Modeling and Analysis of Reverberation Time Measurements at the Center for Change

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ABSTRACT

The most common challenge faced in architectural acoustics is designing a room with a proper reverberation time that will suit the purposes of the space. At the Center for Change located at 1790 N State St in Orem, Utah, a room known as the Dance Room exhibits an extraordinarily high reverberation time, making communication in the room extremely difficult. Using the EASERA system (Electronic and Acoustic System Evaluation and Response Analysis), as well as a starter pistol with multiple Larson Davis 824 sound level meters, measurements of the reverberation time were made in the room at the Center for Change on March 26th, 2016. Several possible solutions designed to lower the reverberation time were investigated and tested by constructing a computational model of the room using the Sabine equation as well as EASE software (Enhanced Acoustic Simulator for Engineers). Two solutions were chosen, and proposed in a written report to the Physical Facilities Manager at the center, Glenn Klemetson.

I. INTRODUCTION

Ever since the work of Wallace Clement Sabine of Harvard University in the late eighteen hundreds, what he termed an "RT60" has been the standard for quantifying reverberation time in architectural acoustic applications. The RT60 is defined as the time required for the sound level of a given frequency in a room to decay 60 dB from its original level. To this day, it remains the most fundamental parameter used to characterize a room. (Sabine, 1922) (Associates, 2016)

Today, architectural acousticians employ various methods to measure the RT60 of a room. The simplest of these methods measures the decay of an impulsive sound using sound level meters. (Jaffe & Cooper, 2000) More complex methods include the use of automated systems that generate sounds and measure responses of a room, such as EASERA (Electronic and Acoustic System Evaluation and Response Analysis). Besides finding RT60's experimentally, acousticians today can also estimate the RT60 of a room with great reliability using an analytical model generated with software packages such as CAD Acoustics or EASE to virtually construct a room and predict the RT60 time before a room is built. In addition, these tools greatly aid an acoustician in finding solutions to improper RT60 times of a given room.

The "ideal" RT60 for a given room depends on the use of the room. For example, classrooms, where speech audibility is paramount, call for a standard RT60 of about 0.5 seconds, while large theaters used for musical performance can benefit greatly from a much greater reverberation time, usually anywhere from 2.0 seconds to as much as 4.0 seconds for organ performance. Rooms with multiple uses, therefore, present a unique challenge, as a lower RT60 is necessary for applications involving speech, such as a conference or other discussion setting, and a higher RT60 may then be desired if the room is used for the performing or listening of music. Surprisingly, some acoustical treatments do provide the ability to change the RT60 of the room depending on the use. One fascinating example is the LDS conference center in Salt Lake City, Utah. With an enormous volume of around 8,000,000 ft^3, a rather sophisticated electronic system, known as the ERES system, uses microphones and loudspeakers in the building to switch between an RT60 of 2.0 seconds for speeches given, and around 3.9 seconds for musical performance. (Hoffman, Storch, & Foulkes, 2003)

The Dance Room at the Center for Change, a specialized treatment center for women with eating disorders, located in Orem, UT, is just such a room, as it is used for multiple purposes. The room is used for dancing, of course, and music is therefore played in the room. However, it is also used for meditation, exercise classes, teaching, and conferences. A suitable reverberation time for the room is therefore difficult to determine. A simplified method to accomplish variable reverberation times was proposed, as well as a more traditional static method. Each method was designed to reduce the reverberation time from the current average of about three seconds, to at least below two seconds across the octave bands, but not below one second.

This project employed strategies used by industry professionals today, in a real-world application. The experimental process, analysis, and testing of proposed solutions, as well as the drafting of a written report communicating the methods and results to the concerned audience, provided invaluable first-hand experience to all students involved, and prepared students for a prospective career in acoustical consulting. The project also provided an opportunity for students of the PHYSCS 461 Winter 2016 class at Brigham Young University to utilize skills and knowledge developed in the classroom, and showcased the relevance and applicability of the material taught. I was primarily responsible for organizing, and leading the students to take measurements of the room using sound level meters and the EASERA system. In addition, I created an extensive room model using the Sabine equation and EASE modeling software after the initial recordings to verify the accuracy of the collected data, and ensure precision in any proposed solutions provided to the Center for Change.

