DESIGN OF AN ARCHITECTURAL ACOUSTICAL TREATMENT INCORPORATING REUSED COTTON CLOTHING: AN EXPIRMENTAL EVALUATION AND CASE STUDY

A THESIS SUBMITTED TO THE GRADUATE DIVISION OF THE UNIVERSITY OF HAWAIʻI AT MĀNOA IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

MASTER OF SCIENCE

IN

MECHANICAL ENGINEERING

DECEMBER 2010

By

Todd R. Beiler

Thesis Committee:

Ronald Knapp, Chairperson
Homer Williams
Whitlow Au

Keywords: Sound Absorption, Reverberation, Reuse, Recycle, Cotton

Acknowledgements

I would like to thank my advisor, Professor Ronald Knapp, for his guidance and motivation in completing this research. I would also like to thank the Mechanical Engineering Department and the University of Hawai'i for allowing me to conduct this important research in the area of acoustics and noise control and for the pursuit of finding a practical, eco-friendly solutions to problematic acoustical environments in reverberant spaces.

I would like to give a special thanks to Joe Hegedorn for his generosity in helping me brainstorm and with the fabrication of the acoustic pillows. Without his help, the prototype may not have been possible. A special appreciation is also given to Sean Croucher and Emily Brewer for the use of their racquetball court and for their assistance during the acoustical tests. I would lastly like to thank my friends and family for their support during my research and for everyone who donated their tee shirts.

Table of Contents

List of Tables

List of Figures

Chapter 1 Introduction

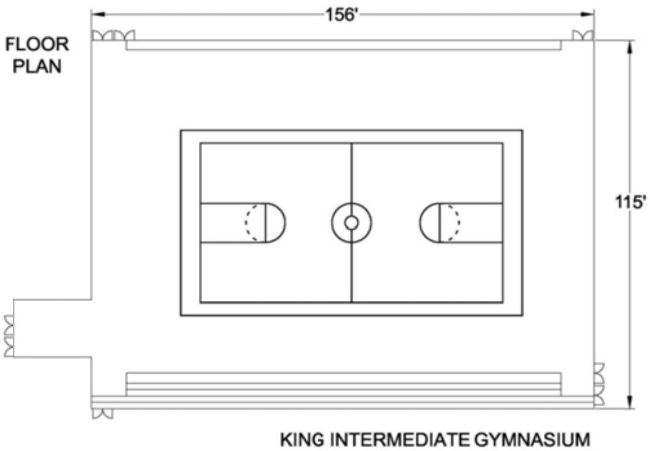
1.1 Design Considerations and Objectives

The natural acoustics within a room is often overlooked or ignored when determining the functional use of the space. The electrical, ventilation, structural, and architectural requirements, as well as other key engineering disciplines, have long been incorporated into building construction industry standards for proper building design. However, acoustics, sound insulation, and noise control are also quickly becoming dominant design issues in certain building types. This increase in attention to acoustics has generated not only the recognition of well-designed and constructed new buildings, but also an awareness of the lack of desirable acoustics in existing buildings and aging structures.

Although there are many different types of acoustical related problems facing the building construction industry, this paper focuses solely on the natural acoustics within large reverberant spaces. The goal of this research is to develop a cost effective and environmentally minded solution for controlling the build-up of reverberant sound energy in these acoustically “live” spaces. This paper also includes a case study of the King Intermediate School and of how the application of the solution developed herein would benefit the multipurpose gymnasium, currently existing as a very large and excessively reverberant space.

1.1.1 Background of King Intermediate School

King Intermediate School is located in Kaneohe, Hawaii and has a multiuse gymnasium with very poor natural acoustics. This gymnasium is not only used for sporting events, but it is also used for music performances by the school band and choir and for plays and other performances by the drama and art departments. The gymnasium is also used for speeches, presentations, political rallies, general assembly meetings and other community events and activities. The gymnasium is very large with a footprint size of 158 feet by 115 feet and an air volume of approximately 565,000 cubic feet. A floor plan, reflected ceiling plan, and a photograph of the gymnasium is shown in Figure 1 below.



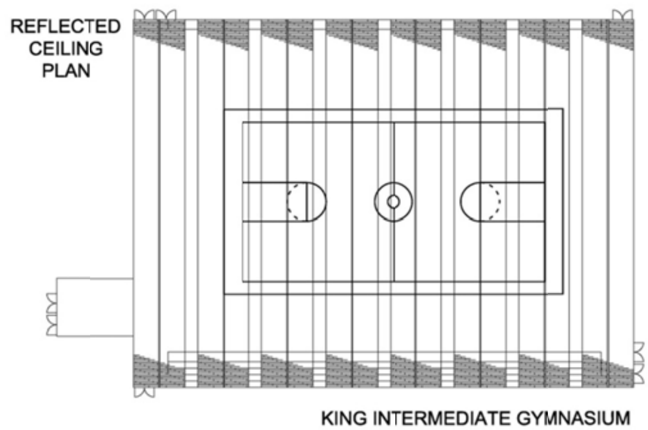


Figure 1. King Intermediate School Gymnasium

The floor is hardwood sports flooring on sleepers for the basketball court, and polished concrete in the pedestrian walkways and all other areas. The walls are painted concrete masonry unit (CMU) block walls, and the ceiling is a barrel shaped wood plank structure supported by large arched enclosed trusses that span the width of the gymnasium. With these reflective room finishes the resulting natural acoustics and long reverberation time within the gymnasium is immediately noticeable. Spoken words, even when amplified, are largely unintelligible and blend into one continuous sound, and musical phrasings are not discernable to the listener. The excessive reverberation time in the gymnasium render the space to be non-effective or minimally effective for the many uses.

1.1.2 Design Objectives

The design objectives for acoustically treating the King Intermediate School gymnasium were thoroughly discussed with the school staff. First and foremost, the treatment must be effective and perform well. The improvement gained by adding the treatment must be significant and easily noticeable to the students, staff, and community users of the facility. Developing a product with a sound absorbing performance similar to fiberglass insulation would be ideal, since fiberglass insulation is highly absorptive. There was a strong desire amongst the school staff to use recycled materials in an effort for the school to promote environmentally friendly practices. The most difficult design objective discussed with the school staff was the cost of the treatment. Given the size of the space and the anticipated amount of treatment necessary to make a significant improvement, a target installed cost of $2.00 / ft^2 was established. As can be seen in the section below, this target cost rules out all commercially available products, so the school was hopeful for an unconventional solution that could satisfy their cost requirement. The school was interested in involving the community, school staff, and students for this project. A sense of ownership in improving the use of the gymnasium in a collaborative working environment with the community, staff, and students could be considered a benefit for the school. However, because the project may involve a large number of people, the acoustical treatment should have the capability of being installed in phases in order to reduce the burden in any given year. A total of four project phases was discussed such that the total treatment could be installed within four years.

1.2 Background

1.2.1 Acoustics Overview

Generically speaking, acoustics is defined as the scientific study of sound, especially its generation, transmission, and reception (Egan 1988). Some of the basic metrics of sound, include the frequency (Hz), wavelength (ft), period (s), and amplitude, or relative amplitude (dB). The frequency of sound (also referred to as the pitch in music references) is just as important as the sound level. The human audible frequency range is 20 Hz to 20,000 Hz. Typical speech ranges from 250 Hz to 2,000 Hz and most music falls within the range from 60 Hz to 8,000 Hz.

The Decibel (dB) is named after Alexander Graham Bell who was Scottish born in 1847 before he moved to the United States and invented the telephone in 1876. The Decibel is defined as the logarithmic ratio of a signal level to a reference level. One Bel is when the signal level is 10 times the reference, so one decibel is 1/10th of a Bel.

$$L\ [dB] = 10\ Log\left(\frac{X}{X_{ref}}\right) \tag{1}$$

Sound levels range from 0 dB at the threshold of hearing to approximately 140 dB at the upper pain threshold, although louder sounds are certainly possible. The corresponding sound pressure ranges from 0.00002 Pa to 200 Pa. It's because of this dynamic range of *sound pressure* (Pa) that the *sound pressure level* (dB) is used to evaluate sound. Common sound levels for everyday noises can be found in the figure below (Egan 1988).

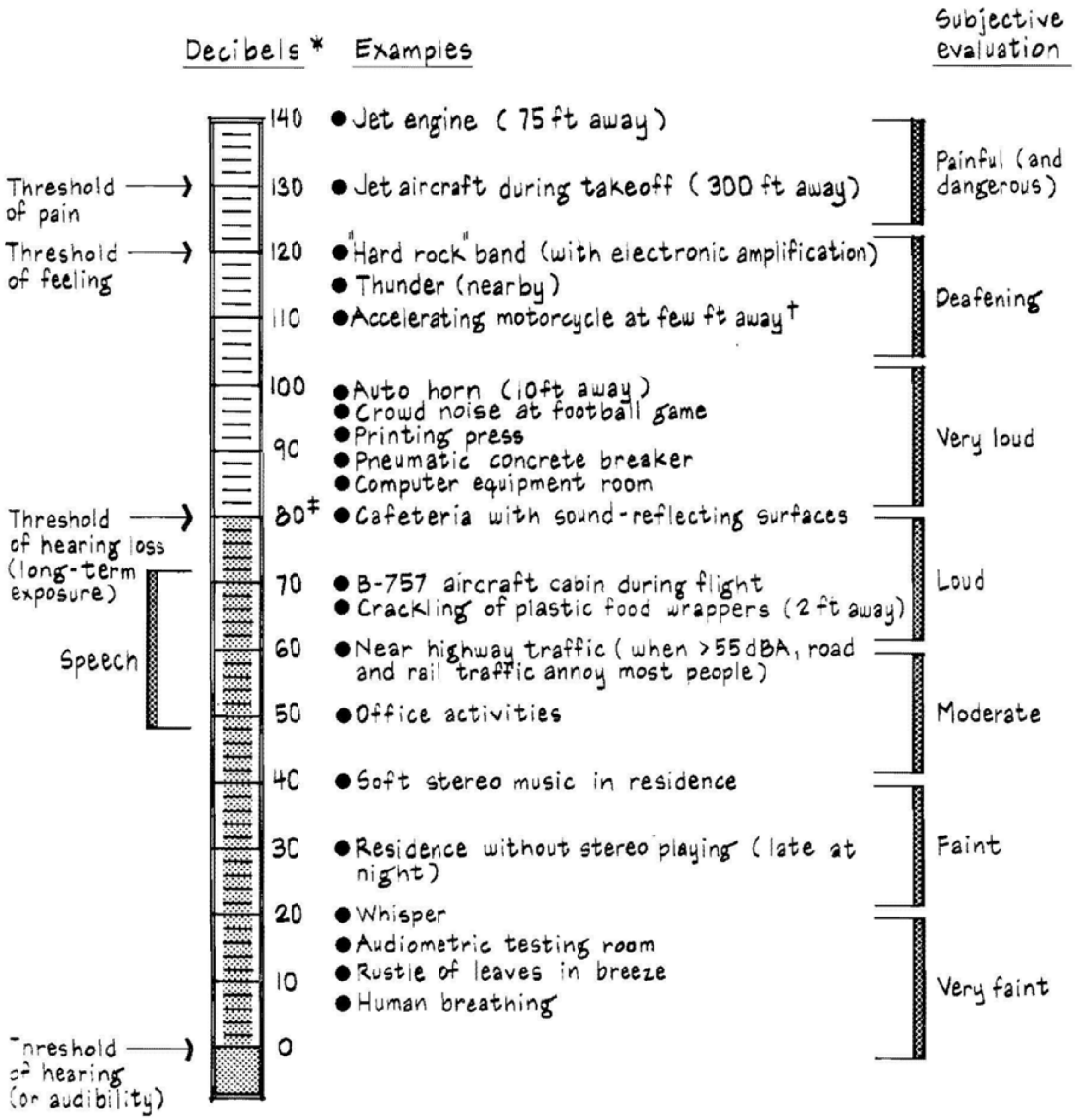


Figure 2. Common Sound Levels (Egan 1988)

It is important to remember this logarithmic relationship when considering the addition of two sound levels or sound sources. Sound levels must be logarithmically added versus linear addition. Solving the above equation for X/X_{ref} the relationship can be written as:

$$10^{\left(\frac{L}{10}\right)} = \frac{X}{X_{ref}} \quad (1)$$

The addition of two values, X_1 and X_2, can be combined linearly. But to determine the change level (dB), the following relationship describes the calculation for logarithmic addition of two source values.

$$\frac{X_{1+2}}{X_{ref}} = \frac{X_1}{X_{ref}} + \frac{X_2}{X_{ref}} \quad (2)$$

$$10^{\left(\frac{L_{1+2}}{10}\right)} = 10^{\left(\frac{L_1}{10}\right)} + 10^{\left(\frac{L_2}{10}\right)} \quad (3)$$

$$L_{1+2}\ [dB] = 10\ Log\left(10^{\left(\frac{L_1}{10}\right)} + 10^{\left(\frac{L_2}{10}\right)}\right) \quad (4)$$

1.2.2 Existing Acoustical Treatment Options

There are a wide variety of commercially available acoustically treatment options ranging in aesthetics, installation method, durability, effectiveness, cost, and many other factors. The following is not an exhaustive list of all available products, but it includes some of the main types of products used for absorbing reverberant sound energy within a room.

Table 1. Commercially Available Acoustical Treatments

Treatment Type	Material Description	Estimated Installed Cost
Spray-on	Chemically treated recycled natural fibers	\$8.00 / sq. ft.
Wood Fiber Panels	Cementitious wood fiber board	\$10.00 / sq. ft.
Wrapped Fiberglass Panels	Semi-rigid fiberglass core with acoustically transparent wrap	\$14.00 / sq. ft.
Processed Cotton Panels	Processed from recycled cotton into semi-rigid panels	\$14.00 / sq. ft.

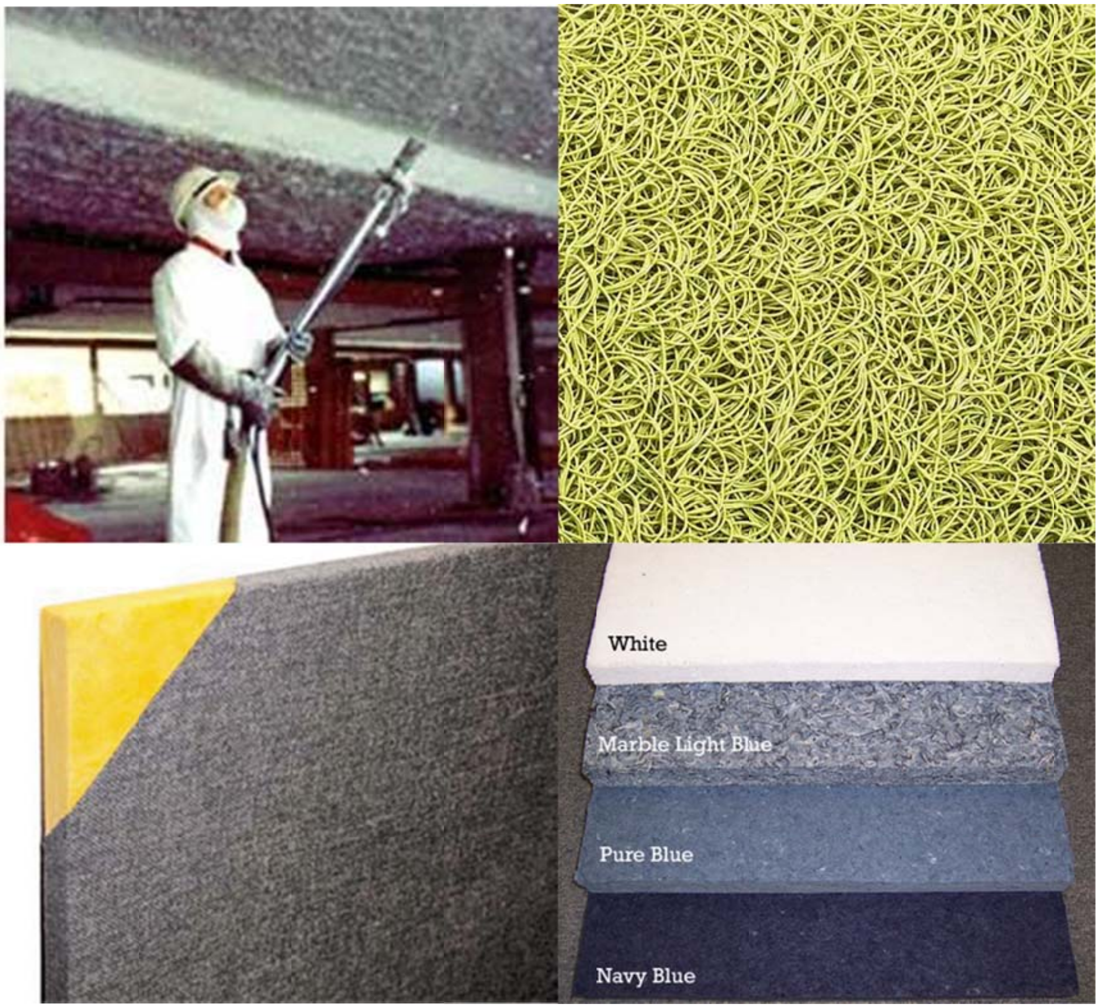


Figure 3. Existing Acoustical Treatments: Spray-on (Top Left), Wood Fiber (Top Right), Wrapped Fiberglass Panels (Bottom Left), and Processed Cotton Panels (Bottom Right)

The above acoustical treatments have many similar characteristics. They are all porous, and relatively lightweight. Three of the four products are soft to the touch (the wood fiber panels are rigid), and all resist air flow. This air flow resistance absorbs energy as sound waves attempt to pass through the treatment and reflect off of the wall or ceiling surface behind the acoustical treatment. The combination of being porous and resistant to air flow is important for materials that perform well for absorbing sound. For this reason fibrous materials like fiberglass insulation and cotton can be very effective sound absorbers. Conversely, closed cell foams although soft, are not effective sound absorbers because they are not porous. The do not *resist* air flow, they completely block it.

In addition to evaluating the sound absorption of commercially available treatments, non-standard building materials have also been evaluated. Bosmans' et al (1999) measured the sound absorption coefficients of a multi-layered stretched ceiling using an impervious synthetic PVC membrane. The results from Bosmans' research showed that the absorption coefficients varied significantly with frequency and were most absorptive at the resonant frequency of the system. As expected the resonant frequency and resulting sound absorption changed with increasing and decreasing cavity depths behind the membrane.

McGinnes et al (2005) conducted research on non-standard building materials by testing the absorption coefficients of straw, as an eco-friendly building element. McGinnes concluded that the performance of natural fibers, such as straw can be similar to non-natural fibers, such as fiberglass or rock wool. However, he noted a general trend showing a large reduction in sound absorption of the natural fibers at frequencies below 1,000 Hz. This recent study reinforces the importance and interest of using environmentally friendly acoustical materials.

