A STUDY AND EVALUATION OF THE ACOUSTICS OF MUSIC ROOMS IN THE TUCSON PUBLIC SCHOOLS

by

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CHAPTER I

INTRODUCTION

The Importance of Proper Acoustics

Most public school music teachers at some time during their careers have been confronted with acoustical problems which they knew not how to solve. These acoustical imperfections were obvious; it is not uncommon to hear teachers say that their musical organizations sounded well indoors but not outdoors. The acoustical conditions are very different, and certainly one is more desirable than the other.

Music seems to our trained and untrained ears to have no connection with such scientific things as the compression of air, reflection of sound waves by walls, the sensitivity of hearing, and the absorption of sound. However, a great deal has been added to the science of musical sound since Helmholtz first published his great work on the Sensations of Tone[1] in 1862. The new knowledge, of which not many are aware, has been described often, but mostly by scientists writing for scientists in the technical

1. Hermann L.F. Helmholtz. On the Sensations of Tone as a Physiological Basis for the Theory of Music, p. vi.

language of science. This thesis is not primarily intended for physicists nor architects, but for the musician and his teacher.

The importance to the musician of the acoustic quality of the room in which he rehearses or performs is not disputed, although until the early years of this century not many could say why music sounded well in some rooms while in other rooms it disappointed both listeners and performers. The fundamental fact to be grasped is that the room in which music is played is in reality only an extension of the musical instrument--voice, clarinet, cello, or whatever it may be--and that the tone of the instrument is modified by the characteristics of the room. Just as the original reed tone of the bassoon is modified by the design of the bassoon itself, so the tone of the instrument is modified by the room in which it is played, according to principles which shall be discussed and applied.

Problem of This Study

The problem of this study was to determine the acoustical properties in regard to those rooms in the Tucson Public Schools which are used specifically for music, and on the basis of the findings, to make suggestions and recommendations for acoustical improvements and for future practice.

Limitations of This Study

Various topics usually found in discussion of the acoustics of music are here touched very lightly or even omitted entirely, as having no particular bearing on acoustics of music rooms. Certain other topics are omitted because of their complexity and the incomplete state of research done on them up to date.

Since this investigation was designed for the acoustical study of music rooms as such, it eliminated those classrooms of the school system which are used for academic subjects other than music. This included classrooms of the elementary schools where instructors are responsible for the teaching of all subjects on a particular grade level. For similar reasons all auditoriums, with the exception of one, were not considered.

It was also found that gymnasiums are sometimes used for music rooms, just as clothes and broom closets are occasionally used as a practice room by one or two students. However, these can hardly be assumed to be rooms which are utilized solely for musical purposes.

Related Studies

There have been many studies of acoustics and related subjects previously made in this country and in England. Recently they have come about as an outgrowth of the Acoustical Society of America, the Acoustical Materials

Association, and the Physical Society of London. However Helmholtz, a German physician who became interested in the physiology of the ear in the whole field of sound, Koenig, a scientist and instrument maker in Paris, and Lord Rayleigh, an English mathematician and physicist, contributed much to the early development of acoustics in its musical aspects.[2]

With the advent of radio broadcasting and sound in motion pictures, great stress has been placed on sound production, transmission, and reception. Sound engineers employed by radio and movie studios are still investigating and experimenting for possible improvements and new discoveries.

Considering the wealth of material available in a field which has crystallized sufficiently to make textbooks, laboratory experiments, government employees, acoustical engineers, and teachers of acoustics a necessary part of our society, it is impossible to acknowledge all of the many contributions.

Nevertheless, it should be mentioned that the late Wallace C. Sabine, Professor of Physics at Harvard University, was the first to make a scientific investigation of

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2. Wilmer T. Bartholomew. Acoustics of Music, p. 2.

the problem of the acoustics of music rooms; and although his work has opened up many avenues which have not been completely explored, the main principles have been fully established and it is now a practical possibility to design rooms for music.[3] Many scientists have elaborated on the problem, but all have used Sabine's fundamental principles since his work was published in 1922.[4] His principles will be explained in a later chapter.

Sources of Data

The data for this study were secured from observations and measurements of seven music rooms within the Tucson school system. These are the following: vocal classrooms of Catalina, Dunbar, Mansfeld, Roskruge, and Safford Junior High Schools, and the vocal and instrumental classrooms of Tucson Senior High School. Further data were obtained from available literature of the University of Arizona Library, and from Mr. Richard K. Warren, Tucson representative of the J.B. Matz, Incorporated, of Phoenix, distributors of Celotex Acoustical Products in the State of Arizona. Pertinent information was also learned in consultation with Mr. Ralph H. King, Business Manager of

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3. Alexander Wood. The Physics of Music, p. 220.
4. Wallace C. Sabine. Collected Papers on Acoustics.

the Tucson Public Schools; Mr. Paul B. Conway, Custodian of Supplies, Tucson Public Schools; and Dr. Leon Blitzer, Professor of Physics, University of Arizona. Letters received from Mr. John J. Oberle and from Dr. Hale I. Sabine, both of the Acoustical Department of the Celotex Corporation, also assisted in the writing of this thesis.

