This IQP project report is submitted in partial fulfillment of the degree requirements

of

Worcester Polytechnic Institute

Report Submitted to:

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In Cooperation With

Thomas Prince School, Princeton, MA

Acoustics of a School Gymnasium

March 11, 1999

The views and opinions expressed herein are those of the authors and do not necessarily reflect the positions or opinions of Thomas Prince School or Worcester Polytechnic Institute

Abstract

This project, performed in cooperation with Thomas Prince School, in Princeton, MA, involved the evaluation of the acoustics of a school gymnasium. On-site tests were performed for speech intelligibility and reverberation time, and computer modeling was performed, in order to evaluate the value of suggested solutions. Explanations of testing and results were presented to a group of sixth grade students at Thomas Prince School, in order to provide them with some education on the subject of acoustics. Included within this report are the final recommendations for acoustical treatment for the gymnasium

Acknowledgements

Throughout our project we received help and support from numerous people, and we would like to thank these people for their contribution to our project.

Our advisor, Professor Thompson, we are grateful for your guidance and the opportunity to work on this project

Thomas Prince School, and all of its staff and students, we appreciate all your cooperation, and we hope you will benefit greatly from this project.

Mrs. Thompson and Dr. Giantris, your help in providing the idea for this project, and for helping to coordinate our efforts with Thomas Prince School was greatly appreciated.

Mr. Kingdon and Mrs. Goulet, we appreciate your tireless help with scheduling times for testing and for providing us your classes for testing and presentation. You and your students assisted us greatly in the completion of this project.

Professor Campbell and Professor Bianchi, your guidance and the use of your equipment was invaluable. Without your assistance, this project never could have been completed.

Finally, we would like to thank each of the following people for contributing to our project in one way or another: Professor Michalson, Pete De Bonte, Colin Parker, Glen Demetruss, and Adam White.

1 Introduction

This project involved finding a solution for the acoustical problems of a school gymnasium. The gymnasium is located at the Thomas Prince school, in Princeton, MA, and is used for many school functions. These functions include band concerts, chorus recitals, meetings, etc.; all involving communication and performance, through sound.

Our first step in this project was to gain a familiarity with acoustics. This was accomplished by reviewing literature, widely accepted in the field of acoustics, on the different aspects of acoustic architecture, acoustic materials, acoustic measurements and overall acoustic theory. This research gave us the background we needed to evaluate the acoustic problems present in the school's gymnasium as well as to evaluate proposed solutions for these problems.

In order to find a solution for the acoustical problems of the gymnasium we first needed to quantify the room's acoustics, and to identify the exact problems. This was accomplished by imploring well-established acoustical testing procedures such as speech intelligibility tests and "balloon pop" reverberation time tests.

Once the problems were identified, solutions had to be found. These solutions had to be as cost-effective as possible, and had to perform well. In order to judge the viability of each solution we used an acoustic modeling program, CATT-Acoustic™, to simulate each solution on a computer. These solutions could not hinder any Physical Education classes, or any sports events, which also take place in the gymnasium. This meant that the basic room structure had to stay the same, such as the surface of the floor and the bleachers. Also, these solutions needed to comply with Massachusetts State fire codes, which in some instances affected the cost-effectiveness of the solutions greatly.

An effort was made to involve the students as much as possible. We involved the students by including them in the testing procedures, such as the speech intelligibility tests, and by presenting the results of our tests and simulations to them. In this way, we were helping to educate the students, showing them how acoustics and engineering affect their every day lives.

2 Literature Review

2.1 Acoustic Architecture

One necessary step towards the improvement of the gymnasium's acoustics was to determine what exactly the problems were. A method towards quantifying the acoustical characteristics of the room had to be established. One way of accomplishing this was to compare the gym to other auditorium or concert hall settings.

The gymnasium layout can be most closely compared to a "shoebox" design. This is a narrow, box-shaped hall, with the stage placed along one of the shorter dimensions. This design is employed in such halls as Mechanics Hall, in Worcester, MA, Symphony Hall, in Boston, MA, St. Andrews Hall, in Glasgow, Scotland, and Neues Gewandhaus, in Leipzig, Germany. This design is famed for having excellent acoustics, even with highly reflective walls, floor, and ceiling.

One major problem for large halls is reverberation. Reverberation time is the length of time it takes for the reverberant sound to decrease by 60 dB (Beranek 1962, pg. 28). Long reverberation times can interfere with speech intelligibility, and will generally provide for an undesirable acoustical effect. However, reverberation can also be helpful to acoustics. As stated by Wallace Clement Sabine:

> *"It should be borne in mind that 'perfect acoustics' does not mean the total elimination of reverberation, even were that possible. Loudness and reverberation are almost, though not quite, proportional qualities. The result to be sought is a balance between the two qualities, dependent on the size of the auditorium and the use to which it is to be applied"*
>
> (Sabine, pg. 140)

What Sabine means is that if a room is to be sufficiently "loud", when a person speaks or when music is played, it must have some reverberation to add to and enhance the sound that was initially produced. For concert halls, in particular, reverberation is very important as it not only increases the loudness, but also the "fullness of tone" of a concert instrument (Beranek, 1962, pg. 34-5). This is one area in which the shoe box design excels. The time between the original sound and the first reflection is called the initial-time-delay gap. In the shoe box shape the first reflections are usually those that reflect off the side walls and this is what allows the shoe box design to have a short initial-time-delay gap as long as the total dimensions of the hall are not excessively large. This is very desirable, as a quick reflection will serve to reinforce the original sound, usually giving the hall a gain. This is because our ears cannot differentiate between the original sound and its reflections, within the first 30 msec after the sound is produced. This is called the "fusion zone". If the time delay is too long, the human ear will then be able to perceive the sound and its reflection as two separate acoustical events. The first 80 msec are designated as early-arriving sound energy, which is very important for clarity and definition. Clarity is the ratio of early sound energy to late sound energy (Egan, pg. 98). If the clarity is high, most of the sound energy is early, meaning that there is not a lot of destructive echo. Thus, a hall is said to have good definition, or clarity, if the sound is clear and distinct, instead of being blurred and muddy (Beranek 1962, pg. 66).

The height of the ceiling plays a part in the reverberation time, also. The average ceiling height for an auditorium with upholstered seats and absorptive rear walls is:

$$H \cong 20T_{60}$$

where H is the ceiling height in ft., and T_{60} is the mid-frequency reverberation time in seconds. Thus, for example, if the desired reverberation time is 2 seconds, then the average ceiling height should be 40 ft. high (Egan, pg. 100).

In Mechanics Hall, the walls are highly ornamented with paintings and other decorations. This provides irregular surfaces for the sound to reflect off of, and evenly disperses the sound throughout the hall. If the walls were bare, the sound would repeatedly interreflect between the opposing sidewalls. This is called a flutter-echo and is a very poor quality for a hall to have, if it is to be acoustically efficient (Egan, pg. 112). Other materials can be used to evenly disperse sound throughout a hall, such as convex ceiling splays, illustrated in Figure 1, which are solid, bowl-shaped sections constructed of reflective material. These can be attached to the ceiling, in strategic groupings, to disperse sound waves traveling upward towards the ceiling from a concentrated source (e.g. a person speaking) down towards the audience, in a more uniform distribution. Convex wall splays can also be used instead of ornamentation on the sidewalls.

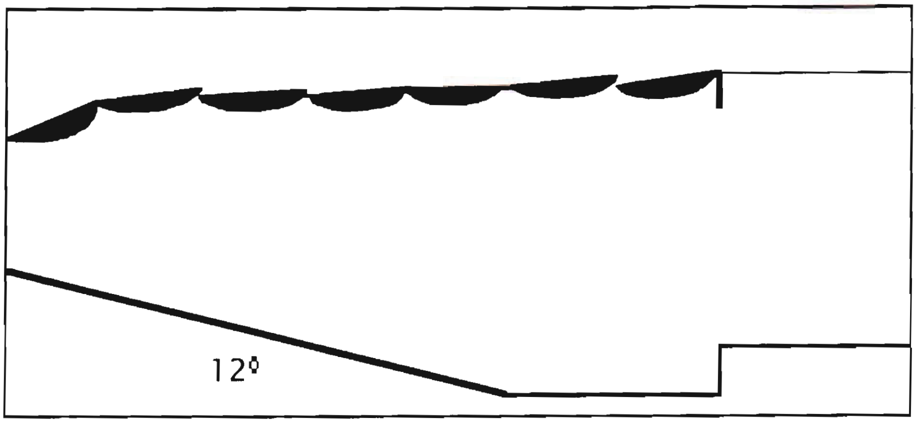

Figure 1: Convex ceiling splays (Rettinger, pg. 165)

Another wall covering would be Acoustic Reflection Phase Gratings, as shown in Figure 2, constructed of 1 or 2 mm thick baffles or panels, evenly spaced with grooves of various depths in between. These gratings can be as large as 10' wide by 10' high. Also, downward slanting sidewall sections near the ceiling, as in Figure 3, can be used to redirect sound rays from the stage that would otherwise be directed towards the ceiling, down towards the audience area, reducing reverberation time (Rettinger, pg. 164-65).

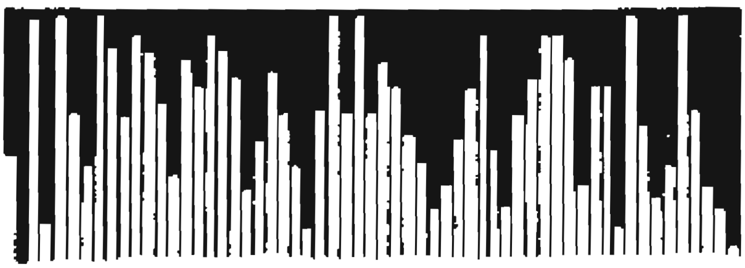

Figure 2: Sound reflection phase grating (Rettinger, pg. 165)

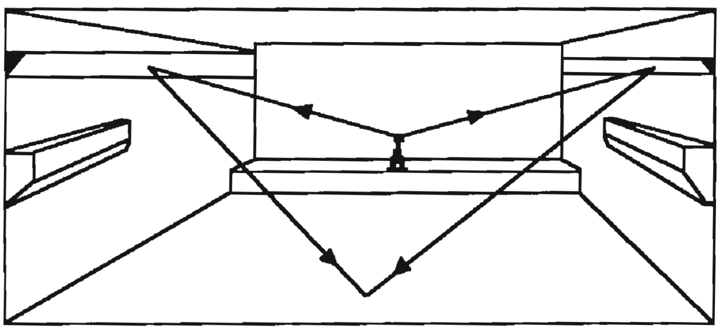

Figure 3: Downward slanting sidewall sections (Rettinger, pg. 165)

Mechanics Hall also has a thrust stage, which is a raised stage, with no curtains or overhangs. As opposed to a stage with a proscenium arch (a normal stage with curtains, ceiling etc.), a thrust stage does not trap any of the sound from the stage, delivering everything to the audience, whereas a proscenium arch's curtains and ceiling keep some of the sound from escaping to the audience (Egan, pg. 138). To further aid the delivery of the sound to the audience, Forestage Canopies or Coupled Stage Houses may be used. A Forestage Canopy includes a stage shell, and suspended sound-reflecting panels, which extend the shell into the audience, as shown in Figure 4.

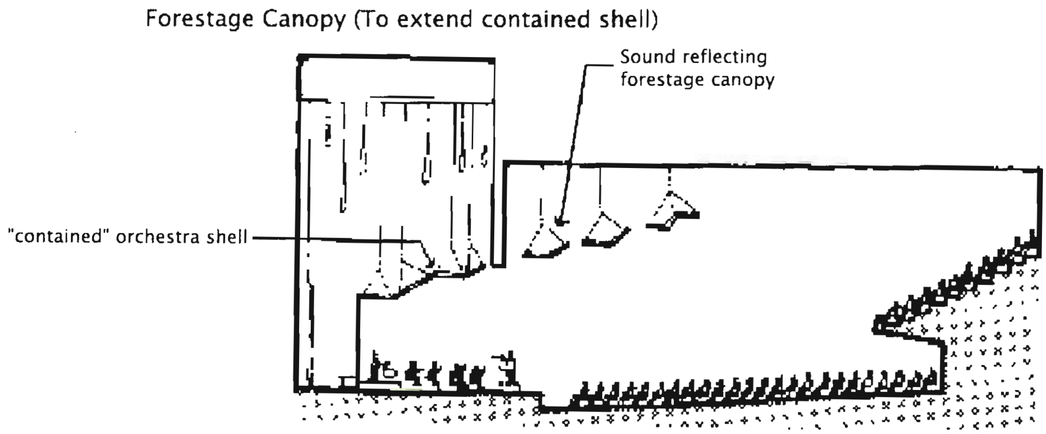

Figure 4: Stage incorporating a sound-reflecting forestage canopy (Egan, pg. 141)

A Coupled Stage House, illustrated in Figure 5, pairs sound-reflecting panels, spaced apart, with an open shell, to allow the flow of low-frequency sound energy (Egan, pg. 141). The Tanglewood Music Shed has a shell covering the orchestra, which is extended by an acoustic canopy, spanning the front one third of the hall. The result, despite the large size, dirt floor, and open-air rear, is an increase in definition (Beranek 1962, pg. 139-44).

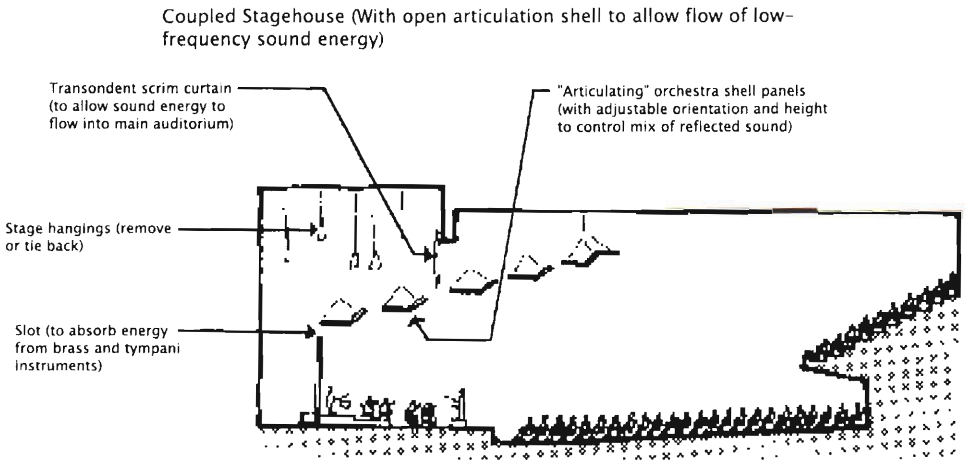

Figure 5: Coupled stagehouse with sound-reflective panels and open stage (Egan, pg. 141)

The combination of the highly reflective surfaces and wall ornamentation seems to work very well together. The reflection time is very short, with every reflection removing some power from the sound wave. Since the reflections are dispersed, the power is also dispersed. Thus, the sound wave rapidly loses power and dies out. With a flutter echo, i.e. without wall ornamentation, the echo would not die out nearly as quickly.

Though highly reflective surfaces are essential to the good acoustics of box-shaped halls, in some instances where speech intelligibility is a goal it is also desirable to have sound-absorbing material on the surfaces furthest from the sound source (Egan, pg. 101). This keeps the reverberation time down by keeping sound waves that would have to travel the entire length of the hall from reverberating and causing an echo. By lowering the reverberation time in this manner, there is less chance for time aliasing to occur. (Time aliasing is when decay from a previous signal is still present when the next signal is produced)

Another major problem in a hall would be background noise, such as ventilation fans, cars from outside, or people conversing elsewhere in the building. Isolation is very important for a low noise rating. (Beranek 1962, pg. 69) Even lights can contribute to background noise. Light dimmers can cause incandescent lights to hum and fluorescent lights naturally hum. Mechanics Hall has a very low noise rating of NC-14, meaning that if the hall were unoccupied, the noise would be 14 dB. Such low background noise allows for excellent speech intelligibility as well as a more pleasant concert experience.

2.2 *Acoustic Materials*

The materials used for a room's surfaces are very important. They greatly affect a room's reverberation characteristic. Different materials are classified by their absorption coefficients. Each material has been assigned an α_n, or absorption coefficient, between 0 and 1.0, 0 being a perfect reflector, and 1.0 being a perfect absorber. The absorption coefficient is a measure of a bounding surface's absorbing power per unit area. An open window would have an α_n of 1.0, since all of the signal will go outside, and none will be reflected. (This is only true if the window's dimensions are several wavelengths in measure)

The α_n of a material also depends on frequency; therefore, a complete reverberation analysis would involve an absorption coefficient curve. It is standard practice to supply the absorption coefficients, in manufacturer's literature, at 125, 250, 500, 1000, 2000, and 4000 cps (cycles per second). To give a general absorption coefficient for a particular material, it is typical to specify the α_n at 500 cps.

The absorption constant for an entire room is determined, using the following equation.

$$\bar{\alpha} = \frac{S_1\alpha_1 + S_2\alpha_2 + S_3\alpha_3 + \ldots + S_n\alpha_n}{S}$$

Each $S_n\alpha_n$ is the surface area and the absorption coefficient for a particular frequency of each corresponding material. The S in the denominator is the total surface area, or the sum of all the S_n values. People, chairs, tables, etc. must also be taken into account. Their $S_n\alpha_n$ values are added into the numerator, but their surface area is not added into the total S. (Beranek, 1996, pg. 302). Though it seems, in light of the previous statements, that the $\bar{\alpha}$ of a room could be greater than 1.0, it is assumed that the upper limit of $\bar{\alpha}$ is to be 1.0 regardless of further additions of absorptive material.

It is unlikely that a diffuse sound field, that is an even disbursement of sound in a given area, will exist in a room with an $\bar{\alpha}$ that is much higher than 0.3. This is because the sound waves will be absorbed too quickly.

It is common design practice not to concentrate absorbing materials in one part of the room. Smaller patches, distributed more evenly throughout the room, will provide a better reverberation characteristic (Beranek 1996, pg. 299-302). A more even distribution of sound absorbing materials also allows for more sound energy to be absorbed than is absorbed by the same amount of material in one concentrated area. For example a checkerboard pattern of 25, 2 ft by 2 ft, sound-absorbing panels will absorb much more sound energy than the same amount of material in a concentrated 10-ft by 10-ft section. This is because the 25 checkerboard sections have a ratio of perimeter to surface area 5 times the ratio for the concentrated coverage absorbers (Egan, pg. 59).

2.3 Measurements

2.3.1 Sound Pressure Level

One of the most important measurements used in acoustics, is Sound Pressure Level, or SPL. Sound can be related to pressure, since it is pressure that allows the human ear to detect sound. The word "level" indicates that the measure is logarithmic therefore Sound Pressure Level is a logarithmic quantity.

To measure this pressure level, a few different pieces of equipment are required: a calibrated microphone, a calibrated amplifier, and a calibrated indicator. If the sound is anything besides a simple tone, the response of the equipment must be uniform over a range of frequencies. An SPL meter is used to achieve this purpose.

If the sound is complex, a single value may not be sufficient. As stated by Sabine:

> *"It was obvious from the beginning that an investigation relating only to a single pitch was but a preliminary excursion, and that the complete solution of the problem called for an extension of the investigation to cover the whole range in pitch of the speaking voice and of the musical scale"*
>
> (Sabine, pg. 199)

It may be desired that the SPL be determined as a function of frequency. In that case, band-pass filters must be used, in conjunction with the other equipment. Band-pass filters are electronic circuits that allow only a specific "band" or range of frequencies of an input signal through. By using band-pass filters whose pass bands can be changed, the sound pressure may be measured in known bands of frequencies.

There are three types of analyzers that are commonly used; the Constant Bandwidth Analyzer, the Constant-Percentage Narrow Bandwidth Analyzer, and the Octave, Half-Octave, or Third-Octave Bandwidth Analyzer. These analyzers determine the harmonic components of sound, meaning that, over the range of frequencies designated, the analyzer will show the amplitudes at each frequency.

The Constant Bandwidth Analyzer has a pass band a fixed number of cycles wide. The common range is between 5 and 200 cps (cycles per second). This analyzer is used when the frequencies in the sound being analyzed are stable enough not to shift in and out of the narrow pass band that the instrument is measuring at.

The Constant-Percentage Narrow Bandwidth Analyzer has bandwidths, which are a constant percentage of the mid-band frequency wide. In other words, the width of each pass band is determined by its center frequency, with each bandwidth being the same percentage of its center frequency wide. This way fewer measurements are needed at higher frequencies. This is useful when measuring the harmonic components of waves where the fundamental frequency fluctuates. If the band is wide enough to compensate the fluctuation of the fundamental, it will always be able to compensate for the harmonics, since the bandwidth gets wider for higher frequencies.

The Octave Bandwidth Analyzer is used when the analysis of continuous spectrum noises is not required to be in great detail, such as when you are making a cursory examination of a room or when the acoustics of the room you are examining are not vital to the functionality of that room. The commonly used filter bands are 37.5 to 75 cps, 75 to 150 cps, 150 to 300 cps, 300 to 600 cps, 600 to 1200 cps, 1200 to 2400 cps, 2400 to 4800 cps, and 4800 to 9600 cps. (Beranek 1996, pg. 362-64)

To take measurements more conducive to the functions of the human ear, a dummy head may be used instead of a simple microphone. In this case, microphones are placed on either side of the dummy head, where the human ears would normally be. This would relate better to the human aural system, which is binaural, unlike a simple microphone measurement (Rettinger, pg. 167)

2.3.2 Impulse Response

Another very important measurement is the impulse response of a system. The impulse response is the output of a linear time-invariant (LTI) system, when the input is the impulse function. The frequency response of an impulse has an amplitude of one at every frequency; thus the impulse response is the result of a simultaneous excitation at all frequencies. The impulse response describes the entire LTI system; therefore, any desired information can be extrapolated from these results, using post-processing algorithms.

A true impulse function cannot be generated in practice, so another method must be used. A very high, very narrow pulse can be generated, but there is a risk of damaging equipment, or overloading the system being measured. If the amplitude is lowered, then each frequency is only delivered a low power, and the resulting signal-to-noise ratio (SNR) is poor. Signal-to-noise ratio is the ratio of the sound amplitude to the amplitude of the background noise present. Noise seems to be the best stimulus available. True white noise has equal average power over all frequencies, and is completely random.

Pseudo-random noise can also be used for input, generated using a Maximum Length Sequence (MLS). An MLS is a discrete-time signal, which toggles between two values, in an almost random fashion.

An MLS is generated by taking a clocked shift register and XOR-ing two or more taps, through a negative feedback loop, to the first register location, once every clock cycle. An XOR gate (exclusive OR Gate) will output a 1 if one input is a 1 and one input is a zero, otherwise the output is 0. A tap is designated as an input to the XOR gate, coming from a register location. The last tap is considered the output of the MLS sequence. Even though the output noise looks and behaves like a completely random signal, it is, in fact, not, having a period of $2^n - 1$ seconds, where n is the number of locations in the shift register.

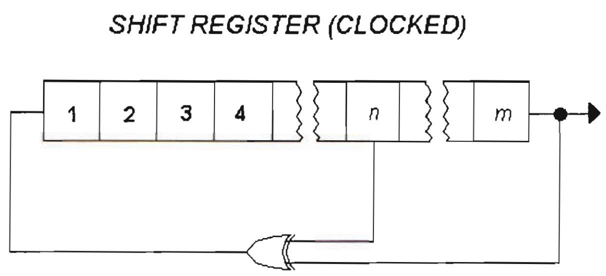

Figure 6: Maximum Length Sequence Generator

To characterize the pseudo-random noise generated, using an MLS, autocorrelation is used. Autocorrelation multiplies the original signal with many different shifted versions of itself, and sums these results. This provides a method of determining where the signal resembles itself. For example, the value at zero, on a plot of the autocorrelation of white noise, would be a spike of unity value. Everywhere else would have a value of zero, meaning the signal only resembles itself when no shift is added, since it is totally random. Autocorrelation of MLS yields unity spikes at zero and multiples of the period. Everywhere else, the value is -1/L. In exactly one period of the MLS, each frequency will contain equal power, except at DC. The longer delivery of the excitation to the LTI system supplies more energy to each frequency, resulting in a higher SNR.

Another important operation is cross correlation. This is like autocorrelation, except with two different signals. In fact, autocorrelation is considered a special case of cross correlation using the same signal twice. Cross correlation determines how closely two signals resemble each other, which is useful when a signal is corrupted by noise, and it is not obvious, through sight alone, whether the original signal is still present.

A Maximum Length Sequence System Analyzer (MLSSA) uses a pseudo-random MLS noise source, and fast, powerful digital signals processing techniques to determine the impulse response very accurately.

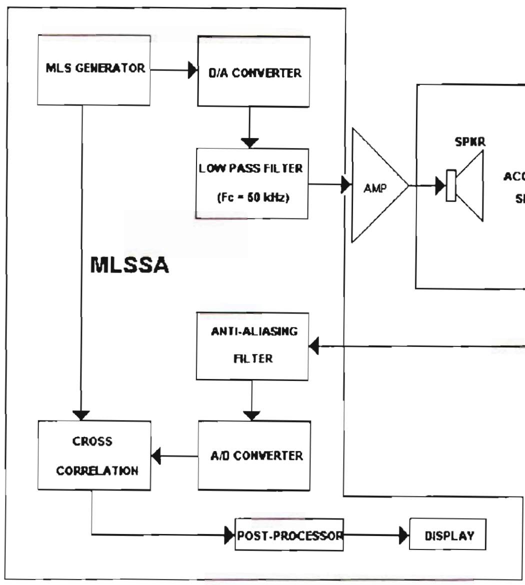

Figure 7: MLLSA Setup Diagram

In the case where MLSSA is to be used to measure the impulse response of an acoustic space, the digital analyzer must be interfaced with the analog system of the space. To do this, the MLS noise is passed through a digital-to-analog (D/A) converter, before it is output. The side-effect of this operation is a 1 dB drop, occurring at one third of the sampling rate; therefore, the sampling rate should be chosen at three times the maximum frequency, to ensure a nearly flat output, over the desired range of frequencies.