The absorption coefficients are used to predict the reverberation time within a space, and they offer a key metric for quantifying the acoustics. This assessment of the reverberation time is essential in spaces where the ability to hear and comprehend is important. Sato et al (2008) conducted an objective evaluation of the speech intelligibility within reverberant rooms and found a very strong correlation between listening difficulty/speech intelligibility and the reverberation time.

1.2.3 Environmental Concerns & Green Building Design

In recent years there has been a significant emphasis on green building design. Environmental considerations are often a key design parameter for many new construction buildings and even in building renovations. The establishment of the Leadership in Energy and Environmental Design (LEED) Green Building Rating System has sparked a surge in environmentally friendly building design. The LEED rating system consists of four levels of achievement for sustainability, including Platinum, Gold, Silver, and Certified ratings.

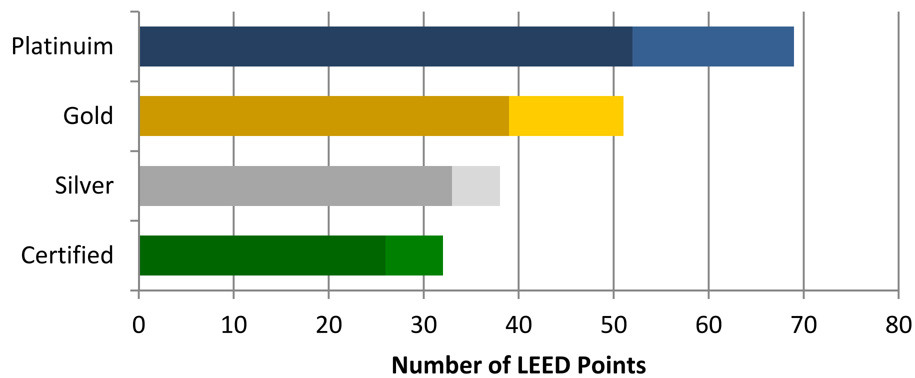


Figure 4. Number of LEED Points Required for Each Level of Certification

The use and implementation of environmentally friendly acoustical treatments can help a building achieve LEED certification. Although a full discussion of the LEED rating system is not part of the scope of this research project, it is important to note the growing LEED presence in architectural design and the direction of the building construction industry's focus on environmentally friendly, reused, and recycled materials.

There are many products that are already commercially available which use recycled materials, many of which are LEED approved products. However, all these products require a significant amount processing and energy consumption to manufacture so that they can be sold as a marketable product. If recycled products are beneficial to the environment and conserving resources, then reused products requiring no manufacturer reprocessing is even better. The mindset of reusing existing products for a second use is going a significant step further than simply using products made from recycled materials. This paper investigates the possibility of one such solution.

1.3 *Acoustics Models*

In its basic form sound is defined as a vibration in an elastic medium (Yerges 1969). Our human perception of sound is usually caused by oscillating pressure of air near our ears. The basic properties of sound waves are governed by the following relationship (Beranek 1988)

$$\lambda = \frac{f}{c} \tag{5}$$

Where λ is the wavelength, f is the frequency, and c is the speed of sound. The speed of sound in air primarily varies with temperature, although the ratio of specific heat at constant pressure to the specific heat at constant volume is also considered. If we assume that air acts like an ideal gas, the follow relationship develops (Beranek 1988),

$$c = 49.03\sqrt{R} \tag{6}$$

where R is the absolute temperature in Rankin. Assuming a standard temperature of 70^{o}F the resulting speed of sound is 1,128 ft/sec (344 m/sec). Based on this calculated speed of sound, the following table lists the wavelengths for various frequencies. It is important to keep in mind the wavelength of sound when evaluating the acoustics within an enclosed space, because for certain room sizes and certain frequencies, the wavelength can be longer than any dimension within the room. For example the wavelength at 16 Hz is 70.5 feet.

Table 2. Wavelengths for Corresponding Frequencies

Speed of Sound	Frequency (Hz)	Wavelength, λ
1,128 ft/sec	16	70.5ft
	31.5	35.8ft
	63	17.9ft
	125	9.0ft
	250	4.5ft
	500	2.3ft
	1,000	1.1ft
	2,000	7in
	4,000	3.4in
	8,000	1.7in
	16,000	0.85in

For a pure sine wave the mathematical representation of the pressure oscillations is expressed by

$$p = A\,sin(2\pi f)t \tag{7}$$

where *t* is time in seconds, *A* is the pressure amplitude, and *p* is the resulting pressure. As mentioned above, the change in sound pressure can be very dynamic from quiet sounds to louds sounds. Therefore, sound pressure is typically stated in terms of a sound pressure level (dB) with a standardized reference sound pressure of 20 μPa (pressure at the threshold of hearing). The following equation describes the relationship between sound pressure (Pa) and sound pressure level (dB). NOTES: Root Mean square (effective pressure) of eq 7 to get eq 8)

$$L_p = 10log_{10}\left(\frac{p}{p_o}\right)^2 = 20log_{10}\left(\frac{p}{p_o}\right) \tag{8}$$

L_p is the sound pressure level (dB), *p* is the sound pressure (Pa), and p_o is the reference sound pressure of 20 μPa.

Knowing that the sound pressure level will vary with distance from the sound source due to spherical spreading and geometric divergence (Harris

1998), the relationship between sound pressure level, L_p, and sound power level, L_w, is governed by:

$$L_p = L_w - 20log_{10}(r) - 0.6 + C \tag{9}$$

where r is the distance to the sound source in feet, and C is a correction term due to the ambient air temperature and pressure. At standard pressure and temperature, $C = 0$. The above equation only considers the direct sound path, L_d, where the direct sound pressure level $L_d = L_p$ in equation 9 However, when sound propagates in an enclosed space, we must also consider the reverberant or reflected sound level, L_r. According to Harris 1998,

$$L_r = L_w - 20log_{10}A + 16.3 \tag{10}$$

where A is the total absorption in Sabins. It is important to note that this relationship is only valid for uniform diffuse sound fields, where L_r is independent of the distance from the sound source. For the research contained in this report the absorption A is pivotal to the understanding of sound absorbing surfaces, so it may be prudent to elaborate on the discussion of the units of Sabin. The Sabin is a quantitative measure of the sound absorbing performance of a particular surface. The sabin is equal to 1 ft^2 of a perfectly absorptive surface. For real surfaces that are not perfectly absorptive, the absorption coefficient, α, is used to describe the sound absorbing performance of that real surface, where

$$\alpha = \frac{absorbed\ acoustic\ energy}{incident\ acoustic\ energy} \tag{11}$$

A surface that has an absorption coefficient of $\alpha = 0.90$ is a surface that absorbs 90% of the energy that is incident upon it. Therefore, the absorption, *A,* in sabins of a surface is determined by:

$$A = \alpha S \tag{12}$$

where S is the surface area in ft^2. For example, a surface that has an area of 100 ft^2 and an absorption coefficient of 0.90 would a total absorption of 90 Sabins.

In order to determine the total sound absorption within a space, we must consider the sound absorption of air, A_{air}, and furnishings, $A_{furnishings}$, in addition to the walls, floor, and ceiling surfaces, $A_{surface}$. The following relationship develops (Harris 1998):

$$A_{Total} = A_{surface} + A_{air} + A_{furnishings} \tag{13}$$

The sound absorption of the furnishings includes tables, chairs, etc. In the case of an auditorium or theater, the seating manufacturers will often provide absorption coefficient data for their products. The data may include empty seats (unoccupied), partially filled seats, or full capacity seating. The absorption of air is frequency dependent, where low frequencies are not absorbed as much as higher frequencies given a specific volume. The absorption of air is also dependent on the relative humidity. A_{air} can be calculated by the relationship:

$$A_{air} = 4mV \tag{14}$$

Where V is the volume of air (ft^3), and m is the air attenuation coefficient per foot or per meter as shown by Kinsler et al (1982)

$$m \cong 5.5 \times 10^{-4} \left(\frac{50}{h}\right)\left(\frac{f}{1000}\right)^{1.7} \tag{15}$$

h is the relative humidity (in percent) between 20% and 70% and f is the frequency between 1.5 and 10 kHz. Values for m can also be found in a chart provided by Harris (1998).

The following three methods have been developed to quantify the relationship between the sound absorption in the room and the reverberation time. The Reverberation Time, T_{60} or RT60, is the time it takes (seconds) for sound to decay 60 decibels after the sound has been turned off. It's a quantitative measure of how acoustically "live" or "dead" the space sounds. A long reverberation time means that there are few sound absorbing surfaces within the room. Conversely, a short reverberation time means that the room has many absorptive surfaces.

In most cases the reverberation time is not simply calculated for the entire audible frequency range as a single value. Instead the audible frequency range is typically divided into many frequency bands, usually octave bands or one-third octave bands ranging from 125 Hz to 4,000 Hz, each with its own reverberation time value. Although the audible frequency range extends below this range (down to 20 Hz) and above (up to 20 kHz), the extremes are ignored from most calculations. Low frequency reverberation times are often difficult to predict because of the longer wavelengths do not allow for a truly diffuse sound field within the room. Higher frequency sound is more easily absorbed by air and other surfaces, and they do not generally significantly aid the evaluation of how a room "sounds".

1.3.1 Sabine Method

Early studies on the effects of reverberant sound energy were conducted by Wallace C. Sabine. The Sabine Method for calculating reverberation time and sound absorption is undoubtedly the most common and most widely used. The Sabine equation was first developed in the last decade of the 19th century. The empirical formula is stated as (Harris 1998):

$$T_{60} = \frac{0.049V}{A} \tag{16}$$

$$T_{60} = \frac{0.049V}{S\alpha} \tag{17}$$

Since there are likely to be many different surfaces and types of finishes (S_i -ft^2) within a space, where each of these surfaces has a different sound absorption performance (α_i), the equation can also be rewritten as:

$$T_{60} = \frac{0.049V}{\sum S_i \, \alpha_i} \tag{18}$$

1.3.2 Eyring Method

The Eyring–Norris Equation differs from the Sabine Equation by using an average sound absorption coefficient, $\bar{\alpha}$, for the entire space versus summing up the product of the absorption coefficient and area for each surface. The resulting equation follows (Eyring 1933):

$$T_{60} = \frac{0.049V}{-S \, ln(1-\bar{\alpha})} \tag{19}$$

1.3.3 Millington-Sette Method

The Millington-Sette Equation is similar to the Sabine equation where the absorption of each surface is summed together using the relationship below. However, as the absorption coefficient approaches unity, the T_{60} goes to zero, which does not actually happen (Beranek 1988). The equation simply does not hold true for highly absorptive surfaces, and is better suited for situations with moderately absorptive finishes, or if the highly absorptive surface can be averaged into larger less absorptive surfaces.

$$T_{60} = \frac{0.049V}{-\sum S_i \;\, ln(1-\alpha_i)} \tag{20}$$

Chapter 2 Test Assembly

2.1 Acoustic Filler

The primary sound absorbing material in the test assembly, the acoustic filler, is comprised entirely of used tee shirts made from 100% cotton. The cotton tee shirts were not altered in any way from their existing condition. No dyes, chemical treatments, or any processing of the tee shirts were used, other than the processing treatments that were used to originally manufacture the tee shirts.

100% cotton tee shirts were selected as the acoustic filler because of the fibrous nature of cotton at its ability to restrict air flow while remaining porous, a desirable material property for high performing sound absorbing products. In addition, the availability of discarded, recycled, and reused cotton clothing is easy to find. For this research, all of the cotton tee shirts were donated by local residents.

Cotton is already used in certain types of acoustical treatment products. Recycled blue jeans are used to make products from exterior wall insulation to surface applied semi-rigid acoustical panels. Although these products already make use of recycled cotton clothing, a considerable amount of energy and resources is required to process the manufactured cotton insulation into the final product. The goal of this research was to take the already environmentally friendly recycled cotton products one step further in conservation by eliminating the manufacturing processes. Eliminating the manufacturing processing not only reduces energy consumption but it also greatly reduces the financial cost of the finished product.

2.2 Outer Wrap

The outer wrap protecting the tee shirts and holding the acoustic filler together was a pair of square shaped sailcloth sewn into “pillowcases.” Sailcloth was selected for the outer wrap for several reasons. Although sailcloth is selected for sailing use because of its stretch resistance (elasticity), tensile strength, creep resistance and the ability to stand up to the ultraviolet solar radiation, for this experiment sailcloth was selected because of porous nature and durability. Sailcloth was also selected as the outer is because discarded sailcloth is relatively easy to find in coastal communities. Boat owners and sailcloth fabricators routinely retire weathered sailcloth that is no longer seaworthy. However this material, in its weathered state, is still in a satisfactory condition for use in the proposed acoustic pillows. Again, the reuse of a product that would normally not have a second life is noteworthy environmental consideration.

Although there are many different types of sailcloth, the most common and most available is Polyester (PET), polyethylene terephthalate, which is made from a thermoplastic polymer resin. Many sailors refer to this type of sailcloth by its brand name, Dacron, which was created in 1950 by Dupont. PET is a very strong fiber that when woven into a fabric mesh is by nature, porous. In fact, some types of PET have a translucent or somewhat transparent appearance. The sound absorption of the sailcloth is assumed to be negligible compared to the sound absorption of the acoustic filler.

2.3 Material Properties

Not all of the sailcloth and tee shirt acoustic pillows were fabricated to exactly the same size. Some pillows were slightly larger than others. However, the average size was approximately 17in x 17in. The average pillow thickness was approximately 2in. The 17in x 17in size was selected for of many reasons including the ease of fabrication and transportation. The size was also selected because its resistance to sag while still allowing the 2in thickness to be maintained. Pillows larger than 17in x 17in tended to sag in the middle, where the tee shirts would gather in the middle. This caused the pillow to be thicker in the middle and thin around the perimeter. Essentially, the larger pillows became too thick and fabrication was more cumbersome. On the other hand, the pillows would end up being too thin if they were made smaller than 17in x 17in. The smaller pillows would also add time to fabrication because the they would require a greater number of pillows be fabricated for the same coverage area as

17inx17in pillows. Although other pillow sizes can still be used effectively, the author recommends a square pillow ranging from no smaller than 14” to no larger than 24” be used.

2.3.1 Acoustic Filler Properties

Cotton is a desirable clothing textile because it is lightweight and breathable. It is composed primarily of cellulose, possibly the most common organic compound found on earth. Also in cotton are trace amounts of Protoplasm, waxes, mineral salts, and water.

The tee shirts used in this research came in a variety of different sizes, weights, and densities. The average density of the acoustic filler was calculated to be approximately 9.4 lb/ft^3 based on an average filler weight of 2.9 lb per pillow (excluding the weight of the sailcloth) and an estimated volume of approximately 0.31 ft^3 per pillow. The stated density should be considered an average density since not all tee shirts are manufactured with the same fabric weight and density. In addition, the air gaps within the folds of the tee shirts that are stuffed inside of the pillowcase create and inherently inhomogeneous material. This average density is slightly higher than the density of most commercially available acoustical treatment products. By comparison, the typical fabric-wrapped fiberglass wall panel has a core density of 5 to 7 lb/ft^3. The manufactured cotton panels typically have a core density in the range of 3 to 6 lb/ft^3.

2.3.2 Outer Wrap Properties

The properties of PET sailcloth used in this research have not been verified, since the origin of the donated sailcloth is unknown. However, the area density of the PET sailcloth was measured to be approximately 7oz/yd^2, which is slightly heavier than the expected material area density of 5 oz/yd^2 . The sailcloth used for this experiment was somewhat heavier and thicker than ideal conditions. PET has a tensile strength of 55 to 75 MPa.

2.4 Fabrication of the Tested Assembly

After obtaining all of the materials, mostly donated tee shirts and sailcloth, the process begins by cutting the sailcloth into the desired size and shape, in this case 17in x 17in squares. The square pieces of sailcloth were paired and sewn together on three sides to create a pillowcase. The remaining side was left open for stuffing with tee shirts. The tee shirts were carefully stuffed into the sailcloth pillowcases. Approximately 6 to 8 tee shirts were stuffed into each pillowcase, depending on the tee shirt size and material weight. Attention was given to evenly distribute the cotton tee shirts inside of the pillowcase. After stuffing the pillowcases, the last seam was taped with packaging tape to seal the contents inside.

Figure 5. Sailcloth Pillowcase Being Filled with Tee shirts

Figure 6. Finished Acoustic Pillow Profile

Figure 7. Finished Acoustic Pillow Plan View

The thickness of the finished product is critical to the sound absorbing performance. In general thinner products tend to be less effective for absorbing low frequency sound compared to thicker products. Lower frequencies have a longer wavelength, which means the ¼ wavelength is further away from the sound absorbing surface. The ¼ wavelength is the position on the wave that has the greatest displacement. Therefore, the more the sound absorbing product can interfere with the ¼ wavelength (i.e. resist the displacement), the better the treatment will be for absorbing sound. Hence a 4” thick acoustical wall panel will generally be more effective than a 1” thick acoustical wall panel for absorbing low frequency noise.

Chapter 3 Test Setup, Methods, and Procedures

3.1 Test Equipment & Setup

3.1.1 Reverberant Room Test Chamber

Figure 8. Test Chamber

The goal of a Reverberation Room is to create a diffuse sound field under steady state conditions (when the sound source is turned on), and also during transient conditions during the sound decay (when the sound source is turned off). A Reverberation Room laboratory was not available for conducting this research; therefore, acoustical measurements were conducted under “field conditions” inside of a racquetball court. The acoustical measurements were conducted in general accordance with ASTM C423-07a, which is discussed in detail in the sections below. Annex X2 of this standard describes the test procedure for conducting the desired acoustical measurements under “field” conditions, when a laboratory is not available or not practical. Although the testing methods and procedures for the field conditions were used, the author attempted to emulate the laboratory conditions as much as possible. A racquetball court was chosen as the reverberant room test chamber because it is a highly reverberant space. Although a racquetball court does not meet all of the qualifications for a laboratory test facility per the requirements in ASTM C423-07a, it is still a highly reverberant space. The racquetball court was constructed with sealed tile flooring and high density composite panels on the ceiling and walls. Parts of the rear and side walls were constructed with a combination of composite panels and glass panels.

Since the acoustical measurements were conducted in field conditions, following the conditions outlined in Annex X2 of ASTM C423-07a, it is important to note the deviations of the field test chamber compared to an ideal laboratory reverberant test chamber. The primary deviations are the room air volume and associating room dimensions, which are discussed below.

3.1.1.1 Room Air Volume

The dimensions of a racquetball court had a room air volume of 16,000 ft^3 (450 m^3), which is above the recommend air volume of 200 m^3 per Section 7.3 of ASTM Standard Designation C 423-07a, but it satisfies the minimum size requirement of 125 m^3. The larger than ideal room size means that there will be more air absorption than in a smaller room.

