufficient for the supplemental green roof load.

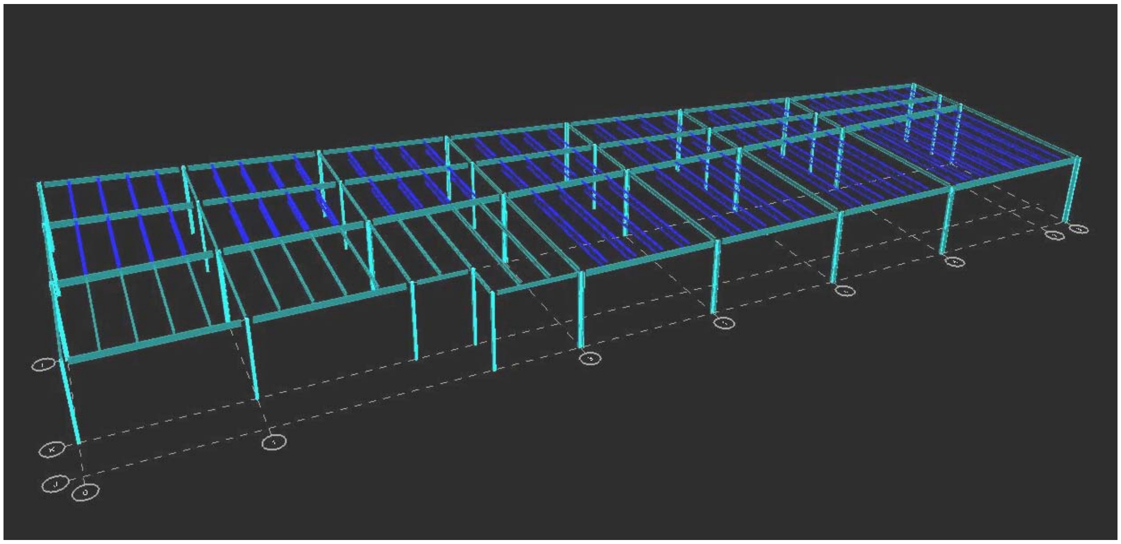


Figure 8.5: RAM Model of second floor roof.

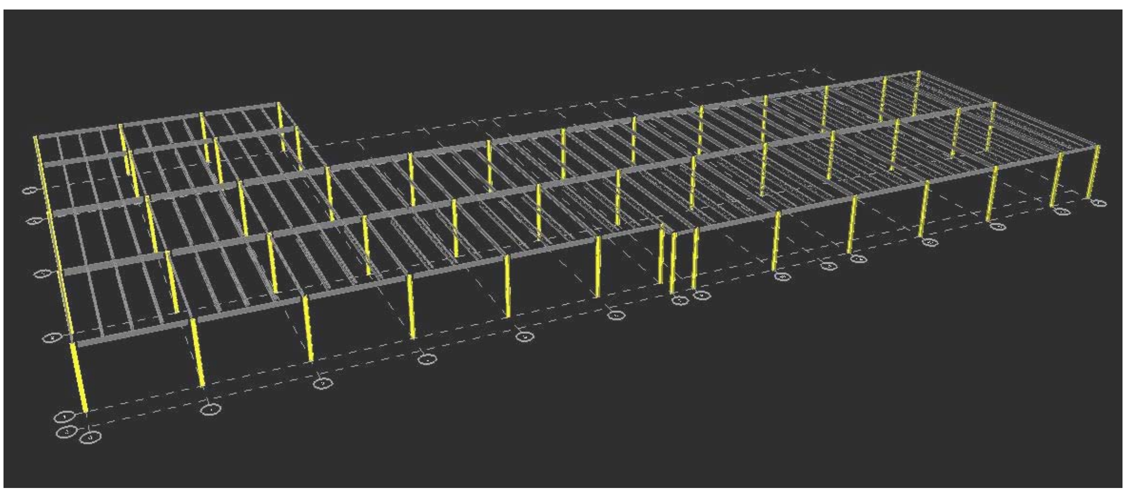


Figure 8.6: RAM Model of third floor roof.

8.5. CONCLUSION

The results of this structural analysis show that the originally designed structure should be capable of carrying the additional 25psf load of an extensive green roof. The structure is significantly oversized for the expected load cases. This is likely the product of using standard member sizes (e.g. W24 beams and K6 joists), safety factors, and allowances for future loads. Therefore, no changes to the structure are necessary for the proposed green roof.

9. ACOUSTIC ANALYSIS

Given the numerous audiology labs, hearing clinics, and hearing therapy rooms, the SLCC Facility requires particular acoustic sensitivity in its design. Many of these spaces require NC-25 or quieter conditions. Mechanical systems – particularly conditioned air delivery – are the most significant source of noise in these rooms. Sound transmission from outside these spaces through the walls, floors, and ceilings/roofs is another likely source of noise. The outdoor ambient noise is a particular concern because the facility is located in downtown Washington, DC near Florida Avenue.

This section analyzes these sources of noise and estimates the NC level in four (4) different spaces for the original design and the proposed chilled beam and green roof designs: a classroom with an exterior roof wall (NC-25), a hearing-aid fitting room between occupied floors and with an exterior wall (NC-20), and two (2) different audiology labs in the center of the building with a roof exposure (<NC-25).

9.1. ACOUSTIC ANALYSIS METHODOLOGY

Noise levels for ambient outdoor noise were measured using a PDA version of IE-33 Software v.5.9.5 during the morning rush hour (8:45am) of Monday, March 12, 2007. Measurements were obtained for three scenarios: average conditions over a five minute period (case 1); instantaneous conditions as a car drove by the site (case 2); and instantaneous conditions as a large diesel truck drove by the site (case 3). These measurements can be seen in Table 9.1. Noise from adjoining spaces was conservatively approximated as equal to the design NC level for each of these spaces (NC-35). These values are also included in Table 9.1.

Ambient Noise at Gallaudet University SLCC Site

Measured: Monday, March 12, 2007, 8:45am

	Average Ambient Sound Pressure Level (L_p) [dB]						NC Level
Frequency [Hz] →	125	250	500	1000	2000	4000	
Case 1: Typical ambient conditions	57	49	51	45	40	28	47
Case 2: Car driving by site	69	63	56	57	55	47	58
Case 3: Diesel truck driving by site	63	65	56	57	59	50	61
Surrounding Spaces Inside SLCC[1]	52	45	40	36	34	33	35

[1] Worst case for Design NC Level of surrounding spaces.

Table 9.1: Ambient noise measurements at site.

Surface sound absorption coefficients are assumed to be equal to those listed in *Architectural Acoustics* (Egan) for various surface types. Assumptions relating the actual surfaces of the studied rooms and those in the table are listed on page 49. These values are used to calculate the room constant for each octave band.

Transmission losses are approximated using values from *Architectural Acoustics* (Egan) for various types of building construction. Assumptions comparing actual wall construction and those in the table are listed on page 49 as well. Transmission losses are weighted based on surface area for composite walls with doors and/or windows. These transmission losses are then used with the room constants to calculate the noise reduction through the building construction.

Mechanical noise is investigated using the Trane Acoustical Program (TAP). Noise sources (fans, VAV boxes, and diffusers) and transmission paths (ducts, elbows, and junctions) are input into the program which calculates the mechanical sound at the terminal unit. This is done for both the original VAV system and the proposed DOAS system.

All noise that enters the room is then compounded to calculate the total room noise at each octave band. These values are used to calculate the NC level for each space and thus determine if it meets the design criteria.

9.1.1. ACOUSTICS EQUATIONS

Solve for:	Equation	[Units]
Room Constant	$R_T = \sum (S_i \alpha_i) / (1 - \alpha_{SAB})$	-
Area weighted sound absorption coefficient	$\alpha_{SAB} = \sum (S_i \alpha_i) / \sum S_i$	-
Composite Transmission Loss	$TL_C = -10 \log (\tau_{avg})$	[dB]
Transmission Loss	$TL = 20 \log (M_1 / M_2)$	[dB]
Transmission Loss for Soil	$TL_{soil} = f\ t\ sc$	[dB]
Area weighted transmission coefficient	$\tau_{avg} = \sum (S_i \tau_i) / \sum S_i$	-
Transmission Coefficient	$\tau_i = 10 \wedge (-TL_i / 10)$	-
Noise Reduction	$NR = TL + 10 \log (R_T / S)$	[dB]
Sound Pressure Level (Transmitted into receiver room)	$(L_p)_{rec} = (L_p)_{source} - NR$	[dB]
Sound Pressure Level (Conversion from Sound Power Level)	$L_p = L_w + 6 - (10 \log R_T)$	[dB]
Sound Pressure Level (Sum from all sources)	$(L_p)_{total} = 10 \log [\sum 10 \wedge ((L_p)_i / 10)]$	[dB]

Variable	Symbol	[Units]
Surface Area	S_i	[m^2]
Absorption Coefficient	α_i	-
Construction Mass Per Unit Area	M	[$lb\ ft^{-2}$]
Octave Band Frequency	f	[khz]
Soil Thickness	t	[cm]
Soil Attenuation Coefficient	sc	[$dB\ cm^{-1}\ khz^{-1}$]

9.1.2. ABSORPTION COEFFICIENT ASSUMPTIONS

Floor Construction equivalent to:	Carpet, heavy, with impermeable latex backing on foam rubber.
Internal Wall Construction equivalent to:	Two (2) layers 5/8” thick gypsum board screwed to 1x3s 16” o.c. with airspaces filled with fibrous insulation.
External Wall Construction equivalent to:	One (1) layer 5/8” thick gypsum board screwed to 1x3s 16” o.c. with airspaces filled with fibrous insulation.
Doors equivalent to:	Wood, 1” paneling with airspace behind.
Glass equivalent to:	Glass, heavy (large panes).
Ceiling Construction equivalent to:	Acoustical board, 3/4” thick, in suspension system.

9.1.3. TRANSMISSION LOSS ASSUMPTIONS

Floor Construction equivalent to:	6” reinforced concrete slab with 3/4” wood battens floated on 1” glass fiber.
Internal Wall Construction equivalent to:	3 5/8” steel channel studs 24” o.c. with two layers 5/8” gypsum board both sides, with 3” mineral fiber insulation in cavity.
External Wall Construction equivalent to:	4 1/2” face brick PLUS one (1) layer 5/8” thick gypsum board screwed to 1x3s 16” o.c. with airspaces filled with fibrous insulation.
Glazing Construction equivalent to:	Double glass: Two (2) 1/4” laminated panes with 1/2” airspace.
Original Roof Construction equivalent to:	Corrugated steel, 24 gauge with 1 3/8” sprayed cellulose insulation on ceiling side.
Green Roof Construction equivalent to:	Original roof construction plus 10cm soil for frequencies greater than 1khz, and determined based on assumed green roof mass for frequencies 1khz or less.

9.1.4. OTHER ASSUMPTIONS

- Soil attenuation constant is assumed to be 0.5 dB cm^{-1} khz^{-1} based on an average attenuation coefficient for saturated soil (Oelze, et al.).
- The mass of the soil, plant matter, etc on the green roof is assumed to be approximately 20 lbs per square foot since the structure is designed to hold an additional 25psf for the green roof.
- Footfall is not included in calculations for ceiling/roof noise.
- Structure borne noise is negligible. Only one rooftop fan on the third floor roof operates during normally occupied hours and is physically removed from the study spaces by several bays.

9.2. SAMPLE CALCULATIONS

9.2.1. GREEN ROOF TRANSMISSION LOSS (f ≥ 2000hz)

The following is a calculation for the total green roof transmission loss based on attenuation properties of soil at and above 2000hz:

$$TL_{soil,\ 2000hz} = (2khz)\ (10cm)\ (0.5\ dB\ cm^{-1}\ khz^{-1}) = 10\ dB$$

9.2.2. GREEN ROOF TRANSMISSION LOSS (f ≤ 1000hz)

The following is a calculation for the total green roof transmission loss at and below 1000hz based on the mass of the soil and original roof construction:

$$TL_{green\ roof} = 20 \log ((10 + 20)psf \,/\, 10psf) = 10\ dB$$

9.2.3. COMBINED NOISE

The following is a calculation for the total noise inside the HSLS Audiology Hearing Science Lab (3122) at the 125 hz octave band with the original mechanical system and original roof design.

$$\alpha_{SAB,\,125} = \frac{[\,(97.55)*(0.28) + (75.81)*(0.08) + (75.81)*(0.76) + (19.51)*(0.19)\,]}{[\,97.55 + 75.81 + 75.81 + 19.51\,]} \approx 0.35$$

$$R_{T,\,125} = \frac{[\,(97.55)*(0.28) + (75.81)*(0.08) + (75.81)*(0.76) + (19.51)*(0.19)\,]}{[\,1 - 0.35\,]} \approx 146.24$$

$$\tau_{125,\,Walls} = 10 \wedge (\,-38/10\,) \approx 1.58 \times 10^{-4}$$

$$\tau_{125,\,Doors} = 10 \wedge (\,-29/10\,) \approx 1.26 \times 10^{-3}$$

$$\tau_{avg,\,125} = \frac{[\,(19.51)*(1.26 \times 10^{-3}) + (97.55)*(1.58 \times 10^{-4})\,]}{[\,19.51 + 97.55\,]} \approx 3.4 \times 10^{-4}$$

$$TL_{C,\,125,\,partitions} = -10 \log (\,3.4 \times 10^{-4}\,) \approx 34.67 \text{ dB}$$

$$NR_{125,\,partitions} = 34.67 + 10 \log [\,146.24/(\,97.55 + 19.51\,)\,] = 35.63 \text{ dB}$$

$$(L_p)_{rec,\,125,\,partitions} = 52 - 35.63 = 16.37 \text{ dB}$$

$$(L_p)_{total,\,125,\,original\ roof} = 10 \log [\,10^{1.6} + 10^{1.1} + 10^{3.7} + 10^{4.0}\,] = 41.93 \text{ dB}$$

$$\mathbf{\approx 42\ dB}$$

9.3. CASE 1: EXISTING CONDITIONS

The original airside mechanical system delivers air via fan powered VAV boxes. Sound attenuators on both the supply and return sides of the AHUs and supply sides of the VAV units minimize noise transmitted to occupied spaces from mechanical equipment. Transfer ducts are also sized to limit a direct path for sound propagation from the hallways to the spaces. Table 9.2 shows the contribution of this mechanical system to the room noise, and Table 9.3 shows the resulting combination of all noise sources.

DOAS Mechanical System Noise in Occupied Spaces

		125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz	NC-Level
Original Mechanical Design	HSLS Audiology Lab (3122)	31	26	20	11	5	13	<15
	HSLS Fac. Lab (3122 B-C, H-L)	20	13	6	5	5	5	16
	Hearing-Aid Fitting Room (2207)	36	32	23	14	5	5	19
	Classroom (2302)*	39	36	32	23	14	5	26

* Space as four (4) terminal diffusers.

Table 9.2: Room noise produced by the original mechanical system.

NC Levels for Various Scenarios and System Designs

Scenario			NC Level [dB] within SLCC			
			HSLS Audiology Lab (3122)	HSLS Fac. Lab (3122B-C, H-L)	Classroom (2302)	Hearing-Aid Fitting (2207)
Design Goal (per Project Narrative) →			<25	<25	25	20
Original Mechanical System	Original Roof	Case 1: Average Outdoor Noise	25	20	20	16
		Case 2: Car driving by site	32	32	33	20
		Case 3: Large truck driving by site	32	32	33	19

Table 9.3: NC levels of combined noise for original roof, VAV system.

Table 9.3 shows that the original mechanical system and envelope designs effectively meet the acoustic design criteria for average noise outside. However, note that traffic outside the building causes the room noise to exceed the design NC level (red values).

9.4. CASE 2: PROPOSED MECHANICAL SYSTEM CONDITIONS

The proposed airside mechanical system delivers air directly from the supply fans in each AHU. The airflow is greatly reduced compared to the original system, ductwork is downsized, and noise producing VAV boxes are eliminated. As a result, sound attenuators are not necessary to quiet the mechanical system before air is delivered to the occupied space. Table 9.4 shows the contribution of this mechanical system to the room noise, and Table 9.5 shows the resulting combination of all noise sources.

DOAS Mechanical System Noise in Occupied Spaces

		125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz	NC-Level
Proposed Mechanical Design	HSLS Audiology Lab (3122)	34	27	20	11	5	5	<15
	HSLS Fac. Lab (3122 B-C, H-L)	39	32	24	13	5	5	19
	Hearing-Aid Fitting Room (2207)	21	14	7	5	5	5	<15
	Classroom (2302)	30	27	20	11	5	5	<15

Table 9.4: Room noise produced by the proposed DOAS system.

NC Levels for Original Roof and DOAS System Design

Scenario			NC Level [dB] within SLCC			
			HSLS Audiology Lab (3122)	HSLS Fac. Lab (3122B-C, H-L)	Classroom (2302)	Hearing-Aid Fitting (2207)
Design Goal (per Project Narrative) →			<25	<25	25	20
Proposed DOAS System	Original Roof	Case 1: Average Outdoor Noise	20	23	20	<15
		Case 2: Car driving by site	31	33	33	18
		Case 3: Large truck driving by site	30	31	32	<15

Table 9.5: NC Levels of combined noise for original roof, DOAS system.

The system and enclosure effectively meet the acoustic design criteria for average noise outside. However, much like the original system, traffic outside the building causes the room noise to exceed the design NC level. This result with values from Table 9.3 suggest that the outdoor traffic noise dominates the indoor noise and implies that something should to be done to increase the transmission loss of the outdoor noise through the envelope.

9.5. CASE 3: GREEN ROOF CONDITIONS

The Hearing Aid Clinic (Room 2207) does not experience the peak noise from traffic. This is also the only space analyzed is not exposed to the roof. The green roof is expected to act as a mass damper and acoustic insulator. Table 9.6 shows that all spaces with a green roof meet design noise criteria for all three ambient noise conditions.

NC Levels for Green Roof and Original System Designs

Scenario			NC Level [dB] within SLCC			
			HSLS Audiology Lab (3122)	HSLS Fac. Lab (3122B-C, H-L)	Classroom (2302)	Hearing-Aid Fitting (2207)
Design Goal (per Project Narrative) →			<25	<25	25	20
Original Mechanical System	Green Roof	Case 1: Average Outdoor Noise	25	17	20	
		Case 2: Car driving by site	25	20	21	
		Case 3: Large truck driving by site	25	21	23	

Table 9.6: NC Levels of combined noise for green roof, VAV system.

These results show that the green roof dampens outdoor noise enough to allow mechanical noise to govern in all ambient noise cases studied. Also, this shows that the original mechanical system is capable of maintaining optimum acoustic conditions while providing ventilation and thermal comfort.

9.6. CASE 4: OVERALL IMPACT OF PROPOSED DESIGN

While the green roof clearly benefits the room acoustics it is important to evaluate the combined effect of the green roof and proposed mechanical system. Table 9.7 shows the NC levels for these spaces with both design elements employed.

NC Levels for Green Roof and DOAS System Designs

Scenario			NC Level [dB] within SLCC			
			HSLS Audiology Lab (3122)	HSLS Fac. Lab (3122B-C, H-L)	Classroom (2302)	Hearing-Aid Fitting (2207)
Design Goal (per Project Narrative) →			<25	<25	25	20
Proposed DOAS System	Green Roof	Case 1: Average Outdoor Noise	20	20	20	
		Case 2: Car driving by site	20	23	20	
		Case 3: Large truck driving by site	20	23	20	

Table 9.7: NC levels of combined noise for green roof, DOAS system.

The proposed DOAS mechanical system does not necessarily provide notable improvements in room noise criteria under the green roof, unlike in case 2. However, the DOAS system does not exceed noise criteria and eliminates both the VAV box and sound attenuator.

Figure 9.1-9.3 below show combined space noise plotted on an NC-curve for the three ambient noise cases and three design combinations. They show that the green roof dampens outdoor noise enough to allow mechanical noise to govern and meet the noise criteria while the proposed mechanical system is quieter still. These results are typical for all spaces analyzed. The red line represents the NC-25 curve, blue represents the average ambient noise conditions, green represents the car driving by the site, and purple represents a large diesel truck driving by the site.

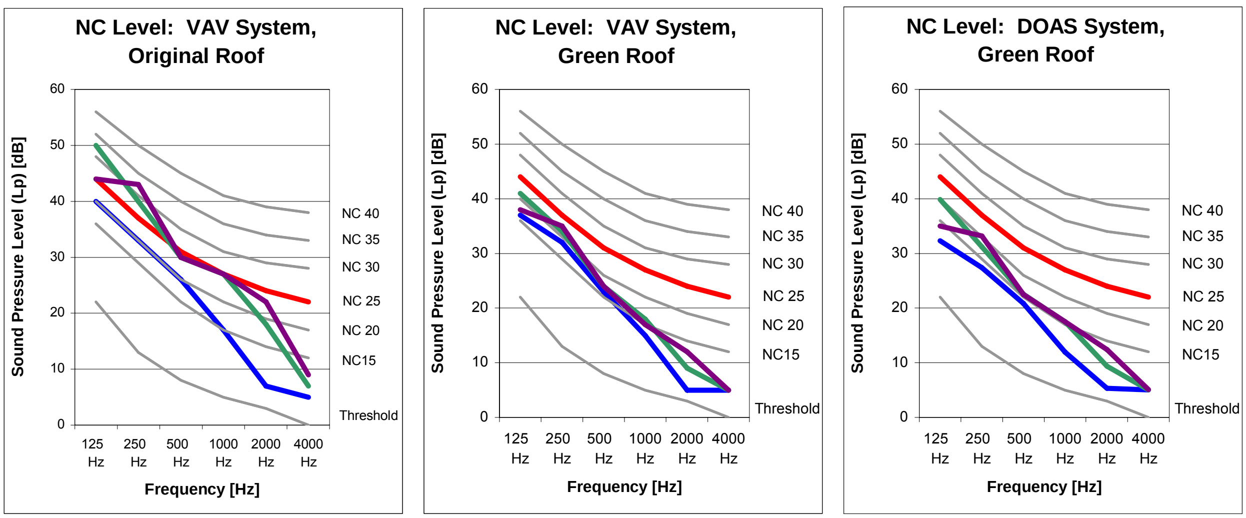


Figure 9.1-9.3: NC performance of original, VAV with green roof, and DOAS with green roof designs.

9.7. CONCLUSION

The calculations for room noise demonstrate the effect of the green roof, DOAS system, and the combination of the two systems on the acoustics within the SLCC. The results also show the dramatic impact of traffic noise on the acoustic conditions inside the SLCC.

Mechanical system noise dominates other noise sources during average ambient noise conditions (case 1) with the original roof design. However, as traffic noise increases outside the facility (cases 2, 3) the mechanical system noise is drowned out by the traffic noise. This result is more common for spaces with roof exposure rather than exterior wall exposure according to a comparison of results between the Hearing-Aid Fitting Room and the other spaces.

A green roof is able to mitigate peak traffic noises according to the results in Table 9.6 and Table 9.7. The additional mass of the green roof dampens low frequency vibrations (below 1 khz) that govern the NC Rating for these scenarios. Therefore under a green roof the mechanical system noise will always dominate the space acoustics.

The combination of the proposed mechanical system and green roof will slightly improve the NC levels for all typical cases in the SLCC. While the green roof dampens outdoor noise the proposed mechanical system reduces total noise in each space and eliminates the need for sound attenuators and lined ducts. As a result, all spaces meet or exceed the design noise criteria with a combination of both designs.

10. LEED RATING EVALUATION

In order to quantify the “green-ness” of a building, the United States Green Building Council (USGBC) utilizes a point system for sustainable design elements. The total points a building earns can receive a LEED Rating of Certified (26-32 points), Silver (33-38 points), Gold (39-51 points), or Platinum (greater than 51 points) (LEED). The SLCC is designed to LEED-NC v2.1 Standards. This section will evaluate the existing and proposed design with respect to this rating system.

10.1. ORIGINAL DESIGN RATING

A preliminary LEED analysis of the project design was conducted by the primary architect SmithGroup (Table 10.1). It is important to note that this facility has not gone through the LEED Submittal and Review Process and thus this analysis is not an official rating by the USGBC. Also, assumptions were made on several “maybe” points such as ID Credit 1. Here, innovation points were assumed to be garnered for an “educational case study” of visucentric design and for exceeding the recycled content requirement by at least 25%.

