THESIS

EVALUATION OF SABINE'S FORMULA ON THE PREDICTION AND CONTROL OF REVERBERANT NOISE IN A MODERN LEED PLATINUM CERTIFIED RESEARCH BUILDING

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ABSTRACT

EVALUATION OF SABINE'S FORMULA ON THE PREDICTION AND CONTROL OF REVERBERANT NOISE IN A MODERN LEED PLATINUM CERTIFIED RESEARCH BUILDING

The Powerhouse Energy Campus is a LEED Platinum certified research building located in Fort Collins, Colorado and is part of Colorado State University. Completed in 2014, the renovated interior of the Powerhouse consists largely of open floor plans with minimal closed rooms to allow the building's heating and cooling system to function. The open floor plan and use of interior building materials with hard surfaces created problematic noise levels for the office occupants as noise from laboratory spaces or offices could be heard throughout the building. This project provided a unique opportunity to evaluate the method available to most industrial hygienists to measure and predict reverberant noise: Sabine's Formula and the impulse noise method of reverberation measurement.

Reverberation times (RT_{60}) in five interior spaces ranging from 76 m^3 to 5400 m^3 were modeled using a Sabine's Formula model. The RT_{60} predictions were then compared to the reverberation times measured in each location, and reverberant noise treatments were designed for two rooms using the same models. The RT_{60} times were taken again after the installation of the recommended treatments for two rooms. This allowed for the evaluation of both the modeling capabilities of Sabine's Formula and the practical industrial hygiene application of the equation to select effective acoustic treatments to control reverberant noise.

The model performed well in room volumes 620 m^3 and below, and would have likely performed better in the large volume rooms if they did not have such complex, open acoustic environments. The model was still slightly underestimating reverberation times at 620 m^3 indicating that it would perform well in larger volume spaces, though this study was not able to identify the room volume at which Sabine's Formula begins to overestimate reverberation times.

The RT_{60} time reductions in both the first floor classroom and the second floor conference room indicated that the reverberant noise treatment design was successful in reducing the problem acoustics in those areas. The treatment reduced the RT_{60} times at the problematic low frequencies in both rooms and brought the times near the goal of 0.5-1 second. The researchers found that the Sabine's Formula model is able to adequately predict the reverberant field behavior when different acoustic treatments are applied to the space. The impulse noise method of reverberation measurement is also sufficient to characterize the acoustics of a room to aid in the design and selection of acoustic treatments.

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CHAPTER 1: INTRODUCTION

Mac McGoldrick, assistant director of operations at the CSU Energy Institute, contacted Environmental and Radiological Health Sciences faculty member Dr. William Brazile in Spring 2015. Mr. McGoldrick reported that undesirable levels of noise reverberation were occurring within the Powerhouse Energy Campus, specifically the first through third floors of the renovated office and lab space. The renovated interior of the Powerhouse consisted largely of open floor plans with minimal closed rooms to allow the building's heating and cooling system to function. The open floor plan and use of hard surface interior building materials created problematic noise levels for the office occupants as noise from laboratory spaces or offices could be heard throughout the building. Mr. McGoldrick requested that a noise evaluation be conducted for the interior of the Powerhouse to identify potential acoustical treatments to reduce the reverberant noise in the space.

The project was assigned to Industrial Hygiene Master's student Christopher Quinn-Vawter, who conducted reverberation measurements. During the walkthrough, room dimensions and materials were noted. In some rooms, acoustical baffles had been installed to reduce reverberant noise levels (baffles were noted in the classroom and conference room) however, the baffles were not designed to control the specific lower frequency noise issues within the Powerhouse. Under the guidance of Dr. Brazile, absorptive acoustic materials were researched to control the problematic noise identified in the walkthrough. Treatment options were selected that would both effectively control the reverberant noise based on the frequency spectrum, and would require minimal alterations to the interior of the Powerhouse.

Highly reverberant environments, i.e., spaces with higher than desired reverberation decay times, can have many different effects depending on how the space is configured and used. An industrial hygienist would be most likely to encounter reverberant noise problems when the reverberant field is either propagating high levels of noise from equipment or the field is causing speech communication issues for workers [1-3]. Low intensity reverberant fields, such as a high bay with light equipment use or a large office space, can still be a significant source of distraction and irritation for workers. Building spaces with high reverberation can create irritating environments for occupants and can interfere with communication, especially when workers try to talk to each other across a room [4, 5]. Both speech and telecommunication equipment such as phones or radios can be significantly impeded in a highly reverberant environment.

This project provided a unique opportunity to evaluate the method available to most industrial hygienists to measure and predict reverberant noise: Sabine's Formula and the impulse noise method of reverberation measurement. These methods are relatively simple and require no specialized equipment other than a clapper board or other impulse generating device that can be purchased for no more than two or three hundred dollars. This is a sharp contrast to the popular methods of reverberation measurement that require speaker and amplification systems costing several thousand dollars and advanced computer programs to model the acoustic fields. These expensive and complex systems are impractical for all but the most specialized industrial hygiene consultant, and as a result many industrial hygienists try to avoid reverberant field evaluations or do not consider it in a noise evaluation.

Reverberation decay times were measured in several locations on the first, second, and third floors inside the Powerhouse building. The reverberation decay time (RT_{60}) is measured as the time required for a frequency band to decrease by 60 dB after a loud sound pulse. RT_{60} times were measured at 125, 250, 500, 1000, 2000, and 4000 Hz. These frequency ranges are most commonly associated with undesirable acoustic properties in interior spaces [1, 3, 6]. Using notes taken during the building walkthrough and construction diagrams of the Powerhouse remodel provided for this evaluation, a reverberation model was created to test acoustical treatments. The model was created using only basic calculations with Sabine's Formula [1, 3, 7]. Building material sound absorption coefficients were determined using standard absorption coefficient tables; materials and surface areas were determined through building walkthroughs and the specifications of the construction diagrams [1, 8-10]. The reverberation models were then used to calculate new RT_{60} times after treating the areas with different acoustic materials such as panels and baffles using the material specifications provided by the manufacturers.

Sabine's Formula has fallen out of favor with acoustic engineers, being replaced with much more precise computer programs. While no longer used in precise acoustic applications, Sabine's Formula is likely to meet the needs of any industrial hygienist faced with a reverberant noise problem. To use the unique environment of the Powerhouse to evaluate the use of Sabine's Formula for industrial hygiene applications, the RT_{60} predictions calculated with the Sabine's Formula model were then compared to the RT_{60} times measured in each location. The RT_{60} times were taken again after the installation of the recommended treatments for two rooms. This allowed for the evaluation of both the modeling capabilities of Sabine's Formula and the practical industrial hygiene application of the equation to select effective acoustic treatments to control reverberant noise.

CHAPTER 2: LITERATURE REVIEW

Introduction

The behavior and control of sound has been a vital component of building design since the construction of large performance arenas and meeting halls began. From the ancient Greek amphitheaters to the Gothic cathedrals of Europe to 19th century American university lecture halls, the control of sound was vital for speech and music to be heard throughout the space. Despite the fact that building acoustics was critical to the success of these spaces, acoustics was still more of a guessing game. Architects would borrow design aspects from other buildings, hoping to create a similar acoustic environment without truly understanding what factors influenced the acoustics of the rooms.

Acoustic problems were very difficult and expensive to correct. With no widely accepted methodology for guidance, the hapless engineers were left to a guessing game trying to get the room acoustics right. The Fogg Art Museum at Harvard University was built with a lecture hall modeled directly after Harvard University's Sanders Theatre [11]. The Sanders Theatre had excellent acoustic properties, a speaker could be heard clearly and easily throughout the audience, and naturally the designers of the Fogg Art Museum thought that by copying the layout of the Sanders Theatre the Fogg's new lecture hall would have the same excellent acoustics. However, after the new lecture hall was completed the acoustics in the hall were so bad it was barely useable for its intended purpose. Clearly the acoustics are affected by more than just the structure of the room. The materials used in the Fogg's construction were quickly listed as the cause of the acoustic problems, the new hall was finished in plaster laid over tile while the Sanders was finished almost entirely in wood and wood paneling [11]. While this explanation seemed reasonable, it was quickly countered with examples of auditoriums finished in wood that had equally terrible acoustics. Clearly finding a solution to room acoustic problems would be a complex process with many different factors contributing to the acoustic environment [11].

Harvard University enlisted the help of physics professor Wallace Clement Sabine to correct the acoustics of the Fogg's lecture hall in 1895 [11]. Frustrated with the absence of empirical evidence to guide him, Sabine began a years-long project to quantify the behavior of sound in enclosed spaces and started the field of modern acoustic research [3-5, 11, 12]. Sabine's research was the first to explore the characteristics of different sound frequencies in enclosed spaces in a quantifiable and reproducible way. This led to a breakthrough in the quantification of the reflection and absorption of sound by different materials in a room, a vital component to understanding and controlling the acoustics in a room. Sabine was ultimately able to use the concepts and equations he developed to vastly improve the acoustics of the Fogg's lecture hall, and used the same techniques to assist in the design of the Boston Music Hall [3-5, 11, 12]. Sabine had demonstrated that the control of room acoustics was not the impossible task that had been thought, but could be controlled and even predicted before a space was built.

Reverberation

Sabine's major breakthrough was the study and modeling of sound reverberation in an enclosed space. A reverberant noise field is created when the sound reflects off of one or more surfaces before reaching the subject, in contrast to a free or direct field in which the sound travels directly from the source to the subject (Figure 2.1) [1, 3]. While the direct field generated by a source can be easy to predict and control, the reverberant field created by the same source can be much more complex. For an industrial hygienist trying to develop noise controls in an environment such as a warehouse or high bay, being able to calculate the reverberant field effects

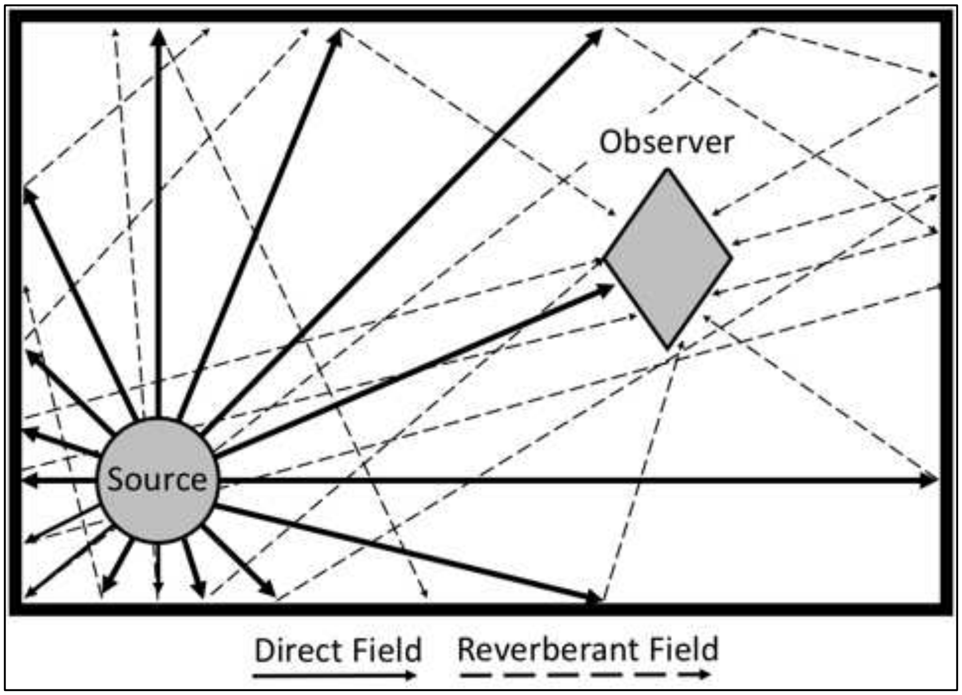


Figure 2.1: Direct vs. Reverberant fields.

can be a critical step in selecting effective noise controls. Depending on the acoustic characteristics of the space and the distance from the noise source(s), the reverberant field may be contributing significantly more to a worker's noise exposure than the direct noise field [1-3].

The direct noise field is what many industrial hygienists are familiar with and comfortable using, and it is most commonly considered during a noise survey for a new piece of equipment or process change. A direct field can be controlled at the source, isolating or reducing the power of the source will have an immediate effect on the observer's perception of the noise. The direct field is also very easy to model to determine an observer's exposure and to model changes in the field when the noise source is changed. The intensity of the direct field is heavily reliant on the power and intensity of the noise source and can be effectively modeled with equation 2.1 [1]:

Equation 2.1:

$$L_p = L_w + 10\log\left(\frac{Q}{4\pi r^2}\right) + k$$

where;

L_p = sound pressure level in decibels (dB)

L_w = sound power level of the source in watts

Q = directivity factor

r = distance to source

k = constant factor, 10.5 if English units, 0 if metric

The directivity factor (Q) in this equation accounts for some reverberant effect on the sound pressure level, but only for a single reflection back to the observer. Q may equal 1, 2, 4, 8, or 16 depending on the number of reflective surfaces near the source (0-4, walls, floor, ceiling), and the measured sound level will increase by 3 dB for each reflective surface added. The directivity factor alone is sufficient when the reflections off the nearby walls are the only major source of reverberation [1-3]. For example, the noise level from an air compressor installed outside against the side of a warehouse may be adequately predicted by only using the directivity factor. However, if the air compressor were to be installed inside of the warehouse the reverberant field become significantly more complex and the directivity factor may not be enough to predict the noise levels, especially as the distance from the compressor increases and the reverberant field becomes the dominant noise source.

A reverberant field can significantly increase the sound pressure level created by a noise source as the sound waves are reflected back rather than dissipating in a free field. Reverberant fields rely entirely on the characteristics of the room and the capacity of the materials to reflect or absorb the noise. These fields must be measured or modeled in each space to characterize and treat the reverberant noise, and are usually presented as reverberation decay times or a room constant (R) [1-3]. The direct field equation can be modified to account for the reverberant field of an enclosed space with equation 2.2 [1]:

Equation 2.2:

$$L_p = L_w + 10\log\left(\frac{Q}{4\pi r^2} + \frac{4}{R}\right) + k$$

where;

R = room constant of the selected octave band (ft^2or m^2)

The room constant for single octave band represents the capacity of the room to absorb or reflect acoustic energy within that frequency range. It is calculated using the noise absorption coefficient, or α value, of the materials present in the room. This method allows for a more accurate prediction of the noise generated by a piece of equipment because it will account for the added reflections and absorptions of the sound wave when it encounters the materials in the room. Like all reverberant field calculations, it requires additional information regarding the room materials and their associated α values [1, 3, 12].

An α value represents the percent of energy that is absorbed by the material instead of reflected back into the space, these values range from 0 (all reflected) to 1 (all absorbed). A material can have significantly different acoustic properties at different frequencies, making the α values critical to understanding a reverberant field in a room [1, 3, 12]. An example of three different α value trends is presented in Table 2.1, the window glass absorbs more of the low frequency noise and reflects the high frequency, the carpet on concrete will reflect the low frequency noise but absorb the high frequency, and the tile is highly reflective across all

Table 2.1: Example α values for glass, heavy carpet, and tile from 125-4000 Hz [1].

Material	Single octave band (Hz)					
	125	250	500	1000	2000	4000
Window glass	0.35	0.25	0.18	0.12	0.07	0.04
Heavy carpet on concrete	0.02	0.06	0.14	0.37	0.60	0.65
Tile on concrete	0.02	0.03	0.03	0.03	0.03	0.02

frequencies. A material's α value is determined by the material's physical properties. In general, a hard, smooth surface such as tile will be highly reflective and have very low α values while a soft or porous surface will have high α values [12]. Absorption of acoustic energy within a material occurs through two primary mechanisms, direct interaction with the material to transform the acoustic energy to heat, and through dissipation of the sound wave as it travels through the air spaces within the material [12]. The absorption of sound by a material is highly frequency dependent. As illustrated in Figure 2.2, a material may completely absorb the acoustic energy at 1000 Hz, and may reflect a majority of the energy at 250 Hz. The high variability in the reflectivity of materials as the frequency changes makes it imperative to know the materials in a room and the associated α values before attempting any reverberant noise controls in the room. Attempting reverberation controls without first understanding the acoustic characteristics of the room can lead to completely ineffective controls or even make the problem worse if the control materials added are actually reflective to the problem frequencies in the room [1, 3, 12].