3.1.1.2 Room Dimensions

ASTM Standard Designation C 423-07a, Section 7.3 *Size and Shape,* also states “No two room dimensions shall be equal nor shall the ratio of the largest to the smallest dimension be greater than 2:1.” The requirement aims at reducing the possibility of standing waves within the space, which have an easier time forming when the room has a lot of symmetry. Unfortunately, the racquetball court has a lot of symmetry. The dimensions of the racquetball court were 20 feet (W) x 40 feet (L) x 20 feet (H), standard regulation court dimensions. Therefore, the room width and room height are the same dimension. In addition, the room length is exactly two times the other two dimensions, which is not ideal. The scope of this research was not to compare the effectiveness of field conditions versus laboratory conditions, but it is important to note these deviations. The presence of standing waves within the racquetball court could not be ruled out.

3.1.1.3 Sound Diffusion

Under ideal conditions, the reverberant room would be perfectly diffuse. Section 7.4.1 of ASTM c423-07a discusses the use of sound reflective panels hung throughout the room with random orientations. The standard also discusses the possibility of incorporating diffusive panels on a rotating shaft. Since the test chamber used to conduct this research was not a laboratory and had other uses, these diffusive treatments were not incorporated into the field test chamber.

3.1.2 Measurement Equipment

The acoustic measurements were conducted using a sound source to generate the audio signal, a pair of amplified loudspeakers to create a full sound field within the test chamber, and a sound level meter to record the data. The sound source used for the experiment was an Apple iPhone with pink noise WAV file saved as an audio track. The iPhone was connected to a pair of powered loudspeakers. The loudspeakers were placed in opposite corners of the test chamber with a random aiming angle. The handheld sound level meter was a Model 824 along with a Model 2541 random incidence microphone and Model 902 microphone preamp, all manufactured by Larson Davis. The sound level meter, preamp, and microphone are certified Type I equipment per American National Standards Institute (ANSI) S1.4, *Specification for Sound Level Meters*. A summary of the measurement equipment can be found in Table 3 below.

Table 3. Measurement Equipment

Equipment	Manufacturer	Model #
Sound Level Meter	Larson Davis	824
Microphone	Larson Davis	2541
Microphone Preamp	Larson Davis	902
Acoustic Calibrator	Larson Davis	CAL 200
Sound Source / Pink Noise Generator	Apple	iPhone 3Gs
Powered Loudspeakers (pair)	QSC	K-10

Figure 9. Sound Level Meter, Microphone, Calibrator, and Windscreen

Figure 10. Powered Loudspeakers and iPhone Sound Source

3.2 Test Methods & Procedures

The test method was in general accordance with ASTM C423-07a, *Standard Test Method for Sound Absorption and Sound Absorption Coefficients by the Reverberation Room Method*.

3.2.1 Test Assembly Mounting and Placement

The test assembly, as described above, was arranged on the floor of the test chamber in a diamond shaped pattern with the overall dimensions shown in the drawing of the test assembly below. The total area of the test assembly was 63 ft^2 (5.9 m^2). The test assembly was rotated such that the no edge of the assembly was parallel to any wall surface, as specified in Section 9.1.3 of ASTM C423-07a. Also as described in the same section, the test assembly was not placed in the center of the room. Instead, the test assembly was positioned slightly to the off-center in both length and width. See the figure below for a photograph of the test assembly placement. Type A mounting was used for the measurements. Type A mounting is positioning the test assembly immediately against the surface with no air cavity between the floor surface and the test assembly.

Figure 11. Test Assembly Mounting and Position Photograph

A drawing of the test assembly placement is shown in the figure below. The dimensions shown from the front and side walls of the racquetball court are to the approximate center of the test assembly.

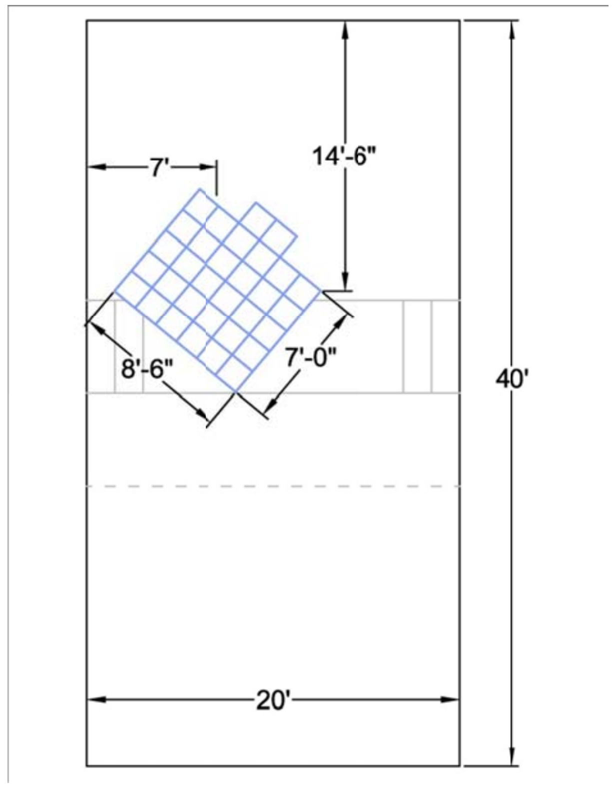


Figure 12. Test Assembly Mounting and Position Drawing

3.2.2 Ambient Noise and Signal-to-Noise Ratio

Background ambient noise was measured in the test chamber to document the noise floor with the room empty. The goal was to have at least 45 dB of signal to noise ratio for accurate test results. For these measurements a 60 second microphone sweep was used to get a temporal and spatial average of the space. The 60 second measurement was taken with the sound source turned on and with the sound source turned off (background ambient noise). The sound level meter was set to a “slow” response, and the Equivalent Sound Level, L_{eq}, was recorded.

3.2.3 Measuring Decay Rate

For all recorded measurements, data was collected in one-third octave bands, as defined and specified in ANSI S1.11. The frequency range used for this experiment included the 100 Hz frequency band up through the 5,000 Hz frequency band. The decay rate measurements were recorded using the Real Time Analyzer setting in the sound level meter. Sound pressure levels were recorded continuously in each one-third octave band with a time interval and integration of 20 ms (using linear averaging). Although Section 8.4.1 of ASTM C423-07a requires only a maximum time interval of 50 ms, a faster time interval was desired to increase the number of data points and smooth the resulting time history plots.

The sound signal used in the measurements was pink noise (equal acoustic energy at each frequency band), as generated from a WAV file audio test track. For each measurement the sound source was turned on for several seconds in order to fill the room with a steady state sound field. The sound source was then turned off and the time history of the decay was recorded. Four microphone position locations were selected and random, and such that each position was at least 1m away from any other position or any reflective surface, as required by Section X2.4.3 of ASTM C423-07a. Five decays were collected at each of the four microphone positions for a total of 20 decays, as per Section X2.4.4 of ASTM C423-07a.

A complete set of decays was collected first with the room empty, and then with the test assembly installed.   The sound level meter was calibrated before and after the measurements with a Larson Davis CAL 200 acoustic calibrator with a 1 kHz sine tone at 114 dB.

Figure 13. Test Procedure with Sound Source, Sound Level Meter, and Loudspeaker

3.3 Case Study: Supplemental Test of Existing King Intermediate School Gymnasium Reverberation Time

Although the natural acoustics in the King Intermediate School Gymnasium was described as “very poor”, no quantitative evaluations had been conducted within the space in the many decades since the building was constructed. In recent years an upgraded sound reinforcement system was added to the Gymnasium in hopes of improving the speech and music intelligibility. However, the new sound system did very little to solve the poor acoustics problem in the Gym. Therefore, in 2007 when discussions first began with the school regarding the acoustics within the gymnasium, a set of acoustical measurements was conducted to assess the existing conditions. This assessment was the first step in the solution process, and it was important for defining the magnitude of the problem.

Reverberation time was measured in the existing gym, as described in ASTM E2235-04. The test equipment setup, procedure, and methodology for measuring the reverberation time in the gym is very similar to the racquetball court measurements described above. However, the primary difference between the two test methods is that ASTM E2235-04 simply stops at the reverberation time data collection, and is often used in conjunction with other sound insulation measurements within buildings. The primary goal of ASTM C423-07a is to attain the sound absorption and sound absorption coefficients of a test sample. However, the two standards are very closely related and the methodologies are virtually identical. Four microphone measurements positions were uses, with five decays at each microphone position for a total of 20 decays.

Chapter 4 Test Results

Using the test methods and procedures outlined above, a measure of the sound level as a function of time was collected for analysis. The time history of these measurements was used to calculate the Reverberation Time, T_{60}, at each one-third octave band. A comparison of the T_{60} data for the empty room and for the same room with the test sample installed is the link for determining the sound absorption performance of the test sample. Knowing the area of the test sample allows the absorption coefficients to be calculated.

Prior to conducting the measurements the ambient background noise was compared to the sound level with the sound source activated. The ambient sound level was measured in A-weighted decibels at 48 dBA. With the sound level turned on, the measured sound level increased to 100 dBA, a difference of 52 dB, which exceeds the signal-to-noise ratio goal of 45 dB.

4.1 Time History Plots

4.1.1 Empty Room

The figure below shows an example of the time history output plots from the sound level meter. Although not specified in the figure, the x-axis is time (sec) and the y-axis is sound pressure level (dB re: 20 μPa). The plot shown in Figure 14. Time History Plot at 400 Hz for an Empty Room (1 of 20 decays)Figure 14 is for the measurement taken at 400 Hz for 1 of the 20 decays in the empty test chamber.

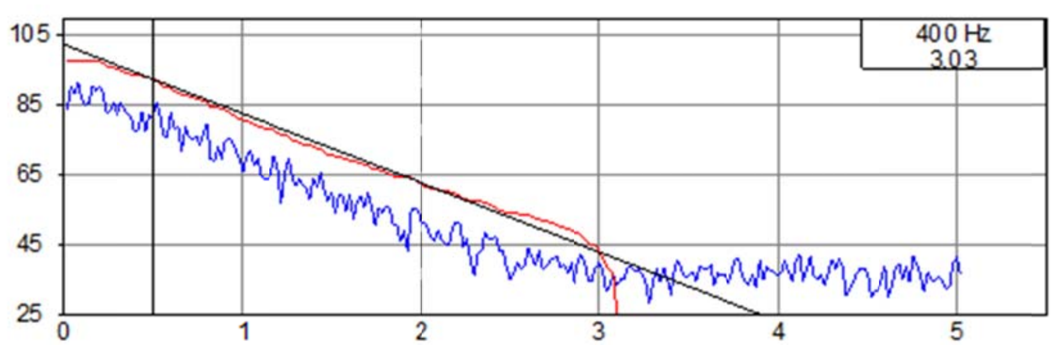


Figure 14. Time History Plot at 400 Hz for an Empty Room (1 of 20 decays)

As a supplement to this graph, the following figure shows the time history plots for all of the one-third octave bands during 1 of the 20 decays.

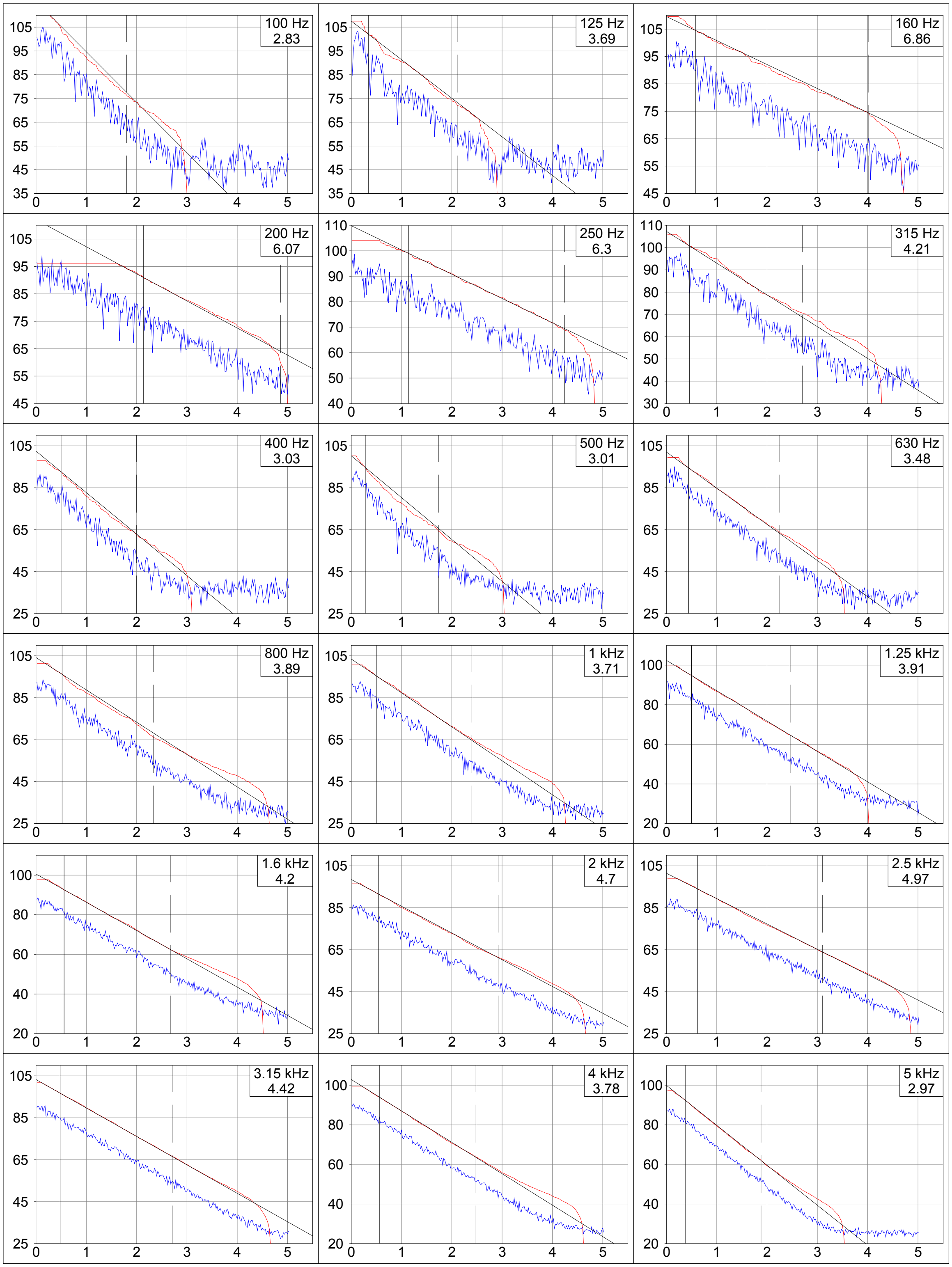


Figure 15. Time History Plot at all one-third octave bands for an Empty Room (1 of 20 decays)

4.1.2 Room with the Test Sample

The same set of measurements was conducted with the test sample installed in the room. Again, a total of 20 decays were recorded, 4 decays at each of 5 microphone positions. The plot shown in Figure 16Figure 14. Time History Plot at 400 Hz for an Empty Room (1 of 20 decays) is for the measurement taken at 400 Hz for 1 of the 20 decays with the test sample installed in the room.

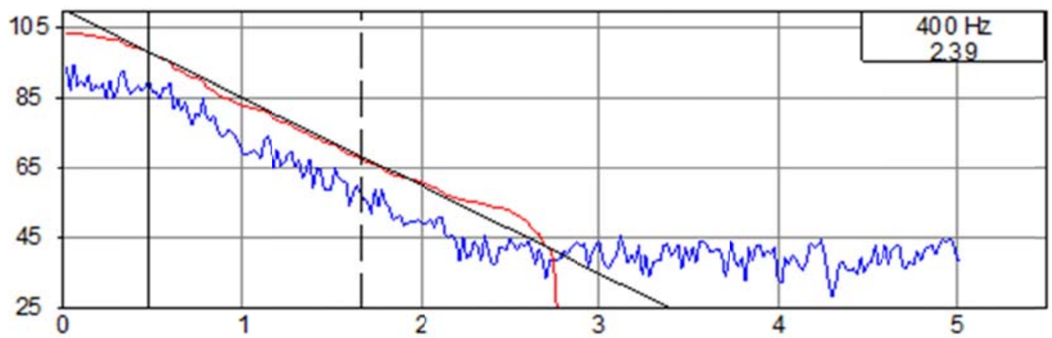


Figure 16. Time History Plot at 400 Hz for the Test Sample (1 of 20 decays)

As expected, the time history plots show a steeper slope for the measurements taken with the test sample. This result indicates a faster reverberation time, which means there is more absorption in the room, compared to the empty room. At a minimum, the data is trending in the right direction simply by looking at the time history plots. It is also important to take note of the comparison of the high frequency time history plots to the low frequency plots. The higher frequency curves are generally smoother than their low frequency counterparts. This result is typical for these measurements and is expected. Since higher frequency sound waves have a much shorter wavelength, the diffuse sound field is easy to establish. The smooth plots indicate that there are many sound waves incident on the microphone at many angles. Conversely at low frequencies, the wavelength is much longer and the sound field is naturally less diffuse because of these long wavelengths. Compounding this problem with the long wavelengths is the fact that the room is symmetrical with parallel reflective surfaces, a non-ideal condition that can create standing waves (not desirable). The figure below shows all of the one-third octave band results for 1 of the 20 decays with the test sample.

