Acoustic Management of Library Fishbowls

A Senior Project
presented to
the faculty of the Materials Engineering Department
California Polytechnic State University, San Luis Obispo

In Partial Fulfillment
of the Requirements for the Degree
Bachelor of Science

by

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Abstract

The purpose of this project is to aid the Cal Poly Robert E. Kennedy library in modifying the "fishbowl" study spaces to more effectively maintain the desirable sound that is generated within the fishbowls while avoiding the entrance and exit of excess noise to and from the fishbowls. A collaboration between the Materials Engineering Department and the Architecture Department provided the combined expertise needed to design, test, and install a prototype acoustic treatment in fishbowl 216-R in consultation with the Cal Poly Library as the voice of the customer. The fishbowl's undesirable acoustic properties can be attributed to the hard surfaces within the fishbowl and the large air gap between the top of the walls of the fishbowl and the ceiling of the room. Working with industry standard sound measurement equipment and noise pollution expertise provided by Dr. Tracy Thatcher of the Environmental Engineering Department, wool felt was chosen and found to be a material satisfactory in improving fishbowl sound quality. The felt reduced reverberation within the fishbowl by about 0.1 seconds. With the help of the Architecture Department, the wool felt was incorporated into a fishbowl to provide both an acoustically effective and aesthetically pleasing treatment. The prototype acoustic treatment will be installed in fishbowl 216-R during finals week of the Spring 2017 quarter.

Introduction

Noise dampening in workspaces has been an important focus in many companies. Previous solutions to reduce unwanted sound in office buildings involved installing sound absorbing materials throughout the office[1] and incorporating white noise speakers to mask distracting sounds for workers[2].

Similar to the role of offices and work spaces in companies, Cal Poly's Robert E. Kennedy Library has an array of resources to utilize for studying and group work. One of the resources is the library "fishbowls" located on the second and third floors of the library. These glass-walled cubicles (Figure 1) allow students an open space to meet to discuss projects and to study; however, the fishbowls are located directly near a busy café and quiet study spaces. Maintaining the desirable sound that is generated within the fishbowls while avoiding the entrance and exit of excess noise to and from the fishbowls are essential for an effective library resource.

Figure 1. The fishbowl of interest, room 216-R.

The fishbowl's poor acoustic properties can be attributed to its large air gap between the ceiling and the top of the fishbowl as well as its primarily glass construction. The large air gap serves as a pathway for excess noise both from within and outside the fishbowls to leave and enter the fishbowl, respectively. The glass construction provides a highly reflective surface for sound waves within the fishbowl to be reflected back towards the fishbowl user. These additional reflections produce unwanted reverberation, which greatly affects sound quality within the study space.

Materials implemented in acoustic applications tend to be either sound-absorbing materials or sound-isolation materials. When a sound wave strikes a material, it can reflect, absorb, or do a combination of both (Figure 2).

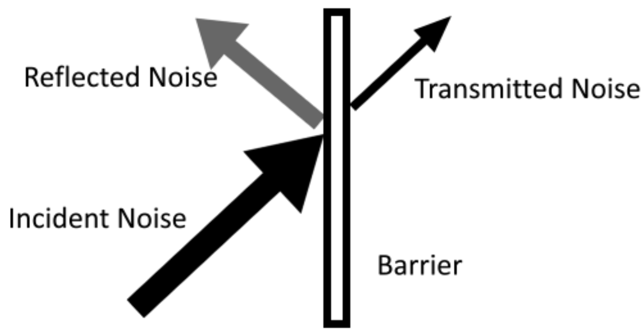

Figure 2. The two paths of incident noise after encountering a barrier.

Effective sound-absorbing materials reduce the amount of reflected noise. Effective sound-isolation materials focus on hindering transmitted noise. Incident noise inside a confined space produces both a direct and indirect field of sound[3] (Figure 3).

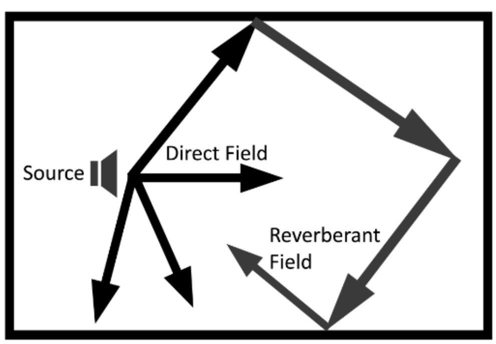

Figure 3. Direct and indirect acoustic waves within a room. (Adapted from Irwin, J. David, and E. R. Graf. *Industrial Noise and Vibration Control*. Englewood Cliffs, NJ: Prentice-Hall, 1979. Print. Page 137)

<u>Sound-Isolation Materials</u>

Sound-isolation materials are massive and airtight to produce a proper sound-insulating structure between noise sources and those hearing the noise sources. An effective sound-insulating structure results in little transmitted noise through the material. These acoustic barriers serve to reduce the

sound pressure levels due to the direct field of the source at a specified location[3]. Sound isolation materials are rated based on the insertion loss when the material is inserted in a finite environment as shown in Equation 1.

$$IL = L_{p0} - L_{p2} \quad (1)$$

where L_{p0} is the sound pressure level without the material

L_{p2} is the sound pressure level with the material

<u>Sound-Absorbing Materials</u>

Sound-absorbing materials are generally light and porous, which work to disperse sound waves by allowing the partial penetration of the sound into the material, absorbing the wave as thermal energy instead of reflecting the wave. The loss mechanisms in the energy transfer are viscous flow losses due to propagated waves in the material and the internal frictional losses caused by motion of the material's individual fibers[3]. Materials are rated for absorption based on the ratio of acoustic energy absorbed to the acoustic energy incident upon the material. This ratio is defined as the *statistical absorption coefficient* or the *random incidence sound-absorption coefficient,* α.

Holistically decreasing sound propagation can be achieved by coupling a low frequency sound absorber with a high-density material. High-density materials are known to block sound propagation of high frequencies around 1.5-2 kHz[4]. Glass composite materials that involve sheets of glass sandwiching a thin plastic film have been developed to prevent sound propagation while maintaining transparency. In addition, these glass composites can also be made with holes arranged in them to maintain ventilation while substantially reducing noise[5].

Complex geometries have been developed to aid in combating unwanted sound. "Double porous materials" are one such invention. By incorporating a porous material with varying hole profiles within the solid material (Figure 4), it is possible to greatly reduce unwanted sound depending on the hole profile[6].

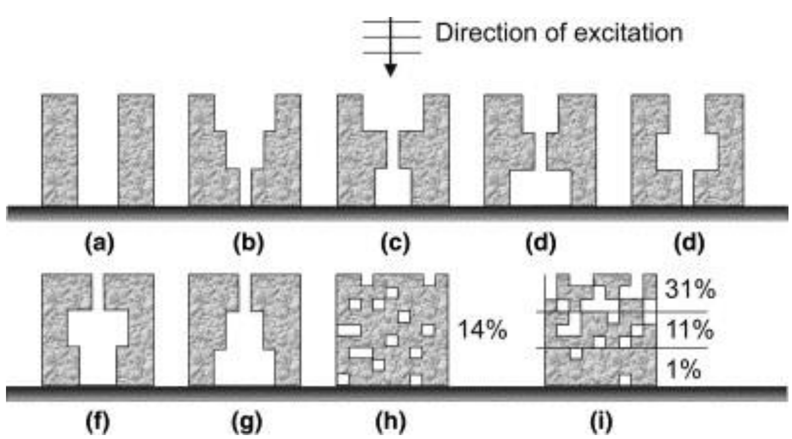

Figure 4. Varying hole profiles of double porous materials. Percentages refer to percent porosity.

Various surface shapes and sizes of foams have been tested to discover levels of sound absorbing effectiveness in specific sound ranges. Overall, the effective sound dampening of frequencies below 1500 Hz was primarily dependent on material thickness. At frequencies of 1500 - 3000 Hz, triangular and semicircular shapes were ideal, and at above 3000 Hz a plate shape was recommended[6].

Room Acoustics

Sound behavior can be modelled by employing fundamental noise source and room characteristics[3]. Derivations for sound pressure, average room absorption coefficients, and reverberation time were developed using solutions of the wave equation for velocity and pressure[7]. Sound pressure is commonly expressed in terms of decibel levels to incorporate a logarithmic scale versus using a linear scale.