LEED™ Scorecard - Gallaudet University - SLCC

Y	?	N		Total Project Score	Possible Points
28	4	37		Total Project Score	69

Certified 26 to 32 points **Silver** 33 to 38 points **Gold** 39 to 51 points **Platinum** 52 or more points

Y	?	N		Sustainable Sites	Possible Points 14
6	1	7			
Y			Prereq 1	**Erosion & Sedimentation Control**	
1			Credit 1	**Site Selection**	1
		1	Credit 2	**Urban Redevelopment**	1
		1	Credit 3	**Brownfield Redevelopment**	1
1			Credit 4.1	**Alternative Transportation**, Public Transportation Access	1
		1	Credit 4.2	**Alternative Transportation**, Bicycle Storage & Changing Rooms	1
		1	Credit 4.3	**Alternative Transportation**, Alternative Fuel Refueling Stations	1
	1		Credit 4.4	**Alternative Transportation**, Parking Capacity	1
		1	Credit 5.1	**Reduced Site Disturbance**, Protect or Restore Open Space	1
1			Credit 5.2	**Reduced Site Disturbance**, Development Footprint	1
		1	Credit 6.1	**Stormwater Management**, Rate and Quantity	1
1			Credit 6.2	**Stormwater Management**, Treatment	1
1			Credit 7.1	**Landscape & Exterior Design to Reduce Heat Islands**, Non-Roof	1
1			Credit 7.2	**Landscape & Exterior Design to Reduce Heat Islands**, Roof	1
		1	Credit 8	**Light Pollution Reduction**	1

Y	?	N		Water Efficiency	Possible Points 5
4		1			
1			Credit 1.1	**Water Efficient Landscaping**, Reduce by 50%	1
1			Credit 1.2	**Water Efficient Landscaping**, No Potable Use or No Irrigation	1
		1	Credit 2	**Innovative Wastewater Technologies**	1
1			Credit 3.1	**Water Use Reduction**, 20% Reduction	1
1			Credit 3.2	**Water Use Reduction**, 30% Reduction	1

Y	?	N		Energy & Atmosphere	Possible Points 17
3	2	12			
Y			Prereq 1	**Fundamental Building Systems Commissioning**	
Y			Prereq 2	**Minimum Energy Performance**	
Y			Prereq 3	**CFC Reduction in HVAC&R Equipment**	
1	1		Credit 1.1	**Optimize Energy Performance**, 20% New / 10% Existing	2
		2	Credit 1.2	**Optimize Energy Performance**, 30% New / 20% Existing	2
		2	Credit 1.3	**Optimize Energy Performance**, 40% New / 30% Existing	2
		2	Credit 1.4	**Optimize Energy Performance**, 50% New / 40% Existing	2
		2	Credit 1.5	**Optimize Energy Performance**, 60% New / 50% Existing	2
		1	Credit 2.1	**Renewable Energy**, 5%	1
		1	Credit 2.2	**Renewable Energy**, 10%	1
		1	Credit 2.3	**Renewable Energy**, 20%	1
1			Credit 3	**Additional Commissioning**	1
1			Credit 4	**Ozone Depletion**	1
		1	Credit 5	**Measurement & Verification**	1
	1		Credit 6	**Green Power**	1

Y	?	N		Materials & Resources	Possible Points 13
6		7			
Y			Prereq 1	**Storage & Collection of Recyclables**	
		1	Credit 1.1	**Building Reuse**, Maintain 75% of Existing Shell	1
		1	Credit 1.2	**Building Reuse**, Maintain 100% of Existing Shell	1
		1	Credit 1.3	**Building Reuse**, Maintain 100% Shell & 50% Non-Shell	1
1			Credit 2.1	**Construction Waste Management**, Divert 50%	1
1			Credit 2.2	**Construction Waste Management**, Divert 75%	1
		1	Credit 3.1	**Resource Reuse**, Specify 5%	1
		1	Credit 3.2	**Resource Reuse**, Specify 10%	1
1			Credit 4.1	**Recycled Content**, Specify 25%	1
1			Credit 4.2	**Recycled Content**, Specify 50%	1
1			Credit 5.1	**Local/Regional Materials**, 20% Manufactured Locally	1
1			Credit 5.2	**Local/Regional Materials**, of 20% Above, 50% Harvested Locally	1
		1	Credit 6	**Rapidly Renewable Materials**	1
		1	Credit 7	**Certified Wood**	1

Y	?	N		Indoor Environmental Quality	Possible Points 15
6	1	8			
Y			Prereq 1	**Minimum IAQ Performance**	
Y			Prereq 2	**Environmental Tobacco Smoke** (ETS) **Control**	
		1	Credit 1	**Carbon Dioxide** (CO_2) **Monitoring**	1
		1	Credit 2	**Increase Ventilation Effectiveness**	1
1			Credit 3.1	**Construction IAQ Management Plan**, During Construction	1
	1		Credit 3.2	**Construction IAQ Management Plan**, Before Occupancy	1
1			Credit 4.1	**Low-Emitting Materials**, Adhesives & Sealants	1
1			Credit 4.2	**Low-Emitting Materials**, Paints	1
1			Credit 4.3	**Low-Emitting Materials**, Carpet	1
1			Credit 4.4	**Low-Emitting Materials**, Composite Wood	1
1			Credit 5	**Indoor Chemical & Pollutant Source Control**	1
		1	Credit 6.1	**Controllability of Systems**, Perimeter	1
		1	Credit 6.2	**Controllability of Systems**, Non-Perimeter	1
		1	Credit 7.1	**Thermal Comfort**, Comply with ASHRAE 55-1992	1
		1	Credit 7.2	**Thermal Comfort**, Permanent Monitoring System	1
		1	Credit 8.1	**Daylight & Views**, Daylight 75% of Spaces	1
		1	Credit 8.2	**Daylight & Views**, Views for 90% of Spaces	1

Y	?	N		Innovation & Design Process	Possible Points 5
3		2			
1			Credit 1.1	**Innovation**: Educational Case Study	1
		1	Credit 1.2	**Innovation**: Exceed Water Use Reduction by an additional 10%	1
1			Credit 1.3	**Innovation in Design**: Exceed Recycled content by an additional 25%	1
		1	Credit 1.4	**Innovation in Design**: Process Load Reduction	1
1			Credit 2	**LEED™ Accredited Professional**	1

Table 10.1: LEED Scorecard for original SLCC design.

The results of this LEED analysis show that the project expects to earn 28 points and thus a "LEED Certified" Rating. The point for Sustainable Sites Credit 7.2 for reducing the urban heat island effect is expected to be earned because the original design includes a highly reflective "cool roof." Some notable credits where points are not earned are the Sustainable Sites Credit 6.1 and at least eight (8) of ten (10) Energy and Atmosphere Credits (EA CR 1.1-1.5).

10.1.1. SUSTAINABLE SITES CREDIT 6.1

The intent for LEED-NC v2.1 SS CR 6.1 is to "limit disruption and pollution of natural water flows by managing stormwater runoff." In order to gain a point for this credit one of two requirements must be met: if the existing site is greater than 50% impervious by area, the post-construction site must have at least 25% less impervious area; if the existing site is less than 50% impervious by area, the post-construction site impervious area must not exceed that of the original site (LEED).

The calculations for the Sustainable Sites Credit 6.1 for the actual site design may be found in Table 10.2 below. The undeveloped site has over 65% impervious surface area so the post-construction site must have 25% less impervious area. These results show that the actual site design increases the impervious area of the site. While pavement area is reduced from the original site, the building (primarily the roof) increases the impervious area. Therefore this credit is not earned for the actual site design.

Annual Site Stormwater Runoff

	Runoff	Undeveloped Site			Actual Design		
	Coefficient	Area [SF]	% of Site	Runoff [CF]	Area [SF]	% of Site	Runoff [CF]
Total Pervious:	0.00	26665	34.4%	0	13260	17.1%	0
Total Impervious:	1.00	50935	**65.6%**	163968	64340	**82.9%**	207121
TOTAL		77600		**163968**	77600		**207121**

Percent Reduction in Pervious Area = **-26.3%**
LEED Points earned = **0**

Table 10.2: Sustainable Sites Credit 6.1 calculation for original SLCC design.

10.1.2. ENERGY & ATMOSPHERE CREDIT 1

The LEED-NC v2.1 EA Credit 1 is intended to "achieve increasing levels of energy performance above the prerequisite standard (ASHRAE Std. 90.1-1999) to reduce environmental impacts associated with excessive energy use" (LEED). Points are awarded for reducing the design energy cost relative to the energy cost budget for energy systems regulated by ASHRAE Std. 90.1-1999. For new buildings one (1) point is earned for a 15% reduction in annual energy cost, and an additional point is awarded for each 5% greater reduction up to ten (10) points for a 60% energy cost reduction.

The calculations for the energy budget case and original annual energy cost for EA CR 1 may be found in Table 10.3 and Table 10.4 on below, and the LEED points earned can be seen in Table 10.5 on page 59.

Budget Case Data

End Use	Energy Type	Electric [kWh]	Oil [kBtu]	Energy Use [10^3 Btu]	Annual Cost
Regulated					
Lighting	Electric	304,679		1,039,565	$27,543
Space Heating	Oil		756,460	756,460	$10,477
Space Heating	Electric				
Space Cooling	Electric			2,458,524	$65,138
Fans / Pumps	Electric	225,330		768,826	$20,370
Hot Water	Oil		300,750	300,750	$4,165
Subtotal Regulated (ECB')		530,009	1,057,210	5,324,125	$127,693
Non-Regulated					
Receptacles	Electric	978,965		3,340,229	$25,937
Space Heating	Oil		15,030	15,030	$208
Space cooling	Electric		1,294,311	1,294,311	$34,292
Fans / Pumps	Electric	23155		79,005	$2,093
Subtotal Non-Regulated		1,002,120	1,309,341	4,728,574	$62,531
Total Building		1,532,129	2,366,551	10,052,699	$190,224
ECB''				5,324,125	**$127,693**

Table 10.3: Energy cost budget for the SLCC.

Design Case LEED-NC EA CR 1 Summary (Cool Roof, VAV System)

End Use	Energy Type	Electric [kWh]	Oil [kBtu]	Energy Use [10^3 Btu]	Annual Cost
Regulated					
Lighting	Electric	223,695		763,246	$20,222
Space Heating	Oil		74,957	74,957	$1,038
Space Heating	Electric				
Space Cooling	Electric			2,167,121	$57,417
Fans / Pumps	Electric	176,864		603,461	$15,989
Subtotal Regulated (DEC')		400,559	74,957	3,608,785	$94,666
Non-Regulated					
Receptacles	Electric	978,965		3,340,229	$23,381
Space Heating	Oil		15,030	15,030	$199
Space cooling	Electric		1,294,311	1,294,311	$32,757
Fans / Pumps	Electric	23155		79,005	$1,999
Subtotal Non-Regulated		1,002,120	1,309,341	4,728,574	$58,336
Total Building		1,402,679	1,384,298	8,337,359	$153,002
DEC''				3,608,785	**$94,666**

Table 10.4: Annual energy costs of regulated, unregulated energy.

Design Case LEED-NC CR 7.1 Summary (Cool Roof, VAV System)						
Energy & Cost Summary by Fuel	**DEC'' Use** [10^3 Btu]	**DEC'' Cost** [$]	**ECB' Use** [10^3 Btu]	**ECB' Cost** [$]	**DEC'' / ECB'** Energy %	Cost %
Electricity	3,533,828	$93,628	4,266,915	$113,051	82.8%	82.8%
Oil	74,957	$1,038	1,057,210	$14,642	7.1%	7.1%
Total	**3,608,785**	**$94,666**	**5,324,125**	**$127,693**		
				Percent Savings = 100 x (ECB' $ - DEC'' $) / ECB' $ =		**25.9%**
				Credit 1 Points Earned =		**1**
				Credit 1 Points Possibly Earned =		**1**

Table 10.5: LEED-NC v2.1 Energy and Atmosphere Credit 1 calculation for original SLCC design.

These results confirm that the building energy use is expected to be about 25% less than the energy cost budget model. Because the second point of ES CR 1.1 requires at least a 25% reduction in energy this credit may or may not be earned. The submittal, review, and commissioning process would likely determine whether this point is earned or not.

10.2. PROPOSED DESIGN RATING

The proposals for this thesis should earn some of these points that were not counted towards the original design. The DOAS system alone saves significant energy and could earn five (5) and possibly six (6) EA Credit 1 points. The green roof and pervious pavement could also earn the SS Credit 6.1 point, and would help ensure the sixth EA Credit 1 point.

As a result, the proposed DOAS mechanical system in tandem with the proposed extensive green roof and new pavement will likely change the LEED Rating of the SLCC from Certified to Silver (Table 10.6).

LEED™ Scorecard - Gallaudet University - SLCC (Proposed Design)

Y	?	N	Total Project Score	Possible Points
34	4	31	Total Project Score	69

Certified 26 to 32 points **Silver** 33 to 38 points **Gold** 39 to 51 points **Platinum** 52 or more points

Y	?	N		Sustainable Sites	Possible Points 14
7	1	6			
Y			Prereq 1	**Erosion & Sedimentation Control**	
1			Credit 1	**Site Selection**	1
		1	Credit 2	**Urban Redevelopment**	1
		1	Credit 3	**Brownfield Redevelopment**	1
1			Credit 4.1	**Alternative Transportation**, Public Transportation Access	1
		1	Credit 4.2	**Alternative Transportation**, Bicycle Storage & Changing Rooms	1
		1	Credit 4.3	**Alternative Transportation**, Alternative Fuel Refueling Stations	1
	1		Credit 4.4	**Alternative Transportation**, Parking Capacity	1
		1	Credit 5.1	**Reduced Site Disturbance**, Protect or Restore Open Space	1
1			Credit 5.2	**Reduced Site Disturbance**, Development Footprint	1
1			Credit 6.1	**Stormwater Management**, Rate and Quantity	1
1			Credit 6.2	**Stormwater Management**, Treatment	1
1			Credit 7.1	**Landscape & Exterior Design to Reduce Heat Islands**, Non-Roof	1
1			Credit 7.2	**Landscape & Exterior Design to Reduce Heat Islands**, Roof	1
		1	Credit 8	**Light Pollution Reduction**	1

Y	?	N		Water Efficiency	Possible Points 5
4		1			
1			Credit 1.1	**Water Efficient Landscaping**, Reduce by 50%	1
1			Credit 1.2	**Water Efficient Landscaping**, No Potable Use or No Irrigation	1
		1	Credit 2	**Innovative Wastewater Technologies**	1
1			Credit 3.1	**Water Use Reduction**, 20% Reduction	1
1			Credit 3.2	**Water Use Reduction**, 30% Reduction	1

Y	?	N		Energy & Atmosphere	Possible Points 17
8	1	8			
Y			Prereq 1	**Fundamental Building Systems Commissioning**	
Y			Prereq 2	**Minimum Energy Performance**	
Y			Prereq 3	**CFC Reduction in HVAC&R Equipment**	
2			Credit 1.1	**Optimize Energy Performance**, 20% New / 10% Existing	2
2			Credit 1.2	**Optimize Energy Performance**, 30% New / 20% Existing	2
2			Credit 1.3	**Optimize Energy Performance**, 40% New / 30% Existing	2
		2	Credit 1.4	**Optimize Energy Performance**, 50% New / 40% Existing	2
		2	Credit 1.5	**Optimize Energy Performance**, 60% New / 50% Existing	2
		1	Credit 2.1	**Renewable Energy**, 5%	1
		1	Credit 2.2	**Renewable Energy**, 10%	1
		1	Credit 2.3	**Renewable Energy**, 20%	1
1			Credit 3	**Additional Commissioning**	1
1			Credit 4	**Ozone Depletion**	1
		1	Credit 5	**Measurement & Verification**	1
	1		Credit 6	**Green Power**	1

Y	?	N		Materials & Resources	Possible Points 13
6		7			
Y			Prereq 1	**Storage & Collection of Recyclables**	
		1	Credit 1.1	**Building Reuse**, Maintain 75% of Existing Shell	1
		1	Credit 1.2	**Building Reuse**, Maintain 100% of Existing Shell	1
		1	Credit 1.3	**Building Reuse**, Maintain 100% Shell & 50% Non-Shell	1
1			Credit 2.1	**Construction Waste Management**, Divert 50%	1
1			Credit 2.2	**Construction Waste Management**, Divert 75%	1
		1	Credit 3.1	**Resource Reuse**, Specify 5%	1
		1	Credit 3.2	**Resource Reuse**, Specify 10%	1
1			Credit 4.1	**Recycled Content**, Specify 25%	1
1			Credit 4.2	**Recycled Content**, Specify 50%	1
1			Credit 5.1	**Local/Regional Materials**, 20% Manufactured Locally	1
1			Credit 5.2	**Local/Regional Materials**, of 20% Above, 50% Harvested Locally	1
		1	Credit 6	**Rapidly Renewable Materials**	1
		1	Credit 7	**Certified Wood**	1

Y	?	N		Indoor Environmental Quality	Possible Points 15
6	1	8			
Y			Prereq 1	**Minimum IAQ Performance**	
Y			Prereq 2	**Environmental Tobacco Smoke** (ETS) **Control**	
		1	Credit 1	**Carbon Dioxide** (CO_2) **Monitoring**	1
		1	Credit 2	**Increase Ventilation Effectiveness**	1
1			Credit 3.1	**Construction IAQ Management Plan**, During Construction	1
	1		Credit 3.2	**Construction IAQ Management Plan**, Before Occupancy	1
1			Credit 4.1	**Low-Emitting Materials**, Adhesives & Sealants	1
1			Credit 4.2	**Low-Emitting Materials**, Paints	1
1			Credit 4.3	**Low-Emitting Materials**, Carpet	1
1			Credit 4.4	**Low-Emitting Materials**, Composite Wood	1
1			Credit 5	**Indoor Chemical & Pollutant Source Control**	1
		1	Credit 6.1	**Controllability of Systems**, Perimeter	1
		1	Credit 6.2	**Controllability of Systems**, Non-Perimeter	1
		1	Credit 7.1	**Thermal Comfort**, Comply with ASHRAE 55-1992	1
		1	Credit 7.2	**Thermal Comfort**, Permanent Monitoring System	1
		1	Credit 8.1	**Daylight & Views**, Daylight 75% of Spaces	1
		1	Credit 8.2	**Daylight & Views**, Views for 90% of Spaces	1

Y	?	N		Innovation & Design Process	Possible Points 5
3	1	1			
1			Credit 1.1	**Innovation**: Educational Case Study	1
	1		Credit 1.2	**Innovation**: Exceed Water Use Reduction by an additional 10%	1
1			Credit 1.3	**Innovation in Design**: Exceed Recycled content by an additional 25%	1
		1	Credit 1.4	**Innovation in Design**: Process Load Reduction	1
1			Credit 2	**LEED™ Accredited Professional**	1

Table 10.6: LEED Scorecard for SLCC with green roof and DOAS system designs.

10.2.1. ENERGY AND ATMOSPHERE CREDIT 1

The DOAS system in combination with the original cool roof produces an expected total energy cost savings of $24,344/yr. Table 10.7 shows the difference between regulated and unregulated costs that factor into Table 10.8.

Design Case LEED-NC EA CR 1 Summary (Green Roof, DOAS System)

End Use	Energy Type	Electric [kWh]	Oil [kBtu]	Energy Use [10^3 Btu]	Cost
Regulated					
Lighting	Electric	223,053		761,057	$20,164
Space Heating	Oil		24,233	24,233	$336
Space Heating	Electric				
Space Cooling	Electric			1,544,992	$40,934
Fans / Pumps	Electric	103,556		353,333	$9,361
Subtotal Regulated (DEC')		326,609	24,233	2,683,616	$70,795
Non-Regulated					
Receptacles	Electric	978,965		3,340,229	$23,226
Space Heating	Oil		15,030	15,030	$158
Space cooling	Electric		1,294,311	1,294,311	$26,090
Fans / Pumps	Electric	23155		79,005	$1,593
Subtotal Non-Regulated		1,002,120	1,309,341	4,728,574	$51,067
Total Building		1,328,729	1,333,574	7,412,190	$121,862
DEC''				2,683,616	**$70,795**

Table 10.7: Summary of energy use in the SLCC for the DOAS system and green roof.

Design Case LEED-NC EA CR 1 Summary (Green Roof, DOAS System)

Energy & Cost Summary by Fuel	DEC'' Use [10^3 Btu]	DEC'' Cost [$]	ECB' Use [10^3 Btu]	ECB' Cost [$]	DEC'' / ECB' Energy %	DEC'' / ECB' Cost %
Electricity	2,659,383	$70,460	4,266,915	$113,051	62.3%	62.3%
Oil	23,595	$327	1,057,210	$14,642	2.2%	2.2%
Total	**2,682,978**	**$70,786**	**5,324,125**	**$127,693**		

Percent Savings = 100 x (ECB' $ - DEC'' $) / ECB' $ = 44.6%

Credit 1 Points Earned = 6

Credit 1 Points Possibly Earned = 0

Table 10.8: EA Credit 1 points earned with DOAS system and green roof.

10.2.2. SUSTAINABLE SITES CREDIT 6.1

The addition of the green roof has a significant impact on the amount of stormwater drained from the SLCC site. It accounts for an approximately 25% reduction of impervious area compared to the original SLCC design with the cool roof (Table 6.4) and an approximately 5% reduction of impervious area compared to the pre-construction site. This is not enough, however, to earn the LEED SS CR 6.1 Point as there needs to be a 25% reduction in impervious area on the site compared to the pre-construction site. This can be achieved by replacing the parking pavement with pervious concrete (Figure 10.1), thus earning the LEED point (Table 10.9). The total reduction in impervious area can be improved to over 42% if all stormwater drainage from the roof is captured and used to water the roof (Table 10.10). This could potentially be worthy of an Innovation & Design Credit point, but this LEED analysis conservatively assumes that this point would not be awarded.

Figure 10.1: Pervious concrete.

Annual Site Stormwater Runoff

	Runoff Coefficient	Undeveloped Site		Green Roof, Perv. Parking		
		Area [SF]	Runoff [CF]	Area [SF]	% of Total	Runoff [CF]
Total Pervious:	0.00	26665	0	44430	57.3%	0
Total Impervious:	1.00	50935	163968	33171	**42.7%**	106781
TOTAL		77600	**163968**	77600		**122427**

Percent Reduction in Pervious Area = **25.3%**

LEED Points earned = **1**

Table 10.9: Sustainable Sites Credit 6.1 calculation for green roof, pervious parking.

Annual Site Stormwater Runoff

	Runoff Coefficient	Undeveloped Site		Green Roof, Perv. Parking		
		Area [SF]	Runoff [CF]	Area [SF]	% of Total	Runoff [CF]
Asphalt/Concrete:	0.95	42550	130127	22260	28.7%	68076
Pervious Concrete	0.60	0	0	8100	10.4%	15645
Building (roof):	0.00	0	0	9130	11.8%	0
Grass:	0.25	28050	22574	13400	17.3%	10784
Green Roof:	0.00	0	0	24710	31.8%	0
Other:	0.50	7000	11267	0	0.0%	0
Total Pervious:	0.00	26665	0	53103	68.4%	0
Total Impervious:	1.00	50935	163968	24497	**31.6%**	78860
TOTAL		77600	**163968**	77600		**94505**

Percent Reduction in Pervious Area = **42.4%**

LEED Points earned = **1**

LEED Points possibly earned = **1**

Table 10.10: Sustainable Sites Credit 6.1 calculation for proposed design and stormwater reuse.

11. COST ANALYSIS

The proposed system requires the addition of many design elements and the elimination of others. The goal of the proposed systems is also to reduce energy use and costs, which factor into the payback period of the proposed design. This section analyzes the costs associated with the construction of the original VAV and "cool roof" design and the proposed DOAS and green roof design..

11.1. ORIGINAL DESIGN COST

Heery International prepared a cost estimate when 100% construction documents were completed in September, 2006. The breakdown of the estimated project cost by CSI Division is included in Table 11.1 below.

100% Cost Estimate

CSI Division	Description	Estimate	Per SF*	$ %
1	General Requirements, OH&P	$3,089,683	$35.23	13.5%
2	Site Work	$1,892,332	$21.58	8.3%
3	Concrete Work	$1,450,126	$16.53	6.4%
4	Masonry Work	$672,143	$7.66	2.9%
5	Metals	$2,457,684	$28.02	10.8%
6	Wood and Plastics	$297,970	$3.40	1.3%
7	Thermal and Moisture Protection	$1,331,078	$15.18	5.8%
8	Doors and Windows	$1,351,056	$15.40	5.9%
9	Finishes	$2,407,854	$27.45	10.6%
10	Specialties	$145,529	$1.66	0.6%
11	Equipment	$69,701	$0.79	0.3%
12	Furnishings	$33,018	$0.38	0.1%
13	Special Construction	$0	$0.00	0.0%
14	Conveying Systems	$274,720	$3.13	1.2%
15	Mechanical Systems	$3,835,441	$43.73	16.8%
16	Electrical Systems	$2,364,277	$26.96	10.4%
SUB-TOTAL		$21,672,612	$247.11	
5.25% Escalation to Const.:		$22,810,424	$260.08	

*Area [SF] = 87,704

Table 11.1: Total project cost estimate (Heery).

11.2. PROPOSED DESIGN FIRST COST

Based on the costs estimates of the original design and proposed changes, an itemized cost analysis (Table 11.2) shows an additional $1.83M first cost for the proposed DOAS system and green roof. The breakdown of the project cost by CSI division may be seen in Table 11.3. This increase in first cost equates to about a 4.74% increase in the total project first cost (Table 11.4).

Itemized Cost of Proposed Systems

CSI Code	Description	Original Design				Proposed Design				Additional Cost
		Quantity	Unit	Unit Cost	Total	Quantity	Unit	Unit Cost	Total	
02510	Chilled Water Supply & Return Piping	1	LS	$182,500.00	$182,500	1	LS	$209,875.00	$209,875	$27,375
02630	Storm Drains Structures	11	EA	$3,052.50	$33,578	7	EA	$3,052.50	$21,368	-$12,210
2	**Site Work Changes SUB-TOTAL**				$216,078				$231,243	**$15,165**
07202	Storm Drainage System	900	LF	$35.00	$31,500	900	LF	$28.00	$25,200	-$6,300
07203	Asphalt Paving	1,220	SY	$35.25	$43,005	1,220	SF	$40.00	$48,800	$5,795
07200	Green Roof	0	SF	$7.00	$0	24,400	SF	$7.00	$170,800	$170,800
07500	Waterproofing	24,400	SF	$5.09	$124,196	24,400	SF	$10.00	$244,000	$119,804
7	**T&M Protection Changes SUB-TOTAL**				$198,701				$488,800	**$290,099**
09510	Suspended Acoustic Ceilings	46,566	SF	$4.07	$189,524	41,966	SF	$4.07	$170,802	-$18,722
9	**Finishes Changes SUB-TOTAL**				$189,524				$170,802	**-$18,722**
15160	Booster Pump Equip. (to water roof)	1	EA	$12,000.00	$12,000	2	EA	$8,040.00	$16,080	$4,080
15160	Roof Drainage System	1,445	LF	$42.21	$60,993	1,445	LF	$30.15	$43,567	-$17,427
15514	Plate & Frame Heat Exchanger	0	EA	$32,500.00	$0	1	EA	$32,500.00	$32,500	$32,500
15114	Energy Recovery Ventilator	0	EA	$25,000.00	$0	6	EA	$25,000.00	$150,000	$150,000
15000	Chilled Water Expansion Tank	1	EA	$3,500.00	$3,500	1	EA	$5,000.00	$5,000	$1,500
15000	Chilled Water Air Separator	1	EA	$4,000.00	$4,000	1	SF	$5,500.00	$5,500	$1,500
15181	Hot Water Pipe w/ Insulation	7,834	LF	$25.50	$199,767	23,502	LF	$25.50	$599,301	$399,534
15181	Chilled Water Pipe w/ Insulation	1,862	LF	$48.50	$90,307	9,310	LF	$48.50	$451,535	$361,228
15110	Valves and Fittings	1	LS	$63,024.00	$63,024	1	LS	$88,233.60	$88,234	$25,210
15185	Chilled Water Pumps (w/ VFD)	2	EA	$13,653.00	$27,306	5	EA	$13,653.00	$68,265	$40,959
15185	Hot Water Pumps (w/ VFD)	7	EA	$3,693.00	$25,851	10	EA	$3,693.00	$36,930	$11,079
15855	Duct Heating Coils	5	EA	$1,000.00	$5,000	0	EA	$5,000.00	$0	-$5,000
15725	Air Handling Units	6	EA	$29,525.00	$177,150	5	EA	$16,238.75	$81,194	-$95,956
15840	VAV Boxes	140	EA	$810.00	$113,400	0	EA	$810.00	$0	-$113,400
15840	Chilled Beams	0	LF	$165.00	$0	2,300	LF	$165.00	$379,500	$379,500
15080	Ductwork Blanket Insulation	41,884	SF	$2.50	$104,710	25,130	EA	$2.50	$62,826	-$41,884
15080	Ductwork Internal Soud Lining	23,167	SF	$5.00	$115,835	10,425	EA	$5.00	$52,126	-$63,709
15836	Fans & Ventilators	17	EA	$4,250.00	$72,250	16	EA	$2,337.50	$37,400	-$34,850
15071	Sound Attenuators	55	EA	$755.00	$41,525	0	EA	755	$0	-$41,525
15815	Ductwork	94,878	LBS	$7.25	$687,866	61671	EA	$7.25	$447,113	-$240,753
15855	Grilles/Registers/Diffusers	549	EA	$115.00	$63,135	686	EA	$115.00	$78,919	$15,784
15855	Linear Diffusers	655	LF	$70.00	$45,850	262	EA	$70.00	$18,340	-$27,510
15	**Mechanical Systems Changes SUB-TOTAL**				$1,913,469				$2,654,328	**$740,859**
	PROPOSED SYSTEM CHANGES SUB-TOTAL				**$2,517,771**				**$3,545,172**	**$1,027,401**

Table 11.2: Itemized cost of proposed changes to SLCC design.