CHAPTER II

APPLYING THE ACTION OF SOUND

As a basis to the understanding of the action of sound in music rooms, it was first necessary to study some aspects of the physics of sound. The first part of this chapter will be devoted to a discussion of those facts, and a clarification of terminology.

Origin of Sound

Sound consists of a series of spherical compressions and rarefactions that are generated by a vibrating object and which travel outward in the surrounding medium at a definite speed.[1] Sound waves are set up by any vibrating body, and if their pitch and loudness are within certain ranges, they produce the sensation of hearing. Therefore the physical aspect of sound, as distinguished from the psychological, concerns itself with (1) the source, (2) the transmission, and (3) the detection or reception of sound.

The action of sound waves has often been described as analogous to the waves which arise when a stone is dropped in water, or when a breeze sweeps over a wheat

1. C.W. Glover. Practical Acoustics for the Constructor, p. 8.

field.[2] As each blade of wheat moves back and forth within a restricted space, the gust of wind progresses across the field. In the case of sound, each air particle oscillates about its rest position by means of condensations and rarefactions while the waves which result travel rapidly through the air.

Propagation of Sound

All sound waves travel at an approximate speed of 1,120 feet per second.[3] This speed is the same regardless of the pitch or loudness of the sound.[4] The fact that sound takes time to travel explains why thunder is heard after a flash of lightning is seen.

Cycle and Frequency

Each complete to and fro movement of any vibrating body, starting from its neutral position, moving to one side, then to the other side, and back to neutral, is called a cycle. The number of cycles or complete vibrations per second is termed the frequency, and the frequency determines the pitch. In acoustical work, frequencies are laid out in octaves; and an octave is physically defined as the interval between any two sounds having

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2. Clarence G. Hamilton. Sound and Its Relation to Music, p. 8.
3. Actually, the speed varies slightly with the temperature. The velocity at 70° F. is approximately 1,125 ft. per sec., and at 32° F., 1086 ft. per sec.
4. James Jeans. Science and Music, pp. 116-118.

a frequency ratio of 2:1.[5]

The series of frequencies most commonly used in acoustical measurements were found to be 128, 256, 512, 1024, 2048, and 4096 cycles. These frequencies are used in measuring the absorption coefficients of various building and sound absorbing materials.[6] The frequency 256 cycles is approximately that of middle C, 128 cycles is the C an octave below, and 4096 cycles is four octaves above middle C, the top note of the piano. This series of frequencies covers most of the frequency ranges in music, as may be seen in Figure 1 on page 10.

Action of Various Materials on Sound

When sound waves traveling through a medium encounter another medium with a different density or elasticity, the regular wave pattern is disturbed.[7] Part of the sound energy is thrown back in the form of reflected waves, part is absorbed in the new medium, and part is transmitted, the relative amounts depending on the differences in elasticity and density between the first and second mediums. Watson illustrates these three phenomena in Figure 2 on page 11.[8]

5. John Broadhouse. Musical Acoustics, pp. 82-83, 295.
6. C.W. Glover. op. cit., pp. 366-409.
7. Hope Bagenal. Practical Acoustics and Planning Against Noise, pp. 56-63.
8. Floyd R. Watson. Sound-Proof Partitions, p. 12.