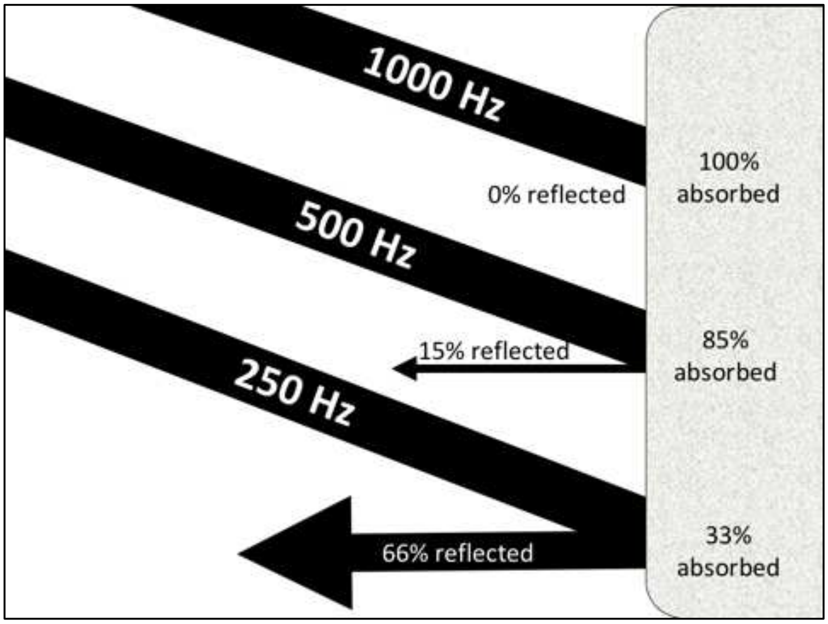


Figure 2.2: Example sound pressure wave absorption for a material with α values of 1.00, 0.85, and 0.33 at 1000, 500, and 250 Hz, respectively.

Reverberant Field Measurement

The reverberant field in a room is typically quantified by using reverberation decay times. The reverberation decay time (RT_{60}) is measured as the time required for a frequency band to decrease by 60 dB after a loud sound pulse. RT_{60} times are measured at single octave bands centered at 125, 250, 500, 1000, 2000, and 4000 Hz. These frequency ranges are most commonly associated with undesirable acoustic properties in interior spaces [1, 3-5]. In a highly reflective environment, the sound wave will not be absorbed and will be reflected around the room. As the sound wave is reflected off the surfaces, it loses energy very slowly and may take several seconds for the sound pressure level to drop by 60 dB leading to a relatively long RT_{60} time. Conversely, in a highly absorptive environment, the sound wave will quickly transfer its energy to the surface materials as it is absorbed. This causes the sound pressure level to drop by 60 dB very quickly, resulting in a relatively short RT_{60} time [12].

Measuring RT_{60} times is done with one of two methods: the impulse method or the interrupted noise method [3, 12-15]. The interrupted noise method is widely accepted as the most accurate and most repeatable RT_{60} measurement. This method requires a large omnidirectional speaker system to generate a loud white noise signal evenly across 125-4000 Hz (minimum) to build up and sustain the reverberant field in the room. Once the reverberant field is sustained, the speakers are shut off and the sound level meter (SLM) records the time for the sound pressure levels of each octave band to drop and calculates the corresponding RT_{60} times [3, 12-15]. While this method is the most precise, the high cost and size of the speaker and amplifier systems make it impractical for all but the most specialized industrial hygiene consultants. In most noise control scenarios, the simpler impulse method will be sufficient to begin evaluating the acoustic properties of a room [16, 17]. With the impulse method, the constant reverberant field is replaced with a single loud sound pulse. The impulse sound may be generated by multiple different methods as long as the impulse is loud enough to be detected by the SLM over the background noise [14, 18, 19]. The impulse may be created by methods such as popping a regular party balloon, a firecracker, a starter pistol, or a specially designed clapper board. The simplicity and low cost of this method make it a good option for most industrial hygienists faced with a reverberant noise problem.

Reverberant Field Effects

Highly reverberant environments, spaces with higher than desired RT_{60} times, can have many different effects depending on how the space is configured and used. An industrial hygienist would be most likely to encounter reverberant noise problems when the reverberant field is either propagating high levels of noise from equipment or the field is causing speech communication issues for workers [1-3]. In these scenarios, high-intensity reverberant fields can cause significant health and safety issues with potentials for hearing loss and communication interference that must be addressed.

However, low intensity reverberant fields, such as a high bay with light equipment use or a large office space, can still be a significant source of distraction and irritation for workers. Building spaces with high reverberation can create irritating environments for occupants and can interfere with communication, especially when workers try to talk to each other across a room [4, 5]. Both speech and telecommunication equipment such as phones or radios can be significantly impeded in a highly reverberant environment. When RT_{60} times approach 3 seconds, voice communication becomes impeded as syllables can begin to overlap and determining directionality becomes difficult [4, 5, 20]. To prevent communication difficulties and occupant irritation, RT_{60} time recommendations have been developed for different building uses, and are typically between 0.5-1.0 second for large open-floor office spaces and general work areas [4-6, 12, 21]. This RT_{60} time range prevents a significant buildup of the reverberant field, and because the buildup and persistence of the reverberant field is what causes problem acoustics, the short-lived reverberation cannot contribute significantly to the noise perceived in the space [4, 5, 12].

Reverberant Field Controls

Once the reverberant field of a space has been measured and characterized, acoustic controls can be selected and installed to modify the field. Controls must be selected based on the characteristics of the room, the room may require control of only the low or high frequencies, or may require controls that focus on the midrange frequencies. Selecting and installing reverberation controls without first understanding the acoustic characteristics of the room can lead to completely ineffective controls or even make the problem worse if the control materials added are actually reflective to the problem frequencies in the room [1, 3, 12].

Two main types of controls are used for reverberant fields: diffusive materials and absorptive materials [12]. Diffusive materials work by reflecting the noise away from the source so they are not reflected back as a reverberant field. These materials only minimally absorb the acoustic energy and instead rely on the sound being reflected on a path that will not reach the observer. Diffusive materials must be installed with great precision and engineering in order to function correctly, they are frequently seen in environments like theaters and stadiums. However, the complexity involved with using large amounts of diffusive surfaces makes them an unlikely choice for anyone other than an acoustic engineer [3, 6, 12]. Absorptive materials, as the name would imply, do absorb the acoustic energy, transforming it to thermal energy in the material and preventing the soundwave from being reflected back out into the space. Absorptive materials can only absorb acoustic energy at specific frequencies dependent on their physical properties; that ability to absorb energy is quantified as the α value [12]. To control a reverberant field consisting primarily of low frequencies, a material with high α values in the low frequency ranges must be selected. To control a reverberant field consisting primarily of high frequencies, a material with high α values in the higher frequencies must be selected. If an absorptive material is selected that has low α values in the problem frequencies, the attempted treatment can actually make the reverberant field worse as the material is reflecting those frequencies instead of absorbing them. Absorptive materials are much easier to install; many are designed to be hung as panels on the walls or ceiling or can be attached directly to the walls or ceiling of the space. The simplicity of absorptive materials makes them by far the most common reverberant noise control and the one most likely to be used by an industrial hygienist to control a problem space [3, 6, 12].

Reverberant Field Prediction

In order to select an effective acoustical treatment, the industrial hygienist must have a way to model the reverberant field of the room. With his work on the Fogg Art Museum, Sabine developed the first model for reverberant field prediction with Sabine's Formula [3, 11]. The use of Sabine's Formula requires knowing the room volume, the surface areas of all major materials in the room, and the associated α value for each material. With these three pieces of information, the RT_{60} time for an octave band may be calculated. This was the first time that a reverberant field could be modeled and used to aid in the design of new spaces and to improve the acoustics of existing spaces like the lecture hall in the Fogg Art Museum [3, 11]. The simplicity of Sabine's formula, however, leaves it susceptible to error as spaces become more complex. Using modern reverberation measurement equipment, the error range of Sabine's formula predictions varies from approximately 10% to 32% as a 125-4000 Hz average [22-24].

Soon after the development of Sabine's Formula, acoustic researchers began the push for more accurate models to aid in design [25]. Carl Eyring led the development of new models with the creation of Eyring's Formula for use in highly absorptive acoustic environments such as sound booths [5, 6, 12, 25]. This was followed by increasingly specialized formulas to address problems in a wide variety of acoustic environments. To further improve the ability to handle larger and more complex models, software programs have been developed such as Odeon Room Acoustics Software (Odeon A/S, Lyngby, Denmark) and LMS Virtual.Lab Acoustics (Siemens Product Lifecycle Management Software Inc., Plano, TX). These advanced software programs are able to model very small changes to the acoustic environment, and are frequently used when designing environments such as sound booths and theaters, and testing components in aerospace and other industries [17, 22-24, 26].

While the computer programs are able to handle extremely complex and detailed models of acoustic environments, they are not practical for use within general industrial hygiene. The simplicity of Sabine's Formula, and the ability to run the models and take acoustic measurements without highly specialized and costly equipment make it the most practical model for an industrial hygienist to use when faced with a reverberant noise problem.

CHAPTER 3: PURPOSE AND SCOPE

The aim of this study was to determine the ability of Sabine's Formula to model reverberant noise for the selection and installation of acoustical treatments. The researchers also evaluated the room characteristics at which Sabine's Formula performs best or begins to generate unreliable results. The consistency of materials used in the interior of the Powerhouse allowed rooms with similar reflectivity but different configurations and volumes to be compared.

The first study within the project (Study 1: Model Performance) evaluated the ability of Sabine's Formula to adequately model reverberation in the current room conditions at different room volumes ranging from 76 m^3 to 5400 m^3. Reverberation times were measured at the single octave-bands 125, 250, 500, 1000, 2000, 4000, and 8000 Hz. Reverberation times were taken in the selected areas of the Powerhouse (classroom, first/second floor entry and office area, second floor conference rooms, and third floor office area) in the original room configurations. Reverberation models were also created for each area of the building using Sabine's Formula at the single octave-bands from 125- 4000 Hz, and the modeled and measured times were compared. This comparison was used to determine the accuracy of Sabine's Formula in different room configurations and volumes.

The second study within the project (Study 2: Room Treatment) evaluated the practical use and performance of Sabine's Formula and the impulse noise method of reverberation measurement to select effective acoustic treatments in an industrial hygiene application. A goal 125-4000 Hz mean RT_{60} time of 0.5-1.0 second was selected using industry recommendations for large open-floor office spaces and general work areas [4-6, 12, 21]. Multiple commercially available acoustic panels and baffles were modeled in different configurations until a treatment was created that met the required RT_{60} time benchmark in the model. The selected treatment was then installed in the classroom and the second floor conference room. Reverberant noise measurements were then taken using the same method as the measurements taken in the original spaces. The treated room RT_{60} times were then compared to the RT_{60} times of the original room configurations to assess the ability of simple reverberation measuring and modeling techniques to design effective acoustic treatments.

CHAPTER 4: METHODS AND MATERIALS

Study 1: Model Performance

Reverberant Noise Modeling

Six rooms in the Powerhouse Energy Campus were selected for reverberant noise modeling. In order to model the reverberant noise in the different areas, the reverberation times (RT_{60}) were calculated for each room at the octave band frequencies 125, 250, 500, 1000, 2000, and 4000 Hz. Calculating the RT_{60} time for each of the identified frequencies required the use of Sabine's Formula. Two versions of Sabine's Formula were used for this study; for frequencies 1000 Hz and below equation 4.1 was used [3, 11, 22, 27]:

Equation 4.1:

$$RT_{60} = \frac{0.161V}{A}$$

for frequencies 2000 Hz and above equation 4.2 was used [3, 11, 22, 27]:

Equation 4.2:

$$RT_{60} = \frac{0.161V}{(A + 4mV)}$$

where;

V = room volume (m^3)

A = total room absorption (Sabins)

m = air absorption coefficient

The air absorption coefficient (m) only has a significant impact on RT_{60} times for frequencies 2,000 Hz and higher. The value of m is heavily dependent on the relative humidity and temperature of the room air [3, 28]. In this study the values for m were selected using a relative humidity of 20%, near the relative humidity maintained by the climate control systems of the Powerhouse. The total room absorption in Sabins (A) was determined using equation 4.3 [1, 11, 22, 27]:

Equation 4.3:

$$A = \sum_{i=1}^{n} (S_1\alpha_1 + S_2\alpha_2 \ldots + S_n\alpha_n)$$

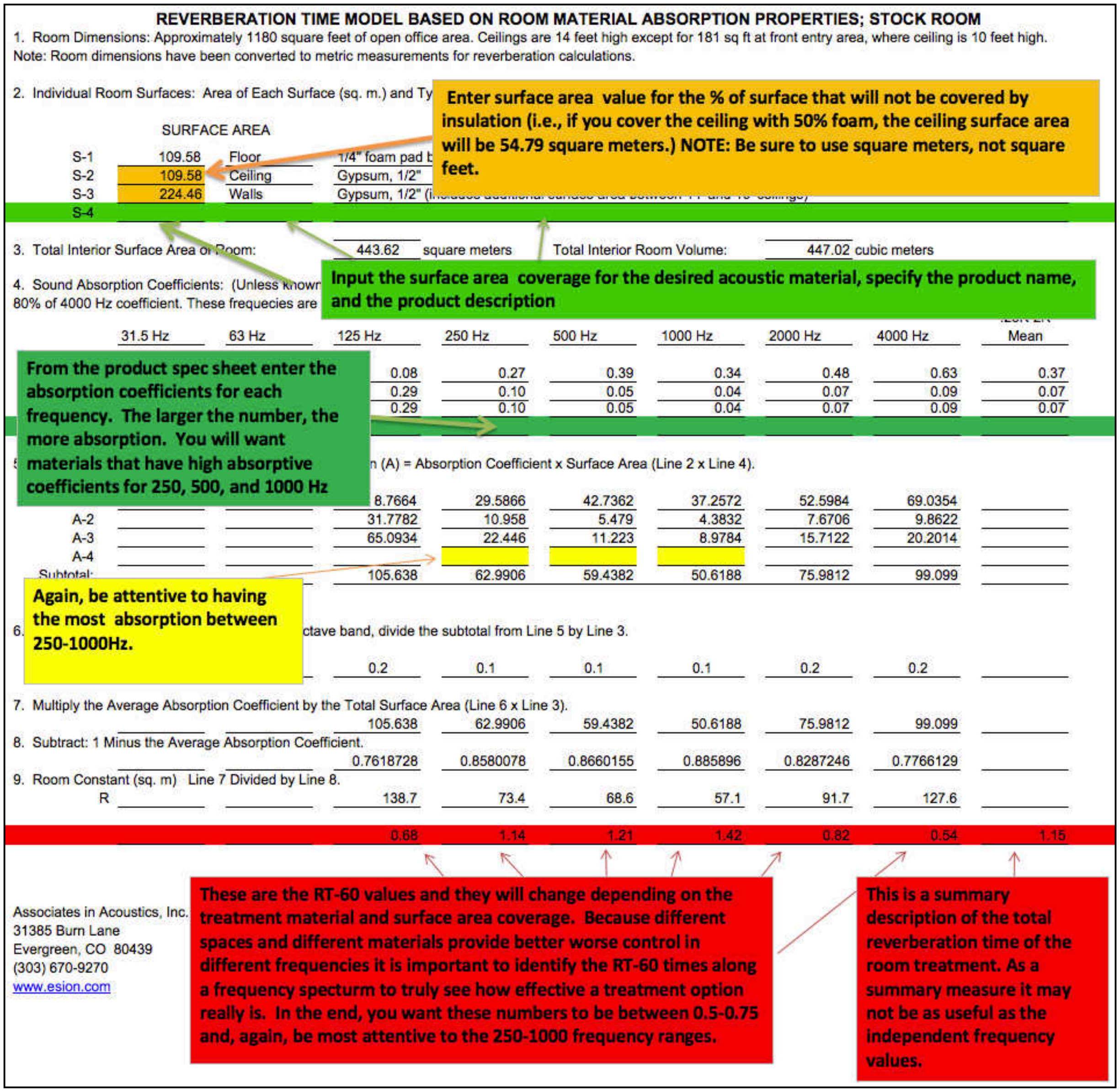
where;

S_n = area of the n^{th} surface in the room (m^2)

α_n = absorption coefficient of the n^{th} surface in the room

The area of each surface type was determined using the floor plans obtained from the construction of the Powerhouse, along with notes and photographs taken during the site walkthroughs. When calculating surface areas, all materials contributing significantly to the total surface area of the room were measured (e.g., wood tables, doors, and wall panels); smaller, highly variable surfaces were not measured (e.g., laboratory equipment, desktop computers). The individual surface areas of similar materials were combined to create a single total for each common material such as drywall, glass, and steel. After the material surface totals were determined, each material was assigned its corresponding noise absorption coefficient, or α value, for each single octave band from 125-4000 Hz. The material α values were obtained from available sound absorption coefficient tables [1, 8-10, 29]. If α values for a specific room material were not available, the α values from the most similar material listed were used.