Proposed 100% Cost Estimate

CSI Division	Description	Estimate	Per SF*	$ %
1	General Requirements, OH&P	$3,089,683	$35.23	12.9%
2	Site Work	$1,907,497	$21.75	8.0%
3	Concrete Work	$1,450,126	$16.53	6.1%
4	Masonry Work	$672,143	$7.66	2.8%
5	Metals	$2,457,684	$28.02	10.3%
6	Wood and Plastics	$297,970	$3.40	1.2%
7	Thermal and Moisture Protection	$1,621,177	$18.48	6.8%
8	Doors and Windows	$1,351,056	$15.40	5.7%
9	Finishes	$2,389,132	$27.24	10.0%
10	Specialties	$145,529	$1.66	0.6%
11	Equipment	$69,701	$0.79	0.3%
12	Furnishings	$33,018	$0.38	0.1%
13	Special Construction	$0	$0.00	0.0%
14	Conveying Systems	$274,720	$3.13	1.1%
15	Mechanical Systems	$4,576,300	$52.18	19.2%
16	Electrical Systems	$2,364,277	$26.96	9.9%
SUB-TOTAL		$22,700,013	$258.83	
5.25% Escalation to Const.:		$23,891,764	$272.41	

*Area [SF] = 87,704

Table 11.3: Total proposed project cost estimate.

Comparison of Design First Costs

	First Cost	Change	% Change
Original SLCC Design	$22,810,424	0	0.00%
Proposed SLCC Design	$23,891,764	$1,081,340	4.74%

Table 11.4: Comparison of design first costs.

Table 11.5: Additional parallel cooling system cost (green roof).

11.3. ENERGY & MAINTENANCE COSTS

Based on the energy cost data from the Carrier HAP models annual energy costs estimates are approximated for both the original design and proposed design. The proposed system saves approximately $25.000 per year in energy costs. Regular maintenance is also an issue. The expected annual maintenance cost of the mechanical system is assumed to be approximately 3-5% of the mechanical system first cost. The proposed system is assumed to have less maintenance costs because there is smaller equipment and fewer moving parts. Regular overhauls of the system are assumed to occur every 5 years with major overhauls every 20 years. Finally, the green roof is assumed to require approximately the same total annual maintenance cost over its life because the plants are relatively self sustaining, but may need replacement. The cool roof, however, requires regular cleaning to maintain the high reflectance and thermal performance. Table 11.6 shows the O&M costs for the original design and Table 11.7 shows the O&M costs for the proposed design.

Operation and Maintenance Costs (Original Design)

Description	Unit	Total	Comment
Electricity	$/yr	$61,591.00	
Chilled Water	$/yr	$90,174.00	
Hot Water	$/yr	$1,237.00	
Mech. System Maintenance	$/yr	$115,063.23	3% of first cost
Mech. System Repairs/Replacement	$/5yr	$575,316.15	15% of first cost
Mech. System Repairs/Replacement	$/20yr	$2,876,580.75	75% of first cost
Roof Maintenance	$/yr	$9,935.05	5% of first cost
Roof Replacement	$/20yr	$198,701.00	100% of first cost

Table 11.6: Original design operation and maintenance costs.

Operation and Maintenance Costs (Proposed Design)

Description	Unit	Total	Comment
Electricity	$/yr	$54,344.00	
Chilled Water	$/yr	$67,024.00	
Hot Water	$/yr	$494.00	
Mech. System Maintenance	$/yr	$137,289.01	3% of first cost
Mech. System Repairs/Replacement	$/5yr	$686,445.03	15% of first cost
Mech. System Repairs/Replacement	$/20yr	$3,432,225.17	75% of first cost
Roof Maintenance	$/yr	$9,776.00	2% of first cost
Roof Replacement	$/20yr	$0.00	0% of first cost

Table 11.7: Original design operation and maintenance costs.

11.4. SIMPLE PAYBACK PERIOD

Based on the first cost and annual energy, operation, and maintenance costs, a simple payback period of 4.02 years is expected. The desired payback period is typically less than 3 years, but since the building owner is an institution a slightly longer payback period may be justified. Also, there are additional intangible benefits of the proposed system such as an increased LEED Rating and improved interior acoustics.

Simple Payback Period

	First Cost	Change in First Cost	O&M Cost	Payback (yrs.)
Original Design	$22,810,424	$0	$278,000	0.00
Proposed Design	$23,891,764	$1,081,340	$268,927	4.02

Table 11.8: Simple payback period for proposed design.

12. CONCLUSIONS & RECOMMENDATIONS

The findings of this thesis report suggest that adding an extensive green roof to the SLCC would have many benefits on the sustainability of the building. The acoustics, stormwater retention, and urban heat island effect are improved with its installation without the need to redesign the structure. However, there would not be significant energy savings because the original roof included a highly reflective "cool roof."

DOAS System is a viable alternative to the original VAV system. There are significant energy use and cost savings expected, and much of the mechanical equipment can be downsized. The proposed system supplies 30% more outdoor air than the ASHRAE Standard 62.1 minimum, yet delivers only about 20% of the air to each space that the original VAV system does. Savings in fan energy result from this decrease in air distribution, but these savings are negated by the increase in pumping energy for the chilled water supply to chilled beam units in each space.

A combination of these systems achieves the goals for this thesis of improving energy efficiency and acoustics. The two systems together reduce regulated energy costs by about 44%. Also, the smaller amount of air distributed throughout the building and added acoustic insulation of the green roof are likely to provide optimum conditions based on design noise criteria. The complete proposed design would also earn enough extra LEED points to raise the SLCC's rating from "Certified" to "Silver."

The expected first cost is expected to increase by about $1.83M, but savings in energy, operation, and maintenance costs allow the proposed design to have a 4 year payback. With all of these benefits, it is suggested that the SLCC be redesigned to follow the proposals set forth in this thesis.

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Appendix A

Green Roof Thermal Analysis

Average Peak Instantaneous Solar Radiation

MONTH	n	δ	Θz	G_{on} [W/m^2]	G_b [W/m^2]	G_d [W/m^2]	G_{total} [W/m^2]
JANUARY	17	-20.92	59.80	1410.19	417.29	69.57	486.86
FEBRUARY	47	-12.95	51.83	1398.13	508.19	84.72	592.91
MARCH	75	-2.42	41.30	1379.46	609.61	101.63	711.24
APRIL	105	9.41	29.47	1356.42	694.67	115.81	810.48
MAY	135	18.79	20.09	1336.15	738.13	123.06	861.19
JUNE	162	23.09	15.79	1324.67	749.77	125.00	874.77
JULY	198	21.18	17.70	1323.49	741.65	123.65	865.30
AUGUST	228	13.45	25.43	1335.03	709.23	118.24	827.47
SEPTEMBER	248	6.18	32.70	1347.65	667.09	111.22	778.31
OCTOBER	288	-9.60	48.48	1377.96	537.29	89.58	626.87
NOVEMBER	318	-18.91	57.79	1398.13	438.34	73.08	511.41
DECEMBER	344	-23.05	61.93	1409.20	390.05	65.03	455.07

Location: Washington, DC

A [km] = 0.125	φ = 38.88	ω = 0	
τ_b = 0.588	a_0^* = 0.14033	r_0 = 0.97	a_0 = 0.13612
τ_d = 0.098	a_1^* = 0.74731	r_1 = 0.99	a_1 = 0.73984
G_{sc} [W/m^2] = 1367.0	k^* = 0.37590	r_k = 1.02	k = 0.38342

Average Daytime Peak Heat Gain (Cooling Load) Through Typical Roof

Month → Energy Flux Mode↓	January	February	March	April	May	June	July	August	September	October	November	December	ANNUAL
$Shortwave_{dn}$ [W/m²]:	486.9	592.9	711.2	810.5	861.2	874.8	865.3	827.5	778.3	626.9	511.4	455.1	700.5
$Shortwave_{up}$ [W/m²]:	-97.4	-118.6	-142.2	-162.1	-172.2	-175.0	-173.1	-165.5	-155.7	-125.4	-102.3	-91.0	-140.1
$Longwave_{dn}$ [W/m²]:	209.0	215.2	234.2	253.8	273.1	291.4	299.9	296.3	281.4	258.6	237.6	217.1	255.8
$Longwave_{up}$ [W/m²]:	-328.0	-337.4	-366.1	-395.5	-424.4	-451.6	-464.1	-458.8	-436.7	-402.6	-371.2	-340.3	-398.3
Q_{conv} [W/m²]:	-85.0	-87.7	-91.1	-88.4	-80.2	-77.5	-73.3	-71.8	-74.0	-76.1	-80.2	-82.3	-80.6
Q_{lat} [W/m²]:	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Q_{total} [W/m²]:	185.5	264.4	346.0	418.3	457.5	462.2	454.8	427.6	393.4	281.4	195.3	158.6	337.3
Q_{total} [BTU/hr-ft²]:	**58.8**	**83.8**	**109.7**	**132.6**	**145.0**	**146.5**	**144.2**	**135.6**	**124.7**	**89.2**	**61.9**	**50.3**	**106.9**

Ambient Conditions:

	January	February	March	April	May	June	July	August	September	October	November	December	ANNUAL
T_{OA} [K]:	278.9	280.9	286.8	292.4	297.7	302.4	304.5	303.7	299.9	293.8	287.8	281.5	292.6
T_{OA} [°F]:	42.3	45.9	56.5	66.7	76.2	84.7	88.5	86.9	80.1	69.1	58.3	47	66.9
T_{roof} [K]:	283.2	285.2	291.0	296.7	302.0	306.7	308.8	307.9	304.2	298.0	292.0	285.8	296.8
T_{roof} [°F]:	50	53.6	64.2	74.4	83.9	92.4	96.2	94.6	87.8	76.8	66	54.7	74.6
T_{RA} [K]:	295.4	295.4	295.4	298.7	298.7	298.7	298.7	298.7	298.7	298.7	295.4	295.4	297.3
T_{RA} [°F]:	72	72	72	78	78	78	78	78	78	78	72	72	75.5
P_{vapor} [millibars]:	0.0089	0.0101	0.0151	0.0218	0.0298	0.0384	0.0426	0.0408	0.0336	0.0237	0.0161	0.0106	0.0244
U_{wind} [m/s]:	4.5	4.6	4.9	4.7	4.2	4.0	3.7	3.6	3.8	3.9	4.2	4.3	4.2
Direct Solar (G_b):	417.29	508.19	609.61	694.67	738.13	749.77	741.65	709.23	667.09	537.29	438.34	390.05	600.4
Diffuse Solar (G_d):	69.57	84.72	101.63	115.81	123.06	125	123.65	118.24	111.22	89.58	73.08	65.03	100.1
Hours of Sun/Day:	10.3	11.3	12.2	13.1	14.0	14.9	14.0	13.1	12.2	11.3	10.3	9.43	4444.0
Avg. Precipitation [in]:	2.72	2.71	3.17	2.71	3.66	3.38	3.80	3.91	3.31	3.02	3.12	3.12	38.63

Properties/Constants:

albedo [α]:	0.20	
Stefan Boltzmann const. [σ]:	5.67E-08	[W/m²-K⁴]
Thermal Conductivity [k]:	0.38	[W/m-K]
Longwave Emissivity [ε_s]:	0.9	
[γ_1]:	12	
Convective Heat Transfer Coeff.[γ_1]:	6	[W/m²-K]
Convective Heat Transof Water [ρ]:	10	[W/m²-K]
Evaporation Enthalpy [h_e]:	2257	[J/kg]
Bowen Ratio:	0.17	

ENERGY BALANCE CALCULATIONS FOR A COOL ROOF, DAYTIME

Average Daytime Peak Heat Gain (Cooling Load) Through Cool Roof

Month → Energy Flux Mode↓	January	February	March	April	May	June	July	August	September	October	November	December	ANNUAL
$Shortwave_{dn}$ [W/m^2]:	486.9	592.9	711.2	810.5	861.2	874.8	865.3	827.5	778.3	626.9	511.4	455.1	700.5
$Shortwave_{up}$ [W/m^2]:	-379.8	-462.5	-554.8	-632.2	-671.7	-682.3	-674.9	-645.4	-607.1	-489.0	-398.9	-355.0	-546.4
$Longwave_{dn}$ [W/m^2]:	209.0	215.2	234.2	253.8	273.1	291.4	299.9	296.3	281.4	258.6	237.6	217.1	255.8
$Longwave_{up}$ [W/m^2]:	-328.0	-337.4	-366.1	-395.5	-424.4	-451.6	-464.1	-458.8	-436.7	-402.6	-371.2	-340.3	-398.3
Q_{conv} [W/m^2]:	-85.0	-87.7	-91.1	-88.4	-80.2	-77.5	-73.3	-71.8	-74.0	-76.1	-80.2	-82.3	-80.6
Q_{lat} [W/m^2]:	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Q_{total} [W/m^2]:	-96.9	-79.5	-66.5	-51.8	-42.0	-45.1	-47.1	-52.3	-58.0	-82.2	-101.3	-105.4	-69.0
Q_{total} [BTU/hr-ft^2]:	**-30.7**	**-25.2**	**-21.1**	**-16.4**	**-13.3**	**-14.3**	**-14.9**	**-16.6**	**-18.4**	**-26.1**	**-32.1**	**-33.4**	**-21.86891**

Ambient Conditions:

	January	February	March	April	May	June	July	August	September	October	November	December	ANNUAL
T_{OA} [K]:	278.9	280.9	286.8	292.4	297.7	302.4	304.5	303.7	299.9	293.8	287.8	281.5	292.6
T_{OA} [°F]:	42.3	45.9	56.5	66.7	76.2	84.7	88.5	86.9	80.1	69.1	58.3	47	66.9
T_{roof} [K]:	283.2	285.2	291.0	296.7	302.0	306.7	308.8	307.9	304.2	298.0	292.0	285.8	296.8
T_{roof} [°F]:	50	53.6	64.2	74.4	83.9	92.4	96.2	94.6	87.8	76.8	66	54.7	74.6
T_{RA} [K]:	295.4	295.4	295.4	298.7	298.7	298.7	298.7	298.7	298.7	298.7	295.4	295.4	297.3
T_{RA} [°F]:	72	72	72	78	78	78	78	78	78	78	72	72	75.5
P_{vapor} [millibars]:	0.0089	0.0101	0.0151	0.0218	0.0298	0.0384	0.0426	0.0408	0.0336	0.0237	0.0161	0.0106	0.0244
U_{wind} [m/s]:	4.5	4.6	4.9	4.7	4.2	4.0	3.7	3.6	3.8	3.9	4.2	4.3	4.2
Direct Solar (G_b):	417.29	508.19	609.61	694.67	738.13	749.77	741.65	709.23	667.09	537.29	438.34	390.05	600.4
Diffuse Solar (G_d):	69.57	84.72	101.63	115.81	123.06	125	123.65	118.24	111.22	89.58	73.08	65.03	100.1
Hours of Sun/Day:	10.3	11.3	12.2	13.1	14.0	14.9	14.0	13.1	12.2	11.3	10.3	9.43	4444.0
Avg. Precipitation [in]:	2.72	2.71	3.17	2.71	3.66	3.38	3.80	3.91	3.31	3.02	3.12	3.12	38.63

Properties/Constants:

albedo [α]:	0.78	
Stefan Boltzmann const. [σ]:	5.67E-08	[W/m^2-K^4]
Thermal Conductivity [k]:	3.62305194	[W/m-K]
Longwave Emissivity [ε_s]:	0.9	
Convective Heat Transfer Coeff.[γ_1]:	12	
Convective Heat Transfer Coeff.[γ_2]:	6	[W/m^2-K]
Density of Water [ρ]:	10	[W/m^2-K]
Evaporation Enthalpy [h_e]:	2257	[J/kg]
Bowen Ratio:	0.17	

ENERGY BALANCE CALCULATIONS FOR A GREEN ROOF, NIGHT

Average Nightime Base Heat Gain (Cooling Load) Through Green Roof

Month → Energy Flux Mode↓	January	February	March	April	May	June	July	August	September	October	November	December	ANNUAL
$Shortwave_{dn}$ [W/m^2]:	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$Shortwave_{up}$ [W/m^2]:	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$Longwave_{dn}$ [W/m^2]:	184.2	187.7	201.4	216.1	234.4	253.4	263.2	260.4	245.6	222.9	207.0	191.7	222.5
$Longwave_{up}$ [W/m^2]:	-289.9	-296.5	-318.8	-342.7	-372.0	-402.3	-418.8	-412.9	-389.0	-353.2	-327.5	-302.8	-352.5
Q_{conv} [W/m^2]:	-42.8	-45.6	-48.3	-51.1	-53.9	-56.7	-59.4	-56.7	-53.9	-51.1	-48.3	-45.6	-51.1
Q_{lat} [W/m^2]:	-122.2	-130.2	-138.1	-146.0	-154.0	-161.9	-169.8	-161.9	-154.0	-146.0	-138.1	-130.2	-146.1
Q_{total} [W/m^2]:	-270.7	-284.5	-303.9	-323.8	-345.5	-367.5	-384.8	-371.1	-351.3	-327.4	-306.9	-286.8	-327.2
Q_{total} [BTU/hr-ft^2]:	**-85.8**	**-90.2**	**-96.3**	**-102.6**	**-109.5**	**-116.5**	**-122.0**	**-117.6**	**-111.4**	**-103.8**	**-97.3**	**-90.9**	**-103.7**

Ambient Conditions:

	January	February	March	April	May	June	July	August	September	October	November	December	ANNUAL
T_{OA} [K]:	270.3	271.5	276.3	281.2	286.8	292.3	295.0	294.3	290.1	283.3	278.2	273.0	282.7
T_{OA} [°F]:	26.8	29.1	37.7	46.4	56.6	66.5	71.4	70	62.5	50.3	41.1	31.7	49.3
T_{roof} [K]:	274.5	276.1	281.2	286.3	292.2	298.0	301.0	299.9	295.5	288.4	283.0	277.5	287.9
T_{roof} [°F]:	34.5	37.3	46.4	55.6	66.3	76.7	82.1	80.2	72.2	59.5	49.8	39.9	58.5
T_{RA} [K]:	293.2	293.2	293.2	300.9	300.9	300.9	300.9	300.9	300.9	300.9	293.2	293.2	297.7
T_{RA} [°F]:	68	68	68	82	82	82	82	82	82	82	68	68	76.2
P_{vapor} [millibars]:	0.0065	0.0066	0.0077	0.0103	0.0151	0.0217	0.0256	0.0244	0.0188	0.0119	0.0086	0.0068	0.0137
U_{wind} [m/s]:	4.5	4.6	4.9	4.7	4.2	4.0	3.7	3.6	3.8	3.9	4.2	4.3	4.2
Direct Solar (G_b):	0	0	0	0	0	0	0	0	0	0	0	0	0.0
Diffuse Solar (G_d):	0	0	0	0	0	0	0	0	0	0	0	0	0.0
Hours of Sun/Day:	10.3	11.3	12.2	13.1	14.0	14.9	14.0	13.1	12.2	11.3	10.3	9.43	4444.0
Avg. Precipitation [in]:	2.72	2.71	3.17	2.71	3.66	3.38	3.80	3.91	3.31	3.02	3.12	3.12	38.63
Supp. Watering [in]:	0.00	0.00	0.00	0.68	0.92	0.85	0.95	0.98	0.83	0.00	0.00	0.00	5.19

0.009286

Properties/Constants:

albedo [α]:	0.25	
Stefan Boltzmann const. [σ]:	5.67E-08	[W/m^2-K^4]
Thermal Conductivity [k]:	0.38	[W/m^2-K]
Longwave Emissivity [ε_s]:	0.9	
onvective Heat Transfer Coeff.[γ_1]:	6	[W/m^2-K]
onvective Heat Transfer Coeff.[γ_2]:	10	[W/m^2-K]
Density of Water [ρ]:	998	[kg/m^3]
Evaporation Enthalpy [h_e]:	2257	[J/kg]
Bowen Ratio:	0.35	

ENERGY BALANCE CALCULATIONS FOR A GREEN ROOF, NIGHT

Average Nightime Base Heat Gain (Cooling Load) Through Cool Roof

Month → / Energy Flux Mode ↓	January	February	March	April	May	June	July	August	September	October	November	December	ANNUAL
$Shortwave_{dn}$ [W/m²]:	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$Shortwave_{up}$ [W/m²]:	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$Longwave_{dn}$ [W/m²]:	184.2	187.7	201.4	216.1	234.4	253.4	263.2	260.4	245.6	222.9	207.0	191.7	222.5
$Longwave_{up}$ [W/m²]:	-289.9	-297.7	-321.4	-346.7	-377.7	-409.9	-428.1	-420.6	-394.9	-357.3	-330.1	-304.0	-356.8
Q_{conv} [W/m²]:	-85.0	-99.1	-114.8	-122.9	-121.9	-127.8	-130.3	-118.5	-112.4	-105.7	-101.1	-93.0	-111.1
Q_{lat} [W/m²]:	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Q_{total} [W/m²]:	-190.7	-209.2	-234.8	-253.5	-265.2	-284.3	-295.3	-278.7	-261.7	-240.0	-224.1	-205.2	-245.4
Q_{total} [BTU/hr-ft²]:	**-60.5**	**-66.3**	**-74.4**	**-80.3**	**-84.1**	**-90.1**	**-93.6**	**-88.4**	**-83.0**	**-76.1**	**-71.1**	**-65.1**	**-77.8**

Ambient Conditions:

T_{OA} [K]:	270.3	271.5	276.3	281.2	286.8	292.3	295.0	294.3	290.1	283.3	278.2	273.0	282.7
T_{OA} [°F]:	26.8	29.1	37.7	46.4	56.6	66.5	71.4	70	62.5	50.3	41.1	31.7	49.3
T_{roof} [K]:	274.5	276.4	281.7	287.1	293.3	299.4	302.7	301.3	296.6	289.3	283.6	277.8	288.7
T_{roof} [°F]:	34.5	37.8	47.4	57.1	68.3	79.2	85.1	82.7	74.2	61	50.8	40.4	60.0
T_{RA} [K]:	293.2	293.2	293.2	300.9	300.9	300.9	300.9	300.9	300.9	300.9	293.2	293.2	297.7
T_{RA} [°F]:	68	68	68	82	82	82	82	82	82	82	68	68	76.2
P_{vapor} [millibars]:	0.0065	0.0066	0.0077	0.0103	0.0151	0.0217	0.0256	0.0244	0.0188	0.0119	0.0086	0.0068	0.0137
U_{wind} [m/s]:	4.5	4.6	4.9	4.7	4.2	4.0	3.7	3.6	3.8	3.9	4.2	4.3	4.2
Direct Solar (G_b):	0	0	0	0	0	0	0	0	0	0	0	0	0.0
Diffuse Solar (G_d):	0	0	0	0	0	0	0	0	0	0	0	0	0.0
Hours of Sun/Day:	10.3	11.3	12.2	13.1	14.0	14.9	14.0	13.1	12.2	11.3	10.3	9.43	4444.0
Avg. Precipitation [in]:	2.72	2.71	3.17	2.71	3.66	3.38	3.80	3.91	3.31	3.02	3.12	3.12	38.63
Supp. Watering [in]:	0.00	0.00	0.00	0.68	0.92	0.85	0.95	0.98	0.83	0.00	0.00	0.00	5.19

Properties/Constants:

albedo [α]:	0.78	
Stefan Boltzmann const. [σ]:	5.67E-08	[W/m²-K⁴]
Thermal Conductivity [k]:	0.38	[W/m²-K]
Longwave Emissivity [ε_s]:	0.9	
onvective Heat Transfer Coeff.[γ_1]:	6	[W/m²-K]
onvective Heat Transfer Coeff.[γ_2]:	10	[W/m²-K]
Density of Water [ρ]:	998	[kg/m³]
Evaporation Enthalpy [h_e]:	2257	[J/kg]
Bowen Ratio:	0.17	

ENERGY BALANCE CALCULATIONS FOR A GREEN ROOF, NIGHT, MONTHLY

Average Daily Roof Heat Flux

	GREEN ROOF											
	January	February	March	April	May	June	July	August	September	October	November	December
Peak (Day)	-107.47	-89.19	-71.46	-45.12	-18.24	-11.78	-6.15	-11.51	-25.54	-62.58	-95.80	-110.39
Average 24hr	-96.64	-89.69	-83.90	-73.87	-63.88	-64.14	-64.07	-64.58	-68.44	-83.18	-96.55	-100.65
Base (Night)	-85.81	-90.20	-96.33	-102.62	-109.51	-116.50	-121.99	-117.64	-111.35	-103.77	-97.29	-90.90
Δ Heat Flux	21.66	1.01	24.87	57.51	91.27	104.71	115.84	106.13	85.81	41.19	1.49	19.50