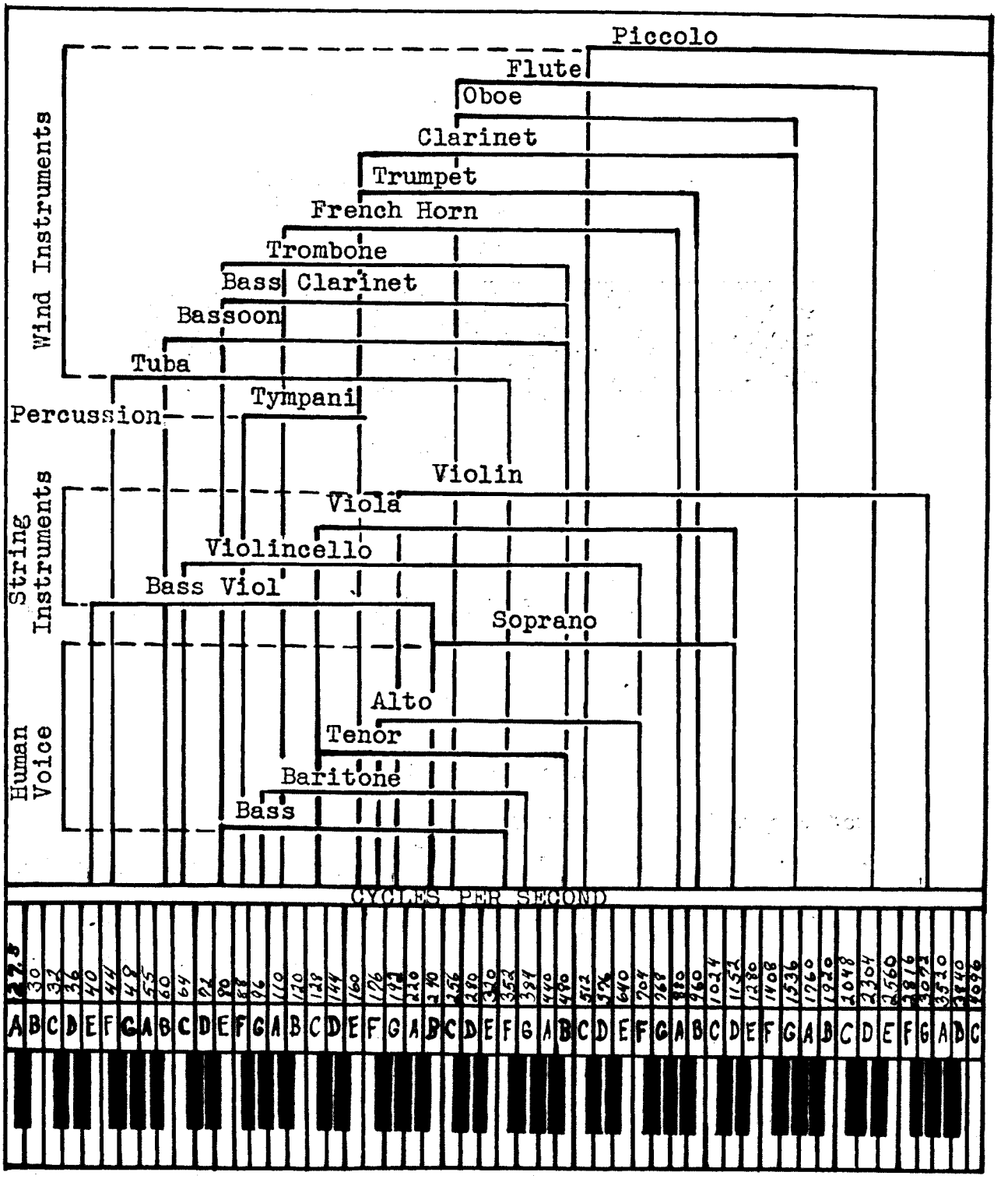

FIGURE 1

COMPASS OF MUSICAL INSTRUMENTS COMPARED WITH PITCHES AND FREQUENCIES OF THE PIANO KEYBOARD

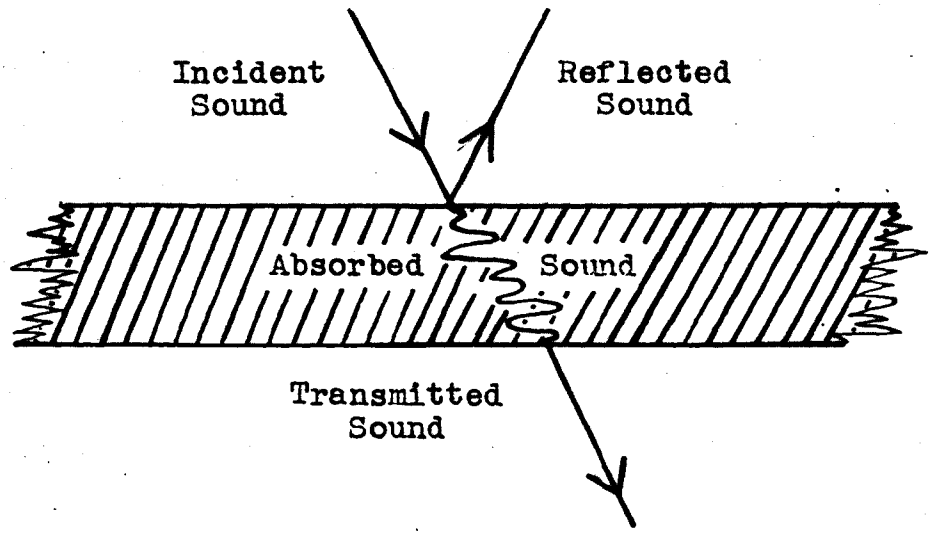

FIGURE 2

REFLECTION, ABSORPTION, AND
TRANSMISSION OF SOUND

Reflection of Sound

If the sound generated in a room meets solid plaster walls of sufficient rigidity, they will suffer almost 100 per cent reflection because of the large change in the elasticity and density between air and solids.[9] If a ventilator opening is encountered, instead of a wall, the waves travel through the air channel with little hindrance since there is no change in the medium. Most of the sound is confined in the ventilation duct by reflection of the metal walls.[10]

9. Floyd R. Watson. Sound, p. 174.
10. Ibid., p. 175.

If sound can be imagined to travel in straight lines or "rays," a single ray is reflected in a way similar to the bouncing of a ball, or the reflection of a ray of light, in both of which the angle of incidence is equal to the angle of reflection.[11] The reflection of sound is never limited to straight lines to the extent that the reflection of light often appears to be. Since sound proceeds through a medium with spherical wave fronts of increasing radius, rather than with "rays," there is necessarily some spreading of sound energy to either side of the angle of reflection.

If sound strikes a relatively large reflecting surface perpendicularly, it will be returned along the same line, and sound striking it obliquely will be reflected at an equal angle to a distant point. This accounts for the effect of an apparent change in the direction of a sound.

Absorption of Sound

Absorption is the weakening of sound waves through incomplete reflection.[12] The fraction of the sound energy which is not reflected, either because of being lost in the material of the reflecting surface or being transmitted through it, is called the "coefficient of

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11. Hope Bagenal. op. cit., p. 73.
12. C.W. Glover. op. cit., pp. 90-93.

absorption."[13] Because materials differ greatly in their ability to absorb sound, the materials of which a room is constructed and furnished are of primary importance in determining the acoustic action of a room.

Air passages which are very minute in cross section will cause much resistance to the movement of vibrating air molecules. When the compression of a sound wave approaches a carpet or other porous media, air is driven into the interstices; when rarefaction follows, air surges out of the pores. This friction converts part of the sound energy into heat energy, thereby absorbing it.[14] The absorption of sound is therefore an essential factor in the solution of sound insulation. It is not sufficient to reflect and scatter sound waves, for the energy cannot be destroyed in this manner; it must be absorbed, that is, transformed by friction into heat energy. For this reason, acoustical materials are effective in the acoustic correction of exceptionally reverberant rooms.