II. METHODS

A. SABINE EQUATION

The reverberation time of a room, given by the RT60 mentioned above is calculated by the Sabine equation. The equation, developed by Wallace Sabine, expresses an enclosure's reverberation time as a function of room volume, V, and the total acoustic absorption of all surfaces in the room, A, as shown in Equation 1.

$$RT60 = \frac{0.161\ V}{A} \tag{1}$$

The constant 0.161 varies slightly with ambient pressure and temperature, but is generally accepted as applicable to most applications where linear acoustical methods are employed.

Absorption coefficients are used to quantify how acoustically "absorptive" or "reflective" a material is at a given frequency. For example, a material with a known coefficient of 0.00 denotes that the material is completely reflective, and no sound will be absorbed from an incident sound wave. On the other hand, if a material has a coefficient of 1.00, this material is completely absorptive, and, theoretically, no sound will be reflected, but an incident sound wave will be entirely absorbed. In practice, however, an ideally reflective material is extremely uncommon. Additionally, due to a phenomenon known as the edge effect or diffraction effect, materials may have absorption coefficients exceeding 1.0, as is seen in some materials described in this report. (Blatt, 1987) The total room absorption, A, is the sum of the surface areas of all surfaces in the room multiplied by their respective absorption coefficients. Some examples of absorption coefficients of common construction materials is given in Table 1 below.

Table 1: Absorption coefficients of commonly used construction materials.

Material	**Absorption**					
	125 Hz	**250 Hz**	**500 Hz**	**1000 Hz**	**2000 Hz**	**4000 Hz**
Concrete	0.02	0.03	0.03	0.03	0.04	0.07
Gypsum Board, ½"	0.29	0.10	0.05	0.04	0.07	0.09
Glass	0.35	0.25	0.18	0.12	0.07	0.09
Wood	0.15	0.11	0.10	0.07	0.06	0.07

As absorption coefficients are not given as just a single value, the acoustic absorption of a material is frequency-dependent, meaning that lower frequency sounds may be absorbed more or less effectively by a the same object than higher frequency sounds. Naturally, if rigorous enough testing were done on a given material, a narrowband absorption curve could be obtained for the substance. However, measuring and providing coefficients for the six octave bands shown in Table 1 is the industry standard. These coefficients are traditionally provided with any material specifically designed to absorb sound, and are well documented for other common building supplies.

B. EXPERIMENT

Octave band RT60 times were measured in the Dance Room at the Center for Change with two different methods. The first was the more straightforward method of recording a loud impulse sound, in this case a starter pistol, with a sound level meter, and observing the frequency-dependent RT60 value over the six octave bands. The second was with the use of an automated system, called EASERA, which simultaneously gives a separate RT60 time for each of multiple locations in a room.

A basic rectangular model of the room is displayed in Figure 1, labeling the four walls for further reference. A starter pistol was fired at the location (7.31 m, 5.37 m) with the origin of the room being the southeast corner, or the intersection of Wall A and Wall D. Larson Davis 824 sound level meters were positioned at the locations listed in Table 2. The measured RT60 for each location over the six octave bands is also shown.

Table 2: Locations and measured RT60 of Larson Davis 824 Sound Level Meters in the Dance Room at the Center for Change.