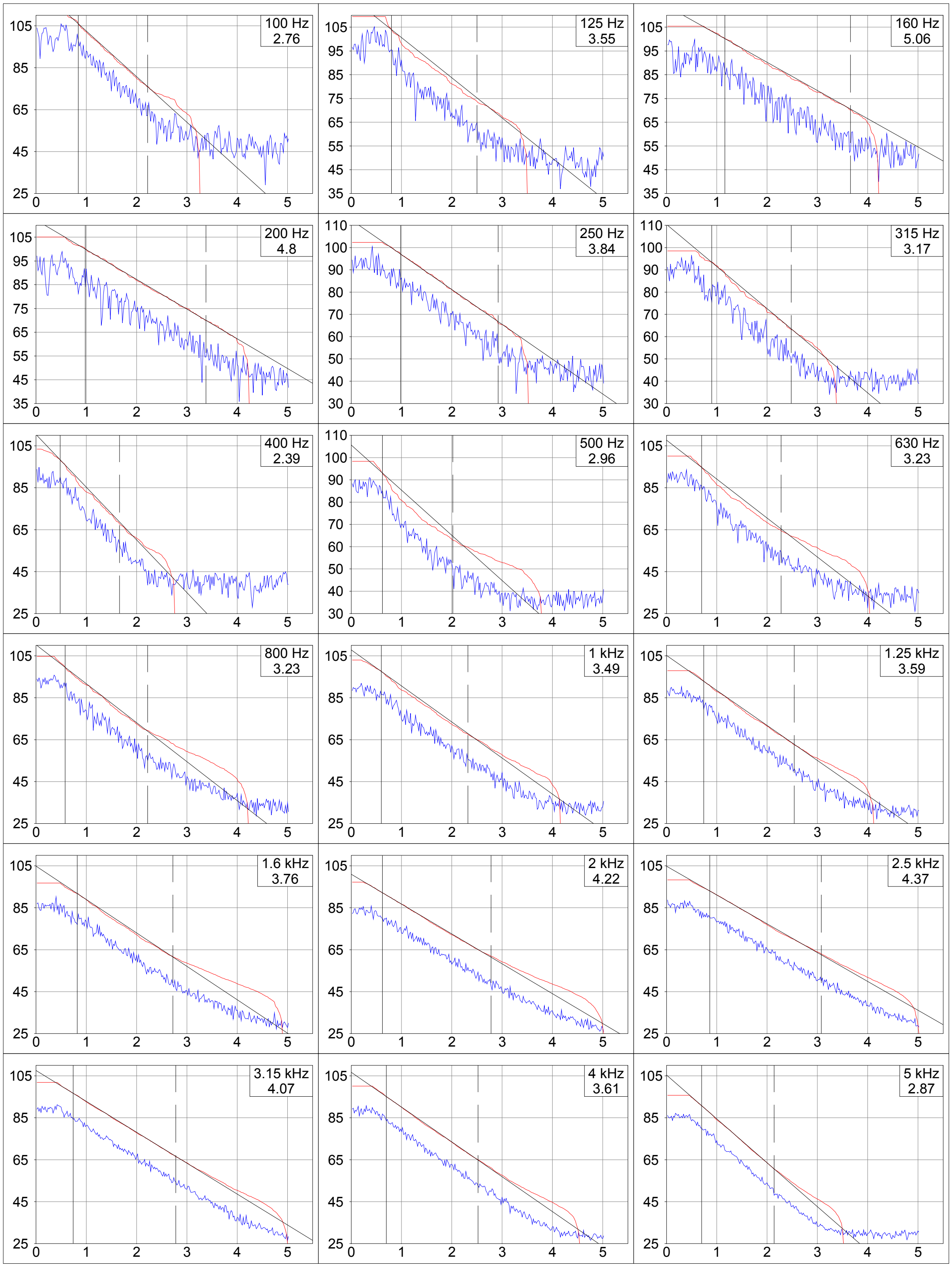


Figure 17. Time History Plot at all one-third octave bands for the Test Sample (1 of 20 decays)

4.2 Reverberation Time, T_{60}

As defined above, the T_{60} is the time it takes for sound to decay 60 decibels after the sound has been turned off. For the decay rate measurements, the T_{60} was obtained using the Standard Schroeder backward integration calculation settings within the sound level meter. The start offset was set to 5 dB and the dynamic range was set to 30 dB. The figure below shows a result of the T_{60} measurements for all 20 decays. The results indicate consistent data at high frequencies, but less agreement at low frequencies. This result is expected for the reasons stated above regarding diffuse sound fields.

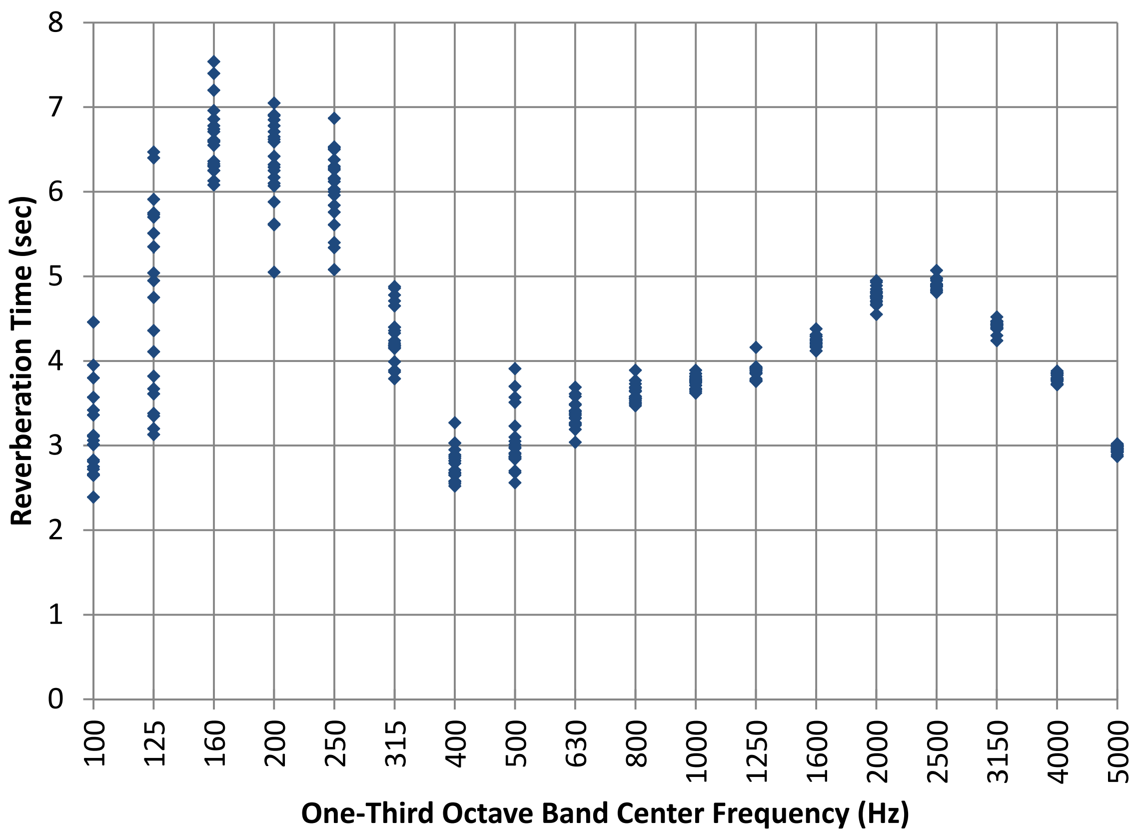


Figure 18. Reverberation Time for all 20 decays in the Empty Room

The results for the room with the test sample show similar trends with excellent agreement at high frequencies and less consistency at low frequencies.

The figure below shows the results from all 20 decays for the room with the test sample.

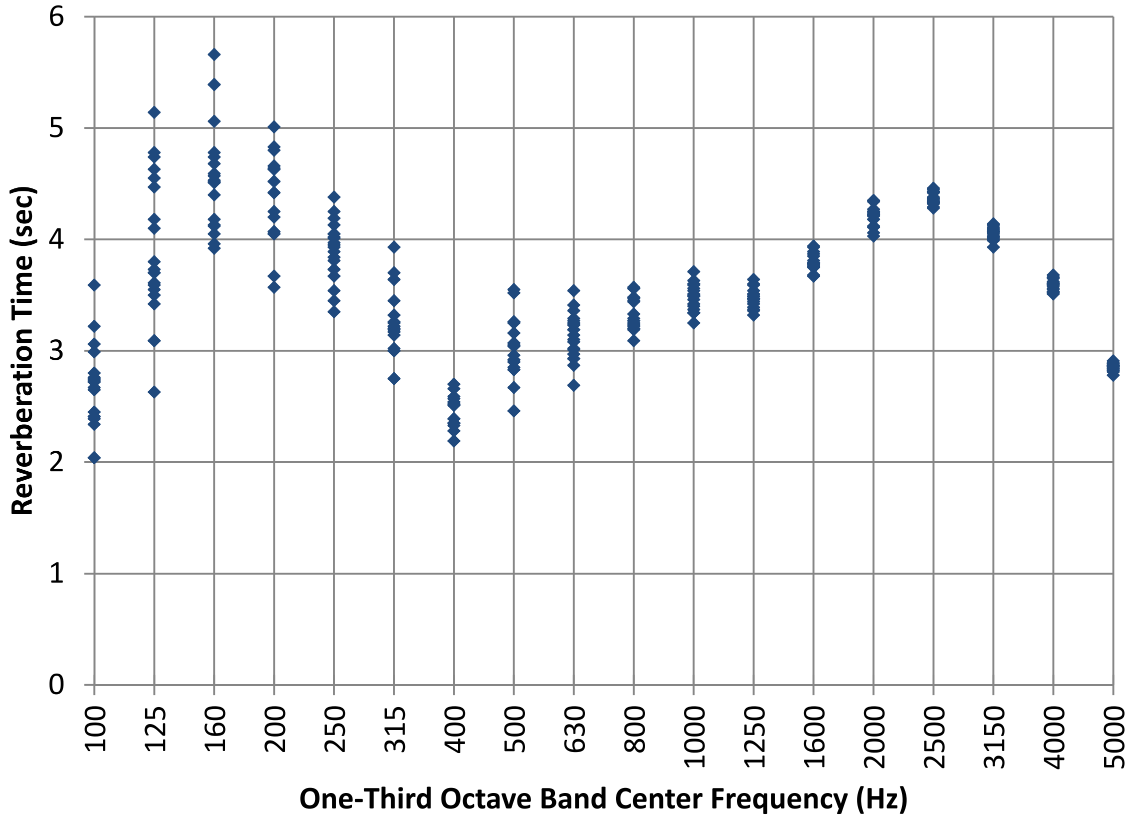


Figure 19. Reverberation Time for all 20 decays in the Room with the Test Sample

For both test conditions (empty room and test sample), the 20 decays were linearly averaged. The figure below shows a comparison of the averaged T_{60} measurements with the empty room to the measurements with the test sample. Immediately noticeable is the large difference between these two curves at the lower frequencies. This difference hints at an elevated sound absorption performance at these frequencies.

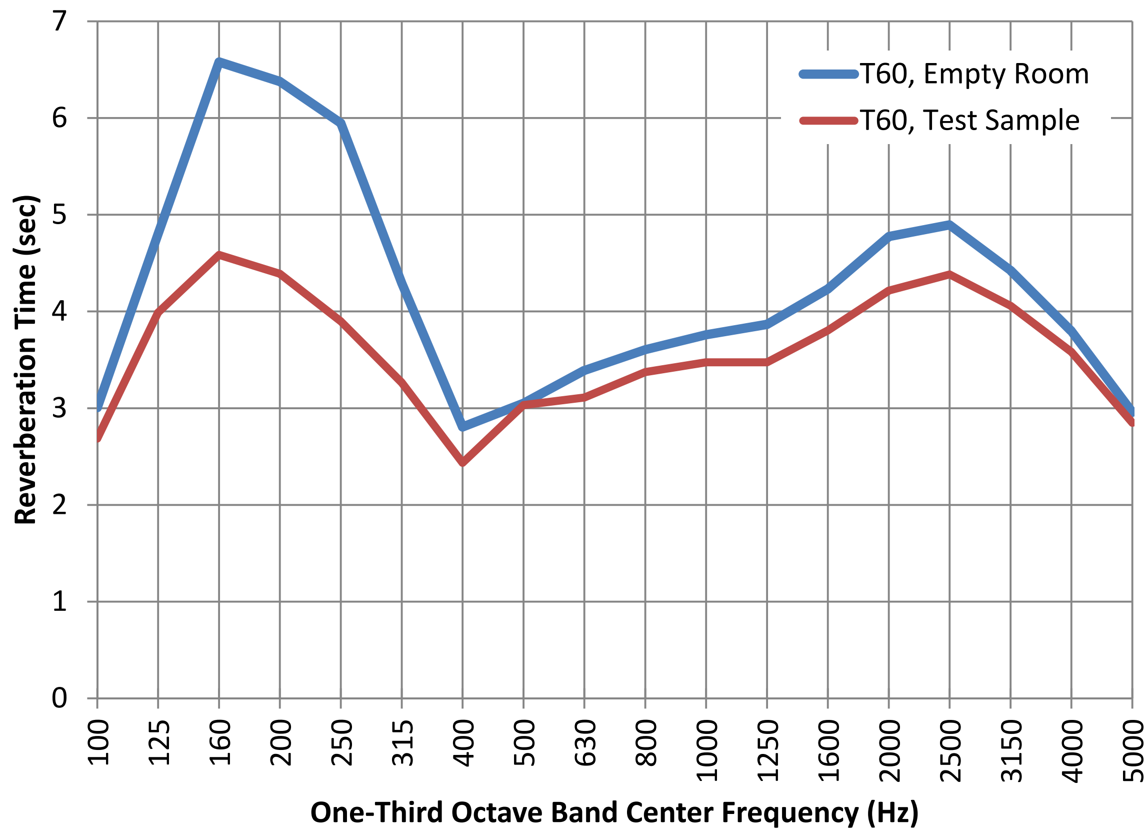


Figure 20. Averaged T_{60} Comparison for the Empty Room and Test Sample

Also apparent in this graph is the unexpectedly low performance at the 500 Hz frequency band. The two curves appear nearly identical at this frequency, which implies that the test sample did not reduce the reverberation time. The table below numerically compares these two curves.

Table 4. Averaged T_{60} Measurement Results

	One-Third Octave Band Center Frequency (Hz)																	
	100	**125**	**160**	**200**	**250**	**315**	**400**	**500**	**630**	**800**	**1000**	**1250**	**1600**	**2000**	**2500**	**3150**	**4000**	**5000**
T60 (sec) Empty Room	3.01	4.80	6.58	6.38	5.95	4.29	2.81	3.05	3.39	3.61	3.76	3.87	4.23	4.77	4.89	4.43	3.80	2.96
T60 (sec) Test Sample	2.68	3.99	4.58	4.39	3.90	3.26	2.44	3.03	3.11	3.37	3.47	3.47	3.80	4.22	4.38	4.06	3.58	2.85

4.3 Absorption Coefficients, α

Determining the absorption coefficients of the test sample is the primary objective of this research. Recalling equation 16 from above, the Sabine equation states the following, which can be rewritten in terms of the absorption, *A*.

$$T_{60} = \frac{0.049V}{A} \tag{21}$$

$$A = \frac{0.049V}{T_{60}} \tag{22}$$

The absorption can be calculated for both the empty room and for the room with the test sample using equation 22. The difference between the empty room and the room with the test sample is the change in absorption added by the test sample where,

$$A_{change} = A_{room\ with\ sample} - A_{empty\ room} = A_{sample} \tag{23}$$

$$A_{sample} = \left(\frac{0.049V}{T_{60}}\right)_{room\ with\ sample} - \left(\frac{0.049V}{T_{60}}\right)_{empty\ room} \tag{24}$$

The volume of the room, V, is a constant, so the change in the absorption is solely based on the change in reverberation time between the two conditions. The table below shows the absorption in Sabins for the empty room and for the room with the test sample at each one-third octave band. The difference between the empty room and test sample is also shown in the table.

Table 5. Total Absorption for the Empty Room and Test Sample

	One-Third Octave Band Center Frequency (Hz)																	
	100	125	160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150	4000	5000
Empty Room (Sabins)	261	163	119	123	132	183	279	257	231	217	209	203	185	164	160	177	206	265
Test Sample (Sabins)	292	197	171	179	201	240	322	259	252	232	226	226	206	186	179	193	219	275
Difference (Sabins)	31	33	52	56	69	57	43	2	21	15	17	23	21	22	19	16	12	10

The next and final step is to calculate the absorption coefficients. Recalling equation 12 from above, and rewriting in terms of the absorption coefficient, *α*, the following relationship develops:

$$A = \alpha S \tag{25}$$

$$\alpha_{sample} = \frac{A_{sample}}{S_{sample}} \tag{26}$$

The area of the sample, *S,* was calculated from the field dimensions at 63 ft^2. The resulting absorption coefficients are shown in the table below.

Table 6. One-Third Octave Band Absorption Coefficients of the Test Assembly

	One-Third Octave Band Center Frequency (Hz)																	
	100	125	160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150	4000	5000
Test Sample Absorption Coefficient, α	0.50	0.53	0.82	0.88	1.10	0.91	0.67	0.02	0.33	0.24	0.27	0.36	0.33	0.35	0.30	0.25	0.20	0.16
Test Sample Area (sq ft)								63										

Absorption coefficients are frequently used in octave bands versus one-third octave bands for calculations of reverberation times within a space. Therefore, the above one-third octave band absorption coefficients were translated to octave band absorption coefficients using a logarithmic average calculation. The three one-third octave bands were logarithmically averaged in order to obtain the octave band absorption coefficients. For example, the 100 Hz, 125 Hz, and 160 Hz one-third octave band values were averaged to obtain the 125 Hz octave band value. The following relationship was used for these calculations (Beranek 1988):

$$Average = 10^{\frac{\sum Log(x)}{n}} \tag{27}$$

$$\propto_{125Hz\ Octave} = 10^{\frac{Log(\propto_{100\ Hz})+Log(\propto_{125\ Hz})+Log(\propto_{160\ Hz})}{3}} \tag{28}$$

The following table shows the resulting octave band absorption coefficients, which are also graphed in the figure below.

Table 7. Octave Band Absorption Coefficients of the Test Assembly

	Octave Band Center Frequency (Hz)					
	125	250	500	1000	2000	4000
Test Sample Absorption Coefficient, α	0.60	0.96	0.18	0.29	0.32	0.20
Test Sample Area (sq ft)			63			

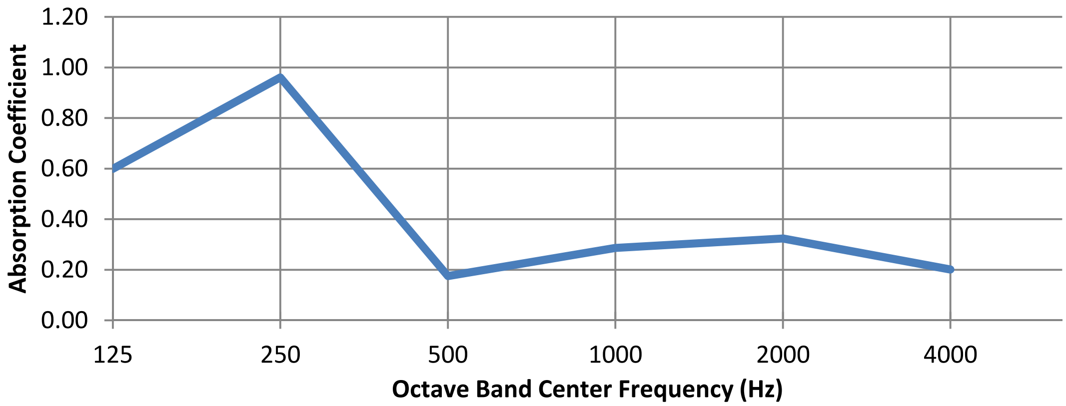


Figure 21. Graph of Octave Band Absorption Coefficients of Test Assembly

4.4 Data Analysis

4.4.1 Comparison of the Test Assembly to Commercial Products

Although the acoustical performance at high frequencies is less than the author had hoped, the low frequency performance is impressive and higher than expected. The peak absorption at the 250 Hz frequency band is not common, especially for acoustical treatments that are only 2 inches thick. As mentioned earlier, the thickness of the acoustical treatment will have a significant impact on the low frequency sound absorption performance of a particular material. Essentially, the thicker the material, the better for absorbing low frequency sound. Therefore, it is useful to compare the performance of the test assembly to other products that also have a product thickness of 2 inches. The following table includes the octave band absorption coefficients for several products.

Product information can be found in the associated website links. Although there are many other types of acoustical products available in the commercial market, these four options are very common products, and they have similar uses and applications.