After the major reflective surfaces of a room were identified, the surface areas of each material were calculated, and each material was assigned an α value; the information was entered into a Microsoft Excel® spreadsheet created by Associates in Acoustics Inc. to perform room RT_{60} calculations [7]. The spreadsheet model tracks all room parameters entered and uses Sabine's Formula to generate RT_{60} times for each octave band from 125-4000 Hz (Figure 4.1). The spreadsheet model also adjusts for the air absorption coefficient at 2000 and 4000 Hz. The air absorption coefficient for 20% relative humidity ($m = 0.0066$ at 2000 Hz and $m = 0.0197$ at 4000 Hz [3]) was entered into the model. The modeling procedure was repeated for each of the six selected room areas in the new addition of the Powerhouse Energy Campus.



REVERBERATION TIME MODEL BASED ON ROOM MATERIAL ABSORPTION PROPERTIES; STOCK ROOM

1. Room Dimensions: Approximately 1180 square feet of open office area. Ceilings are 14 feet high except for 181 sq ft at front entry area, where ceiling is 10 feet high.
Note: Room dimensions have been converted to metric measurements for reverberation calculations.

2. Individual Room Surfaces: Area of Each Surface (sq. m.) and Ty

	SURFACE AREA		
S-1	109.58	Floor	1/4" foam pad b
S-2	109.58	Ceiling	Gypsum, 1/2"
S-3	224.46	Walls	Gypsum, 1/2" (i
S-4			

Enter surface area value for the % of surface that will not be covered by insulation (i.e., if you cover the ceiling with 50% foam, the ceiling surface area will be 54.79 square meters.) NOTE: Be sure to use square meters, not square feet.

3. Total Interior Surface Area of Room: 443.62 square meters Total Interior Room Volume: 447.02 cubic meters

4. Sound Absorption Coefficients: (Unless known
80% of 4000 Hz coefficient. These frequecies are

Input the surface area coverage for the desired acoustic material, specify the product name, and the product description

	31.5 Hz	63 Hz	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz	Mean
			0.08	0.27	0.39	0.34	0.48	0.63	0.37
			0.29	0.10	0.05	0.04	0.07	0.09	0.07
			0.29	0.10	0.05	0.04	0.07	0.09	0.07

From the product spec sheet enter the absorption coefficients for each frequency. The larger the number, the more absorption. You will want materials that have high absorptive coefficients for 250, 500, and 1000 Hz

n (A) = Absorption Coefficient x Surface Area (Line 2 x Line 4).

			8.7664	29.5866	42.7362	37.2572	52.5984	69.0354	
A-2			31.7782	10.958	5.479	4.3832	7.6706	9.8622	
A-3			65.0934	22.446	11.223	8.9784	15.7122	20.2014	
A-4									
Subtotal:			105.638	62.9906	59.4382	50.6188	75.9812	99.099	

Again, be attentive to having the most absorption between 250-1000Hz.

6. ctave band, divide the subtotal from Line 5 by Line 3.

			0.2	0.1	0.1	0.1	0.2	0.2	

7. Multiply the Average Absorption Coefficient by the Total Surface Area (Line 6 x Line 3).

			105.638	62.9906	59.4382	50.6188	75.9812	99.099	

8. Subtract: 1 Minus the Average Absorption Coefficient.

			0.7618728	0.8580078	0.8660155	0.885896	0.8287246	0.7766129	

9. Room Constant (sq. m) Line 7 Divided by Line 8.

R			138.7	73.4	68.6	57.1	91.7	127.6	
			0.68	1.14	1.21	1.42	0.82	0.54	1.15

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These are the RT-60 values and they will change depending on the treatment material and surface area coverage. Because different spaces and different materials provide better worse control in different frequencies it is important to identify the RT-60 times along a frequency specturm to truly see how effective a treatment option really is. In the end, you want these numbers to be between 0.5-0.75 and, again, be most attentive to the 250-1000 frequency ranges.

This is a summary description of the total reverberation time of the room treatment. As a summary measure it may not be as useful as the independent frequency values.

Figure 4.1: Room reverberation time model example [7].

Room areas were selected for the project through two processes. The first selection method was through the recommendations of building management to identify areas with problem acoustics. Areas identified by building management included: the classroom, two frequently used conference rooms, and the large combined atrium and office space. Once these priority areas were identified, additional rooms with similar construction materials were selected. The additional similar material areas included the third floor office space, and the first floor laboratory space. The six areas selected for the study ranged in volume from 76 m^3 to 5400 m^3, and all areas were constructed of similar materials with the exception of the atrium area which contained large sections of brick and glass.

Reverberant Noise Measurement

Each area within the Powerhouse that was selected for the RT_{60} time model was also used for RT_{60} measurements after the models had been completed. RT_{60} measurements were taken using a class 1 Larson Davis model 831 sound level meter (SLM) (Larson Davis, Depew, NY) with the reverberation time measurement firmware option installed, a PRM831 preamplifier and a 377B02 free-field microphone. The SLM was pre and post calibrated using a Larson Davis CAL150 field calibration unit. The SLM was mounted securely on a tripod with the microphone perpendicular to the floor at a height of 54 inches (Figure 4.2). The SLM software settings used for all RT_{60} measurements are listed in Appendix A: RT60 Measurement Operating Procedure. The sound impulse was generated using a Larson Davis BAS006 clapper board which is capable of generating an average impulse noise over 80 dB from 125-8000 Hz [18]. The reverberation measurement procedure was based on the recommendations of Larson Davis, and the methodologies specified in American Society for Testing and Materials (ASTM) C423-09a and International Organization for Standardization (ISO) 3382 with modifications for use with

Figure 4.2: SLM mounted on tripod. SLM mounted perpendicular to floor at a height of 54 inches for all measurements.

available equipment [13-15]. The microphone and tripod were placed in a location at least 0.75 m (2.46 ft) from any reflective surfaces such as walls or tables. The impulse noise was generated with the clapper board approximately 4.5 m (15 ft) from the SLM to obtain one RT_{60} decay measurement. The impulses were generated in three different locations around the SLM for a total of three RT_{60} decay measurements per SLM position (Figure 4.3). The SLM was moved to

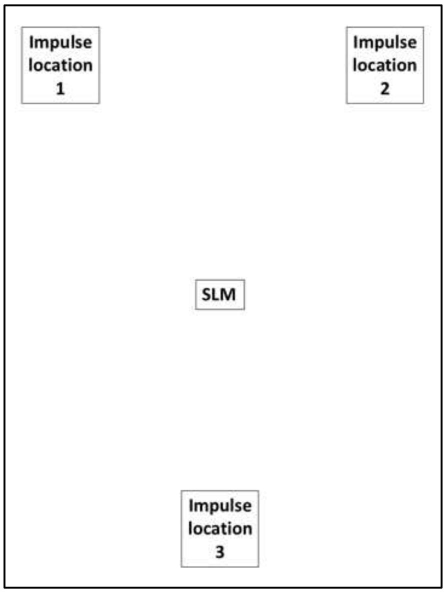

Figure 4.3: Example impulse locations around the SLM.

a minimum of three different locations along the midline of the room to obtain a minimum of nine RT_{60} decay measurements per area (Figure 4.4). The RT_{60} measurement procedure is listed in Appendix A: RT60 Measurement Operating Procedure. To provide the best conditions for the reverberation measurements and to generate the largest possible impulse decays, sampling was only performed when the building was empty and no large equipment was operating. After sampling was completed, the RT_{60} measurement data were downloaded and imported into an Excel® spreadsheet for analysis. The arithmetic mean was calculated using the RT_{30} data to generate the mean RT_{60} times for each single octave band being evaluated. The RT_{30} data are created by the SLM's reverberation time software and uses a 30 dB decay to calculate the RT_{60} time for each octave band. The RT_{30} data are more accurate than the RT_{20} data, and is the preferred method for RT_{60} calculations when the acoustic environment allows for a large enough impulse decay [14].

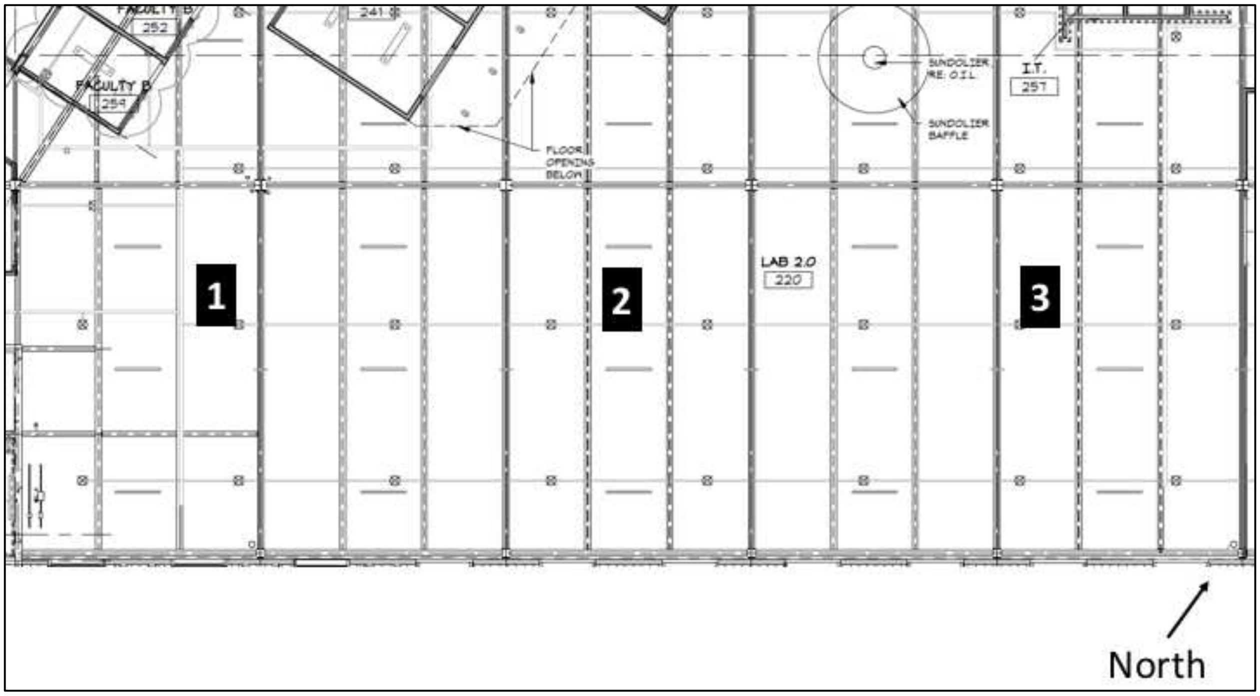

Figure 4.4: Example SLM positions in a room. Each SLM position had three separate impulse decay measurements.

Statistical Analysis

For each of the measured single octave-band mean RT_{60} times, a 95% two-sided confidence interval was applied using a one-sample *t* test. The sample standard deviation for each RT_{60} time was taken from the value calculated by the Larson Davis reverberation time measurement software [14]. The 95% CI from the measured times was then compared to the modeled times, the modeled times were considered successful if the prediction was within the bounds of the 95% CI. To evaluate the predictive ability of the Sabine's Formula model against potential influencing factors such as room volume and frequency, a repeated measures mixed model was used. Using JMP® statistical software from Statistical Analysis System (SAS®) Institute Inc., a mixed model was created setting the room volume, octave-band frequency, and modeled RT_{60} times as factors. The octave band frequency measurement was set as a repeated factor, and the room used for measurements was set as a random factor. The alpha level was set at 0.05 when investigating significant interactions between the factors.

Study 2: Room Treatments

Treatment Models

Using the same reverberant noise modeling methods as were used for the original room spaces, an acoustic treatment was selected that would adequately control the reverberant noise. A goal 125-4000 Hz mean RT_{60} time of 0.5-1.0 second was selected using industry recommendations for large open-floor office spaces and general work areas [4-6, 12, 21]. Multiple commercially available acoustic panels and baffles were modeled in different configurations until a treatment was created that met the required RT_{60} time benchmark in the model. The selected treatment was then installed in the classroom and the second floor conference room. Reverberant noise measurements were then taken using the same method as the measurements taken in the original spaces.

Treatment Selection and Design

Due to the large size of the building and the potential for acoustic environments to change as room use changes, a treatment method that could both be applied to any area of the Powerhouse interior, and be easily expanded on in the future was selected. The treatments tested used 2-inch-thick Echo Eliminator™ bonded acoustical cotton (BAC) panels manufactured by Acoustical Surfaces, Inc. (Acoustical Surfaces, Inc., Chaska, MN). These panels had α values of 0.35 for 125 Hz, 0.94 for 250 Hz and 1 for 500-4000 Hz [30], which made them ideal for the acoustic environment in the Powerhouse. The 2-inch-thick BAC panels had the best low frequency noise attenuation and could be easily cut to size and mounted to any flat surface using adhesive.

To provide the largest reverberation reduction using the fewest acoustical panels, the BAC panel were installed to cover the highly reflective steel surfaces in the Powerhouse. Steel provides between 1-2% noise absorption across all frequencies, and the extensive use of exposed steel in the interior of the Powerhouse significantly contributed to the noise reverberation issues [1, 3]. To simultaneously add noise-absorbing surfaces and reduce the area of steel present, the BAC treatments modeled were installed directly onto the widest face of the horizontal steel support beams along the ceiling of the Powerhouse (see Figure 4.5). Both models were run using increasing areas of BAC panels until the calculated RT_{60} times for 250- 4000 Hz were below one second, and 125 Hz was near one second. To achieve the desired acoustic environment for office use, 60% of the total surface area of the largest face of the horizontal steel beams in the ceiling should be covered with BAC panels in the classroom, and 30% in the conference room.

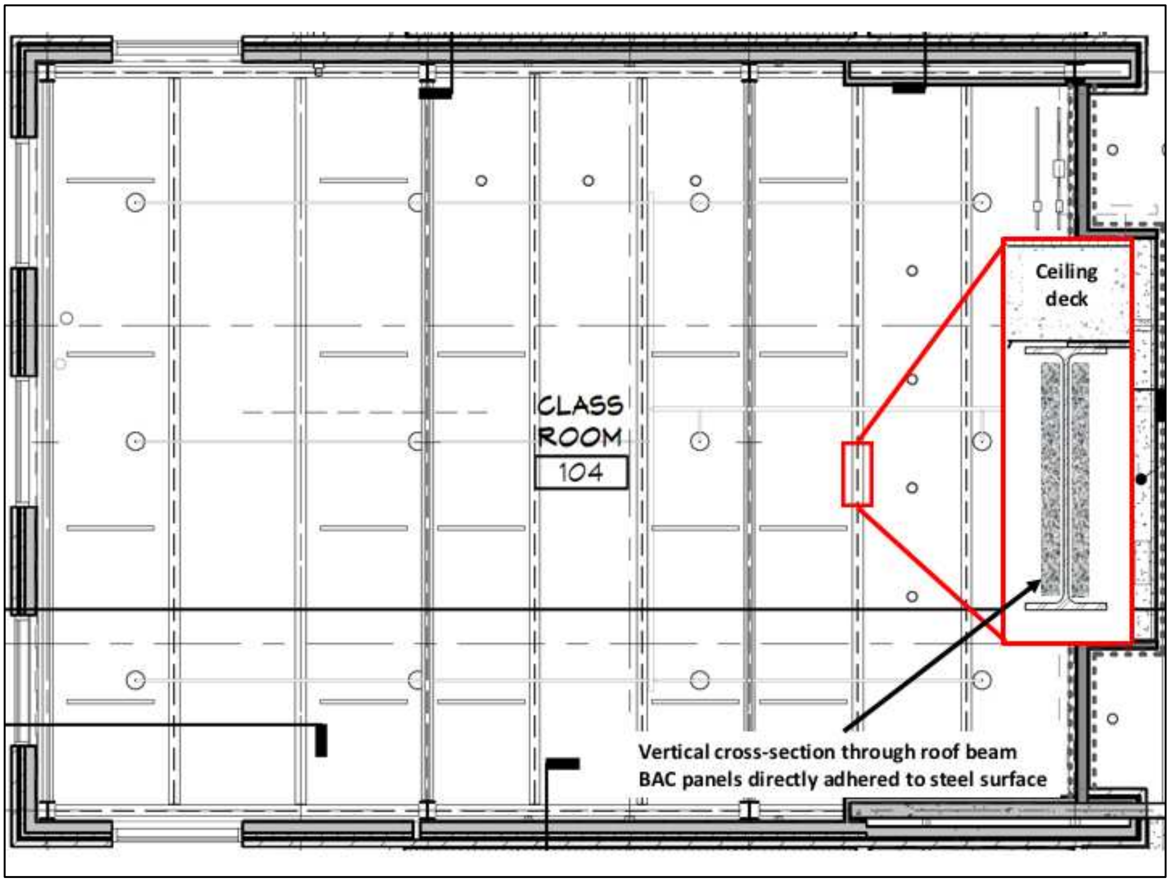

Figure 4.5: BAC panel installation plan.