Location	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
(3.94, 8.35)	1.43	1.637	2.859	2.969	2.32	1.785
(9.05, 9.68)	1.352	1.734	2.844	3.02	2.422	1.73
(1.91, 4.18)	1.188	1.699	2.883	2.992	2.43	1.684
(6.76, 1.46)	1.313	1.742	2.828	2.977	2.414	1.73

Locations (m):
I1: (1.55, 9.90)
I2: (3.86, 10.79)
I3: (6.68, 10.70)
I4: (9.05, 9.68)
II1: (2.36, 7.16)
II2: (3.94, 8.35)
II3: (6.44, 8.41)
II4: (8.29, 7.31)
III1: (1.91, 4.18)
III2: (4.50, 4.66)
III3: (6.01, 4.69)
III4: (8.76, 4.13)
IV1: (1.50, 1.50)
IV2: (3.63, 1.41)
IV3: (6.76, 1.46)
IV4: (9.01, 1.81)
Speaker: (7.31, 5.37)

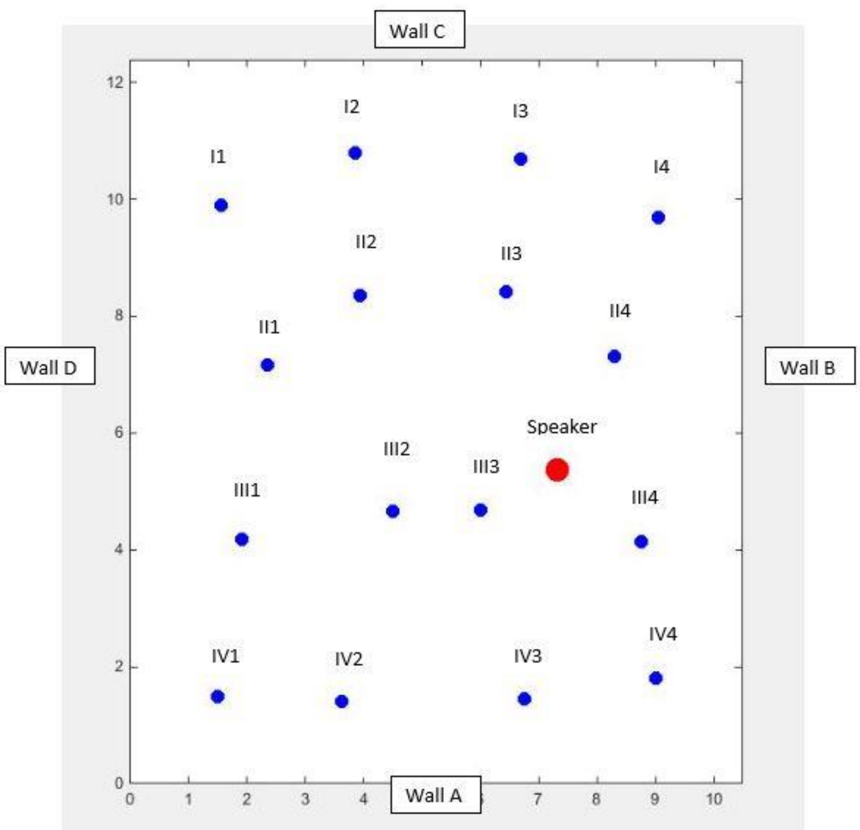

Figure 1: Locations of all microphones and speaker used in automated EASERA measurements.

To verify these results, the EASERA system, made available by the BYU Acoustics department, in conjunction with a Presonus Firepod Microphone Interphase, and a Crown Audio Amplifier were used to make the same measurements at additional locations in the room. Four microphones were used at the locations shown below in Figure 1. The locations for all four microphones in their first position are denoted by the Roman numeral “I”. The second, by Roman numeral “II” and so forth. The numbers “1”, “2”, “3” etc. refer to the microphone number. Additionally, a letter, “a” or “b” was assigned to distinguish between the two trials taken at each location respectively. So, “I1a” refers to position I, microphone 1, first trial, and “II4b” refers to position II, microphone 4, second trial. All coordinates are measured in meters with respect to the origin defined previously. The larger red dot represents a dodecahedron shaped loudspeaker used as a diffusive, omni-directional source.

III. ANALYSIS

A. MEASURED RT60

The EASERA system calculates the RT60 using the average of other metrics at each microphone. These data from each microphone were then averaged together to get reverberation times for the entire room across 6 octave bands, from 125 to 4,000 Hz and are displayed in Table 3.