A. K-13 by International Cellulose
   www.internationalcellulose.com
B. Interior Wall Panels by Tectum, Inc.
   www.tectum.com
C. AP Acoustical Panels by Decoustics
   www.decoustics.com
D. Echo Eliminator by Acoustical Surfaces, Inc.
   www.acousticalsurfaces.com

Table 8. Direct Comparison of Test Assembly to other Common 2" Acoustical Treatments

	Absorption Coefficients					
	Octave Band Center Frequency					
	125	**250**	**500**	**1000**	**2000**	**4000**
2" thick Test Assembly	0.60	0.96	0.18	0.29	0.32	0.20
(A) 2" K-13 Cellulose Spray-on	0.26	0.68	1.05	1.10	1.03	0.98
(B) 2" Tectum Wood Fiber Panels	0.15	0.26	0.62	0.94	0.62	0.92
(C) 2" Decoustics Fabric Fiberglass Panels	0.23	0.81	1.01	1.13	1.10	1.03
(D) 2" Processed Cotton Panels	0.35	0.94	1.32	1.22	1.06	1.03

The test assembly shows superior low frequency sound absorption compared to all of the above common acoustical treatment options. However, at higher frequencies the test assembly is significantly less absorptive. Ideally, the treatment would be perfectly absorptive at all frequencies, but there are several advantages to a product that is better performing at particular frequency bands, especially low frequency bands. In general, high frequency sounds are easier to absorb than low frequencies because the wavelength is much shorter. Because of the difficulty in absorbing low frequency sound, the improper application of thin acoustical products can often “unbalance” the room. This phenomenon happens when the surfaces in a room are effective for absorbing high frequency sounds, but not very effective for absorbing low frequency sounds. The resulting room will sound “boomy”, with low frequency sounds that have many reflections within the space before they die away. On the other hand, high frequency sounds may be easily absorbed in the room and quickly die away. This type of condition will be acoustical “live” at low frequencies with a long reverberation time, and “dead” at high frequencies with a short reverberation time. The unbalanced room is typically not desired.

These unbalanced rooms are very common. For example, many high school and middle school music rooms are acoustically unbalanced. These rehearsal spaces often incorporate some type of acoustical treatment for the walls and/or ceiling. However, they often also incorporate carpet floors. Although carpet flooring can absorb sound, it usually only absorbs high frequency sounds, especially the thin pile carpet that is commonly used in these spaces. Therefore, the carpet flooring naturally tends to unbalance the acoustics in these spaces creating a “boomy” sounding room. The tee shirt and sailcloth test assembly can aid the acoustics in this type of space by targeting the frequencies that are most challenging to absorb.

Of course there are commercially available products that are marketed to absorb low frequency sounds and not high frequency sounds. One example is the Low Frequency Tuner (LFT) by Decoustics. A comparison of this product to the test assembly is shown in the table below. The comparison shows overlapping performance which can easily be seen in the figure below.

Table 9. Direct Comparison of Test Assembly to Decoustics Low Frequency Tuner (LFT) Panel

	Absorption Coefficients					
	Octave Band Center Frequency					
	125	250	500	1000	2000	4000
2" thick Test Assembly	0.60	0.96	0.18	0.29	0.32	0.20
2” Decoustics LFT Panel	0.36	1.07	0.76	0.24	0.07	0.08

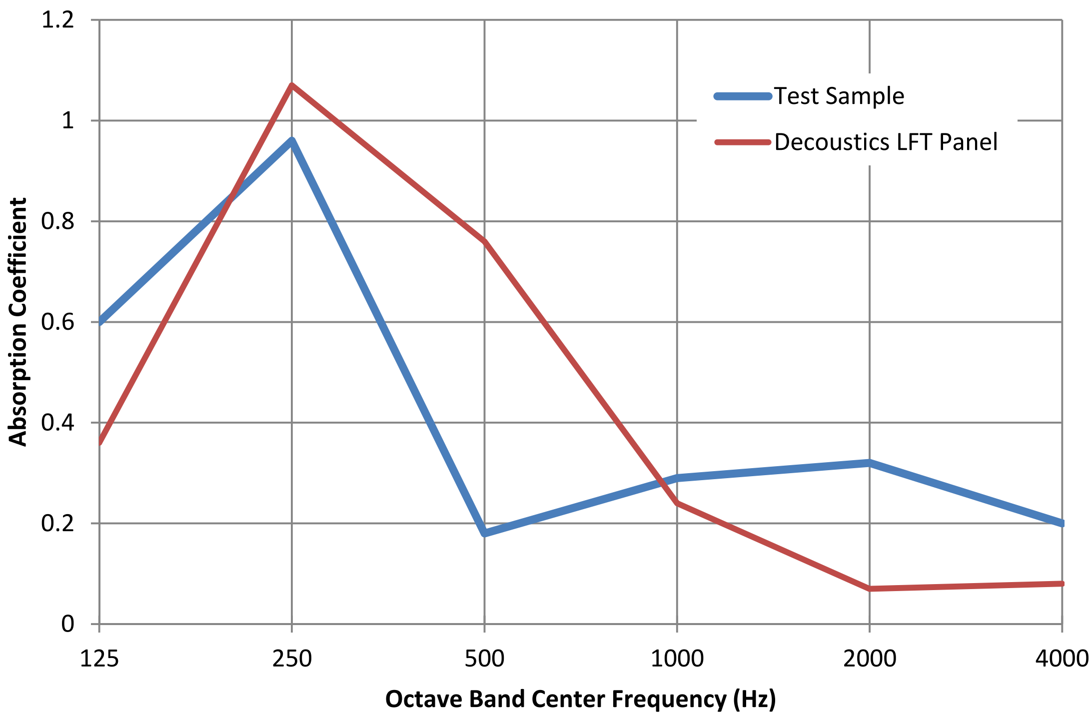


Figure 22. Graph of Absorption Coefficients of Test Assembly and Decoustics LFT Panel

It is important to note the composition of the Decoustics LFT panel because it helps with the understanding of the acoustical performance of the test assembly. The LFT panel has an absorptive fiberglass core with a density of 6 to 7 lb/ft^3, which is the standard density for most fiberglass core acoustical products. The unique feature that makes the LFT absorb low frequency sounds but reflect high frequency sounds is the rigid membrane that is placed over the absorptive core. This membrane acts somewhat like a drum head. Because the membrane is thin, low frequency sounds can pass through it and get absorbed by the fiberglass core behind the membrane. High frequency sounds, on the other hand, never reach the core because they reflect off of the membrane. The high frequency sounds have a wavelength that is too short to pass through the membrane surface.

Since the acoustical performance of the tee shirt and sailcloth test assembly is more similar to a low frequency absorber than a standard acoustical panel, the outer sailcloth wrap may not be acoustically transparent, as originally anticipated. Upon reevaluation of the sailcloth wrap, the sailcloth used to fabricate the test assembly was from a main sail of the boat. The main sail is generally made with the strongest sailcloth fabric that is reinforced with cross stitching and double layering in some areas. This thicker sailcloth was somewhat rigid, and although slightly porous, was likely acoustically transparent at low frequencies only. Based on the measurement results, some high frequencies were absorbed, but there was a substantial amount of high frequency sound that reflected off of the sailcloth and was not absorbed.

Although the performance of the test assembly being similar to a low frequency absorber was not anticipated at the start of the research, the result is intriguing and can be seen as an advantageous attribute. As mentioned above, there are commercially available low frequency absorbing products, but they are not particularly common and the selection of available products is slim.

Manufactured acoustical products are not the only surfaces that absorb sound. In fact all surfaces absorb sound, albeit very minimally for some surfaces. Therefore, in order to predict the reverberation time with the space, the sound absorption of all surfaces must be included in the calculation, not just the acoustical products.

The table below shows a small sample of the absorption coefficients for some common building elements and room finishes. There are a variety of sources which can be referenced for obtaining the absorption coefficients of these common elements.

Table 10. Absorption Coefficients for Common Building Materials (Harris 1998)

TABLE 30.1 Sound Absorption Coefficients of Construction Materials

	Sound absorption coefficients					
	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
Ballast or other crushed stone:						
3.18 cm (1 ¼ in) screened ballast 15.2 cm (6 in) deep	0.19	0.23	0.43	0.37	0.58	0.62
3.18 cm (1 ¼ in) 30.5 cm (12 in) deep	0.27	0.58	0.48	0.54	0.73	0.63
3.18 cm (1 ¼ in) 45.7 cm (18 in) deep	0.41	0.53	0.64	0.84	0.91	0.63
0.64 cm (¼ in) or less granite aggregate 15.2 cm (6 in) deep	0.22	0.64	0.70	0.79	0.88	0.72
Brick, unglazed	0.03	0.03	0.03	0.04	0.0	0.07
Brick, unglazed, painted	0.01	0.01	0.02	0.02	0.02	0.03
Carpet, heavy:						
On concrete	0.02	0.06	0.14	0.37	0.60	0.65
On 1350 g/m² (40 oz/yd²) hairfelt or foam rubber	0.08	0.24	0.57	0.69	0.71	0.73
With impermeable latex backing on 1350 g/m² (40 oz/yd²) hairfelt or foam rubber	0.08	0.27	0.39	0.34	0.48	0.63
Concrete block, coarse	0.36	0.44	0.31	0.29	0.39	0.25
Concrete block, painted	0.10	0.05	0.06	0.07	0.09	0.08
Drapes (also see Figs. 30.15–30.17):						
Light velour 338 g/m² (10 oz/yd²) hung straight, in contact with wall	0.03	0.04	0.11	0.17	0.24	0.35
Medium velour, 475 g/m² (14 oz/yd²) draped to half area	0.07	0.31	0.49	0.75	0.70	0.60
Heavy velour, 610 g/m² (18 oz/yd²) draped to half area	0.14	0.35	0.55	0.72	0.70	0.65
Fiberglass boards and blankets:						
2.54-cm (1-in) glass wool, 24 kg to 48 kg/m³ (1.5 to 3.0 lb/ft³)	0.08	0.25	0.65	0.85	0.80	0.75
5.1-cm (2-in) glass wool, 24 kg to 48 kg/m³ (1.5 to 3.0 lb/ft³)	0.17	0.55	0.80	0.90	0.85	0.80
2.54-cm (1-in) glass wool, 2.54-cm (1-in) airspace	0.15	0.55	0.80	0.90	0.85	0.80
5.1-cm (2-in) fiberglass panels with plastic sheet wrapping and perforated metal facing, as installed	0.33	0.79	0.99	0.91	0.76	0.64

4.4.2 Mid Frequency Performance Dip

The T_{60} data and the absorption coefficient data of the test assembly show a dip in the sound absorbing performance at 500 Hz dip. For the octave band data, this dip becomes somewhat “averaged out”, but it is more easily seen by reviewing the one-third octave band data, as shown in the figure below.

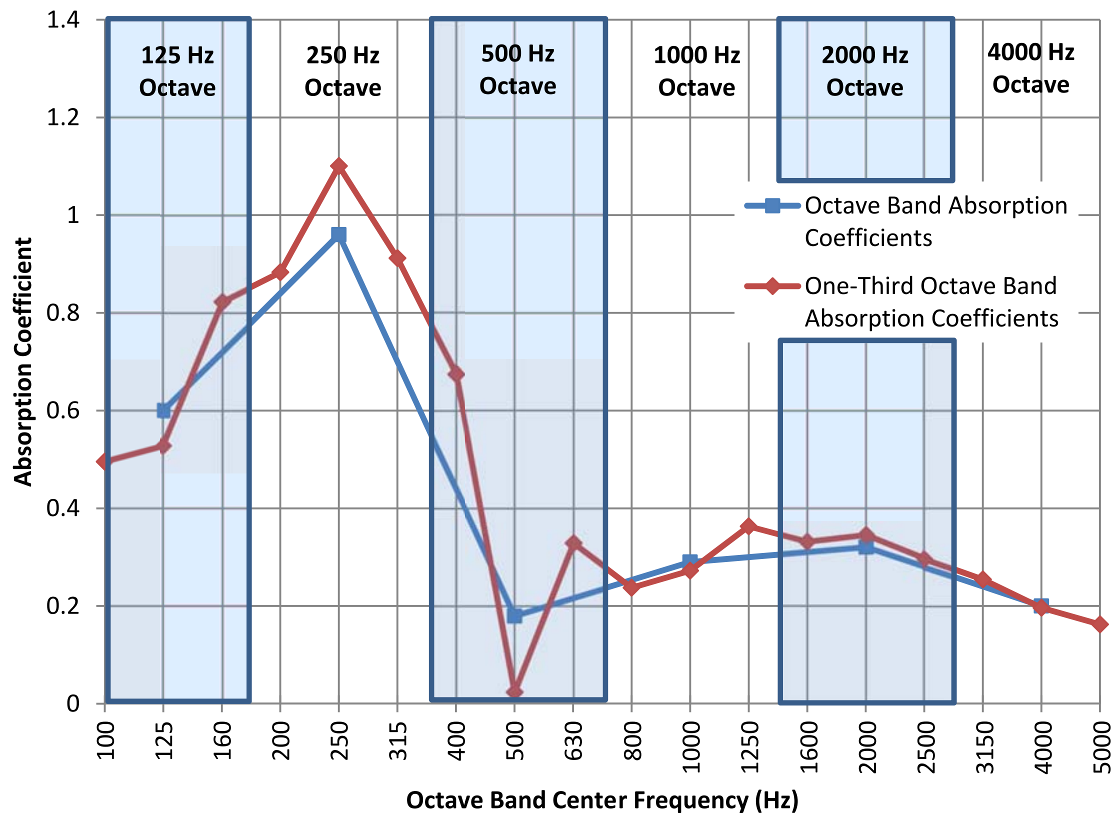


Figure 23. A comparison of Octave Band to One-Third Octave Band Results

As can be seen in the figure above, the one-third octave band data shows a dramatic drop in the sound absorption performance at 500 Hz. In fact the absorption coefficient at this one-third octave band is only 0.02, a value that indicates very minimal sound absorption. This dip in performance is not expected. The performance dip is also out of line with the general shape and trend of the performance curve. An anomaly in the collection of the measurement data is unlikely since 20 decays were recorded at varying microphone locations and positions. However, reviewing the data shown in Figure 18 and Figure 19 shows a greater degree of variance in the reverberation time at 500 Hz compared to the two adjacent frequency bands. These results indicate that standing waves in this frequency band could be present in the test chamber. The regular shape of the racquetball court, along with the parallel surfaces and integer multiplier of the physical room dimensions (40 ft x 20 ft x 20 ft) make the possibility of standing waves likely. The wavelengths of sound waves in the 500 Hz one-third octave band are approximately 2 ft. Therefore, standing waves in this frequency band are certainly plausible, especially considering that the wavelength is an even integer multiplier of the length, width, and height of the test chamber. A standing wave would negatively affect the test results because, as the name implies, the standing wave remains stationary and does not move. The sound wave bounces between two parallel surfaces, hitting the same location on the surface with each reflection. This phenomenon allows the sound wave to avoid any interaction with the test assembly. Standing waves would result in no change of the measurement data from the empty room to the room with the test assembly installed, which was the case for the measurement data collected. The reverberation times for the empty room and for the room with the test sample are virtually identical at 500 Hz. The author believes that repeating the series of tests in a laboratory (compared to the racquetball court mock laboratory) could prove or disprove this theory.

4.5 King Intermediate Gymnasium Existing Condition T_{60} Test Results

A total of 20 decays were measured in the gymnasium, each with a recorded time history at each octave band. The reverberation time was determined from the slope of the time history plot for each octave band. All 20 decays were averaged with the results summarized in Figure 24 below. The results clearly show excessive reverberation at all frequency bands, but especially at the low frequency bands (less than 250 Hz). The reverberation time in the existing space is so severe that it is several times the design goal (discussed below). Given these results, speech intelligibility is likely to be extremely low and complaints on the poor acoustics within the space are more than warranted.

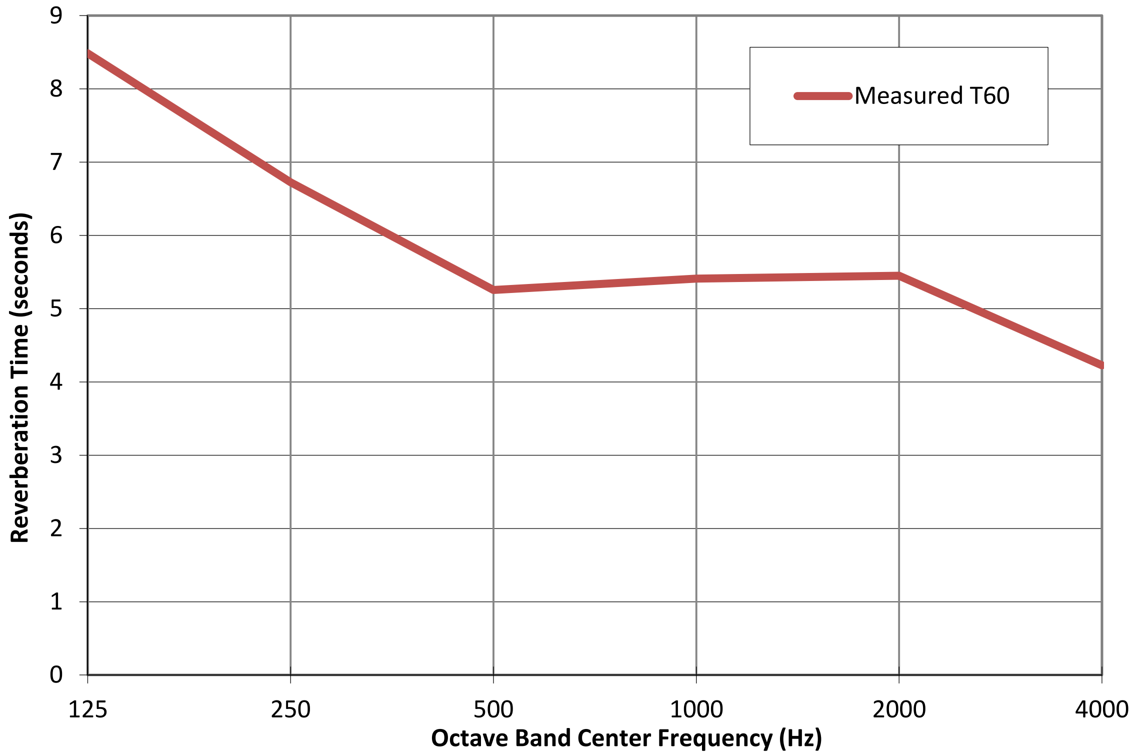


Figure 24. Reverberation Time in the Existing King Intermediate School Gymnasium

Chapter 5 Case Study: King Intermediate School Gymnasium Proposed Acoustical Treatment

5.1 Gymnasium T_{60} Design Goal

The design goal for reverberation time (T_{60}) depends significantly on the size of the space (air volume), but it depends equally on the use of the space. For example, a room used for choral or orchestral music performance should be designed for a longer reverberation time than a room designed for speech and presentations, given the same size space. The longer reverberation time in music performance spaces aids the performance by blending musical phrases together. However, for speech the consonances and diction of the speaker must be easily heard and distinct. Therefore, the reverberation time in these spaces, where speech is the predominant use, must be lower than for musical performances. Selected the design goal for mixed-use spaces can be challenging.