	GREEN ROOF											
Hour of Day	January	February	March	April	May	June	July	August	September	October	November	December
0	-100.79	-89.88	-88.66	-84.87	-81.34	-84.18	-86.24	-84.88	-84.86	-91.06	-96.83	-104.38
1	-103.24	-90.00	-91.47	-91.37	-91.66	-96.01	-99.33	-96.88	-94.56	-95.71	-97.00	-106.58
2	-105.23	-90.09	-93.76	-96.68	-100.08	-105.68	-110.02	-106.68	-102.48	-99.52	-97.14	-108.38
3	-106.65	-90.16	-95.39	-100.43	-106.04	-112.51	-117.58	-113.60	-108.08	-102.20	-97.23	-109.65
4	-107.38	-90.19	-96.23	-102.38	-109.12	-116.05	-121.49	-117.19	-110.98	-103.59	-97.28	-110.31
5	-107.38	-90.19	-96.23	-102.38	-109.12	-116.05	-121.49	-117.19	-110.98	-103.59	-97.28	-110.31
6	-106.65	-90.16	-95.39	-100.43	-106.04	-112.51	-117.58	-113.60	-108.08	-102.20	-97.23	-109.65
7	-105.23	-90.09	-93.76	-96.68	-100.08	-105.68	-110.02	-106.68	-102.48	-99.52	-97.14	-108.38
8	-103.24	-90.00	-91.47	-91.37	-91.66	-96.01	-99.33	-96.88	-94.56	-95.71	-97.00	-106.58
9	-100.79	-89.88	-88.66	-84.87	-81.34	-84.18	-86.24	-84.88	-84.86	-91.06	-96.83	-104.38
10	-98.06	-89.76	-85.52	-77.62	-69.83	-70.97	-71.63	-71.50	-74.04	-85.86	-96.64	-101.92
11	-95.23	-89.63	-82.27	-70.12	-57.92	-57.31	-56.51	-57.65	-62.84	-80.49	-96.45	-99.37
12	-92.50	-89.50	-79.14	-62.87	-46.41	-44.10	-41.91	-44.27	-52.02	-75.29	-96.26	-96.91
13	-90.05	-89.38	-76.33	-56.37	-36.09	-32.27	-28.81	-32.27	-42.32	-70.64	-96.09	-94.71
14	-88.05	-89.29	-74.03	-51.06	-27.67	-22.60	-18.12	-22.48	-34.40	-66.84	-95.96	-92.91
15	-86.64	-89.23	-72.41	-47.31	-21.71	-15.77	-10.56	-15.55	-28.80	-64.15	-95.86	-91.64
16	-85.91	-89.19	-71.57	-45.36	-18.63	-12.23	-6.65	-11.96	-25.90	-62.76	-95.81	-90.98
17	-85.91	-89.19	-71.57	-45.36	-18.63	-12.23	-6.65	-11.96	-25.90	-62.76	-95.81	-90.98
18	-86.64	-89.23	-72.41	-47.31	-21.71	-15.77	-10.56	-15.55	-28.80	-64.15	-95.86	-91.64
19	-88.05	-89.29	-74.03	-51.06	-27.67	-22.60	-18.12	-22.48	-34.40	-66.84	-95.96	-92.91
20	-90.05	-89.38	-76.33	-56.37	-36.09	-32.27	-28.81	-32.27	-42.32	-70.64	-96.09	-94.71
21	-92.50	-89.50	-79.14	-62.87	-46.41	-44.10	-41.91	-44.27	-52.02	-75.29	-96.26	-96.91
22	-95.23	-89.63	-82.27	-70.12	-57.92	-57.31	-56.51	-57.65	-62.84	-80.49	-96.45	-99.37
23	-98.06	-89.76	-85.52	-77.62	-69.83	-70.97	-71.63	-71.50	-74.04	-85.86	-96.64	-101.92
24	-100.79	-89.88	-88.66	-84.87	-81.34	-84.18	-86.24	-84.88	-84.86	-91.06	-96.83	-104.38

	TYPICAL ROOF											
	January	February	March	April	May	June	July	August	September	October	November	December
Peak (Day)	58.79	83.81	109.67	132.59	145.01	146.52	144.15	135.56	124.70	89.19	61.91	50.27
Average 24hr	-0.84	8.76	17.63	26.12	30.47	28.20	25.28	23.60	20.88	6.55	-4.57	-7.39
Base (Night)	-60.46	-66.30	-74.42	-80.35	-84.07	-90.11	-93.59	-88.36	-82.95	-76.09	-71.05	-65.06
Δ Heat Flux	119.26	150.11	184.09	212.93	229.09	236.62	237.74	223.91	207.66	165.27	132.96	115.33

	TYPICAL ROOF											
Hour of Day	January	February	March	April	May	June	July	August	September	October	November	December
0	-43.00	-44.32	-47.46	-49.16	-50.52	-55.45	-58.77	-55.57	-52.54	-51.88	-51.58	-48.17
1	-52.48	-56.24	-62.09	-66.08	-68.73	-74.26	-77.66	-73.36	-69.04	-65.01	-62.14	-57.33
2	-58.43	-63.74	-71.28	-76.72	-80.17	-86.07	-89.54	-84.54	-79.41	-73.27	-68.79	-63.09
3	-60.46	-66.30	-74.42	-80.35	-84.07	-90.11	-93.59	-88.36	-82.95	-76.09	-71.05	-65.06
4	-58.43	-63.74	-71.28	-76.72	-80.17	-86.07	-89.54	-84.54	-79.41	-73.27	-68.79	-63.09
5	-52.48	-56.24	-62.09	-66.08	-68.73	-74.26	-77.66	-73.36	-69.04	-65.01	-62.14	-57.33
6	-43.00	-44.32	-47.46	-49.16	-50.52	-55.45	-58.77	-55.57	-52.54	-51.88	-51.58	-48.17
7	-30.65	-28.77	-28.39	-27.11	-26.80	-30.95	-34.15	-32.38	-31.04	-34.77	-37.81	-36.22
8	-16.27	-10.67	-6.19	-1.44	0.82	-2.42	-5.49	-5.38	-6.00	-14.84	-21.78	-22.32
9	-0.84	8.76	17.63	26.12	30.47	28.20	25.28	23.60	20.88	6.55	-4.57	-7.39
10	14.60	28.18	41.45	53.67	60.12	58.83	56.05	52.58	47.75	27.94	12.63	7.53
11	28.98	46.28	63.65	79.35	87.74	87.36	84.72	79.58	72.79	47.87	28.67	21.44
12	41.33	61.83	82.71	101.40	111.46	111.86	109.33	102.76	94.29	64.98	42.44	33.38
13	50.80	73.76	97.34	118.32	129.67	130.67	128.23	120.56	110.79	78.12	53.00	42.55
14	56.76	81.25	106.54	128.96	141.11	142.48	140.10	131.74	121.17	86.37	59.64	48.31
15	58.79	83.81	109.67	132.59	145.01	146.52	144.15	135.56	124.70	89.19	61.91	50.27
16	56.76	81.25	106.54	128.96	141.11	142.48	140.10	131.74	121.17	86.37	59.64	48.31
17	50.80	73.76	97.34	118.32	129.67	130.67	128.23	120.56	110.79	78.12	53.00	42.55
18	41.33	61.83	82.71	101.40	111.46	111.86	109.33	102.76	94.29	64.98	42.44	33.38
19	28.98	46.28	63.65	79.35	87.74	87.36	84.72	79.58	72.79	47.87	28.67	21.44
20	14.60	28.18	41.45	53.67	60.12	58.83	56.05	52.58	47.75	27.94	12.63	7.53
21	-0.84	8.76	17.63	26.12	30.47	28.20	25.28	23.60	20.88	6.55	-4.57	-7.39
22	-16.27	-10.67	-6.19	-1.44	0.82	-2.42	-5.49	-5.38	-6.00	-14.84	-21.78	-22.32
23	-30.65	-28.77	-28.39	-27.11	-26.80	-30.95	-34.15	-32.38	-31.04	-34.77	-37.81	-36.22
24	-43.00	-44.32	-47.46	-49.16	-50.52	-55.45	-58.77	-55.57	-52.54	-51.88	-51.58	-48.17

	ORIGINAL ROOF											
	January	February	March	April	May	June	July	August	September	October	November	December
Peak (Day)	-30.72	-25.20	-21.09	-16.42	-13.32	-14.31	-14.93	-16.57	-18.39	-26.06	-32.12	-33.40
Average 24hr	-45.59	-45.75	-47.75	-48.38	-48.69	-52.21	-54.26	-52.47	-50.67	-51.07	-51.58	-49.23
Base (Night)	-60.46	-66.30	-74.42	-80.35	-84.07	-90.11	-93.59	-88.36	-82.95	-76.09	-71.05	-65.06
Δ Heat Flux	29.75	41.10	53.33	63.93	70.76	75.80	78.66	71.78	64.56	50.02	38.93	31.66

	ORIGINAL ROOF											
Hour of Day	January	February	March	April	May	June	July	August	September	October	November	December
0	-56.11	-60.28	-66.61	-70.99	-73.71	-79.01	-82.07	-77.85	-73.50	-68.76	-65.35	-60.42
1	-58.47	-63.55	-70.84	-76.07	-79.33	-85.03	-88.32	-83.55	-78.63	-72.73	-68.44	-62.94
2	-59.96	-65.60	-73.51	-79.26	-82.87	-88.81	-92.25	-87.14	-81.85	-75.23	-70.39	-64.52
3	-60.46	-66.30	-74.42	-80.35	-84.07	-90.11	-93.59	-88.36	-82.95	-76.09	-71.05	-65.06
4	-59.96	-65.60	-73.51	-79.26	-82.87	-88.81	-92.25	-87.14	-81.85	-75.23	-70.39	-64.52
5	-58.47	-63.55	-70.84	-76.07	-79.33	-85.03	-88.32	-83.55	-78.63	-72.73	-68.44	-62.94
6	-56.11	-60.28	-66.61	-70.99	-73.71	-79.01	-82.07	-77.85	-73.50	-68.76	-65.35	-60.42
7	-53.03	-56.02	-61.08	-64.37	-66.38	-71.16	-73.93	-70.41	-66.81	-63.58	-61.32	-57.14
8	-49.44	-51.07	-54.65	-56.66	-57.85	-62.02	-64.44	-61.76	-59.02	-57.55	-56.62	-53.32
9	-45.59	-45.75	-47.75	-48.38	-48.69	-52.21	-54.26	-52.47	-50.67	-51.07	-51.58	-49.23
10	-41.74	-40.43	-40.85	-40.11	-39.54	-42.40	-44.08	-43.18	-42.31	-44.60	-46.55	-45.13
11	-38.15	-35.47	-34.42	-32.40	-31.01	-33.26	-34.60	-34.52	-34.53	-38.57	-41.85	-41.31
12	-35.07	-31.22	-28.90	-25.78	-23.68	-25.41	-26.45	-27.09	-27.84	-33.39	-37.82	-38.03
13	-32.71	-27.95	-24.66	-20.70	-18.06	-19.39	-20.20	-21.38	-22.71	-29.41	-34.72	-35.52
14	-31.22	-25.90	-22.00	-17.51	-14.52	-15.60	-16.27	-17.80	-19.49	-26.91	-32.78	-33.93
15	-30.72	-25.20	-21.09	-16.42	-13.32	-14.31	-14.93	-16.57	-18.39	-26.06	-32.12	-33.40
16	-31.22	-25.90	-22.00	-17.51	-14.52	-15.60	-16.27	-17.80	-19.49	-26.91	-32.78	-33.93
17	-32.71	-27.95	-24.66	-20.70	-18.06	-19.39	-20.20	-21.38	-22.71	-29.41	-34.72	-35.52
18	-35.07	-31.22	-28.90	-25.78	-23.68	-25.41	-26.45	-27.09	-27.84	-33.39	-37.82	-38.03
19	-38.15	-35.47	-34.42	-32.40	-31.01	-33.26	-34.60	-34.52	-34.53	-38.57	-41.85	-41.31
20	-41.74	-40.43	-40.85	-40.11	-39.54	-42.40	-44.08	-43.18	-42.31	-44.60	-46.55	-45.13
21	-45.59	-45.75	-47.75	-48.38	-48.69	-52.21	-54.26	-52.47	-50.67	-51.07	-51.58	-49.23
22	-49.44	-51.07	-54.65	-56.66	-57.85	-62.02	-64.44	-61.76	-59.02	-57.55	-56.62	-53.32
23	-53.03	-56.02	-61.08	-64.37	-66.38	-71.16	-73.93	-70.41	-66.81	-63.58	-61.32	-57.14
24	-56.11	-60.28	-66.61	-70.99	-73.71	-79.01	-82.07	-77.85	-73.50	-68.76	-65.35	-60.42

Appendix B

Existing System Energy Analysis

Carrier's Hourly Analysis Program (HAP) output for the original VAV system:

ANNUAL COST SUMMARY:

Table 1. Annual Costs

Component	Gallaudet University SLCC ($)
Air System Fans	10,409
Cooling	90,174
Heating	1,237
Pumps	7,579
Cooling Tower Fans	0
HVAC Sub-Total	**109,399**
Lights	20,222
Electric Equipment	23,381
Misc. Electric	0
Misc. Fuel Use	0
Non-HVAC Sub-Total	**43,602**
Grand Total	**153,002**

Table 2. Annual Cost per Unit Floor Area

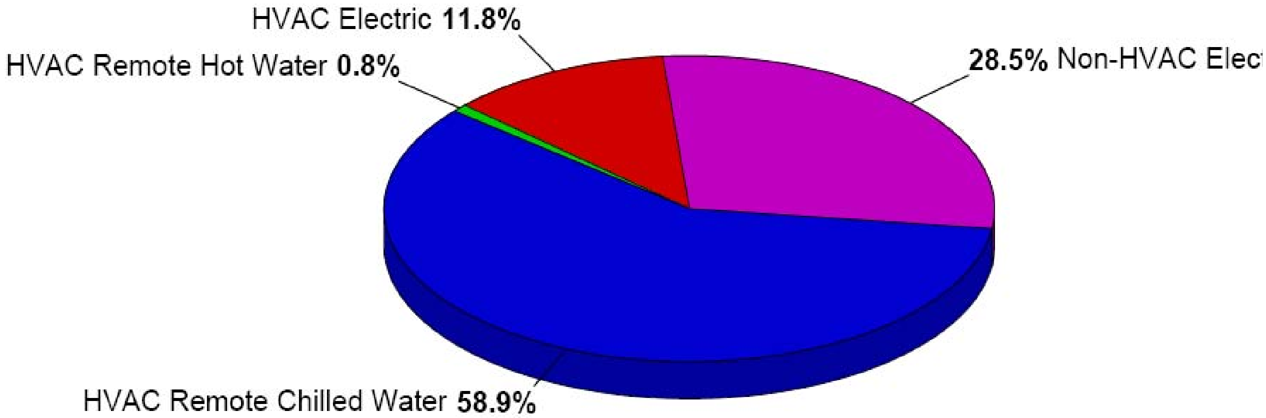
Component	Gallaudet University SLCC ($/ft²)
Air System Fans	0.151
Cooling	1.307
Heating	0.018
Pumps	0.110
Cooling Tower Fans	0.000
HVAC Sub-Total	**1.585**
Lights	0.293
Electric Equipment	0.339
Misc. Electric	0.000
Misc. Fuel Use	0.000
Non-HVAC Sub-Total	**0.632**
Grand Total	**2.217**
Gross Floor Area (ft²)	69014.0
Conditioned Floor Area (ft²)	69014.0

Note: Values in this table are calculated using the Gross Floor Area.

Table 3. Component Cost as a Percentage of Total Cost

Component	Gallaudet University SLCC (%)
Air System Fans	6.8
Cooling	58.9
Heating	0.8
Pumps	5.0
Cooling Tower Fans	0.0
HVAC Sub-Total	**71.5**
Lights	13.2
Electric Equipment	15.3
Misc. Electric	0.0
Misc. Fuel Use	0.0
Non-HVAC Sub-Total	**28.5**
Grand Total	**100.0**

ANNUAL ENERGY COSTS

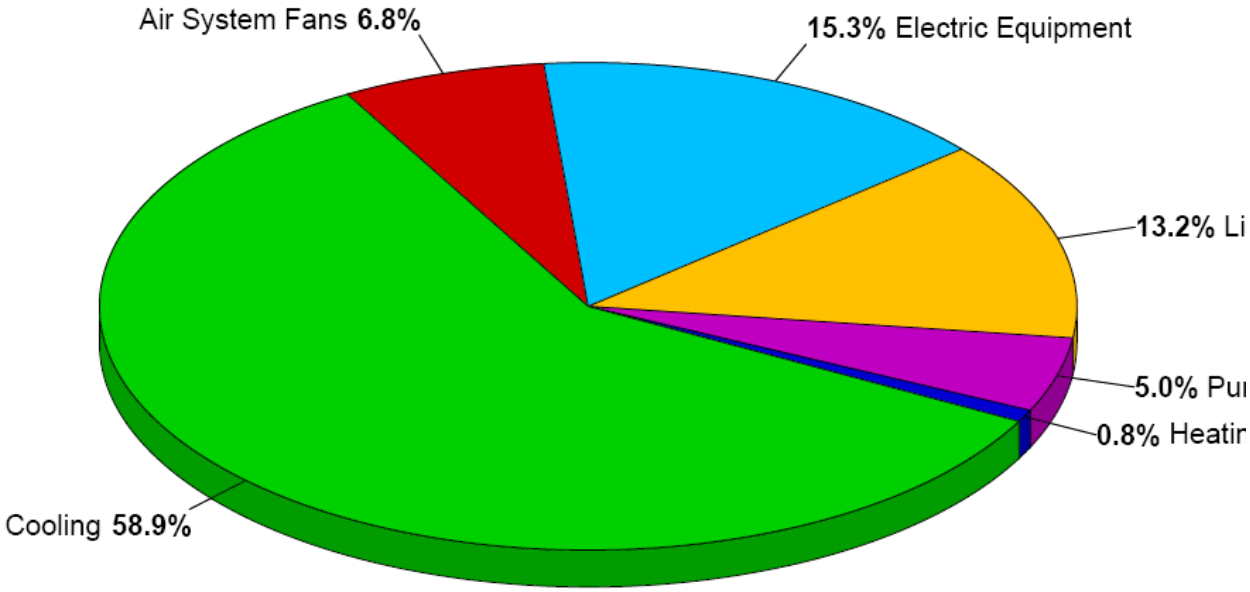


Component	Annual Cost ($/yr)	($/ft²)	Percent of Total (%)
HVAC Components			
Electric	17,988	0.261	11.8
Natural Gas	0	0.000	0.0
Fuel Oil	0	0.000	0.0
Propane	0	0.000	0.0
Remote Hot Water	1,237	0.018	0.8
Remote Steam	0	0.000	0.0
Remote Chilled Water	90,174	1.307	58.9
HVAC Sub-Total	**109,399**	**1.585**	**71.5**
Non-HVAC Components			
Electric	43,607	0.632	28.5
Natural Gas	0	0.000	0.0
Fuel Oil	0	0.000	0.0
Propane	0	0.000	0.0
Remote Hot Water	0	0.000	0.0
Remote Steam	0	0.000	0.0
Non-HVAC Sub-Total	**43,607**	**0.632**	**28.5**
Grand Total	**153,006**	**2.217**	**100.0**

Note: Cost per unit floor area is based on the gross building floor area.

Gross Floor Area .... **69014.0** ft²
Conditioned Floor Area .... **69014.0** ft²

ANNUAL COMPONENT COSTS



Component	Annual Cost ($)	($/ft²)	Percent of Total (%)
Air System Fans	10,409	0.151	6.8
Cooling	90,174	1.307	58.9
Heating	1,237	0.018	0.8
Pumps	7,579	0.110	5.0
Cooling Tower Fans	0	0.000	0.0
HVAC Sub-Total	**109,399**	**1.585**	**71.5**
Lights	20,222	0.293	13.2
Electric Equipment	23,381	0.339	15.3
Misc. Electric	0	0.000	0.0
Misc. Fuel Use	0	0.000	0.0
Non-HVAC Sub-Total	**43,602**	**0.632**	**28.5**
Grand Total	**153,002**	**2.217**	**100.0**

Note: Cost per unit floor area is based on the gross building floor area.

Gross Floor Area .... **69014.0** ft²
Conditioned Floor Area .... **69014.0** ft²

ANNUAL ENERGY SUMMARY

Table 1. Annual Costs

Component	Gallaudet University SLCC ($)
HVAC Components	
Electric	17,988
Natural Gas	0
Fuel Oil	0
Propane	0
Remote HW	1,237
Remote Steam	0
Remote CW	90,174
HVAC Sub-Total	**109,399**
Non-HVAC Components	
Electric	43,607
Natural Gas	0
Fuel Oil	0
Propane	0
Remote HW	0
Remote Steam	0
Non-HVAC Sub-Total	**43,607**
Grand Total	**153,006**

Table 2. Annual Energy Consumption

Component	Gallaudet University SLCC
HVAC Components	
Electric (kWh)	198,978
Natural Gas (na)	0
Fuel Oil (na)	0
Propane (na)	0
Remote HW (kBTU)	89,340
Remote Steam (na)	0
Remote CW (kBTU)	3,402,805
Non-HVAC Components	
Electric (kWh)	482,375
Natural Gas (na)	0
Fuel Oil (na)	0
Propane (na)	0
Remote HW (kBTU)	0
Remote Steam (na)	0
Totals	
Electric (kWh)	681,353
Natural Gas (na)	0
Fuel Oil (na)	0
Propane (na)	0
Remote HW (kBTU)	89,340
Remote Steam (na)	0
Remote CW (kBTU)	3,402,805

Table 4. Annual Cost per Unit Floor Area

Component	Gallaudet University SLCC ($/ft²)
HVAC Components	
Electric	0.261
Natural Gas	0.000
Fuel Oil	0.000
Propane	0.000
Remote HW	0.018
Remote Steam	0.000
Remote CW	1.307
HVAC Sub-Total	**1.585**
Non-HVAC Components	
Electric	0.632
Natural Gas	0.000
Fuel Oil	0.000
Propane	0.000
Remote HW	0.000
Remote Steam	0.000
Non-HVAC Sub-Total	**0.632**
Grand Total	**2.217**
Gross Floor Area (ft²)	69014.0
Conditioned Floor Area (ft²)	69014.0

Note: Values in this table are calculated using the Gross Floor Area.

Table 5. Component Cost as a Percentage of Total Cost

Component	Gallaudet University SLCC (%)
HVAC Components	
Electric	11.8
Natural Gas	0.0
Fuel Oil	0.0
Propane	0.0
Remote HW	0.8
Remote Steam	0.0
Remote CW	58.9
HVAC Sub-Total	**71.5**
Non-HVAC Components	
Electric	28.5
Natural Gas	0.0
Fuel Oil	0.0
Propane	0.0
Remote HW	0.0
Remote Steam	0.0
Non-HVAC Sub-Total	**28.5**
Grand Total	**100.0**

ENERGY BUDGET BY SOURCE

1. Annual Coil Loads

Component	Load (kBTU)	(kBTU/ft²)
Cooling Coil Loads	3,181,617	46.101
Heating Coil Loads	1,287,048	18.649
Grand Total	**4,468,665**	**64.750**

2. Energy Consumption by Energy Source

Component	Site Energy (kBTU)	Site Energy (kBTU/ft²)	Source Energy (kBTU)	Source Energy (kBTU/ft²)
HVAC Components				
Electric	678,911	9.837	2,424,683	35.133
Natural Gas	0	0.000	0	0.000
Fuel Oil	0	0.000	0	0.000
Propane	0	0.000	0	0.000
Remote Hot Water	1,250,765	18.123	1,250,765	18.123
Remote Steam	0	0.000	0	0.000
Remote Chilled Water	3,402,805	49.306	3,402,805	49.306
HVAC Sub-Total	**5,332,481**	**77.267**	**7,078,252**	**102.563**
Non-HVAC Components				
Electric	1,645,865	23.848	5,878,088	85.172
Natural Gas	0	0.000	0	0.000
Fuel Oil	0	0.000	0	0.000
Propane	0	0.000	0	0.000
Remote Hot Water	0	0.000	0	0.000
Remote Steam	0	0.000	0	0.000
Non-HVAC Sub-Total	**1,645,865**	**23.848**	**5,878,088**	**85.172**
Grand Total	**6,978,346**	**101.115**	**12,956,340**	**187.735**

Notes:
1. 'Cooling Coil Loads' is the sum of all air system cooling coil loads.
2. 'Heating Coil Loads' is the sum of all air system heating coil loads.
3. Site Energy is the actual energy consumed.
4. Source Energy is the site energy divided by the electric generating efficiency (28.0%).
5. Source Energy for fuels equals the site energy value.
6. Energy per unit floor area is based on the gross building floor area.
   Gross Floor Area .... **69014.0** ft²
   Conditioned Floor Area .... **69014.0** ft²

Appendix C

DOAS System Energy Analysis

Carrier's Hourly Analysis Program (HAP) output for the proposed DOAS system:

ANNUAL COST SUMMARY:

Table 1. Annual Costs

Component	Gallaudet University SLCC(DOAS) ($)
Air System Fans	9,184
Cooling	73,820
Heating	494
Pumps	17,170
Cooling Tower Fans	0
HVAC Sub-Total	**100,668**
Lights	20,164
Electric Equipment	23,226
Misc. Electric	0
Misc. Fuel Use	0
Non-HVAC Sub-Total	**43,390**
Grand Total	**144,057**

Table 2. Annual Cost per Unit Floor Area

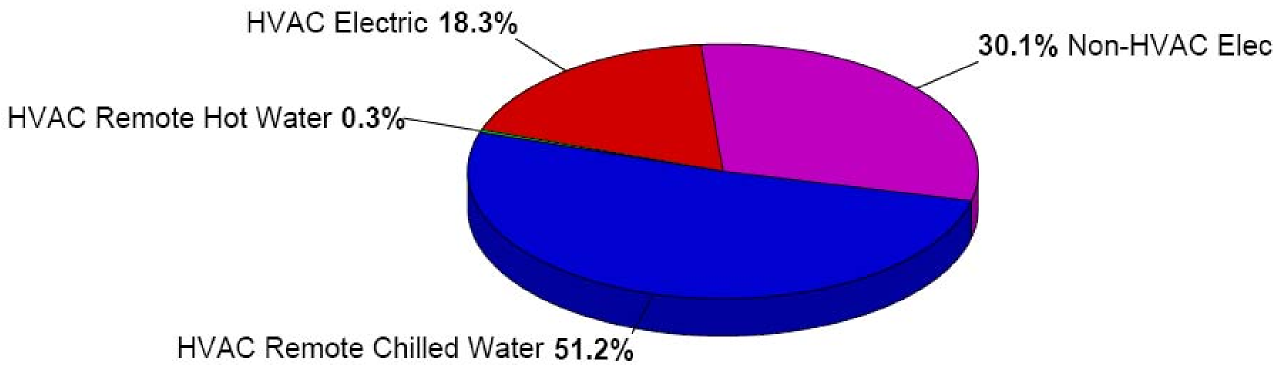
Component	Gallaudet University SLCC(DOAS) ($/ft²)
Air System Fans	0.048
Cooling	0.389
Heating	0.003
Pumps	0.090
Cooling Tower Fans	0.000
HVAC Sub-Total	**0.530**
Lights	0.106
Electric Equipment	0.122
Misc. Electric	0.000
Misc. Fuel Use	0.000
Non-HVAC Sub-Total	**0.228**
Grand Total	**0.758**
Gross Floor Area (ft²)	190014.0
Conditioned Floor Area (ft²)	190014.0

Note: Values in this table are calculated using the Gross Floor Area.