CHAPTER 5: RESULTS

Study 1: Model Performance

Measured and Modeled RT_{60} Times

The mean measured RT_{60} times and the modeled RT_{60} times at the single octave bands from 125-4000 Hz are listed in Figures 5.1-5.5. A 95% confidence interval (CI) band was applied to the mean measured RT_{60} times. The RT_{60} measurement at the 8000 Hz octave band was included in the graphs, however, a RT_{60} time for 8000 Hz was not modeled. Results of the reverberation measurements and models of all areas indicate that the reverberant field primarily consisted of low frequencies from 125-500 Hz.

The results from the small 76 m^3 second floor conference room are summarized in Figure 5.1. The Sabine's Formula model closely followed the measured reverberation times, ranging from 0.18 (at 125 Hz) to 0.05 (at 1000 Hz) seconds below the measured times. All modeled reverberation times were well within the 95% CI band, though the CI was much larger at lower frequencies.

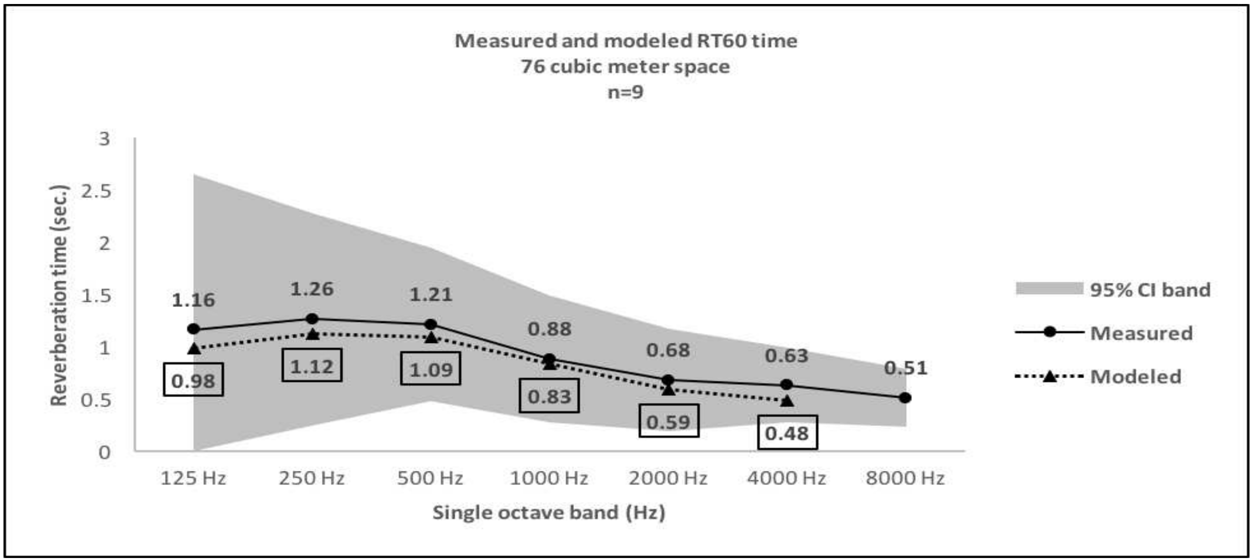

Figure 5.1: Measured and modeled RT_{60} times, 76 m^3 conference room.

The results from the 82 m^3 second floor conference room are summarized in Figure 5.2. The Sabine's Formula model closely followed the measured reverberation times, ranging from 0.24 (at 2000 and 4000 Hz) to 0.02 (at 125 Hz) seconds below the measured times. All modeled reverberation times were within the 95% CI band, though the CI band was much larger at lower frequencies.

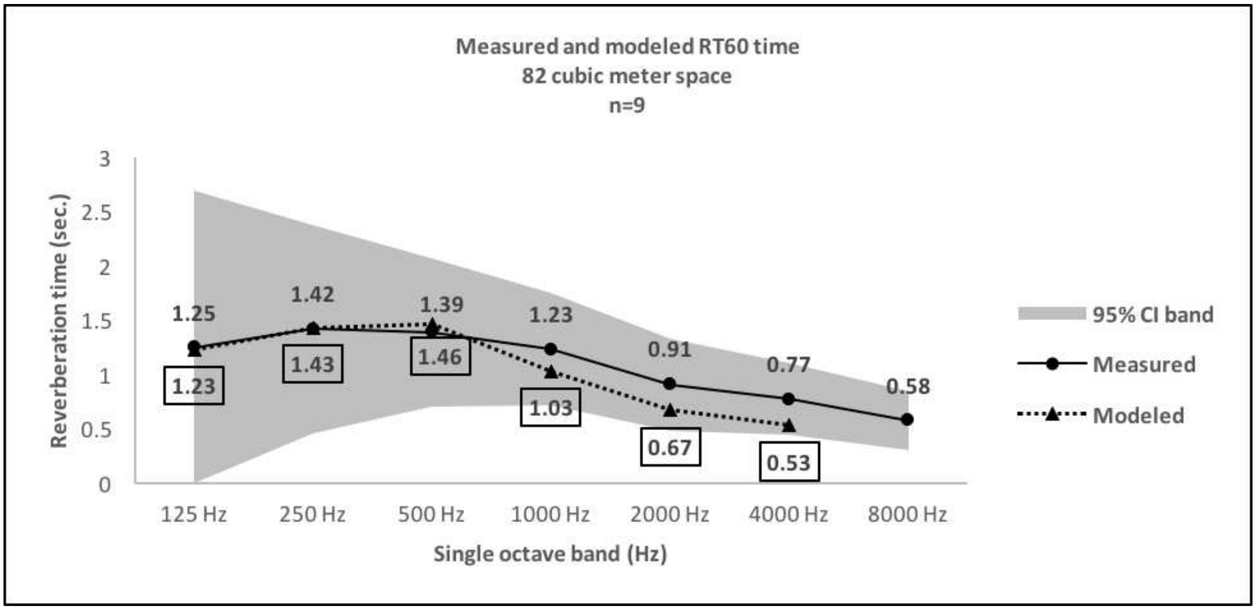

Figure 5.2: Measured and modeled RT_{60} times, 82 m^3 conference room.

The results from the 620 m^3 first floor classroom are summarized in Figure 5.3. The Sabine's Formula model follows the measured reverberation times though not as well as the smaller rooms, ranging from 0.56 (at 250 Hz) seconds above to 0.04 (at 1000 Hz) seconds below the measured times. All modeled reverberation times from 125-2000 Hz were within the 95% CI band, the modeled time exceeded the lower boundary of the CI at 4000 Hz.

The results from the 2100 m^3 third floor office area are summarized in Figure 5.4. The Sabine's Formula model widely overestimated the reverberation times, ranging from 0.94 (at 1000 Hz) to 0.04 (at 4000 Hz) seconds above the measured times. All modeled reverberation

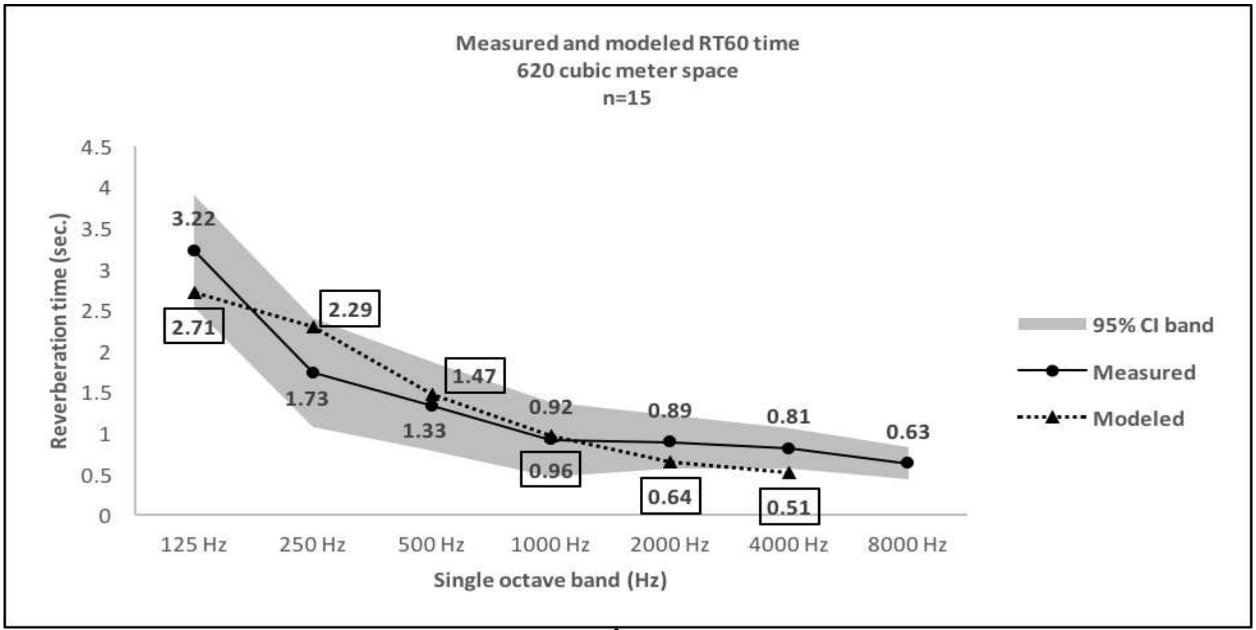

Figure 5.3: Measured and modeled RT_{60} times, 620 m^3 classroom.

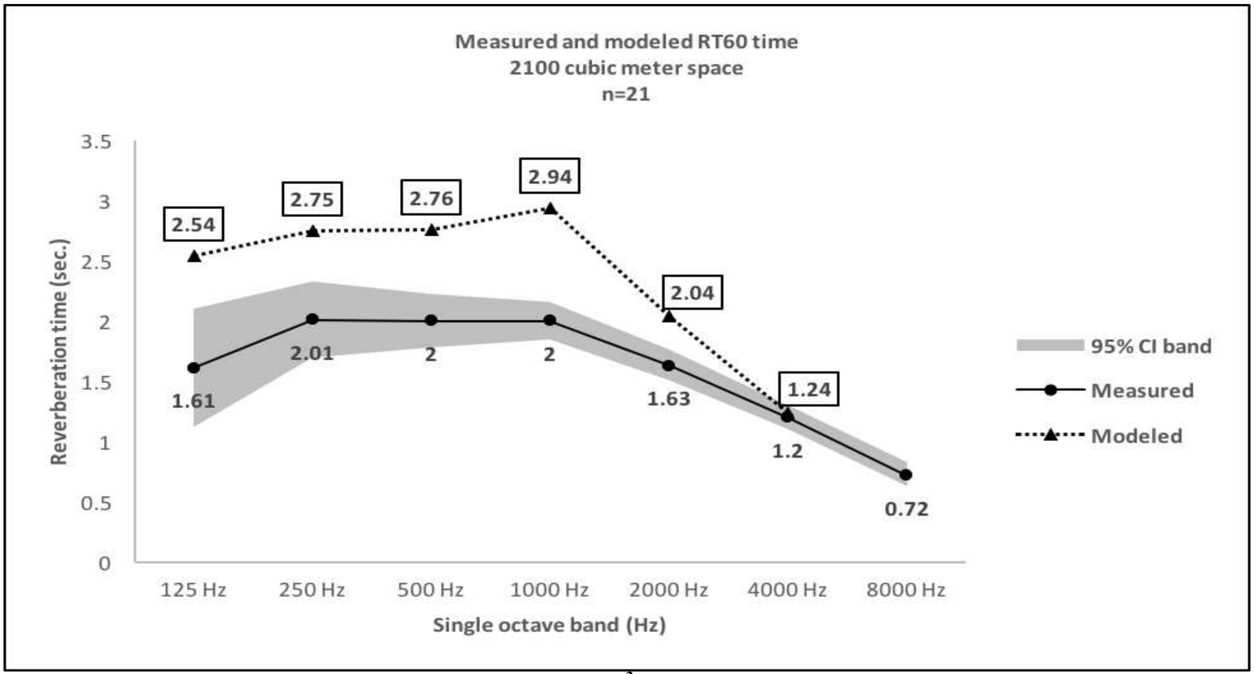

Figure 5.4: Measured and modeled RT_{60} times, 2100 m^3 office area.

times from 125-2000 Hz exceeded the upper 95% CI band, the modeled time fell within the CI at 4000 Hz.

The results from the 5400 m^3 first and second floor atrium and office area are summarized in Figure 5.5. The Sabine's Formula model widely overestimated the reverberation

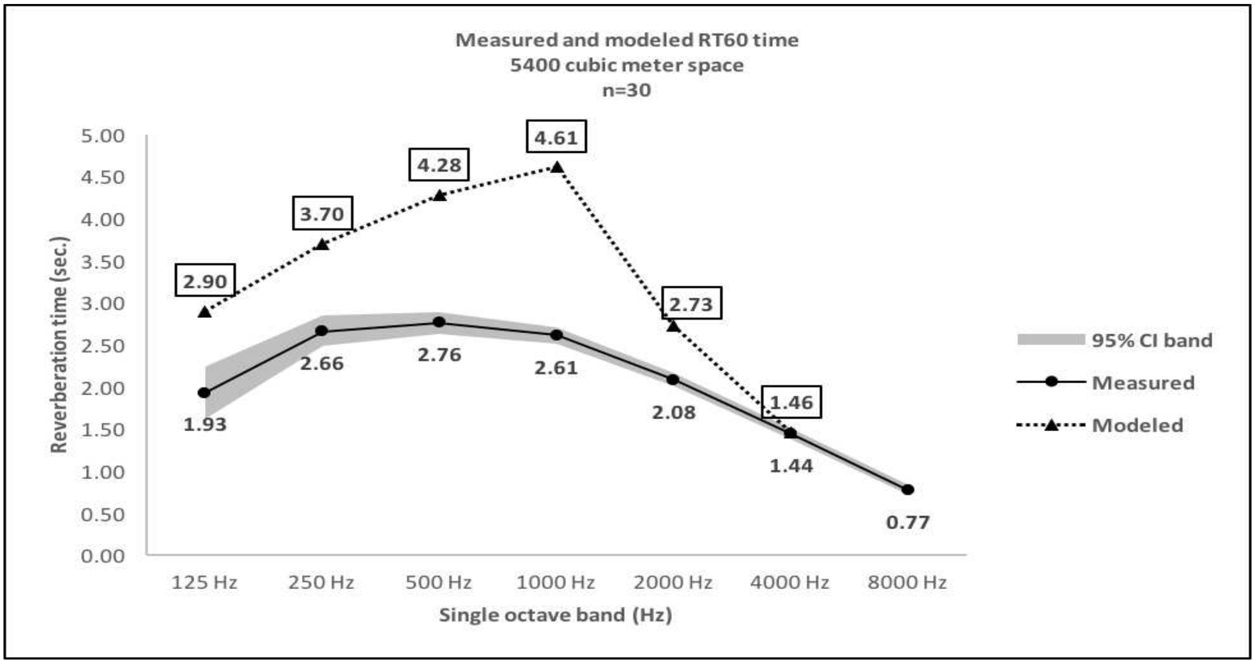

Figure 5.5: Measured and modeled RT_{60} times, 5400 m^3 office area and atrium.

times, ranging from 2.00 (at 1000 Hz) to 0.02 (at 4000 Hz) seconds above the measured times. All modeled reverberation times from 125-2000 Hz exceeded the upper 95% CI band, the modeled time fell within the CI at 4000 Hz.