Intensity Scale and Decibels

The manner in which the human ear responds to sounds of various frequencies and intensities and changes them respectively into psychological sensations of pitch and

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13. C.W. Glover. op. cit., pp. 90-93.
14. Hope Bagenal. op. cit., p. 222.

loudness is quite complicated. Two sounds of identical intensity but of different frequencies do not necessarily sound equally loud, nor does one sound with double the intensity of another sound appear twice as loud. The Weber-Fechner law, a psychological rule, states that equal increments of sensation are associated with equal ratios, or equal increments of the logarithm of the stimulus.[15] Thus the human ear responds approximately logarithmically to the physical energy in a sound wave.

Because of this a unit of loudness, measured on a logarithmic scale, has become standard practice in acoustical work; this unit is called the decibel.[16] The decibel is approximately equal to the smallest change in loudness that is perceptible to the average listener.

Reverberation Time

The length of time that a sound continues to be heard in a room, through reflections, after its source has stopped sounding, is called the reverberation time of the room. An arbitrary definition has been given as "the time required for a sound to fall down sixty decibel steps...," or in other words, for the intensity level to decrease by sixty decibels, a millionth of its original value.[17]

15. Charles A. Culver. Musical Acoustics, p. 28.
16. John Mills. A Fugue in Cycles and Bels, pp. 32-39.
17. Ibid., p. 162.

A certain amount of reverberation was found as desirable[18] in order to increase the sound energy in a room. Just what should be the correct reverberation time for a music room is a matter of musical taste and judgment and of tradition. For example, habit and tradition associate organ music with churches and cathedrals where reverberation is very pronounced. As Mills says:

> "A string quartette or a vocal soloist is at a disadvantage when there is no reverberation. On the other hand, whether by tradition or otherwise, a band seems more mellow in the open air where its sounds are quickly dissipated and only the direct sound reaches the listener."[19]

He further states that musicians have made little effort to correlate their judgments with physical quantities so that better music rooms can be constructed according to a scientific basis.