Another problem is that of slew rate. Slew rate is the rate at which the transition between two values on a curve occurs. Because the MLS toggles between two values, very quickly, the slew rate is very high. To smooth this steep transition, a 50 kHz low pass filter is used. Low pass filters pass only low frequencies, and cut the amplitudes at high frequencies down to approximately zero. In this case, the border between low and high frequencies would be 50 kHz.

Once the noise has been converted and filtered, the signal is amplified, and is input to the LTI system. For example, for the impulse response of an acoustical space, the signal would be output from a loudspeaker into the acoustic space. A microphone, placed a certain distance away from the speaker, picks up the resulting sound in the space, and feeds the signal back to the computer.

Once it is fed back to the computer, the signal is passed through an anti-aliasing filter, limiting the signal bandwidth to one half the sampling rate. The signal is then converted to a digital signal, using an analog-to-digital (A/D) converter.

Finally, the resulting samples are cross correlated with the original MLS signal, and the result of this correlation is the estimated impulse response. The computer can generate the impulse response of 32,768 samples.

2.3.3 Speech Intelligibility

Speech Intelligibility, or how well a speaker can be understood in the audience, is related to three things: the noise level in the room, the signal level in the room, and the reverberation time. Different sounds affect the intelligibility more than others. Vowels are produced by the vocal cords, while consonants are produced by air moving past the tongues, lips and teeth. This causes vowel sounds to be much stronger than consonant sounds, leaving consonants more susceptible to being masked by noise. For these reasons, consonants are more important to speech intelligibility than vowels (Beranek 1996, pg. 407).

In the 1940's, Harvard was deeply involved in research on the subject of speech intelligibility. This led to the development of phonetically balanced word lists (PB lists). PB lists consisted of 50 monosyllabic words designed to represent all of the possible sounds a system would encounter, equally. The word lists are found on tape and CD, with each word spoken clearly, one-at-a time, in the sentence, "You will write ____ on the line". Each listener has a sheet, with 50 lines, one for each word, and he/she will write the word that they think they heard on the corresponding line. The percent intelligibility is the number of words the listener correctly identifies multiplied by two.

Another type of intelligibility test is the rhyme test. This test also uses 50 monosyllabic words, on tape or CD, except they are read in the sentence, " Please choose ____ now" or "Mark the word ____, please". Each listener has an answer sheet, with six choices for each word. Each of the six choices rhymes, and the listener must choose which of the rhyming words was spoken, and mark it on the sheet. The percent intelligibility is also the number of correct answers multiplied by two. This type of testing is used most often by the Air Force, in Patterson, Ohio. The test is used during flight simulations, to determine how well the communication system allows the pilot to fly and understand orders, at the same time.

From the percent intelligibility number, the Articulation Index (AI) can be determined, using a particular set of curves, each curve corresponding to a certain number of PB words. Perfect percent intelligibility is 100%, which corresponds with an AI of 1. Articulation Index ranges from 0 to 1, and is an accepted way to characterize the intelligibility of an acoustic space. Speech Transmission Index (STI) is another name for AI, and RASTI (Rapid Assessment Speech Transmission Index) is an algorithm to more quickly assess the STI of a system. The only drawback is a small decrease in accuracy. An AI/STI greater than 60% is considered satisfactory, an AI/STI less than 30% is considered poor, and an AI/STI between 30% and 60% is considered to be an inconclusive result, which should be viewed with suspicion.

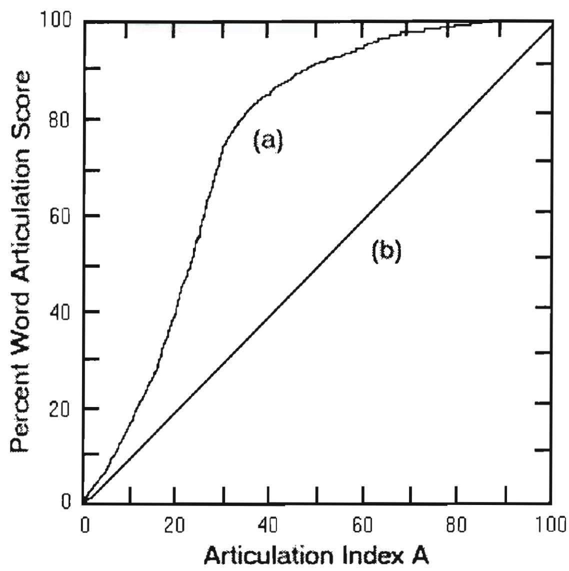

Figure 8: Percentage word articulation score versus articulation index for (a) trained listeners familiar with the content of the word lists and (b) untrained listeners from the general population (Beranek, 1996, pg. 411)

Neither of the aforementioned tests is infallible. There are a few factors that could adversely affect the results. One is the education of the listeners. If the listener has a limited vocabulary, he/she might not know one of the test words, and in the case of the PB list test, would most likely not write that word on the line. Using the rhyme test, on the other hand, if they see what they think they heard they would be more likely to give this as an answer. It is also possible, when using the rhyme test, to allow the listeners to go over the answer sheets beforehand to be sure that all the words are known to them. This allows for more accurate speech intelligibility testing as well. Another factor is the number of sounds in a word. The more sounds there are, the more likely they will not all be understood completely. Also, different speakers speak differently. If the speaker is from Boston, and the listener is from Texas, the listener would probably not understand some of the sounds the speaker produces, solely because of his/her accent. This is why the tapes and CD's use standard speakers, who speak clearly, and without a harsh accent. Finally, the more times a listener has taken these tests, the more accustomed he/she would be to these tests, and the better the results would be. This corresponds to a "learning curve" for performing accurately. Some typical results are shown in Figure 8.

2.4 Acoustic Theory

There are ways of determining the theoretical results for an acoustic space, relating to reverberation. This involves many equations, and relates to the materials, surface area, and volume of the room, and the speed of sound, approximately 340 m/s.

2.4.1 Mean Absorption Coefficient

The mean absorption coefficient, or $\bar{\alpha}$, is described in the **Materials** section of the Background. This is one of the first values that must be determined, as it is used often, in other equations.

2.4.2 Room Constant

The room constant, R, is a value assigned to a room, to characterize its general absorption qualities.

$$R = \frac{S\bar{\alpha}}{1-\bar{\alpha}}$$

where S is the total Surface Area of the room.

2.4.3 Mean Free Path

The Mean Free Path (MFP), or d, is the mean distance a sound wave has to travel, before it reflects off of a surface.

$$d = \frac{4V}{S}$$

where V is the total volume of the room.

2.4.4 Transit Time

The transit time, t', is the time it takes for a sound wave to travel one MFP.

$$t' = \frac{d}{c}$$

where c is the speed of sound.

2.4.5 Decay Rate

The decay rate, A, is the rate at which the impulse response decays. This decay rate will be higher, if the room is very absorptive, because the reverberations of the initial impulse will diminish faster than if the room was highly reflective.

$$A = 1.085\frac{cS}{V}\left[-2.30\log\left(1-\overline{\alpha}\right)\right]$$

This equation can be further simplified, by substituting a', the Metric Absorption Unit.

$$a' = S\left[-2.30\log\left(1-\overline{\alpha}\right)\right]$$

This has units of m^2, and when substituted into the decay rate formula yields

$$A = 1.085\frac{ca'}{V}$$

2.4.6 Reverberation Time

Reverberation time, or T_{60}, is the time it takes for the sound energy in an acoustic space, from some excitation, to decay 60 dB. This will be the most important value to us, since it is easily measured, in practice.

$$T_{60} = \frac{60V}{1.085ca'}$$

If the decay rate has already been determined, this can be substituted into the equation, yielding

$$T_{60} = \frac{60}{A}$$

2.5 Computer Modeling Software

There are several different acoustics modeling programs on the market that allow the design of a room to be tested acoustically before it is even built. In all of these programs a 3D CAD model is used to represent the room that is to be tested. Frequency dependent material properties, such as absorption and diffusion, are assigned to the room surfaces of the model and source directivities are assigned to sound sources. Some programs also include auralization capabilities that allow one to hear what a room will sound like before changes are made to a room or before the room is even built (Dalenback, [display.htm#Prediction]). CATT™ was used to serve our purposes as we could test the acoustic effect of any changes we wished to make to the gymnasium, without actually making the changes. This ability to predetermine the effect of structural and material changes to the gymnasium also helped us convince school officials that our proposed modifications would in fact have a beneficial effect. Below we discuss the characteristics and attributes of several acoustics modeling programs.

The ODEON™ acoustics modeling program was designed by a team at the Department of Acoustic Technology and six Danish consulting companies in 1984. In 1995, ODEON™ 2.5 competed in the 'International Round Robin on Room Acoustical Computer Simulations' and was one of only three programs out of 16 to be acknowledged 'Unquestionably reliable in the prediction of room acoustical parameters' (Lynge, [/~odeon/about.htm]). The latest version available is ODEON™ 3.1, a Windows™ based version released in 1997, and can be purchased in the three different versions of Industrial, Auditorium, and Combined (includes features of both Industrial and Auditorium versions). ODEON™ 3.1 allows a 3-D representation of a room, created in a CAD program, to be imported and used for simulated acoustical testing. A variety of materials can be specified for the different surfaces of the room inside ODEON™ 3.1. When testing the room the program provides a variety of results including, but not limited too, reverberation time, early decay time, and sound pressure level for a wide range of frequencies. Graphical results are also given, including decay curves, reflectograms, and 3D reflection paths (Lynge, [/~odeon/products.htm]). ODEON™ does not, however, provide for the auralization of prediction results. Though ODEON™ is very inexpensive, retailing at 60 Danish Kroners, or about 10 US dollars, payment must be made using an order form and the software must then be shipped from Denmark. This means the software would not arrive for at least 6 to 8 weeks.

Another reliable acoustic modeling program is CATT-Acoustic™ developed by Bengt-Inge Dalenback (Ph.D.). The most recent version of CATT™ is the Windows™ based version 7.1 released in October 1998. Like ODEON™, CATT-Acoustic™ competed in the 'International Round Robin on Room Acoustical Computer Simulations' and was one of the three programs to be acknowledged 'Unquestionably reliable in the prediction of room acoustical parameters'. The CATT™ acoustics modeling program features an AutoCAD™ interface that allows the creation of 3D CAD models directly in the CATT™ format (Dalenback, [/display.htm#Prediction]). This means that rooms do not have to be designed in other CAD programs and then imported into CATT™, as is the case with ODEON™. Surfaces in the room can be assigned an absorption factor and a diffusion factor. The room acoustic measurements included in the program are reverberation time, SPL, RASTI, definition, clarity, lateral energy fraction, center-time, direct to reverberant ration, mean absorption factor, and mean free path. Graphical examinations include interactive 3D geometry projection, interactive reflection tracing, reverberation decays; impulse response, absorption statistics, early part SPL and ray direction mapping (Pedersen, [/sl_acous.html]). Desktop auralization is also included in the program and can be binaural auralization, stereo auralization, or mono auralization. CATT-Acoustic™ uses Microsoft Windows™ WAVE format to produce its auralization files, which can be played on a computer with a 16-bit sound card or transferred to other media such as CD. CATT-Acoustic™ is a very well designed and comprehensive program and thus is very expensive. For the prediction part of CATT-Acoustic™ it is approximately $2500 US dollars. For the auralization part of CATT-Acoustic™ it is another $2500 US dollars (Pedersen, [/sl_acous.html]). However, the audio lab here at WPI has a registered full copy of CATT-Acoustic™ on its PC that is available under restricted access through Professor Michalson. A free demo version was also available so that we could construct the gym model on our own machine and then run it on the PC in the audio lab to get the results.

Another acoustic modeling program is EASE™ (Electro-Acoustic Simulator for Engineers). EASE™ was developed by ADA (Acoustic Design Ahnert) under the direction of Dr. Wolfgang Ahnert and is distributed by Renkus-Heinz Incorporated. Unlike ODEON™ and CATT™ it is an MS-DOS™ based program and lends itself more to speaker and sound reinforcement design than it does to architectural and material design as it does not allow the defining of the characteristics of room materials. EASE™ has a vast loudspeaker database including such speaker manufacturers as Altec, Apogee, EV, JBL, Community, Klipsch, Frazier, OAP, PAS and University. Like CATT™ it allows for auralization of a modeled room. This is accomplished using a supplementary program, distributed by Renkus-Heinz Inc., called EARS™ (Electronically Auralized Room Simulation). The post processing files created by EASE™ must be imported into EARS™ as well as the 'dry' signal from a CD or DAT recording in order for EARS™ to be able to 'auralize' a room (Renkus-Heinz, [/easeinf.htm]). EASE™ retails for about $1995 and is of not much use to us considering its propensity towards speaker and sound-reinforcement design (Pedersen, [/sl_acous.html]).

Some other programs that were considered but were ruled out due to their price, availability, functionality, or a combination thereof are listed below in Table 1 along with their computer requirements, distributor, and price. The ODEON™, CATT™, and EASE™ programs are also included in the table.

Table 1: Acoustic modeling programs and their computer requirements, distributor, and price (Pedersen, [/sl_acous.html])

Name	Computer	Distributor	Price
AcoustaCADD™	MS-DOS™	Altec-Lansing	$1000
CADP2™	MS-DOS™	JBL	$1800
CATT-Acoustic™	Microsoft Windows™	CATT	$2500/prediction $2500/auralization
Convolvotron™	Not Listed	Crystal River Engineering	Not Listed
EASE™	MS-DOS™	Renkus-Heinz, Inc.	$1995
Modeller™	Apple Macintosh™	Bose Corporation	$700
ODEON™	MS-DOS™	Department of Acoustic Technology	Approx. $10

2.6 *Relevant Fire Codes*

This section discusses the fire code requirements for specific relevant materials, used for different purposes. These fire codes are taken from the Massachusetts Fire Codes, 780 CMR, 6th Edition. The particular segments we discuss in this section are included, in their entirety, in Appendix C.

First is the section discussing thermal- and sound-insulating materials, *780 CMR 722.2 and 722.3.* These state that exposed installations must have a flame spread rating of less than or equal to 25, and a smoke-developed rating of less than or equal to 450. Concealed installations, on the other hand, should have a flame spread rating of less than or equal to 75, and the same smoke-developed rating as exposed installations.

Next is the discussion of carpet, or carpet-like textile wall coverings, in *780 CMR 803.6.* This includes any textile wall covering that is napped, tufted, looped, woven or nonwoven. Since felt is a textile, when applied to a wall, it would fall under this category. This section states that the aforementioned materials should have a Class I flame spread classification and be applied only to rooms or areas protected by an automatic sprinkler system. This requirement had a major effect on the cost-effectiveness of some solutions and thus had a major impact on our recommendations.

In *780 CMR 804.3*, wall coverings with Class II or III flame spread classifications are discussed. This section states that the aforementioned materials may be applied to a noncombustible backing, or substrate, as long as it is less than ¼" thick.

Finally, in *780 CMR 807.0*, interior hangings and decorations are discussed. This includes felt, when hung as a banner, drapery material, and acoustic panels. First, in *780 CMR 807.1.1*, it states that the amount of non-combustible materials allowed is unlimited. This would be for acoustic panels, since they are non-combustible. Next, in *780 CMR 807.1.2*, it states that the amount of flame-resistant materials allowed is less than or equal to 10% of the total wall and ceiling area. This would include felt and drapery, if treated to be flame-resistant. In *780 CMR 807.2* it states that material treated to be flame-resistant should not generate more smoke than untreated wood or paper, burning under similar conditions. Finally, in *780 CMR 807.2.1*, it states that, when treated to be flame-resistant, all organic materials approved, will only be approved for one year. An affidavit must be filed with a code official, certifying the treatment process, the date the material was treated, and the proven period of effectiveness. This means that these materials must be fire-treated and re-certified every year.

3 Methodology & Results

3.1 Preparation for the Speech Intelligibility Testing

As we were dealing with children, it was more beneficial to use the rhyme testing. This is because children have a smaller vocabulary, in general, and taking part in the rhyme test would seem more fun. The number of words was also decreased, since children tend to lose interest quickly. If the listener loses interest, he/she would, most likely, pay less attention to the words, and this factor would skew the results. Even though using less words, say 20 or 25, would decrease the accuracy somewhat, this accuracy loss would be much less of a factor than the listeners losing interest.

To create the best possible test, we listened to several different prepared rhyme tests, on the CD, "Intelligibility and Measurement Test Disc 2". From these tests, we devised two of our own personalized tests, with each of the 25 selected word lists as follows:

List 1(male voice on CD):

went	*wed*	*back*	*hang*
fold	*tin*	*weigh*	*hook*
pass	*dud*	*cave*	*lick*
lake	*sum*	*boil*	*bun*
sit	*lot*	*heel*	
must	*rest*	*ten*	
dig	*pill*	*heat*	

List 2(female voice on CD):

tent	*not*	*fill*	*sick*
hold	*nest*	*same*	*sale*
pat	*big*	*feel*	*sap*
lace	*page*	*jaw*	*run*
just	*cake*	*meat*	
bed	*cop*	*rip*	
pen	*foil*	*shook*	

This particular test uses the sentences, "You will mark the word ____, please". Answer sheets were devised, with the six rhyming possible responses for each word. In order to increase the accuracy of the test we proposed that the teachers review the answer sheets with the children so they would know all of the words that may have been used in the test. This helped to negate the factor that a child would not know a word and therefore not mark it on the test.

Results of Speech Intelligibility Tests

3.1.1 Public Address System Test

On Friday, December 4th, 1998, we performed two rhyme tests with Mrs. Theresa Goulet's 6th grade students. The lists for each test are shown in the **Speech Intelligibility Testing** section of the report.

First, we set up nineteen metal folding chairs, and marked these folding chairs, and 16 designated spots in the bleachers, with numbers. These seats are shown in the map of the room, in Appendix R. The measurements were taken with a 25-foot tape measure, and were measured from the centers of each seat.

Next, with the help of student Adam White, the Public Address system for the gymnasium was assembled, as it would normally be set up, during a function. As shown in the map, a speaker was placed on either side of the gymnasium.

The testing process, and reasons for the test, were discussed with the class, during their "home room" period, and from there, they proceeded to the gymnasium, for their scheduled gym class.

We handed out a test to each student, and instructed him or her to proceed to their particular seat, designated by the number on the right-hand corner of their test sheets. This went very smoothly and quickly. We tried to disperse the 18 students present among the 35 seats, as evenly as possible.

Using the prepared testing CD, we administered the first test, which was read by a male voice. The students were very quiet, and behaved very well. We collected all of the test sheets, and then distributed test sheets for the second test, which was read by a female voice.

The second test went as smoothly as the first, and after collecting the test sheets, the students helped us to put away the chairs, and we disassembled the PA system. The results were very good, in terms of percentage correct. An acceptable average percentage correct for a room, as stated in the **Speech Intelligibility Testing** section, is greater than 60% correct. For the first test, the average percent correct was 91.9% correct, for the second, it was 92.4% correct. This shows an above average speech intelligibility for the room, with the PA system in use. These results are shown in Table 2.

Table 2: Percent words correct by seat number for tests 1 and 2

Seat #	Test #1		Test #2	
	# Right Out of 24	% Right	# Right Out of 25	% Right
1	22	91.7 %	24	96 %
2	23	95.8 %	21	84 %
6	24	100 %	22	88 %
7	23	95.8 %	22	88 %
8	24	100 %	25	100 %
12	21	87.5 %	25	100 %
13	24	100 %	25	100 %
14	16	66.7 %	25	100 %
18	21	87.5 %	18	72 %
19	21	87.5 %	25	100 %
20	23	95.8 %	23	92 %
23	23	95.8 %	24	96 %
24	22	91.7 %	19	76 %
25	22	91.7 %	24	96 %
26	21	87.5 %	21	84 %
29	22	91.7 %	23	92 %
30	24	100 %	25	100 %
31	21	87.5 %	25	100 %
	$\%_{AVE}$ = 91.9 %		$\%_{AVE}$ = 92.4 %	

Also shown in Table 2 are the individual scores. There seemed to be no consistency with bad scores. For example, the student in seat number 14 scored a 66.7% on the first test (the lowest score for that test), but scored a 100% on the second test. Also, a look at the seating map showed no correlation between location in the room and bad scores on the test.

Shown in Tables 3 and 4, are the percentages right and wrong for each particular word. This does show a correlation between words starting with the letter "p" or the letter "b", and a high percentage incorrect. Every word that was marked incorrectly over 20% of the time started with either a "p" or a "b". The reverse was not true, however, with such words as "bed" and "page" being marked correctly by everybody.

Table 3: Percentages right and wrong for each word in test 1

Word	**# Right**	**% Right**	**# Wrong**	**% Wrong**
1) went	16	88.9 %	2	11.1
2) fold	16	88.9 %	2	11.1
3) pass	17	94.4 %	1	5.6
4) lake	16	88.9 %	2	11.1
5) sit	18	100 %	0	0
6) must	18	100 %	0	0
7) dig	17	94.4 %	1	5.6
8) wed	16	88.9 %	2	11.1
9) tin	18	100 %	0	0
10) dud	16	88.9 %	2	11.1
11) sum	18	100 %	0	0
12) lot	18	100 %	0	0
13) rest	18	100 %	0	0
14) pill	17	94.4 %	1	5.6
15) back	14	77.8 %	4	22.2
16) way	18	100 %	0	0
17) cave	17	94.4 %	1	5.6
18) boil	10	55.6 %	8	44.4
19) heel	17	94.4 %	1	5.6
20) ten	18	100 %	0	0
21) N / A	N /A	N / A	N / A	N / A
22) hang	17	94.4 %	1	5.6
23) hook	17	94.4 %	1	5.6
24) lick	18	100 %	0	0
25) bun	12	66.7 %	6	33.3

Table 4: Percentages right and wrong for each word in test 2

Word	# Right	% Right	# Wrong	% Wrong
1) tent	18	100 %	0	0 %
2) hold	17	94.4 %	1	5.6 %
3) pat	14	77.8 %	4	22.2 %
4) lace	18	100 %	0	0 %
5) just	18	100 %	0	0 %
6) bed	18	100 %	0	0 %
7) pen	9	50 %	9	50 %
8) not	15	83.3 %	3	16.7 %
9) nest	18	100 %	0	0 %
10) big	11	61.1 %	7	38.9 %
11) page	18	100 %	0	0 %
12) cake	18	100 %	0	0 %
13) cap	17	94.4 %	1	5.6 %
14) foil	17	94.4 %	1	5.6 %
15) fill	18	100 %	0	0 %
16) same	17	94.4 %	1	5.6 %
17) feel	18	100 %	0	0 %
18) jaw	18	100 %	0	0 %
19) meat	16	88.9 %	2	11.1 %
20) rip	15	83.3 %	3	16.7 %
21) shook	18	100 %	0	0 %
22) sick	18	100 %	0	0 %
23) sale	17	94.4 %	1	5.6 %
24) sap	18	100 %	0	0 %
25) run	17	94.4 %	1	5.6 %

Finally, shown in Table 5, are the percentages of responses for each wrong answer given, for all of the words marked incorrectly over 10% of the time. No correlation was found with this analysis.

Table 5: Percentage of wrong answers for all words marked incorrectly more than 10% of the time

Test #1	% Wrong	Answers Chosen
1) went	11.1 %	b) tent & c) rent : 1 ; c) rent : 1
2) fold	11.1 %	d) told : 2
4) lake	11.1 %	c) bake :2
8) wed	11.1 %	d) said : 1 ; none : 1
10) dud	11.1 %	a) bud & d) dud : 1 ; a) bud : 1
15) back	22.2 %	d) pack : 2 ; f) rack : 1 ; none :1
18) boil	44.4 %	b) oil : 7 ; none : 1
25) bun	33.3 %	b) gun : 2 ; d) fun : 2 ; e) done :1 ; none :1
Test #2	**% Wrong**	**Answers Chosen**
3) pat	22.2 %	c) hat : 4
7) pen	50 %	b) hen : 8 ; e) when : 1
8) not	16.7 %	a) lot : 3
10) big	38.9 %	b) fig : 6 ; e) pig :1
19) meat	11.1 %	b) feet : 1 ; e) wheat :1
20) rip	16.7 %	d) lip : 3

Overall, this test shows a small problem with "p" and "b" sounds, but indicates that there is not a real problem present with speech intelligibility, when the PA system is in use.

3.1.2 Human Speaker Test

In order to better qualify the speech intelligibility in the gymnasium we also needed to do a speech intelligibility test with a human speaker rather than a voice broadcast over the PA system. We did this using the same word lists as before but this time with Mrs. Brenda Thompson doing the speaking for both tests, and a different group of students listening. For this test the speaker's voice was not amplified or enhanced in any way. The chairs were put in the same places with the students evenly distributed throughout the room just as in the previous test.

Though there was a slight decrease in the average percentage correct for these tests, the average was still well above the acceptable 60%. As shown in Table 6, the percentage correct for the first test was 80.1% and for the second test was 75.8%. This means that the intelligibility in the room was not as good when there is a human speaker as when there was a voice broadcast over the PA system. However, it seems the speech intelligibility in the room was not a major problem considering the well above acceptable average scores on both the PA system and human speaker tests.

Table 6: Percent words correct by seat number for tests 1 and 2 read by Mrs. Thompson

Seat #	Test #1		Test #2	
	# Right Out of 24	% Right	# Right Out of 25	% Right
1	20	83.3 %	17	68 %
2	18	75 %	15	60 %
6	18	75 %	20	80 %
7	23	95.8 %	21	84 %
8	21	87.5 %	22	88 %
12	19	79.2 %	16	64 %
13	20	83.3 %	19	76 %
14	20	83.3 %	19	76 %
18	21	87.5 %	21	84 %
19	18	75 %	16	64 %
20	21	87.5 %	20	80 %
23	16	66.7 %	17	68 %
25	19	79.2 %	21	84 %
26	17	70.8 %	22	88 %
29	18	75 %	19	76 %
30	20	83.3 %	20	80 %
31	16	66.7 %	19	76 %
32	21	87.5 %	17	68 %
	$\%_{AVE}$ = 80.1 %		$\%_{AVE}$ = 75.8 %	

As before there doesn't seem to be any consistency in bad scores. The student in seat 2 scored a 75% on the first test while he scored a 60%, the lowest score, on the second test, a difference of 15%. In fact the average difference between first test and second test scores for the students was about 8.6%.