Table 3: Average RT60 values for the Dance Room at the Center for Change as taken with the EASERA System

	125 Hz	**250 Hz**	**500 Hz**	**1000 Hz**	**2000 Hz**	**4000 Hz**
RT60	2.6	2.5	3.2	3.5	3.1	2.7

The RT60 values taken from the sound level meters, from Table 2, and the spatially averaged results from the EASERA system, in Table 3, at first glance do not seem to agree very well. However, when the results are plotted, as in Figure 2, a correlation can be seen more readily. It appears that they agree very well in overall shape of the frequency-dependent curves, however, there seems to be an offset of up to one second that differentiates the RT60 values obtained from the two methods. This is most likely due to peak clipping of the recorded shots from the starter pistol used. In any case, the data taken with the EASERA system was chosen to model the room because there were significantly

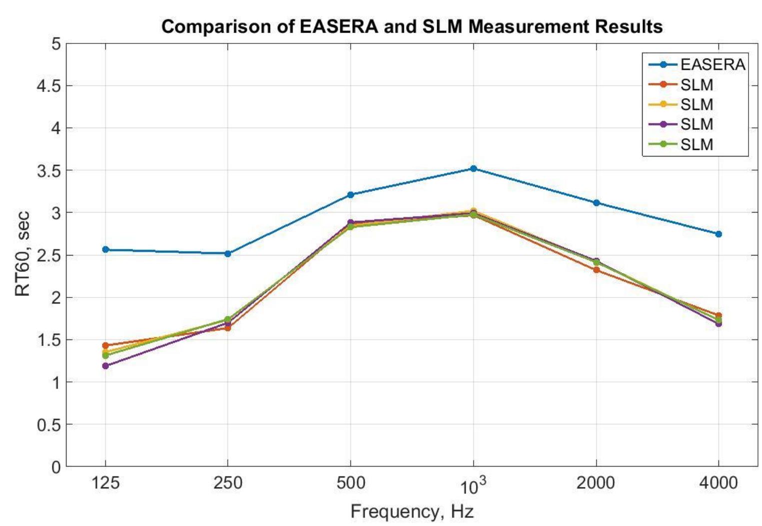

Figure 2: Plot of averaged EASERA data (blue line) and sound level meter data (other colored lines) for comparison

more trials of data taken in many more locations. In addition, when modeling the room using the Sabine equation, the resulting modeled RT60 times before treatment was significantly closer to the EASERA measurements than those obtained using sound level meters. Also, when decreasing reverberation time, we would rather err on the high end of reverberation times so as to produce, by project end, *lower* than normal reverberation, as opposed to RT60's that are higher than initially reported to the client.

B. MODELED RT60

As mentioned, a model of the room was created using the Sabine equation, using octave band absorption coefficients for the common materials in the room. On the first attempt, the modeled RT60s of the untreated Dance Room did not match our measurements very well. Upon investigation of data, however, there seemed to be outliers in the measurements that were significant sources of error. Specifically the second trial (trial "b") at position III and the first trial at position IV were consistently drastic outliers for all four microphones. Upon investigation of the experimental setup, this is most likely due to the fact that for those particular recordings, the microphones were much closer to the source than for the other measurements. Although EASERA did not give any warnings of clipping in the data, as we would expect, it is possible that this threshold shift could have caused some inaccuracy in the data, or that clipping was occurring at these measurement locations, but not to the extent that the automated system would easily recognize it. In any case, those two of 32 measurements were ignored.

This adjustment helped to reconcile the measured data with the model to a certain degree, but the unknown floor material, as well as the whiteboard present in the room remained difficult to model, as no information regarding absorption coefficients were found. Estimates, therefore, had to be made to include these materials that would seem reasonable for the type of material, and that would agree with the measurements.

In order to deduce the absorption coefficients of the materials that did not have documented acoustic specifications, such as the floor, the white board, and the plastic light covers mounted in the ceiling, educated guesses as to what the coefficients would be similar to were used, and the frequency-dependent RT60 of the room was calculated and compared to the measured values. The absorption coefficients were then adjusted accordingly until the modeled RT60 values matched the measured values within a margin of error, determined by the standard deviation of the measured data.