Model Performance Factors

The percent error of the mean measured RT_{60} times compared to the modeled RT_{60} times are listed in Figure 5.6. The breakdown of percent error by octave band and room size appears to indicate an increasing percent error of the model as the room size increases. There appears to be no significant trend in the error within the octave bands, indicating that the error is dependent on the room volume rather than the frequency being measured and modeled.

Using the repeated measures mixed model, the fit of the measured versus modeled RT_{60} times was evaluated and significant interacting factors with the model were identified. The measured versus modeled RT_{60} time correlation generated a p value less than 0.0001, indicating that the reverberation times calculated by the model are significant predictors of the measured

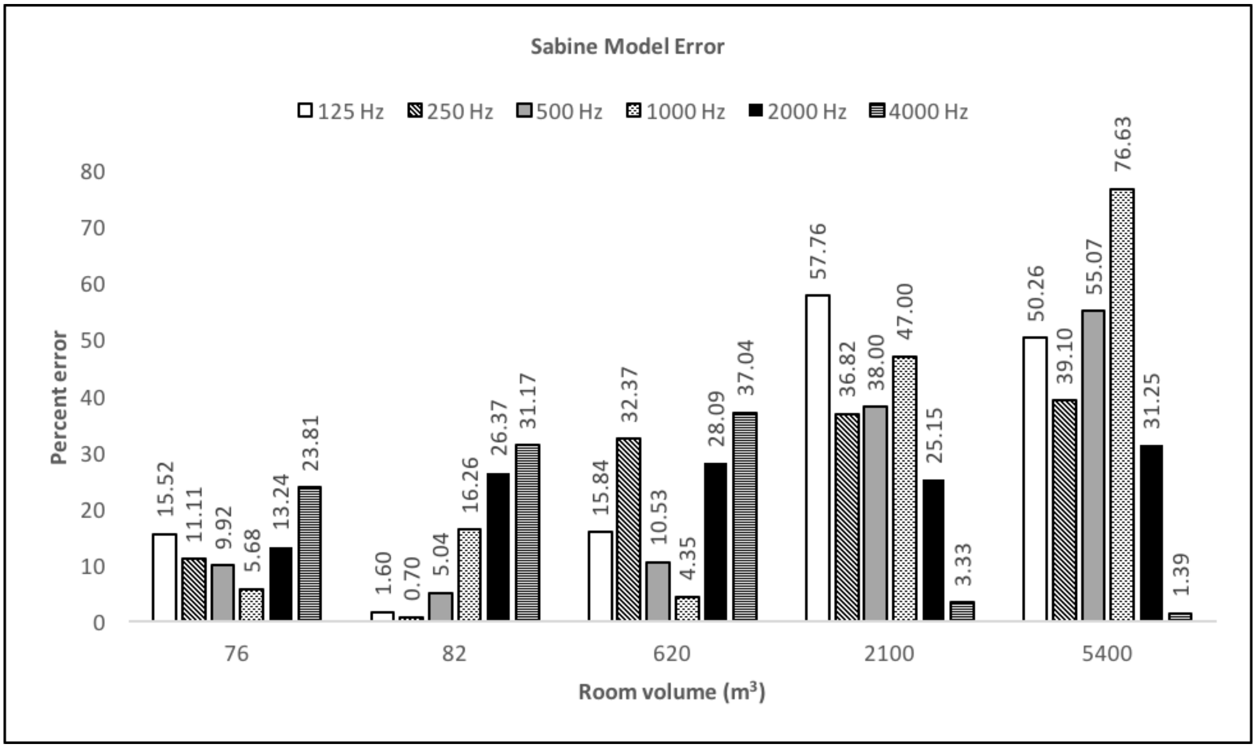

Figure 5.6: Sabine model error by room volume. Error calculated using the mean RT_{60} measurements for each single octave band.

times. The modeled RT_{60} time interaction with room volume generated a p value of 0.01, indicating that the room volume had a significant effect on the predicted reverberation times and the Sabine's Formula model became less effective as the room volume increased. The modeled RT_{60} time interaction with octave band frequency generated a p value of 0.67, indicating that there was no significant interaction with the frequencies being modeled and measured. The Sabine's Formula model had no significant trend for higher or lower percent errors at higher or lower frequencies. The graph in Figure 5.7 is a fit plot of the measured and modeled RT_{60} times plotted by the room volume in which each set of measurements were taken. The equation for each set of measurements is listed in the top left corner of the graph. A fit line slope below 1 is representative of the Sabine's Formula model overestimating the reverberation times; the farther away from 1, the larger the overestimation. A fit line slope of 1 is representative of the Sabine's Formula model correctly predicting the reverberation times. A fit line slope greater than 1 is

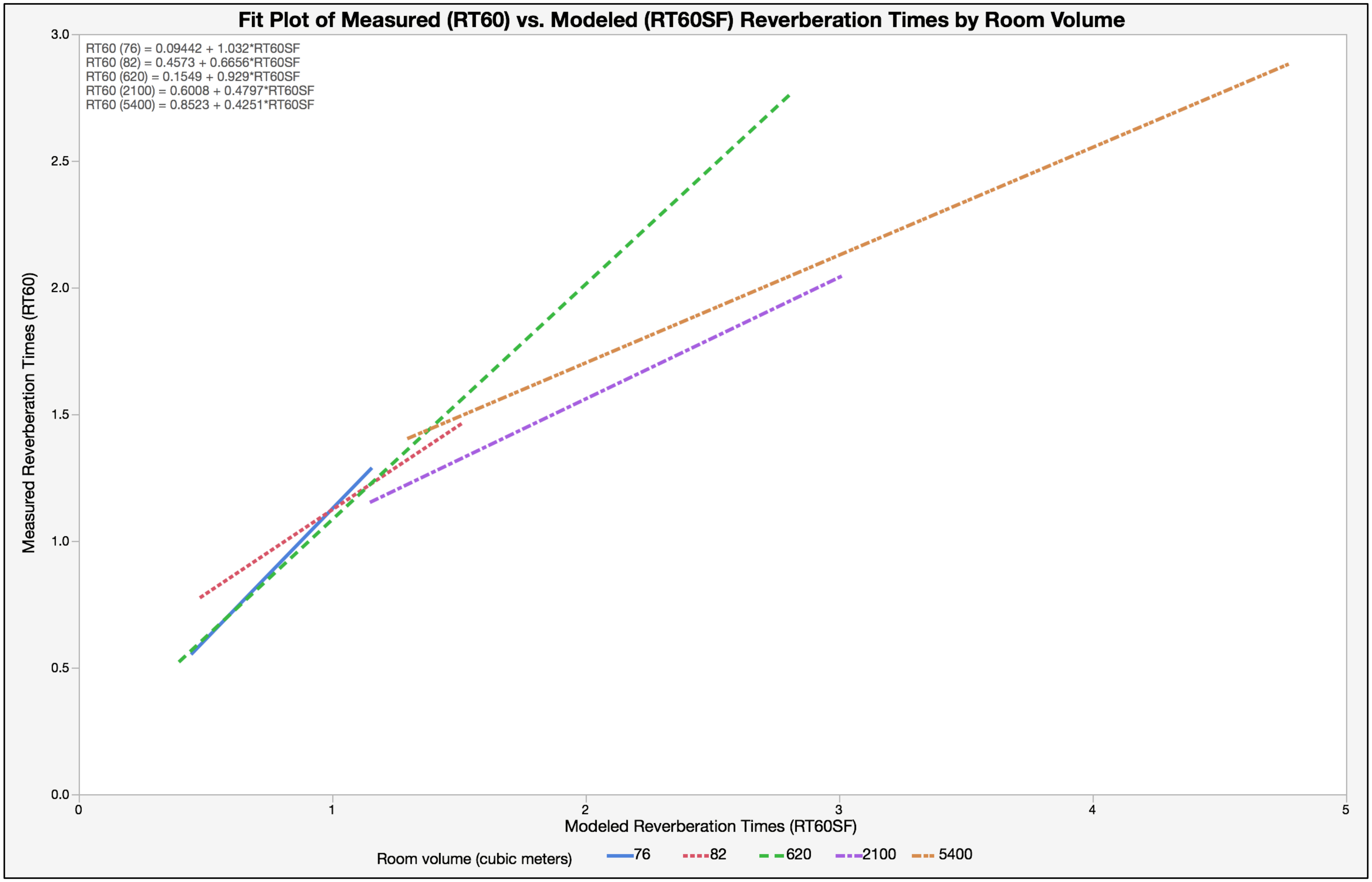

Figure 5.7: Fit plot of measured and modeled reverberation times by room volume.

representative of the Sabine's Formula model underestimating the reverberation times; the farther away from 1, the larger the underestimation. As the room volumes increase, the slopes move farther below 1, indicating that the Sabine's Formula model overestimates the reverberation times by larger margins as the room volume increases.

Study 2: Room Treatments

For the second study within this project, bonded acoustical cotton (BAC) absorptive panels were installed in two areas, the small second floor conference room and the first floor classroom. Reverberation measurements were taken in the original room configurations and again after the installation of the acoustic treatment.

Treatment Models

RT_{60} models were created for the classroom area and second floor conference room. The classroom area was estimated at 156 m^2 with an internal volume of 620 m^3. The total reflective surface area (including Wisperwave™ Ribbon Sound Baffles) was estimated at 627 m^2. The classroom model predicted an average 125-4000 Hz RT_{60} time of 1.43 seconds, the difference between the modeled and measured mean RT_{60} times was 0.05 seconds (3.38 %) (Table 5.1). Individual octave band differences ranged from 0.04 seconds (4.35%) at 1000 Hz to 0.30 seconds (37.04%) at 4000 Hz. The 125-4000 Hz mean differences and octave band differences were within the expected ranges based on previous studies [22-24]. The model created for the classroom was determined to be accurate enough to begin evaluating acoustic treatments.

Table 5.1: Measured and Modeled RT_{60} times, first floor classroom original conditions.

First floor classroom original conditions	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz	125-4000 Hz mean
Measured RT_{60} times (sec)	3.22	1.73	1.33	0.92	0.89	0.81	1.48
Modeled RT_{60} times (sec)	2.71	2.29	1.47	0.96	0.64	0.51	1.43

The selected BAC panels were installed in the classroom covering 39% of the total steel framing in the ceiling. While a BAC panel coverage total of 60% was recommended, the 39% coverage was reached by installing panels only on the most accessible beams and avoiding all beams with lighting or wiring. Once the installation was completed on the selected beams, the RT_{60} times were measured again using the same methods and the model was run using the 39% BAC panel coverage area. Results of the measured and modeled RT_{60} times are summarized in Table 5.2. The model predicted an average 125-4000 Hz RT_{60} time of 1.05 seconds, the difference between the modeled and measured mean RT_{60} times was 0.20 seconds (16.00%). Individual octave band differences ranged from 0.04 seconds (3.42%) at 500 Hz to 0.52 seconds (52.53%) at 4000 Hz. The increase in model error suggests that the model had become less accurate with the addition of the absorptive surface, though was still within the expected performance parameters.

Table 5.2: Measured and Modeled RT_{60} times, first floor classroom 39% BAC treated.

First floor classroom 39% BAC treated	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz	125-4000 Hz mean
Measured RT_{60} times (sec)	1.79	1.44	1.17	1.06	1.04	0.99	1.25
Modeled RT_{60} times (sec)	2.01	1.28	1.13	0.83	0.59	0.47	1.05

The predictions of the original 60% BAC treated room model are presented in Table 5.3. The model predictions indicated that 60% BAC panel coverage of the steel framing in the ceiling would drop the 125-4000 Hz mean RT_{60} time to 0.91 seconds, reaching the selected goal of an RT_{60} time of 0.5-1 second. The 60% treatment level model also predicted a drop in the lower frequencies which were problematic in the original room setup. The model predicted a drop at

Table 5.3: Modeled RT_{60} times, first floor classroom 60% BAC treated.

First floor classroom 60% BAC treated	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz	125-4000 Hz mean
Modeled RT_{60} times (sec)	1.77	1.04	0.93	0.72	0.53	0.44	0.91

125 Hz from 2.71 seconds to 1.77 seconds, nearing the selected goal of reducing the RT_{60} times of the low frequencies to near or below one second.

The other room selected for treatment was the second floor conference room. The conference room was estimated at 22 m^2 with an internal volume of 76 m^3. The total reflective surface area (including Wisperwave™ Ribbon Sound Baffles) was estimated at 130 m^2. The conference room model predicted an average 125-4000 Hz RT_{60} time of 0.97 seconds, the difference between the modeled and actual RT_{60} times was 0.06 seconds (6.19%) (Table 5.4). Individual octave band differences ranged from 0.05 seconds (5.68%) at 1000 Hz to 0.15 seconds (23.81%) at 4000 Hz. As with the classroom model, the errors in the conference room model were within the expected ranges based on previous studies, and was deemed accurate enough to use for treatment evaluations [22-24].

Table 5.4: Measured and Modeled RT_{60} times, second floor conference room original conditions.

Second floor conference room original conditions	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz	125-4000 Hz mean
Measured RT_{60} times (sec)	1.16	1.26	1.21	0.88	0.68	0.63	0.97
Modeled RT_{60} times (sec)	0.98	1.12	1.09	0.83	0.59	0.48	0.91

Unlike the acoustic panel installation in the classroom, the BAC panels could easily be installed at the surface area coverage recommended by the model. The treatment model indicated that installing BAC panels over 30% of the steel framing of the ceiling would easily bring all RT_{60} times below one second. Results of the measured and modeled RT_{60} times are summarized in Table 5.5. The model predicted an average 125-4000 Hz RT_{60} time of 0.64 seconds, the difference between the modeled and measured mean RT_{60} times was 0.07 seconds (9.86%). Individual octave band differences ranged from 0.03 seconds (5.08%) at 1000 Hz to 0.15 seconds (27.27%) at 4000 Hz. This small increase in model error suggests that the model

Table 5.5: Measured and Modeled RT_{60} times, second floor conference room 30% BAC treated.

Second floor conference room 30% BAC treated	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz	125-4000 Hz mean
Measured RT_{60} times (sec)	0.93	0.90	0.77	0.59	0.53	0.55	0.71
Modeled RT_{60} times (sec)	0.83	0.72	0.73	0.62	0.47	0.40	0.64

had become less accurate with the addition of the absorptive surface, though was still well within the expected performance parameters.

Treated Room Measurements

The treatment results in the small 76 m^3 second floor conference room are summarized in Figure 5.8. The BAC acoustic treatment effectively met the goal of lowering the 125-4000 Hz RT_{60} times to 0.5-1.0 seconds, with a large reduction in reverberation times below 1000 Hz. The treatment results in the 620 m^3 first floor classroom are summarized in Figure 5.9. The BAC acoustic treatment nearly met the goal of lowering the 125-4000 Hz RT_{60} times to 0.5-1.0 seconds, with a very large reduction in reverberation time of 44% (3.22 seconds to 1.79 seconds) at 125 Hz. Reverberation times were also reduced at 250 and 500 Hz, and slightly raised at 1000 Hz and above. The Pre-treatment measurements were taken in the original room configuration which had a large number of Wisperwave™ Ribbon Sound Baffles which begin effectively absorbing noise at 1000 Hz and above [29].