Although there are many published opinions and recommendations for setting design goals on reverberation within spaces, one such example is from Forman (1990), as shown in the figure below showing recommended design goals as a function of room air volume and use of the space.

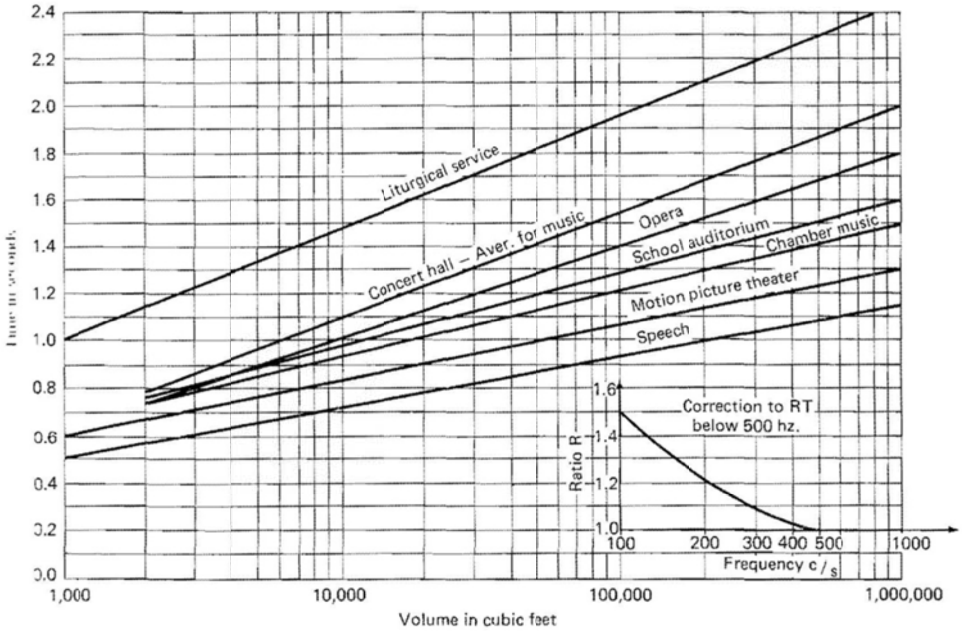


Fig. 5.33. Optimum reverberation time (500–800 Hz) versus volume (and correction below 500 Hz).

Figure 25. Optimum Reverberation Time as a Function of Room Volume, Foreman (1990)

The criteria stated in the graph, which is similar in format to other authors, states the design criteria for “mid frequency” which in this case is designated as 500 to 800 Hz. In addition to this mid frequency design criteria, Forman adds a correction factor to frequencies below 500 Hz. The reader must keep in mind the subjectivity when evaluating this design criterion. The acceptability or non-acceptability of the acoustics within the space can depend greatly on personal preference and point of view (i.e. performer vs. audience member). Kuttruff (1973) reinforces this point by stating “… the term ‘optimum reverberation time’ is frequently used. When using this expression, however, one must be aware of the numerous factors of uncertainty which are involved in the process of gaining these values.” He continues with a paradoxical argument on who decides or defines which spaces “sound good”, the musician, the audience member, or the acoustician, each with their own faults and biases. Kuttruff’s point is well taken. Even amongst scholars and published texts, there is only marginal agreement regarding design criteria. The author does not propose a solution for determining the most effective design criteria for reverberation time within a space, but rather highlights the subjectivity of its application. Because of these uncertainties, the author recommends evaluating design criteria using multiple references. The following two figures show the design criteria from two other separate sources.

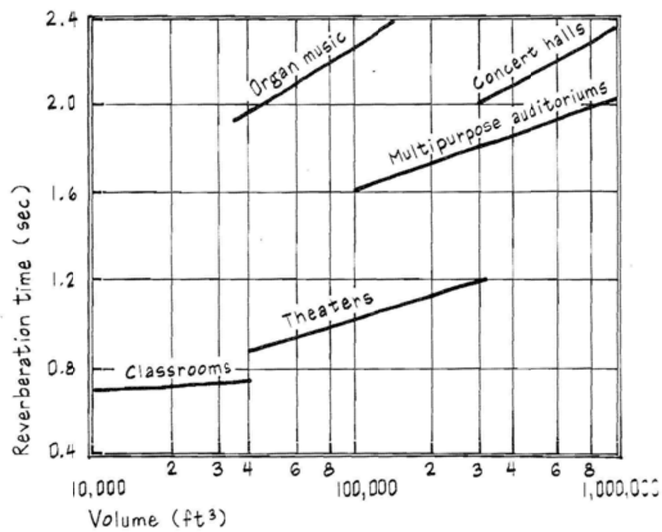


Figure 26. Optimum Reverberation Time as a Function of Room Volume, Egan (1988)

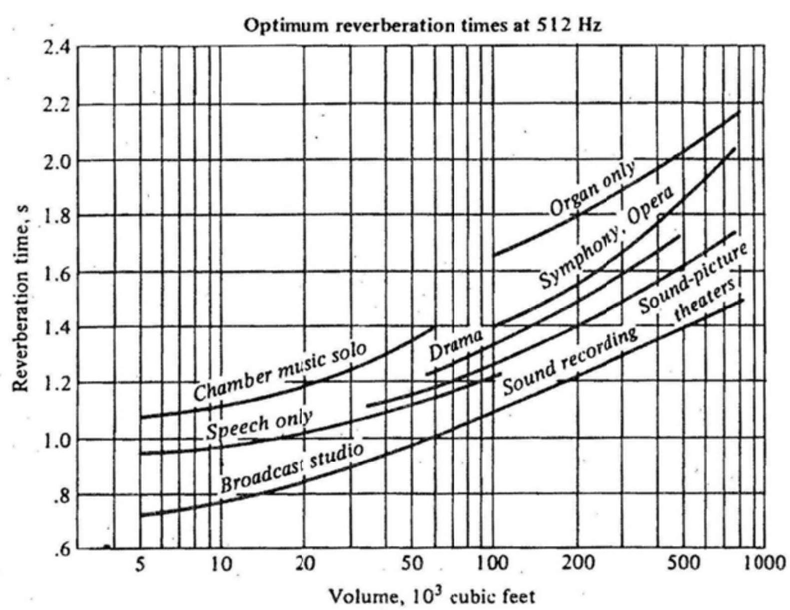


Figure 27. Optimum Reverberation Time as a Function of Room Volume, Lord et al (1980)

The correction factor at low frequencies allows for, or rather recommends, longer reverberation times at these low frequencies. In general, most spaces will naturally respond with longer reverberation times at low frequencies, primarily because low frequency sound is much harder to absorb than high frequency sound. Thick and soft materials are usually needed to absorb sound at these frequencies, and common building materials (i.e., carpet, wall coverings, etc.) are too thin for effective low frequency sound absorption. For music performance spaces, a boost in the low frequency reverberation time can actually be a desirable condition for many types of music. The room will give the listener a sensation of a warm sounding space because the bass notes will more easily blend together, while the shorter reverberation time at mid and high frequencies offers definition to individual musical notes in the melody and harmony of musical phrases.

The King Intermediate School gymnasium has many uses, including speeches, presentations, and musical performances. Since selecting one design goal for all program uses is not possible, a range of design goals was selected, an upper limit and lower limit. The speech use sets the low end of the design goal, the lower limit. And the upper limit is set for musical performance use. Based on a calculated room volume of approximately 565,000 cubic feet for the gymnasium, the lower limit for reverberation time should be approximately 1.2 seconds, and the upper limit for musical performances should be approximately 2.0 seconds. For a space of this size, achieving the lower limit design goal for speech is not practical. It would require an extraordinary amount of sound absorbing surfaces to be added to the room. Even achieving the upper limit design goal for the gymnasium would be a significant accomplishment. Figure 28 below shows a comparison of the exiting reverberation time in the gymnasium to the design goal. The difference between the existing (measured) and the design goal is staggering.

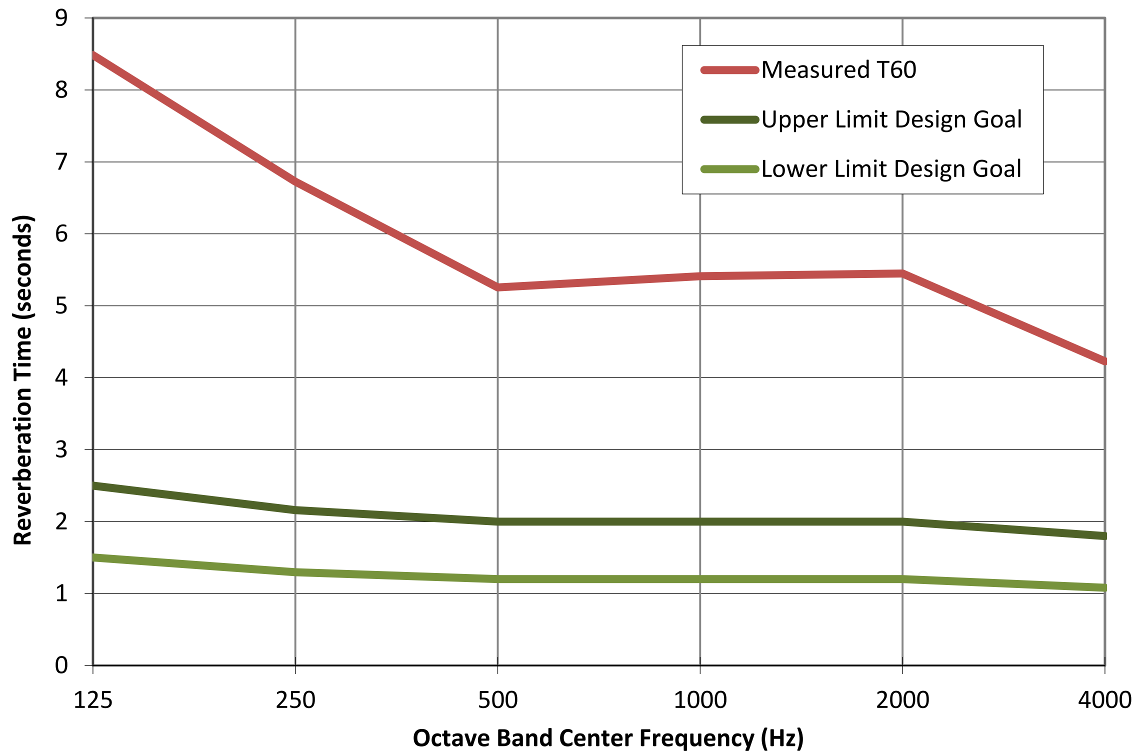


Figure 28. Comparison of the Design Goal to the Existing Reverberation Time in the Gymnasium

5.2 Gymnasium Acoustical Treatment Recommendations

The primary goal of this case study was to determine the effect of the sailcloth and tee shirt product on the acoustical environment of the King Intermediate School Gymnasium. Without question, adding sound absorbing treatments like the tee shirt and sailcloth product would certainly reduce the reverberation time in the space, but by how much? How much area of the treatment is needed in order to make a substantial difference, or even better, meet the design goal? Where should the treatment be placed and how should it be installed? These important questions were considered in developing the acoustical treatment solution for the gymnasium.

5.2.1 Acoustical Treatment Location

The location of an acoustical treatment can be just as important as the quantity, at least to some degree. First, we must consider the availability of

potential locations for acoustical treatment. For the gymnasium, the floor is a hard reflective surface, but treating the floor with a soft absorptive material is not practical. A soft floor would certainly be detrimental to the use of the gym, and is simply not a good idea. The walls are all hard reflective surfaces.
Because of its porosity, Concrete Masonry Unit (CMU) block walls can be somewhat sound absorbing, but only left unpainted. All of the walls in the gymnasium have been painted leaving them highly reflective. The walls are certainly a potential location for acoustical treatment. The reflective ceiling is also a potential location for acoustical treatment. It was determined that the ceiling was the most effective location for treatment. Based on the room dimensions, the ceiling is likely to generate more sound reflections to the listener (audience) than the walls, although the walls will certainly reflect sound to the listener. A simple ray tracing method can be used to illustrate this point. Assuming a sound source located in the middle of the basketball court and a listener located in the middle of the audience seats, sound reflecting off of the side walls will have to travel 160 feet. The figure below illustrates the ray tracing for the sound wave reflecting off of the gymnasium side walls. That same sound wave will only have to travel 80 feet for a reflection off of the ceiling. Essentially, the ceiling is closer to the listener (audience member) than the walls.

Of course by the very nature of a highly reverberant room, a single sound wave may reflect off of multiple surfaces before reaching the listener. However, with each reflection the sound wave weakens not only due to sound energy lost at the interface with the surface (i.e., the sound absorption performance), but also because of the distance it travels before it reaches the listener. As discussed earlier in this paper, sound energy is lost by spherical spreading, also called geometric divergence (Harris 1998).

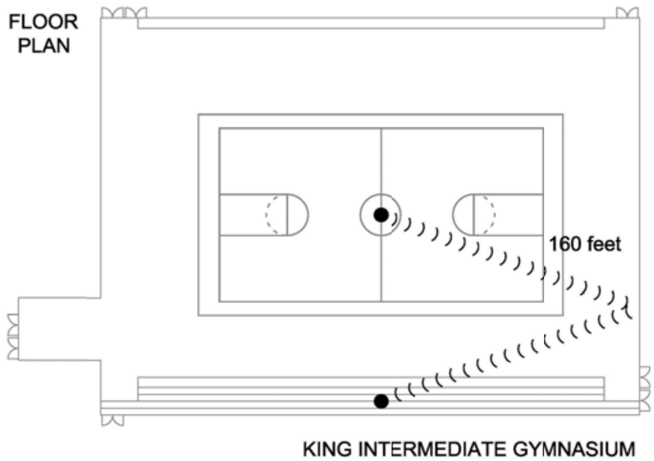


Figure 29. Sound Reflection Path Length for Wall Reflection

Although the walls should certainly not be ignored, the dominant and strongest sound reflection path is via the ceiling. For the same reasoning, sound absorptive treatments placed near the center of the ceiling will be more effective the treatments placed near the outer perimeter of the ceiling. These practices can be generally applied to many different room types and shapes. For the King Intermediate School Gymnasium, the ceiling is of particular importance. This ceiling is barrel-shaped with a slight arc or pitch that has a high ridge along the centerline of the gymnasium. This ceiling shape will naturally tend to reflect or focus sound waves toward the middle of the room.

5.2.2 Ceiling Acoustical Treatment Installation Method

For aesthetics and architectural design, there are many methods of attachment that can be used to secure the sound absorbing pillows to the ceiling, including the use of grommets, suspension cable, etc. However, the simplest approach may be to screw the sound absorbing pillows directly into the roof deck. The author recommends using a small square or a strip or wood blocking at the attachment point. The wood blocking serves two purposes. First, it offers a sacrificial screwing strip, or “nailer”, that can be replaced if necessary. It’ll help reduce the number of screws that need to penetrate into the roof deck.

Secondly, the wood blocking adds a small gap between the pillow and roof deck. This gap will help the pillow maintain its natural shape. If the wood blocking was not installed, the pillow would tend to flatten as it gets screwed into the roof deck. The small gap will also help boost the low frequency sound absorption performance of the pillows even further. Separating the sound absorbing pillow for the roof deck increases its effective thickness. The sound absorbing material is moved further away from the reflective surface, which means that it will have an easier time absorbing low frequency sound waves that have longer wavelengths.

The idea of offsetting the acoustical treatment from the reflective surface is not a new one. In fact, some acoustical treatment manufacturers publish sound absorption coefficient data for a variety of mounting methods. The most common alternates to the Type A mounting (direct mount), are the Type D20 (20mm [0.75in] gap without insulation), C20 (20mm [0.75in] gap with insulation), and C40 (1.5in] gap with insulation). Although a comparison of these mounting method types is not included in the scope of this research, it is important to note that alternates to Type A mounting are not uncommon and they typically show an increase in performance for low frequency sound absorption.

The actual improvement in low frequency sound absorption gained by adding a small gap between the sound absorbing pillows and the roof deck is not known since Type A mounting was used for the acoustical tests. Future research in this area could help quantify the differences in mounting methods. However, a dramatic change in low frequency sound absorption performance is not expected. Rather, the gap may only improve the performance by a small amount, and may not be noticeable to the average listener. Regardless, the improvement is noteworthy, and could be investigated further.

Figure 30 below shows a plan and section drawing of the proposed installation assembly method.

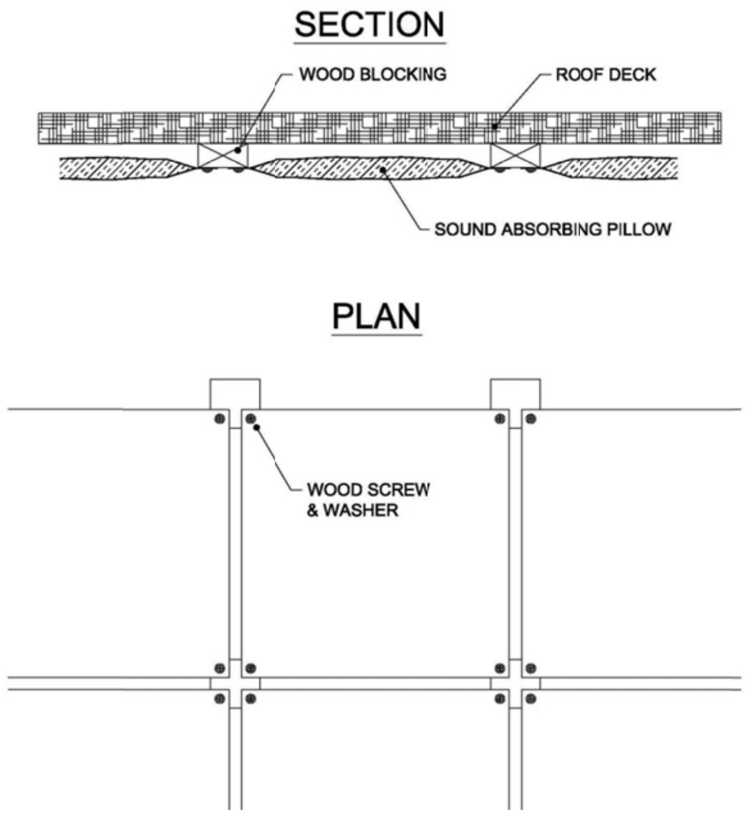


Figure 30. Plan and Section Drawings of the Sound Absorbing Pillows

The sound absorbing pillows should be arranged in a tight grid pattern using square shaped pillows. As described above, the recommended pillow size ranges from 14in x14in to 24in x 24in, with an ideal size of approximately 17inx17in. A wood screw and washer could be screwed into each corner of the sound absorbing pillow to support its weight. The sailcloth outer covering was selected because of its high strength and resistance to tearing. The weight of each pillow is only on the order of a few pounds, so the four screws per pillow may be sufficient. However, reinforcing fabric or cable ribbing could be sewn into the pillows for increased support and failure safety, but these items may likely add material cost and labor time to the final product.