The absorption coefficients finally used in the model for all materials in the room are shown in Table 4, and the modeled RT60 values are shown in Figure 3 along with the measured values and associated error bars.

Table 4: Absorption coefficients of all materials in Dance Room at the Center for Change. The coefficients for the whiteboard as well as the plastic light covers were educated guesses based on average coefficients of similar materials. The floor coefficients were based off that of a standard hard wood floor and adjusted to more accurately reflect the measurements. It is therefore a best guess of the absorptivity of the floor, but is not known exactly.

Material	**125 Hz**	**250 Hz**	**500 Hz**	**1000 Hz**	**2000 Hz**	**4000 Hz**
½" drywall over wood 2x4's, single sheet	0.08	0.11	0.05	0.03	0.02	0.03
½" drywall over brick	0.01	0.01	0.02	0.03	0.04	0.05
Dance floor	0.02	0.02	0.04	0.06	0.08	0.10
Glass (windows)	0.10	0.06	0.04	0.03	0.02	0.02
Wood door, hollow	0.30	0.25	0.15	0.10	0.10	0.07
Whiteboard	0.10	0.10	0.10	0.10	0.10	0.10
Plastic Light Covers	0.20	0.20	0.20	0.20	0.20	0.20
Thin plywood paneling (cabinet in corner)	0.42	0.21	0.10	0.08	0.06	0.06

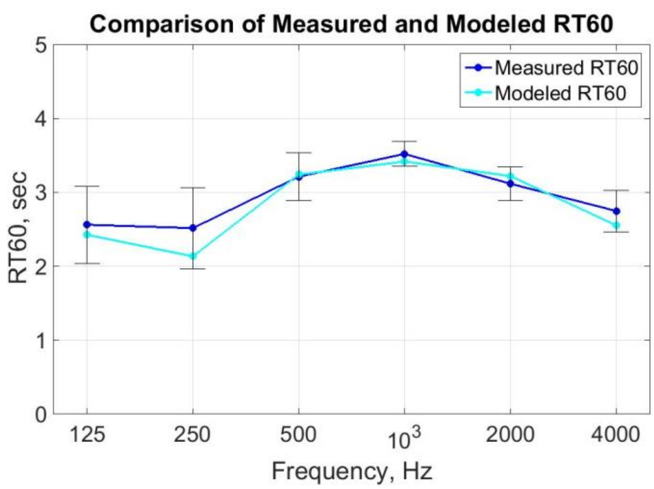

Figure 3: The modeled RT60 curve fits within the error bars of our measured data using the absorption coefficients in figure 13.

Using this model (the cyan curve in Figure 3), various different acoustic damping materials were researched and their octave band absorptivities were added to the model along with their surface areas to update the Sabine equation for the room, and display the resulting predicted RT60 curve after treatment.

The absorption coefficients for the two treatment materials chosen to report to the Center for Change are shown in Table 5 below.

Table 5: Absorption Coefficients for Treatment Material

Material	**125 Hz**	**250 Hz**	**500 Hz**	**1000 Hz**	**2000 Hz**	**4000 Hz**
Owens Corning 2" Fiberglass	0.17	0.86	1.14	1.07	1.02	0.98
"Crescent Velour" *Quiet Curtains*	0.04	0.43	1.06	0.99	1.06	1.15

To further verify the validity of our measured data, as well as the model constructed and used for further analysis, EASE modeling software (Enhanced Acoustic Simulator for Engineers) was used to construct an additional model of the room, and a simple visualization of the computer rendered model is shown below in Figure 5, along with a picture of the actual room as equipment was set up in Figure 4. As EASE uses the same Sabine equation used in the model above, the resulting reverberation times given by the software were almost exactly the same, with very little error. This proved useful in verifying the accuracy of the proposed solutions.

Figure 4: The Dance Room at the Center for Change as measurement equipment is set up.