Sound pressure levels (L_p) are determined using sound equipment and are typically averaged over time to obtain a more accurate representation of the typical value. The average L_p is determined using Equation 2[3].

$$\bar{L}_p = 10 \log\left(\frac{1}{n}\sum_{i=1}^{n} 10^{L_p/10}\right) \tag{2}$$

The total absorption coefficient for a given room as a whole is useful in calculating the reverberation time of a room. The total absorption is a function of the absorption coefficient of the *i*th surface, α_i and the surface area of the *i*th surface, S_i. The total average absorption is determined using Equation 3[3].

$$\bar{\alpha} = \frac{\sum_{i=1}^{n} S_i\, \alpha_i}{\sum_{i=1}^{n} S_i} \tag{3}$$

It is important to note that absorption coefficients vary with frequency[8]. 500-2kHz is the range at which sounds important to speech typically occur[9]. The sum of all the absorption coefficients and their respective surface areas is defined by A (Equation 4). Dividing the volume of the room by A and then multiplying that value by a constant result in the reverberation time or T (Equation 5)[3].

$$A \stackrel{\text{def}}{=} \sum_{i=1}^{n} S_i\, \alpha_i \tag{4}$$

$$T = 0.049 \left(\frac{V}{A}\right) \tag{5}$$

Note that the constant in Equation 5 is used for English units of V and A. The reverberation time is defined by the time required for the energy density in the acoustic field to reduce by a level 60 dB below its steady-state value[8].

Materials and Method

Initial Fishbowl Measurements

To begin developing prototypes to help deter excess noise levels, there must be a better understanding of the vulnerabilities of the fishbowl (i.e. where sound is primarily coming from and what points within the fishbowl are more susceptible to sound propagation). ASTM standards have not been developed specifically for the measurement of fishbowls or even cubicles. However, we can develop a similar standard with known decibel measuring techniques for different applications as a reference.

For our experiment, the iNVH application software by Bosch[10] was incorporated into a Samsung Galaxy s7 phone to record sound data. The application used with the Galaxy s7 allows for decibel measurements to be taken every 0.02 s, allowing for well-refined temporal data collection. However, the microphone is unidirectional which requires averaging over the orientation of the microphone to gather consistent sound data like the sound data averaging method in ASTM E1124-107[11].

The experiment involves a noise source placed in various areas of typical student and environmental noise generation, with the decibel measurement device placed in the fishbowl of interest to record data. The noise source is a constant sound played at a specific decibel level (75 dB). With a controlled sound level, the experiment can incorporate the ASTM E336-16 standard of known source level and simultaneous data collection to simulate sound loss between rooms effectively[12]. The full procedure of the initial fishbowl measurements is outlined in Appendix 1.

Monolithic Wool Felt Treatment

Wool felt was investigated to see whether it is a viable material for mitigating unwanted noise. The wool felt serves as a lightweight sound-absorbing material. For this experiment, long monolithic wool felt sheets were draped along the walls of the fishbowl (Figure 5). Using monolithic wool felt was recommended by the ENVE 309 professor, Dr. Tracy Thatcher who had done work in previous years with her students on the exact fishbowls tested in this project.

Figure 5. Wool felt being hung from the top of the fishbowl.

SoundPro 3M meters (Figure 6a) measuring in the 1000 Hz band were used to record sound pressure levels at the 8 locations in the fishbowl shown in Figure 6b.

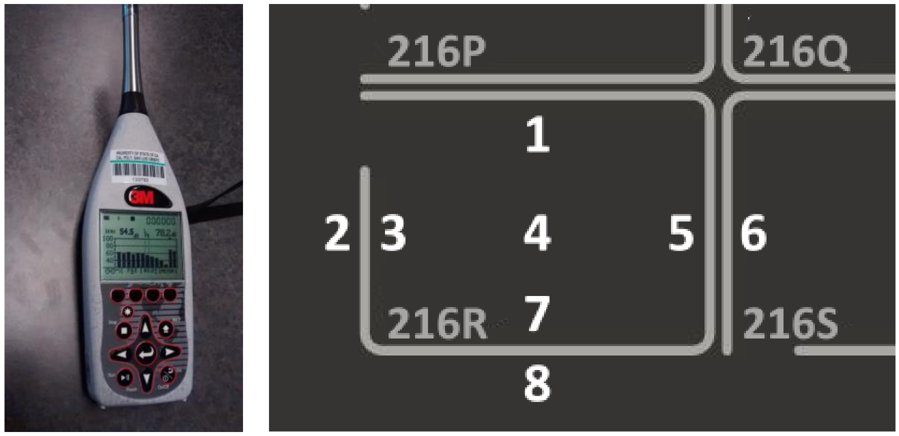

Figure 6. (a) Sound level meter implemented in testing. (b) Locations of eight sound level meters used for sound pressure measurements of fishbowl 216-R.

A 1000 Hz spherical sound source was placed inside and then outside the fishbowl for the sound measurements. Eight sound meters took simultaneous sound level measurements at 15 second intervals for 4 minutes. Three locations of sound sources (ambient, inside, and outside the fishbowl) were paired with two treatments (with and without the felt) for a total of six trials. Sound pressure levels and reverberation were measured, and average absorption coefficients were calculated. The complete outline of the procedure is described in Appendix 2.

Results and Discussion:

The initial fishbowl measurements determined that the fishbowl is more prone to transmitting unwanted sound at the faces of the fishbowl as opposed to its corners (Figure 7). This means that eliminating sound from the neighboring 216-S and 216-P fishbowls takes precedence over sound from 216-Q, which is contacting 216-R only by its corner.

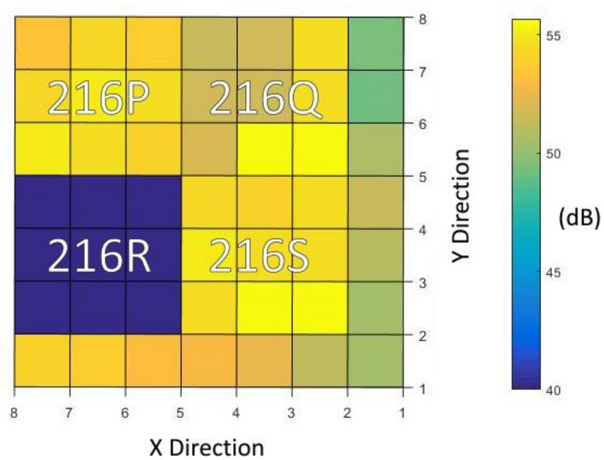

Figure 7. Average sound pressure levels based on location relative to 216-R for 75 dB sound source.

Knowing the weak points for sound transmission of the fishbowl allows the design process to focus on these points to target unwanted noise within the fishbowl.

The average sound pressure level was determined for all eight locations using Equation 2 and highlighted in Appendix 3b and 3c. Results of the monolithic wool felt experiment showed that the overall average sound pressure level decreased insignificantly in the fishbowl with and without the treatment (Figure 8).

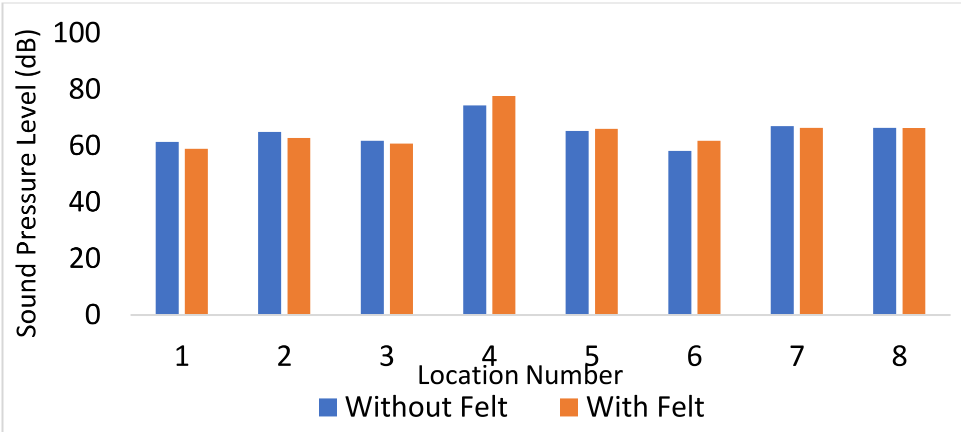

Figure 8. Sound pressure levels at different locations around the fishbowl with and without the monolithic wool felt treatment, with the sound source located outside the fishbowl.

The sound pressure levels remained relatively unchanged because administering felt to reduce reverberation does not account for sound transmission reduction, resulting in a minor change of overall noise reduction. However, noise reduction is not the only deciding factor for an effective treatment. Qualitatively, fishbowl users could hear a significant decrease in noise when the wool felt treatment was administered. This is due to the increase in average sound absorption by covering some of the hard surfaces in the room with the felt. This increase in sound absorption results in a lower reverberation time (Figure 9), which in turn results in higher sound quality within the fishbowl. The values of total average sound absorption and reverberation time were calculated using equations 3 and 4 and the resulting Excel worksheet is highlighted in Appendix 3a.