Table 3. Component Cost as a Percentage of Total Cost

Component	Gallaudet University SLCC(DOAS) (%)
Air System Fans	6.4
Cooling	51.2
Heating	0.3
Pumps	11.9
Cooling Tower Fans	0.0
HVAC Sub-Total	**69.9**
Lights	14.0
Electric Equipment	16.1
Misc. Electric	0.0
Misc. Fuel Use	0.0
Non-HVAC Sub-Total	**30.1**
Grand Total	**100.0**

ANNUAL ENERGY COSTS

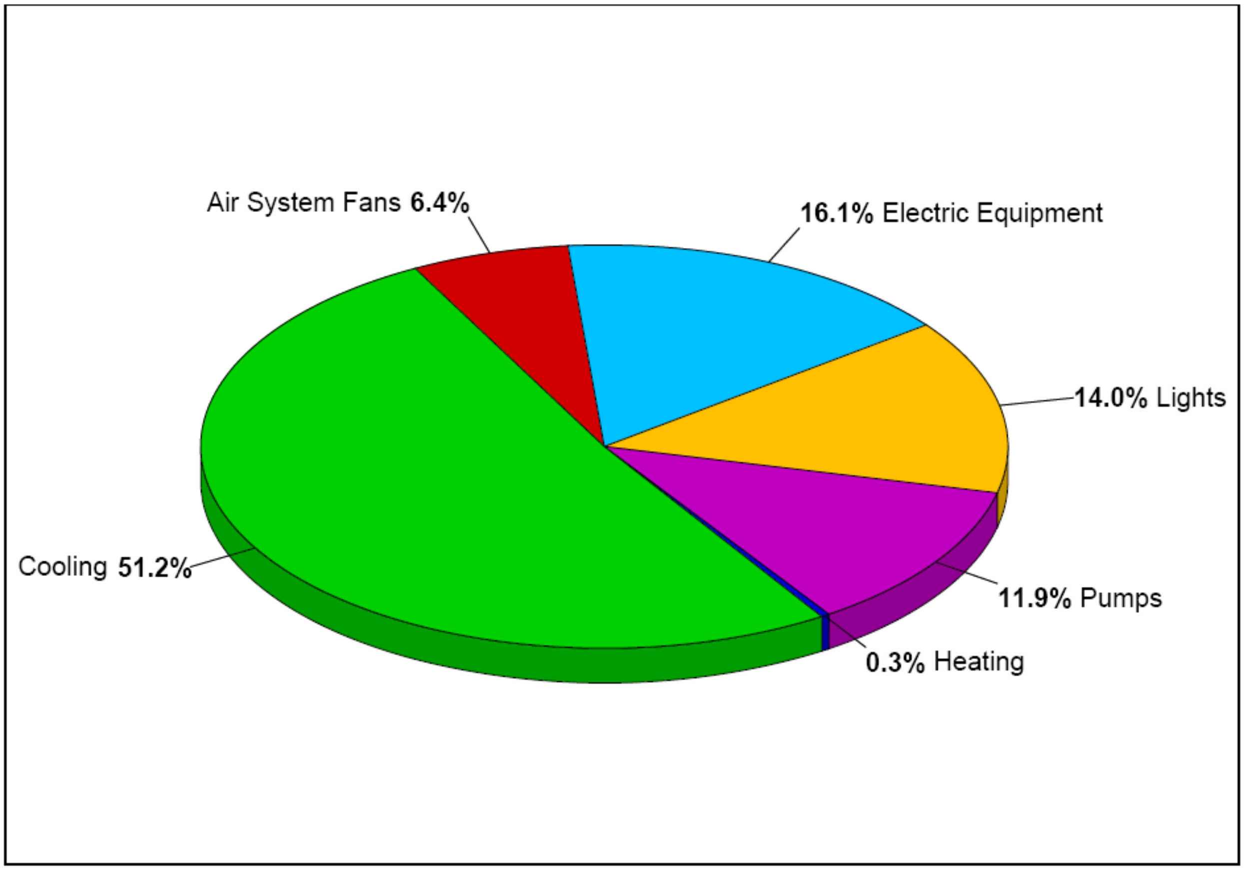


Component	Annual Cost ($/yr)	($/ft²)	Percent of Total (%)
HVAC Components			
Electric	26,352	0.139	18.3
Natural Gas	0	0.000	0.0
Fuel Oil	0	0.000	0.0
Propane	0	0.000	0.0
Remote Hot Water	494	0.003	0.3
Remote Steam	0	0.000	0.0
Remote Chilled Water	73,820	0.389	51.2
HVAC Sub-Total	**100,666**	**0.530**	**69.9**
Non-HVAC Components			
Electric	43,388	0.228	30.1
Natural Gas	0	0.000	0.0
Fuel Oil	0	0.000	0.0
Propane	0	0.000	0.0
Remote Hot Water	0	0.000	0.0
Remote Steam	0	0.000	0.0
Non-HVAC Sub-Total	**43,388**	**0.228**	**30.1**
Grand Total	**144,054**	**0.758**	**100.0**

Note: Cost per unit floor area is based on the gross building floor area.

Gross Floor Area .... **190014.0** ft²
Conditioned Floor Area .... **190014.0** ft²

ANNUAL COMPONENT COSTS



1. Annual Costs

Component	Annual Cost ($)	($/ft²)	Percent of Total (%)
Air System Fans	9,184	0.048	6.4
Cooling	73,820	0.389	51.2
Heating	494	0.003	0.3
Pumps	17,170	0.090	11.9
Cooling Tower Fans	0	0.000	0.0
HVAC Sub-Total	**100,668**	**0.530**	**69.9**
Lights	20,164	0.106	14.0
Electric Equipment	23,226	0.122	16.1
Misc. Electric	0	0.000	0.0
Misc. Fuel Use	0	0.000	0.0
Non-HVAC Sub-Total	**43,390**	**0.228**	**30.1**

ENERGY BUDGET BY SOURCE

1. Annual Coil Loads

Component	Load (kBTU)	(kBTU/ft²)
Cooling Coil Loads	2,224,520	11.707
Heating Coil Loads	525,583	2.766
Grand Total	**2,750,102**	**14.473**

2. Energy Consumption by Energy Source

Component	Site Energy (kBTU)	Site Energy (kBTU/ft²)	Source Energy (kBTU)	Source Energy (kBTU/ft²)
HVAC Components				
Electric	994,613	5.234	3,552,190	18.694
Natural Gas	0	0.000	0	0.000
Fuel Oil	0	0.000	0	0.000
Propane	0	0.000	0	0.000
Remote Hot Water	499,672	2.630	499,672	2.630
Remote Steam	0	0.000	0	0.000
Remote Chilled Water	2,785,649	14.660	2,785,649	14.660
HVAC Sub-Total	**4,279,934**	**22.524**	**6,837,511**	**35.984**
Non-HVAC Components				
Electric	1,637,618	8.618	5,848,634	30.780
Natural Gas	0	0.000	0	0.000
Fuel Oil	0	0.000	0	0.000
Propane	0	0.000	0	0.000
Remote Hot Water	0	0.000	0	0.000
Remote Steam	0	0.000	0	0.000
Non-HVAC Sub-Total	**1,637,618**	**8.618**	**5,848,634**	**30.780**
Grand Total	**5,917,551**	**31.143**	**12,686,145**	**66.764**

Notes:

1. 'Cooling Coil Loads' is the sum of all air system cooling coil loads.
2. 'Heating Coil Loads' is the sum of all air system heating coil loads.
3. Site Energy is the actual energy consumed.
4. Source Energy is the site energy divided by the electric generating efficiency (28.0%).
5. Source Energy for fuels equals the site energy value.
6. Energy per unit floor area is based on the gross building floor area.

Gross Floor Area .... **190014.0** ft²
Conditioned Floor Area .... **190014.0** ft²

Appendix D

Structural Analysis

Comparison of actual design to RAM Steel outputs for model of second floor roof joists.

Second Floor Roof Structural Design (Joists)

Joist No.	Actual Size	RAM Design (Original Roof)	RAM Design (Green Roof)	OK?
8	W 24 x 68	W 16 x 31	W 16 x 36	✓
9	W 24 x 68	W 12 x 26	W 18 x 35	✓
10	W 24 x 68	W 16 x 31	W 6 x 36	✓
11	W 24 x 68	W 14 x 22	W 16 x 31	✓
12	W 24 x 68	W 14 x 22	W 16 x 31	✓
13	W 24 x 68	W 14 x 22	W 16 x 31	✓
14	W 24 x 68	W 16 x 26	W 18 x 35	✓
15	W 24 x 68	W 12 x 19	W 16 x 26	✓
16	W 24 x 68	W 12 x 19	W 16 x 26	✓
17	W 24 x 68	W 12 x 19	W 16 x 26	✓
18	W 24 x 68	W 14 x 22	W 16 x 31	✓
19	W 24 x 55	W 14 x 22	W 12 x 26	✓
20	W 16 x 51	W 8 x 10	W 8 x 10	✓
21	W 16 x 31	W 10 x 12	W 12 x 14	✓
22	W 22 x 84	W 12 x 14	W 12 x 19	✓
23	W 21 x 44	W 10 x 12	W 12 x 14	✓
24	W 21 x 44	W 10 x 12	W 12 x 14	✓
25	W 21 x 44	W 8 x 10	W 12 x 14	✓
26	W 21 x 44	W 8 x 10	W 8 x 10	✓
27	W 16 x 31	W 10 x 12	W 12 x 14	✓
28	W 16 x 51	W 8 x 10	W 8 x 10	✓
29	W 18 x 46	W 8 x 10	W 8 x 10	✓
30	W 12 x 16	W 8 x 10	W 8 x 10	✓
31	W 12 x 14	W 8 x 10	W 8 x 10	✓
32	W 12 x 14	W 8 x 10	W 8 x 10	✓
33	W 12 x 14	W 8 x 10	W 8 x 10	✓
34	W 12 x 14	W 8 x 10	W 8 x 10	✓
35	W 14 x 22	W 8 x 10	W 8 x 10	✓
36	W 12 x 14	W 8 x 10	W 8 x 10	✓
37	W 12 x 14	W 8 x 10	W 8 x 10	✓
38	W 12 x 14	W 8 x 10	W 8 x 10	✓
39	W 12 x 14	W 8 x 10	W 8 x 10	✓
40	W 12 x 14	W 8 x 10	W 8 x 10	✓
41	W 12 x 14	W 8 x 10	W 8 x 10	✓
42	W 12 x 14	W 8 x 10	W 8 x 10	✓
43	W 12 x 14	W 8 x 10	W 8 x 10	✓
44	W 18 x 15	W 8 x 10	W 8 x 10	✓
45	W 24 x 55	W 14 x 22	W 12 x 26	✓
46	W 24 x 55	W 8 x 10	W 8 x 10	✓

Second Floor Roof Structural Design (Joists)

Joist No.	Actual Size	RAM Design (Original Roof)	RAM Design (Green Roof)	OK?
47	W 21 x 50	W 12 x 14	W 12 x 19	✓
48	W 18 x 35	W 14 x 22	W 12 x 26	✓
49	W 18 x 35	W 12 x 19	W 14 x 26	✓
50	W 18 x 35	W 12 x 19	W 16 x 26	✓
51	W 18 x 35	W 12 x 16	W 14 x 22	✓
52	W 18 x 35	W 12 x 16	W 14 x 22	✓
53	W 18 x 35	W 12 x 14	W 14 x 22	✓
54	W 18 x 35	W 12 x 16	W 14 x 22	✓
55	W 24 x 55	W 10 x 12	W 12 x 19	✓
56	W 24 x 55	W 10 x 12	W 12 x 19	✓
57	W 24 x 55	W 10 x 12	W 12 x 16	✓
58	W 24 x 55	W 10 x 12	W 12 x 14	✓
59	W 24 x 55	W 8 x 10	W 12 x 14	✓
60	W 24 x 55	W 8 x 10	W 12 x 14	✓
61	W 24 x 55	W 10 x 12	W 12 x 16	✓
62	20 K 4	14 K 1	16 K 2	✓
63	20 K 4	12 K 1	16 K 2	✓
64	20 K 4	12 K 1	16 K 2	✓
65	20 K 4	12 K 1	16 K 2	✓
66	16 K 3	12 K 1	16 K 2	✓
67	16 K 3	12 K 1	14 K 1	✓
68	16 K 3	10 K 1	14 K 1	✓
69	16 K 3	10 K 1	14 K 1	✓
70	14 K 1	10 K 1	12 K 1	✓
71	14 K 1	10 K 1	12 K 1	✓
72	14 K 1	10 K 1	12 K 1	✓
73	14 K 1	10 K 1	12 K 1	✓
74	12 K 1	10 K 1	10 K 1	✓
75	12 K 1	10 K 1	10 K 1	✓
76	12 K 1	10 K 1	10 K 1	✓
77	12 K 1	10 K 1	10 K 1	✓
78	10 K 1	10 K 1	10 K 1	✓
79	10 K 1	10 K 1	10 K 1	✓
80	10 K 1	10 K 1	10 K 1	✓
81	10 K 1	10 K 1	10 K 1	✓
82	10 K 1	10 K 1	10 K 1	✓
83	10 K 1	10 K 1	10 K 1	✓
84	10 K 1	10 K 1	10 K 1	✓
85	10 K 1	10 K 1	10 K 1	✓

Second Floor Roof Structural Design (Joists)

Joist No.	Actual Size	RAM Design (Original Roof)	RAM Design (Green Roof)	OK?
86	14 K 1	10 K 1	12 K 1	✓
87	14 K 1	10 K 1	12 K 1	✓
88	14 K 1	10 K 1	12 K 1	✓
89	14 K 1	10 K 1	12 K 1	✓
90	12 K 1	10 K 1	12 K 1	✓
91	12 K 1	10 K 1	12 K 1	✓
92	12 K 1	10 K 1	12 K 1	✓
93	12 K 1	10 K 1	10 K 1	✓
94	12 K 1	10 K 1	10 K 1	✓
95	12 K 1	10 K 1	10 K 1	✓
96	12 K 1	10 K 1	10 K 1	✓
97	12 K 1	10 K 1	10 K 1	✓
98	12 K 1	10 K 1	10 K 1	✓
99	12 K 1	10 K 1	10 K 1	✓
100	12 K 1	10 K 1	10 K 1	✓
101	12 K 1	10 K 1	10 K 1	✓
102	10 K 1	10 K 1	10 K 1	✓
103	10 K 1	10 K 1	10 K 1	✓
104	10 K 1	10 K 1	10 K 1	✓
105	10 K 1	10 K 1	10 K 1	✓
106	10 K 1	10 K 1	10 K 1	✓
107	10 K 1	10 K 1	10 K 1	✓
108	10 K 1	10 K 1	10 K 1	✓
109	10 K 1	10 K 1	10 K 1	✓
110	10 K 1	20 K 3	22 K 5	✓
111	10 K 1	20 K 3	22 K 5	✓
112	10 K 1	20 K 3	22 K 5	✓
113	10 K 1	20 K 3	22 K 5	✓
114	10 K 1	20 K 3	22 K 5	✓
115	10 K 1	20 K 3	22 K 5	✓
116	10 K 1	20 K 3	22 K 5	✓
117	10 K 1	20 K 3	22 K 5	✓
118	10 K 1	20 K 3	22 K 5	✓
119	10 K 1	20 K 3	22 K 5	✓
120	10 K 1	20 K 3	22 K 5	✓
121	10 K 1	20 K 3	22 K 5	✓
122	10 K 1	18 K 3	22 K 4	✓
123	10 K 1	18 K 3	22 K 4	✓
124	10 K 1	18 K 3	22 K 4	✓

Second Floor Roof Structural Design (Joists)

Joist No.	Actual Size	RAM Design (Original Roof)	RAM Design (Green Roof)	OK?
125	10 K 1	18 K 3	22 K 4	✓
126	10 K 1	18 K 3	22 K 4	✓
127	10 K 1	18 K 3	22 K 4	✓
128	10 K 1	18 K 3	22 K 4	✓
129	10 K 1	10 K 1	10 K 1	✓
130	10 K 1	10 K 1	10 K 1	✓
131	10 K 1	10 K 1	10 K 1	✓
132	10 K 1	10 K 1	10 K 1	✓
133	10 K 1	10 K 1	10 K 1	✓
134	10 K 1	10 K 1	10 K 1	✓
135	10 K 1	10 K 1	10 K 1	✓
136	10 K 1	10 K 1	10 K 1	✓
137	10 K 1	10 K 1	10 K 1	✓
138	10 K 1	10 K 1	10 K 1	✓
139	10 K 1	10 K 1	10 K 1	✓
140	10 K 1	10 K 1	10 K 1	✓
141	10 K 1	10 K 1	10 K 1	✓
142	10 K 1	10 K 1	10 K 1	✓
143	W 16 x 31	W 10 x 12	W 12 x 14	✓
144	W 16 x 31	W 10 x 12	W 12 x 14	✓
145	W 16 x 31	W 10 x 12	W 12 x 14	✓
146	W 16 x 31	W 10 x 12	W 12 x 14	✓
147	W 16 x 31	W 10 x 12	W 12 x 14	✓
148	W 16 x 31	W 10 x 12	W 12 x 14	✓
149	W 16 x 31	W 10 x 12	W 12 x 14	✓
150	W 16 x 31	W 10 x 12	W 12 x 14	✓
155	W 16 x 31	W 10 x 12	W 12 x 14	✓
156	W 16 x 31	W 10 x 12	W 12 x 14	✓
157	W 16 x 31	W 12 x 16	W 14 x 22	✓
158	W 16 x 31	W 12 x 16	W 14 x 22	✓

Comparison of actual design to RAM Steel outputs for model of thrid floor roof joists.

Third Floor Roof Structural Design (Joists)

Joist No.	Actual Size	RAM Design (Original Roof)	RAM Design (Green Roof)	OK?
1	W 18 x 35	W 12 x 14	W 12 x 19	✓
2	W 18 x 35	W 12 x 14	W 12 x 19	✓
3	W 18 x 35	W 12 x 14	W 12 x 19	✓
4	W 18 x 35	W 12 x 14	W 12 x 19	✓
5	W 14 x 22	W 8 x 10	W 10 x 12	✓
6	W 18 x 35	W 12 x 14	W 12 x 19	✓
7	W 14 x 22	W 8 x 10	W 8 x 10	✓
9	W 18 x 35	W 12 x 14	W 14 x 22	✓
10	W 18 x 35	W 12 x 14	W 14 x 22	✓
11	W 18 x 35	W 12 x 14	W 14 x 22	✓
12	W 18 x 35	W 12 x 14	W 14 x 22	✓
13	W 14 x 22	W 8 x 10	W 8 x 10	✓
14	W 24 x 22	W 8 x 10	W 8 x 10	✓
15	W 21 x 50	W 8 x 10	W 8 x 10	✓
16	W 16 x 26	W 14 x 22	W 16 x 31	✓
17	W 18 x 40	W 14 x 22	W 16 x 31	✓
18	W 27 x 94	W 16 x 31	W 16 x 36	✓
19	W 24 x 55	W 14 x 22	W 16 x 26	✓
20	W 24 x 55	W 14 x 22	W 16 x 26	✓
23	W 18 x 35	W 14 x 22	W 16 x 26	✓
24	W 18 x 35	W 14 x 22	W 16 x 26	✓
25	W 18 x 35	W 12 x 14	W 12 x 19	✓
26	W 18 x 35	W 12 x 14	W 12 x 19	✓
27	W 14 x 22	W 8 x 10	W 8 x 10	✓
28	W 18 x 35	W 14 x 22	W 16 x 31	✓
29	W 18 x 35	W 14 x 22	W 16 x 31	✓
30	W 24 x 84	W 16 x 26	W 18 x 35	✓
31	W 18 x 35	W 16 x 26	W 18 x 35	✓
32	W 18 x 35	W 16 x 26	W 18 x 35	✓
35	W 21 x 50	W 12 x 26	W 18 x 35	✓
36	W 18 x 40	W 12 x 26	W 18 x 35	✓
37	W 18 x 40	W 14 x 22	W 16 x 31	✓
38	W 18 x 40	W 14 x 22	W 16 x 31	✓
39	W 14 x 22	W 8 x 10	W 12 x 14	✓
40	W 16 x 26	W 12 x 19	W 16 x 26	✓
41	W 18 x 35	W 12 x 19	W 16 x 26	✓
42	W 24 x 76	W 12 x 14	W 12 x 16	✓
43	W 16 x 26	W 16 x 31	W 18 x 35	✓
44	W 16 x 26	W 10 x 12	W 12 x 14	✓

Third Floor Roof Structural Design (Joists)

Joist No.	Actual Size	RAM Design (Original Roof)	RAM Design (Green Roof)	OK?
45	W 16 x 26	W 10 x 12	W 12 x 14	✓
46	W 21 x 44	W 12 x 16	W 14 x 22	✓
47	W 24 x 62	W 8 x 10	W 12 x 14	✓
48	W 24 x 76	W 12 x 16	W 12 x 19	✓
49	W 12 x 40	W 8 x 10	W 10 x 12	✓
50	W 21 x 44	W 8 x 10	W 8 x 10	✓
51	W 21 x 44	W 8 x 10	W 12 x 14	✓
52	W 21 x 44	W 12 x 14	W 12 x 16	✓
53	W 16 x 31	W 8 x 10	W 8 x 10	✓
54	W 21 x 44	W 8 x 10	W 12 x 14	✓
55	W 21 x 44	W 8 x 10	W 12 x 14	✓
56	W 21 x 44	W 8 x 10	W 12 x 14	✓
57	W 14 x 22	W 8 x 10	W 8 x 10	✓
58	W 21 x 50	W 8 x 10	W 8 x 10	✓
59	W 21 x 50	W 8 x 10	W 8 x 10	✓
60	W 21 x 50	W 8 x 10	W 8 x 10	✓
61	W 16 x 26	W 8 x 10	W 8 x 10	✓
62	W 21 x 44	W 8 x 10	W 12 x 14	✓
63	W 24 x 68	W 12 x 16	W 12 x 19	✓
64	W 21 x 44	W 8 x 10	W 12 x 14	✓
65	W 24 x 68	W 12 x 16	W 12 x 19	✓
68	W 24 x 55	W 10 x 12	W 12 x 19	✓
69	W 21 x 44	W 12 x 16	W 12 x 19	✓
70	W 24 x 55	W 10 x 12	W 12 x 19	✓
71	W 21 x 44	W 12 x 16	W 12 x 19	✓
72	W 24 x 55	W 10 x 12	W 12 x 19	✓
73	W 21 x 44	W 12 x 14	W 12 x 16	✓
74	W 24 x 55	W 10 x 12	W 12 x 19	✓
75	W 21 x 44	W 8 x 10	W 12 x 14	✓
76	W 24 x 55	W 10 x 12	W 12 x 16	✓
77	W 21 x 44	W 8 x 10	W 12 x 14	✓
78	24 K 6	18 K 3	24 K 4	✓
79	24 K 6	18 K 3	24 K 4	✓
80	24 K 6	18 K 3	24 K 4	✓
81	24 K 6	18 K 3	24 K 4	✓
82	24 K 6	18 K 3	24 K 4	✓
83	24 K 6	18 K 3	24 K 4	✓
84	24 K 6	18 K 3	24 K 4	✓
85	24 K 6	18 K 3	24 K 4	✓

Third Floor Roof Structural Design (Joists)

Joist No.	Actual Size	RAM Design (Original Roof)	RAM Design (Green Roof)	OK?
86	24 K 6	18 K 3	24 K 4	✓
87	24 K 6	18 K 3	24 K 4	✓
88	24 K 6	18 K 3	24 K 4	✓
89	24 K 6	18 K 3	24 K 4	✓
90	24 K 6	18 K 3	24 K 4	✓
91	24 K 6	18 K 3	24 K 4	✓
92	24 K 6	18 K 3	24 K 4	✓
93	W 24 x 55	W 14 x 22	W 16 x 26	✓
95	W 24 x 68	W 12 x 16	W 12 x 19	✓
96	W 18 x 46	W 16 x 26	W 18 x 35	✓
97	W 18 x 46	W 12 x 26	W 18 x 35	✓
98	W 24 x 55	W 10 x 12	W 12 x 19	✓
99	W 14 x 22	W 8 x 10	W 8 x 10	✓
100	W 14 x 22	W 12 x 14	W 14 x 22	✓
101	28 K 7	22 K 4	24 K 7	✓
102	28 K 7	22 K 4	24 K 7	✓
103	28 K 7	22 K 4	24 K 7	✓
104	28 K 7	22 K 4	24 K 7	✓
105	28 K 7	22 K 4	24 K 7	✓
106	28 K 7	22 K 4	24 K 7	✓
107	28 K 7	22 K 4	24 K 7	✓
108	28 K 7	22 K 4	24 K 7	✓
109	28 K 7	22 K 4	24 K 7	✓
110	28 K 7	22 K 4	24 K 7	✓
111	28 K 7	22 K 4	24 K 7	✓
112	28 K 7	22 K 4	24 K 7	✓
113	28 K 7	22 K 4	24 K 7	✓
114	28 K 7	22 K 4	24 K 7	✓
115	28 K 7	22 K 4	24 K 7	✓
116	24 K 6	18 K 3	24 K 4	✓
117	24 K 6	18 K 3	24 K 4	✓
118	24 K 6	18 K 3	24 K 4	✓
119	24 K 6	18 K 3	24 K 4	✓
120	24 K 6	18 K 3	24 K 4	✓
121	24 K 6	18 K 3	24 K 4	✓
134	24 K 6	18 K 3	24 K 4	✓
135	24 K 6	18 K 3	24 K 4	✓
136	24 K 6	22 K 4	24 K 6	✓
146	24 K 6	18 K 3	24 K 4	✓

Third Floor Roof Structural Design (Joists)

Joist No.	Actual Size	RAM Design (Original Roof)	RAM Design (Green Roof)	OK?
147	24 K 6	18 K 3	4 K 4	✓
148	24 K 6	18 K 3	24 K 4	✓
149	24 K 6	18 K 3	24 K 4	✓
150	24 K 6	18 K 3	24 K 4	✓
151	24 K 6	18 K 3	24 K 4	✓
152	24 K 6	18 K 3	24 K 4	✓
153	24 K 6	18 K 3	24 K 4	✓
154	24 K 6	18 K 3	24 K 4	✓
155	24 K 6	18 K 3	24 K 4	✓
156	24 K 6	18 K 3	24 K 4	✓
157	24 K 6	18 K 3	24 K 4	✓
164	18 K 4	12 K 1	16 K 2	✓
165	18 K 4	12 K 1	16 K 2	✓
166	18 K 4	12 K 1	16 K 2	✓
167	18 K 4	12 K 1	16 K 2	✓
168	18 K 4	12 K 1	16 K 2	✓
169	18 K 4	12 K 1	16 K 2	✓
170	24 K 6	16 K 3	20 K 4	✓
171	24 K 6	16 K 3	20 K 4	✓
172	28 K 7	20 K 3	22 K 6	✓
173	28 K 7	20 K 3	22 K 6	✓
174	W 16 x 31	W 8 x 10	W 10 x 12	✓
175	W 16 x 31	W 8 x 10	W 10 x 12	✓
176	W 18 x 35	W 8 x 10	W 10 x 12	✓
177	W 21 x 44	W 12 x 16	W 12 x 19	✓
178	W 21 x 44	W 12 x 16	W 12 x 19	✓
179	W 21 x 44	W 12 x 16	W 12 x 19	✓
180	W 21 x 44	W 12 x 16	W 12 x 19	✓
181	W 21 x 44	W 12 x 16	W 12 x 19	✓
182	W 21 x 44	W 12 x 16	W 12 x 19	✓
183	W 21 x 44	W 12 x 16	W 12 x 19	✓
184	W 21 x 44	W 12 x 16	W 12 x 19	✓
185	W 21 x 44	W 12 x 16	W 12 x 19	✓
186	W 21 x 44	W 12 x 16	W 12 x 19	✓
187	W 21 x 44	W 12 x 16	W 12 x 19	✓
188	W 21 x 44	W 12 x 16	W 12 x 19	✓
189	W 16 x 26	W 12 x 16	W 12 x 19	✓
190	W 16 x 26	W 12 x 16	W 12 x 19	✓
191	W 16 x 26	W 12 x 16	W 12 x 19	✓

Third Floor Roof Structural Design (Joists)

Joist No.	Actual Size	RAM Design (Original Roof)	RAM Design (Green Roof)	OK?
192	W 16 x 26	W 12 x 16	W 12 x 19	✓
193	W 16 x 26	W 12 x 16	W 12 x 19	✓
194	W 16 x 26	W 12 x 16	W 12 x 19	✓
195	W 16 x 26	W 12 x 16	W 12 x 19	✓
196	W 16 x 26	W 12 x 16	W 12 x 19	✓
197	W 16 x 26	W 12 x 16	W 12 x 19	✓
198	W 21 x 44	W 12 x 16	W 12 x 19	✓
199	W 21 x 44	W 12 x 16	W 12 x 19	✓
200	W 21 x 44	W 12 x 16	W 12 x 19	✓

Comparison of actual design to RAM Steel outputs for model of second floor roof columns.