Tables 7 and 8 show the percentages right and wrong for each word in both tests. There again appeared to be a problem with hearing words beginning with 'b' or 'p'. Six words beginning with 'b' or 'p' were marked wrong more than 30% of the time and the word that was marked wrong the most on test one was "bun" at 66.7% and the word marked wrong the most on test two was "pat" at 88.9%. Some words that do not begin with 'b' or 'p' appeared to be a bigger problem on this test than they were for the PA system test. For example, the word "wed" was marked wrong 44.4% on the human speaker test but only 11.1% on the PA system test and the word "rip" was marked wrong 55.6% on the human speaker test but only 16.7% on the PA system test. This is probably the most convincing evidence of the difference between having a single human speaker and having a stereo system producing the words.

Table 7: Percentages right and wrong for each word in test 1 read by Mrs. Thompson

Word	**# Right**	**% Right**	**# Wrong**	**% Wrong**
1) went	15	83.3 %	3	16.7 %
2) fold	14	77.8 %	4	22.2 %
3) pass	18	100 %	0	0 %
4) lake	11	61.1 %	7	38.9 %
5) sit	18	100 %	0	0 %
6) must	17	94.4 %	1	5.6 %
7) dig	13	72.2 %	5	27.8 %
8) wed	10	55.6 %	8	44.4 %
9) tin	18	100 %	0	0 %
10) dud	17	94.4 %	1	5.6 %
11) sum	18	100 %	0	0 %
12) lot	9	50 %	9	50 %
13) rest	18	100 %	0	0 %
14) pill	18	100 %	0	0 %
15) back	14	77.8 %	4	22.2 %
16) way	15	83.3 %	3	16.7 %
17) cave	13	72.2 %	5	27.8 %
18) boil	12	66.7 %	6	33.3 %
19) heel	12	66.7 %	6	33.3 %
20) ten	18	100 %	0	0 %
21) N / A	N /A	N / A	N / A	N / A
22) hang	13	72.2 %	5	27.8 %
23) hook	14	77.8 %	4	22.2 %
24) lick	16	88.9 %	2	11.1 %
25) bun	6	33.3 %	12	66.7 %

Table 8: Percentages right and wrong for each word in test 2 read by Mrs. Thompson

Word	# Right	% Right	# Wrong	% Wrong
1) tent	18	100 %	0	0 %
2) hold	14	77.8 %	4	22.2 %
3) pat	2	11.1 %	16	88.9 %
4) lace	9	50 %	9	50 %
5) just	18	100 %	0	0 %
6) bed	16	88.9 %	2	11.1 %
7) pen	6	33.3 %	12	66.7 %
8) not	18	100 %	0	0 %
9) nest	14	77.8 %	4	22.2 %
10) big	4	22.2 %	14	77.8 %
11) page	8	44.4 %	10	55.6 %
12) cake	15	83.3 %	3	16.7 %
13) cap	15	83.3 %	3	16.7 %
14) foil	18	100 %	0	0 %
15) fill	17	94.4 %	1	5.6 %
16) same	18	100 %	0	0 %
17) feel	18	100 %	0	0 %
18) jaw	15	83.3 %	3	16.7 %
19) meat	10	55.6 %	8	44.4 %
20) rip	8	44.4 %	10	55.6 %
21) shook	18	100 %	0	0 %
22) sick	17	94.4 %	1	5.6 %
23) sale	18	100 %	0	0 %
24) sap	17	94.4 %	1	5.6 %
25) run	9	50 %	9	50 %

The human speaker, speech intelligibility test, in conjunction with the PA system test affirm that there was a small problem with interpreting ‘b’ and ‘p’ sounds but that there was no major problem with the overall speech intelligibility in the room. The fact that the students were so well behaved and quiet may have increased the intelligibility, compared to during a performance. When we visited the school during the students’ Christmas Concert, the noise level in the room was definitely much higher.

3.2 CATT™ Computer Modeling

To help us simulate any possible changes we could have considered making to the gym, we used CATT™ to "draw" the gymnasium, and to analyze the acoustical properties of the room.

First, we entered code for a stripped down version of the gym, including the walls, angled ceiling, and the wooden track for the retractable divider. This was done by programming a .GEO file, or geometry file. The model was entered on our computer, and was then brought to WPI, for acoustical simulation on a computer in Atwater Kent Labs. The programmed model of the gym is shown below in Figure 9.

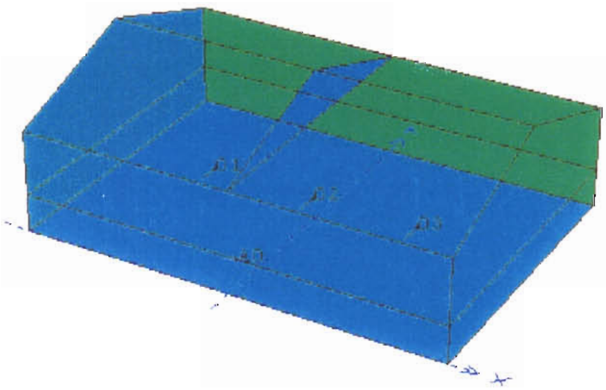

Figure 9: Diagram of CATT Modeled Empty Gym

The code for the design of the room as defined in the file GYM.GEO is included in Appendix K. The first parameters listed in this code are the variables used to define the dimensions of the gymnasium, which were obtained from blueprints, provided to us by Dr. Giantris. These variables were defined as either LOCAL or GLOBAL depending on whether they were needed in files other than GYM.GEO. For instance, some of these variables were needed in the receiver file, REC.LOC, and so were defined as GLOBAL. The next parameters defined in the file were the absorption characteristics of the different surface types in the gymnasium. The percent absorption figures (100*α), for each surface type, was supplied for each of 6 octave bands (See **Literature Review**).

In order to define walls and other planes in the model, first one must declare corners in the .GEO file. Each corner was declared by assigning it a number and then supplying its coordinates in relation to the x, y, z-axes, so as to center the room on these axes. With the corners of the room defined we were then able to define the planes that give us the structure of the room. The planes were defined by giving each one a number, followed by a plane name, then the corners that define the room, and finally the surface

```
;rec.loc
RECEIVERS
1     -w/4  d/2   1.3
2     0     d/2   1.3
3     w/4   d/2   1.3
```

Figure 10: Receiver File

type of the plane. CATT™ requires that the corners defining a plane be listed in the order they would be seen clockwise from the back, or non-reflective, surface of each plane. For instance, if one were defining the wall of a room one would want to list the corners in the order they would be seen clockwise from the exterior surface of the plane, which is the surface that would not be hit by sound waves in a simulation. It is not important which corner is listed first, as long as they follow the correct order.

The points labeled 01, 02, and 03, in Figure 10, are designated "receivers". These represent measurement points, such as a recording microphone, or the location of a person in the audience. These were designated by programming a .LOC file. This code is shown in Figure 10. To define a receiver we needed to specify first, a number for the receiver and then the x, y, and z coordinates of the receiver in the room. CATT allows for the specification of as many as100 different receivers, labeled 00 to 99.

The point labeled A is a "source". This represents an object like a speaker or person. These were also designated by programming a .LOC file. This code is shown in Figure 11. To define a source we needed to first specify a source label.

```
;src.loc
LOCAL src_z = 1.5
SOURCES
A0    0     1     src_z      OMNI 0     3     src_z<70 73 76 79 82 95>
```

Figure 11: Source File

CATT™ allows for the specification of up to 26 different sources, labeled from A to Z. The next parameter we needed to specify for a source was the x, y and z coordinates of the source within the room. Then, we needed to specify the directivity of the source, either omni-directional, or another directivity pattern. To make one's own directivity pattern, the directivity pattern window must be opened, in CATT™. In the directivity pattern window, there is a spherical "balloon" pattern. Using a mouse, and clicking and dragging the different points on the sphere, one can reshape the spherical directivity, to any directivity pattern desired. Then, the coordinates of the point, which the source is pointed at, were specified. Finally, the SPL for each of the six octave bands was specified for the source.

First, we used CATT™ to simulate the response of the original room, with no changes made. This is the basic shape of the room, with the painted steel ceiling, wood floor, wooden divider track, and walls, appropriately divided into sections of ceramic tile and cement block. Three receivers were used: one in the middle of the entire room, and one in the middle of each half of the room. The omni-directional source in the simulation was placed 1m off of the middle of the stage wall, at a height of 1.5 m.

The results of this simulation definitely showed how bad the room's acoustics were. All of the surfaces in the room were very highly reflective, and the Mean Free Path (MFP), i.e. the average length a sound ray travels before it hits a wall, was long. This leads to a high reverberation time, since the reflective surfaces take very little energy out of the sound reflections, and the frequency at which reflections hit a wall is low, because of the long MFP. The MFP and reverberation time values for each octave band are shown in Table 9. The reverberation time, SabT, is a very good estimation, made by CATT™, of the time it takes for the sound power to drop 60 dB in a room after a quick impulse of sound. This reverberation time is known as T_{60} (See **Literature Review**), and is virtually equivalent to SabT.

Table 9: MFP and Reverb. Time for Empty Gymnasium for Six Octave Bands

	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz
MFP	8.92 m	8.92 m	8.91 m	8.90 m	8.91 m	8.92 m
SabT	4.02 sec	4.50 sec	4.53 sec	4.88 sec	4.87 sec	4.21 sec

In the **Literature Review** we mentioned that the appropriate height of a room, H, when a desired reverberation time of the room, T_{60}, is known, can be estimated by the formula:

$$H \cong 20T_{60}$$

From this equation we can calculate the appropriate reverberation time for the gym, since we known that the gym has a height of 30 ft. This time turns out to be about 1.5 sec. A comparison of this time to those shown in Table 9 shows that the approximate reverberation time of the gym is much higher, an average of about 3 sec higher, than it really should be.

We also noticed from a plot of percentage of wall hits vs. plane number, that the majority of reflections were hitting the floor, and the two slanted ceiling sections. The floor could not be changed, but the ceiling sections, with a percentage of wall hits at approximately 15.5% each, could. A table of percentage of wall hits for each plane is shown below in Table 10.

Table 10: Percentage Wall Hits for Each Plane in the Empty Gym

Plane Number	Plane Name	% Hits
1	Audience Floor	28%
2	Bottom Stage Wall (tile)	3.5%
3	Top Stage Wall	6.5%
4	Bottom Left Wall (tile)	2.5%
5	Top Left Wall	6.5%
6	Bottom Right Wall (tile)	2.5%
7	Top Right Wall	6.5%
8	Bottom Rear Wall (tile)	3.5%
9	Top Rear Wall	6.5%
10	Roof Section 1 (stage wall)	15.5%
11	Roof Section 2 (rear wall)	15.5%
12	Divider Section 1 (right)	1.5%
13	Divider Section 2 (left)	1.5%

Though the floor's absorption can not be changed structurally, when the gym is full of people the absorption of the floor is essentially increased because people and clothing have high absorption coefficients. This meant that we needed to concentrate on the ceiling sections of the gym for our solution.

From this information, we decided to simulate the addition of 16 banners measuring 1 m x 0.5 m, made of medium-weight drapery material. This material could be fire-treated, but the total drapery area had to be kept fewer than 10 percent of the total wall and ceiling area to adhere to fire code #780 CMR 807.1.2. For this room the value of 10 percent of the total wall and ceiling area was 110.148 m^2. We used 16 banners, in the simulation, for a total surface area of 16 m^2 and a total of 8 m^2 of material, which is well under the limit. The arrangement of these banners hanging from the gym ceiling can be seen in Figure 17 in Appendix E.

The results for this simulation were not very good. The reverberation times, shown in Table 11, did not change much at all.

Table 11: Reverberation Time and Change in Reverberation Time for the Room with Banners

	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz
SabT	3.99 sec	4.34 sec	4.27 sec	4.44 sec	4.46 sec	3.94 sec
ΔSabT	0.03 sec	0.16 sec	0.26 sec	0.44 sec	0.41 sec	0.27 sec

With less than half of a second change in each octave band, this definitely did not warrant the effort or investment. We decided to try simulating the room with carpeting on the back wall. The one drawback to this solution was in the fire codes. Fire code #780 CMR 803.6 states that when carpet or carpet-like material is put on a wall or hung in a room, it must have a Class I flame spread rating and an automatic sprinkler system must be installed. In the simulation, we used absorption coefficients corresponding to carpeting placed on a fiberboard backing, with airspace behind it. The total simulated carpeted area was 52.200 m^2, less than half of the limit. The diagram for this solution is shown in Figure 22 in Appendix F.

The results of the carpet simulation were much better than the results of the banner simulation. The reverberation times dropped an average of about 1.3 sec over all six-octave bands. The drops were particularly large at the higher frequency octave bands. This is because carpet has higher absorption coefficients at the higher octave bands. The reverberation time values and changes in reverberation times, for each octave band, are shown in Table 12. The results showed that the predicted reverberation times were still much higher than the desired 1.5 sec.

Table 12: Reverb. Times and Changes in Reverb. Time for Room with Carpeted Back Wall

	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz
SabT	3.20 sec	3.49 sec	3.26 sec	3.21 sec	3.05 sec	2.63 sec
ΔSabT	0.82 sec	1.01 sec	1.27 sec	1.67 sec	1.82 sec	1.58 sec

To determine if small absorptive surface area was the problem, we simulated the entire ceiling being carpeted. This could not actually be implemented, because this total surface area is about 504 m^2, well above the 110.1 m^2 limit. However, this simulation gave us a good idea of what kind of reverberation times could be achieved by increasing the surface area of an absorptive material in the gym. This simulation showed a very large change in reverberation time. Reverberation times dropped by at least 2.1 seconds, for every octave band, and as much as 3.83 sec, as shown in Table 13, much closer to the desired value of 1.5 sec.

Table 13: Reverb. Times and Changes in Reverb. Times for Room with Carpeted Ceiling

	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz
SabT	1.92 sec	2.06 sec	1.49 sec	1.18 sec	1.04 sec	1.00 sec
ΔSabT	2.10 sec	2.44 sec	3.04 sec	3.70 sec	3.83 sec	3.21 sec

These results indicated that there were some possible solutions, but that we needed to increase the surface area of absorptive materials, to increase the room constant (see Background). Examination of the wall hits plot file, produced by the CATT™ simulation of the empty gym, showed that we also needed to focus our attention in the vicinity of the ceiling. This wall hits plot file is shown in Figure 13 of Appendix D and was summarized in Table 10. With this in mind we decided to try simulating the banner solution again. This time, however, we increased the banner size and the number of banners in order to use the maximum amount of material allowed, 110.1 m^2. The diagram for this solution is shown in Figure 27 in Appendix G. The simulated reverberation times for the gym with the maximized banners are shown below in Table 14.

Table 14: Reverb. Times and Changes in Reverb. Times for Room with Maximized Banners

	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz
SabT	3.64 sec	2.97 sec	2.49 sec	2.07 sec	2.15 sec	2.18 sec
ΔSabT	0.38 sec	1.53 sec	2.04 sec	2.81 sec	2.72 sec	2.03 sec

These reverberation times showed a marked improvement on the empty gymnasium, although they are not down to 1.5 sec. Though the low frequency reverberation did not change much, because drapery has a much lower absorption coefficient at low frequencies, the higher frequencies show an average drop in reverberation time of about 2.2 sec. From these data, it seems that maximizing hanging banners in the gymnasium would provide a viable solution. The advantage of using banners rather than carpeted back wall sections is that while the banners still need to be fire treated like the carpet, an automatic sprinkler system would not need to be installed in the gym.

Our next attempt at simulating a possible solution involved using the maximum allowed amount of hanging material, 110.1 m^2, in a combination of larger sized banners of drapery and padded rear wall sections of carpet. The diagram for this solution is shown in Figure 32 in Appendix H. Though these implementations could not be made without both materials being fire-treated and an automatic sprinkler system being installed, we performed the test to see if this would be in any way a viable option. The results of the simulation are shown below in Table 15. Though the improvements in reverberation time are not as drastic as in the case of the carpeted ceiling, and are not near the desired 1.5 sec. range, the results do indicate a slight improvement, the highest being 1.42 sec.

Table 15: Reverb. Time and Change in Reverb. Time for Room with Padded Back Wall and Enlarged Banners

	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz
SabT	3.79 sec	3.83 sec	3.59 sec	3.46 sec	3.52 sec	3.29 sec
ΔSabT	0.23 sec	0.67 sec	0.94 sec	1.42 sec	1.35 sec	0.92 sec

Though these simulated solutions indicate some improvement in reverberation time when using conventional materials such as carpet and drapery we realized that in order to get closer to the target reverberation time of around 1.5 sec, we would need to use materials with very high absorption coefficients. This requirement also meant that the cost of the solution would be increased.

One suggestion, made by Prof. Campbell, of the WPI Electrical Engineering Dept., was to hang panels, covered on both sides with woven acoustic covering. This material has a 90% absorption coefficient over all octave bands, and is non-combustible, meaning we could add as much of this material to the room as needed, because Massachusetts fire code 780 CMR 807.1.1 states that an unlimited amount of non-combustible materials may be used for hangings. The drawback is that this material is extremely expensive, and must be mounted on plywood, or some such backing, making it even more expensive.

Using CATT™ we simulated a room with 10 of these highly absorbent panels suspended from the ceiling. The panels were made to be about 2.44 m by 1.22 m, or 8 ft. by 4 ft., so that they were approximately the size of a piece of plywood, which the material would be attached to if implemented. The panels were also made to be about 0.07 m thick (3/4'' of plywood with 1'' of acoustic material on either side) as they would be in implementation. The diagram for this solution is shown in Figure 37 in Appendix I. The results of the simulation, shown below in Table 16, were very good. The reverberation times for each octave band dropped at least 1.21 sec.

Table 16: Reverb. Time and Change in Reverb. Time for Room with Acoustical Panels

	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz
SabT	2.81 sec	3.04 sec	3.05 sec	3.21 sec	3.20 sec	2.91 sec
ΔSabT	1.21 sec	1.46 sec	1.48 sec	1.67 sec	1.67 sec	1.30 sec

A more cost-effective solution involving these acoustic panels, suggested by Prof. Thompson, is to mount them directly on the ceiling. Since there would not need to be any plywood or chains for hanging the panels, the cost would be decreased. Also, the same amount of panels could be used, but they could be more spread out since they would not need to be double sided as in the hanging panels. As mentioned in the **Literature Review**, this spreading out of sound-absorbing materials should increase their effectiveness in reducing the reverberation time. We simulated attaching 20, 8 ft. by 4 ft. sections of acoustic paneling to the ceiling using CATT™. The diagram for this solution is shown in Figure 42 in Appendix J. The resulting reverberation times and changes in reverberation are shown below Table 17.

Table 17: Reverb. Times and Changes in Reverb. Times for Room with Ceiling Panels

	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz
SabT	2.67 sec	2.76 sec	2.86 sec	2.84 sec	2.81 sec	2.46 sec
ΔSabT	1.35 sec	1.74 sec	1.67 sec	2.04 sec	2.06 sec	1.75 sec

As can be seen from Table 17, the reverberation times are slightly better than those achieved from the hanging acoustic panels. On average they are about 0.2 sec lower than the reverberation times of the room with hanging acoustic panel. This makes the attachment of acoustic panels to the ceiling of the gym a much more viable solution, since it is cheaper than hanging acoustic panels and it provides better reverberation times.

3.3 Balloon Test

To help determine the actual reverberation time of the room, before any corrections were made to its acoustics, we performed a balloon test. The sound of a balloon popping is considered a relatively good representation of an impulse function, and contains a good portion of the frequency spectrum. The basic concept of the balloon test is to pop a balloon in the room, record the resulting sound in the room, and use a .WAV file editor, to estimate the reverberation time, T_{60}, of the balloon bursts.

We performed the test on the afternoon of February 11, 1999, after school, in the empty gymnasium. We obtained a DAT recorder, a mixer, a microphone, a microphone stand, and the necessary cables from Prof. Bianchi, of the WPI Music Dept. The microphone was placed in its stand, and connected, through the mixer, to the DAT recorder. We chose a designated spot, centered along the "stage wall" of the gym, to pop all of the balloons. The microphone was placed at seven different locations in the gym: in the center of the gym, on the four corners of the basketball court boundary lines, and on the border between the 12' and 16' segments of each section of bleachers.

One at a time, we placed the microphone at each location, which we measured by hand, and then popped a balloon for every microphone location. Each pop was recorded as a separate track on the DAT tape.

Next, the seven balloon pop recordings were transferred from the DAT tape to a computer. To transfer the DAT recordings to .WAV files, the audio output of the DAT player had to be hooked into the audio input of a computer sound card. Then, using a .WAV editor, the track from the DAT player was recorded as a .WAV file, on the computer. The DAT player sampled its recording at the Nyquist rate, or 44.1 kHz. This ensured that the full range of sound could be properly represented. For acoustics purposes, the very high frequencies are not of great interest, so we reduced the sampling rate in half, to 22.05 kHz, for the .WAV file recording. This provided a rather large advantage, since the file size was cut in half. With the original 44.1 kHz sampling rate, the .WAV files were very large, and any saved space reduced the transfer time of these files.

Once the DAT recordings were transferred to .WAV file format, it was straightforward to estimate reverberation time. First, we determined the peak amplitude value of the waveform. This was done using the cursor on the PC screen, which gave us the value of the time and amplitude at any point we clicked on. Then, we found the amplitude value at a point right before the decay reached the ambient noise level. The ambient noise level is where the decay levels off, and where the ambient noise in the room registers higher than the decaying reverberations. The exact time was found using Sound Forge™ .WAV editor. These two points were used to make a straight-line estimation for T_{60}. An example of one of these estimations is shown in Appendix S.

These amplitudes represented voltages, but to determine reverberation time, we had to convert these values to a power ratio, i.e. a dB value. To convert voltage to power, we had to square the voltage, and to find the dB value we had to take $10 \log (P_{peak}/P_{1sec})$. Thus, we had to take $20 \log (V_{peak}/V_{1sec})$ to find the power drop, in dB, over the given time separation.

The reverberation time, by definition, is found by finding the time it takes for a 60 dB drop in power to occur. Since it is a straight-line approximation, we can use a simple ratio to find reverberation time. We will use the symbol Δt, for the time separation between the two selected amplitude points.

$$T_{60} = [60\ \text{dB}(\Delta t)]/[20 \log (V_{peak}/V_{1sec})\ \text{dB}]$$

Using Sound Forge™, .WAV editor, we made estimates for T_{60}, for each of the seven balloon bursts. The results were found to have some error, since after performing the balloon tests, we were informed that the directivity pattern of the microphone can make a very large difference in results. What was needed was an omni-directional microphone. We were equipped with a cardioid microphone, which will only pick up sounds coming from the front or sides of the microphone. An omni-directional microphone, on the other hand, will pick up sound from all directions. This was a necessity for our purposes, because the reflections came from all directions. Since we were not made aware of this distinction until after we performed the test, we did not attempt to obtain an omni-directional microphone for our test.

This shortcoming posed a problem with our measurements. Because T_{60} depends on a drop in power, it is very important to get all of the reflections recorded. Since only a fraction of the reflections were picked up by the cardioid microphone, the power present in our reflections was lower than the actual level. Since the microphone was pointed towards the stage wall, the initial burst was actually recorded at full power. The final result was that the power appeared to drop faster than it really was, and the reverberation time, T_{60}, was estimated to be shorter than the actual value in the room.

The values for the gymnasium's T_{60}, as estimated from the .WAV files, are as shown in Table 18.

Table 18: Estimated Reverb. Time for Balloon Bursts

	Burst 1	Burst 2	Burst 3	Burst 4	Burst 5	Burst 6	Burst 7
T_{60}	1.70 sec	1.90 sec	2.50 sec	1.87 sec	1.92 sec	1.74 sec	1.60 sec

Though these values are incorrect, they should not be that far off. Since with a cardioid microphone the decaying impulse was recorded as having less power than it really did, the reverberation time indicated by such a recording was a little lower than the real reverberation time, but should be comparable. Thus we can say that the empty gymnasium most likely has a reverberation time of around 2.5 sec.

3.4 CATT™ Results with Adjusted Absorption Coefficients

Though some error was present in the balloon tests, that error, caused by the use of a cardiod microphone instead of an omni-directional microphone, did not account for the difference in over two seconds, for reverberation time. This error lied in the inability to accurately model the absorption coefficients of the room's materials using a chart. The coefficients should have been close, but not all painted cement block, for example, has exactly the same absorption coefficients. A change of five percent absorption, for example, could have made a very big change in our results. Therefore, to make our results closer to the balloon test results, we adjusted the coefficients, for the empty room, and ran the simulations for the changed rooms again, with the new coefficients.

After making large adjustments to the coefficients, and then fine-tuning our changes, we found coefficients which gave us reverberation times between 2.56 seconds and 2.87 seconds. The new absorption coefficients are shown in Table 19.

Table 19: Chart Values and Adjusted Values for Absorption Coefficients, for the Six Octave Bands

Surface Type	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz
Wood from Chart	15%	11%	10%	7%	6%	7%
Adj. Wood	21%	17%	16%	13%	12%	13%
Tile from Chart	1%	1%	1%	1%	2%	2%
Adj. Tile	7%	7%	7%	7%	8%	8%
Painted Concrete Block from Chart	10%	5%	6%	7%	9%	8%
Adj. Painted Concrete Block	16%	11%	12%	13%	15%	14%
Painted Steel from Chart	5%	10%	10%	10%	7%	2%
Adj. Painted Steel	11%	16%	16%	16%	13%	8%

The old and the new adjusted values for the empty gymnasium CATT™ simulation are shown in Table 20.

