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]						
Frequency [Hz] →	125	250	500	1000	2000	4000	NC Level
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.

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

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

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

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

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

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

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

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

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

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

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.

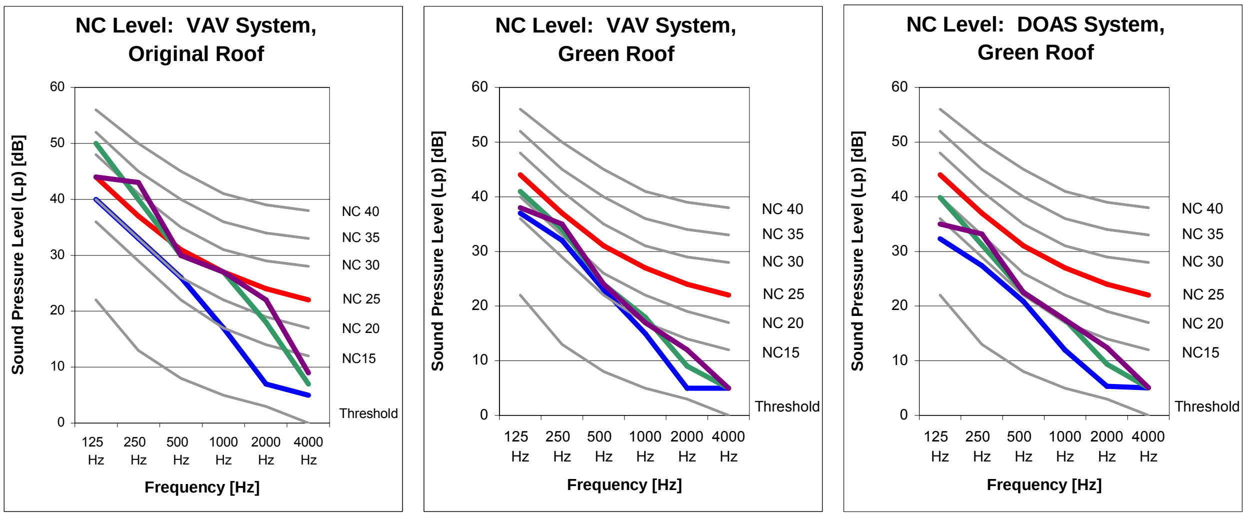

Figure 9.1-9.3: NC performance of original, VAV with green roof, and DOAS with green roof designs.

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.