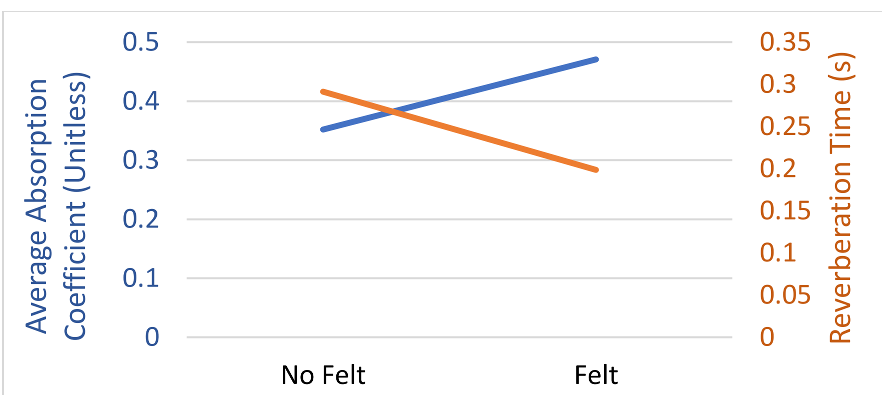

Figure 9. The average absorption coefficient and reverberation time within a fishbowl with and without the monolithic wool felt treatment.

Segmented Wool Felt Treatment

It was found from the monolithic wool felt treatment that felt can be used to improve the sound quality within fishbowls. However, the monolithic wool treatment obscures the transparent and airy qualities that define a fishbowl. This led to a segmented wool felt design that is hypothesized to be both aesthetically pleasing and acoustically satisfactory while attempting to preserve the transparent and airy characteristics of fishbowls. The prototype segmented design consists of many wool felt hexagons mounted on an acrylic frame (Figure 10a). The wavelength of sound for 500 to 2kHz is 27.01 and 6.75 inches respectively[13]. The wool felt hexagons were chosen to be 19 square inches to fit within the typical sound range's wavelengths. The frame (Figure 10b) allows individual two-dimensional wool hexagons to be bent into three-dimensional forms that help increase sound absorbance [akin to the foam "spikes" that often line the walls of anechoic chambers (Figure 10c)] and increase visual interest.

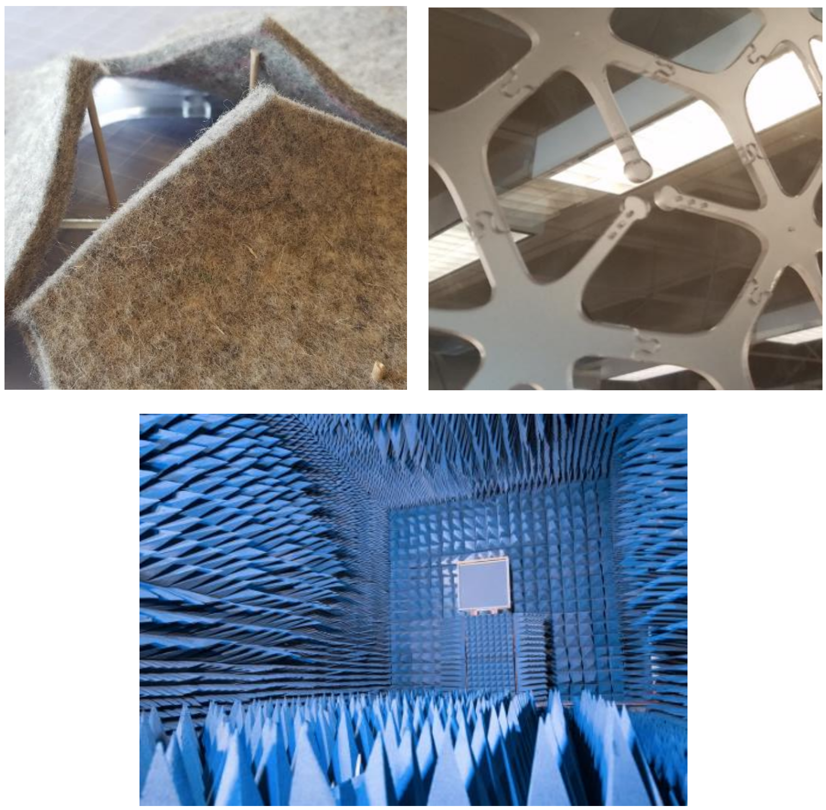

Figure 10. (a) Acrylic frame with wood attached to bend the hexagonal wool to allow the transmission of light. (b) Acrylic frame attached to the fishbowl glass walls. (c) The bent hexagons create a three-dimensional form that are intended to mimic foam "spikes" in an anechoic chamber. (From http://kitsapcomposites.com/quality/inspection-testing/anechoic-chamber/)

Design of the segmented wool felt treatment is inspired by a nucleation and growth approach: nucleation sites were chosen at random on each wall of the fishbowl. A felt hexagon is placed at each nucleation site, and a "colony" of felt hexagons is "grown" around each nucleation site (Figure 11). The prototype was modeled using *Rhinoceros* software, and the nucleation and the random growth script was developed using a plug-in called *Grasshopper.* The size and shape of the colonies are customizable with the script to try to preserve the transparent and airy nature of the fishbowl.

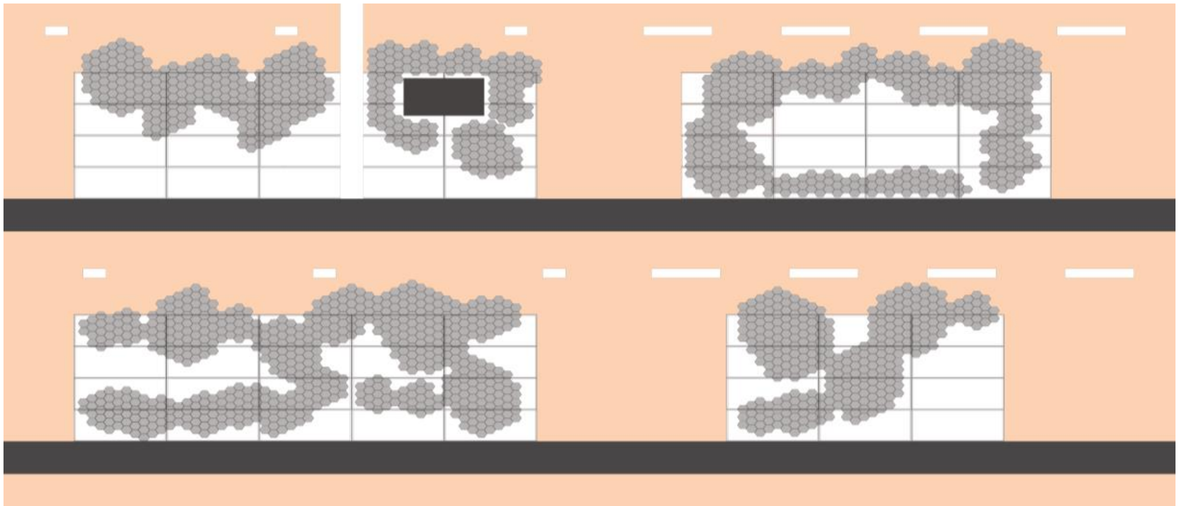

Figure 11. Rendering of nucleation and growth approach for segmented wool felt treatment, showing "colonies" of felt hexagons for each of the four walls of the fishbowl.

The segmented wool felt treatment can be mounted so that part of it reaches above the tops of the fishbowl walls. This serves to reduce reverberation time and sound transmission by partially absorbing sound that enters or exits the fishbowl from above. This treatment targets reduction of the five-foot air gap between the tops of the fishbowl walls and the ceiling by 17% to reduce sound transmission in and out of the fishbowl. Calculations were performed based on the surface area of the segmented wool felt treatment to determine its acoustic efficacy using Equations 3 and 4 highlighted in Appendix 3a. The treatment is expected to increase the absorption coefficient of the fishbowl and reduce the reverberation time within the fishbowl (Figure 12). This treatment will be installed in fishbowl 216-R during finals week of the Spring 2017 quarter.