Second Floor Roof Structural Design (Columns)

Column No.	Actual Size	RAM Design (Original Roof)	RAM Design (Green Roof)	OK?
J 7.5	HSS 12 x 12 x 5/8	HSS 6 x 6 x 3/16	HSS 6 x 6 x 3/16	✓
J 24	W 10 x 60	W 10 x 33	W 10 x 33	✓
J 25	W 10 x 60	W 10 x 33	W 10 x 33	✓
J 26	W 10 x 60	W 10 x 33	W 10 x 33	✓
J 27	W 10 x 60	W 10 x 33	W 10 x 33	✓
J 29	W 10 x 60	W 10 x 33	W 10 x 33	✓
K 21	HSS 10 x 10 x 5/8	HSS 6 x 6 x 3/16	HSS 6 x 6 x 3/16	✓
K 22	HSS 10 x 10 x 5/8	HSS 6 x 6 x 3/16	HSS 6 x 6 x 3/16	✓
K 23	HSS 12 x 12 x 5/8	HSS 6 x 6 x 3/16	HSS 6 x 6 x 3/16	✓
K 24	HSS 12 x 12 x 5/8	HSS 6 x 6 x 3/16	HSS 6 x 6 x 3/16	✓
M 21	W 12 x 65	W 10 x 33	W 10 x 33	✓
M 22	W 12 x 65	W 10 x 33	W 10 x 33	✓
M 23	W 12 x 65	W 10 x 33	W 10 x 33	✓
M 24	W 12 x 65	W 10 x 33	W 10 x 33	✓
M 25	W 12 x 65	W 10 x 33	W 10 x 33	✓
M 26	W 12 x 65	W 10 x 33	W 10 x 33	✓
M 27	W 12 x 65	W 10 x 33	W 10 x 33	✓
M 29	W 12 x 65	W 10 x 33	W 10 x 33	✓
N 21	W 12 x 65	W 10 x 33	W 10 x 33	✓
N 22	HSS 8 x 8 x 1/2	HSS 6 x 6 x 3/16	HSS 6 x 6 x 3/16	✓
N 23	HSS 8 x 8 x 3/8	HSS 6 x 6 x 3/16	HSS 6 x 6 x 3/16	✓
N 24	HSS 8 x 8 x 3/8	HSS 6 x 6 x 3/16	HSS 6 x 6 x 3/16	✓
N 25	HSS 8 x 8 x 3/8	HSS 6 x 6 x 3/16	HSS 6 x 6 x 3/16	✓
N 26	HSS 8 x 8 x 5/16	HSS 6 x 6 x 3/16	HSS 6 x 6 x 3/16	✓
N 27	HSS 8 x 8 x 5/16	HSS 6 x 6 x 3/16	HSS 6 x 6 x 3/16	✓
N 29	HSS 8 x 8 x 5/16	HSS 6 x 6 x 3/16	HSS 6 x 6 x 3/16	✓
O 21	W 10 x 39	W 10 x 33	W 10 x 33	✓
O 22	W 10 x 54	W 10 x 33	W 10 x 33	✓
O 23	W 10 x 54	W 10 x 33	W 10 x 33	✓
O 24	W 10 x 54	W 10 x 33	W 10 x 33	✓
O 25	W 10 x 54	W 10 x 33	W 10 x 33	✓
O 26	W 10 x 54	W 10 x 33	W 10 x 33	✓
O 27	W 10 x 39	W 10 x 33	W 10 x 33	✓
O 29	W 10 x 39	W 10 x 33	W 10 x 33	✓

Comparison of actual design to RAM Steel outputs for model of thrid floor roof columns.

Third Floor Roof Structural Design (Columns)

Column No.	Actual Size	RAM Design (Original Roof)	RAM Design (Green Roof)	OK?
A 5	W 10 x 54	W 10 x 33	W 10 x 33	✓
A 6	W 10 x 60	W 10 x 33	W 10 x 33	✓
A 7	W 10 x 60	W 10 x 33	W 10 x 33	✓
A 8	W 12 x 65	W 10 x 33	W 10 x 33	✓
A 9	W 12 x 65	W 10 x 33	W 10 x 33	✓
A 10	W 12 x 65	W 10 x 33	W 10 x 33	✓
A 11	W 12 x 65	W 10 x 33	W 10 x 33	✓
A 12	W 12 x 54	W 10 x 33	W 10 x 33	✓
B 1	W 10 x 54	W 10 x 33	W 10 x 33	✓
B 2	W 10 x 60	W 10 x 33	W 10 x 33	✓
B 3	W 10 x 60	W 10 x 33	W 10 x 33	✓
B 3.6	W 10 x 54	W 10 x 33	W 10 x 33	✓
B 4	W 10 x 54	W 10 x 33	W 10 x 33	✓
B 4.6	W 10 x 54	W 10 x 33	W 10 x 33	✓
B 5	W 10 x 39	W 10 x 33	W 10 x 33	✓
C 1	W 10 x 54	W 10 x 33	W 10 x 33	✓
C 2	W 12 x 65	W 10 x 33	W 10 x 33	✓
C 3	W 12 x 65	W 10 x 33	W 10 x 33	✓
C 3.6	W 12 x 65	W 10 x 33	W 10 x 33	✓
C 4	W 12 x 65	W 10 x 33	W 10 x 33	✓
C 4.6	W 10 x 60	W 10 x 33	W 10 x 33	✓
C 6	W 12 x 65	W 10 x 33	W 10 x 33	✓
C 7	W 10 x 77	W 10 x 33	W 10 x 33	✓
C 8	W 12 x 87	W 10 x 33	W 10 x 33	✓
C 9	W 12 x 87	W 10 x 33	W 10 x 33	✓
C 10	W 12 x 87	W 10 x 33	W 10 x 33	✓
C 11	W 12 x 87	W 10 x 33	W 10 x 33	✓
C 12	W 12 x 87	W 10 x 33	W 10 x 33	✓
E 1	W 10 x 54	W 10 x 33	W 10 x 33	✓
E 2	W 10 x 54	W 10 x 33	W 10 x 33	✓
E 3	W 12 x 65	W 10 x 33	W 10 x 33	✓
E 3.6	W 12 x 65	W 10 x 33	W 10 x 33	✓
E 4	W 10 x 60	W 10 x 33	W 10 x 33	✓
E 4.6	W 10 x 60	W 10 x 33	W 10 x 33	✓
E 6	W 12 x 65	W 10 x 33	W 10 x 33	✓
E 7	W 12 x 65	W 10 x 33	W 10 x 33	✓
E 8	W 12 x 65	W 10 x 33	W 10 x 33	✓
E 9	W 12 x 65	W 10 x 33	W 10 x 33	✓
E 10	W 12 x 65	W 10 x 33	W 10 x 33	✓
E 11	W 12 x 65	W 10 x 33	W 10 x 33	✓
E 12	W 10 x 54	W 10 x 33	W 10 x 33	✓
H 1	W 10 x 54	W 10 x 33	W 10 x 33	✓
H 2	W 12 x 65	W 10 x 33	W 10 x 33	✓
H 3	W 12 x 87	W 10 x 33	W 10 x 33	✓
H 3.6	W 12 x 87	W 10 x 33	W 10 x 33	✓
I 1	W 10 x 54	W 10 x 33	W 10 x 33	✓
I 2	W 10 x 54	W 10 x 33	W 10 x 33	✓
I 3	W 10 x 54	W 10 x 33	W 10 x 33	✓
I 3.6	W 10 x 54	W 10 x 33	W 10 x 33	✓

Appendix E

Acoustic Analysis

Room Constant Calculation for Hearing Science Lab (3122).

Room Constant Calculation for:

HSLS Audiology Hearing Science Lab (3122)

Surface	Material	Area [m²]	Material Absorption Coefficient (α) 125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
Walls	Gypsum Board (2)	97.54883	0.28	0.12	0.10	0.07	0.13	0.09
Floor	Carpet	75.8064	0.08	0.27	0.39	0.34	0.48	0.63
Ceiling[1]	Acoustical Board	75.8064	0.76	0.93	0.83	0.99	0.99	0.94
Doors	Wood	19.509	0.19	0.14	0.09	0.06	0.06	0.05
	Total:	268.6706						
		α_{SAB} :	0.35247	0.39232	0.38707	0.40504	0.46632	0.47929
		Room Constant (R_T) :	**146.24**	**173.45**	**169.67**	**182.90**	**234.76**	**247.30**

Transmission Losses for Hearing Science Lab (3122).

Transmission Losses Through Building Construction (TL) [dB]

Calculation for Room: HSLS Audiology Hearing Science Lab (3122)

Building Construction		Transmission Loss [dB] 125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
Walls		38	52	59	60	56	62
Doors		29	31	31	31	39	43
Partitions[1]		35	39	39	39	46	51
Floor		38	44	52	55	60	65
Roof	original	17	22	26	30	35	41
	green	27	32	36	40	45	61

[1] Composite of doors and walls.

Noise Reductions for Hearing Science Lab (3122).

Noise Reduction Through Building Construction (L_p) [dB]

Calculation for Room: HSLS Audiology Hearing Science Lab (3122)

Building Construction		Noise Reduction[1] [dB] 125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
Partitions[2]		36	40	40	41	49	54
Floor		41	48	55	59	65	70
Roof	original	20	26	29	34	40	46
	green	29	35	39	43	50	66

[1] Noise reduction of average sound pressure levels through building construction.

[2] Composite of walls and doors.

Room Noise from each source for Hearing Science Lab (3122), original VAV system.

Noise in Receiver Room $(L_p)_{rec}$ [dB]

Calculation for Room: HSLS Audiology Hearing Science Lab (3122)

Source		Average Ambient Sound Pressure Level (L_p) [dB]					
		125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
Original Roof	Case 1	37	24	21	11	0	0
	Case 2	49	37	27	24	15	1
	Case 3	43	40	27	24	19	4
Green Roof	Case 1	28	14	11	2	0	0
	Case 2	39	27	17	14	5	0
	Case 3	33	30	17	14	9	0
Partitions[1]		16	5	0	0	0	0
Floor[1]		11	0	0	0	0	0
Mechanical Noise		34	31	26	20	11	5

[1] Worst case for Design NC Level of surrounding spaces.

Combined Room Noise for Hearing Science Lab (3122), original VAV system.

Combined Noise in Receiver Room $(L_p)_{rec}$ [dB]

Calculation for Room: HSLS Audiology Hearing Science Lab (3122)

Case		Average Ambient Sound Pressure Level (L_p) [dB]						NC Level
		125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz	
Original Roof	Case 1	39	32	27	21	11	5	**21**
	Case 2	49	38	29	25	16	6	**31**
	Case 3	43	40	29	25	20	7	**30**
Green Roof	Case 1	35	31	26	20	11	5	**20**
	Case 2	40	33	27	21	12	5	**20**
	Case 3	37	34	27	21	13	5	**20**

Case 1: Typical ambient conditions
Case 2: Car driving by site
Case 3: Diesel truck driving by site

Room Noise from each source for Hearing Science Lab (3122), proposed DOAS system.

Noise in Receiver Room $(L_p)_{rec}$ [dB]

Calculation for Room: HSLS Audiology Hearing Science Lab (3122)

		Average Ambient Sound Pressure Level (L_p) [dB]					
Source		125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
Original Roof	Case 1	37	24	21	11	0	0
	Case 2	49	37	27	24	15	1
	Case 3	43	40	27	24	19	4
Green Roof	Case 1	28	14	11	2	0	0
	Case 2	39	27	17	14	5	0
	Case 3	33	30	17	14	9	0
Partitions[1]		16	5	0	0	0	0
Floor[1]		11	-3	0	0	0	0
Mechanical Noise		34	27	20	11	5	5

[1] Worst case for Design NC Level of surrounding spaces.

Combined Room Noise for Hearing Science Lab (3122), proposed DOAS system.

Combined Noise in Receiver Room $(L_p)_{rec}$ [dB]

Calculation for Room: HSLS Audiology Hearing Science Lab (3122)

		Average Ambient Sound Pressure Level (L_p) [dB]						
Case		125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz	NC Level
Original Roof	Case 1	39	29	24	14	6	5	**20**
	Case 2	49	37	28	24	15	6	**31**
	Case 3	43	40	28	24	19	7	**30**
Green Roof	Case 1	35	27	21	12	5	5	**20**
	Case 2	40	30	22	16	8	5	**20**
	Case 3	37	32	22	16	11	5	**20**

Case 1: Typical ambient conditions
Case 2: Car driving by site
Case 3: Diesel truck driving by site

Output from Trane Acoustical Program (TAP) for HSLS Audiology and Hearing Science Lab (3122), original VAV system.

Path Table View -- Path1:

LINE ELEMENT	Octave Band Data 63	125	250	500	1k	2k	4k	COMMENTS
ASHRAE Fan	**98**	**98**	**97**	**95**	**88**	**81**	**77**	
Elbow (ln.sq.rct)	**0**	**-1**	**-6**	**-11**	**-10**	**-10**	**-10**	
SubSum	98	97	91	84	78	71	67	
	62	**57**	**49**	**42**	**34**	**25**	**14**	Regenerated sound from elbow.
SubSum	98	97	91	84	78	71	67	
Straight Duct(RL)	**-10**	**-13**	**-36**	**-40**	**-40**	**-40**	**-40**	
Elbow (ln.sq.rct)	**0**	**-1**	**-4**	**-7**	**-7**	**-7**	**-7**	
SubSum	88	83	51	37	31	24	20	
	64	**65**	**63**	**58**	**50**	**39**	**24**	Regenerated sound from elbow.
SubSum	88	83	63	58	50	39	25	
Straight Duct(RL)	**-1**	**-1**	**-3**	**-11**	**-9**	**-7**	**-7**	
Straight Duct(RL)	**-2**	**-3**	**-7**	**-23**	**-20**	**-16**	**-16**	
Elbow (ul.sq.rct)	**-1**	**-3**	**-6**	**-4**	**-4**	**-4**	**-4**	
SubSum	84	76	47	20	17	12	5	
	64	**63**	**60**	**54**	**45**	**33**	**16**	Regenerated sound from elbow.
SubSum	84	76	60	54	45	33	16	
Straight Duct(RU1)	**-8**	**-5**	**-3**	**-1**	**-1**	**-1**	**-1**	
Straight Duct(RU1)	**-1**	**-1**	**0**	**0**	**0**	**0**	**0**	
Elbow (ul.sq.rct)	**0**	**-1**	**-3**	**-6**	**-4**	**-4**	**-4**	
SubSum	75	69	54	47	40	28	11	
	59	**56**	**51**	**42**	**30**	**14**	**0**	Regenerated sound from elbow.
SubSum	75	69	56	48	40	28	11	
Straight Duct(RU1)	**-1**	**-1**	**-1**	**0**	**0**	**0**	**0**	
Junction (T,atten.)	**-7**	**-7**	**-7**	**-7**	**-7**	**-7**	**-7**	
SubSum	67	61	48	41	33	21	5	
	43	**39**	**34**	**28**	**22**	**15**	**7**	Regenerated sound from junction.
SubSum	67	61	48	41	33	22	9	
Straight Duct(RU1)	**-3**	**-2**	**-1**	**0**	**0**	**0**	**0**	
Elbow (ul.rad.rct)	**-1**	**-2**	**-3**	**-3**	**-3**	**-3**	**-3**	
SubSum	63	57	44	38	30	19	6	
	0	**0**	**0**	**0**	**0**	**0**	**0**	Regenerated sound from elbow.
SubSum	63	57	44	38	30	19	7	
Junction (90,atten.)AB	**-1**	**-1**	**-1**	**-1**	**-1**	**-1**	**-1**	
SubSum	62	56	43	37	29	18	6	
	7	**5**	**1**	**0**	**0**	**0**	**0**	Regenerated sound from junction.
SubSum	62	56	43	37	29	18	7	
Straight Duct(RU1)	**-2**	**-1**	**0**	**0**	**0**	**0**	**0**	
Junction (90,atten.)AB	**-1**	**-1**	**-1**	**-1**	**-1**	**-1**	**-1**	
SubSum	59	54	42	36	28	17	6	
	5	**1**	**0**	**0**	**0**	**0**	**0**	Regenerated sound from junction.
SubSum	59	54	42	36	28	17	7	
Junction (90,atten.)AB	**-5**	**-5**	**-5**	**-5**	**-5**	**-5**	**-5**	
SubSum	54	49	37	31	23	12	5	
	14	**9**	**4**	**0**	**0**	**0**	**0**	Regenerated sound from junction.

SubSum	54	49	37	31	23	12	6	
Straight Duct(RU1)	**-2**	**-1**	**-1**	**0**	**0**	**0**	**0**	
SubSum	52	48	36	31	23	12	6	
Custom Element	**0**	**70**	**64**	**60**	**62**	**65**	**69**	VAV-125
SubSum	52	70	64	60	62	65	69	
Custom Element	**-18**	**-42**	**-40**	**-48**	**-52**	**-50**	**-39**	SA-3
Junction (90,atten.)	**-2**	**-2**	**-2**	**-2**	**-2**	**-2**	**-2**	
SubSum	32	26	22	10	8	13	28	
	38	**33**	**25**	**16**	**7**	**0**	**0**	Regenerated sound from junction.
SubSum	39	34	27	17	11	13	28	
Straight Duct(RU1)	**-5**	**-3**	**-1**	**-1**	**-1**	**-1**	**-1**	
SubSum	34	31	26	16	10	12	27	
Diffuser	**42**	**40**	**37**	**31**	**23**	**13**	**1**	
SubSum	43	41	37	31	23	16	27	
Indoor (Regression)	**-9**	**-10**	**-11**	**-11**	**-12**	**-13**	**-14**	
SUM	34	31	26	20	11	5	13	
RATING	NC 16			RC 12(H)		23 dBA		

Output from Trane Acoustical Program (TAP) for HSLS Audiology and Hearing Science Lab (3122), proposed DOAS system.

Path Table View -- Path1:

	Octave Band Data							
LINE ELEMENT	**63**	**125**	**250**	**500**	**1k**	**2k**	**4k**	**COMMENTS**
ASHRAE Fan	88	88	90	82	78	71	67	
Elbow (In.sq.rct)	0	-1	-6	-11	-10	-10	-10	
SubSum	88	87	84	71	68	61	57	
	49	42	36	28	20	11	0	Regenerated sound from elbow.
SubSum	88	87	84	71	68	61	57	
Straight Duct(RL)	-14	-19	-40	-40	-40	-40	-40	
Elbow (In.sq.rct)	0	-1	-4	-7	-7	-7	-7	
SubSum	74	67	40	24	21	14	10	
	53	53	50	45	37	25	10	Regenerated sound from elbow.
SubSum	74	67	50	45	37	25	13	
Straight Duct(RL)	-1	-2	-4	-13	-12	-10	-8	
Straight Duct(RL)	-3	-4	-10	-28	-26	-22	-19	
Elbow (ul.sq.rct)	0	-1	-3	-6	-4	-4	-4	
SubSum	70	60	33	5	5	5	5	
	53	53	50	45	37	25	10	Regenerated sound from elbow.
SubSum	70	61	50	45	37	25	11	
Straight Duct(RU1)	-10	-7	-4	-1	-1	-1	-1	
Straight Duct(RU1)	-1	-1	0	0	0	0	0	
Elbow (ul.sq.rct)	0	-1	-3	-6	-4	-4	-4	
SubSum	59	52	43	38	32	20	6	
	53	53	50	45	37	25	10	Regenerated sound from elbow.
SubSum	60	56	51	46	38	26	11	
Straight Duct(RU1)	-2	-1	-1	0	0	0	0	
Junction (T,atten.)	-7	-7	-7	-7	-7	-7	-7	
SubSum	51	48	43	39	31	19	5	
	37	34	28	22	16	8	0	Regenerated sound from junction.
SubSum	51	48	43	39	31	19	6	
Straight Duct(RU1)	-3	-2	-1	-1	-1	-1	-1	
Elbow (ul.rad.rct)	0	0	-1	-2	-3	-3	-3	
SubSum	48	46	41	36	27	15	5	
	0	0	0	0	0	0	0	Regenerated sound from elbow.
SubSum	48	46	41	36	27	15	6	
Junction (90,atten.)	-1	-1	-1	-1	-1	-1	-1	
SubSum	47	45	40	35	26	14	5	
	0	0	0	0	0	0	0	Regenerated sound from junction.
SubSum	47	45	40	35	26	14	6	
Straight Duct(RU1)	-1	-1	0	0	0	0	0	
Junction (90,atten.)	-1	-1	-1	-1	-1	-1	-1	
SubSum	45	43	39	34	25	13	5	
	0	0	0	0	0	0	0	Regenerated sound from junction.
SubSum	45	43	39	34	25	13	6	
Junction (90,atten.)	-3	-3	-3	-3	-2	-2	-2	
SubSum	42	40	36	31	23	11	5	
	0	0	0	0	0	0	0	Regenerated sound from junction.

SubSum	42	40	36	31	23	11	6	
Straight Duct(RL)	**-7**	**-8**	**-12**	**-25**	**-40**	**-40**	**-33**	
Junction (90,atten.)	**-1**	**-1**	**-1**	**-1**	**-1**	**-1**	**-1**	
SubSum	34	31	23	5	5	5	5	
	56	**53**	**48**	**42**	**34**	**24**	**14**	Regenerated sound from junction.
SubSum	56	53	48	42	34	24	15	
Straight Duct(RL)	**-10**	**-11**	**-17**	**-34**	**-40**	**-40**	**-40**	
SubSum	46	42	31	8	5	5	5	
Diffuser	**42**	**40**	**37**	**31**	**23**	**13**	**1**	
SubSum	47	44	38	31	23	14	6	
Indoor (Regression)	**-9**	**-10**	**-11**	**-11**	**-12**	**-13**	**-14**	
SUM	38	34	27	20	11	5	5	
RATING	NC < 15			RC 12(R)		23 dBA		

Room Constant Calculation for HSLS Fac. Lab (3122H).

Room Constant Calculation for:
HSLS Fac. Lab (3122H)

Surface	Material	Area [m^2]	Material Absorption Coefficient (α) 125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
Walls	Gypsum Board (2)	21.36834	0.28	0.12	0.10	0.07	0.13	0.09
Floor	Carpet	11.148	0.08	0.27	0.39	0.34	0.48	0.63
Ceiling[1]	Acoustical Board	5.574	0.76	0.93	0.83	0.99	0.99	0.94
	Spray fib. insul.	11.148	0.08	0.29	0.75	0.98	0.93	0.76
Doors	Wood	19.509	0.19	0.14	0.09	0.06	0.06	0.05
	Total:	68.74734						
		α_{SAB} :	0.21554	0.19621	0.18716	0.17419	0.21554	0.22054
		Room Constant (R_T) :	**18.89**	**16.78**	**15.83**	**14.50**	**18.89**	**19.45**

[1] The ceiling must be a blend of acoustic board and perforated ceiling panels in a passive chilled beam application.

Transmission Losses for HSLS Fac. Lab (3122H).

Transmission Losses Through Building Construction (L_p) [dB]
Calculation for Room: HSLS Fac. Lab (3122H)

Building Construction		Transmission Loss [dB] 125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
Walls		38	52	59	60	56	62
Doors		29	31	31	31	39	43
Partitions[1]		32	34	34	34	42	46
Floor		38	44	52	55	60	65
Roof	original	17	22	26	30	35	41
	green	27	32	36	40	45	61

[1] Composite of doors and walls.

Noise Reductions for HSLS Fac. Lab (3122H).

Noise Reduction Through Building Construction (L_p) [dB]
Calculation for Room: HSLS Fac. Lab (3122H)

Building Construction		Noise Reduction[1] [dB] 125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
Partitions[2]		28	30	30	30	39	43
Floor		40	46	54	56	62	67
Roof	original	19	24	28	31	37	43
	green	29	34	38	41	47	63

[1] Noise reduction of average sound pressure levels through building construction.
[1] Composite of walls and doors.

Room Noise from each source for HSLS Fac. Lab (3122H), original VAV system.

Noise in Receiver Room $(L_p)_{rec}$ [dB]

Calculation for Room: HSLS Fac. Lab (3122H)

Source		Average Ambient Sound Pressure Level (L_p) [dB] 125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
Original Roof	Case 1	38	26	23	14	3	0
	Case 2	49	39	29	26	18	4
	Case 3	43	42	29	26	22	6
Green Roof	Case 1	28	16	13	4	0	0
	Case 2	39	29	19	16	8	0
	Case 3	33	32	19	16	12	0
Partitions[1]		24	15	10	6	0	0
Floor[1]		12	0	0	0	0	0
Mechanical Noise		35	30	23	15	5	5

[1] Worst case for Design NC Level of surrounding spaces.

Combined Room Noise for HSLS Fac. Lab (3122H), original VAV system.

Combined Noise in Receiver Room $(L_p)_{rec}$ [dB]

Calculation for Room: HSLS Fac. Lab (3122H)

Case		Average Ambient Sound Pressure Level (L_p) [dB] 125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz	NC Level
Original Roof	Case 1	40	31	26	18	7	5	**20**
	Case 2	50	39	30	27	18	8	**32**
	Case 3	44	42	30	27	22	9	**32**
Green Roof	Case 1	36	30	24	16	6	5	**17**
	Case 2	41	32	25	19	10	5	**20**
	Case 3	37	34	25	19	13	5	**21**

Case 1: Typical ambient conditions
Case 2: Car driving by site
Case 3: Diesel truck driving by site

Room Noise from each source for HSLS Fac. Lab (3122H), proposed DOAS system.

Noise in Receiver Room $(L_p)_{rec}$ [dB]

Calculation for Room: HSLS Fac. Lab (3122H)

Source		Average Ambient Sound Pressure Level (L_p) [dB]					
		125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
Original Roof	Case 1	38	26	23	14	3	0
	Case 2	49	39	29	26	18	4
	Case 3	43	42	29	26	22	6
Green Roof	Case 1	28	16	13	4	0	0
	Case 2	39	29	19	16	8	0
	Case 3	33	32	19	16	12	0
Partitions[1]		24	15	10	6	0	0
Floor[1]		12	0	0	0	0	0
Mechanical Noise		39	32	24	13	5	5

[1] Worst case for Design NC Level of surrounding spaces.