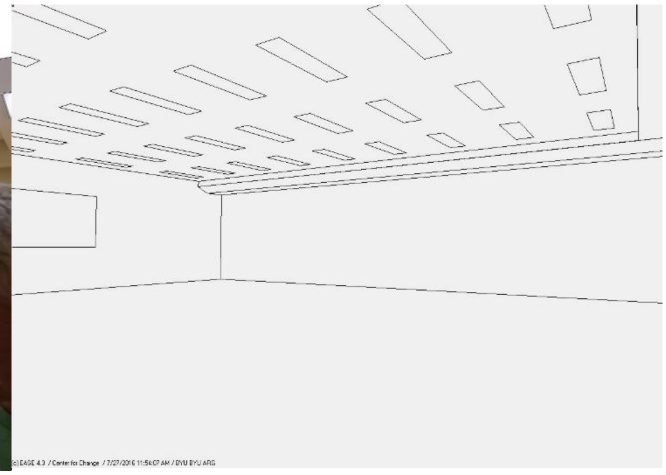

Figure 5: Computer generated model of the Dance Room. The model was used to verify all measurements and results.

C. PROPOSED SOLUTIONS

The unique uses of the Dance Room made the target region rather difficult to initially determine, because the “ideal” RT60 for a specific room of a certain purpose or use varies widely depending on the source. For the Dance Room in particular, an RT60 that would be both conducive to speech and music was desired. According to Acoustical Solutions Inc., in an article published in 2012, there were multiple case studies done on mainly worship houses. When talking about places of worship (where there is both speech and music) they said, “The RT60 of a sanctuary should be between 1.6 to 2 seconds. This is long enough for a sermon or music to resonate beautifully, but still be clear.” (The Basics: Acoustics Treatment Design for a Worship Space, 2012) Additionally, a second church in Virginia with very similar dimensions to the Dance Room analyzed in this project had an excessive RT60 that was reduced to about 1.9 seconds. The client later described the room as “the perfect balance of reverb where groups can use the room for activities, but music will still sound full and live. Acoustically, this is exactly what we were going for.” (Vanderwilt, 2012) With those considerations, a target region of 1 to 2 seconds was chosen.

The overall cost for each of the proposed solutions include the price of all materials, together with any hardware needed to finish, or install the treatment.

Option 1: 32 Owens Corning Fiber Glass Panels
Overall Cost: $768.00
Installation Labor: Moderate

Fiberglass threads are arguably one of the most effective sound damping materials available. Owens Corning (as well as many other companies) produces 2 ft. x 4 ft. x 2 in. rigid panels of bare fiberglass insulation that can be wrapped in fabric, usually a twine or jute material, and placed on a wall, as shown in Figure 6. 32 panels are recommended to effectively reduce the RT60 octave band into the target region, with an average of about 1.5 seconds. The new reverberation time over the octave bands is shown in red in Figure 7. At $67.00 for a pack of 6, they are extremely cost effective, however, as panels are added to the room, the effectiveness of each additional panel decreases, as in Figure 8.

Additionally, as any acoustic absorption material has the risk of having a negative impact on the overall aesthetics of the room, the panels can be wrapped with a wide variety of colored or patterned material. It is also important to note that 32 panels will take up 256 ft^2 of wall space. Although panels could be placed on the ceiling, a large portion of the present wall surface area of the room would be needed to mount the panels.

Installation of the panels is somewhat involved. As mentioned, the panels would need to be wrapped as exposed fiberglass is not an ideal surface material for a public space. They are traditionally mounted using hooks that are inserted into the wall, as well as into the fiberglass material. Fiberglass panels have an additional benefit, in that in the event the panels do not reduce the reverberation time as much as desired, the panels can be mounted further from the wall leaving an air gap between the panel and the wall. This increases the overall surface area of the panels exposed to sound in the room, and therefore, increases the absorption of the panels.