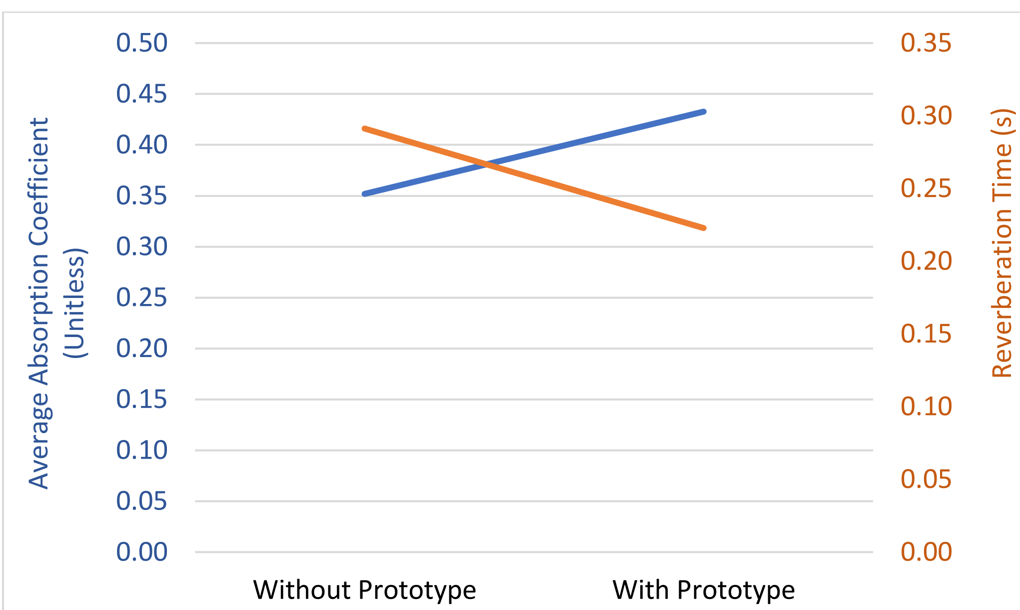

Figure 12. Calculated average absorption coefficient and reverberation time within a fishbowl with and without the segmented wool felt treatment.

Of the four walls indicated in Figure 13a, the segmented wool felt was applied to Wall 1 of fishbowl 216-R (Figure 13b). Due to limitations in laser jet cutting capacity, it is presently undetermined when walls 2-4 will have the segmented wool felt treatment installed.

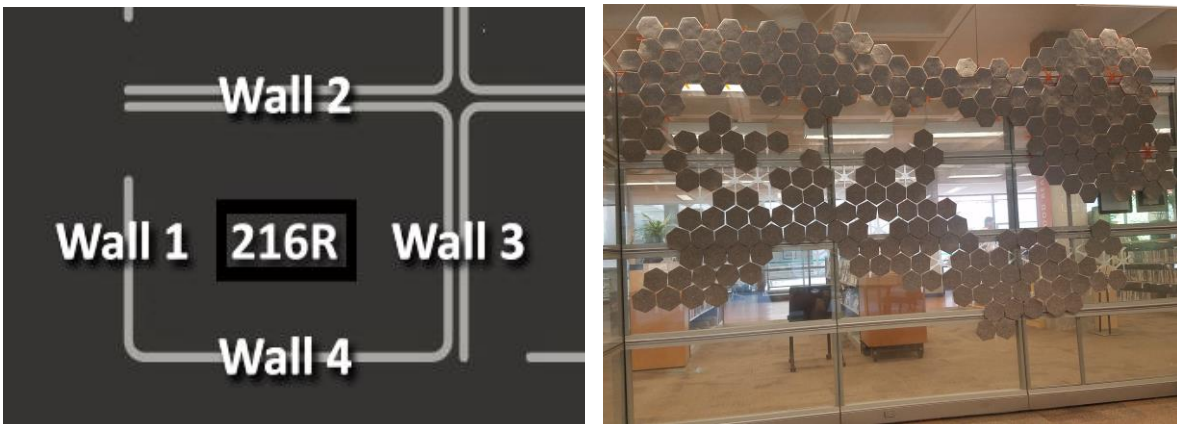

Figure 13. (a) 216-R wall designations for segmented wool felt. (b) Segmented wool felt treatment installed on Wall 1 of the 216-R fishbowl.

Wall 1 was tested according to the standard operating procedure for monolithic and segmented wool felt treatment testing (Appendix 2) with two sound meters facing Wall 1 two feet away from inside and outside the fishbowl, respectively, to determine the noise reduction with and without the segmented wool felt treatment (Figure 14).

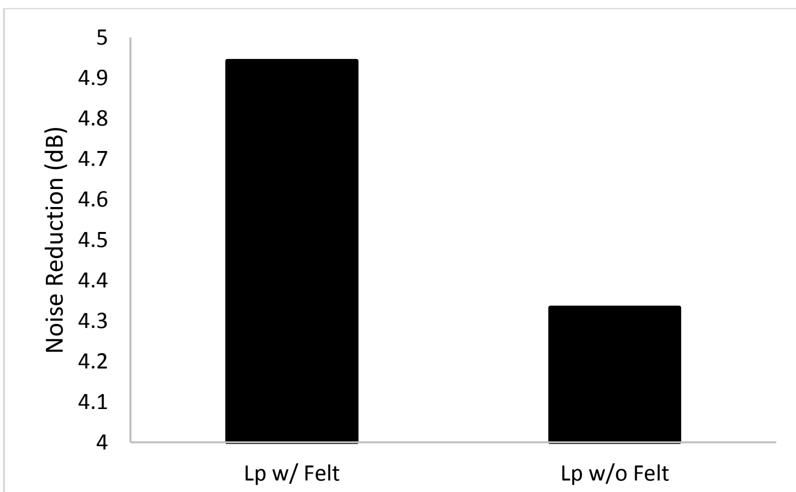

Figure 14. Noise Reduction of the entrance wall with and without the segmented wool felt treatment.

With the introduction of the segmented wool felt treatment on Wall 1, the sound pressure was reduced by 0.6 dB. Reduction of noise is primarily a factor of the concentration of sound blocking materials to mitigate sound transmission[3]. To further decrease noise, it is recommended to incorporate a greater amount of sound blocking elements compared to sound absorbing elements above the fishbowl walls in this treatment.

Conclusions:

1. Using a monolithic wool felt approach, a decrease in reverberation time of 70 ms was achieved within the fishbowl.
2. The segmented wool felt treatment results in a noise reduction of 0.6 dB more from the outside of the fishbowl to the inside of the fishbowl compared to without the segmented wool felt treatment.
3. Reducing the air gap at the top of the fishbowl walls with sound absorbing and sound blocking materials reduces the sound transmission between the outside and inside of the fishbowl.

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14. Daniel, E. *Noise and Hearing Loss: A Review* 2007, (Accessed Nov. 12, 2016).

Appendix 1:

Standard Operating Procedure for Initial Fishbowl Experiment

1. Check that the iNVH software calibration is reset to ensure consistent data collection.

2. Check that the volume of the noise source is at 75 dB using the iNVH meter. Adjust volume if necessary.

The fishbowl that will act as the receiver in the experiment will be 216-R (Figure A1). 216-R has been chosen as the fishbowl of interest because it is closest to Julian's Cafe which through observation generates a large amount of unwanted noise.

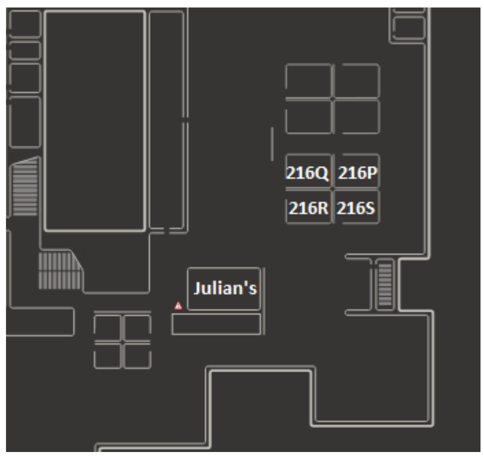

Figure A1. Location of fishbowl 216-R in relation to Julian's Cafe and fishbowls 216-P, 216-Q, and 216-S on the second floor of the Robert E. Kennedy Library.

3. Place the sound source.

    a. For adjacent fishbowl testing: Begin at 216-Q and place the sound source facing 216-R in the middle of the room at approximately 4 feet above the floor.
    b. For fishbowl testing of outside noise: Begin along the line of columns closest to Julian's (starting point circled in Figure A2.) approximately 4 feet above the floor.

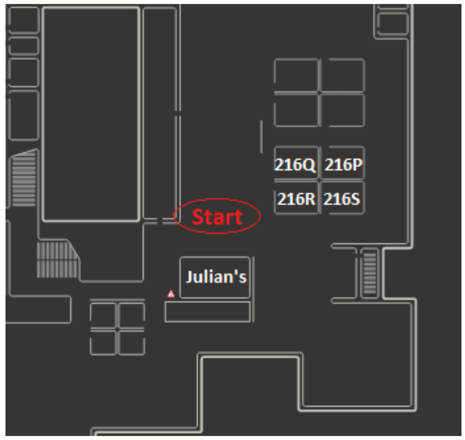

Figure A2. Starting position of outside noise testing experiment.