Combined Room Noise for HSLS Fac. Lab (3122H), proposed DOAS system.

Combined Noise in Receiver Room $(L_p)_{rec}$ [dB]

Calculation for Room: HSLS Fac. Lab (3122H)

Case		Average Ambient Sound Pressure Level (L_p) [dB]						
		125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz	NC Level
Original Roof	Case 1	42	33	27	17	7	5	**23**
	Case 2	50	40	30	27	18	8	**33**
	Case 3	45	42	30	27	22	9	**31**
Green Roof	Case 1	39	32	24	14	6	5	**20**
	Case 2	42	34	25	18	10	5	**23**
	Case 3	40	35	25	18	13	5	**23**

Case 1: Typical ambient conditions
Case 2: Car driving by site
Case 3: Diesel truck driving by site

Output from Trane Acoustical Program (TAP) for HSLS Fac. Lab (3122H), original VAV system.

Path Table View -- Path1:

	Octave Band Data							
LINE ELEMENT	**63**	**125**	**250**	**500**	**1k**	**2k**	**4k**	**COMMENTS**
ASHRAE Fan	**98**	**98**	**97**	**95**	**88**	**81**	**77**	
Elbow (ln.sq.rct)	**0**	**-1**	**-6**	**-11**	**-10**	**-10**	**-10**	
SubSum	98	97	91	84	78	71	67	
	62	**57**	**49**	**42**	**34**	**25**	**14**	Regenerated sound from elbow.
SubSum	98	97	91	84	78	71	67	
Straight Duct(RL)	**-10**	**-13**	**-36**	**-40**	**-40**	**-40**	**-40**	
Elbow (ln.sq.rct)	**0**	**-1**	**-4**	**-7**	**-7**	**-7**	**-7**	
SubSum	88	83	51	37	31	24	20	
	64	**65**	**63**	**58**	**50**	**39**	**24**	Regenerated sound from elbow.
SubSum	88	83	63	58	50	39	25	
Straight Duct(RL)	**-1**	**-1**	**-3**	**-11**	**-9**	**-7**	**-7**	
Straight Duct(RL)	**-2**	**-3**	**-7**	**-23**	**-20**	**-16**	**-16**	
Elbow (ul.sq.rct)	**-1**	**-3**	**-6**	**-4**	**-4**	**-4**	**-4**	
SubSum	84	76	47	20	17	12	5	
	64	**63**	**60**	**54**	**45**	**33**	**16**	Regenerated sound from elbow.
SubSum	84	76	60	54	45	33	16	
Straight Duct(RU1)	**-8**	**-5**	**-3**	**-1**	**-1**	**-1**	**-1**	
Straight Duct(RU1)	**-1**	**-1**	**0**	**0**	**0**	**0**	**0**	
Elbow (ul.sq.rct)	**0**	**-1**	**-3**	**-6**	**-4**	**-4**	**-4**	
SubSum	75	69	54	47	40	28	11	
	59	**56**	**51**	**42**	**30**	**14**	**0**	Regenerated sound from elbow.
SubSum	75	69	56	48	40	28	11	
Straight Duct(RU1)	**-1**	**-1**	**-1**	**0**	**0**	**0**	**0**	
Junction (T,atten.)	**-7**	**-7**	**-7**	**-7**	**-7**	**-7**	**-7**	
SubSum	67	61	48	41	33	21	5	
	43	**39**	**34**	**28**	**22**	**15**	**7**	Regenerated sound from junction.
SubSum	67	61	48	41	33	22	9	
Straight Duct(RU1)	**-3**	**-2**	**-1**	**0**	**0**	**0**	**0**	
Elbow (ul.rad.rct)	**-1**	**-2**	**-3**	**-3**	**-3**	**-3**	**-3**	
SubSum	63	57	44	38	30	19	6	
	0	**0**	**0**	**0**	**0**	**0**	**0**	Regenerated sound from elbow.
SubSum	63	57	44	38	30	19	7	
Junction (90,atten.)AB	**-10**	**-10**	**-10**	**-10**	**-10**	**-10**	**-10**	
SubSum	53	47	34	28	20	9	5	
	0	**0**	**0**	**0**	**0**	**0**	**0**	Regenerated sound from junction.
SubSum	53	47	34	28	20	10	6	
Straight Duct(RU1)	**-1**	**-1**	**0**	**0**	**0**	**0**	**0**	
SubSum	52	46	34	28	20	10	6	
Custom Element	**0**	**70**	**64**	**60**	**62**	**65**	**69**	VAV-125
SubSum	52	70	64	60	62	65	69	
Custom Element	**-18**	**-42**	**-40**	**-48**	**-52**	**-50**	**-39**	SA-3
Junction (90,atten.)AB	**-2**	**-2**	**-2**	**-2**	**-2**	**-2**	**-2**	
SubSum	32	26	22	10	8	13	28	
	0	**0**	**0**	**0**	**0**	**0**	**0**	Regenerated sound from junction.
SubSum	32	26	22	10	9	13	28	
Straight Duct(RL)	**-11**	**-12**	**-16**	**-30**	**-40**	**-40**	**-40**	

Elbow (In.sq.rct)	**0**	**0**	**0**	**-1**	**-6**	**-11**	**-10**	
SubSum	21	14	6	5	5	5	5	
	0	**0**	**0**	**0**	**0**	**0**	**0**	Regenerated sound from elbow.
Diffuser	**44**	**42**	**39**	**33**	**25**	**15**	**3**	
SubSum	44	42	39	33	25	16	8	
Indoor (Regression)	**-8**	**-9**	**-9**	**-10**	**-10**	**-11**	**-12**	
SUM	36	33	30	23	15	5	5	
RATING	NC 16			RC 14(R)		25 dBA		

Output from Trane Acoustical Program (TAP) for HSLS Fac. Lab (3122H), proposed DOAS system.

Path Table View -- Path1:

	Octave Band Data							
LINE ELEMENT	**63**	**125**	**250**	**500**	**1k**	**2k**	**4k**	**COMMENTS**
ASHRAE Fan	**88**	**88**	**90**	**82**	**78**	**71**	**67**	
Elbow (ln.sq.rct)	**0**	**-1**	**-6**	**-11**	**-10**	**-10**	**-10**	
SubSum	88	87	84	71	68	61	57	
	49	**42**	**36**	**28**	**20**	**11**	**0**	Regenerated sound from elbow.
SubSum	88	87	84	71	68	61	57	
Straight Duct(RL)	**-14**	**-19**	**-40**	**-40**	**-40**	**-40**	**-40**	
Elbow (ln.sq.rct)	**0**	**-1**	**-4**	**-7**	**-7**	**-7**	**-7**	
SubSum	74	67	40	24	21	14	10	
	53	**53**	**50**	**45**	**37**	**25**	**10**	Regenerated sound from elbow.
SubSum	74	67	50	45	37	25	13	
Straight Duct(RL)	**-1**	**-2**	**-4**	**-13**	**-12**	**-10**	**-8**	
Straight Duct(RL)	**-3**	**-4**	**-10**	**-28**	**-26**	**-22**	**-19**	
Elbow (ul.sq.rct)	**0**	**-1**	**-3**	**-6**	**-4**	**-4**	**-4**	
SubSum	70	60	33	5	5	5	5	
	53	**53**	**50**	**45**	**37**	**25**	**10**	Regenerated sound from elbow.
SubSum	70	61	50	45	37	25	11	
Straight Duct(RU1)	**-10**	**-7**	**-4**	**-1**	**-1**	**-1**	**-1**	
Straight Duct(RU1)	**-1**	**-1**	**0**	**0**	**0**	**0**	**0**	
Elbow (ul.sq.rct)	**0**	**-1**	**-3**	**-6**	**-4**	**-4**	**-4**	
SubSum	59	52	43	38	32	20	6	
	53	**53**	**50**	**45**	**37**	**25**	**10**	Regenerated sound from elbow.
SubSum	60	56	51	46	38	26	11	
Straight Duct(RU1)	**-2**	**-1**	**-1**	**0**	**0**	**0**	**0**	
Junction (T,atten.)	**-7**	**-7**	**-7**	**-7**	**-7**	**-7**	**-7**	
SubSum	51	48	43	39	31	19	5	
	37	**34**	**28**	**22**	**16**	**8**	**0**	Regenerated sound from junction.
SubSum	51	48	43	39	31	19	6	
Straight Duct(RU1)	**-3**	**-2**	**-1**	**-1**	**-1**	**-1**	**-1**	
Elbow (ul.rad.rct)	**0**	**0**	**-1**	**-2**	**-3**	**-3**	**-3**	
SubSum	48	46	41	36	27	15	5	
	0	**0**	**0**	**0**	**0**	**0**	**0**	Regenerated sound from elbow.
SubSum	48	46	41	36	27	15	6	
Junction (90,atten.)	**-1**	**-1**	**-1**	**-1**	**-1**	**-1**	**-1**	
SubSum	47	45	40	35	26	14	5	
	0	**0**	**0**	**0**	**0**	**0**	**0**	Regenerated sound from junction.
SubSum	47	45	40	35	26	14	6	
Straight Duct(RU1)	**-1**	**-1**	**0**	**0**	**0**	**0**	**0**	
Junction (90,atten.)	**-7**	**-7**	**-7**	**-7**	**-7**	**-7**	**-7**	
SubSum	39	37	33	28	19	7	5	
	0	**0**	**0**	**0**	**0**	**0**	**0**	Regenerated sound from junction.
SubSum	39	37	33	28	19	8	6	
Straight Duct(RL)	**-40**	**-40**	**-40**	**-40**	**-40**	**-40**	**-40**	
Junction (90,atten.)	**-3**	**-3**	**-3**	**-3**	**-3**	**-3**	**-3**	
SubSum	5	5	5	5	5	5	5	
	0	**0**	**0**	**0**	**0**	**0**	**0**	Regenerated sound from junction.

SubSum	6	6	6	6	6	6	6	
Elbow (ul.sq.rct)	**0**	**0**	**0**	**-1**	**-5**	**-8**	**-4**	
SubSum	6	6	6	5	5	5	5	
	17	**12**	**8**	**1**	**0**	**0**	**0**	Regenerated sound from elbow.
SubSum	17	13	10	6	6	6	6	
Straight Duct(RL)	**-28**	**-29**	**-31**	**-40**	**-40**	**-40**	**-40**	
Diffuser	**47**	**44**	**38**	**30**	**20**	**8**	**-7**	
Indoor (Regression)	**-9**	**-10**	**-11**	**-11**	**-12**	**-13**	**-14**	
SUM	43	39	32	24	13	5	5	
RATING	NC 19			RC 14(R)		28 dBA		

Room Constant Calculation for Hearing Aid Fitting Room (2207).

Room Constant Calculation for:
Hearing Aid Fitting Room (2207)

Surface	Material	Area [m²]	Material Absorption Coefficient (α) 125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
Int. Walls	Gypsum Board (2)	29.73	0.28	0.12	0.10	0.07	0.13	0.09
Ext. Walls	Gypsum Board (1)	5.39	0.55	0.14	0.08	0.04	0.12	0.11
Floor	Carpet	10.22	0.08	0.27	0.39	0.34	0.48	0.63
Ceiling[1]	Acoustical Board	5.11	0.76	0.93	0.83	0.99	0.99	0.94
	Spray fib. insul.	10.22	0.08	0.29	0.75	0.98	0.93	0.76
Doors	Wood	1.95	0.19	0.14	0.09	0.06	0.06	0.05
Windows	Glass	1.95	0.18	0.06	0.04	0.03	0.02	0.02
	Total:	62.61581						
		α_{SAB} :	0.21954	0.18316	0.18291	0.17231	0.22334	0.22443
		Room Constant (R_T) :	**17.61**	**14.04**	**14.02**	**13.04**	**18.01**	**18.12**

[1] The ceiling must be a blend of acoustic board and perforated ceiling panels in a passive chilled beam application.

Transmission Losses for Hearing Aid Fitting Room (2207) Exterior Wall.

Calculated Transmission Loss Through Exterior Wall (TL) [dB]
Calculation for Room: Hearing Aid Fitting Room (2207)

Building Construction	Transmission Loss [dB] 125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
Int. Wall Surface	28	45	54	55	47	54
Ext. Wall Surface	32	34	40	47	55	61
Total Ext. Wall	60	79	94	102	102	115

Transmission Losses for Hearing Aid Fitting Room (2207).

Transmission Losses Through Building Construction (TL) [dB]
Calculation for Room: Hearing Aid Fitting Room (2207)

Building Construction	Transmission Loss [dB] 125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
Int. Walls	38	52	59	60	56	62
Ext. Walls	60	79	94	102	102	115
Glass	21	30	40	44	46	57
Doors	29	31	31	31	39	43
Partitions[1]	36	43	43	43	50	54
Exterior Wall[2]	27	36	46	50	52	63
Floor	38	44	52	55	60	65

[1] Composite of doors and walls.

[2] Composite of glass and wall.

Noise Reductions for Hearing Aid Fitting Room (2207).

Noise Reduction Through Building Construction (L_p) [dB]

Calculation for Room: Hearing Aid Fitting Room (2207)

Building Construction	Noise Reduction[1] [dB]					
	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
Partitions[2]	34	39	39	39	47	52
Exterior Wall[3]	31	39	49	52	56	67
Floor	40	45	53	56	62	67

[1] Noise reduction of average sound pressure levels through building construction.

[2] Composite of walls and doors.

[3] Composite of glass and doors.

Room Noise from each source for Hearing Aid Fitting Room (2207), original VAV system.

Noise in Receiver Room $(L_p)_{rec}$ [dB]

Calculation for Room: Hearing Aid Fitting Room (2207)

Source		Average Ambient Sound Pressure Level (L_p) [dB]					
		125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
Exterior Wall	Case 1	27	11	2	-7	0	0
	Case 2	38	24	8	5	0	0
	Case 3	32	27	8	5	3	0
Partitions[1]		18	6	1	-3	0	0
Floor[1]		12	0	0	0	0	0
Mechanical Noise		36.0	29.0	22.0	17.0	14.0	12.0

[1] Worst case for Design NC Level of surrounding spaces.

Combined Room Noise for Hearing Aid Fitting Room (2207), original VAV system.

Combined Noise in Receiver Room $(L_p)_{rec}$ [dB]

Calculation for Room: Hearing Aid Fitting Room (2207)

	Average Ambient Sound Pressure Level (L_p) [dB]						NC Level
	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz	
Case 1	37	29	22	17	14	12	16
Case 2	40	30	22	17	14	12	20
Case 3	38	31	22	17	14	12	19

Case 1: Typical ambient conditions
Case 2: Car driving by site
Case 3: Diesel truck driving by site

Room Noise from each source for Hearing Aid Fitting Room (2207), proposed DOAS system.

Noise in Receiver Room $(L_p)_{rec}$ [dB]

Calculation for Room: Hearing Aid Fitting Room (2207)

Source		Average Ambient Sound Pressure Level (L_p) [dB] 125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
Exterior Wall	Case 1	27	11	2	0	0	0
	Case 2	38	24	8	5	0	0
	Case 3	32	27	8	5	3	0
Partitions[1]		18	6	1	0	0	0
Floor[1]		12	0	0	0	0	0
Mechanical Noise		21.0	14.0	7.0	5.0	5.0	5.0

[1] Worst case for Design NC Level of surrounding spaces.

Combined Room Noise for Hearing Aid Fitting Room (2207), proposed DOAS system.

Combined Noise in Receiver Room $(L_p)_{rec}$ [dB]

Calculation for Room: Hearing Aid Fitting Room (2207)

	Average Ambient Sound Pressure Level (L_p) [dB] 125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz	NC Level
Case 1	28	16	9	6	5	5	<15
Case 2	38	24	11	8	6	5	18
Case 3	33	27	11	8	7	5	<15

Case 1: Typical ambient conditions
Case 2: Car driving by site
Case 3: Diesel truck driving by site

Output from Trane Acoustical Program (TAP) for Hearing Aid Fitting Room (2207), original VAV system.

Path Table View -- Path1:

	Octave Band Data							
LINE ELEMENT	**63**	**125**	**250**	**500**	**1k**	**2k**	**4k**	**COMMENTS**
ASHRAE Fan	**101**	**101**	**100**	**98**	**91**	**84**	**80**	
Elbow (In.sq.rct)	**0**	**-1**	**-6**	**-11**	**-10**	**-10**	**-10**	
SubSum	101	100	94	87	81	74	70	
	57	**51**	**45**	**37**	**29**	**19**	**9**	Regenerated sound from elbow.
SubSum	101	100	94	87	81	74	70	
Straight Duct(RL)	**-4**	**-5**	**-14**	**-40**	**-38**	**-31**	**-29**	
Elbow (In.sq.rct)	**-1**	**-4**	**-7**	**-7**	**-7**	**-7**	**-7**	
SubSum	96	91	73	40	36	36	34	
	62	**63**	**61**	**56**	**48**	**37**	**22**	Regenerated sound from elbow.
SubSum	96	91	73	56	48	40	34	
Straight Duct(RL)	**-1**	**-1**	**-4**	**-11**	**-9**	**-8**	**-7**	
Elbow (In.sq.rct)	**-1**	**-4**	**-7**	**-7**	**-7**	**-7**	**-7**	
SubSum	94	86	62	38	32	25	20	
	62	**63**	**61**	**56**	**48**	**37**	**22**	Regenerated sound from elbow.
SubSum	94	86	65	56	48	37	24	
Straight Duct(RL)	**-1**	**-1**	**-2**	**-5**	**-5**	**-4**	**-4**	
Elbow (In.sq.rct)	**0**	**-1**	**-4**	**-7**	**-7**	**-7**	**-7**	
SubSum	93	84	59	44	36	26	13	
	65	**65**	**63**	**59**	**52**	**41**	**27**	Regenerated sound from elbow.
SubSum	93	84	64	59	52	41	27	
Straight Duct(RL)	**-4**	**-5**	**-12**	**-38**	**-33**	**-27**	**-26**	
Elbow (In.sq.rct)	**0**	**-1**	**-4**	**-7**	**-7**	**-7**	**-7**	
SubSum	89	78	48	14	12	7	5	
	62	**63**	**61**	**56**	**48**	**37**	**22**	Regenerated sound from elbow.
SubSum	89	78	61	56	48	37	22	
Elbow (In.sq.rct)	**0**	**-1**	**-4**	**-7**	**-7**	**-7**	**-7**	
SubSum	89	77	57	49	41	30	15	
	62	**63**	**61**	**56**	**48**	**37**	**22**	Regenerated sound from elbow.
SubSum	89	77	62	57	49	38	23	
Straight Duct(RL)	**-3**	**-4**	**-11**	**-33**	**-28**	**-23**	**-22**	
Elbow (ul.sq.rct)	**0**	**-1**	**-5**	**-8**	**-4**	**-3**	**-3**	
SubSum	86	72	46	16	17	12	5	
	57	**51**	**45**	**37**	**29**	**19**	**9**	Regenerated sound from elbow.
SubSum	86	72	49	37	29	20	10	
Junction (T,atten.)	**-1**	**-1**	**-1**	**-1**	**-1**	**-1**	**-1**	
SubSum	85	71	48	36	28	19	9	
	55	**49**	**42**	**33**	**24**	**14**	**3**	Regenerated sound from junction.
SubSum	85	71	49	38	29	20	10	
Junction (90,atten.)AB	**-1**	**-1**	**-1**	**-1**	**-1**	**-1**	**-1**	
SubSum	84	70	48	37	28	19	9	
	43	**39**	**35**	**31**	**26**	**20**	**12**	Regenerated sound from junction.
SubSum	84	70	48	38	30	23	14	
Straight Duct(RU1)	**-3**	**-2**	**-1**	**0**	**0**	**0**	**0**	
Junction (90,atten.)AB	**-1**	**-1**	**-1**	**-1**	**-1**	**-1**	**-1**	
SubSum	80	67	46	37	29	22	13	

	51	46	40	34	27	20	11	Regenerated
sound from junction.								
Junction (T,atten.)	0	0	0	0	0	0	0	
	29	25	20	15	9	2	0	Regenerated
sound from junction.								
SubSum	80	67	47	39	31	24	15	
Straight Duct(RU1)	-4	-2	-2	0	0	0	0	
Junction (90,atten.)AB	-1	-1	-1	-1	-1	-1	-1	
SubSum	75	64	44	38	30	23	14	
	36	32	26	21	14	7	0	Regenerated
sound from junction.								
SubSum	75	64	44	38	30	23	14	
Straight Duct(RU1)	-3	-2	-1	0	0	0	0	
Junction (90,atten.)AB	-1	-1	-1	-1	-1	-1	-1	
SubSum	71	61	42	37	29	22	13	
	33	29	24	19	12	4	0	Regenerated
sound from junction.								
SubSum	71	61	42	37	29	22	13	
Straight Duct(RU1)	-3	-2	-1	0	0	0	0	
Junction (90,atten.)AB	-1	-1	-1	-1	-1	-1	-1	
SubSum	67	58	40	36	28	21	12	
	32	27	22	16	9	2	0	Regenerated
sound from junction.								
SubSum	67	58	40	36	28	21	12	
Straight Duct(RU1)	-6	-4	-3	-1	-1	-1	-1	
Junction (90,atten.)AB	0	-4	0	0	0	0	0	
SubSum	61	50	37	35	27	20	11	
	34	29	24	18	12	4	0	Regenerated
sound from junction.								
SubSum	61	50	37	35	27	20	11	
Straight Duct(RU1)	-1	-1	-1	0	0	0	0	
Junction (T,atten.)	-2	-4	-2	-2	-2	-2	-2	
SubSum	58	45	34	33	25	18	9	
	16	6	0	0	0	0	0	Regenerated
sound from junction.								
SubSum	58	45	34	33	25	18	10	
Straight Duct(RU1)	-1	-1	-1	0	0	0	0	
Junction (90,atten.)AB	-6	-6	-6	-6	-6	-6	-6	
SubSum	51	38	27	27	19	12	5	
	24	19	13	6	0	0	0	Regenerated
sound from junction.								
SubSum	51	38	27	27	19	12	6	
Elbow (ul.rad.rct)	0	0	-1	-2	-3	-3	-3	
SubSum	51	38	26	25	16	9	5	
	4	0	0	0	0	0	0	Regenerated
sound from elbow.								
SubSum	51	38	26	25	16	10	6	
Straight Duct(RU1)	-3	-1	-1	0	0	0	0	
Junction (T,atten.)	-2	-2	-2	-2	-2	-2	-2	
SubSum	46	35	23	23	14	8	5	
	19	13	8	0	0	0	0	Regenerated
sound from junction.								
Custom Element	0	70	64	60	62	65	69	VAV-064
SubSum	46	70	64	60	62	65	69	
Custom Element	-12	-40	-35	-31	-27	-28	-42	SA-2
Straight Duct(RL)	-2	-2	-3	-7	-15	-14	-9	
Junction (T,atten.)	-3	-3	-3	-3	-3	-3	-3	
SubSum	29	25	23	19	17	20	15	
	0	0	0	0	0	0	0	Regenerated
sound from junction.								
SubSum	29	25	23	19	17	20	15	

Straight Duct(RL)	**-2**	**-3**	**-4**	**-8**	**-19**	**-18**	**-10**	
SubSum	27	22	19	11	5	5	5	
Custom Element	**34**	**29**	**22**	**15**	**11**	**9**	**6**	Diffuser
SubSum	35	30	24	16	12	10	9	
Indoor (Regression)	**-9**	**-9**	**-10**	**-10**	**-11**	**-11**	**-12**	
SUM	26	21	14	6	5	5	5	
RATING	NC < 15			RC 5(H)		13 dBA		

Output from Trane Acoustical Program (TAP) for Hearing Aid Fitting Room (2207), proposed DOAS system.