Table 20: Old and New Values for CATT™ Empty Gymnasium Reverberation Time, SabT

Room Model	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz
Old Empty Gym	4.02 sec	4.50 sec	4.53 sec	4.88 sec	4.87 sec	4.21 sec
New Empty Gym	2.56 sec	2.75 sec	2.76 sec	2.87 sec	2.81 sec	2.40 sec

Using the new absorption coefficient values, shown in Table 19, we also re-simulated all of our possible solutions. The values for the adjusted reverberation times for each gymnasium model are shown in Table 21. Note that, for high frequencies, the

Table 21: Reverberation Times, SabT, for Adjusted CATT™ Gymnasium Models

Gym Model	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz
Small Banners	2.38 sec	2.50 sec	2.48 sec	2.52 sec	2.48 sec	2.17 sec
Carpeted Back Wall	2.02 sec	2.13 sec	2.04 sec	2.02 sec	1.96 sec	1.78 sec
Maximized Banners	2.25 sec	1.97 sec	1.74 sec	1.52 sec	1.55 sec	1.50 sec
Enlarged Banners & Carpeted Back Wall	2.09 sec	1.99 sec	1.79 sec	1.63 sec	1.61 sec	1.52 sec
Hanging Acoustic Panels	1.94 sec	1.96 sec	2.02 sec	1.99 sec	1.96 sec	1.77 sec
Acoustic Panels on Ceiling	1.75 sec	1.79 sec	1.83 sec	1.82 sec	1.81 sec	1.66 sec

maximized banners reduced the reverberation time to approximately 1.5 seconds, which was our desired reverberation time, but it also was a costly remedy. The values for change in reverberation time, as shown in Table 22 have changed, but the relative worth of each solution remained approximately the same.

Table 22: Change in Reverberation Time, SabT, for the Adjusted CATT™ Gymnasium Models

Gym Model	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz
Small Banners	0.18sec	0.25 sec	0.28 sec	0.35 sec	0.33 sec	0.23 sec
Carpeted Back Wall	0.54 sec	0.62 sec	0.72 sec	0.85 sec	0.85 sec	0.62 sec
Maximized Banners	0.31 sec	0.78 sec	1.02 sec	1.35 sec	1.26 sec	0.90 sec
Enlarged Banners & Carpeted Back Wall	0.47 sec	0.76 sec	0.97 sec	1.24 sec	1.20 sec	0.88 sec
Hanging Acoustic Panels	0.62 sec	0.79 sec	0.74 sec	0.88 sec	0.85 sec	0.70 sec
Acoustic Panels on Ceiling	0.81 sec	0.96 sec	0.93 sec	1.05 sec	1.00 sec	0.74 sec

After running simulations for the adjusted gymnasium models, we decided to try covering the entire ceiling with the acoustic panel material. We did not take the I-beams into account, so in reality, the reverberation time should be a little bit higher, because there are some metal I-beams on the ceilings, with lower absorption coefficients, that would not be covered. The reverberation times for this model and the change in reverberation time, over each octave band, for this model are shown in Table 23. The

Table 23: Reverberation Time, SabT, and Change in Reverberation Time for the Gymnasium with Ceiling Covered in Acoustical Panels

	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz
SabT	1.02 sec	0.95 sec	1.03 sec	0.92 sec	0.89sec	0.84 sec
ΔSabT	1.54 sec	1.80 sec	1.73 sec	1.95 sec	1.92 sec	1.56 sec

reverberation times are very low for this model, and at the same time, are undesirable. Since they are, at the least, around half a second less than our desired reverberation time of 1.50 seconds, we know that the reverberation time is too low. The room will be good for oratory purposes, but for music, the room will be very dead. There would be no warmth to any music performed in such an environment.

4 Conclusions & Recommendations

4.1 Proposals

In this section, we list the proposed solutions to the acoustic problem in the order of effectiveness. None of the proposals include labor costs since it may be possible to have faculty members or parents of students volunteer time or equipment, for the installation of a particular solution. The different reverberation times, SabT, resulting from the CATT™ simulation of each treatment are also included. The target reverberation time is around 1.5 seconds. This would be a reverberation time which would effectively decrease the amount of echo heard by an audience member, but does not decrease reverberation so much that music would lose its warmth. It should be stressed that this target reverberation time of 1.5 seconds is a rough estimate of an appropriate reverberation time for the room. Since the gymnasium is often used for musical purposes, a reverberation time as high as 2 seconds would probably still be acceptable. The proposals are as follows.

4.1.1 Proposal #1

One possible solution was to mount four sections of carpet on the rear wall of the gymnasium (see Appendix F). The prices for this treatment are seen in Table 24.

Table 24: Prices for Gymnasium with Carpeted Back Wall

Material	Price	Amount	Total
Carpet	\$8.50 per m^2	50.1 m^2	\$425.85
Peg Board	\$10.95 per sheet	17 sheets	\$186.15
Studs	\$2.04 per stud	25 studs	\$51.00
Automatic Sprinkler System	\$1.25 per ft^2	5425.6 ft^2	\$6782 to \$20,000
			\$7445 to \$20,663

This price does not include the cost for some sort of fasteners or mounting equipment that would be needed to implement this solution. The maximum cost of about \$20,000 for the sprinkler system would be if the school did not have a high-pressure water source, and one had to be installed. The reverberation times simulated, using CATT™, SabT, are given in Table 25.

Table 25: Simulated Reverberation Times for Gymnasium with Carpeted Back Wall

	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz
SabT	2.02 sec	2.13 sec	2.04 sec	2.02 sec	1.96 sec	1.78 sec

This was a possible solution, but is not good enough to warrant spending such a large amount of money on installation of the carpet and a sprinkler system. Other solutions performed much better, relative to cost. Also, there is some error inherent in our simulation, since different carpets have varying absorption coefficients.

4.1.2 Proposal #2

Another possible solution was to combine hanging banners, which were enlarged with respect to the original banners, and the carpet sections from Proposal #1 (See Appendix H). The prices for this treatment are seen in Table 26.

Table 26: Prices for Gymnasium with Enlarged Banners and Carpeted Back Wall

Material	Price	Amount	Total
Carpet	\$8.50 per m^2	50.1 m^2	\$425.85
Peg Board	\$10.95 per sheet	17 sheets	\$186.15
Studs	\$2.04 per stud	25 studs	\$51.00
Drapery	\$12.99 per m^2	29.9 m^2	\$388.40
Nylon Rope	\$117.00 per 182.9 m roll	1 roll	\$117.00
Automatic Sprinkler System	\$1.25 per ft^2	5425.6 ft^2	\$6782 to \$20,000
			\$7950.40 to \$21,168.40

Not included in these prices are the costs of fasteners, or clamps for the I-beams. The reverberation times for this particular section are as shown in Table 27. As in the last proposal, the maximum cost of $20,000 for the automatic sprinkler system would be incurred if the school does not have a high-pressure water supply. Also, fire treatment for the banners would be $45 per gallon. We are not quite sure how much coverage a gallon would provide, so we cannot estimate this total cost.

Table 27: Simulated CATT Reverberation Times for the Gymnasium with Enlarged Banners and Carpeted Back Wall

	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz
SabT	2.09 sec	1.99 sec	1.79 sec	1.63 sec	1.61 sec	1.52 sec

This solution was actually very good, especially at high frequencies, but also is not cost-effective enough to warrant spending by the school. If volunteers could not be found, there would be labor costs involved in implementing this solution, since not only do the banners need to be suspended from the ceiling, the carpet has to be mounted on the back wall, and an automatic sprinkler system must be installed. This increased labor would increase the cost even more. Also, there is some error inherent in our simulations, since both carpet and drapery material will have varying absorption coefficients.

4.1.3 Proposal #3

A third possible solution is hanging sheets of plywood, covered on both sides with acoustic panels, from the ceiling (See Appendix I). No fire treatment or automatic sprinkler systems are required, because the panels are non-combustible. The prices for this treatment are shown in Table 28.

Table 28: Prices for Gymnasium with Hanging Acoustic Panels

Material	Price	Amount	Total
Plywood Sheets	$25 per sheet	10 sheets	$250.00
Industry Standard Panels	$230 per 4'x8' section	20 sections	$4600.00
3/16 inch uncoated cable	$69.00 per 76.196 m roll	3 rolls	$207.00
			$5057.00

These prices do not include fasteners, or clamps for attaching the cables to the I-beams. The values for reverberation time are shown in Table 29.

Table 29: Simulated CATT™ Reverberation Times for Gymnasium with Hanging Acoustic Panels

	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz
SabT	1.94 sec	1.96 sec	2.02 sec	1.99 sec	1.96 sec	1.77 sec

This was considered one of our three best solutions, since the absorption coefficients will not change much, as the acoustic panels are an industry standard, and the performance was good over all frequencies. This is discussed in more detail, in the **Recommendations** section.

4.1.4 Proposal #4

The next possible solution was maximized banners, meaning that we tried to maximize the surface area allowed under Massachusetts Fire Code 780 CMR 807.1.2, for flame-resistant materials (See Appendix G). The prices for this remedy are shown in Table 30.

Table 30: Prices for Gymnasium with Maximized Banners

Material	Price	Amount	Total
Drapery	\$12.99 per m^2	109.2 m^2	\$1418.51
Nylon Rope	\$117.00 per 182.9 m roll	1 roll	\$117.00
			\$1535.51

This price does not include clamps to attach the rope to the I-beams. The reverberation times for this solution are shown in Table 31. Also, the cost of fire treatment is \$45 per gallon, and, as mentioned before, we are not sure about the coverage one gallon would provide, so we cannot estimate total cost for this treatment. However, this fire treatment would need to be re-applied annually, so the long-term cost of this procedure would be high.

Table 31: Simulated CATT™ Reverberation Times for Gymnasium with Maximized Banners

	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz
SabT	2.25 sec	1.97 sec	1.74 sec	1.52 sec	1.55 sec	1.50 sec

This was the second of our three best solutions, since the performance at high frequencies was excellent, and the cost was good, compared to its effectiveness. This is discussed in more detail, in our **Recommendations** section.

4.1.5 Proposal #5

The final solution is to mount acoustic panels flush to the ceiling, which would eliminate the cost of cable and plywood entirely (See Appendix J). The prices for this treatment are shown in Table 32.

Table 32: Prices for Gymnasium with Acoustic Panels Mounted Directly to Ceiling

Material	Price	Amount	Total
Industry Standard Panels	$230 per 4'x8' section	20 sections	$4600
			$4600

These prices did not include fasteners or bonding, to attach the panels directly to the ceiling. The reverberation times for this solution are shown in Table 33.

Table 33: Simulated CATT™ Reverberation Times for Gymnasium with Acoustic Panels Directly Mounted to Ceiling

	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz
SabT	1.75 sec	1.79 sec	1.83 sec	1.82 sec	1.81 sec	1.66 sec

This was the last of our top three solutions, since it was very effective over all frequencies. Also, there is no fire-treatment involved with this solution, since the material is non-combustible, so there will be no added labor or material costs in the long run. This is discussed in greater detail in our **Recommendations** section.

4.2 *Recommendations*

After careful consideration of the computer simulation data and the cost projections for each solution, we decided that the three best solutions to the acoustic problem in the gym are: hanging acoustic panels, acoustic panels mounted flush to the ceiling, and maximized banners. There are many factors to consider, when deciding which solution to use, which include effectiveness, ease of implementation, cost, fire-treatment, and error in simulation.

First, we will discuss effectiveness. At very high frequencies, the maximized banners were simulated as having the lowest reverberation time, which happens to be approximately the desired value of 1.50 seconds. There is only about a 0.2 second difference between these reverberation times and the reverberation times for the acoustic panels mounted directly on the ceiling. At low frequencies, however, the acoustic panels on the ceiling are much more effective than maximized banners. In the 125 Hz octave band, the reverberation time is 0.5 seconds better for directly mounted acoustic panels, and in the 250 Hz band, is 0.18 seconds better. Thus, to have a better reverberation time over all frequencies, the directly mounted acoustic panels would be the best solution.

In respect to ease of implementation, hanging acoustic panels is definitely the worst. The panels must be mounted on either side of sheets of plywood, then they must be hung by chains, or strong cable, because of the weight of the plywood, and must be attached with special clamps to the I-beams along the ceiling. The maximized banners are a little easier, because they do not have to be mounted to sheets of plywood, and they do not weigh as much, so they could be suspended much more easily. The directly mounted acoustic panels need only be directly bonded to the ceiling. No special clamps for the I-beams are needed, and neither is plywood. Thus, the acoustic panels, directly mounted to the ceiling would be somewhat easier to implement and less obtrusive.

When considering short-term costs, the maximized banners would definitely be the cheapest, because the material is much cheaper. The implementation is more involved, but is not enough to eclipse the high cost of acoustic panels.

When considering long-term costs, we must also consider fire-treatment. Since the banners must be fire-treated annually, this will result in extra costs every year, whereas the acoustic panels are non-combustible, and never need to be fire-treated. In fact, the long-term costs caused by annual fire-treatment may equalize the total cost.

Finally, we must consider the error inherent in our CATT™ simulation. The drapery material, which we suggested using for banners, does not really have fixed absorption coefficients. Many draperies could be considered medium-weight, thus the actual absorption coefficients vary over a range of different values depending how the drapery is manufactured and exactly what materials it consists of. These coefficients may or may not be the same values we used in our modeling. We saw from the change in our reverberation time results between our initial simulations and the adjusted simulations that a change of 6% absorption could change the reverberation times by as much as 2 seconds. The acoustic panels, however, are an industry standard, and the absorption coefficients do not vary much, if at all. Thus, the maximized banners are much less likely to follow our simulations as closely as the acoustic panels. This variability of absorption characteristics is a very important aspect to consider. If the amounts of money we have been discussing are going to be spent, then the results should be reliable.

With all things considered, we would recommend using 20 acoustic panels, mounted flush against the ceiling, as our first choice for a solution to the acoustic problem in the gymnasium.

Appendix A: Bibliography

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Appendix B: Material Pricing

When we made our trip to Home Depot, we concentrated on materials that could be used to either reflect or to absorb sound inside the gymnasium. Some of the sound reflecting materials that we priced were sheets of plywood, particle board and sheetrock. These materials could have been placed in certain positions on the sidewalls to help diffuse and distribute the sound quicker and direct it towards the audience. We priced other materials that would be used to attach these sound absorbing/reflecting materials in different places in the gym. The sound absorbing materials included canvas, dropcloths, carpeting, and pegboard. These materials could have been placed in the back and the ceiling of the gymnasium to help keep sound from reverberating when it reaches the back of the gym and to keep sound from continuously reverberating in the rafters of the gymnasium; thus causing an echo.

Side panel material and wood:

NAME	SIZE	PRICE
Fire Code Wall Board	4 ft x 8 ft	$6.79 each
¾ Inch Plywood	4 ft x 8 ft	$25.50 each
Pegboard	4 ft x 8 ft	$10.95 each
¾ Inch Particle Board	4 ft x 8 ft	$13.27 each
Studs	2 inch x 4 inch x 92-5/8 inch	$2.04 each

Sound Absorbing Materials:

NAME	SIZE	PRICE
8 oz. Canvas Tarp	10 ft x 12 ft	$37.81 each
Prof. Canvas Drop Cloth	12 ft x 15 ft	$38.18 each
Bound Carpet	6 ft x 9 ft	$39.95 each
Bound Carpet	8 ft x 10 ft	$68.84 each
City Life Carpet 100% nylon	4 ft 7inches x 6 ft 6 inches	$26.00 each

Miscellaneous:

NAME	**SIZE**	**PRICE**
1/8 Inch Uncoated Cable	N/A	18 cents/ft or $67.00 500ft roll
3/16 Inch Uncoated Cable	N/A	40 cents/ft or $69.00 250ft roll
No. 10 Solid Braid Nylon Rope	N/A	26 cents/ft or $117.00 600ft roll
1/8 Inch Cable Clamp	N/A	$1.47 each

Along with Home Depot, we called some other companies for additional materials. We priced felt, carpet, drapery, and special acoustic material. The materials and their prices are shown below.

COMPANY	**MATERIAL**	**SIZE**	**PRICE**
Appletree Fabrics	Felt	72 inches wide	$5.50 per yard
Jo-Ann Fabrics & Crafts	Felt	72 inches wide	$5.99 per yard
The Valley Fabric Outlet	Felt	72 inches wide	$5.98 per yard
Wright's Factory Outlet	Felt	72 inches wide	$6.49 per yard
Eddy's Carpet & Warehouse	Carpet	N/A	$8.45 per sq. yard
ALF Floors	Carpet	N/A	$9.00 per sq. yard
Jo-Ann Fabrics & Crafts	Drapery	54 inches wide	$12.99 - $18.99 per yard
KAMCO Supply Corp. of Boston	Acoustic Material	4 ft x 8 ft 1 inch thick	$230 per section
Baker Fire Equipment	Fire Treatment Spray	1 gallon	$45 per gallon
R.C. Shaw Sprinkler Co., Inc.	Automatic Sprinkler System	N/A	$1.25 per ft^2, up to $20,000, for high-pressure source installation

Appendix C: Relevant Fire Codes

780 CMR 722.0 Thermal- and Sound-Insulating Materials:

722.2 Exposed installations: Such materials, where exposed as installed in rooms or spaces, including attics and crawl spaces of buildings of any type construction, shall have a flame spread rating of 25 or less and a smoke-developed rating of 450 or less when tested in accordance with ASTM E84 listed in *Appendix A*. Plenum installations shall comply with the requirements of 780 CMR 2805.0 and the mechanical code listed in *Appendix A*.

722.3 Concealed installations: Insulating materials, where concealed as installed in buildings of any type of construction, shall have a flame spread rating of 75 or less and a smoke-developed rating of 450 or less when tested in accordance with ASTM E84 listed in *Appendix A*.

(780 CMR, pg. 142)

780 CMR 803.0 Interior Finish and Trim:

803.6 Carpet and carpet-like wall coverings: Textile wall coverings having a napped, tufted, looped, woven, nonwoven or similar surface, shall comply with the following:

1. Such materials shall have a Class I flame spread classification and be installed only in rooms or areas protected by an *automatic sprinkler system* installed in accordance with 780 CMR 9; or
2. Such materials shall be tested in accordance with an eight-foot by 12-foot by eight-foot high (2438 mm by 3658 mm by 2438 mm) room/corner fire test procedure utilizing a product-mounting system, including adhesive, representative of actual installation. Prior to testing, the sample shall be conditioned at 70°F (21° C) ± 5% and at a relative humidity of 50% ± 5% until the sample reaches a rate of weight change of less than 0.1% per day. The product shall be exposed to a flame from a gas diffusion burner for 15 minutes. The fire exposure shall be 40 kW for the first five minutes, followed by an exposure of 150 kW for an additional ten minutes. Such tests shall

demonstrate that a product will not spread fire to the edge of the specimen or cause flashover in the test room.

(780 CMR, Pg. 144)

780 CMR 804.0 Application of Interior Finish

804.3 Class II and III materials: Class II and III interior finish materials which are less than ¼ inch in thickness shall be applied directly against a noncombustible backing or a backing that complies with the requirements of 780 CMR 2310.0, unless the tests under which such material has been classified were made with the materials suspended from the noncombustible backing. The backing material shall provide a continuous surface completely behind the finish. Where the backing does not constitute an integral part of the structural elements or system, the backing shall be attached directly to the structural elements or to the furring as required for the application of finish in 780 CMR 804.2, or shall be suspended from the structural members at any distance and all concealed spaces created thereby shall be *firestopped* in accordance with 780 CMR 720.0.

(780 CMR, Pg. 145)

780 CMR 807.0 Interior Hangings and Decorations

807.1 Decorative material restrictions: In occupancies in Use Groups A, E I-2, I-3, all curtains, draperies, hangings and other decorative materials suspended from walls or ceilings shall be noncombustible or be maintained flame-resistant in accordance with 780 CMR 807.2 as herein specified *and 527 CMR 21.00* as listed in *Appendix A.*

807.1.1 Noncombustible: The permissible amount of non-combustible decorative hangings shall not be limited.

807.1.2 Flame-resistant: The permissible amount of flame-resistant decorative hangings shall not exceed 10% of the total wall and ceiling area.

807.2 Acceptance criteria: Where required to be flame-resistant under the provisions of 780 CMR, all materials used for artistic enhancement, decorations, draperies, curtains, scenery and hangings shall comply with 780 CMR 807.0. I treated to be flame-resistant, these materials shall not generate smoke more dense than that given off be untreated wood or paper burning under comparable conditions when tested in accordance with both the small-scale and large-scale tests in NFiPA 701 listed in *Appendix A.*

807.2.1 Limitation of approval: all approvals of organic decorative material shall be limited to one year. The owner or the owner's authorized agent shall file an affidavit with the code official which certifies that the process and materials utilized comply with 780 CMR and which states the date or treatment and the warranted period of effectiveness of the process.

(780 CMR, Pg.146)

Appendix D: CATT™ Results for Unchanged Room

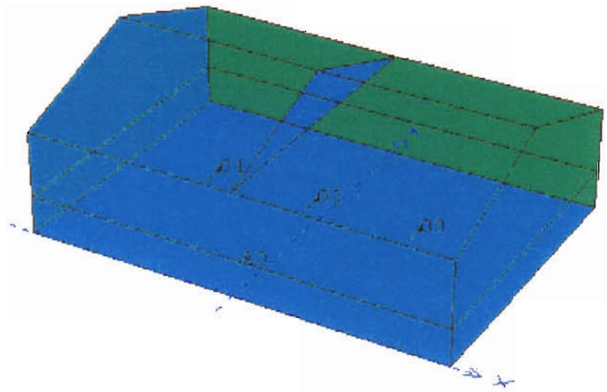


Figure 12: Geometry of Empty Gym

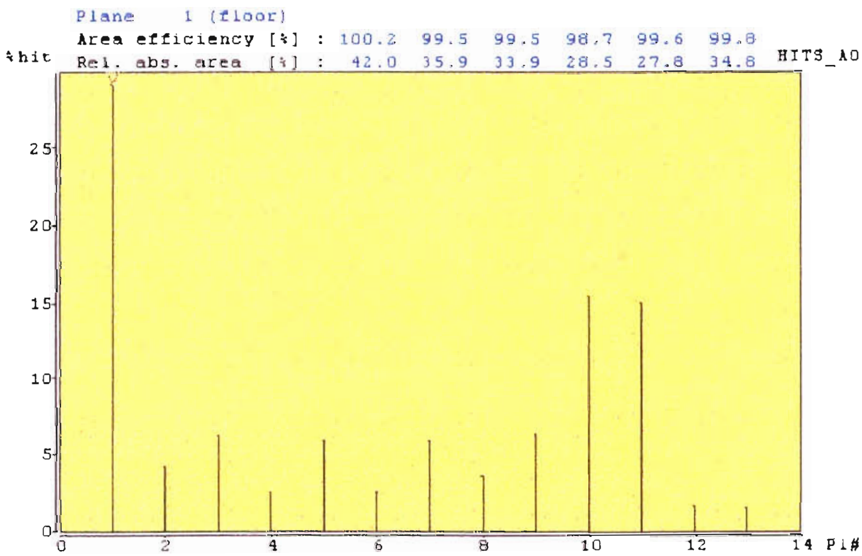


Figure 13: Percent Hits vs. Plane Number, for Empty Gym

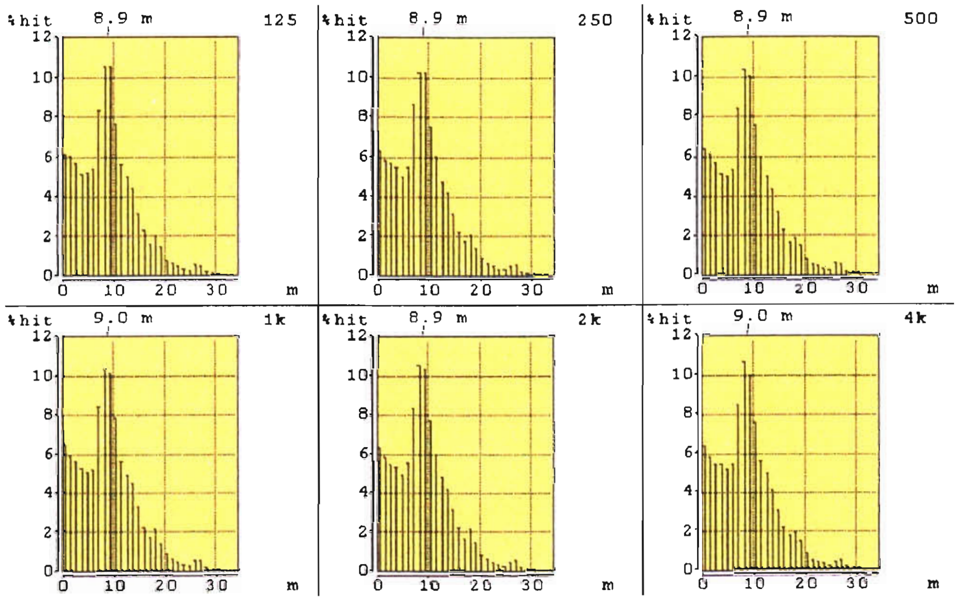
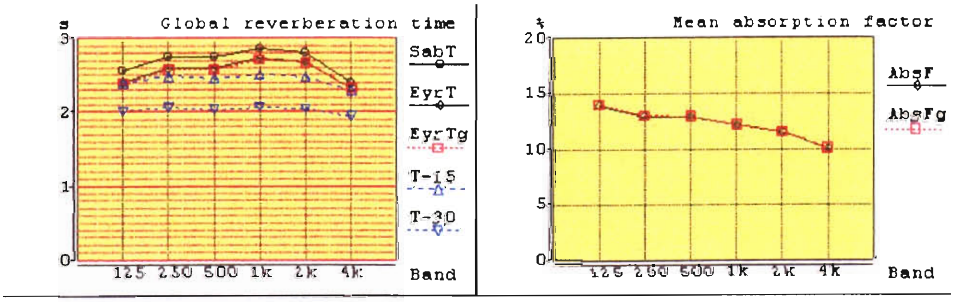


Figure 14: MFP for Six Octave Bands of Empty Gym



	125	250	500	1k	2k	4k	
EyrT	2.40	2.59	2.59	2.73	2.67	2.33	s
EyrTg	2.38	2.58	2.58	2.71	2.67	2.32	s
SabT	2.56	2.75	2.76	2.87	2.81	2.40	s
T-15	2.39	2.49	2.46	2.51	2.47	2.29	s
T-30	2.01	2.06	2.04	2.07	2.04	1.94	s
AbsF	13.94	12.94	12.89	12.14	11.53	10.07	%
AbsFg	14.00	13.01	12.93	12.20	11.55	10.10	%
MFP	8.94	8.94	8.94	8.98	8.95	8.95	m
Diffs	30.35	29.23	30.10	30.11	29.82	29.82	%