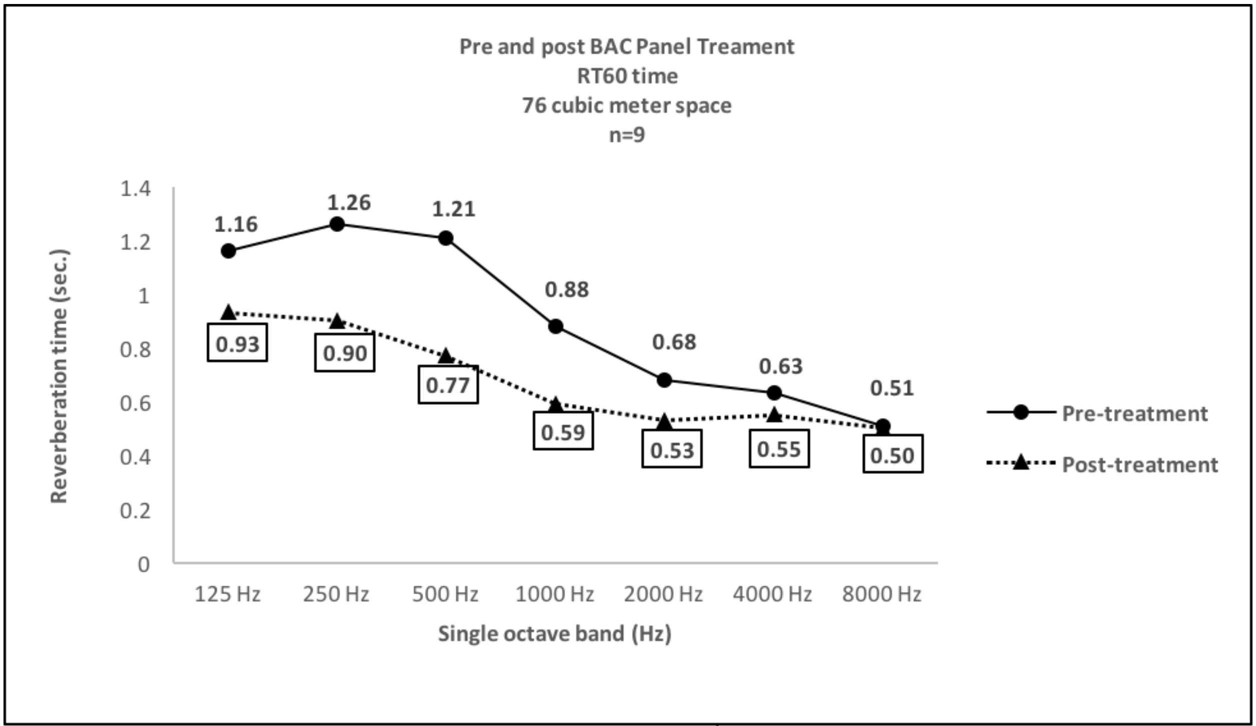

Figure 5.8: Pre and post treatment measured RT_{60} times, 76 m^3 second floor conference room.

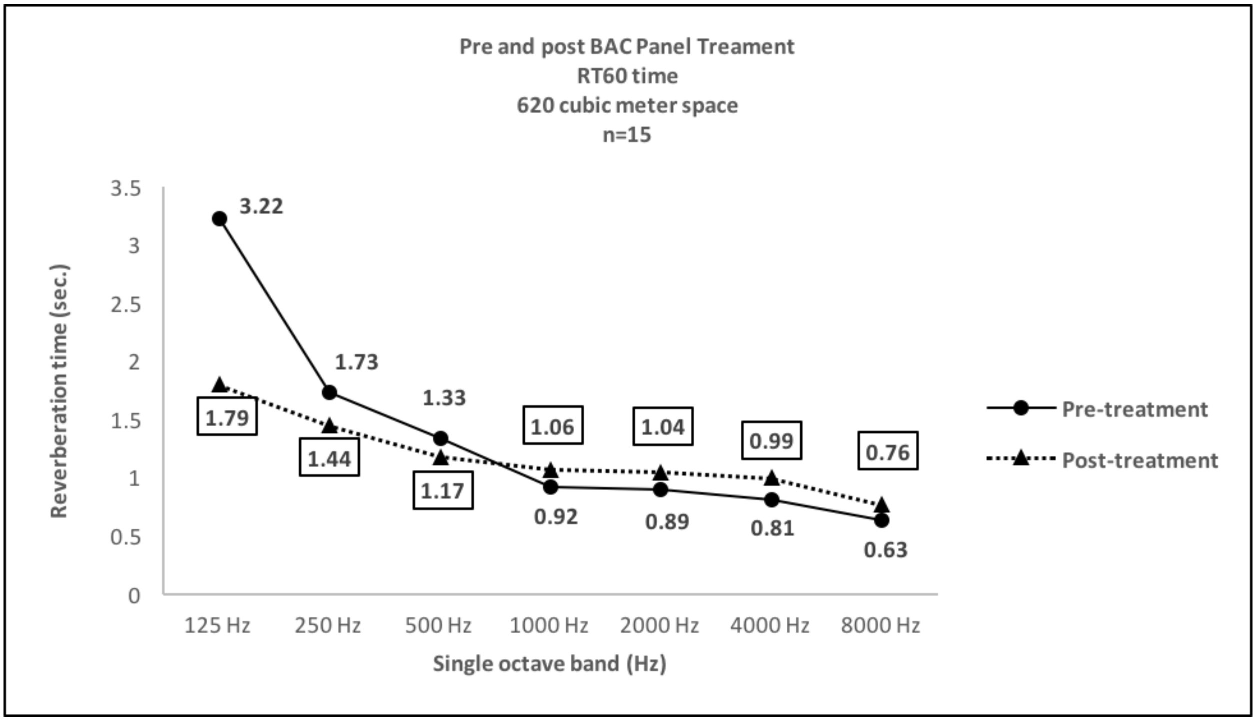

Figure 5.9: Pre and post treatment measured RT_{60} times, 620 m^3 first floor classroom.

CHAPTER 6: DISCUSSION

Study 1: Model Performance

The range of areas inside the Powerhouse building included in this study was vast, ranging from a conference room with a volume of 76 m^3 to a two-story area with a volume of 5400 m^3. The configurations of these areas were also very different, introducing a wide array of acoustic characteristics. The second floor conference rooms (76 m^3 and 82 m^3) and the first floor classroom (620 m^3) are all rectangular and fully enclosed by the walls, floor, and ceiling (Figure 6.1). The 2100 m^3 third floor office area is also completely enclosed and essentially square in shape with the exception of some open hallways. However, the interior of the third floor office space is much more complex than the smaller rooms. Clusters of offices were built in this area, and to work with the high efficiency climate control and lighting systems that were required for the building's Leadership in Energy and Environmental Design (LEED) Platinum certification, the offices do not have ceilings and are open to the common area. This created approximately one meter of open space between the offices and the steel ceiling framing and deck (Figure 6.2). This office design created a complex acoustic environment above all the offices. The open

Figure 6.1: Layout of the first floor classroom.

Figure 6.2: Example of the open-ceiling office design shared by all offices on the second and third floors.

ceilings of the offices act as large diffusive elements, trapping a soundwave and reflecting it within the office until it dissipates [4-6, 12]. This diffusive action of the offices may contribute a large amount of reverberant field reduction in the open office area. However, the reverberant field interaction with the open offices is much too complex for the Sabine's Formula model used in this study. The office area also contained a cluster of desks surrounded by low cubicle walls, which offer a small degree of acoustic absorption and diffusion.

While the other four areas had well-defined acoustic boundaries enclosing the square or rectangular rooms, the first floor atrium and second floor office area were much more open and complex. As seen in Figure 6.3, the large entryway atrium connects the first floor with the open-floor office area on the second floor. The second floor office area also has the same open-ceiling office design as the third floor, but contains a much larger number of offices in addition to an open area of computer desks available to students. The extremely open floor plan of the atrium and second floor office area required that it be treated as a single acoustic environment, though this created an extremely complex environment to model. The openness and the layout of the space created multiple different pathways for a reverberant field to diffuse and dissipate before

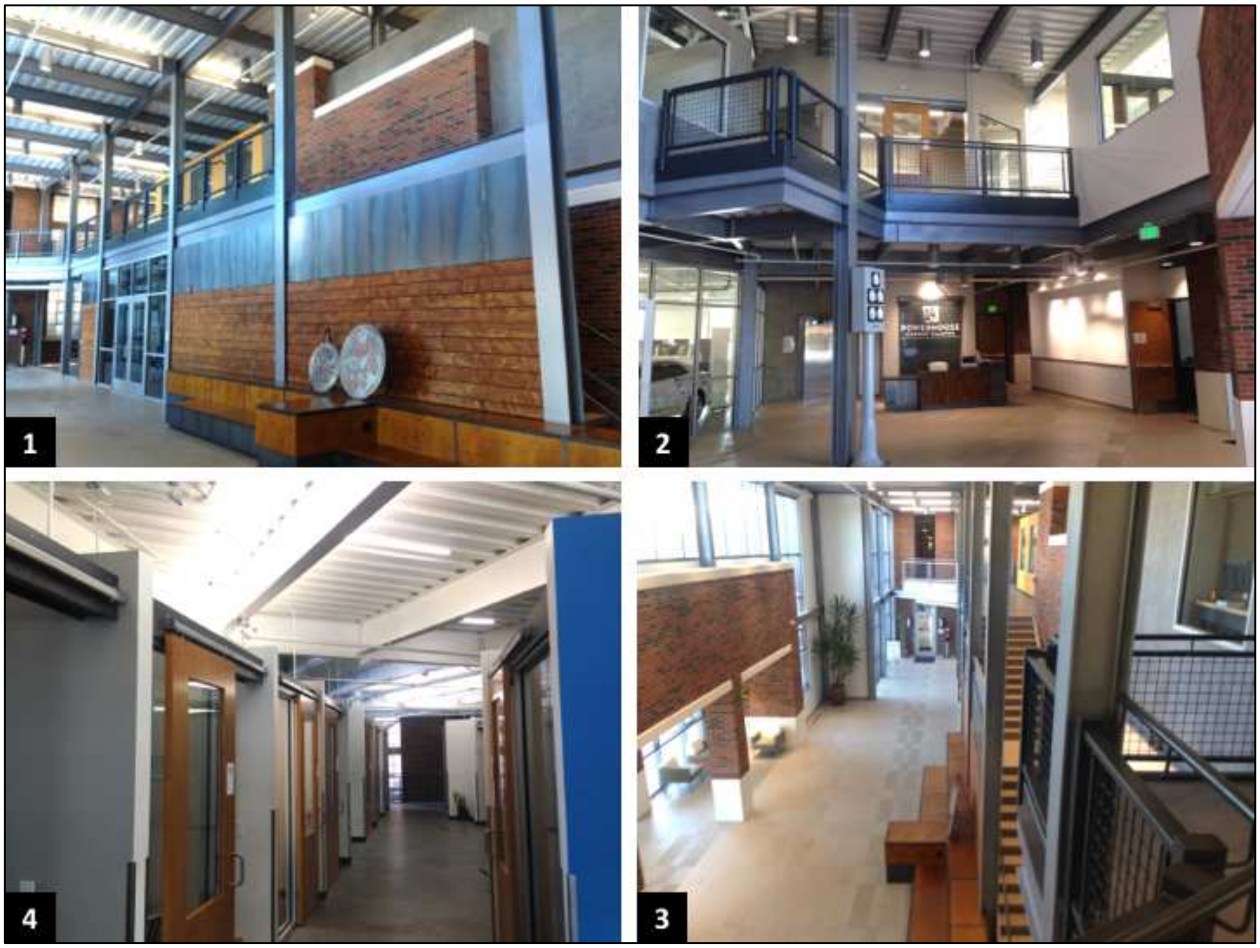

Figure 6.3: First floor atrium and second floor office area. 1-3, entryway atrium and connecting areas to the second floor office space. 4, second floor open-ceiling offices immediately adjacent to the atrium.

returning to an observer. The atrium may have had additional diffusive action on reverberation coming from the second floor. Soundwaves originating in the office area may travel into the atrium and reflect off of the multiple reflective surfaces at different orientations (Figure 6.3 parts 1-3). This could cause an increase in reverberation in the atrium as the soundwaves reflect off the wall, ceiling, and floor of the atrium but do not return to the office area. Diffusion via the open-ceiling offices is likely to play a much larger role on the second floor office area than in the third floor office area, simply because there are more offices present on the second floor. The second floor has twenty-three open-ceiling offices while the third floor has thirteen. The second floor also has hallways in-between offices (Figure 6.3 part 4) that redirect soundwaves traveling through the space. The floor within the office area is also not continuous and has openings to the floor below in multiple areas. In addition to connecting with the atrium on two sides, the floor also has an 11 m^2 opening placed next to a large cluster of offices that connects directly to the laboratory workspace below the offices (Figure 6.4). Not only does this floor opening allow a reverberant field to pass through and diffuse within the laboratory space, it also allows noise from laboratory work to travel directly to the office space and introduces another source of problematic noise. These acoustic characteristics created a challenge for the Sabine's Formula model used in this study.

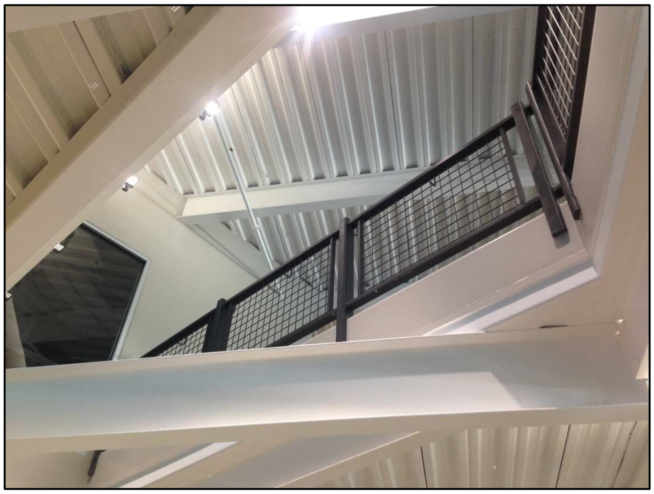

Figure 6.4: 11 m^2 opening in ceiling of first floor laboratory space leading directly to the second floor office area.

The larger interior spaces of the Powerhouse had multiple different factors all contributing to make the spaces very acoustically complex. These factors likely had a large impact on the model performance results observed in this study. The Sabine's Formula model performed well in the three smaller rooms, but proved to be far less accurate in the two largest spaces. When used in the 76 m^3 conference room, the 82 m^3 conference room, and the 620 m^3 classroom, the model followed the measured RT_{60} times well and only exceeded the 95% CI placed on the measured times at 4000 Hz in the 620 m^3 classroom (Figures 5.1-5.3). When used in the 2100 m^3 third floor office space and the 5400 m^3 first floor atrium and second floor office space, however, the model did not perform as well. In these two large spaces, the model only fell within the bounds of the 95% CI on the measured times at 4000 Hz in both areas (Figure 5.4 and 5.5). At all other frequencies the modeled RT_{60} times were well above the measured times in both spaces.

The RT_{60} time overestimation by the model in the largest spaces is confirmed by the analysis of the repeated measures mixed model. The trend of overestimation is summarized in figure 5.7, the fit plot of the measured and modeled RT_{60} times plotted by the room volume in which each set of measurements were taken. The equation for each set of measurements is listed in the top left corner of the graph. A fit line slope below 1 is representative of the Sabine's Formula model overestimating the reverberation times; the farther away from 1, the larger the overestimation. A fit line slope of 1 is representative of the Sabine's Formula model correctly predicting the reverberation times. A fit line slope greater than 1 is representative of the Sabine's Formula model underestimating the reverberation times. The slope generated for the 2100 m^3 room model is 0.48, and the slope generated for the 5400 m^3 room model is 0.43. As the room volumes increase, the slopes move farther below 1, indicating that the Sabine's Formula model overestimates the reverberation times by larger margins as the room volume increases. The modeled RT_{60} time interaction with room volume generated a p value of 0.01, indicating that the room volume had a significant effect on the predicted reverberation times and the Sabine's Formula model became less effective as the room volume increased.

While the complex acoustic environment certainly contributed to the model error in the two largest spaces, the overall trend observed in all five rooms is consistent with previous studies using a Sabine's Formula model. Earlier studies have found that a Sabine's Formula model constantly underestimated reverberation times in smaller spaces such as offices and classrooms, and overestimated reverberation times in large spaces such as auditoriums and theaters [22-24]. The overestimation by Sabine's Formula in large spaces was one of the equation's earliest problems identified by acoustic engineers and Carl Eyring developed what is now known as Eyring's Formula to try to correct the problem in 1930 [25]. However, Eyring's Formula is designed for use with a highly absorptive acoustic environment, and has increasing errors as the environment becomes more reflective [22]. Unfortunately, previous studies on the performance of Sabine's Formula at different room volumes have, by necessity, used rooms of different materials and design (e.g., a classroom and a theater) [24]. The current study using the Powerhouse may be one of the first studies to use rooms that have similar construction materials and building techniques. However, the large differences in room configuration add multiple variables that make any conclusions of model performance based solely on room size tenuous. While there is clearly a significant interaction between the larger rooms and an overestimation of RT_{60} times by the model, it is likely due to a combination of factors involving both the volume of the room and effects of the room configuration.