5.2.3 Modeling the Existing Gymnasium

Achieving an ideal acoustical environment for the gymnasium is certainly the goal. However, dramatically improving the acoustics within the space, even if the design goals are not met is still a significant accomplishment. At 565,000 ft^3, the King Intermediate School gymnasium is undoubtedly a very large space. Naturally, a larger space will require a greater area of treatment for the same desired reverberation time. The reverberation time is directly proportional to the room air volume. Therefore, for the gymnasium, even small reductions in the reverberation time will require a significant amount of acoustical treatment. The first step to assessing how much acoustical treatment is necessary is to model the room using absorption coefficients for the existing building elements and room finishes. Since the existing reverberation time was measured in the gymnasium, the measured levels can be used to “calibrate” the model by adding a correction factor for any discrepancies between the model data and the measured data.

The area of all of the various room finishes were documented from field observations and from the as-built drawings of the gymnasium. The following table lists these surfaces as the estimated area of each surface.

Table 11. Quantity and Type of the Gymnasium Existing Room Finishes

Room Finish / Surface	Area (ft^2)
Floor – Wood Sports Floor on Sleepers	6,150
Floor – Polished Concrete	11,800
Walls – Metal Doors	340
Walls – Ventilation Openings	2,100
Walls – Painted CMU	13,250
Ceiling – Enclosed Beams	8,050
Ceiling – Wood Plank Roof Deck	14,700

The absorption coefficients were obtained by combining several of the sources in the bibliography of this paper, including Beranek (1988), Harris (1998), and others. The following table summarizes the absorption coefficients for each room finish at each octave band.

Table 12. Absorption Coefficients of the Gymnasium Existing Room Finishes

	Absorption Coefficients					
	Octave Band Center Frequency					
	125	**250**	**500**	**1000**	**2000**	**4000**
Floor – Wood Sports	0.18	0.20	0.18	0.12	0.08	0.01
Floor – Polished Concrete	0.01	0.01	0.02	0.02	0.01	0.01
Walls – Metal Doors	0.05	0.06	0.05	0.05	004	0.01
Walls – Ventilation Opening	0.31	0.35	0.42	0.44	0.50	0.20
Walls – Painted CMU	0.04	0.05	0.07	0.07	0.04	0.01
Ceiling – Enclosed Beams	0.04	0.06	0.08	0.08	0.04	0.01
Ceiling – Wood Plank Roof	0.03	0.04	0.04	0.04	0.03	0.01

Using the area of each room finish and the octave band absorption coefficients, the total absorption was calculated using the following relationship.

$$A = \alpha S \tag{29}$$

In addition to calculating the absorption of the room surfaces and finishes, the absorption of air should also be included in the calculations. Air absorption can be significant at higher frequencies and is variant upon the relative humidity. The relationship between the absorption of air is governed by the following equation (Harris 1998).

$$A_{air} = 4mV \tag{30}$$

Where A_{air} is the absorption of the air (sabins), m is the air attenuation coefficient per foot (ft^{-1}) as determined by the figure below, and V is the room air volume (ft^{3}). The air attenuation coefficient can also be calculated using equation 15 above.

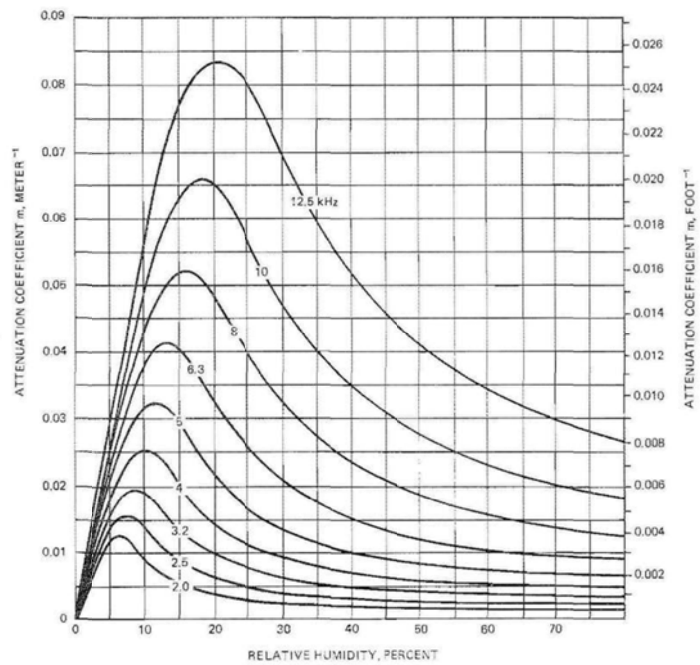


Figure 31. Air Absorption Coefficient as a Function of Relative Humidity (Harris 1998)

The resulting absorption values for the room finishes and for the air within the gymnasium can be found in the table below, including a summary total at each octave band.

Table 13. Absorption Coefficients of the Gymnasium Existing Room Finishes

	Absorption (Sabins)					
	Octave Band Center Frequency					
	125	**250**	**500**	**1000**	**2000**	**4000**
Air	0	0	0	565	1695	5086
Floor – Wood Sports	1107	1230	1107	738	492	62
Floor – Polished Concrete	118	118	236	236	118	118
Walls – Metal Doors	17	20	17	17	14	3
Walls – Ventilation Opening	652	736	882	924	1050	420
Walls – Painted CMU	530	663	928	928	530	133
Ceiling – Enclosed Beams	322	483	644	644	322	81
Ceiling – Wood Plank Roof	441	588	588	588	441	147
Misc. Surfaces	75	280	860	475	420	500
TOTAL	**3261**	**4117**	**5262**	**5115**	**5082**	**6549**

Using the Sabine Equation described above the reverberation time in the gymnasium can be predicted. The Absorption of the miscellaneous surfaces above is estimated and is used to calibrate the model to the measured values. These miscellaneous can include the bleachers, sports equipment, or any other furnishings or equipment that can absorb sound within the space, but were not singled out as individual items in the reverberation time calculations.

5.2.4 Quantity of Treatment and Improvement Gained

Since the sound absorbing tee shirt and sailcloth acoustical pillows are recommend to be installed on the ceiling, the treatment will essentially cover the ceiling surface (or at least a substantial portion of the existing ceiling surface). Therefore, area of the existing ceiling that is covered by the acoustical treatment must be subtracted from the reverberation time calculations because this surface area is no longer exposed to the room.

A total treatment area of 11,000 ft^2 is recommended for the gymnasium, if the acoustic pillows are used. The reverberation time prediction using this acoustical treatment is shown in the figure below.

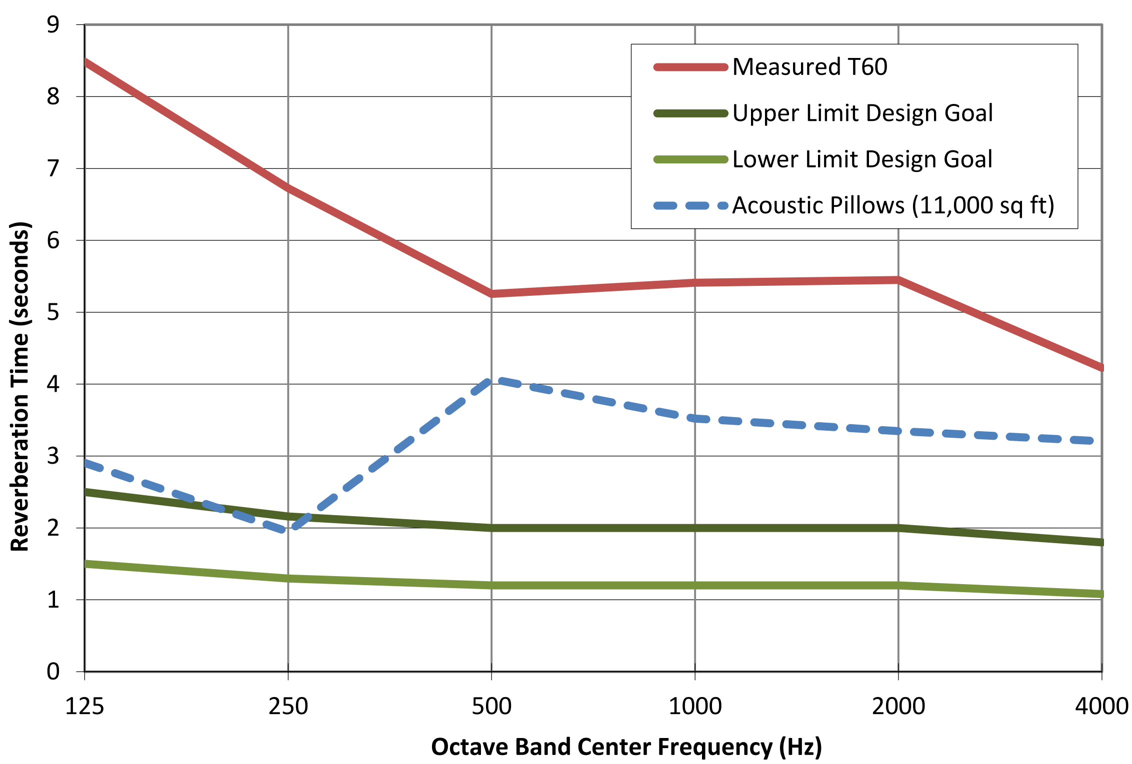


Figure 32. Predicted Reverberation Time in the Gymnasium (11,000 ft^2 of Acoustic Pillows)

The design goal is only satisfied at the 250 Hz octave band, according to the data collected on the test sample. However, with some of the improvements in the design of the acoustic pillow described in Chapter 6 of this paper, the performance of the assembly for frequencies of 500 Hz and above could be dramatically improved. The author believes that with improvements made to the design of the acoustic pillow the design goals for reverberation time in the gymnasium can be achieved with the recommend 11,000 ft^2 of treatment.

The King Intermediate School expressed a desire to complete the work in phases versus all at one time. The work could be divided into a total of four phases (perhaps over 4 years). Since the middle sections of the ceiling are the most important for absorbing sound, the project phasing should begin with the middle section and then move out towards the ceiling perimeter. The recommended project phasing is shown in the figures below.

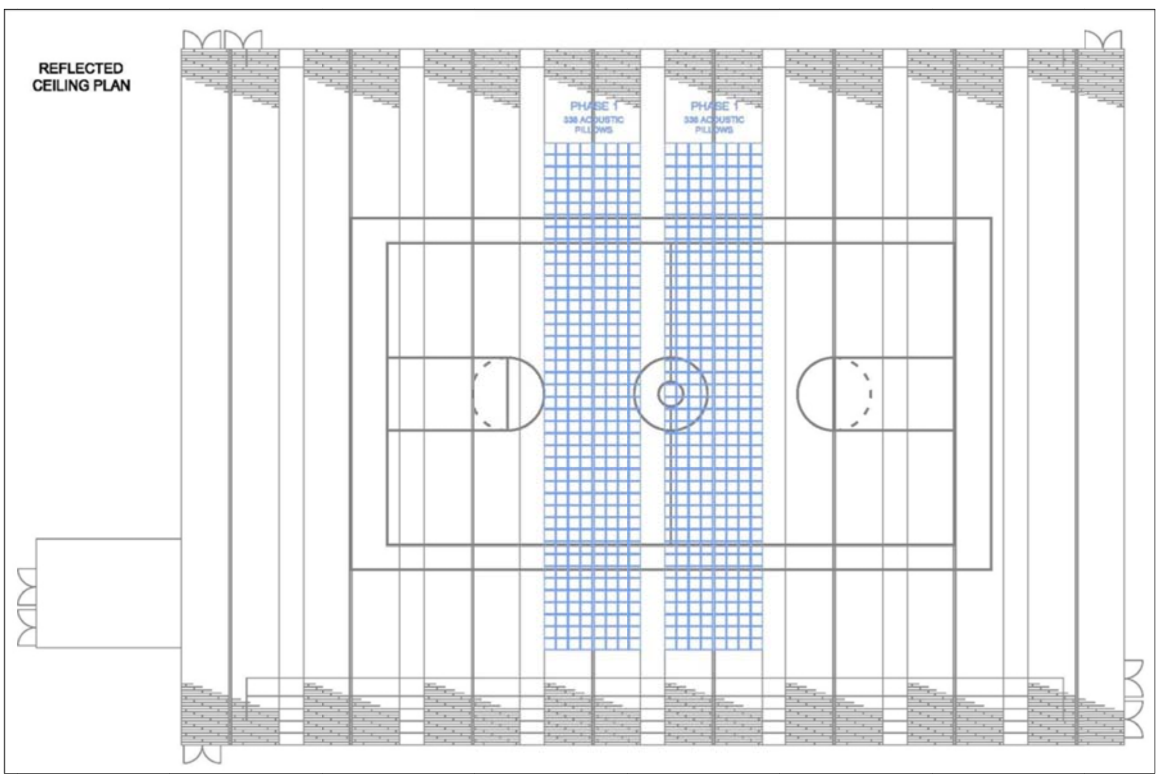


Figure 33. Phase 1 Acoustical Treatment

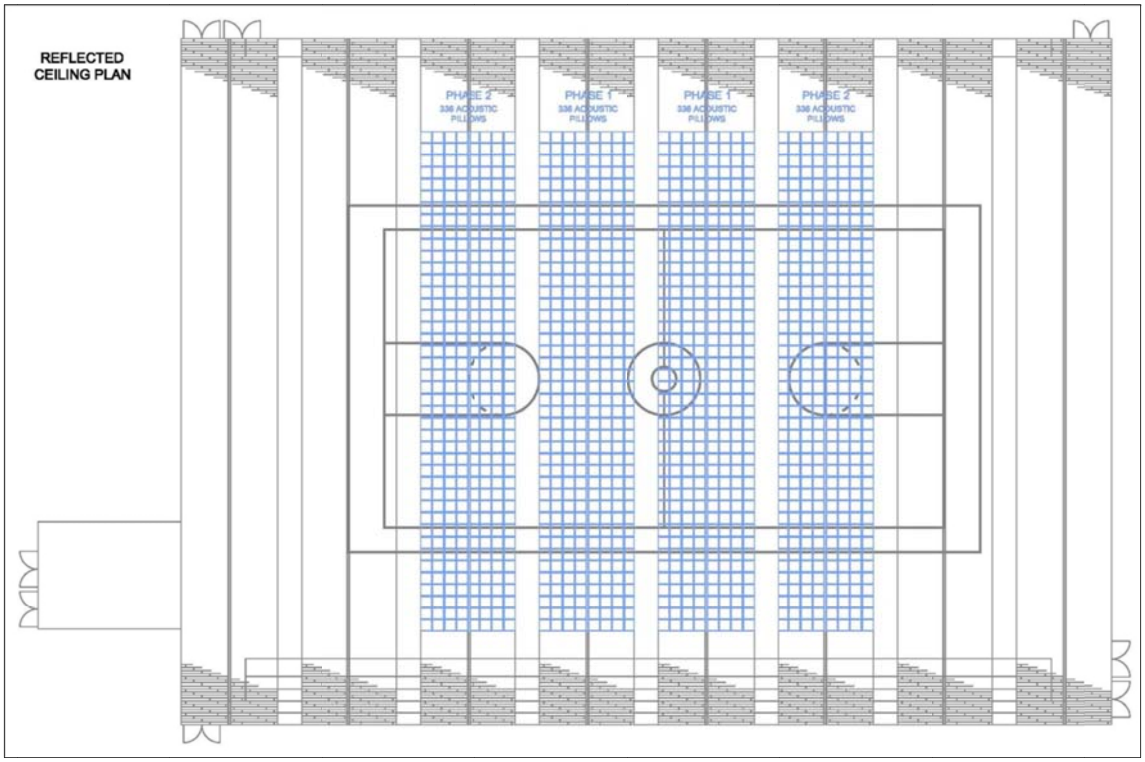


Figure 34. Phase 2 Acoustical Treatment

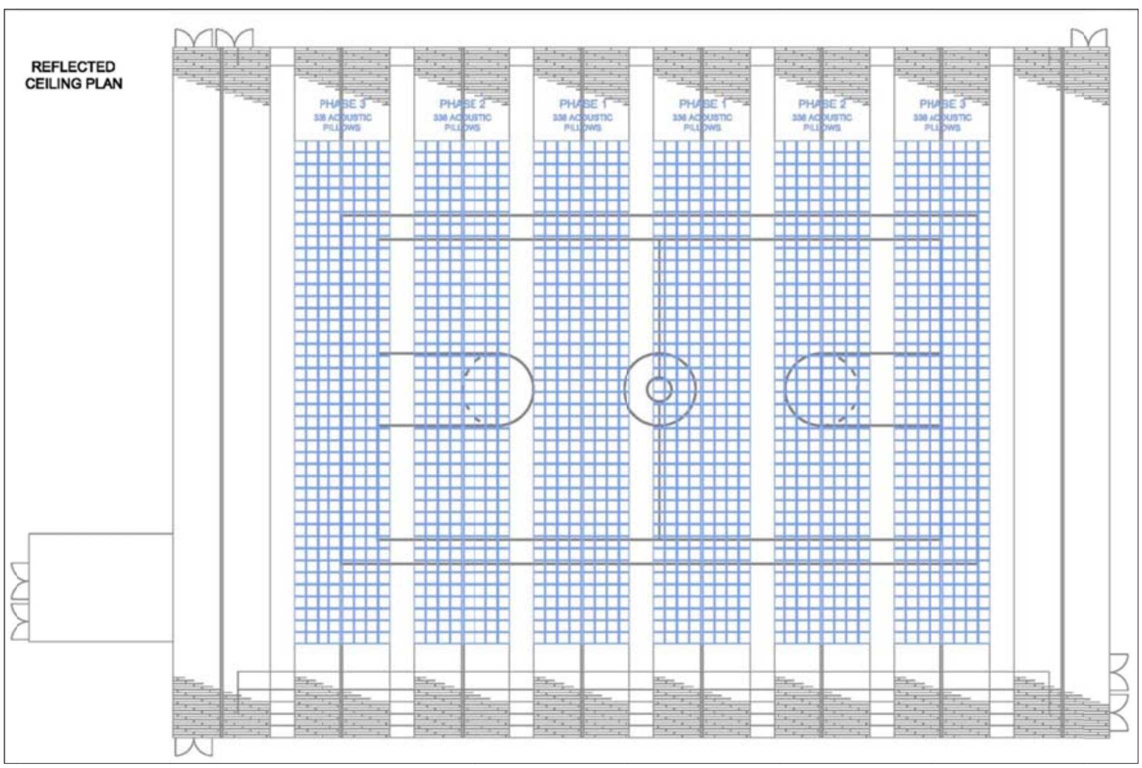


Figure 35. Phase 3 Acoustical Treatment

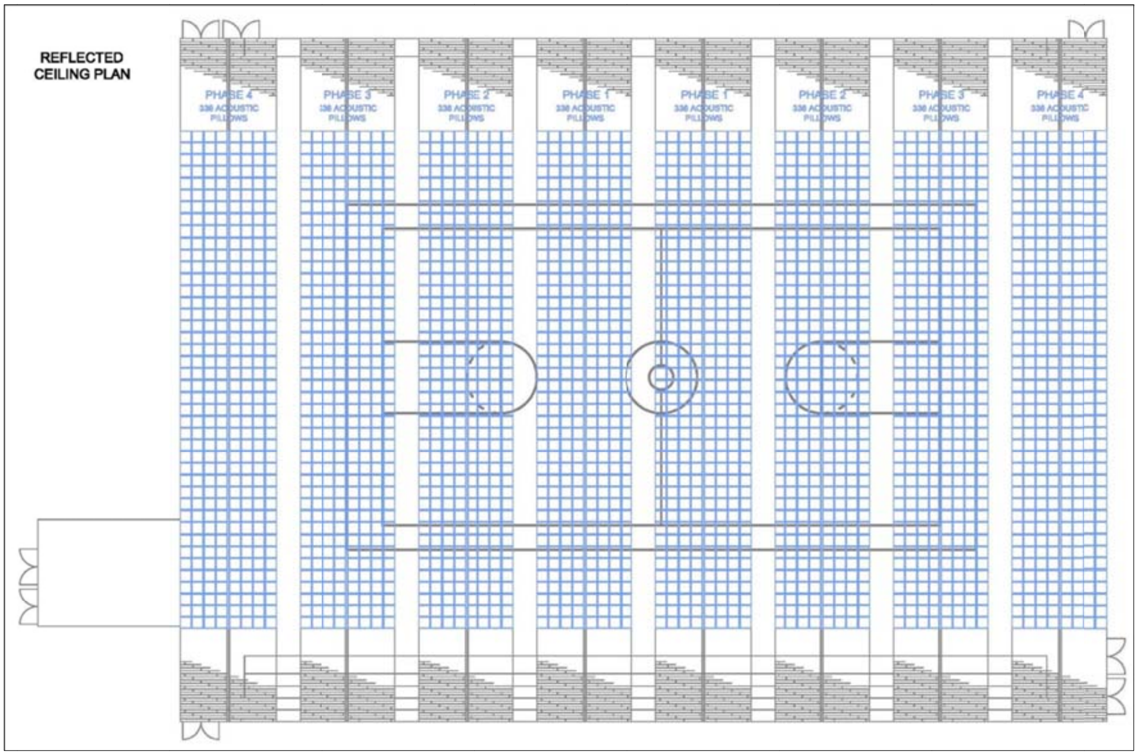


Figure 36. Phase 4 Acoustical Treatment

The quantity of materials required for each project phases is summarized in the table below.