Trunc	1000.0	ms	
Rays	998	(used/oct)	
	0	(lost/oct)	
	0	(absorbed/oct)	
Angle	6.43	degrees	

Figure 15: Reverberation Times for Six Octave Bands of Empty Gym

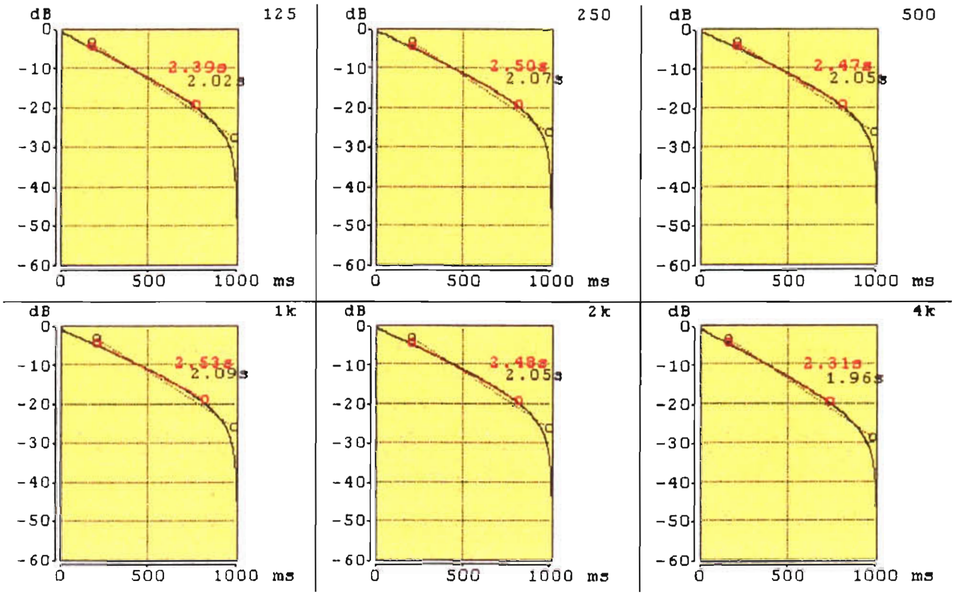


Figure 16: T15-T30 Estimation Curves for Empty Gym

Appendix E: CATT™ Results for Room with Small Banners

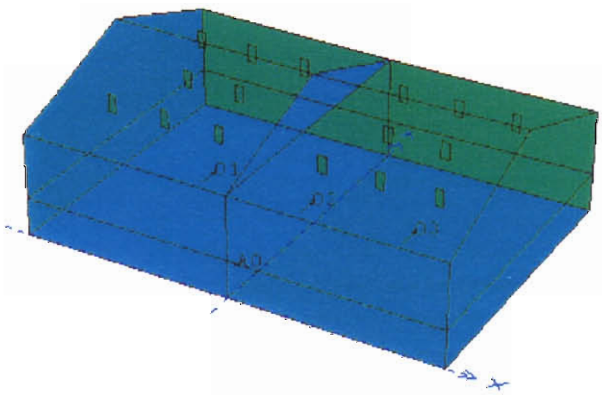


Figure 17: Room Geometry with 16 Small Banners

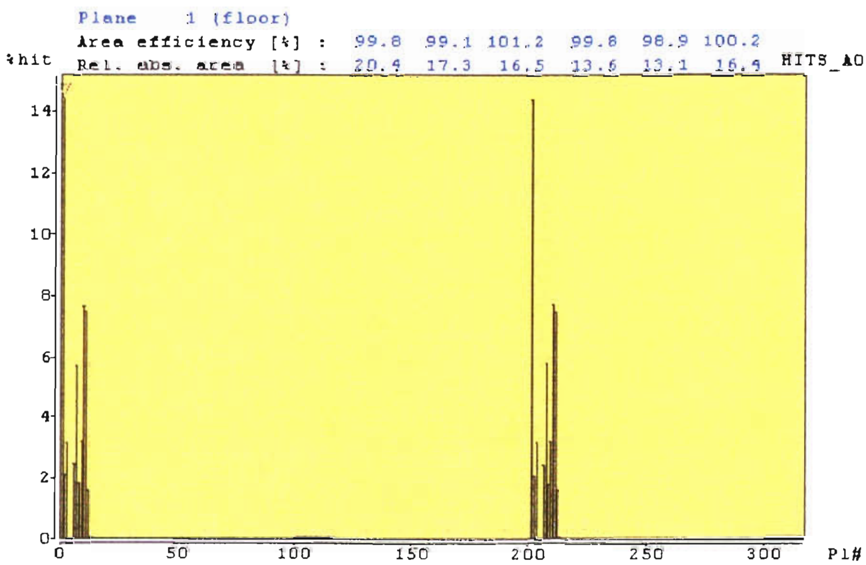


Figure 18: Percentage Hits vs. Plane Number for Room with Small Banners

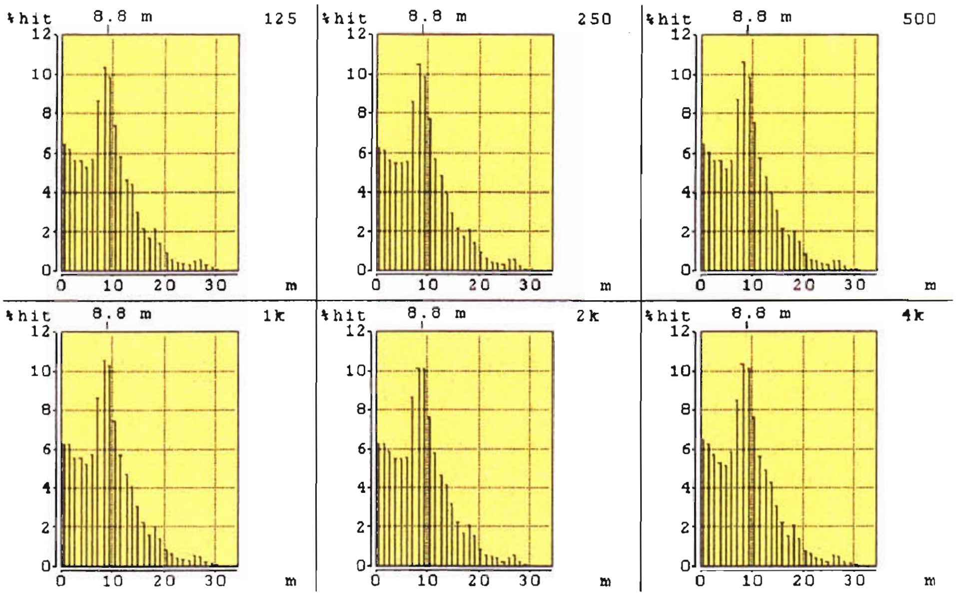
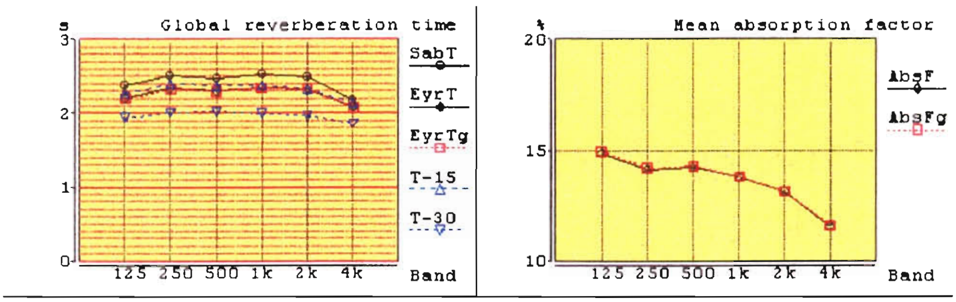


Figure 19: MFP Values for Room with Small Banners



	125	250	500	1k	2k	4k	
EyrT	2.21	2.33	2.30	2.35	2.32	2.08	s
EyrTg	2.20	2.33	2.30	2.34	2.33	2.08	s
SabT	2.38	2.50	2.48	2.52	2.48	2.17	s
T-15	2.27	2.40	2.37	2.38	2.33	2.14	s
T-30	1.94	2.01	2.02	2.00	1.97	1.86	s
AbsF	14.86	14.13	14.24	13.79	13.14	11.53	%
AbsFg	14.92	14.18	14.27	13.79	13.11	11.57	%
MFP	8.84	8.85	8.83	8.82	8.82	8.83	m
Diffs	30.09	29.79	29.91	29.81	29.98	29.92	%

Trunc	1000.0	ms
Rays	998	(used/oct)
	0	(lost/oct)
	0	(absorbed/oct)
Angle	6.43	degrees

Figure 20: Reverberation Times for Room with Small Banners

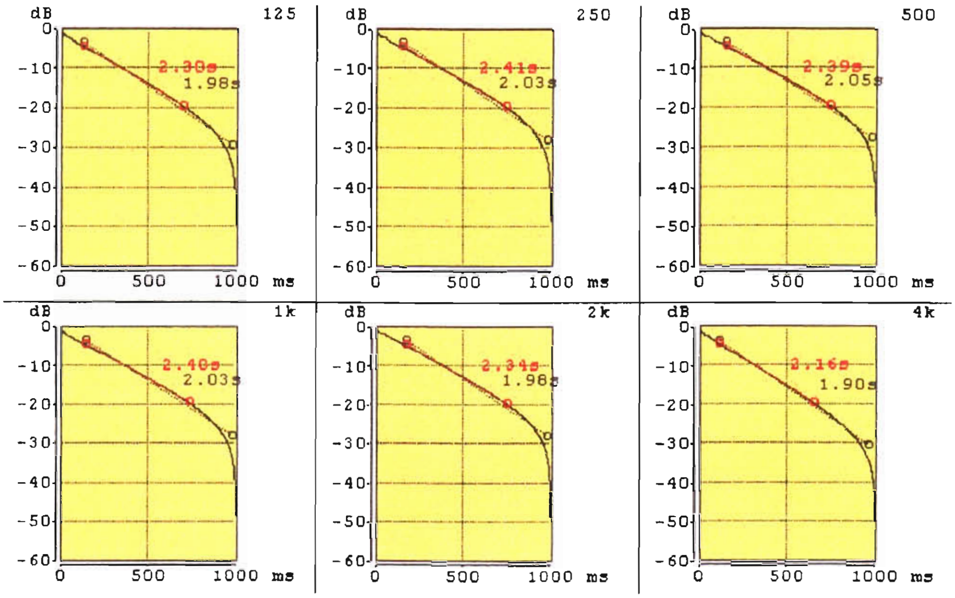


Figure 21: T15 and T30 Estimation Curves for Gym with Small Banners

Appendix F: CATT™ Results for Room with Carpeted Rear Wall

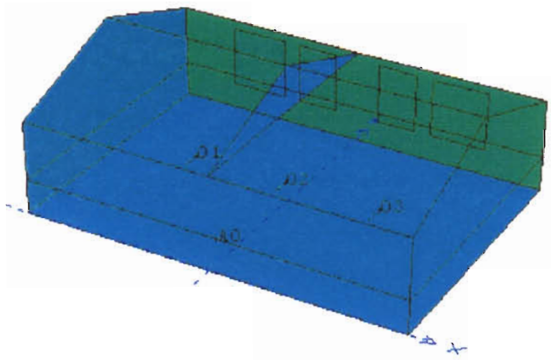


Figure 22: Room Geometry with Carpeted Rear Wall

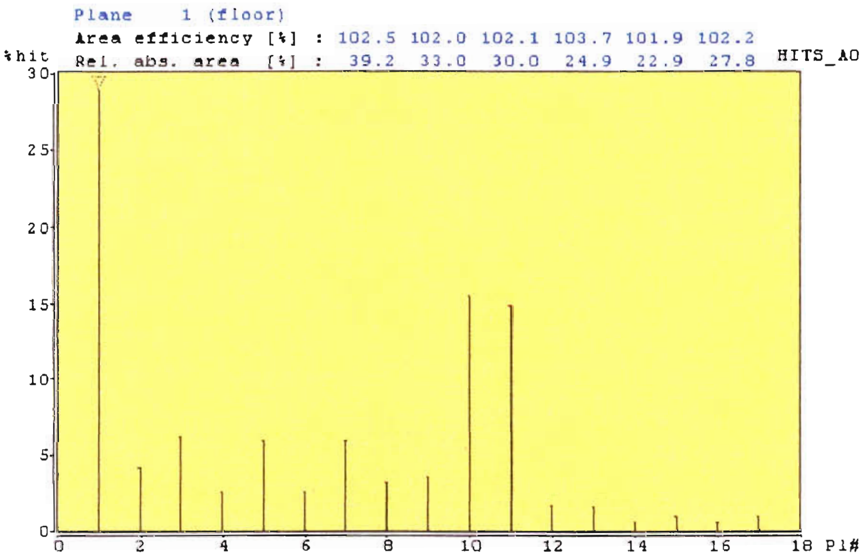


Figure 23: Percentage Hits vs. Plane Numbers for Gym with Carpeted Rear Wall

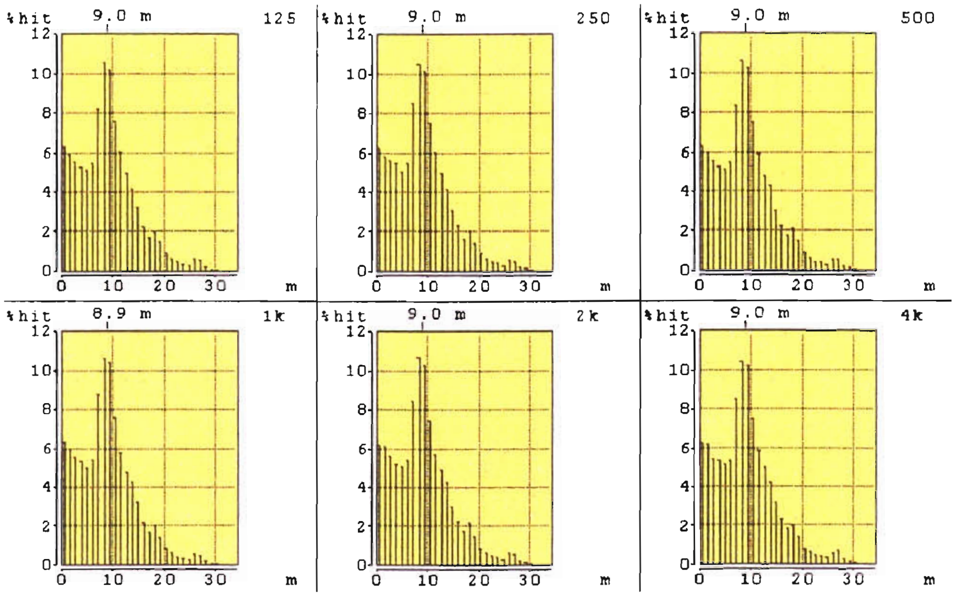
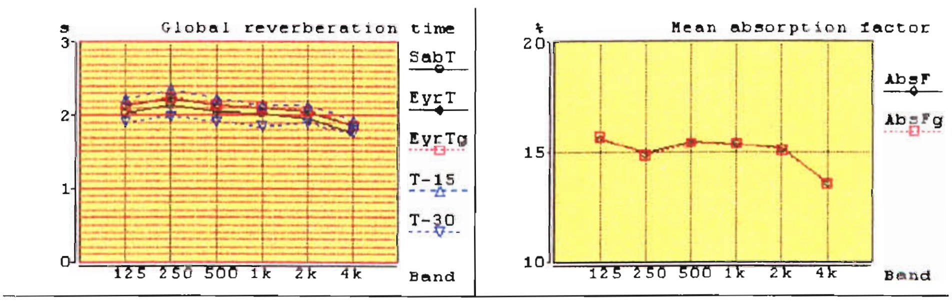


Figure 24: MFP Values for Gym with Carpeted Rear Wall



	125	250	500	1k	2k	4k	
EyrT	2.13	2.23	2.14	2.11	2.05	1.86	s
EyrTg	2.12	2.24	2.15	2.11	2.06	1.86	s
SabT	2.02	2.13	2.04	2.02	1.96	1.78	s
T-15	2.22	2.35	2.23	2.13	2.13	1.93	s
T-30	1.91	1.98	1.91	1.85	1.89	1.75	s
AbsF	15.58	14.90	15.46	15.36	15.13	13.57	%
AbsFg	15.66	14.82	15.41	15.35	15.06	13.53	%
MFP	8.97	8.96	8.96	8.88	8.98	8.97	m
Diffs	29.92	30.02	30.09	29.98	29.98	29.84	%

Trunc	1000.0	ms
Rays	998	(used/oct)
	0	(lost/oct)
	0	(absorbed/oct)
Angle	6.43	degrees

Figure 25: Reverberation Times for Gym with Carpeted Rear Wall

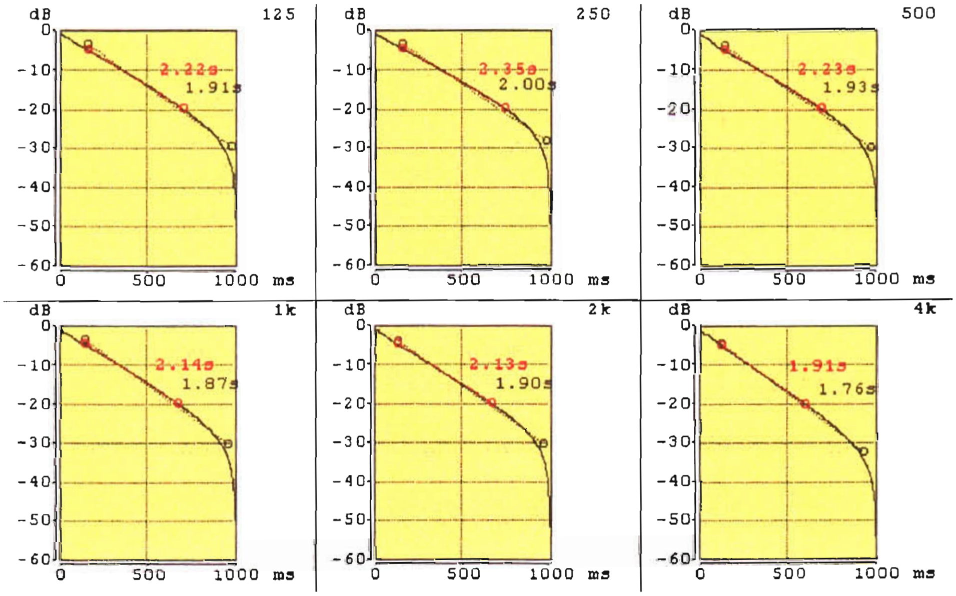


Figure 26: T15 and T30 Estimation Curves for Gym with Carpeted Rear Wall

Appendix G: CATT™ Results for Room with Maximized Banner Area

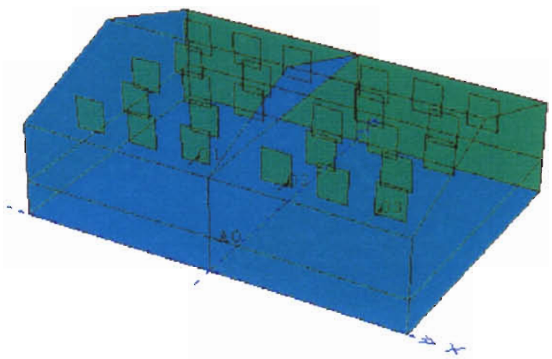


Figure 27: Room Geometry with Maximized Banner Area

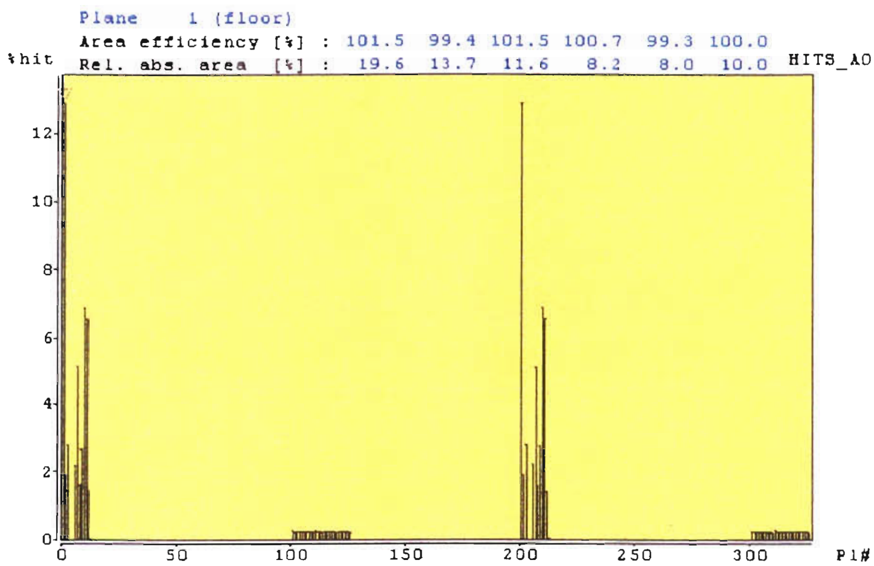


Figure 28: Percentage Hits vs. Plane Numbers for Room with Maximized Banners

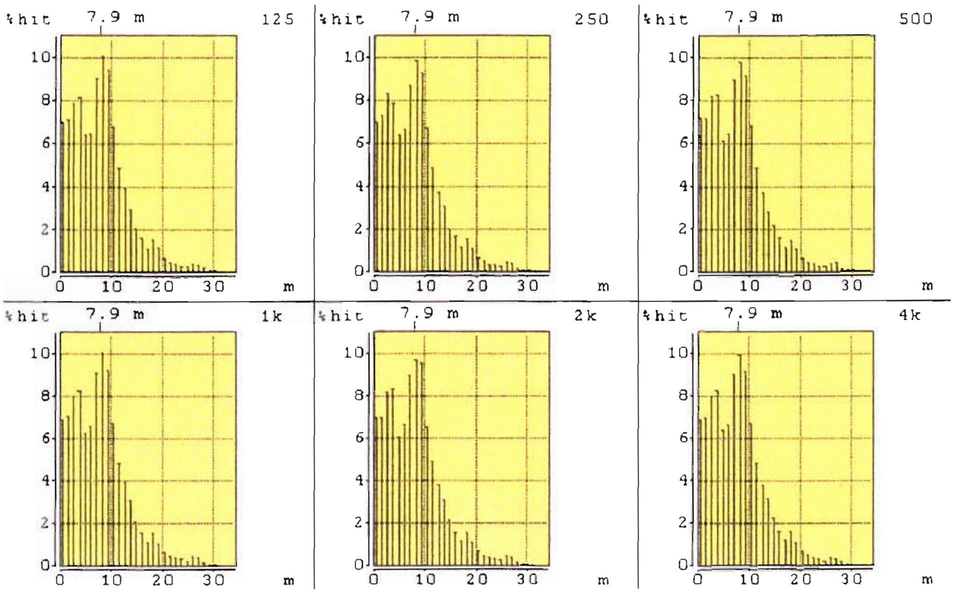
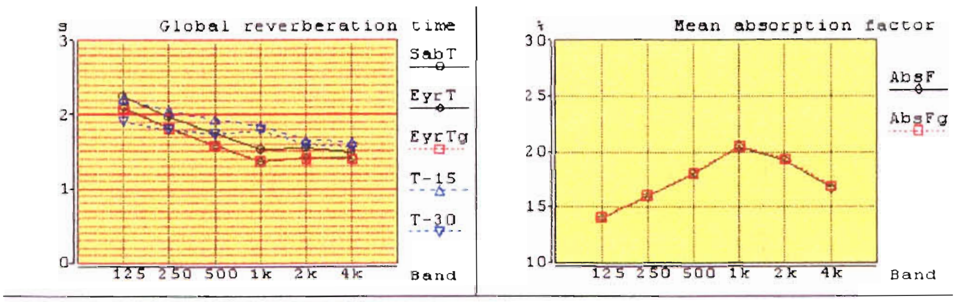


Figure 29: MFP Values for Gym with Maximized Banners



	125	250	500	1k	2k	4k	
EyrT	2.10	1.82	1.59	1.37	1.42	1.41	s
EyrTg	2.09	1.81	1.58	1.37	1.41	1.40	s
SabT	2.25	1.97	1.74	1.52	1.55	1.50	s
T-15	2.22	2.05	1.94	1.84	1.65	1.64	s
T-30	1.91	1.80	1.74	1.79	1.60	1.56	s
AbsF	14.01	15.94	17.99	20.48	19.25	16.69	%
AbsFg	14.06	16.02	18.06	20.48	19.32	16.86	%
MFP	7.87	7.88	7.85	7.88	7.91	7.90	m
Diffs	29.63	30.37	29.98	29.89	30.01	29.66	%

Trunc	1000.0	ms
Rays	998	(used/oct)
	0	(lost/oct)
	0	(absorbed/oct)
Angle	6.43	degrees