Figure 6: Wrapped Owens Corning rigid fiberglass panels 2'x4'x2" installed on a wall. Fiberglass Insulation Panels, photograph courtesy of, http://www.amazon.com/Owens-Corning-703-Fiberglass-Boards/dp/B005V3L834

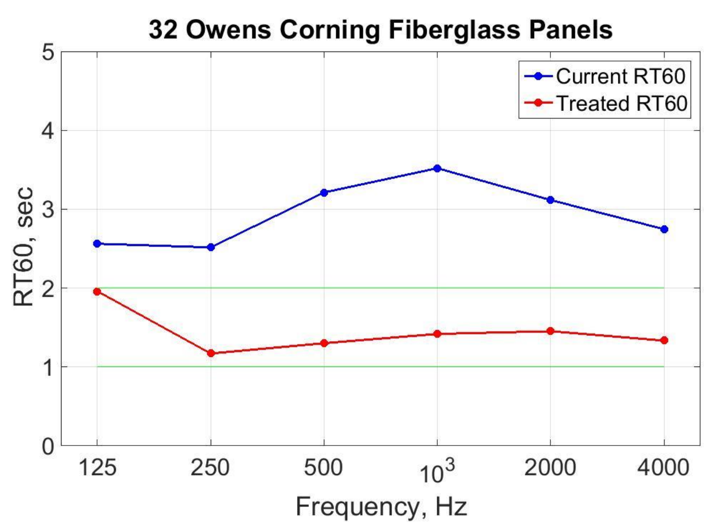

Figure 7: Effect of 32 Owens Corning Fiberglass panels on the RT60 of the Dance Room. The red line represents the RT60 of the room after the installation of the panels to the walls.

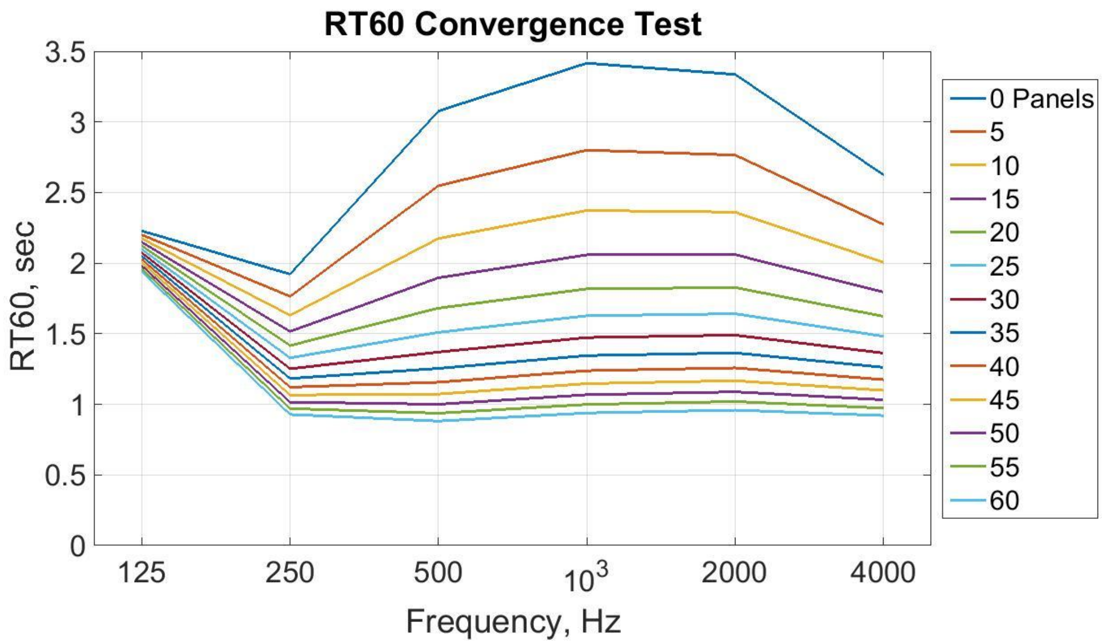

Figure 8: As fiberglass panels are added to the room, the effectiveness of each panel decreases. Each line represents 5 additional panels added to the room from 0 to 60 panels. The first 5 panels reduce the RT60 by almost 1 second, while increasing from 55 to 60