Table 14. Quantity of Materials Required for Each Project Phase

	Phase 1	Phase 2	Phase 3	Phase 4	TOTAL
Treatment Area	2,750	2,750	2,750	2,750	**11,000**
Qty Sailcloth (ft^2)	5,500	5,500	5,500	5,500	**22,000**
Qty Tee Shirts	6,000	6,000	6,000	6,000	**24,000**
Qty of 2'x2' Acoustic Pillows	672	672	672	672	**2688**

Since each phase will be completed at a different time, perhaps a year or more apart, it is important to consider the improvement gained by each project phase. The figure below shows the improvement (reduction) in the reverberation time in the gymnasium for each project phase.

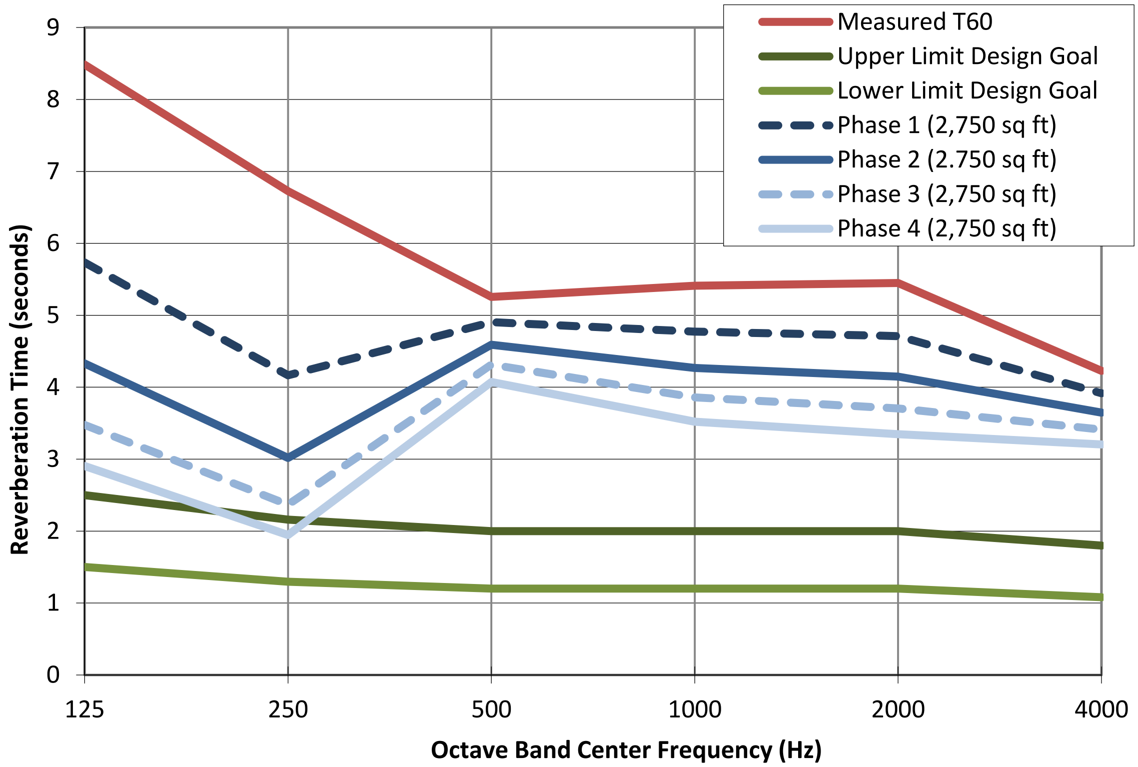


Figure 37. Predicted T_{60} for each Project Phase

The results indicate that a reasonable improvement could be achieved, even by implementing the first phase. The first phase would like be a noticeable improvement to the students, staff, and community members, although it does not achieve the design goal. This graph shows the improvement gained by implementing the acoustic pillows, as currently designed. Adjustments and improvements made the pillow design could radically improve the mid and high frequency performance.

Chapter 6 Conclusions

6.1 Data Analysis and Potential Improvements to the Test Assembly

6.1.1 Test Method and Test Chamber

Overall, the fabrication of the test assembly and accompanying acoustical measurements showed desirable results. The tee shirt and sailcloth acoustic pillows exhibited a sound absorbing performance that is very effective for low frequency sound (250 Hz and below). The high frequency sound absorption performance is less than ideal, but improvements in the design of the acoustic pillow could increase the performance. The performance dip at 500 Hz cannot be fully explained, although standing waves within the test chamber are a very likely culprit to the downgraded performance. Retesting the assembly in a laboratory setting may yield more favorable results in this frequency band.

Although the racquetball court was not an ideal testing laboratory, it was generally effective for most of the measurement data. Finding a space of the right size and one that has all reflective surfaces is not easy. The racquetball court was certainly a very reverberant space and served as a fair approximation for laboratory conditions.

6.1.2 Test Assembly Improvements

The marginal performance in high frequency sound absorption is likely due to the sailcloth wrap, and not the cotton acoustic filler. The sailcloth used for this experiment was thicker and heavier than an ideal material. Selecting a sailcloth material that is thinner and lighter will likely improve the high frequency performance. An evaluation of sailcloth types could be considered for future research. The author recommends using spinnaker sails instead of the sailcloth fabricated for the main sail. The typically colorful spinnaker sail leads the boat in downwind conditions and is not as strong (or as thick) as the main sail, as shown in the figure below. Of course other materials could be used for the out wrap instead of sailcloth. Many other fabrics or even the tee shirt itself could be used.

Any porous or perforated material (even non fabrics) could be considered for evaluation as a method to enclose the acoustic filler.

Figure 38. Spinnaker Sail

There are other improvements that can be made to the acoustic filler. For example, cutting the tee shirts into smaller pieces (or shredding them) may also help improve the performance. Stuffing the tee shirts into the pillowcases as one large piece of fabric leaves a lot of room for potential error. It is difficult to achieve a consistent distribution of cotton in each pillowcase, especially when the shirts are not all the same size and weight. Shredded acoustic filler would allow far better control of the material placed inside each pillow. However, the processing shredding and/or cutting the tee shirts would require additional time and resources. In addition to tee shirts, other fabrics and materials could be considered for the acoustic filler, including discarded insulation or other natural fibrous materials.

6.2 Other Design Considerations

6.2.1 Mold Growth

The sound absorbing performance is not the only attribute which must be considered before the product is put in use. Mold growth is a concern in Hawaii and other warm, humid climates. Naturally ventilated areas have a higher risk of mold growth versus conditioned spaces. Since the King Intermediate School is naturally ventilated, concerns over mold growth should be fully evaluated.

6.2.2 Fire Code Restrictions

Fire code restrictions may limit the use of the proposed acoustic treatment, particularly if installed on the ceiling. The risk of flame spread should be checked by the appropriate personnel. If local fire codes limit the use of the product, a fire retardant incorporated into the acoustic pillow could be considered. The acoustical performance may need to be verified with any modifications required by the fire code restriction.

6.2.3 Structural Support

Although the weight of one acoustic pillow is not significant, the combined weight of a ceiling full of acoustic pillows may add substantial weight to the ceiling/roof structure. A structural engineer should verify the structural support of the building framing can handle the additional weight.

6.3 King Intermediate School Conclusions

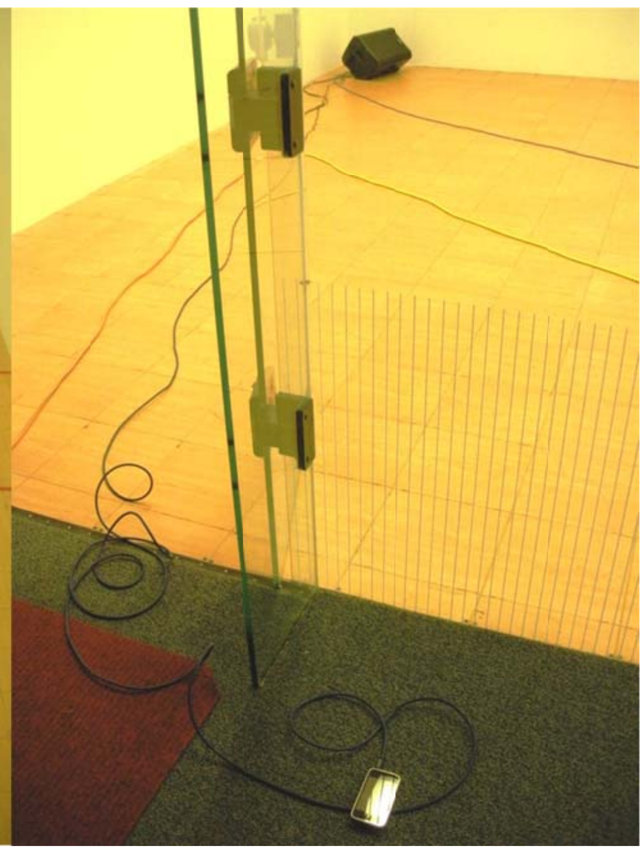
The proposed tee shirt and sailcloth acoustic pillows are certainly a viable option for the King Intermediate School. The assembly satisfies all of the school's goals. The acoustic pillows have a satisfactory performance for absorbing sound. With the improvement of using a thinner sailcloth material, the author believes that the mid and high frequency sound absorption can be significantly improved. The finished product is very environmentally friendly because it provides a second use for materials that would otherwise end up in a land fill.

Although a detailed cost analysis was not included with this research, it is apparent that the material costs would be very low. The main components, the sailcloth and tee shirts, are items that can be salvaged or donated to the school. There will be materials costs for the thread used to sew the acoustic pillows and for the screws and washers used to attach the pillows to structure, but these costs are minimal. Labor time is likely the most significant cost related items. Since the solution is not an “off-the-shelf” item, if will require a lot of time and effort to fabricate and install the pillows. However, since the school stressed community, staff, and student involvement, much of the labor time could be completed with organized school functions, without the need to hire contractors. A “tee shirt drive” could be organized to collect some of the materials. The art department could also be involved in creating a mosaic or some type of artistic design with the pillows. Although the school could save a lot of money by fabricating the acoustic pillows, installation of the pillows on the gymnasium ceiling may need to be done by a contractor. Safety concerns of working at the height of the gymnasium ceiling may require outside help.

The acoustic pillow solution may not be perfect in every way, but it is potential solution to an existing problem. It makes use of local materials that are in the vicinity of the project and can unite students, teachers, and community members in a sizeable project that benefits everyone.

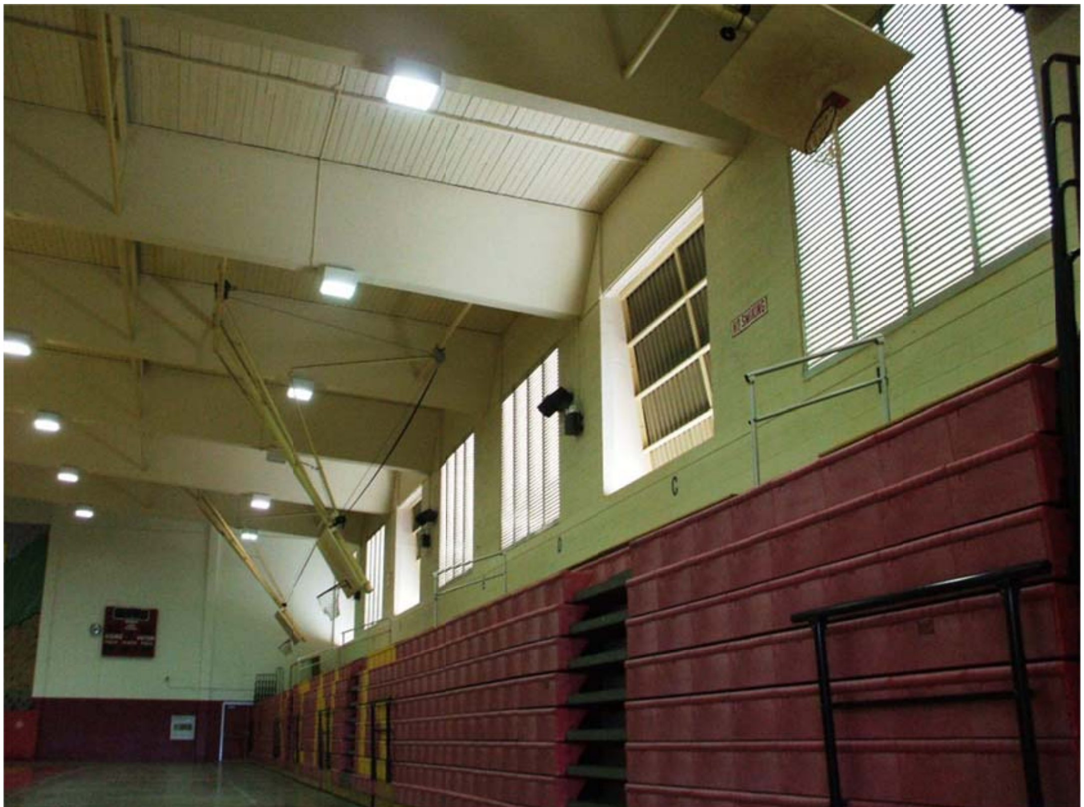
Appendix A Photos of Test Assembly &Test Chamber




SHARE KAILUA

Appendix B Photos of King Intermediate Gymnasium




J
K
L


JEFF PAGAY
2006
NO CLIMBING


KING


KING


COBRAS

Bibliography

American National Standards Institute (ANSI) Standard Designation S1.11-2004 (R2009). *Octave-Band and Fractional-Octave Band Analog and Digital Filters.*

American National Standards Institute (ANSI) Standard Designation S1.4-1983 (R2006) / S1.4A-1985 (R2006). *American National Standard Specification for Sound Level Meters.*

American Society of Testing and Materials (ASTM) Standard Designation C 423-07a (2007). *Standard Test Method of Sound Absorption and Sound Absorption Coefficients by the Reverberation Room Method.*

American Society of Testing and Materials (ASTM) Standard Designation E 2234-04. (2004). *Standard Test Method for Determination of Decay Rates for Use in Sound Insulation Test Methods.*

Beranek, Leo L. (1988). *Noise and Vibration Control, Revised Edition.* Institute of Noise Control Engineering, Washington DC, USA (Previous edition published by McGraw-Hill)

Bosmans, I., Lauriks, W., Lombaert, G., Mermans, J., and Vermeir, G. (1999). "Sound Absorption of Stretched Ceilings with an Impervious Synthetic Membrane", Journal of the Acoustical Society of America, Vol. 106, pp. 233-239.

Egan, David M. (1988). *Architectural Acoustics.* McGraw-Hill, New York, USA

Eyring, C. F. (1933). "Methods of Calculating the Average Coefficient of Sound Absorption", Journal of the Acoustical Society of America, Vol. 4, pp. 178-192.

Foreman, John E. K. (1990). *Sound Analysis and Noise Control.* Van Nostrand Reinhold, New York, USA

Harris, Cyril M. (1998). *Handbook of Acoustical Measurements and Noise Control, Third Edition.* Acoustical Society of America. Melville, New York, USA (Previous editions by McGraw-Hill)

Kinsler, Lawrence E., Frey, Austin R., Coppens Alan B, Sanders, James V. (1982). *Fundamentals of Acoustics, Third Edition.* John Wiley & Sons, Inc. New York, USA

Kuttruff, Heinrich (1973). *Room Acoustics*. Applied Science Publishers LTD, Norfolk, England.

Lord, Harold, Gatley, William S., Eversen, H. A. (1980). *Noise Control for Engineers.* McGraw-Hill, San Francisco, CA, USA

McGinnes, C., Kleiner, M., Xiang, N. (2005). "An Environmental and Economical Solution to Sound Absorption Using Straw", Noise-Con 2005, Institute of Noise Control Engineers.

Sato, H., Morimoto, M. (2008). "Relationship Between Listening Difficulty and Acoustical Objective Measures in Reverberant Sound Fields", Journal of the Acoustical Society of America, Vol. 123, pp. 2087-2093.

USA Racquetball Association (2007). *Standard Specifications for Racquetball Court Construction*. USA Racquetball Association, Colorado Springs, USA.

Yerges, Lyle F. (1969). *Sound, Noise, and Vibration Control*. Van Nostrand Reinhold, New York, USA