Figure 30: Reverberation Times for Gym with Maximized Banners

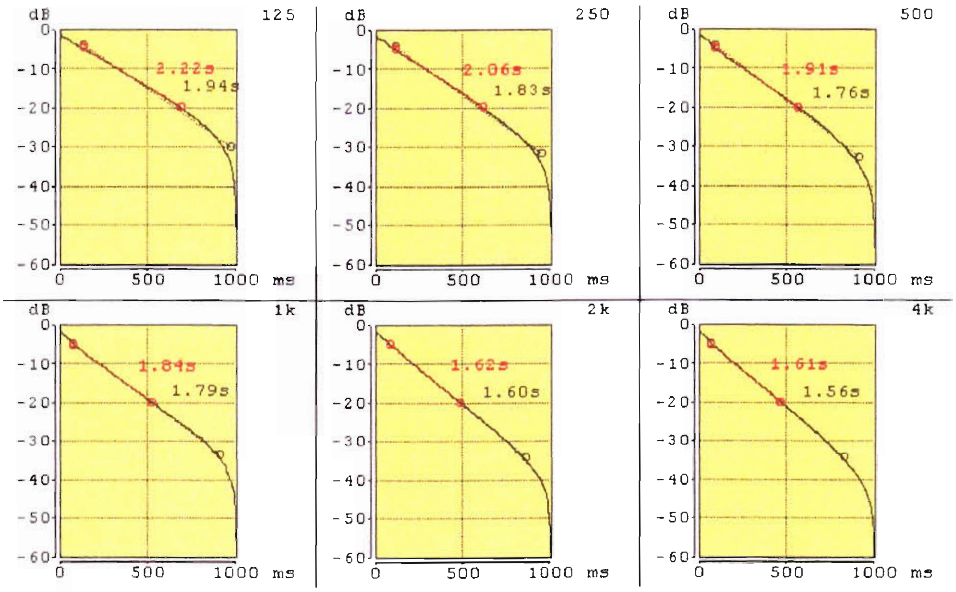


Figure 31: T15 and T30 Estimation Curves for Gym with Maximized Banners

Appendix H: CATT™ Results for Room with Banners and Carpeted Rear Wall

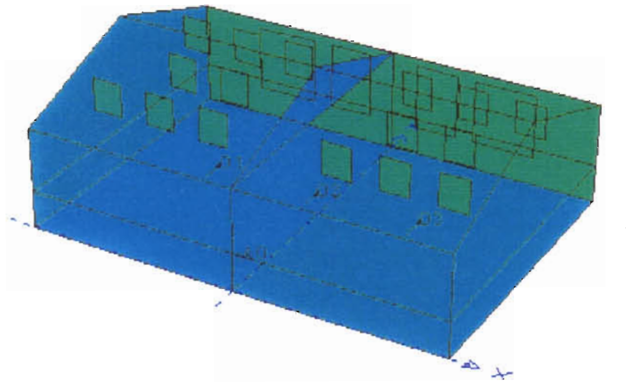


Figure 32: Room Geometry with Enlarged Banners and Carpeted Rear Wall

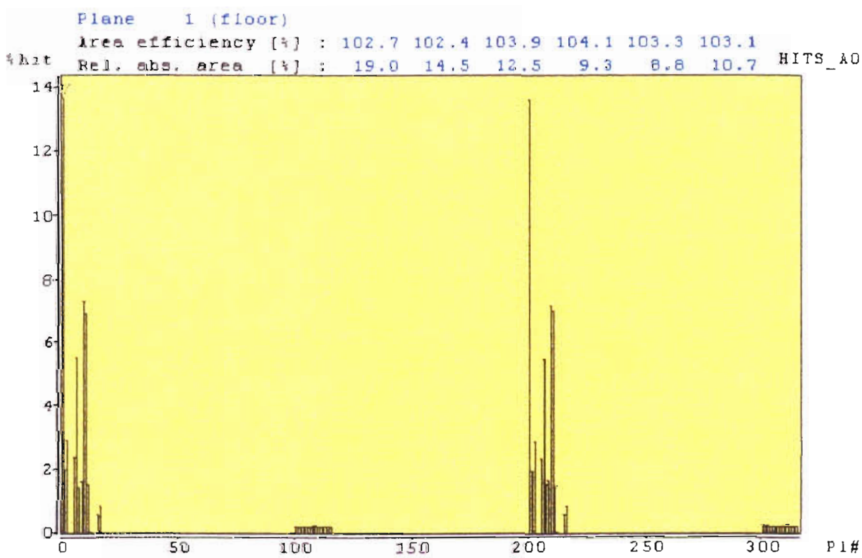


Figure 33: Percentage Hits vs. Plane Numbers for Gym with Enlarged Banners and Carpeted Rear Wall

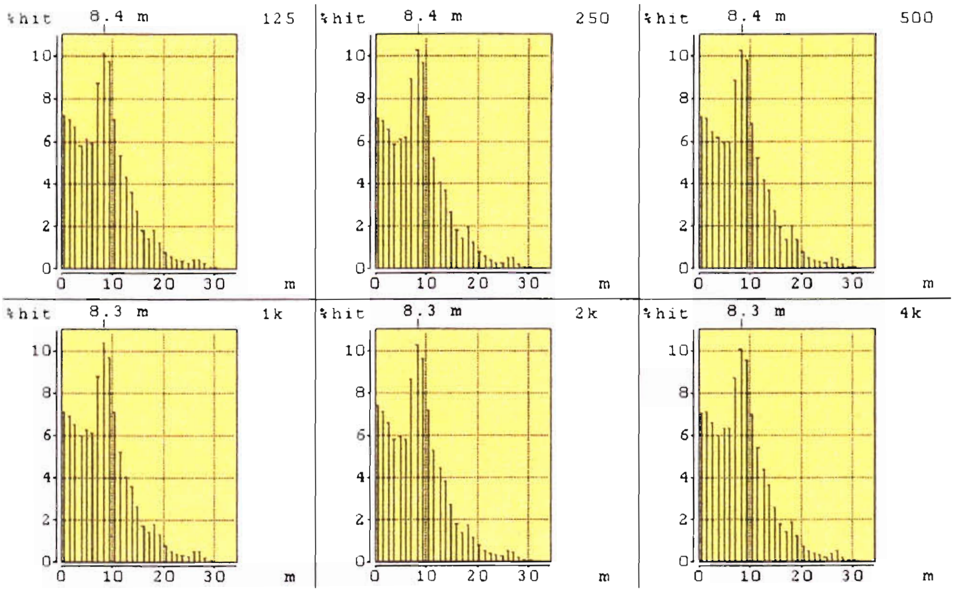
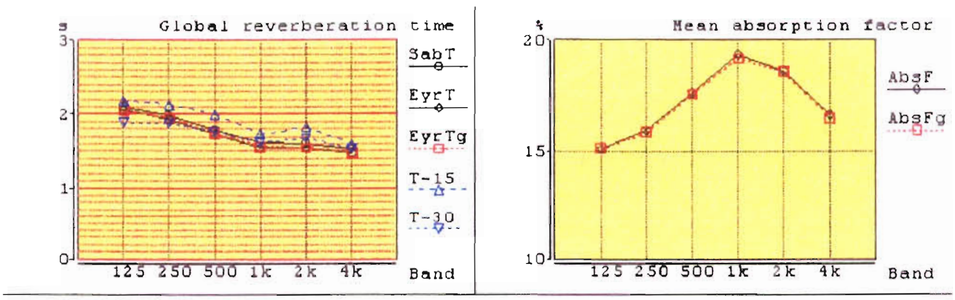


Figure 34: MFP Values for Gym with Enlarged Banners and Carpeted Rear Wall



	125	250	500	1k	2k	4k	
EyrT	2.06	1.94	1.73	1.54	1.54	1.47	s
EyrTg	2.05	1.95	1.74	1.56	1.55	1.48	s
SabT	2.09	1.99	1.79	1.63	1.61	1.52	s
T-15	2.18	2.13	2.00	1.73	1.83	1.60	s
T-30	1.88	1.88	1.77	1.63	1.68	1.54	s
AbsF	15.08	15.93	17.61	19.37	18.63	16.65	%
AbsFg	15.11	15.86	17.55	19.17	18.57	16.50	%
MFP	8.35	8.36	8.37	8.35	8.34	8.31	m
Diffs	29.97	29.94	29.88	30.27	29.92	30.29	%

Trunc	1000.0	ms
Rays	998	(used/oct)
	0	(lost/oct)
	0	(absorbed/oct)
Angle	6.43	degrees

Figure 35: Reverberation Times for Gym with Enlarged Banners and Carpeted Rear Wall

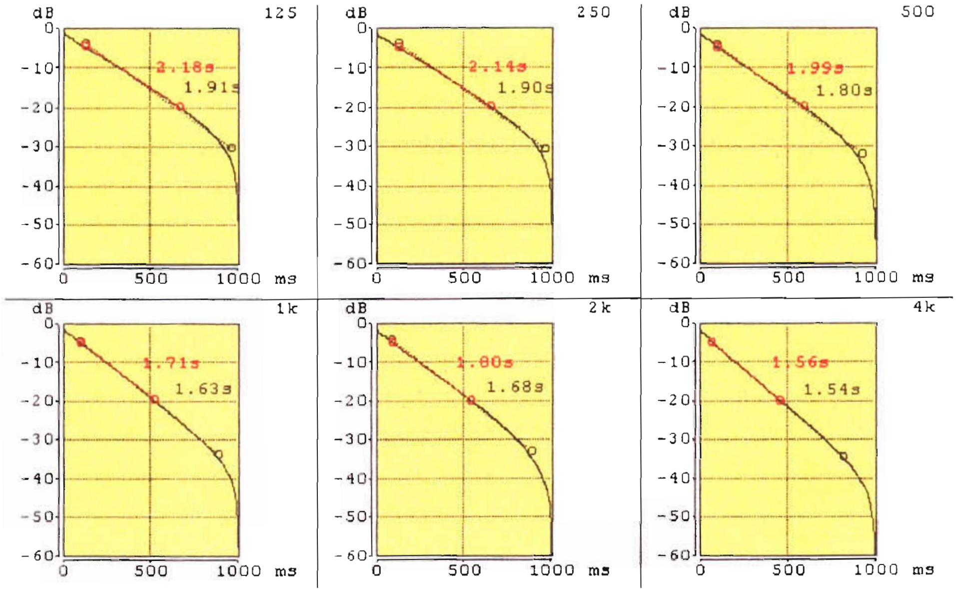


Figure 36: T15 and T30 Estimation Curves for Gym with Enlarged Banners and Carpeted Rear Wall

Appendix I: CATT™ Results for Room with Hanging Acoustic Panels

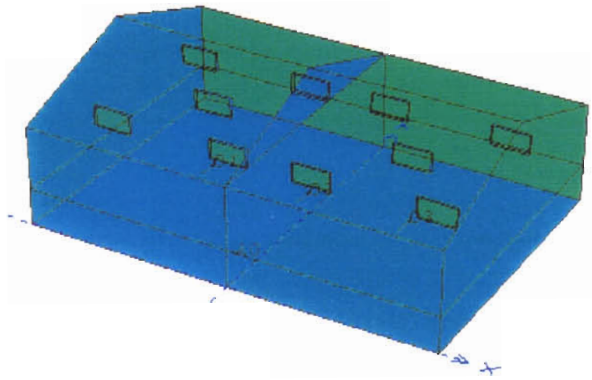


Figure 37: Room Geometry with Hanging Acoustic Panels

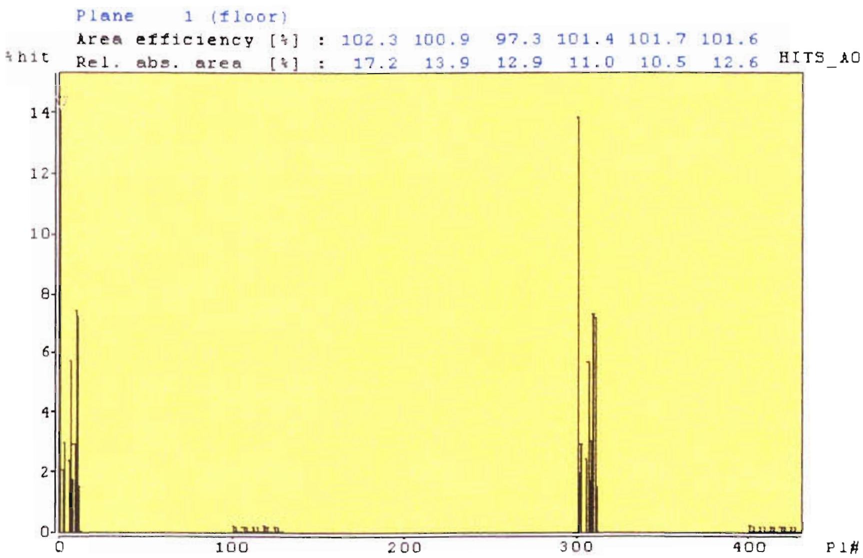


Figure 38: Percentage Hits vs. Plane Numbers for Gym with Hanging Acoustic Panels

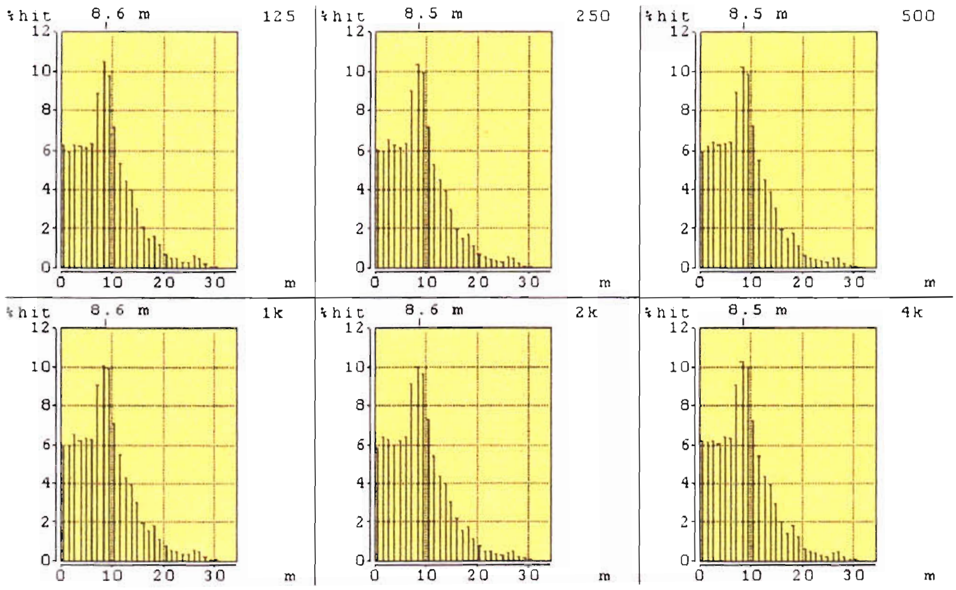
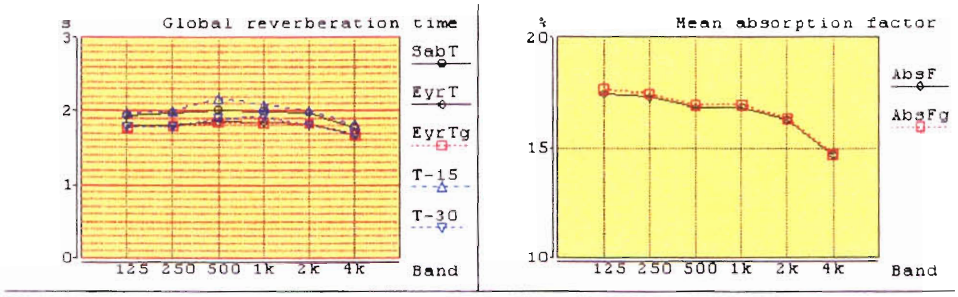


Figure 39: MFP Values for Gym with Hanging Acoustic Panels



	125	250	500	1k	2k	4k	
EyrT	1.80	1.81	1.86	1.84	1.83	1.67	s
EyrTg	1.78	1.79	1.84	1.83	1.82	1.67	s
SabT	1.94	1.96	2.02	1.99	1.96	1.77	s
T-15	1.98	2.00	2.17	2.07	2.01	1.81	s
T-30	1.78	1.78	1.90	1.92	1.81	1.68	s
AbsF	17.44	17.29	16.81	16.82	16.26	14.67	%
AbsFg	17.64	17.44	16.93	16.92	16.30	14.69	%
MFP	8.59	8.54	8.53	8.58	8.60	8.51	m
Diffs	29.91	30.11	29.85	29.66	30.35	30.14	%

Trunc	1000.0	ms
Rays	998	(used/oct)
	0	(lost/oct)
	0	(absorbed/oct)
Angle	6.43	degrees

Figure 40: Reverberation Times for Gym with Hanging Acoustic Panels

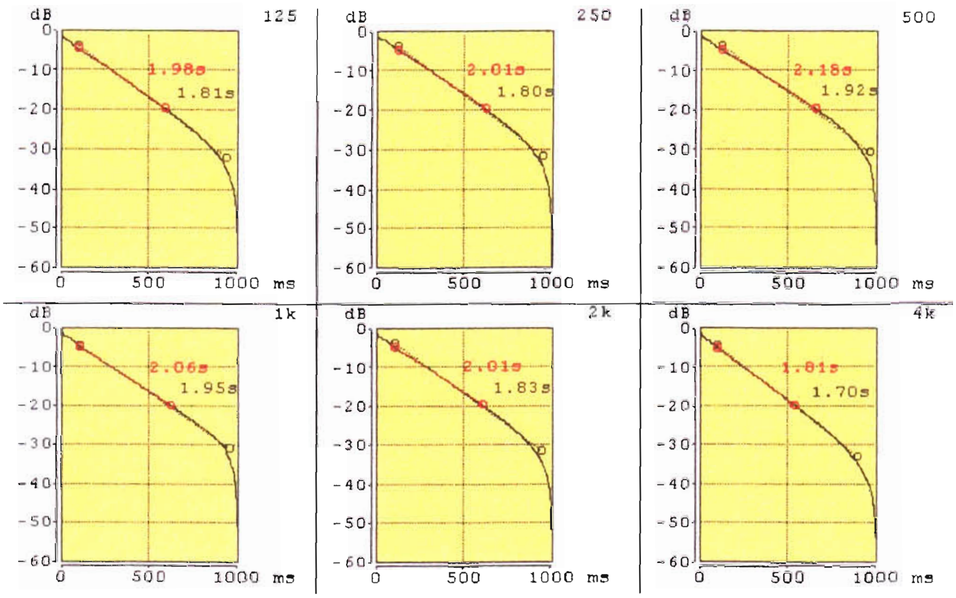


Figure 41: T15 and T30 Estimation Curves for Gym with Hanging Acoustic Panels

Appendix J: CATT™ Results for Room with Acoustic Panels on Ceiling

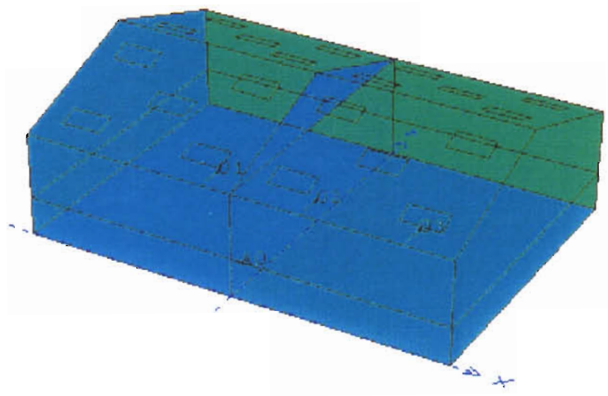


Figure 42: Room Geometry with Acoustic Panels on Ceiling

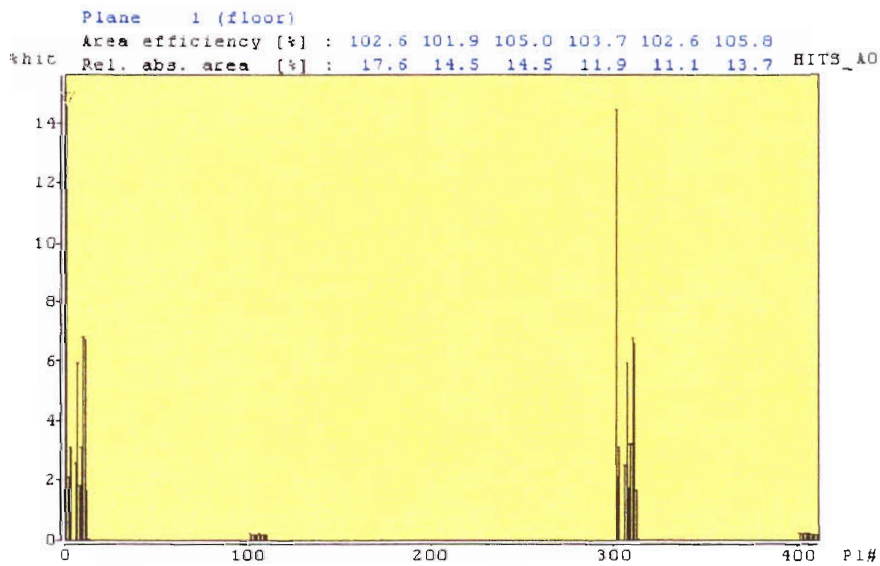


Figure 43: Percentage Hits vs. Plane Numbers for Gym with Acoustic Panels on Ceiling

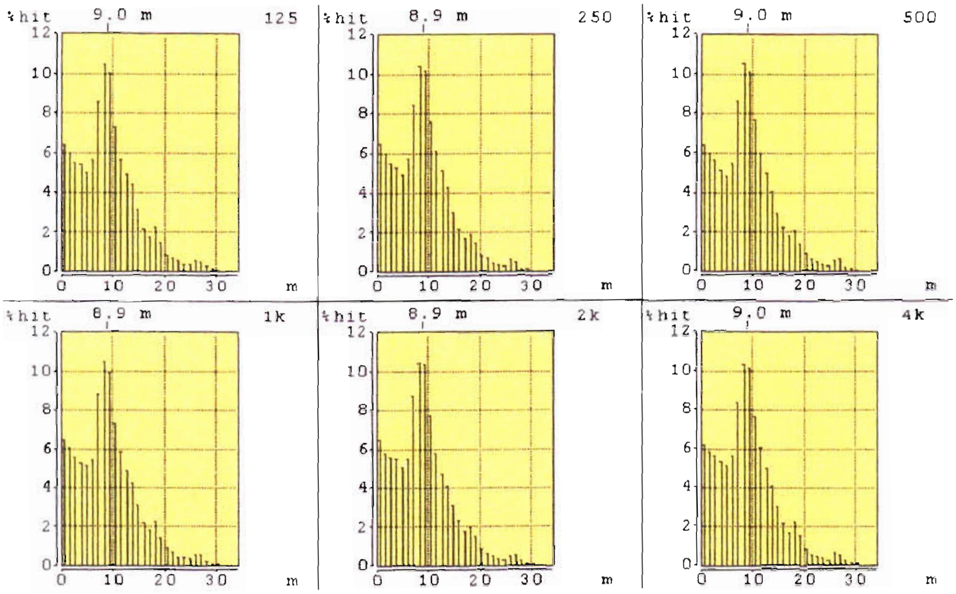
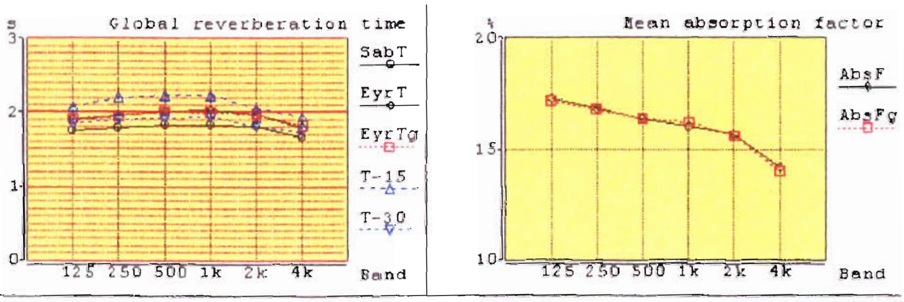


Figure 44: MFP Values for Gym with Acoustic Panels on Ceiling



	125	250	500	1k	2k	4k	
EyrT	1.90	1.95	2.01	2.03	1.97	1.79	s
EyrTg	1.92	1.95	2.01	2.00	1.98	1.81	s
SabT	1.75	1.79	1.83	1.82	1.81	1.66	s
T-15	2.08	2.20	2.23	2.22	2.05	1.93	s
T-30	1.84	1.91	1.92	1.93	1.81	1.74	s
AbsF	17.28	16.79	16.35	16.01	15.65	14.19	%
AbsFg	17.14	16.79	16.36	16.21	15.59	14.01	%
MFP	8.97	8.92	8.96	8.94	8.92	8.99	m
Diffs	29.74	29.76	29.78	29.91	30.17	29.84	%

Trunc	1000.0	ms
Rays	998	(used/oct)
	0	(lost/oct)
	0	(absorbed/oct)
Angle	6.43	degrees

Figure 45: Reverberation Times for Gym with Acoustic Panels on Ceiling

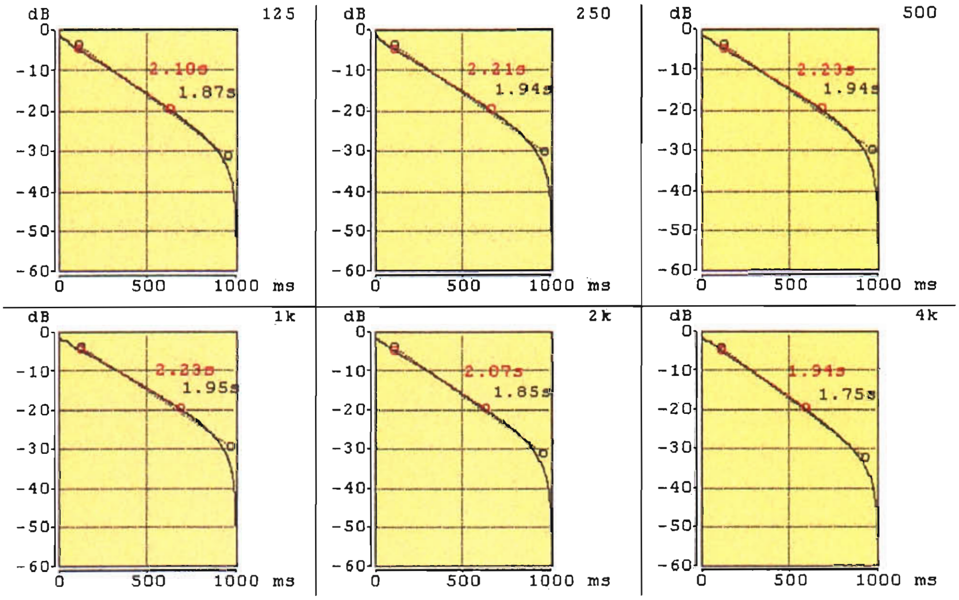


Figure 46: T15 and T30 Estimation Curves for Gym with Acoustic Panels on Ceiling

Appendix K: CATT™ Code for Empty Gymnasium

```
;Empty Gym

;constant declarations
LOCAL c  = 9.143              ;ceiling height in m
LOCAL h  = 6.096              ;wall height in m
LOCAL t  = 2.235              ;tile wall height in m
GLOBAL w = 26.212             ;hall width in m
GLOBAL d = 18.236             ;hall depth in m

;surface declarations
ABS wood        = <21 17 16 13 12 13>
ABS tile        = <7 7 7 7 8 8>
ABS pconcrete   = <16 11 12 13 15 14>
ABS steel       = <11 16 16 16 13 8>

CORNERS

;floor corners
1           -w/2        0          0
2           -w/2        d          0
3            w/2        d          0
4            w/2        0          0

;top of tile wall corners
11          -w/2        0          t
12          -w/2        d          t
13           w/2        d          t
14           w/2        0          t

;top of concrete wall corners
15          -w/2        0          h
16          -w/2        d          h
17           w/2        d          h
18           w/2        0          h

;roof corners
21          -w/2        d/2        c
22           w/2        d/2        c

;divider corners
23          0           0          h
24          0           d          h
25          0           d/2        c

PLANES
(1  floor                  / 4 3 2 1 /                    wood)
(2  bottom stage wall      / 1 11 14 4 /                  tile)
(3  top stage wall         / 11 15 18 14 /           pconcrete)
(4  bottom left wall       / 2 12 11 1 /                  tile)
(5  top left wall          / 12 16 21 15 11 /        pconcrete)
```