One interesting and unexpected observation from this study relates to the reverberation measurements in the small conference rooms. The 95% CI at 125 Hz and 250 Hz was very large in both conference rooms, becoming smaller at 500 Hz and higher (figures 5.1 and 5.2). This may be caused by several different factors, the first of which is the clapper board used to create the impulse noise for the measurements. All impulsive noise sources have an inherent variability in the directionality of the impulse noise they generate. This variability becomes much larger at lower frequencies, and all sources but the sophisticated omnidirectional speaker systems have difficulty generating repeatable and consistent low frequency impulses [16, 19]. This variability does not have much impact on measurements in a large space because the impulse has a large volume in which to dissipate and become more uniform before being reflected back to the microphone. In a smaller room, the impulse does not have this additional volume to become a more uniform field before being reflected back to the microphone, and the variability in the low frequency fields may have much more impact on the variability of the measurements [16].

Another possible explanation is related to the behavior of low frequency soundwaves when they encounter an object. The conference rooms of the Powerhouse are walled with drywall mounted to a steel frame with fiberglass insulation placed in the open areas between studs to reduce sound transmission through the wall. Low frequency noise easily passes through drywall, and walls must be specially designed with either sound absorbing materials or additional framing and drywall panels to prevent sound transmission when using drywall [31]. The walls in the Powerhouse conference rooms were built with a single panel of drywall screwed directly to the metal framing. A low frequency soundwave may be able to pass through the single drywall panel and reflect off the metal frame back into the room, or if it does not encounter the metal framework, it may pass through the other side of the wall and leave the room with minimal reflection back [1, 3, 31]. These different factors may have contributed to the large variability in low frequency measurements observed in the small conference rooms but not in any of the larger spaces.

This model performance study had several notable limitations. The first, and largest, limitation is the small sample size of five rooms being used in the final study. The study had started with six rooms, a 2300 m^3 laboratory space was also included in the initial reverberation modeling and measurements. However, this room was removed from the study due to the extremely poor model performance believed to have been caused by the substantial amount of large lab equipment in the space. The laboratory had multiple large equipment pieces that would be changed as experiments progressed or were started. This added a large amount of acoustically absorptive and diffusive surfaces that were too complex to fit in the Sabine's Formula model. The model was run without being able to account for the equipment and the model errors ranged from 8.95% at 4000 Hz to 253% at 250 Hz. The differences in room configuration and design were also a limitation of the study. The very different space configurations, from the standard rooms of the conference rooms and classroom to the highly irregular combined atrium and office space, made it very difficult to determine if the changes in model performance were due to room volume or caused more by the changes in room shape.

Another limitation is one inherent in all reverberation models: the accuracy of the α values used for all the different room materials [12]. The material α values are a vital foundation of a Sabine's Formula model and any other reverberant field model, and the changing absorption at different frequencies is a major contributor to reverberant fields [1, 3, 11, 12]. Highly reflective materials with low α values are especially susceptible to significant errors in models. Concrete has a listed α value of 0.01 at 125 Hz in most commonly used α value tables [1]. If the concrete in the room being measured behaved slightly different and had an actual α value of 0.013 instead of the 0.01 used in the model, a 30% error has already been introduced at 125 Hz. If the room had a large concrete area, the incorrect α value could have a large impact on the final model even though the α value used in the model is only 0.3% lower (1% vs. 1.3%). This limitation is very difficult to address in models. Beyond using α values for the exact material in the room, or an extremely similar material, there is very little that can be done practically to prevent these errors [12].

Study 2: Room Treatments

The RT_{60} time reductions in both the first floor classroom and the second floor conference room indicated that the BAC panel treatment design was successful in reducing the problem acoustics in those areas. As seen in Figures 5.8 and 5.9, the BAC treatment reduced the RT_{60} times at the problematic low frequencies in both rooms and reduced the reverberation times near the goal of 0.5-1 second. The results of the treatments in both areas indicates that the Sabine's Formula model is able to adequately predict the reverberant field behavior when different acoustic treatments are applied to the space. The results also indicated that the impulse noise method of reverberation measurement is sufficient to characterize the acoustics of a room to aid in the design and selection of acoustic treatments. The modeled and measured RT_{60} times were all within or near the error range of previous studies that used the much more advanced interrupted noise method to compare measurement to Sabine's Formula predictions [22-24]. While the error range of the models may be too large for precise acoustic applications, 3.38%-16.00% as a 125-4000 Hz mean and 3.42%-52.53% as single octave-bands (Tables 5.1-5.5), the Sabine's Formula model was able to sufficiently predict the reverberant fields of the treated rooms.

The construction materials and methods used in the Powerhouse to obtain a LEED Platinum certification created large areas of acoustically reflective steel, concrete, and glass (Figures 6.1 and 6.3). These materials caused a large amount of reverberation (Tables 5.1 and 5.4), with RT_{60} times well above the 0.5-1 second ideal [4-6, 12]. The RT_{60} times were also well above the US Green Building Council recommendation for LEED certified buildings of under 0.6 seconds in meeting rooms or classrooms and under 0.8 seconds for general office areas [21].

Successful control of the reverberant field would require substantial alterations to the acoustic environment of both rooms.

Selecting an acoustic treatment to control a reverberant field without an adequate model is very difficult and is often unsuccessful. To try to reduce the noise problems in the Powerhouse's classroom and conference rooms, Wisperwave™ Ribbon Sound Baffle were hung from the ceiling of the rooms (Figure 6.5). However, this original treatment did very little to change the perceived acoustics in any of the rooms treated; exemplifying the importance of acoustic modeling when designing reverberant noise treatments. To test acoustical treatments before either room was changed, two reverberation room models were created for the first floor classroom and the second floor conference room. The models were created using notes taken during the building walkthrough and construction diagrams of the Powerhouse remodel provided for this evaluation. Building material sound absorption coefficients were determined using standard α values tables; materials and surface areas were determined through building

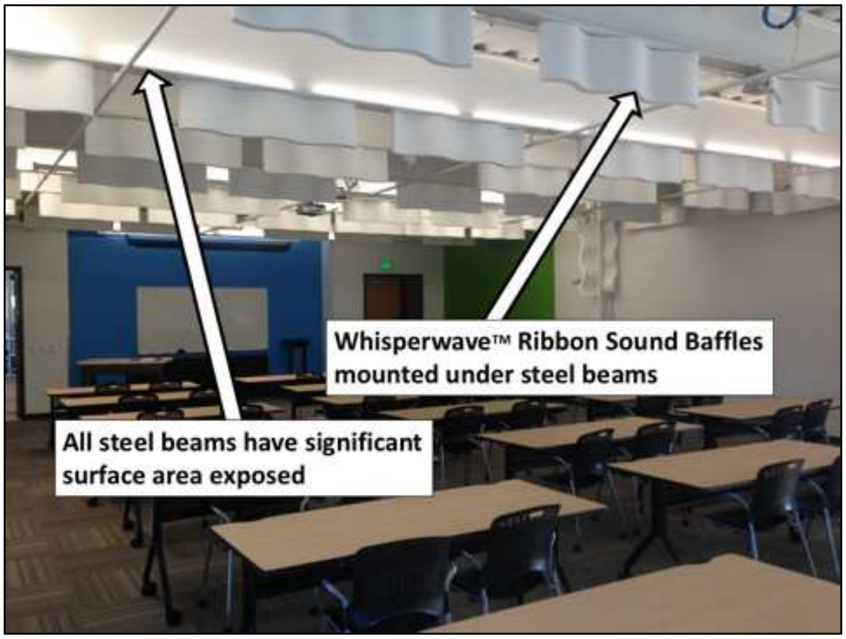

Figure 6.5: First floor classroom original condition. Whisperwave™ Ribbon Sound Baffles had been installed under the steel beams, but nearly all steel in the room remains exposed and available to reflect noise.

walkthroughs and the specifications of the construction diagrams [8-10, 29]. Using these methods, a simple reverberant field model was created for both rooms using a minimal amount of equipment and a simple spreadsheet program. Once the room models were created, acoustic treatment options could be evaluated and tested for each space.

The lower 1000-4000 Hz RT_{60} times measured in the classroom area are a result of the Wisperwave™ Ribbon Sound Baffle treatment installed in the room (Table 5.1, Figures 5.9 and 6.5). The Wisperwave™ melamine foam material provided adequate attenuation of the 1000-4000 Hz range, but was ineffective in the 125-500 Hz range [29]. The second floor conference room also had the same baffles installed, though the results were much less pronounced because very few baffles had been installed relative to the other reflective surfaces in the room (Table 5.4, Figure 5.9). The extensive use of exposed structural steel and concrete flooring in the interior of the Powerhouse would require an acoustic material with high absorption coefficients across all frequencies, especially the lower frequencies that can travel much further in a building [1, 3]. The models for both rooms correctly modeled the reverberant fields, with errors that were within the expected range when compared to the reverberation measurements taken with the impulse noise method. This indicated that the models were performing as expected and could be used to begin testing acoustic treatments as the next step in the project.

To provide the largest reverberation reduction using the fewest acoustical panels, the BAC panel treatments were installed to cover the highly reflective steel surfaces in the Powerhouse. Steel provides between 1-2% noise absorption across all frequencies, and the extensive use of exposed steel in the interior of the Powerhouse significantly contributed to the noise reverberation issues [1]. To simultaneously add noise-absorbing surfaces and reduce the area of steel present, the BAC treatments modeled were installed directly onto the widest face of the horizontal steel support beams along the ceiling of the Powerhouse (Figure 6.6). While the classroom model predicted that covering 60% of the exposed steel framing in the ceiling would reach the desired reverberation times (Table 5.3), the BAC panels were installed first on the easily accessible beams without any interfering lighting or wiring. This left several completely exposed steel beams and a BAC panel coverage area of 39% of the steel ceiling frame (Figure 6.6). While no longer able to evaluate the model predictions in a 60% BAC treated room, the model was run again at the 39% BAC treatment level so the model could be evaluated against the actual room conditions (Table 5.2).

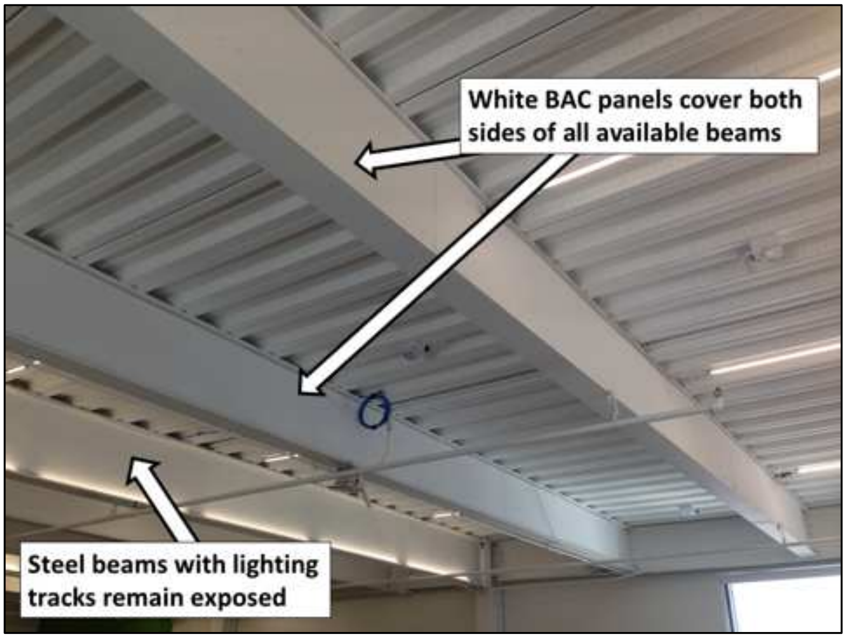

Figure 6.6: First floor classroom 39% BAC treamtment. BAC panels cover both sides of beams were lighting or wiring would not interfere.

The lower BAC 39% coverage still performed well in the classroom, especially at the lower frequencies of 125-500 Hz which had been a major component of the problematic reverberant field in the original room. This indicated that the Sabine's Formula model was able to successfully predict a reduction in low frequency reverberation time using the BAC ceiling beam treatment. The successful reduction in RT_{60} times also indicated that reverberation models do not need to be incredibly precise when the end goal is a general reduction in reverberation and overall noise. The 39% BAC treated classroom model had octave band errors ranging from 0.03 seconds (5.08%) at 1000 Hz to 0.15 seconds (27.27%) at 4000 Hz when compared to the RT_{60} times measured in the actual treated space. Errors in this range could have noticeable consequences to the acoustics of a room in which the acoustics must be precisely controlled such as a studio or conference hall [4-6, 12]. However, when reverberant noise controls are being installed to reduce the overall noise level in a space such as an office or a warehouse, it becomes much less likely that these levels of error would be noticed in daily operations, especially if the RT_{60} times were already greatly reduced at the problem frequencies.

As seen in Figure 6.6, the BAC panels are mounted onto the steel framework in the ceiling, placing them in a vertical position like traditional hanging baffles. This can place them at a very sharp angle relative to the noise source, and reduce the surface area presented to the sound wave. For example, a lecturer standing on the floor directly under a BAC covered beam would have much less BAC paneling in their line-of-sight than if they were to stand on the floor between two BAC covered beams. The surface area in the line-of-sight between the noise source and the panel or other material is known as the solid angle, and can have a large impact on the material surface areas actually involved in first reflection of a source's noise [27]. Sabine's Formula can be modified to use solid angle ratios instead of total surface areas to obtain a more accurate reverberation prediction. Solid angles depend entirely on the position of the noise source in the room, as a result, this model can only be applied to one specific noise source location at a time. This makes it impractical for normal industrial hygiene applications unless the major noise sources creating the reverberant field are stationary and in similar positions, such as one or two large pieces of equipment in a high bay. The standard Sabine's Formula cannot adjust for solid angles and is less accurate, especially when the reflective surfaces are near the source. However, these inaccuracies are typically small, with an average improvement of 10% when using solid angles. This level of error would not create a large enough RT_{60} time difference to be easily perceived unless the treated room was highly reverberant with modeled RT_{60} times above 2 seconds [3, 27].

An average observer is not acutely sensitive to small changes in a reverberant field unless they are focusing intently on the acoustics of the environment. In general, a person is unlikely to be able to notice a difference in acoustics at RT_{60} changes of 0.2 seconds or less in most environments [3, 20]. This 0.2 second "wiggle room," in which acoustic changes are unlikely to be noticed, likely reduces the possibility that the errors of the 39% BAC treatment model would be noticeable even if a room matching the modeled RT_{60} times could be used for comparison. This also introduces more leeway for reverberant noise treatments when trying to reduce RT_{60} times to a more desirable level for the space. If a RT_{60} goal of 1 second is selected, even a 20% model error would result in an RT_{60} time of 1.2 seconds which would sound very similar to the 1 second ideal time to building occupants.

While there is room for error in the reverberant noise controls of a general work environment, acoustic treatments should be designed with as much accuracy as possible to reach the desired outcomes and to prevent budget overruns on wasted materials and installation costs [3, 12]. The Sabine's Formula model and the impulse noise reverberation measurement method both showed very reasonable levels of accuracy in both of the treated rooms, with average errors of 16% and 9.86% for the classroom and conference room models, respectively. This suggests that the simplistic measurement and modeling system can be used by an industrial hygienist to select reverberant noise controls with a reasonable degree of confidence. Having simple and relatively cheap tools available to solve reverberant noise issues can be invaluable to an industrial hygienist trying to reduce noise levels in a warehouse, production floor, or large office space. These tools may not have the same degree of precision as the computer models and specialized omnidirectional speaker towers used with the interrupted noise measurement method (error less than 10% in most cases), but they are more than enough to address common reverberant noise issues [22-24].