4. The Samsung Galaxy s7 will be placed initially in the middle of 216-R (position 1 in Figure A3) at approximately 4 feet above the floor (average ear position for a seated person) with the microphone facing down. Gather data for positions 1, 2, 3, 4, and 5 for each sound source position.

    a. For each sound data measurement record 0.5 s of data with the phone's screen facing North, South, East, and West.

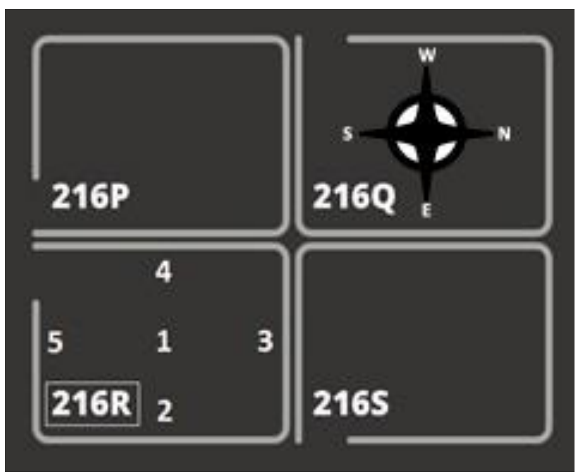

Figure A3. Fishbowl 216-R with numbers referring to the positions where data is recorded as well as the order in data is recorded.

5. Move sound source along path and collect data

    1. <u>For adjacent fishbowl testing:</u> Place source at 216-Q, then 216-P, and finally 216-S
    2. <u>For fishbowl testing of outside noise:</u> Follow source path highlighted in Figure A4 and stop every 5 feet to record sound level for 3 seconds.

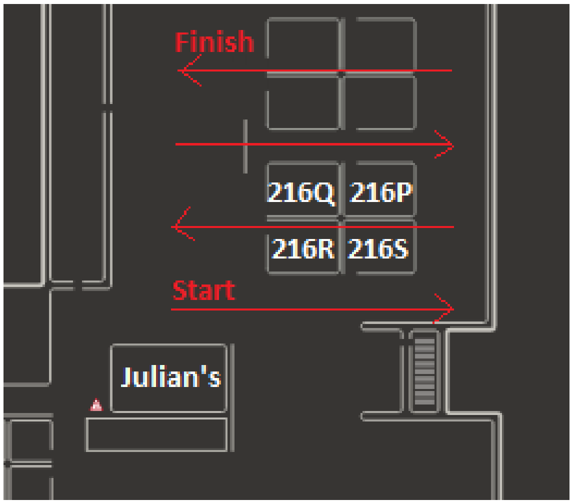

Figure 4. Start and finish path of outside noise experiment.

Note: Safety precautions for the experiment relate to sound levels on the ear. However, no ear protection is required because the maximum dB level the experimenter will be exposed to is far below the minimum threshold for ear damage (<110 dB)[14].

Appendix 2:

<u>Standard Operating Procedure for Monolithic and Segmented Wool Felt Treatment Testing</u>

The purpose of this experiment is to determine if wool felt covering the walls of the library fishbowls produces better sound quality compared to the fishbowl without any wall covering.

The fishbowl of interest is 216-R. Nine sound meters will take simultaneous sound level measurements in 15 second intervals for four minutes totaling 16 data points per location. The sound meters will be positioned based on Figure B1. The position of each individual meter will be approximately six inches from the wall at waist level facing the wall.

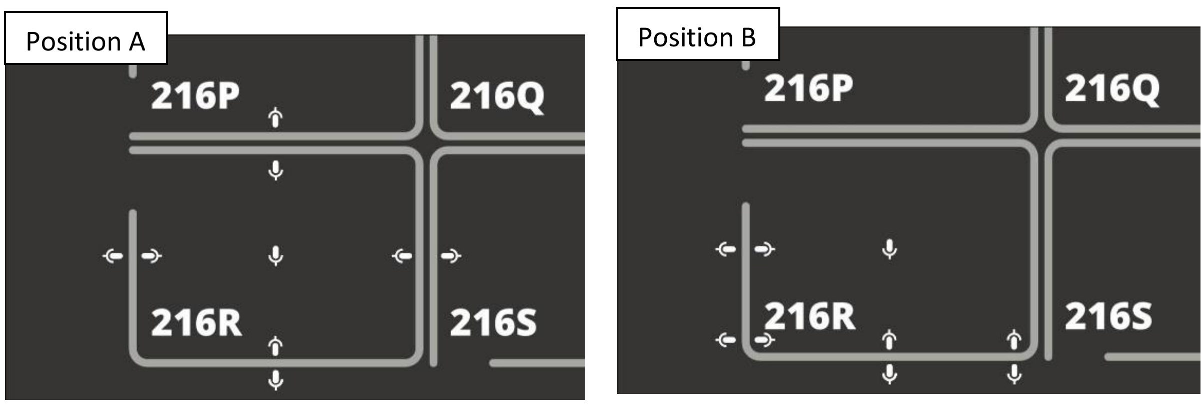

Figure B1. Fishbowl sound meter layout. If access to 216-P and 216-R is possible, use position A layout. If not, use position B layout. If only one of either 216-P or 216-R is available, employ a combination of Position A and B.

The 1000 Hz band will be the frequency of interest for recording measurements. The 1000 Hz band was achieved using the sound source indicated in Figure B2. Trials consist of recording measurements without a speaker, with the speaker positioned outside the fishbowl, and with the speaker in the center of the fishbowl. These three trials will be conducted with and without the treatment, totaling six trials. When the speaker is outside the fishbowl it should be approximately six feet away from the center of the wall containing the fishbowl entrance. The door of the fishbowl is closed when conducting the experiment.

Figure B2. Sound source used to drive 1000 Hz band frequency.

Appendix 3:

<u>Excel Calculations</u>

a. Reverberation calculations for monolithic and segmented wool felt treatment.

	Reverberation Monolithic Felt Treatment													
	Without Felt			With Felt				Alpha Average			Reverberation Time		Room Constant	
Material	αi	Si (ft^2)	Sum (Si*αi)	αi	Si (ft^2)	Sum (Si*αi)	St (ft^2)	No Felt	Felt	V (ft^3)	No Felt	Felt	No Felt	Felt
Glass	0.03	289	8.67	0.03	62.31	1.8693	1541.5	0.351879338	0.470716056	3973.33	0.291232207	0.198514797	836.9151488	1370.925394
Whiteboard	0.02	43.4	0.868	0.02	0	0								
Concrete Column	0.02	74.5	1.49	0.02	74.5	1.49								
Automan	0.89	10.8	9.612	0.89	10.8	9.612								
TV	0.02	7.4	0.148	0.02	7.4	0.148								
Plastic Chairs	0.01	55	0.55	0.01	0.55	0.0055								
Tables	0.04	30	1.2	0.04	30	1.2								
Air	1	373	373	1	373	373								
Concrete Ceiling	0.02	115.4	2.308	0.02	115.4	2.308								
Metal Panel	0.02	115.4	2.308	0.02	85.4	1.708								
Carpet	0.3	320	96	0.3	320	96								
People	0.43	107.6	46.268	0.43	107.6	46.268								
Felt	0.64	0	0	0.64	300	192								

	Reverberation Segmented Prototype																
	No Felt			Prototype				Alpha Average			Reverberation Time		Room Constant		T. Room Absorp.		Rev. Noise Red.
Material	αi	Si (ft^2)	Sum (Si*αi)	αi	Si (ft^2)	Sum (Si*αi)	St (ft^2)	Without Prototype	With Prototype	V (ft^3)	Without Prototype	With Prototype	Without Prototype	With Prototype	Without Prototype	With Prototype	(dB)
Glass	0.03	289	8.67	0.03	80	2.4	1541.5	0.352	0.433	3973.330	0.291	0.223	836.9151488	1175.648279	542.422	666.972	0.897703066
Whiteboard	0.02	43.4	0.868	0.02	40.4	0.808		% Diff	0.186739473		% Diff	0.307021386					
Concrete Column	0.02	74.5	1.49	0.02	74.5	1.49											
Automan	0.89	10.8	9.612	0.89	10.8	9.612											
TV	0.02	7.4	0.148	0.02	7.4	0.148											
Plastic Chairs	0.01	55	0.55	0.01	55	0.55											
Tables	0.04	30	1.2	0.04	30	1.2											
Air	1	373	373	1	308	308											
Concrete Ceiling	0.02	115.4	2.308	0.02	115.4	2.308											
Metal Panel	0.02	115.4	2.308	0.02	85.4	1.708											
Carpet	0.3	320	96	0.3	320	96											
People	0.43	107.6	46.268	0.43	107.6	46.268											
Felt	0.64	0	0	0.64	307	196.48											

b. Measured data and $10^{(L_p/10)}$ for all eight locations with/without monolithic felt.