(6 bottom right wall	/ 4 14 13 3 /	tile)
(7 top right wall	/ 14 18 22 17 13 /	pconcrete)
(8 bottom rear wall	/ 3 13 12 2 /	tile)
(9 top rear wall	/ 13 17 16 12 /	pconcrete)
(10 roof1	/ 15 21 22 18 /	steel)
(11 roof2	/ 17 22 21 16 /	steel)
(12 divider1	/ 23 24 25 /	wood)
(13 divider2	/ 25 24 23 /	wood)

Appendix L: CATT™ Code for Gym with Small Banners

```
;Gym with Small Banners
;constant declarations
LOCAL c = 9.143              ;ceiling height in m
LOCAL h = 6.096              ;wall height in m
LOCAL t = 2.235              ;tile wall height in m

;_______________banner dimensions______________________________

LOCAL row1_d = 4.5           ;depth to first row of banners
LOCAL row2_d = 9.118         ;depth to second row of banners
LOCAL row3_d = 13.736        ;depth to third row of banners
LOCAL col1_w = 3             ;width to first column of banners
LOCAL col2_w = 4.5           ;width to second column of banners
LOCAL col3_w = 6.5           ;width to third column of banners
LOCAL col4_w = 8             ;width to fourth column of bannners
LOCAL col5_w = 10            ;width to fifth column of banners
LOCAL banner_h = 6.2         ;height to bottom of all banners
LOCAL banner_w = 0.5         ;width of all banners
LOCAL banner_l = 1           ;length of all banners
;______________________________________________________________

GLOBAL w = 26.212            ;hall width in m
GLOBAL d = 18.236            ;hall depth in m

;surface declarations
ABS wood          = <21 17 16 13 12 13>
ABS tile          = <7 7 7 7 8 8>
ABS pconcrete     = <16 11 12 13 15 14>
ABS steel         = <11 16 16 16 13 8>
ABS drapery       = <7 31 49 75 70 60>

MIRROR    200    200

CORNERS

;floor corners
1         0         0         0
2         0         d         0
3         w/2       d         0
4         w/2       0         0

;top of tile wall corners
11        0         0         t
12        0         d         t
13        w/2       d         t
14        w/2       0         t

;top of concrete wall corners
15        0         0         h
16        0         d         h
```

```
17      w/2     d       h
18      w/2     0       h

;roof corners
21      0       d/2     c
22      w/2     d/2     c

;divider corners
23      .01     0       h
24      .01     d       h
25      .01     d/2     c
26      0       0       h
27      0       d       h

;banner corners

;banner1
101     col1_w                  row1_d      banner_h
102     col1_w+banner_w         row1_d      banner_h
103     col1_w                  row1_d      banner_h+banner_l
104     col1_w+banner_w         row1_d      banner_h+banner_l

;banner2
105     col3_w                  row1_d      banner_h
106     col3_w+banner_w         row1_d      banner_h
107     col3_w                  row1_d      banner_h+banner_l
108     col3_w+banner_w         row1_d      banner_h+banner_l

;banner3
109     col5_w                  row1_d      banner_h
110     col5_w+banner_w         row1_d      banner_h
111     col5_w                  row1_ d     banner_h+banner_l
112     col5_w+banner_w         row1_d      banner_h+banner_l

;banner4
113     col2_w                  row2_d      banner_h
114     col2_w+banner_w         row2_d      banner_h
115     col2_w                  row2_d      banner_h+banner_l
116     col2_w+banner_w         row2_d      banner_h+banner_l

;banner5
117     col4_w                  row2_d      banner_h
118     col4_w+banner_w         row2_d      banner_h
119     col4_w                  row2_d      banner_h+banner_l
120     col4_w+banner_w         row2_d      banner_h+banner_l

;banner6
121     col1_w                  row3_d      banner_h
122     col1_w+banner_w         row3_d      banner_h
123     col1_w                  row3_d      banner_h+banner_l
124     col1_w+banner_w         row3_ d     banner_h+banner_l
```

```
;banner7
125          col3_w                   row3_d      banner_h
126          col3_w+banner_w          row3_d      banner_h
127          col3_w                   row3_d      banner_h+banner_l
128          col3_w+banner_w          row3_d      banner_h+banner_l

;banner8
129          col5_w                   row3_d      banner_h
130          col5_w+banner_w          row3_d      banner_h
131          col5_w                   row3_d      banner_h+banner_l
132          col5_w+banner_w          row3_d      banner_h+banner_l


PLANES
(1  floor                / 4 3 2 1 /              wood)
(2  bottom stage wall    / 1 11 14 4 /            tile)
(3  top stage wall       / 11 15 18 14 /     pconcrete)
;(4  bottom left wall    / 2 12 11 1 /            tile)
;(5  top left wall       / 12 16 21 15 11 /  pconcrete)
(6  bottom right wall    / 4 14 13 3 /            tile)
(7  top right wall       / 14 18 22 17 13 /  pconcrete)
(8  bottom rear wall     / 3 13 12 2 /            tile)
(9  top rear wall        / 13 17 16 12 /     pconcrete)
(10 roof1                / 15 21 22 18 /         steel)
(11 roof2                / 17 22 21 16 /         steel)
(12 divider1             / 23 24 25 /             wood)
(13 divider2             / 27 24 23 26 /          wood)

;banner planes
(101  banner1_1          / 102 104 103 101 /   drapery)
(102  banner1_2          / 101 103 104 102 /   drapery)
(103  banner2_1          / 106 108 107 105 /   drapery)
(104  banner2_2          / 105 107 108 106 /   drapery)
(105  banner3_1          / 110 112 111 109 /   drapery)
(106  banner3_2          / 109 111 112 110 /   drapery)
(107  banner4_1          / 114 116 115 113 /   drapery)
(108  banner4_2          / 113 115 116 114 /   drapery)
(109  banner5_1          / 118 120 119 117 /   drapery)
(110  banner5_2          / 117 119 120 118 /   drapery)
(111  banner6_1          / 122 124 123 121 /   drapery)
(112  banner6_2          / 121 123 124 122 /   drapery)
(113  banner7_1          / 126 128 127 125 /   drapery)
(114  banner7_2          / 125 127 128 126 /   drapery)
(115  banner8_1          / 130 132 131 129 /   drapery)
(116  banner8_2          / 129 131 132 130 /   drapery)
```

Appendix M: CATT™ Code for Gym With Carpeted Rear Wall

```
;padded.geo
;constant declarations
LOCAL c = 9.143                 ;ceiling height in m
LOCAL h = 6.096                 ;wall height in m
LOCAL t = 2.235                 ;tile wall height in m

;_________rear wall padding dimensions___________________________

LOCAL bottom_h = 1.719          ;height to bottom of rear wall padding
LOCAL padh = 3.877              ;height of a section of padding
LOCAL padw = 1.566              ;distance to first pad from center
LOCAL padd = 18.223             ;distance to all pads from stage wall
LOCAL secondw = 5.375           ;distance to second section of padding
LOCAL sm_w = 2.657              ;width of smaller section of padding
LOCAL lg_w = 3.877              ;width of larger section of padding
;________________________________________________________________

GLOBAL w = 26.212               ;hall width in m
GLOBAL d = 18.236               ;hall depth in m

;surface declarations
ABS wood        = <15 11 10 7 6 7>
ABS tile        = <1 1 1 1 2 2>
ABS pconcrete   = <10 5 6 7 9 8>
ABS steel       = <5 10 10 10 7 2>
ABS carpet      = <37 41 63 85 96 92>

;MIRROR    100    100    EXCLUDE    1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17

CORNERS

;floor corners
1        -w/2        0        0
2        -w/2        d        0
3         w/2        d        0
4         w/2        0        0

;top of tile wall corners
11       -w/2        0        t
12       -w/2        d        t
13        w/2        d        t
14        w/2        0        t

;top of concrete wall corners
15       -w/2        0        h
16       -w/2        d        h
17        w/2        d        h
18        w/2        0        h
```

```
;roof corners
21        -w/2              d/2        c
22         w/2              d/2        c

;divider corners
23         0                0          h
24         0                d          h
25         0                d/2        c

;padding corners
31        -padw             padd       bottom_h
32        -(padw+sm_w)      padd       bottom_h
33        -padw             padd       bottom_h+padh
34        -(padw+sm_w)      padd       bottom_h+padh

35        -secondw          padd       bottom_h
36        -(secondw+lg_w)   padd       bottom_h
37        -secondw          padd       bottom_h+padh
38        -(secondw+lg_w)   padd       bottom_h+padh

41         padw             padd       bottom_h
42         padw+sm_w        padd       bottom_h
43         padw             padd       bottom_h+padh
44         padw+sm_w        padd       bottom_h+padh

45         secondw          padd       bottom_h
46         secondw+lg_w     padd       bottom_h
47         secondw          padd       bottom_h+padh
48         secondw+lg_w     padd       bottom_h+padh


PLANES
(1  floor                / 4 3 2 1 /               wood)
(2  bottom stage wall    / 1 11 14 4 /             tile)
(3  top stage wall       / 11 15 18 14 /      pconcrete)
(4  bottom left wall     / 2 12 11 1 /             tile)
(5  top left wall        / 12 16 21 15 11 /   pconcrete)
(6  bottom right wall    / 4 14 13 3 /             tile)
(7  top right wall       / 14 18 22 17 13 /   pconcrete)
(8  bottom rear wall     / 3 13 12 2 /             tile)
(9  top rear wall        / 13 17 16 12 /      pconcrete)
(10 roof1                / 15 21 22 18 /          steel)
(11 roof2                / 17 22 21 16 /          steel)
(12 divider1             / 23 24 25 /              wood)
(13 divider2             / 25 24 23 /              wood)
;padded planes
(14 pad1                 / 31 33 34 32 /         carpet)
(15 pad2                 / 35 37 38 36 /         carpet)
(16 pad3                 / 42 44 43 41 /         carpet)
(17 pad4                 / 46 48 47 45 /         carpet)
```

Appendix N: CATT™ Code for Gym with Maximized Banners

```
;Gym with Maximized Banners
;constant declarations
LOCAL c = 9.143                          ;ceiling height in m
LOCAL h = 6.096                          ;wall height in m
LOCAL t = 2.235                          ;tile wall height in m

;_______________banner dimensions______________________________

LOCAL row1_d    = 3.03                   ;depth to first row of banners
LOCAL row2_d    = 6.06                   ;depth to second row of banners
LOCAL row3_d    = 9.118                  ;depth to third row of banners
LOCAL row4_d    = 12.148                 ;depth to fourth row of banners
LOCAL row5_d    = 15.178                 ;depth to fifth row of banners
LOCAL col1_w    = 1.77                   ;width to first column of banners
LOCAL col2_w    = 3.04                   ;width to second column of banners
LOCAL col3_w    = 5.54                   ;width to third column of banners
LOCAL col4_ w   = 8.08                   ;width to fourth column of bannners
LOCAL col5_w    = 9.31                   ;width to fifth column of banners
LOCAL banner_h  = 5.0                    ;height to bottom of all banners
LOCAL banner_w  = 2                      ;width of all banners
LOCAL banner_l  = 2.1                    ;length of all banners
;______________________________________________________________

GLOBAL w  = 26.212                  ;hall width in m
GLOBAL d  = 18.236                  ;hall depth in m

;surface declarations
ABS wood            = <21 17 16 13 12 13>
ABS tile            = <7 7 7 7 8 8>
ABS pconcrete       = <16 11 12 13 15 14>
ABS steel           = <11 16 16 16 13 8>
ABS drapery         = <7 31 49 75 70 60>

MIRROR          200   200

CORNERS

;floor corners
1            0            0            0
2            0            d            0
3           w/2           d            0
4           w/2           0            0

;top of tile wall corners
11           0            0            t
12           0            d            t
13          w/2           d            t
14          w/2           0            t

;top of concrete wall corners
```

```
15          0             0          h
16          0             d          h
17          w/2           d          h
18          w/2           0          h

;roof corners
21          0             d/2        c
22          w/2           d/2        c

;divider corners
23          .01           0          h
24          .01           d          h
25.         01            d/2        c
26          0             0          h
27          0             d          h

;banner corners

;banner1
101     col1_w               row1_d              banner_h
102     col1_w+banner_w      row1_d              banner_h
103     col1_w               row1_d              banner_h+banner_l
104     col1_w+banner_w      row1_d              banner_h+banner_l

;banner2
105     col3_w               row1_d              banner_h
106     col3_w+banner_w      row1_d              banner_h
107     col3_w               row1_d              banner_h+banner_l
108     col3_w+banner_w      row1_d              banner_h+banner_l

;banner3
109     col5_w               row1_d              banner_h
110     col5_w+banner_w      row1_d              banner_h
111     col5_w               row1_d              banner_h+banner_l
112     col5_w+banner_w      row1_d              banner_h+banner_l

;banner4
113     col2_w               row2_d              banner_h
114     col2_w+banner_w      row2_d              banner_h
115     col2_w               row2_d              banner_h+banner_l
116     col2_w+banner_w      row2_d              banner_h+banner_l

;banner5
117     col4_w               row2_d              banner_h
118     col4_w+banner_w      row2_d              banner_h
119     col4_w               row2_d              banner_h+banner_l
120     col4_w+banner_w      row2_d              banner_h+banner_l

;banner6
121     col1_w               row3_d              banner_h
122     col1_w+banner_w      row3_d              banner_h
123     col1_w               row3_d              banner_h+banner_l
124     col1_w+banner_w      row3_d              banner_h+banner_l
```

```
;banner7
125     col3_w                  row3_d          banner_h
126     col3_w+banner_w         row3_d          banner_h
127     col3_w                  row3_d          banner_h+banner_l
128     col3_w+banner_w         row3_d          banner_h+banner_l

;banner8
129     col5_w                  row3_d          banner_h
130     col5_w+banner_w         row3_d          banner_h
131     col5_w                  row3_d          banner_h+banner_l
132     col5_w+banner_w         row3_d          banner_h+banner_l

;banner9
133     col2_w                  row4_d          banner_h
134     col2_w+banner_w         row4_d          banner_h
135     col2_w                  row4_d          banner_h+banner_l
136     col2_w+banner_w         row4_d          banner_h+banner_l

;banner10
137     col4_w                  row4_d          banner_h
138     col4_w+banner_w         row4_d          banner_h
139     col4_w                  row4_d          banner_h+banner_l
140     col4_w+banner_w         row4_d          banner_h+banner_l

;banner11
141     col1_w                  row5_d          banner_h
142     col1_w+banner_w         row5_d          banner_h
143     col1_w                  row5_d          banner_h+banner_l
144     col1_w+banner_w         row5_d          banner_h+banner_l

;banner12
145     col3_w                  row5_d          banner_h
146     col3_w+banner_w         row5_d          banner_h
147     col3_w                  row5_d          banner_h+banner_l
148     col3_w+banner_w         row5_d          banner_h+banner_l

;banner13
149     col5_w                  row5_d          banner_h
150     col5_w+banner_w         row5_d          banner_h
151     col5_w                  row5_d          banner_h+banner_l
152     col5_w+banner_w         row5_d          banner_h+banner_l

PLANES
(1  floor                   / 4 3 2 1 /             wood)
(2  bottom stage wall       / 1 11 14 4 /           tile)
(3  top stage wall          / 11 15 18 14 /         pconcrete)
;(4  bottom left wall       / 2 12 11 1 /           tile)
;(5  top left wall          / 12 16 21 15 11 /      pconcrete)
(6  bottom right wall       / 4 14 13 3 /           tile)
(7  top right wall          / 14 18 22 17 13 /      pconcrete)
(8  bottom rear wall        / 3 13 12 2 /           tile)
(9  top rear wall           / 13 17 16 12 /         pconcrete)
(10 roof1                   / 15 21 22 18 /         steel)
(11 roof2                   / 17 22 21 16 /         steel)
```

```
(12 divider1                  / 23 24 25 /               wood)
(13 divider2                  / 27 24 23 26 /            wood)

;banner planes
(101  banner1_1            / 102 104 103 101 /       drapery)
(102  banner1_2            / 101 103 104 102 /       drapery)
(103  banner2_1            / 106 108 107 105 /       drapery)
(104  banner2_2            / 105 107 108 106 /       drapery)
(105  banner3_1            / 110 112 111 109 /       drapery)
(106  banner3_2            / 109 111 112 110 /       drapery)
(107  banner4_1            / 114 116 115 113 /       drapery)
(108  banner4_2            / 113 115 116 114 /       drapery)
(109  banner5_1            / 118 120 119 117 /       drapery)
(110  banner5_2            / 117 119 120 118 /       drapery)
(111  banner6_1            / 122 124 123 121 /       drapery)
(112  banner6_2            / 121 123 124 122 /       drapery)
(113  banner7_1            / 126 128 127 125 /       drapery)
(114  banner7_2            / 125 127 128 126 /       drapery)
(115  banner8_1            / 130 132 131 129 /       drapery)
(116  banner8_2            / 129 131 132 130 /       drapery)
(117  banner9_1            / 134 136 135 133 /       drapery)
(118  banner9_2            / 133 135 136 134 /       drapery)
(119  banner10_1           / 138 140 139 137 /       drapery)
(120  banner10_2           / 137 139 140 138 /       drapery)
(121  banner11_1           / 142 144 143 141 /       drapery)
(122  banner11_2           / 141 143 144 142 /       drapery)
(123  banner12_1           / 146 148 147 145 /       drapery)
(124  banner12_2           / 145 147 148 146 /       drapery)
(125  banner13_1           / 150 152 151 149 /       drapery)
(126  banner13_2           / 149 151 152 150 /       drapery)
```

Appendix O: CATT™ Code for Gym with Enlarged Banners and Carpeted Rear Wall

```
;Gym with Enlarged Banners and Carpeted Rear Wall

;constant declarations
LOCAL c = 9.143                ;ceiling height in m
LOCAL h = 6.096                ;wall height in m
LOCAL t = 2.235                ;tile wall height in m

;________rear wall padding dimensions________________________

LOCAL bottom_h = 1.719         ;height to bottom of rear wall padding
LOCAL padh = 3.877             ;height of a section of padding
LOCAL padw = 1.566             ;distance to first pad from center
LOCAL padd = 18.223            ;distance to all pads from stage wall
LOCAL secondw = 5.375          ;distance to second section of padding
LOCAL sm_w = 2.657             ;width of smaller section of padding
LOCAL lg_w = 3.877             ;width of larger section of padding

;_______________banner dimensions____________________________

LOCAL row1_d = 4.5             ;depth to first row of banners
LOCAL row2_d = 9.118           ;depth to second row of banners
LOCAL row3_d = 13.736          ;depth to third row of banners
LOCAL col1_w = 3               ;width to first column of banners
LOCAL col2_w = 4.5             ;width to second column of banners
LOCAL col3_w = 6.5             ;width to third column of banners
LOCAL col4_w = 8               ;width to fourth column of bannners
LOCAL col5_w = 10              ;width to fifth column of banners
LOCAL banner_h = 5.6           ;height to bottom of all banners
LOCAL banner_w = 1.8           ;width of all banners
LOCAL banner_l = 2             ;length of all banners
;___________________________________________________________

GLOBAL w = 26.212              ;hall width in m
GLOBAL d = 18.236              ;hall depth in m

;surface declarations
ABS wood       = <21 17 16 13 12 13>
ABS tile       = <7 7 7 7 8 8>
ABS pconcrete  = <16 11 12 13 15 14>
ABS steel      = <11 16 16 16 13 8>
ABS carpet     = <37 41 63 85 96 92>
ABS drapery    = <7 31 49 75 70 60>

MIRROR    200    200

CORNERS

;floor corners
1    0    0    0
2    0    d    0
```

```
3       w/2     d       0
4       w/2     0       0


;top of tile wall corners
11      0       0       t
12      0       d       t
13      w/2     d       t
14      w/2     0       t

;top of concrete wall corners
15      0       0       h
16      0       d       h
17      w/2     d       h
18      w/2     0       h

;roof corners
21      0       d/2     c
22      w/2     d/2     c

;divider corners
23      .01     0       h
24      .01     d       h
25      .01     d/2     c
26       0       0      h
27       0      d       h

;padding corners

41      padw                padd                bottom_h
42      padw+sm_w           padd                bottom_h
43      padw                padd                bottom_h+padh
44      padw+sm_w           padd                bottom_h+padh

45      secondw             padd                bottom_h
46      secondw+lg_w        padd                bottom_h
47      secondw             padd                bottom_h+padh
48      secondw+lg_w        padd                bottom_h+padh

;banner corners

;banner1
101     col1_w              row1_d        banner_h
102     col1_w+banner_w     row1_d        banner_h
103     col1_w              row1_d        banner_h+banner_l
104     col1_w+banner_w     row1_d        banner_h+banner_l

;banner2
105     col3_w              row1_d        banner_h
106     col3_w+banner_w     row1_d        banner_h
107     col3_w              row1_d        banner_h+banner_l
108     col3_w+banner_w     row1_d        banner_h+banner_l

;banner3
```

```
109    col5_w                row1_d      banner_h
110    col5_w+banner_w       row1_d      banner_h
111    col5_w                row1_d      banner_h+banner_l
112    col5_w+banner_w       row1_d      banner_h+banner_l

;banner4
113    col2_w                row2_d      banner_h
114    col2_w+banner_w       row2_d      banner_h
115    col2_w                row2_d      banner_h+banner_l
116    col2_w+banner_w       row2_d      banner_h+banner_l

;banner5
117    col4_w                row2_d      banner_h
118    col4_w+banner_w       row2_d      banner_h
119    col4_w                row2_d      banner_h+banner_l
120    col4_w+banner_w       row2_d      banner_h+banner_l

;banner6
121    col1_w                row3_d      banner_h
122    col1_w+banner_w       row3_d      banner_h
123    col1_w                row3_d      banner_h+banner_l
124    col1_w+banner_w       row3_d      banner_h+banner_l

;banner7
125    col3_w                row3_d      banner_h
126    col3_w+banner_w       row3_d      banner_h
127    col3_w                row3_d      banner_h+banner_l
128    col3_w+banner_w       row3_d      banner_h+banner_l

;banner8
129    col5_w                row3_d      banner_h
130    col5_w+banner_w       row3_d      banner_h
131    col5_w                row3_d      banner_h+banner_l
132    col5_w+banner_w       row3_d      banner_h+banner_l


PLANES
(1  floor                /4 3 2 1 /                 wood)
(2  bottom stage wall    / 1 11 14 4 /              tile)
(3  top stage wall       / 11 15 18 14 /       pconcrete)
;(4  bottom left wall    / 2 12 11 1 /              tile)
;(5  top left wall       / 12 16 21 15 11 /    pconcrete)
(6  bottom right wall    / 4 14 13 3 /              tile)
(7  top right wall       / 14 18 22 17 13 /    pconcrete)
(8  bottom rear wall     / 3 13 12 2 /              tile)
(9  top rear wall        / 13 17 16 12 /       pconcrete)
(10  roof1               / 15 21 22 18 /           steel)
(11  roof2               / 17 22 21 16 /           steel)
(12  divider1            / 23 24 25 /               wood)
(13  divider2            / 27 24 23 26 /            wood)
```

```
;padded planes
(16  pad1               / 42 44 43 41 /            carpet)
(17  pad2               / 46 48 47 45 /            carpet)

;banner planes
(101  banner1_1         / 102 104 103 101 /       drapery)
(102  banner1_2         / 101 103 104 102 /       drapery)
(103  banner2_1         / 106 108 107 105 /       drapery)
(104  banner2_2         / 105 107 108 106 /       drapery)
(105  banner3_1         / 110 112 111 109 /       drapery)
(106  banner3_2         / 109 111 112 110 /       drapery)
(107  banner4_1         / 114 116 115 113 /       drapery)
(108  banner4_2         / 113 115 116 114 /       drapery)
(109  banner5_1         / 118 120 119 117 /       drapery)
(110  banner5_2         / 117 119 120 118 /       drapery)
(111  banner6_1         / 122 124 123 121 /       drapery)
(112  banner6_2         / 121 123 124 122 /       drapery)
(113  banner7_1         / 126 128 127 125 /       drapery)
(114  banner7_2         / 125 127 128 126 /       drapery)
(115  banner8_1         / 130 132 131 129 /       drapery)
(116  banner8_2         / 129 131 132 130 /       drapery)
```