Path Table View -- Path1:

LINE ELEMENT	Octave Band Data 63	125	250	500	1k	2k	4k	COMMENTS
ASHRAE Fan	**85**	**85**	**87**	**79**	**75**	**68**	**64**	
Elbow (In.sq.rct)	**0**	**-1**	**-6**	**-11**	**-10**	**-10**	**-10**	
SubSum	85	84	81	68	65	58	54	
	50	**45**	**39**	**31**	**23**	**13**	**4**	Regenerated sound from elbow.
SubSum	85	84	81	68	65	58	54	
Straight Duct(RL)	**-6**	**-8**	**-19**	**-40**	**-40**	**-40**	**-35**	
Elbow (In.sq.rct)	**0**	**-1**	**-4**	**-7**	**-7**	**-7**	**-7**	
SubSum	79	75	58	21	18	11	12	
	53	**53**	**51**	**46**	**37**	**26**	**11**	Regenerated sound from elbow.
SubSum	79	75	59	46	37	26	15	
Straight Duct(RL)	**-2**	**-2**	**-5**	**-13**	**-12**	**-11**	**-9**	
Elbow (In.sq.rct)	**0**	**-1**	**-4**	**-7**	**-7**	**-7**	**-7**	
SubSum	77	72	50	26	18	8	5	
	53	**53**	**51**	**46**	**37**	**26**	**11**	Regenerated sound from elbow.
SubSum	77	72	54	46	37	26	12	
Straight Duct(RL)	**-1**	**-1**	**-2**	**-7**	**-6**	**-5**	**-4**	
Elbow (In.sq.rct)	**0**	**-1**	**-4**	**-7**	**-7**	**-7**	**-7**	
SubSum	76	70	48	32	24	14	5	
	53	**53**	**51**	**46**	**37**	**26**	**11**	Regenerated sound from elbow.
SubSum	76	70	53	46	37	26	12	
Straight Duct(RL)	**-5**	**-7**	**-17**	**-40**	**-40**	**-37**	**-31**	
Elbow (In.sq.rct)	**0**	**-1**	**-4**	**-7**	**-7**	**-7**	**-7**	
SubSum	71	62	32	5	5	5	5	
	53	**53**	**51**	**46**	**37**	**26**	**11**	Regenerated sound from elbow.
SubSum	71	63	51	46	37	26	12	
Elbow (In.sq.rct)	**0**	**-1**	**-4**	**-7**	**-7**	**-7**	**-7**	
SubSum	71	62	47	39	30	19	5	
	53	**53**	**51**	**46**	**37**	**26**	**11**	Regenerated sound from elbow.
SubSum	71	63	52	47	38	27	12	
Straight Duct(RL)	**-5**	**-6**	**-15**	**-40**	**-37**	**-32**	**-26**	
Elbow (ul.sq.rct)	**0**	**-1**	**-5**	**-8**	**-4**	**-3**	**-3**	
SubSum	66	56	32	5	5	5	5	
	25	**19**	**11**	**1**	**0**	**0**	**0**	Regenerated sound from elbow.
SubSum	66	56	32	6	6	6	6	
Junction (T,atten.)	**-6**	**-6**	**-6**	**-6**	**-6**	**-6**	**-6**	
SubSum	60	50	26	5	5	5	5	
	74	**69**	**62**	**55**	**45**	**35**	**23**	Regenerated sound from junction.
Junction (90,atten.)	**0**	**0**	**0**	**0**	**0**	**0**	**0**	
	32	**29**	**27**	**23**	**19**	**15**	**9**	Regenerated sound from junction.
SubSum	74	69	62	55	45	35	23	
Straight Duct(RU1)	**-4**	**-3**	**-2**	**-1**	**-1**	**-1**	**-1**	
Junction (90,atten.)	**-1**	**-1**	**-1**	**-1**	**-1**	**-1**	**-1**	
SubSum	69	65	59	53	43	33	21	

	38	**35**	**30**	**25**	**18**	**11**	**4**	Regenerated
sound from junction.								
Junction (T,atten.)	**0**	**0**	**0**	**0**	**0**	**0**	**0**	
	29	**26**	**22**	**18**	**13**	**7**	**1**	Regenerated
sound from junction.								
SubSum	69	65	59	53	43	33	21	
Straight Duct(RU1)	**-5**	**-3**	**-2**	**-1**	**-1**	**-1**	**-1**	
SubSum	64	62	57	52	42	32	20	
Junction (90,atten.)	**0**	**0**	**0**	**0**	**0**	**0**	**0**	
	38	**36**	**31**	**27**	**22**	**16**	**9**	Regenerated
sound from junction.								
SubSum	64	62	57	52	42	32	20	
Straight Duct(RU1)	**-5**	**-3**	**-2**	**-1**	**-1**	**-1**	**-1**	
SubSum	59	59	55	51	41	31	19	
Junction (90,atten.)	**0**	**0**	**0**	**0**	**0**	**0**	**0**	
	24	**24**	**21**	**18**	**15**	**10**	**5**	Regenerated
sound from junction.								
SubSum	59	59	55	51	41	31	19	
Straight Duct(RU1)	**-4**	**-3**	**-2**	**-1**	**-1**	**-1**	**-1**	
SubSum	55	56	53	50	40	30	18	
Junction (90,atten.)	**0**	**0**	**0**	**0**	**0**	**0**	**0**	
	36	**33**	**29**	**24**	**19**	**12**	**6**	Regenerated
sound from junction.								
SubSum	55	56	53	50	40	30	18	
Straight Duct(RU1)	**-8**	**-5**	**-4**	**-1**	**-1**	**-1**	**-1**	
SubSum	47	51	49	49	39	29	17	
Junction (90,atten.)	**0**	**0**	**0**	**0**	**0**	**0**	**0**	
	42	**37**	**34**	**28**	**22**	**15**	**8**	Regenerated
sound from junction.								
SubSum	48	51	49	49	39	29	18	
Straight Duct(RU1)	**-2**	**-1**	**-1**	**0**	**0**	**0**	**0**	
Junction (T,atten.)	**-1**	**-1**	**-1**	**-1**	**-1**	**-1**	**-1**	
SubSum	45	49	47	48	38	28	17	
	43	**38**	**32**	**25**	**17**	**9**	**0**	Regenerated
sound from junction.								
SubSum	47	49	47	48	38	28	17	
Straight Duct(RU1)	**-2**	**-1**	**-1**	**0**	**0**	**0**	**0**	
Junction (90,atten.)	**-10**	**-10**	**-10**	**-10**	**-10**	**-10**	**-10**	
SubSum	35	38	36	38	28	18	7	
	35	**31**	**26**	**21**	**15**	**8**	**0**	Regenerated
sound from junction.								
SubSum	38	39	36	38	28	18	8	
Elbow (ul.rad.rct)	**0**	**0**	**0**	**-1**	**-2**	**-3**	**-3**	
SubSum	38	39	36	37	26	15	5	
	0	**0**	**0**	**0**	**0**	**0**	**0**	Regenerated
sound from elbow.								
SubSum	38	39	36	37	26	15	6	
Straight Duct(RU1)	**-2**	**-1**	**-1**	**-1**	**-1**	**-1**	**-1**	
Junction (T,atten.)	**-2**	**-2**	**-2**	**-2**	**-2**	**-2**	**-2**	
SubSum	34	36	33	34	23	12	5	
	21	**16**	**12**	**7**	**1**	**0**	**0**	Regenerated
sound from junction.								
SubSum	34	36	33	34	23	12	6	
Straight Duct(RL)	**-3**	**-4**	**-5**	**-9**	**-23**	**-22**	**-12**	
Junction (T,atten.)	**-3**	**-3**	**-3**	**-3**	**-3**	**-3**	**-3**	
SubSum	28	29	25	22	5	5	5	
	15	**10**	**5**	**0**	**0**	**0**	**0**	Regenerated
sound from junction.								
SubSum	28	29	25	22	6	6	6	
Straight Duct(RL)	**-4**	**-5**	**-6**	**-10**	**-27**	**-27**	**-13**	
SubSum	24	24	19	12	5	5	5	

Custom Element	**34**	**29**	**22**	**15**	**11**	**9**	**6**	Diffuser
SubSum	34	30	24	17	12	10	9	
Indoor (Regression)	**-9**	**-9**	**-10**	**-10**	**-11**	**-11**	**-12**	
SUM	25	21	14	7	5	5	5	
RATING	NC < 15			RC 6(H)		13 dBA		

Room Constant Calculation for Classroom (2302).

Room Constant Calculation for:
Classroom (2302)

Surface	Material	Area [m²]	Material Absorption Coefficient (α) 125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
Int. Walls	Gypsum Board (2)	29.73	0.28	0.12	0.10	0.07	0.13	0.09
Ext. Walls	Gypsum Board (1)	5.39	0.55	0.14	0.08	0.04	0.12	0.11
Floor	Carpet	10.22	0.08	0.27	0.39	0.34	0.48	0.63
Ceiling[1]	Acoustical Board	5.11	0.76	0.93	0.83	0.99	0.99	0.94
	Spray fib. insul.	10.22	0.08	0.29	0.75	0.98	0.93	0.76
Doors	Wood	1.95	0.19	0.14	0.09	0.06	0.06	0.05
Windows	Glass	1.95	0.18	0.06	0.04	0.03	0.02	0.02
	Total:	62.61581						
		α_{SAB} :	0.21954	0.18316	0.18291	0.17231	0.22334	0.22443
		Room Constant (R_T) :	**17.61**	**14.04**	**14.02**	**13.04**	**18.01**	**18.12**

[1] The ceiling must be a blend of acoustic board and perforated ceiling panels in a passive chilled beam application.

Transmission Losses for Classroom (2302).

Transmission Losses Through Building Construction (TL) [dB]
Calculation for Room: Classroom (2302)

Building Construction		Transmission Loss [dB] 125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
Int. Walls		38	52	59	60	56	62
Ext. Walls		60	79	94	102	102	115
Glass		21	30	40	44	46	57
Doors		29	31	31	31	39	43
Partitions[1]		36	43	43	43	50	54
Exterior Wall[2]		27	36	46	50	52	63
Floor		38	44	52	55	60	65
Roof	original	17	22	26	30	35	41
	green	27	32	36	40	45	61

[1] Composite of doors and walls.
[2] Composite of glass and wall.

Noise Reductions for Classroom (2302).

Noise Reduction Through Building Construction (L_p) [dB]
Calculation for Room: Classroom (2302)

Building Construction		Noise Reduction[1] [dB] 125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
Walls	w/ insul.	38	52	59	60	56	62
Doors		29	31	31	31	39	43
Partitions[2]		34	39	39	39	47	52
Exterior Wall[3]		31	39	49	52	56	67
Floor		40	45	53	56	62	67
Roof	original	19	23	27	31	37	43
	green	29	33	37	41	47	63

[1] Noise reduction of average sound pressure levels through building construction.
[2] Composite of walls and doors.
[3] Composite of glass and doors.

Room Noise from each source for Classroom (2302), original VAV system.

Noise in Receiver Room $(L_p)_{rec}$ [dB]

Calculation for Room: Classroom (2302)

Source		Average Ambient Sound Pressure Level (L_p) [dB]					
		125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
Original Roof	Case 1	38	26	23	14	3	0
	Case 2	49	39	29	26	17	4
	Case 3	43	42	29	26	22	6
Green Roof	Case 1	28	16	13	4	0	0
	Case 2	39	29	19	16	7	0
	Case 3	33	32	19	16	12	0
Exterior Wall	Case 1	27	11	2	0	0	0
	Case 2	38	24	8	5	0	0
	Case 3	32	27	8	5	3	0
Partitions[1]		18	6	1	0	0	0
Floor[1]		12	0	0	0	0	0
Mechanical Noise		36	32	23	14	5	5

[1] Worst case for Design NC Level of surrounding spaces.

Combined Room Noise for Classroom (2302), original VAV system.

Combined Noise in Receiver Room $(L_p)_{rec}$ [dB]

Calculation for Room: Classroom (2302)

Case		Average Ambient Sound Pressure Level (L_p) [dB]						NC Level
		125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz	
Original Roof	Case 1	40	33	26	17	7	5	**20**
	Case 2	50	40	30	27	18	7	**33**
	Case 3	44	43	30	27	22	9	**33**
Green Roof	Case 1	37	32	23	15	5	5	**20**
	Case 2	41	34	24	18	9	5	**21**
	Case 3	38	35	24	18	12	5	**23**

Case 1: Typical ambient conditions
Case 2: Car driving by site
Case 3: Diesel truck driving by site

Room Noise from each source for Classroom (2302), proposed DOAS system.

Source		Average Ambient Sound Pressure Level (L_p) [dB] 125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
Original Roof	Case 1	38	26	23	14	3	0
	Case 2	49	39	29	26	17	4
	Case 3	43	42	29	26	22	6
Green Roof	Case 1	28	16	13	4	0	0
	Case 2	39	29	19	16	7	0
	Case 3	33	32	19	16	12	0
Exterior Wall	Case 1	27	11	2	0	0	0
	Case 2	38	24	8	5	0	0
	Case 3	32	27	8	5	3	0
Partitions[1]		18	6	1	-3	0	0
Floor[1]		12	0	0	0	0	0
Mechanical Noise		30	27	20	11	5	5

[1] Worst case for Design NC Level of surrounding spaces.

Combined Room Noise for Classroom (2302), proposed DOAS system.

Combined Noise in Receiver Room $(L_p)_{rec}$ [dB]

Calculation for Room: Classroom (2302)

Case		Average Ambient Sound Pressure Level (L_p) [dB] 125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz	NC Level
Original Roof	Case 1	39	30	25	16	7	5	**20**
	Case 2	50	40	29	27	18	7	**33**
	Case 3	44	42	29	27	22	9	**32**
Green Roof	Case 1	32	27	21	12	5	5	**20**
	Case 2	40	31	23	17	9	5	**20**
	Case 3	35	33	22	17	12	5	**20**

Case 1: Typical ambient conditions
Case 2: Car driving by site
Case 3: Diesel truck driving by site

Output from Trane Acoustical Program (TAP) for Classroom (2302), original VAV system.

Path Table View -- Path1:

	Octave Band Data							
LINE ELEMENT	**63**	**125**	**250**	**500**	**1k**	**2k**	**4k**	**COMMENTS**
ASHRAE Fan	**106**	**106**	**105**	**103**	**96**	**89**	**85**	
Elbow (ln.sq.rct)	**-1**	**-6**	**-11**	**-10**	**-10**	**-10**	**-10**	
SubSum	105	100	94	93	86	79	75	
	64	**58**	**51**	**43**	**34**	**25**	**14**	Regenerated sound from elbow.
SubSum	105	100	94	93	86	79	75	
Straight Duct(RL)	**-6**	**-8**	**-22**	**-40**	**-40**	**-40**	**-40**	
Elbow (ln.sq.rct)	**-1**	**-6**	**-11**	**-10**	**-10**	**-10**	**-10**	
SubSum	98	86	61	43	36	29	25	
	64	**58**	**51**	**43**	**34**	**25**	**14**	Regenerated sound from elbow.
SubSum	98	86	61	46	38	30	25	
Straight Duct(RL)	**-2**	**-3**	**-7**	**-25**	**-20**	**-16**	**-17**	
Straight Duct(RU2)	**-5**	**-3**	**-2**	**0**	**0**	**0**	**0**	
Elbow (ul.sq.rct)	**-1**	**-3**	**-6**	**-4**	**-4**	**-4**	**-4**	
SubSum	90	77	46	17	14	10	5	
	64	**64**	**61**	**54**	**45**	**32**	**17**	Regenerated sound from elbow.
SubSum	90	77	61	54	45	32	17	
Straight Duct(RU2)	**-4**	**-3**	**-2**	**0**	**0**	**0**	**0**	
Elbow (ul.sq.rct)	**-1**	**-3**	**-6**	**-4**	**-4**	**-4**	**-4**	
SubSum	85	71	53	50	41	28	13	
	64	**64**	**61**	**54**	**45**	**32**	**17**	Regenerated sound from elbow.
SubSum	85	72	62	55	46	33	18	
Straight Duct(RU2)	**-3**	**-2**	**-2**	**0**	**0**	**0**	**0**	
Elbow (ul.sq.rct)	**-1**	**-3**	**-6**	**-4**	**-4**	**-4**	**-4**	
SubSum	81	67	54	51	42	29	14	
	64	**64**	**61**	**54**	**45**	**32**	**17**	Regenerated sound from elbow.
SubSum	81	69	62	56	47	34	19	
Straight Duct(RU2)	**-22**	**-15**	**-10**	**-2**	**-2**	**-2**	**-2**	
Elbow (ul.sq.rct)	**-1**	**-3**	**-6**	**-4**	**-4**	**-4**	**-4**	
SubSum	58	51	46	50	41	28	13	
	64	**64**	**61**	**54**	**45**	**32**	**17**	Regenerated sound from elbow.
SubSum	65	64	61	55	46	33	18	
Straight Duct(RU2)	**-1**	**-1**	**-1**	**0**	**0**	**0**	**0**	
Elbow (ul.sq.rct)	**-1**	**-3**	**-6**	**-4**	**-4**	**-4**	**-4**	
SubSum	63	60	54	51	42	29	14	
	64	**64**	**60**	**54**	**45**	**32**	**15**	Regenerated sound from elbow.
SubSum	67	65	61	56	47	34	18	
Straight Duct(RU2)	**-5**	**-3**	**-2**	**0**	**0**	**0**	**0**	
Junction (90,atten.)AB	**-3**	**-3**	**-3**	**-3**	**-3**	**-3**	**-3**	
SubSum	59	59	56	53	44	31	15	
	63	**57**	**51**	**43**	**36**	**26**	**17**	Regenerated sound from junction.
SubSum	64	61	57	53	45	32	19	
Straight Duct(RU2)	**-6**	**-4**	**-3**	**0**	**0**	**0**	**0**	
Junction (90,atten.)AB	**-1**	**-1**	**-1**	**-1**	**-1**	**-1**	**-1**	
SubSum	57	56	53	52	44	31	18	
	58	**55**	**49**	**44**	**36**	**29**	**20**	Regenerated sound from junction.

SubSum	61	59	54	53	45	33	22	
Elbow (ul.sq.rct)	**0**	**-1**	**-3**	**-6**	**-4**	**-4**	**-4**	
SubSum	61	58	51	47	41	29	18	
	63	**63**	**62**	**58**	**51**	**40**	**26**	Regenerated sound from elbow.
SubSum	65	64	62	58	51	40	27	
Straight Duct(RU1)	**-2**	**-1**	**-1**	**0**	**0**	**0**	**0**	
Junction (90,atten.)AB	**-1**	**-1**	**-1**	**-1**	**-1**	**-1**	**-1**	
SubSum	62	62	60	57	50	39	26	
	49	**44**	**40**	**34**	**29**	**22**	**15**	Regenerated sound from junction.
SubSum	62	62	60	57	50	39	26	
Straight Duct(RU1)	**-1**	**-1**	**-1**	**0**	**0**	**0**	**0**	
Elbow (ul.sq.rct)	**-1**	**-3**	**-6**	**-4**	**-4**	**-4**	**-4**	
SubSum	60	58	53	53	46	35	22	
	64	**65**	**64**	**61**	**55**	**45**	**32**	Regenerated sound from elbow.
SubSum	65	66	64	62	56	45	32	
Junction (90,atten.)AB	**-1**	**-1**	**-1**	**-1**	**-1**	**-1**	**-1**	
SubSum	64	65	63	61	55	44	31	
	51	**48**	**45**	**41**	**36**	**31**	**25**	Regenerated sound from junction.
SubSum	64	65	63	61	55	44	32	
Junction (90,atten.)AB	**-1**	**-1**	**-1**	**-1**	**-1**	**-1**	**-1**	
SubSum	63	64	62	60	54	43	31	
	52	**49**	**44**	**39**	**34**	**27**	**18**	Regenerated sound from junction.
SubSum	63	64	62	60	54	43	31	
Straight Duct(RU1)	**-6**	**-4**	**-3**	**-1**	**-1**	**-1**	**-1**	
Junction (T,atten.)	**-6**	**-6**	**-6**	**-6**	**-6**	**-6**	**-6**	
SubSum	51	54	53	53	47	36	24	
	41	**36**	**32**	**27**	**21**	**14**	**7**	Regenerated sound from junction.
SubSum	51	54	53	53	47	36	24	
Straight Duct(RU1)	**-5**	**-3**	**-2**	**-1**	**-1**	**-1**	**-1**	
Junction (90,atten.)AB	**-5**	**-5**	**-5**	**-4**	**-4**	**-4**	**-4**	
SubSum	41	46	46	48	42	31	19	
	44	**40**	**36**	**32**	**27**	**21**	**15**	Regenerated sound from junction.
SubSum	46	47	46	48	42	31	20	
Straight Duct(RL)	**-3**	**-3**	**-5**	**-11**	**-22**	**-19**	**-15**	
SubSum	43	44	41	37	20	12	5	
Custom Element	**0**	**74**	**70**	**79**	**87**	**86**	**68**	VAV-196
SubSum	43	74	70	79	87	86	68	
Custom Element	**-9**	**-44**	**-41**	**-40**	**-52**	**-49**	**-41**	
Straight Duct(RL)	**-5**	**-5**	**-9**	**-22**	**-40**	**-39**	**-30**	
Elbow (ul.sq.rct)	**0**	**-1**	**-3**	**-6**	**-4**	**-4**	**-4**	
SubSum	29	24	17	11	5	5	5	
	45	**45**	**43**	**39**	**32**	**21**	**7**	Regenerated sound from elbow.
SubSum	45	45	43	39	32	21	9	
Straight Duct(RL)	**-5**	**-5**	**-9**	**-22**	**-40**	**-39**	**-30**	
SubSum	40	40	34	17	5	5	5	
Diffuser	**42**	**40**	**37**	**31**	**23**	**13**	**1**	
SubSum	44	43	39	31	23	14	6	
Indoor (Regression)	**-5**	**-7**	**-7**	**-8**	**-9**	**-10**	**-13**	
SUM	39	36	32	23	14	5	5	
RATING	NC 19			RC 14(R)		27 dBA		

Output from Trane Acoustical Program (TAP) for Classroom (2302), proposed DOAS system.

Path Table View -- Path1:

	Octave Band Data							
LINE ELEMENT	**63**	**125**	**250**	**500**	**1k**	**2k**	**4k**	**COMMENTS**
ASHRAE Fan	**85**	**85**	**87**	**79**	**75**	**68**	**64**	
Elbow (ln.sq.rct)	**0**	**-1**	**-6**	**-11**	**-10**	**-10**	**-10**	
SubSum	85	84	81	68	65	58	54	
	45	**40**	**33**	**26**	**17**	**8**	**0**	Regenerated sound from elbow.
SubSum	85	84	81	68	65	58	54	
Straight Duct(RL)	**-13**	**-17**	**-39**	**-40**	**-40**	**-40**	**-40**	
Elbow (ln.sq.rct)	**0**	**-1**	**-6**	**-11**	**-10**	**-10**	**-10**	
SubSum	72	66	36	17	15	8	5	
	45	**40**	**33**	**26**	**17**	**8**	**0**	Regenerated sound from elbow.
SubSum	72	66	38	27	19	11	6	
Straight Duct(RL)	**-4**	**-6**	**-13**	**-35**	**-33**	**-28**	**-23**	
Straight Duct(RU2)	**-8**	**-5**	**-4**	**-1**	**-1**	**-1**	**-1**	
Elbow (ul.sq.rct)	**0**	**-1**	**-3**	**-6**	**-4**	**-4**	**-4**	
SubSum	60	54	18	5	5	5	5	
	52	**53**	**51**	**46**	**38**	**27**	**13**	Regenerated sound from elbow.
SubSum	61	57	51	46	38	27	14	
Straight Duct(RU2)	**-7**	**-5**	**-3**	**0**	**0**	**0**	**0**	
Elbow (ul.sq.rct)	**0**	**-1**	**-3**	**-6**	**-4**	**-4**	**-4**	
SubSum	54	51	45	40	34	23	10	
	51	**52**	**50**	**45**	**37**	**26**	**12**	Regenerated sound from elbow.
SubSum	56	55	51	46	39	28	14	
Straight Duct(RU2)	**-6**	**-4**	**-3**	**0**	**0**	**0**	**0**	
Elbow (ul.sq.rct)	**0**	**-1**	**-3**	**-6**	**-4**	**-4**	**-4**	
SubSum	50	50	45	40	35	24	10	
	51	**52**	**50**	**45**	**37**	**26**	**12**	Regenerated sound from elbow.
SubSum	54	54	51	46	39	28	14	
Straight Duct(RU2)	**-37**	**-25**	**-16**	**-3**	**-3**	**-3**	**-3**	
Elbow (ul.sq.rct)	**0**	**-1**	**-3**	**-6**	**-4**	**-4**	**-4**	
SubSum	17	28	32	37	32	21	7	
	51	**52**	**50**	**45**	**37**	**26**	**12**	Regenerated sound from elbow.
SubSum	51	52	50	46	38	27	13	
Straight Duct(RU2)	**-2**	**-2**	**-1**	**0**	**0**	**0**	**0**	
Elbow (ul.sq.rct)	**0**	**-1**	**-3**	**-6**	**-4**	**-4**	**-4**	
SubSum	49	49	46	40	34	23	9	
	51	**52**	**50**	**45**	**37**	**26**	**12**	Regenerated sound from elbow.
SubSum	53	54	51	46	39	28	14	
Straight Duct(RU2)	**-8**	**-5**	**-4**	**-1**	**-1**	**-1**	**-1**	
Junction (90,atten.)	**-2**	**-2**	**-2**	**-2**	**-2**	**-2**	**-2**	
SubSum	43	47	45	43	36	25	11	
	42	**38**	**32**	**26**	**18**	**9**	**0**	Regenerated sound from junction.
SubSum	46	48	45	43	36	25	11	
Straight Duct(RU2)	**-9**	**-6**	**-4**	**-1**	**-1**	**-1**	**-1**	
Junction (90,atten.)	**-1**	**-1**	**-1**	**-1**	**-1**	**-1**	**-1**	
SubSum	36	41	40	41	34	23	9	
	37	**34**	**28**	**23**	**16**	**9**	**0**	Regenerated sound from junction.

SubSum	40	42	40	41	34	23	10	
Elbow (ul.sq.rct)	**0**	**0**	**-1**	**-3**	**-6**	**-4**	**-4**	
SubSum	40	42	39	38	28	19	6	
	48	**48**	**46**	**41**	**34**	**22**	**7**	Regenerated sound from elbow.
SubSum	49	49	47	43	35	24	10	
Straight Duct(RU1)	**-3**	**-2**	**-1**	**0**	**0**	**0**	**0**	
Junction (90,atten.)	**-1**	**-1**	**-1**	**-1**	**-1**	**-1**	**-1**	
SubSum	45	46	45	42	34	23	9	
	34	**29**	**25**	**18**	**12**	**4**	**0**	Regenerated sound from junction.
SubSum	45	46	45	42	34	23	10	
Straight Duct(RU1)	**-2**	**-1**	**-1**	**0**	**0**	**0**	**0**	
Elbow (ul.sq.rct)	**0**	**-1**	**-3**	**-6**	**-4**	**-4**	**-4**	
SubSum	43	44	41	36	30	19	6	
	48	**49**	**48**	**45**	**38**	**29**	**15**	Regenerated sound from elbow.
SubSum	49	50	49	46	39	29	16	
Junction (90,atten.)	**-1**	**-1**	**-1**	**-1**	**-1**	**-1**	**-1**	
SubSum	48	49	48	45	38	28	15	
	26	**23**	**19**	**15**	**9**	**4**	**0**	Regenerated sound from junction.
SubSum	48	49	48	45	38	28	15	
Junction (90,atten.)	**-1**	**-1**	**-1**	**-1**	**-1**	**-1**	**-1**	
SubSum	47	48	47	44	37	27	14	
	16	**14**	**11**	**7**	**2**	**0**	**0**	Regenerated sound from junction.
SubSum	47	48	47	44	37	27	14	
Straight Duct(RU1)	**-10**	**-5**	**-3**	**-1**	**-1**	**-1**	**-1**	
Junction (T,atten.)	**-10**	**-10**	**-10**	**-10**	**-10**	**-10**	**-10**	
SubSum	27	33	34	33	26	16	5	
	19	**16**	**12**	**8**	**2**	**0**	**0**	Regenerated sound from junction.
SubSum	28	33	34	33	26	16	6	
Straight Duct(RU1)	**-7**	**-4**	**-2**	**-1**	**-1**	**-1**	**-1**	
Junction (90,atten.)	**-5**	**-5**	**-5**	**-5**	**-5**	**-5**	**-5**	
SubSum	16	24	27	27	20	10	5	
	22	**18**	**14**	**9**	**2**	**0**	**0**	Regenerated sound from junction.
SubSum	23	25	27	27	20	10	6	
Straight Duct(RL)	**-5**	**-6**	**-8**	**-16**	**-39**	**-38**	**-22**	
Straight Duct(RL)	**-10**	**-12**	**-16**	**-32**	**-40**	**-40**	**-40**	
Elbow (ul.sq.rct)	**0**	**0**	**-1**	**-3**	**-6**	**-4**	**-4**	
SubSum	8	7	5	5	5	5	5	
	37	**39**	**39**	**36**	**30**	**22**	**10**	Regenerated sound from elbow.
SubSum	37	39	39	36	30	22	11	
Straight Duct(RL)	**-10**	**-12**	**-16**	**-32**	**-40**	**-40**	**-40**	
SubSum	27	27	23	5	5	5	5	
Diffuser	**42**	**40**	**37**	**31**	**23**	**13**	**1**	
SubSum	42	40	37	31	23	14	6	
Indoor (Regression)	**-8**	**-10**	**-10**	**-11**	**-12**	**-13**	**-16**	
SUM	34	30	27	20	11	5	5	
RATING	NC < 15			RC 12(N)		22 dBA		