This room treatment study had several notable limitations. The first, and largest, limitation is the small sample size of only two rooms receiving treatment in the timeframe of the study. The small sample size prevented the use of a repeated measure mixed model, similar to the model performance study, to evaluate potential interactions in the treatment predictions. This limitation restricted the study to simply comparing the predicted RT_{60} times to the times actually measured in the spaces. Another limitation is one inherent in all reverberation models: the accuracy of the α values used for all the different room materials [12]. The material α values are a vital foundation of a Sabine's Formula model and any other reverberant field model. The changing absorption at different frequencies is a major contributor to reverberant fields [1, 3, 11, 12]. Highly reflective materials with low α values are especially susceptible to significant errors in models. Concrete has a listed α value of 0.01 at 125 Hz in most commonly used α value tables [1]. If the concrete in the room being measured behaved slightly different and had an actual α value of 0.013 instead of the 0.01 used in the model, a 30% error has already been introduced at 125 Hz. If the room had a large concrete area, the incorrect α value could have a large impact on the final model even though the α value used in the model is only 0.3% lower (1% vs. 1.3%). This limitation is very difficult to address in models. Beyond using α values for the exact material in the room, or an extremely similar material, there is very little that can be done practically to prevent these errors [12]. A third limitation is the effect room furnishings and equipment have on both the models and the reverberation measurements. Room furnishings and equipment such as chairs, bookshelves, and computers will modify the reverberant field both through absorption and diffusion of the sound pressure wave [12, 24, 32]. The rooms that received treatment had a minimal amount of furnishings, mostly tables and chairs, but the physical layout of the tables and chairs may have resulted in some diffusion of the reverberant field away from the SLM when measurements were taken. While the results indicated that these limitations likely did not have a large impact on the study, they may have increased the errors at lower frequencies where α values were extremely low and where interactions with room furnishings would have been different than at higher frequencies due to the long wavelengths [12, 24, 32].

CHAPTER 7: CONCLUSION AND FUTURE WORK

Study 1: Model Performance

Highly reverberant environments, spaces with higher than desired RT_{60} times, can have many different effects depending on how the space is configured and used. An industrial hygienist would be most likely to encounter reverberant noise problems when the reverberant field is either propagating high levels of noise from equipment or the field is causing speech communication issues for workers [1-3]. Low intensity reverberant fields, such as a high bay with light equipment use or a large office space, can still be a significant source of distraction and irritation for workers. Building spaces with high reverberation can create irritating environments for occupants and can interfere with communication, especially when workers try to talk to each other across a room [4, 5]. Both speech and telecommunication equipment such as phones or radios can be significantly impeded in a highly reverberant environment.

This project provided a unique opportunity to evaluate the method available to most industrial hygienists to measure and predict reverberant noise: Sabine's Formula and the impulse noise method of reverberation measurement. These methods are relatively simple and require no specialized equipment other than a clapper board or other impulse generating device that can be purchased for no more than two or three hundred dollars. This is a sharp contrast to the popular methods of reverberation measurement that require speaker and amplification systems costing several thousand dollars and advanced computer programs to model the acoustic fields.

To use the unique environment of the Powerhouse to evaluate the use of Sabine's Formula for industrial hygiene applications, the RT_{60} predictions calculated with the Sabine's Formula model were then compared to the RT_{60} times measured in each location. The larger interior spaces of the Powerhouse had multiple different factors all contributing to make the spaces very acoustically complex. These factors likely had a large impact on the model performance results observed in this study.

The Sabine's Formula model performed well in the three smaller rooms, but proved to be far less accurate in the two largest spaces. When used in the three smaller spaces, the model followed the measured RT_{60} times well and only exceeded the 95% CI placed on the measured times at 4000 Hz in the 620 m^3 classroom. When used in the much larger open office areas, however, the model did not perform as well. In these two large spaces, the model only fell within the bounds of the 95% CI on the measured times at 4000 Hz in both areas. At all other frequencies the modeled RT_{60} times were well above the 95% CI in both spaces.

While the complex acoustic environment certainly contributed to the model error in the two largest spaces, the overall trend observed in all five rooms is consistent with previous studies using a Sabine's Formula model. Earlier studies have found that a Sabine's Formula model consistently underestimated reverberation times in smaller spaces such as offices and classrooms, and overestimated reverberation times in large spaces such as auditoriums and theaters [22-24]. There is clearly a significant interaction between the larger rooms and an overestimation of RT_{60} times by the model, though it is likely due to a combination of factors involving both the volume of the room and effects of the room configuration.

While the impulse noise method of reverberation measurement worked well in this study, there was some variability noted in the low frequency measurements in the small conference rooms. The variability may be caused by the interaction of the low frequencies with the metal framing and insulation in the wall of the conference rooms, but more likely is due to variability in the impulse created by the clapper board. This impulse generation variability becomes much larger at lower frequencies, and all sources but the sophisticated omnidirectional speaker systems have difficulty generating repeatable and consistent low frequency impulses [16, 19]. This variability does not have much impact on measurements in a large space because the impulse has a large volume in which to dissipate and become more even before being reflected back to the microphone. In a smaller room the impulse does not have this extra volume to even out before being reflected back to the microphone, and the variability in the low frequency fields may have much more impact on the variability of the measurements [16]. This variation did not appear to have a major effect on the measurements because the modeled and measured times were very similar. However, the low frequency variations did result in a large 95% CI at 125 Hz and 250 Hz.

Sabine's Formula has fallen out of favor with acoustic engineers, being replaced with the much more precise computer programs. While no longer used in precise acoustic applications, Sabine's Formula is likely to meet the needs of any industrial hygienist faced with a reverberant noise problem. The model performed well in room volumes 620 m^3 and below, and would have likely performed better in the large volume rooms if they did not have such complex acoustic environments. The Sabine's Formula model will likely overestimate RT_{60} times even in an acoustically simple room if the volume is large enough. The model was still slightly underestimating times at 620 m^3 indicating that it would perform well in larger volume spaces, though this study was not able to identify the room volume at which Sabine's Formula begins to overestimate reverberation times.

Future work evaluating the performance of a Sabine's Formula model when applied to different room volumes should use rooms of similar acoustic complexity if possible. Using rooms of a similar design would eliminate significant variables in the room acoustics, and allow stronger conclusions about observed trends when using the Sabine's Formula model. This study was able to use rooms of similar materials and construction methods, but had a wide range of room configurations. One possibility to study rooms of similar materials and configurations but different volumes may be to use warehouses or similar storage areas if possible. Another potential study design could use both the impulse noise method and the interrupted noise method of reverberation measurement to further investigate differences between the two methods that may influence measurements in different room volumes or configurations.

Study 2: Room Treatments

The renovated interior of the Powerhouse consisted largely of open floor plans with minimal closed rooms to allow the building's heating and cooling system to function. The open floor plan and use of hard surface interior building materials created problematic noise levels for the office occupants as noise from laboratory spaces or offices could be heard throughout the building. This study aimed to use the impulse noise method of reverberation measurement and a Sabine's Formula model to complete a noise evaluation for the interior of the Powerhouse and identify potential acoustical treatments to reduce the reverberant noise in the space. A goal 125-4000 Hz mean RT_{60} time of 0.5-1.0 second was selected using industry recommendations for large open-floor office spaces and general work areas [4-6, 12, 21]. Multiple commercially available acoustic panels and baffles were modeled in different configurations until a treatment was created that met the required RT_{60} time benchmark in the model. The selected treatment was then installed in the classroom and the second floor conference room.

To provide the largest reverberation reduction using the fewest acoustical panels, the BAC panel treatments were installed to cover the highly reflective steel surfaces in the Powerhouse. Steel provides between 1-2% noise absorption across all frequencies, and the extensive use of exposed steel in the interior of the Powerhouse significantly contributed to the noise reverberation issues [1]. To simultaneously add noise-absorbing surfaces and reduce the area of steel present, the BAC treatments modeled were installed directly onto the widest face of the horizontal steel support beams along the ceiling of the Powerhouse.

The RT_{60} time reductions in both the first floor classroom and the second floor conference room indicated that the BAC panel treatment design was successful in reducing the problem acoustics in those areas. The BAC treatment reduced the RT_{60} times at the problematic low frequencies in both rooms and brought the times near the goal of 0.5-1 second. The researchers found that the Sabine's Formula model is able to adequately predict the reverberant field behavior when different acoustic treatments are applied to the space. The impulse noise method of reverberation measurement is also sufficient to characterize the acoustics of a room to aid in the design and selection of acoustic treatments.

The simple requirements of a Sabine's Formula model make it an attractive option for an industrial hygienist who is only occasionally faced with a reverberant field issue or whose operational budget precludes the use of more sophisticated systems. The Sabine's Formula model and the impulse noise reverberation measurement method both showed very reasonable levels of accuracy in both of the treated rooms, with average errors of 16% and 9.86% for the classroom and conference room models, respectively. This suggests that the simplistic measurement and modeling system can be used by an industrial hygienist to select reverberant noise controls with a reasonable degree of confidence. Having simple and relatively cheap tools available to solve reverberant noise issues can be invaluable to an industrial hygienist trying to reduce noise levels in a warehouse, production floor, or large office space.

Future work evaluating the effectiveness of a Sabine's Formula model when used to design reverberant noise treatments should include a larger sample size than was available for this study. A larger sample size will allow for more statistical analysis of the results, and stronger conclusions about observed trends when using the Sabine's Formula model. One possibility includes revisiting the Powerhouse building and repeating the measurements in the other rooms once the installation of the panels in the remainder of the building is complete. The same BAC panels will be installed in the other open office areas within the Powerhouse, but the installation schedule went well beyond the available timeframe of this study. Ideally, future studies would involve rooms of all similar volumes and materials to help reduce potential variable that could affect the model performance between rooms. Another potential study design could use both the impulse noise method and the interrupted noise method of reverberation measurement to further investigate differences between the two methods that may influence treatment designs for reverberant noise control.

REFERENCES

1. *The Noise Manual*. 5th ed. 2003: American Industrial Hygiene Association.
2. *The occupational environment its evaluation, control, and management*. 3rd ed, ed. S.R. DiNardi. 2011, Fairfax, Va.: AIHA Press (American Industrial Hygiene Association).
3. Bell, L.H. and D.H. Bell, *Industrial Noise Control Fundamentals and Applications*. Second ed. 1994, New York, NY: Marcel Dekker Inc.
4. Kuttruff, H., *Room acoustics*. 2002, London ;: Spon Press.
5. Mechel, F.P., *Room acoustical fields*. Springer eBook collection. 2013, Berlin ;: Springer-Verlag.
6. Möser, M., *Engineering acoustics an introduction to noise control*. Technische Akustik. 2009, Berlin ;: Springer.
7. *Associates in Acoustics, Inc. Reverberation Time Model Based on Room Material Absorption Properties*, R.T.S.-S.b. Step, Editor., Associates in Acoustics, Inc.: Evergreen, CO.
8. *Sound Absorption Coefficients*. 2016, Acoustical Surfaces Inc.: Chaska, MN.
9. *Absorption Coefficients*, web_absorbtion_data_eng.pdf, Editor. 2014, Acoustic Project Company.
10. *Noise Control Design Guide*. 2004, Toledo, OH: Owens Corning. 44.
11. Sabine, W.C., *Collected papers on acoustics*. 1922, Cambridge, MA: Harvard University Press.
12. Cox, T.J., *Acoustic Absorbers and Diffusers : Theory, Design and Application*. Ebook Library (EBL), ed. P. D'Antonio. 2009, Hoboken: Taylor & Francis.
13. *ASTM C423a. Standard test method for sound absorption and sound absorption coefficients by the reverberation room method.* 2009, American Society for Testing and Materials.
14. *Model 831 Sound Level Meter Manual I831.01 Rev M Supporting Firmware Version 2.3*. 2015, Depew, NY: Larson Davis.
15. *ISO 3382. Acoustics - Measurement of room acoustic parameters*. 2012, International Organization for Standardization.
16. Horvat, M., K. Jambrosic, and H. Domitrovic, *Reverberation Time Measurements in Reverberant Spaces.* 50th International Symposium ELMAR-2008, 10-12 September 2008, 2008.
17. Vorlander, M. and H. Bietz, *Comparison of methods for measuring reverberation time.* Acta Acustica united with Acustica, 1994. **80**(3): p. 205-215.
18. *Larson Davis BAS006 Impulsive Source*. 2015, PCB Group: Depew, NY.
19. Horvat, M., K. Jambrosic, and H. Domitrovic, *A comparison of impulse-like sources to be used in reverberation time measurements.* Acoustics 08 Paris June 29-July 4 2008, 2008.
20. *Basic aspects of hearing physiology and perception*. Advances in experimental medicine and biology, ed. B.C.J. Moore. 2013, New York ;: Springer.
21. *LEED ID+C: Hospitality LEED v4, Acoustic Performance*. 2015, US Green Building Council.
22. Bistafa, S.R. and J.S. Bradley, *Predicting reverberation times in a simulated classroom.* J. Acoust. Soc. Am., 2000. **108**(4): p. 1721-1731.

23. Astolfi, A., V. Corrado, and A. Griginis, *Comparison between measured and calculated parameters for the acoustical charaterization of small classrooms.* Applied Acoustics, 2008. **69**: p. 966-976.
24. Passero, C.R.M. and P.H.T. Zannin, *Statistical comparison of reverberation times measured by the integrated impulse response and interrupted noise methods, computationally simulated with ODEON software, and calculated by Sabine, Eryring and Arau-Puchades' formulas.* Applied Acoustics, 2010. **71**: p. 1204-1210.
25. Eyring, C.F., *Reverberation time in "dead" rooms.* Journal of the Acoustical Society, 1930. **1**: p. 217-241.
26. Hozman, A.D. and W.O. Hughes, *An evaluation of the additional acoustic power needed to overcome the effects of a test-article's absorption during reverberant chamber acoustic testing of spaceflight hardware*. 2014, NASA Scientific and Technical Information Program.
27. Ducournaeau, J. and V. Planeau, *The average absorption coefficient for enclosed spaces with non uniformly distributed absorption.* Applied Acoustics, 2003. **64**: p. 845-862.
28. Knudsen, V.O., *The effect of humidity upon the absorption of sound in a room, and a determination of the coefficients of absorption of sound in air.* Journal of the Acoustical Society, 1931. **3**: p. 126-138.
29. *Whisperwave Ribbon Sound Baffle*. 2015, Acoustical Surfaces Inc.: Chaska, MN.
30. *Echo Eliminator Bonded Acoustical Cotton*. 2015, Acoustical Surfaces Inc.: Chaska, MN.
31. *Gypsum construction handbook*. 2013, Hoboken, New Jersey: John Wiley & Sons, Inc.
32. Meissner, M., *Influence of wall absorption on low-frequency dependence of reverberation time in room of irregular shape.* Applied Acoustics, 2008. **69**: p. 583-590.

APPENDIX

A: RT60 Measurement Operating Procedure

Before Sampling

Equipment

- Larson Davis 831 SLM
- Larson Davis Calibrator
- Larson Davis BAS006 clapper board impulse noise source
- Tripod capable of extending to height of 4.5 ft.
- Measuring tape

Larson Davis 831 SLM setup

Go to:

1. RT-60 mode
2. Setup Manager
3. Select **RT60impl** mode
4. Settings menu:
    - Trigger method: impulse
    - Trigger source: mid band
    - Trigger level: 70.0 dB
    - Noise Source: external
    - Sample period: 5.0 ms
    - OBA range: normal
    - OBA bandwidth: 1/1 octave

Sampling

Setup

- Assemble 831 SLM, preamplifier, and microphone
- Turn 831 SLM on, wait for startup sequence to complete
- Connect 831 SLM to CAL 150 field calibrator
- Select the calibration screen on the 831 SLM
- Select CAL 150 94 dB on the 831 SLM, set calibrator to 94 dB and turn on
- Select calibrate on the 831 SLM, wait for calibration check to complete and accept if successful
- Repeat sequence on the 114 dB setting on both the 831 SLM and CAL 150
- Return to the RT_{60} home screen on the 831 SLM
- Mount 831 SLM to the assembled tripod level to the floor
- Raise the 831 SLM to set the bottom of the microphone 54 inches above the floor

Measurement

- Select location to set the 831 SLM for the measurement. The microphone must be at least 2.46 ft (0.75 m) from any acoustically reflective surface (table, wall). Record the position.
- Press the run/play button on the 831 SLM
- Walk with the BAS006 clapper board to a point approximately 15 ft (4.5 m) from the 831 SLM
- Watch the 831 SLM indicator lights, remain silent when the background noise is being measured (solid green light), when the lights alternate red/green flashing the 831 SLM is ready for the impulse
- Holding the clapper board by the handles and out at shoulder height, firmly close the boards, a solid green light on the 831 SLM indicates a successful measurement
- Hit the stop/store button on the 831 SLM and save the data file
- Repeat measurement procedure in two more impulse locations before moving to the next microphone location

After Sampling

Download data

- Connect 831 SLM with USB cable to computer with the Larson Davis SLM Utility-G4 software installed (available from http://www.larsondavis.com/Support/SoftwareProductsSupport/SLMUtilityG4)
- Turn on the 831 SLM and open the SLM Utility G4 program
- Import the data files from the 831 SLM
- Export the data files from the SLM Utility G4 program as Excel files and save the files in the appropriate location