	Ambient		Inside		Outside	
#1	49.1	50.4	81	71.1	54.5	54
	51.8	49.1	80.7	70	62	59.7
	53.2	45.9	80	71.2	61.5	50.3
	51.6	47.9	79.6	72.6	57.3	55.8
	49.9	51.8	80.6	71.4	56.9	60.2
	53.5	46.1	80.8	71.9	61.1	59.9
	52	47.9	81.5	71.4	56.4	60.6
	49.8	48.8	82	73.4	61.6	56.6
	52.3	45.6	81.8	71.6	63.1	55.6
	52.4	49.5	80.4	72.6	66.5	59
	47.8	49.1	79.1	69.7	65.5	60.1
	53	49.8	81.1	67.2	59.7	56.5
	53.7	46.8	82	62.5	58.6	60.9
	53.9	49.1	79.9	64	60.8	55.7
	52.2	50.4	80.3	68.2	58.4	61.5
	50.3	46.2	79.1	66.5	60.3	62.3
#2	50.2	47.7	73.4	63.3	62	65
	50.4	47.2	74.9	68.1	59.4	67.2
	53.8	44	73.6	64.1	61.5	64.6
	51.9	46.4	74.6	64.2	68.5	62.2
	52.7	45.8	73.2	64.6	64.8	62.3
	52.9	44.8	76.4	66.2	62.9	59.5
	57.3	48	73.5	64.2	67	59.5
	49.2	49.1	65.3	61.9	59.2	62.1
	51.1	43.4	66.8	60.5	69.7	59.3
	53.2	49.2	70.2	69.2	66.1	62.6
	45.9	43.2	70.1	63	67.5	60
	52.8	49.1	73.6	69.5	64.1	60
	54.3	46.5	72.6	71.1	60.4	58.9
	53.2	51.4	76.7	71.5	58.8	61.1
	52	49.4	70.9	67	62	63.2
	50.3	45	72.7	62.1	63.2	65.1

	Measured Data						10^(Lp/10)					
	Lp without Felt (dB)			Lp with Felt (dB)			Lp without Felt (dB)			Lp with Felt (dB)		
Location #	Ambient	Inside	Outside	Ambient	Inside	Outside	Ambient	Inside	Outside	Ambient	Inside	Outside
1	49.1	81	54.5	50.4	71.1	54	81283.1	1.3E+08	281838	109648	1.3E+07	251189
	51.8	80.7	62	49.1	70	59.7	151356	1.2E+08	1584893	81283.1	1E+07	933254
	53.2	80	61.5	45.9	71.2	50.3	208930	1E+08	1412538	38904.5	1.3E+07	107152
	51.6	79.6	57.3	47.9	72.6	55.8	144544	9.1E+07	537032	61659.5	1.8E+07	380189
	49.9	80.6	56.9	51.8	71.4	60.2	97723.7	1.1E+08	489779	151356	1.4E+07	1047129
	53.5	80.8	61.1	46.1	71.9	59.9	223872	1.2E+08	1288250	40738	1.5E+07	977237
	52	81.5	56.4	47.9	71.4	60.6	158489	1.4E+08	436516	61659.5	1.4E+07	1148154
	49.8	82	61.6	48.8	73.4	56.6	95499.3	1.6E+08	1445440	75857.8	2.2E+07	457088
	52.3	81.8	63.1	45.6	71.6	55.6	169824	1.5E+08	2041738	36307.8	1.4E+07	363078
	52.4	80.4	66.5	49.5	72.6	59	173780	1.1E+08	4466836	89125.1	1.8E+07	794328
	47.8	79.1	65.5	49.1	69.7	60.1	60256	8.1E+07	3548134	81283.1	9332543	1023293
	53	81.1	59.7	49.8	67.2	56.5	199526	1.3E+08	933254	95499.3	5248075	446684
	53.7	82	58.6	46.8	62.5	60.9	234423	1.6E+08	724436	47863	1778279	1230269
	53.9	79.9	60.8	49.1	64	55.7	245471	9.8E+07	1202264	81283.1	2511886	371535
	52.2	80.3	58.4	50.4	68.2	61.5	165959	1.1E+08	691831	109648	6606934	1412538
	50.3	79.1	60.3	46.2	66.5	62.3	107152	8.1E+07	1071519	41686.9	4466836	1698244
2	50.2	73.4	62	47.7	63.3	65	104713	2.2E+07	1584893	58884.4	2137962	3162278
	50.4	74.9	59.4	47.2	68.1	67.2	109648	3.1E+07	870964	52480.7	6456542	5248075
	53.8	73.6	61.5	44	64.1	64.6	239883	2.3E+07	1412538	25118.9	2570396	2884032
	51.9	74.6	68.5	46.4	64.2	62.2	154882	2.9E+07	7079458	43651.6	2630268	1659587
	52.7	73.2	64.8	45.8	64.6	62.3	186209	2.1E+07	3019952	38018.9	2884032	1698244
	52.9	76.4	62.9	44.8	66.2	59.5	194984	4.4E+07	1949845	30199.5	4168694	891251
	57.3	73.5	67	48	64.2	59.5	537032	2.2E+07	5011872	63095.7	2630268	891251
	49.2	65.3	59.2	49.1	61.9	62.1	83176.4	3388442	831764	81283.1	1548817	1621810
	51.1	66.8	69.7	43.4	60.5	59.3	128825	4786301	9332543	21877.6	1122018	851138
	53.2	70.2	66.1	49.2	69.2	62.6	208930	1E+07	4073803	83176.4	8317638	1819701
	45.9	70.1	67.5	43.2	63	60	38904.5	1E+07	5623413	20893	1995262	1000000
	52.8	73.6	64.1	49.1	69.5	60	190546	2.3E+07	2570396	81283.1	8912509	1000000
	54.3	72.6	60.4	46.5	71.1	58.9	269153	1.8E+07	1096478	44668.4	1.3E+07	776247
	53.2	76.7	58.8	51.4	71.5	61.1	208930	4.7E+07	758578	138038	1.4E+07	1288250
	52	70.9	62	49.4	67	63.2	158489	1.2E+07	1584893	87096.4	5011872	2089296
	50.3	72.7	63.2	45	62.1	65.1	107152	1.9E+07	2089296	31622.8	1621810	3235937

#3	41.0	50.2	75.7	70.8	56.3	62.6
	57.0	48.6	76.6	68.3	56.9	58.2
	54.5	44.3	75.2	68.5	56.4	56.3
	52.7	47.1	76.0	70.4	53.9	51.7
	51.6	49.7	77.9	69.4	56.3	61.2
	50.7	45.3	76.9	66.7	61.6	59.8
	59.7	52.3	78.7	68.6	61.8	55.5
	50.7	49.3	79.7	67.9	60.2	61.2
	51.6	44.7	80.2	67.1	63.7	60.2
	53.5	50.4	80.0	66.3	69.3	57.0
	47.7	48.9	80.2	65.5	60.2	60.5
	54.2	50.5	80.1	68.3	62.3	60.5
	55.0	45.8	80.5	67.4	56.5	62.7
	54.7	49.0	77.6	68.6	57.2	64.1
	52.0	55.4	79.0	64.1	62.8	62.7
	52.2	50.8	78.1	62.9	62.7	62.9
#4	53.2	55.2	69.4	64.8	71.1	68.6
	55.3	52.3	71.4	67.3	70.1	70.1
	54.8	50.0	72.5	66.5	70.8	71.2
	54.6	50.9	69.6	65.7	75.1	73.0
	53.3	55.6	67.2	66.1	73.3	73.6
	53.8	50.9	67.4	66.0	73.3	71.0
	59.0	53.8	68.9	66.5	74.2	75.6
	52.9	53.2	71.4	65.4	76.9	76.9
	52.6	50.5	70.9	64.6	75.9	76.2
	54.2	52.2	70.3	66.3	75.8	77.9
	50.0	55.6	71.1	65.9	74.0	79.5
	54.7	53.1	71.1	65.0	74.3	80.1
	53.2	51.9	68.8	65.0	75.5	80.7
	52.5	57.0	69.0	64.8	75.2	80.0
	50.9	57.9	71.1	64.0	73.6	81.5
	52.3	49.6	70.6	65.0	73.3	80.3