Option 2: “Crescent Velour” Drapes by *Quiet Curtains*
Overall Cost: ~1,500.00
Installation Labor: Extensive

Hanging drapes along the north wall of the Dance Room would provide a simpler way of changing the reverberation time of the room for different applications as needed, and depending on the drapes chosen, can cover a wide range of reverberation times. For example, if a longer reverberation time is needed for playing music to provide a more full sound, the drapes can be pulled back, revealing the wall again. In contrast, when speech is important, the curtains can be drawn, and the RT60 time would be again reduced. The curtains displayed below in Figure 9 are specifically designed to absorb sound, and very effectively reduce the reverberation time to about 1 second, with the exception of the lowest frequency band at 125 Hz, as shown in Figure 10. This model assumes the drapes are hung along the west wall of the room, covering the entire wall. The drawbacks of such a method, however, include the curtains would cover the three lights on that wall of the room, they are more expensive, and more laborious installation is required. On the other hand, the curtains would provide the most effective sound absorption if ideal reverberation time for the different activities in the room is the priority. Like the panels, these curtains also come in multiple different colors and styles to fit the desired look of the room.

Figure 9:"Quiet Curtains" Crescent Model. Available in a number of colors and custom sizes. Quiet Curtains, Acoustical Solutions, photograph courtesy of, http://www.acoustic-curtains.com/contact.php

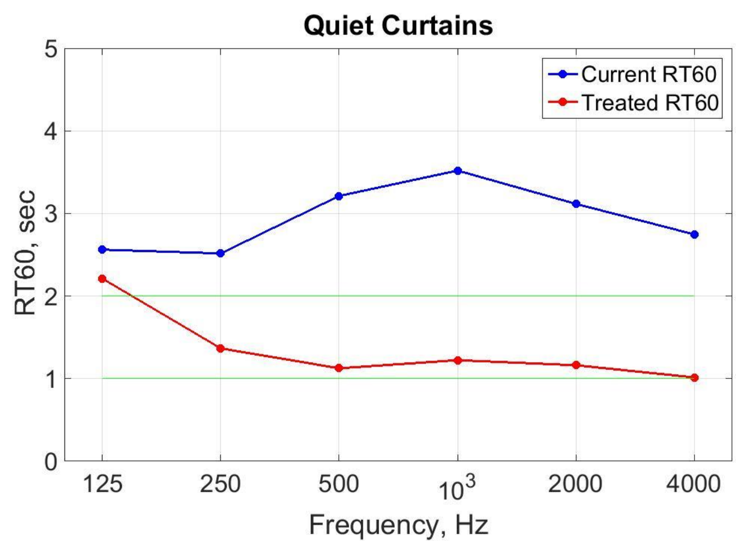

Figure 10: Effect of “Quiet Curtains” Crescent Drapes on the RT60's of the Dance Room. The red line represents the RT60 of the room after the installation curtains covering the entire north wall of the room.

A draft containing a summary of the aforementioned data and results outlining these two proposed solutions was written and submitted to the Center for Change for their review. The final decision of which solution method to use obviously rested on the Center for Change according to their priorities and financial situation. Both of the options provided would certainly improve the acoustical response of the room, and there are more specific variations to each option. The Physical Facilities

Manager at the Center for Change chose to pursue the first option, Fiberglass panels, in order to solve the excessive reverberation time in the room.

IV. CONCLUSION

Although the primary objective of the project was, of course, to provide assistance in designing and analyzing acoustical treatment of a room at a local rehabilitation center, a secondary, yet invaluable outcome of the experience was to provide myself, as well as multiple other students involved in acoustics research at Brigham Young University, the opportunity to use, apply, and practice first hand, principles of acoustics acquired in the classroom. The process of characterizing, analyzing, and proposing solutions to an acoustical problem employed in this project provided significant experience that can be added to resumes for all students involved, and has already led to employment opportunities. Additionally, the university was able to establish new network connections with members of the local community, and provide meaningful and much needed service.

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