Appendix P: CATT™ Code for Gym with Hanging Acoustic Panels

```
;Gym with Hanging Acoustic Panels

;constant declarations
LOCAL c = 9.143                    ;ceiling height in m
LOCAL h = 6.096                    ;wall height in m
LOCAL t = 2.235                    ;tile wall height in m

;_________________absorbing panels dimensions________________________

LOCAL row1_d = 4.5             ;depth to first row of panels
LOCAL row2_d = 9.118           ;depth to second row of panels
LOCAL row3_d = 13.736          ;depth to third row of panels
LOCAL col1_w = 1.45            ;width to first column of panels
LOCAL col2_w = 5.33            ;width to second column of panels
LOCAL col3_w = 9.22            ;width to third column of panels
LOCAL panel_h = 4.6            ;height to bottom of all panels
LOCAL panel_w = 2.44           ;width of all panels
LOCAL panel_l = 1.22           ;length of all panels
LOCAL panel_d = 0.2            ;depth of all panels
;__________________________________________________________________

GLOBAL w = 26.212                  ;hall width in m
GLOBAL d = 18.236                  ;hall depth in m

;surface declarations
ABS wood               = <21 17 16 13 12 13>
ABS tile               = <7 7 7 7 8 8>
ABS pconcrete          = <16 11 12 13 15 14>
ABS steel              = <11 16 16 16 13 8>
ABS absorb             = <76 93 83 99 99 94>

MIRROR        300        300

CORNERS

;floor corners
1     0       0         0
2     0       d         0
3     w/2     d         0
4     w/2     0         0

;top of tile wall corners
11    0       0         t
12    0       d         t
13    w/2     d         t
14    w/2     0         t

;top of concrete wall corners
15    0       0         h
16    0       d         h
```

```
17      w/2             d               h
18      w/2             0               h

;roof corners
21      0               d/2             c
22      w/2             d/2             c

;divider corners
23      .01             0               h
24      .01             d               h
25      .01             d/2             c
26      0               0               h
27      0               d               h

;panel corners
;panel1
101     col1_w                  row1_d                  panel_h
102     col1_w+panel_w          row1_d                  panel_h
103     col1_w                  row1_d                  panel_h+panel_l
104     col1_w+panel_w          row1_d                  panel_h+panel_l
105     col1_w                  row1_d+panel_d          panel_h
106     col1_w+panel_w          row1_d+panel_d          panel_h
107     col1_w                  row1_d+panel_d          panel_h+panel_l
108     col1_w+panel_w          row1_d+panel_d          panel_h+panel_l

;panel2
109     col3_w                  row1_d                  panel_h
110     col3_w+panel_w          row1_d                  panel_h
111     col3_w                  row1_d                  panel_h+panel_l
112     col3_w+panel_w          row1_d                  panel_h+panel_l
113     col3_w                  row1_d+panel_d          panel_h
114     col3_w+panel_w          row1_d+panel_d          panel_h
115     col3_w                  row1_d+panel_d          panel_h+panel_l
116     col3_w+panel_w          row1_d+panel_d          panel_h+panel_l

;panel3
117     col2_w                  row2_d                  panel_h
118     col2_w+panel_w          row2_d                  panel_h
119     col2_w                  row2_d                  panel_h+panel_l
120     col2_w+panel_w          row2_d                  panel_h+panel_l
121     col2_w                  row2_d+panel_d          panel_h
122     col2_w+panel_w          row2_d+panel_d          panel_h
123     col2_w                  row2_d+panel_d          panel_h+panel_l
124     col2_w+panel_w          row2_d+panel_d          panel_h+panel_l

;panel4
125     col1_w                  row3_d                  panel_h
126     col1_w+panel_w          row3_d                  panel_h
127     col1_w                  row3_d                  panel_h+panel_l
128     col1_w+panel_w          row3_d                  panel_h+panel_l
129     col1_w                  row3_d+panel_d          panel_h
130     col1_w+panel_w          row3_d+panel_d          panel_h
131     col1_w                  row3_d+panel_d          panel_h+panel_l
132     col1_w+panel_w          row3_d+panel_d          panel_h+panel_l
```

```
;panel5
133     col3_w              row3_d              panel_h
134     col3_w+panel_w      row3_d              panel_h
135     col3_w              row3_d              panel_h+panel_l
136     col3_w+panel_w      row3_d              panel_h+panel_l
137     col3_w              row3_d+panel_d      panel_h
138     col3_w+panel_w      row3_d+panel_d      panel_h
139     col3_w              row3_d+panel_d      panel_h+panel_l
140     col3_w+panel_w      row3_d+panel_d      panel_h+panel_l


PLANES
(1      floor               / 4 3 2 1 /                 wood)
(2      bottom stage wall   / 1 11 14 4 /               tile)
(3      top stage wall      / 11 15 18 14 /        pconcrete)
;(4     bottom left wall    / 2 12 11 1 /               tile)
;(5     top left wall       / 12 16 21 15 11 /     pconcrete)
(6      bottom right wall   / 4 14 13 3 /               tile)
(7      top right wall      / 14 18 22 17 13 /     pconcrete)
(8      bottom rear wall    / 3 13 12 2 /               tile)
(9      top rear wall       / 13 17 16 12 /        pconcrete)
(10     roof1               / 15 21 22 18 /            steel)
(11     roof2               / 17 22 21 16 /            steel)
(12     divider1            / 23 24 25 /                wood)
(13     divider2            / 27 24 23 26 /             wood)

;panel planes
(101    panel1_1            / 102 104 103 101 /     absorb)
(102    panel1_2            / 101 103 107 105 /     absorb)
(103    panel1_3            / 105 107 108 106 /     absorb)
(104    panel1_4            / 106 108 104 102 /     absorb)
(105    panel1_5            / 105 106 102 101 /     absorb)
(106    panel1_6            / 103 104 108 107 /     absorb)
(107    panel2_1            / 110 112 111 109 /     absorb)
(108    panel2_2            / 109 111 115 113 /     absorb)
(109    panel2_3            / 113 115 116 114 /     absorb)
(110    panel2_4            / 114 116 112 110 /     absorb)
(111    panel2_5            / 113 114 110 109 /     absorb)
(112    panel2_6            / 111 112 116 115 /     absorb)
(113    panel3_1            / 118 120 119 117 /     absorb)
(114    panel3_2            / 117 119 123 121 /     absorb)
(115    panel3_3            / 121 123 124 122 /     absorb)
(116    panel3_4            / 122 124 120 118 /     absorb)
(117    panel3_5            / 121 122 118 117 /     absorb)
(118    panel3_6            / 119 120 124 123 /     absorb)
(119    panel4_1            / 126 128 127 125 /     absorb)
(120    panel4_2            / 125 127 131 129 /     absorb)
(121    panel4_3            / 129 131 132 130 /     absorb)
(122    panel4_4            / 130 132 128 126 /     absorb)
(123    panel4_5            / 125 129 130 126 /     absorb)
(124    panel4_6            / 127 128 132 131 /     absorb)
(125    panel5_1            / 134 136 135 133 /     absorb)
(126    panel5_2            / 133 135 139 137 /     absorb)
```

(127 panel5_3 / 137 139 140 138 / absorb)
(128 panel5_4 / 138 140 136 134 / absorb)
(129 panel5_5 / 133 137 138 134 / absorb)
(130 panel5_6 / 135 136 140 139 / absorb)

Appendix Q: CATT™ Code for Gym with Acoustic Panels Attached to the Ceiling

```
;ceiling_absorb.geo
;constant declarations
LOCAL c = 9.143                     ;ceiling height in m
LOCAL h = 6.096                     ;wall height in m
LOCAL t = 2.235                     ;tile wall height in m

;________________absorbing panels dimensions____________________

LOCAL row1_d = 1.412                ;depth to first row of panels
LOCAL row2_d = 3.981                ;depth to second row of panels
LOCAL row3_d = 6.549                ;depth to third row of panels
LOCAL row4_d = 10.53                ;depth to fourth row of panels
LOCAL row5_d = 13.099               ;depth to fifth row of panels
LOCAL row6_d = 15.667               ;depth to sixth row of panels
LOCAL col1_w = 1.45                 ;width to first column of panels
LOCAL col2_w = 5.34                 ;width to second column of panels
LOCAL col3_w = 9.23                 ;width to third column of panels
LOCAL row1_1h = 6.542               ;height to front of row1 panels
LOCAL row1_2h = 6.929               ;height to back of row1 panels
LOCAL row2_1h = 7.400               ;height to front of row2 panels
LOCAL row2_2h = 7.787               ;height to back of row2 panels
LOCAL row3_1h = 8.259               ;height to front of row3 panels
LOCAL row3_2h = 8.646               ;height to back of row3 panels
LOCAL panel_w = 2.44                ;width of all panels
LOCAL panel_l = 1.157               ;length of all panels

;____________________________________________________________

GLOBAL w = 26.212                   ;hall width in m
GLOBAL d = 18.236                   ;hall depth in m

;surface declarations
ABS wood                            = <21 17 16 13 12 13>
ABS tile                            = <7 7 7 7 8 8>
ABS pconcrete                       = <16 11 12 13 15 14>
ABS steel                           = <11 16 16 16 13 8>
ABS absorb                          = <76 93 83 99 99 94>

MIRROR          300         300

CORNERS

;floor corners
1     0           0           0
2     0           d           0
3     w/2         d           0
4     w/2         0           0

;top of tile wall corners
11    0           0           t
```

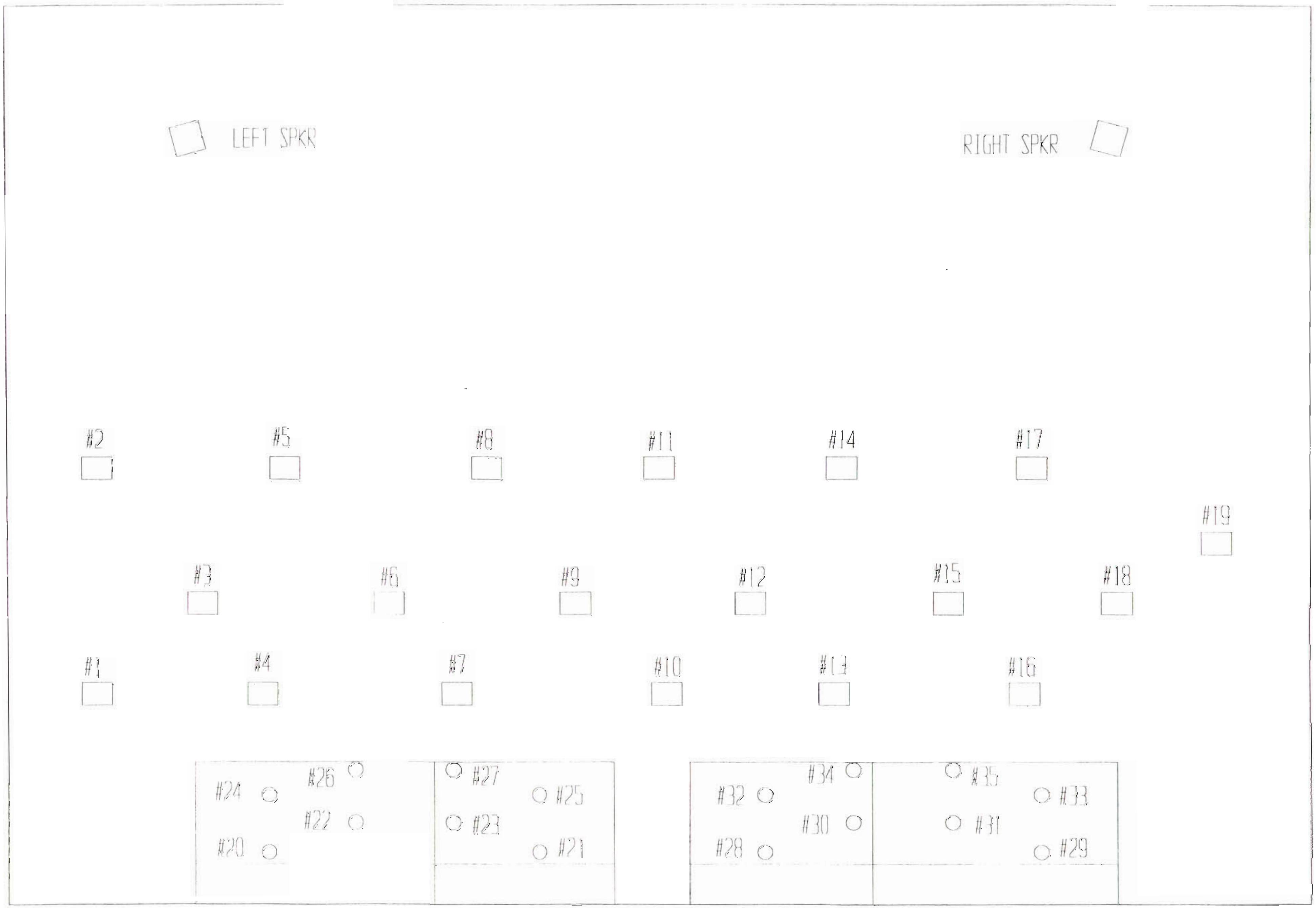
```
12      0                d           t
13      w/2              d           t
14      w/2              0           t

;top of concrete wall corners
15      0                0           h
16      0                d           h
17      w/2              d           h
18      w/2              0           h

;roof corners
21      0                d/2         c
22      w/2              d/2         c

;divider corners
23      .01              0           h
24      .01              d           h
25      .01              d/2         c
26      0                0           h
27      0                d           h

;panel corners
;panel1
101     col1_w           row1_d               row1_1h
102     col1_w+panel_w   row1_d               row1_1h
103     col1_w           row1_d+panel_l       row1_2h
104     col1_w+panel_w   row1_d+panel_l       row1_2h

;panel2
105     col3_w           row1_d               row1_1h
106     col3_w+panel_w   row1_d               row1_1h
107     col3_w           row1_d+panel_l       row1_2h
108     col3_w+panel_w   row1_d+panel_l       row1_2h

;panel3
109     col2_w           row2_d               row2_1h
110     col2_w+panel_w   row2_d               row2_1h
111     col2_w           row2_d+panel_l       row2_2h
112     col2_w+panel_w   row2_d+panel_l       row2_2h

;panel4
113     col1_w           row3_d               row3_1h
114     col1_w+panel_w   row3_d               row3_1h
115     col1_w           row3_d+panel_l       row3_2h
116     col1_w+panel_w   row3_d+panel_l       row3_2h

;panel5
117     col3_w           row3_d               row3_1h
118     col3_w+panel_w   row3_d               row3_1h
119     col3_w           row3_d+panel_l       row3_2h
120     col3_w+panel_w   row3_d+panel_l       row3_2h

;panel6
121     col1_w           row4_d               row3_2h
```

```
122     col1_w+panel_w     row4_d             row3_2h
123     col1_w             row4_d+panel_l     row3_1h
124     col1_w+panel_w     row4_d+panel_l     row3_1h

;panel7
125     col3_w             row4_d             row3_2h
126     col3_w+panel_w     row4_d             row3_2h
127     col3_w             row4_d+panel_l     row3_1h
128     col3_w+panel_w     row4_d+panel_l     row3_1h

;panel8
129     col2_w             row5_d             row2_2h
130     col2_w+panel_w     row5_d             row2_2h
131     col2_w             row5_d+panel_l     row2_1h
132     col2_w+panel_w     row5_d+panel_l     row2_1h

;panel9
133     col1_w             row6_d             row1_2h
134     col1_w+panel_w     row6_d             row1_2h
135     col1_w             row6_d+panel_l     row1_1h
136     col1_w+panel_w     row6_d+panel_l     row1_1h

;panel10
137     col3_w             row6_d             row1_2h
138     col3_w+panel_w     row6_d             row1_2h
139     col3_w             row6_d+panel_l     row1_1h
140     col3_w+panel_w     row6_d+panel_l     row1_1h

PLANES
(1      floor                / 4 3 2 1 /                 wood)
(2      bottom stage wall    / 1 11 14 4 /               tile)
(3      top stage wall       / 11 15 18 14 /        pconcrete)
;(4     bottom left wall     / 2 12 11 1 /               tile)
;(5     top left wall        / 12 16 21 15 11 /     pconcrete)
(6      bottom right wall    / 4 14 13 3 /               tile)
(7      top right wall       / 14 18 22 17 13 /     pconcrete)
(8      bottom rear wall     / 3 13 12 2 /               tile)
(9      top rear wall        / 13 17 16 12 /        pconcrete)
(10     roof1                / 15 21 22 18 /            steel)
(11     roof2                / 17 22 21 16 /            steel)
(12     divider1             / 23 24 25 /                wood)
(13     divider2             / 27 24 23 26 /             wood)

;panel planes
(101    panel1               / 101 103 104 102 /    absorb)
(102    panel2               / 105 107 108 106 /    absorb)
(103    panel3               / 109 111 112 110 /    absorb)
(104    panel4               / 113 115 116 114 /    absorb)
(105    panel5               / 117 119 120 118 /    absorb)
(106    panel6               / 121 123 124 122 /    absorb)
(107    panel7               / 125 127 128 126 /    absorb)
(108    panel8               / 129 131 132 130 /    absorb)
(109    panel9               / 133 135 136 134 /    absorb)
(110    panel10              / 137 139 140 138 /    absorb)
```

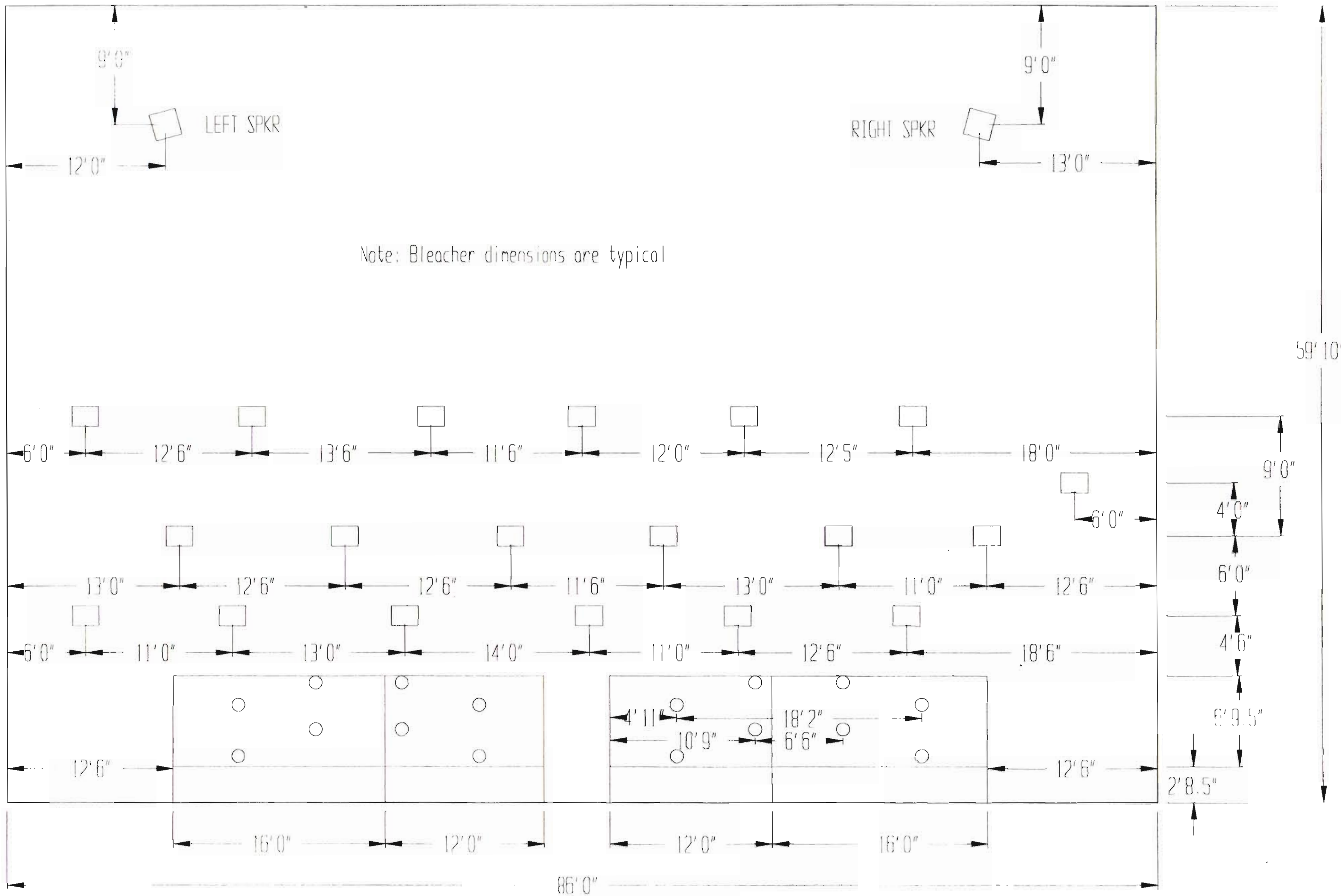
Appendix R: CAD Maps for On-Site Testing

Attached are the following maps, for the speech intelligibility tests and the balloon test:

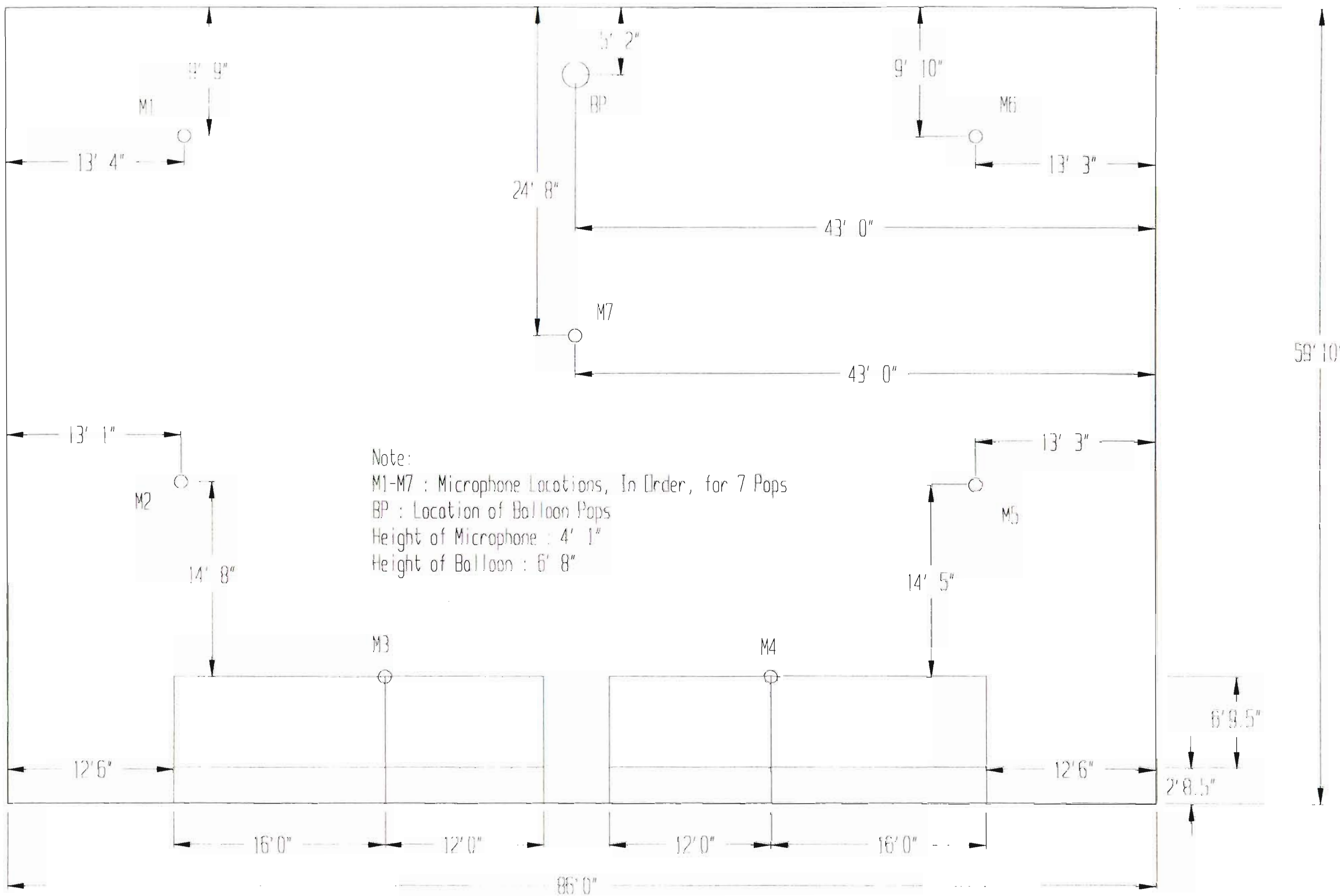
1. Speech Intelligibility Test Seat Map: Seat Numbers
2. Speech Intelligibility Test Seat Map: Dimensions
3. Balloon Test Map: Locations of Balloon Pops and Microphone Placement



Speech Intelligibility Test Seat Map: Seat Numbers



2. Speech Intelligibility Test Seal Map: Dimensions



3 Balloon Test Map: Locations of Balloon Pops and Microphone Placement

Appendix S: Reverberation Time Estimation Curve from Balloon Test

Shown below is an example of an estimation we performed, to determine the reverberation time, T_{60}, from our balloon test results.

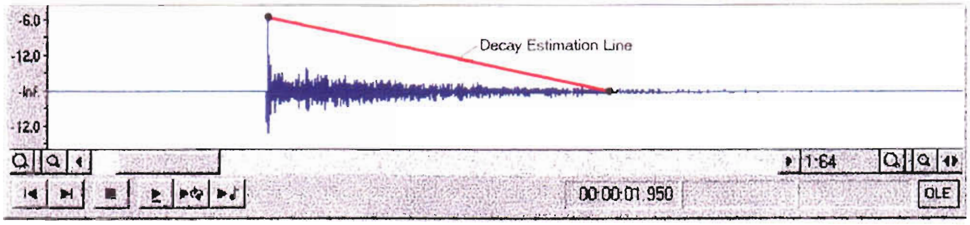


Figure 47: Estimation of Reverberation Time, T_{60}, from Balloon Pop Recording

Using the slope of the Decay Estimation Line shown in Figure 49 we were able to estimate the time it would take for the sound initiated by the balloon pop to decrease by 60 dB. This is the method we used to determine the T_{60} values for all seven balloon pops. This particular example was the first balloon burst, and was estimated as having a T_{60} of 1.70 sec.