3	41	75.7	56.3	50.2	70.8	62.6	12589.3	3.7E+07	426580	104713	1.2E+07	1819701
	57	76.6	56.9	48.6	68.3	58.2	501187	4.6E+07	489779	72443.6	6760830	660693
	54.5	75.2	56.4	44.3	68.5	56.3	281838	3.3E+07	436516	26915.3	7079458	426580
	52.7	76	53.9	47.1	70.4	51.7	186209	4E+07	245471	51286.1	1.1E+07	147911
	51.6	77.9	56.3	49.7	69.4	61.2	144544	6.2E+07	426580	93325.4	8709636	1318257
	50.7	76.9	61.6	45.3	66.7	59.8	117490	4.9E+07	1445440	33884.4	4677351	954993
	59.7	78.7	61.8	52.3	68.6	55.5	933254	7.4E+07	1513561	169824	7244360	354813
	50.7	79.7	60.2	49.3	67.9	61.2	117490	9.3E+07	1047129	85113.8	6165950	1318257
	51.6	80.2	63.7	44.7	67.1	60.2	144544	1E+08	2344229	29512.1	5128614	1047129
	53.5	80	69.3	50.4	66.3	57	223872	1E+08	8511380	109648	4265795	501187
	47.7	80.2	60.2	48.9	65.5	60.5	58884.4	1E+08	1047129	77624.7	3548134	1122018
	54.2	80.1	62.3	50.5	68.3	60.5	263027	1E+08	1698244	112202	6760830	1122018
	55	80.5	56.5	45.8	67.4	62.7	316228	1.1E+08	446684	38018.9	5495409	1862087
	54.7	77.6	57.2	49	68.6	64.1	295121	5.8E+07	524807	79432.8	7244360	2570396
	52	79	62.8	55.4	64.1	62.7	158489	7.9E+07	1905461	346737	2570396	1862087
	52.2	78.1	62.7	50.8	62.9	62.9	165959	6.5E+07	1862087	120226	1949845	1949845
4	53.2	69.4	71.1	55.2	64.8	68.6	208930	8709636	1.3E+07	331131	3019952	7244360
	55.3	71.4	70.1	52.3	67.3	70.1	338844	1.4E+07	1E+07	169824	5370318	1E+07
	54.8	72.5	70.8	50	66.5	71.2	301995	1.8E+07	1.2E+07	100000	4466836	1.3E+07
	54.6	69.6	75.1	50.9	65.7	73	288403	9120108	3.2E+07	123027	3715352	2E+07
	53.3	67.2	73.3	55.6	66.1	73.6	213796	5248075	2.1E+07	363078	4073803	2.3E+07
	53.8	67.4	73.3	50.9	66	71	239883	5495409	2.1E+07	123027	3981072	1.3E+07
	59	68.9	74.2	53.8	66.5	75.6	794328	7762471	2.6E+07	239883	4466836	3.6E+07
	52.9	71.4	76.9	53.2	65.4	76.9	194984	1.4E+07	4.9E+07	208930	3467369	4.9E+07
	52.6	70.9	75.9	50.5	64.6	76.2	181970	1.2E+07	3.9E+07	112202	2884032	4.2E+07
	54.2	70.3	75.8	52.2	66.3	77.9	263027	1.1E+07	3.8E+07	165959	4265795	6.2E+07
	50	71.1	74	55.6	65.9	79.5	100000	1.3E+07	2.5E+07	363078	3890451	8.9E+07
	54.7	71.1	74.3	53.1	65	80.1	295121	1.3E+07	2.7E+07	204174	3162278	1E+08
	53.2	68.8	75.5	51.9	65	80.7	208930	7585776	3.5E+07	154882	3162278	1.2E+08
	52.5	69	75.2	57	64.8	80	177828	7943282	3.3E+07	501187	3019952	1E+08
	50.9	71.1	73.6	57.9	64	81.5	123027	1.3E+07	2.3E+07	616595	2511886	1.4E+08
	52.3	70.6	73.3	49.6	65	80.3	169824	1.1E+07	2.1E+07	91201.1	3162278	1.1E+08

#5	49.5	50.1	62.3	69	57.7	67.3
	50.5	49.6	61	59.7	56.2	64.9
	54.2	45.9	67.6	58.8	54.6	52.3
	52.8	47.5	69.7	71.8	67.5	62.2
	51.2	48.6	67.7	64.7	67.1	62.8
	52.3	45.6	66.5	72	67.5	66.2
	56.1	50.4	59.6	64.7	64	67.3
	50.8	49.8	70.1	65.6	67.5	68.3
	52.3	45.5	72.8	72	66.8	65.8
	52.8	48.3	70.7	67.3	66.2	65
	48.3	44.8	65	63.5	61.9	65.9
	53.4	51.6	71.6	63	67.3	64.7
	53.5	48.7	68.8	64.4	66.3	65.4
	54.9	53.1	66.5	67	62.3	66.2
	53.1	48.7	72.7	66.3	63.7	68.6
	49.9	47.5	73	65	65.9	67.9
#6	54.2	56.3	67.5	63.9	58.6	57.8
	53.4	57.8	69.4	64.8	61.2	62.9
	54.9	52.4	69.7	63.7	57.1	64.0
	55.0	55.0	67.8	67.2	59.4	64.9
	52.7	53.1	69.4	61.6	60.1	62.3
	54.0	52.4	69.5	62.4	56.1	60.8
	53.0	52.9	59.6	59.8	55.2	62.1
	52.6	53.2	61.8	58.0	55.6	59.9
	54.3	53.7	65.8	62.2	55.2	63.3
	55.3	53.5	69.7	63.2	57.2	64.2
	51.4	52.3	65.4	61.0	60.2	60.5
	54.4	52.9	61.9	60.1	56.3	60.2
	55.6	51.1	58.9	55.8	55.9	60.3
	53.6	54.7	61.6	56.4	61.4	56.7
	52.6	58.0	64.7	57.9	54.7	60.9
	52.8	51.6	69.9	58.1	57.9	59.2

5	49.5	62.3	57.7	50.1	69	67.3	89125.1	1698244	588844	102329	7943282	5370318
	50.5	61	56.2	49.6	59.7	64.9	112202	1258925	416869	91201.1	933254	3090295
	54.2	67.6	54.6	45.9	58.8	52.3	263027	5754399	288403	38904.5	758578	169824
	52.8	69.7	67.5	47.5	71.8	62.2	190546	9332543	5623413	56234.1	1.5E+07	1659587
	51.2	67.7	67.1	48.6	64.7	62.8	131826	5888437	5128614	72443.6	2951209	1905461
	52.3	66.5	67.5	45.6	72	66.2	169824	4466836	5623413	36307.8	1.6E+07	4168694
	56.1	59.6	64	50.4	64.7	67.3	407380	912011	2511886	109648	2951209	5370318
	50.8	70.1	67.5	49.8	65.6	68.3	120226	1E+07	5623413	95499.3	3630781	6760830
	52.3	72.8	66.8	45.5	72	65.8	169824	1.9E+07	4786301	35481.3	1.6E+07	3801894
	52.8	70.7	66.2	48.3	67.3	65	190546	1.2E+07	4168694	67608.3	5370318	3162278
	48.3	65	61.9	44.8	63.5	65.9	67608.3	3162278	1548817	30199.5	2238721	3890451
	53.4	71.6	67.3	51.6	63	64.7	218776	1.4E+07	5370318	144544	1995262	2951209
	53.5	68.8	66.3	48.7	64.4	65.4	223872	7585776	4265795	74131	2754229	3467369
	54.9	66.5	62.3	53.1	67	66.2	309030	4466836	1698244	204174	5011872	4168694
	53.1	72.7	63.7	48.7	66.3	68.6	204174	1.9E+07	2344229	74131	4265795	7244360
	49.9	73	65.9	47.5	65	67.9	97723.7	2E+07	3890451	56234.1	3162278	6165950
6	54.2	67.5	58.6	56.3	63.9	57.8	263027	5623413	724436	426580	2454709	602560
	53.4	69.4	61.2	57.8	64.8	62.9	218776	8709636	1318257	602560	3019952	1949845
	54.9	69.7	57.1	52.4	63.7	64	309030	9332543	512861	173780	2344229	2511886
	55	67.8	59.4	55	67.2	64.9	316228	6025596	870964	316228	5248075	3090295
	52.7	69.4	60.1	53.1	61.6	62.3	186209	8709636	1023293	204174	1445440	1698244
	54	69.5	56.1	52.4	62.4	60.8	251189	8912509	407380	173780	1737801	1202264
	53	59.6	55.2	52.9	59.8	62.1	199526	912011	331131	194984	954993	1621810
	52.6	61.8	55.6	53.2	58	59.9	181970	1513561	363078	208930	630957	977237
	54.3	65.8	55.2	53.7	62.2	63.3	269153	3801894	331131	234423	1659587	2137962
	55.3	69.7	57.2	53.5	63.2	64.2	338844	9332543	524807	223872	2089296	2630268
	51.4	65.4	60.2	52.3	61	60.5	138038	3467369	1047129	169824	1258925	1122018
	54.4	61.9	56.3	52.9	60.1	60.2	275423	1548817	426580	194984	1023293	1047129
	55.6	58.9	55.9	51.1	55.8	60.3	363078	776247	389045	128825	380189	1071519
	53.6	61.6	61.4	54.7	56.4	56.7	229087	1445440	1380384	295121	436516	467735
	52.6	64.7	54.7	58	57.9	60.9	181970	2951209	295121	630957	616595	1230269
	52.8	69.9	57.9	51.6	58.1	59.2	190546	9772372	616595	144544	645654	831764

#7	48.9	49.7	72.6	69.2	66.2	63.5	7	48.9	72.6	66.2	49.7	69.2	63.5	77624.7	1.8E+07	4168694	93325.4	8317638	2238721
	49.7	49.8	69.6	67.7	69.7	67.7		49.7	69.6	69.7	49.8	67.7	67.7	93325.4	9120108	9332543	95499.3	5888437	5888437
	53.6	44.3	74.2	67.1	65.4	62.1		53.6	74.2	65.4	44.3	67.1	62.1	229087	2.6E+07	3467369	26915.3	5128614	1621810
	52.5	47.3	70.6	61.3	67.1	66.5		52.5	70.6	67.1	47.3	61.3	66.5	177828	1.1E+07	5128614	53703.2	1348963	4466836
	50.5	51.6	71.5	66.2	68.7	57.8		50.5	71.5	68.7	51.6	66.2	57.8	112202	1.4E+07	7413102	144544	4168694	602560
	53	45.7	72.6	58.4	55.3	61.4		53	72.6	55.3	45.7	58.4	61.4	199526	1.8E+07	338844	37153.5	691831	1380384
	58.7	47.9	72.7	69.9	66.2	69.1		58.7	72.7	66.2	47.9	69.9	69.1	741310	1.9E+07	4168694	61659.5	9772372	8128305
	51.1	50.8	61.9	66.2	67.2	59.3		51.1	61.9	67.2	50.8	66.2	59.3	128825	1548817	5248075	120226	4168694	851138
	51.8	44.9	70.4	71.6	67.8	62.2		51.8	70.4	67.8	44.9	71.6	62.2	151356	1.1E+07	6025596	30903	1.4E+07	1659587
	54.6	48.5	67.9	69.9	69.6	65.6		54.6	67.9	69.6	48.5	69.9	65.6	288403	6165950	9120108	70794.6	9772372	3630781
	50.3	48.2	68.3	70.3	68.4	64.9		50.3	68.3	68.4	48.2	70.3	64.9	107152	6760830	6918310	66069.3	1.1E+07	3090295
	53.9	50.7	67.3	72.4	69	62.9		53.9	67.3	69	50.7	72.4	62.9	245471	5370318	7943282	117490	1.7E+07	1949845
	56.8	46.9	74.1	72.1	66	68.9		56.8	74.1	66	46.9	72.1	68.9	478630	2.6E+07	3981072	48977.9	1.6E+07	7762471
	55.6	54.2	75.8	73.8	64	69.1		55.6	75.8	64	54.2	73.8	69.1	363078	3.8E+07	2511886	263027	2.4E+07	8128305
	53.5	48.9	68.4	71.5	63.6	67.7		53.5	68.4	63.6	48.9	71.5	67.7	223872	6918310	2290868	77624.7	1.4E+07	5888437
	50.4	46.5	69.8	71.2	59.9	71		50.4	69.8	59.9	46.5	71.2	71	109648	9549926	977237	44668.4	1.3E+07	1.3E+07
#8	48.0	46.9	63.7	55.2	65.0	59.2	8	48	63.7	65	46.9	55.2	59.2	63095.7	2344229	3162278	48977.9	331131	831764
	47.7	47.7	62.2	53.5	65.4	59.7		47.7	62.2	65.4	47.7	53.5	59.7	58884.4	1659587	3467369	58884.4	223872	933254
	53.0	43.2	62.7	60.6	65.2	60.6		53	62.7	65.2	43.2	60.6	60.6	199526	1862087	3311311	20893	1148154	1148154
	50.5	46.1	65.7	61.7	65.7	63.4		50.5	65.7	65.7	46.1	61.7	63.4	112202	3715352	3715352	40738	1479108	2187762
	48.6	47.2	65.2	65.3	67.6	64.9		48.6	65.2	67.6	47.2	65.3	64.9	72443.6	3311311	5754399	52480.7	3388442	3090295
	48.7	45.3	66.7	66.4	66.3	65.3		48.7	66.7	66.3	45.3	66.4	65.3	74131	4677351	4265795	33884.4	4365158	3388442
	54.7	49.9	62.8	66.8	66.4	65.9		54.7	62.8	66.4	49.9	66.8	65.9	295121	1905461	4365158	97723.7	4786301	3890451
	48.6	49.7	65.2	65.4	65.1	66.4		48.6	65.2	65.1	49.7	65.4	66.4	72443.6	3311311	3235937	93325.4	3467369	4365158
	51.7	45.4	66.4	65.9	67.1	67.3		51.7	66.4	67.1	45.4	65.9	67.3	147911	4365158	5128614	34673.7	3890451	5370318
	50.5	47.7	66.7	66.6	66.0	66.0		50.5	66.7	66	47.7	66.6	66	112202	4677351	3981072	58884.4	4570882	3981072
	47.0	44.0	68.5	66.8	66.3	67.4		47	68.5	66.3	44	66.8	67.4	50118.7	7079458	4265795	25118.9	4786301	5495409
	50.5	49.9	61.2	66.9	67.0	67.6		50.5	61.2	67	49.9	66.9	67.6	112202	1318257	5011872	97723.7	4897788	5754399
	51.9	45.5	62.2	67.6	65.2	68.3		51.9	62.2	65.2	45.5	67.6	68.3	154882	1659587	3311311	35481.3	5754399	6760830
	52.7	52.0	61.3	66.0	66.7	68.0		52.7	61.3	66.7	52	66	68	186209	1348963	4677351	158489	3981072	6309573
	49.0	49.0	62.7	66.7	67.1	68.5		49	62.7	67.1	49	66.7	68.5	79432.8	1862087	5128614	79432.8	4677351	7079458
	49.5	46.9	65.4	67.7	67.9	67.9		49.5	65.4	67.9	46.9	67.7	67.9	89125.1	3467369	6165950	48977.9	5888437	6165950

c. L_p average and noise reduction with/without monolithic felt.

	Lp Average [(dB)					
	Lp without Felt (dB)			Lp with Felt (dB)		
Location	Ambient	Inside	Outside	Ambient	Inside	Outside
1	51.96950957	80.712	61.414	48.7644	70.555	58.9767
2	52.61479437	73.263	64.851	47.5079	66.936	62.7469
3	53.89246426	78.601	61.828	49.8647	67.984	60.755
4	54.08758232	70.274	74.267	53.8339	65.639	77.6534
5	52.68008793	69.376	65.273	49.0616	67.54	65.9761
6	53.88289283	67.141	58.196	54.3172	62.1	61.7957
7	53.67278829	71.52	66.937	49.2704	69.981	66.4022
8	50.70021433	64.822	66.344	47.8962	65.566	66.2035

	Noise Reduction [NR = Lp1 - Lp2] (dB)					
	Lp without Felt (dB)			Lp with Felt (dB)		
Between	Ambient	Inside	Outside	Ambient	Inside	Outside
3 and 4	0.195118063	8.3275	12.439	3.96921	2.345	16.8984
7 and 8	2.972573964	6.6979	0.5929	1.37423	4.4157	0.19869
in-out	0.07569906	7.2822	2.2087	3.12198	4.1645	5.57945

d. Raw data, Lp average, and noise reduction with/without segmented wool felt

	Measured Data		10^(Lp/10)	
	Lp w/ Felt (dB)	Lp w/ Felt (dB)	Lp w/ Felt (dB)	Lp w/o Felt (dB)
Inside	69	73	7943282.3	19952623.1
	72	75	15848932	31622776.6
	73	76	19952623	39810717.1
	68	76	6309573.4	39810717.1
	70	77	10000000	50118723.4
	69	71	7943282.3	12589254.1
	74	73	25118864	19952623.1
	70	72	10000000	15848931.9
Outside	63	66	1995262.3	3981071.71
	66	58	3981071.7	630957.344
	65	70	3162277.7	10000000
	69	69	7943282.3	7943282.35
	68	75	6309573.4	31622776.6
	66	71	3981071.7	12589254.1
	64	70	2511886.4	10000000
	65	69	3162277.7	7943282.35

Lp Average		
Location	Lp w/ Felt (dB)	Lp w/o Felt (dB)
Inside	71.1023842	74.58083
Outside	66.1603815	70.248479

Noise Reduction		
Lp1-Lp2	Lp w/ Felt (dB)	Lp w/o Felt (dB)
Inside-Outside	4.94200265	4.3323515