Nevertheless it was Sabine who, in 1902 through a series of experiments at the New England Conservatory of Music, learned that musical taste was remarkably sensitive and accurate.[20] This surprising accuracy is perhaps the explanation of the rarity with which it is entirely satisfied, particularly when acoustics are left to chance.

The present tendency is toward shorter reverberation times than were apparently accepted or tolerated a

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18. Wilmer T. Bartholomew. op. cit., p. 69.
19. John Mills. op. cit., p. 166.
20. Wallace C. Sabine. op. cit., pp. 71-77.

generation or two ago. Dr. Hale J. Sabine, Chief Acoustical Engineer of the Celotex Corporation, reports that as an indication of experience, or what might be called "musical taste," reverberation times of .75 to 1.2 seconds for the empty room give best results for rooms in which bands and orchestras rehearse.[21] Likewise, choral rooms with no occupants may have reverberation times of 1.0 to 1.5 seconds.[22]

In a personal letter written by Dr. Hale J. Sabine to the investigator on April 11, 1947, he stated that the above figures "indicate general practice in the treatment of typical rehearsal rooms of various sizes." He continued:

> "The lower limit corresponds roughly to the point where further reduction of reverberation time would not be economically justified by the large amounts of acoustical treatment required. The upper limit is about the point where reverberation is definitely noticeable as such in a room. In other words, it is about the point where a room begins to sound alive rather than dead."

A very reverberant room may be compared to a piano which is played with the sustaining pedal kept down. The result is not only louder, but also badly blurred.

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21. Hale J. Sabine. Less Noise, Better Hearing, p. 60.
22. Loc. cit.

Analyzing Desirable Acoustics in Terms of Psychological and Physical Factors

In rooms for band, orchestra, or chorus, satisfactory acoustical conditions are essential for effective instruction. The director must be able to hear distinctly the individual instruments or voices in order to locate and correct mistakes. At the same time, in order for each student to benefit by the instruction, he must be able to hear his own tones easily above the rest of the group. These conditions are difficult or impossible of attainment in an excessively reverberant room. In the case of band rehearsals, furthermore, where the percussion section is often so prominently employed, the volume of sound in a small, non-absorbent room may frequently build up to a deafening level.

The introduction of acoustical treatment in a music room would produce two advantageous and simultaneous effects, (1) a reduction of reverberation and (2) a reduction in the average intensity of sound in a room. However, the amount of acoustical application is not a matter of chance, but must be governed by the existing reverberation time and the amount of absorbent material already present. It is necessary, therefore, to establish criteria for the erection of acoustical products. By this measure it will be possible to determine (1) the type of material, and (2) the amount of material to be used in order to make the

proper correction of reverberation time.

Measuring Total Absorption

As a pioneer in the field of architectural acoustics, Wallace C. Sabine was able to determine the absorbing power of various substances.[23] The experiments were begun in a lecture room of Harvard University where he found the reverberation time to be excessively high, 5.5 seconds. His methods are well described in his Collected Papers on Acoustics.[24] Without going into a lengthy discussion of the details, it may be said that his tests were so perfected as to give not merely relative, but absolute coefficients of absorption.[25]

An open window of one square foot area is equivalent to one sound absorbing unit, because all the sound which falls on the space of an open window passes out of the room and therefore, so far as the room is concerned, it is completely absorbed.[26] The coefficients of individual materials are found by determining the area of open window space which is equivalent in absorptive power to a square foot of curtain, plaster, wood, or whatever the object might be.[27] The total absorption of the material in a

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23. Floyd R. Watson. Acoustics of Buildings, pp. 27-30.
24. W.C. Sabine. op. cit., pp. 219-236.
25. Ibid., p. 223.
26. John Mills. op. cit., pp. 163-164.
27. George W. Stewart and Robert B. Lindsay, Acoustics, p. 300.

room is obtained in "open window units" (OWU) by multiplying the coefficient of absorption by the area.

Since Sabine's work with absorption was first known, many others have followed his methods of determining absorption coefficients of new building supplies, and particularly commercial acoustical materials. The measurement of sound absorption coefficients is now carried out almost universally by the reverberation method.[28] This method involves the measurement of the reverberation time of a calibrated test chamber before and after the introduction into the room of a given area of the material under test. The change in the absorbing power of the room, determined by the measured change in reverberation, enables the coefficient of absorption of the material to be calculated.

Various authorities have tested the sound absorbing qualities of a large number of materials.[29] The coefficient of absorption at the frequency 512 cycles is normally used as a basis for comparison with other materials.[30] Some of the most common materials and objects usually found in music rooms and their absorption coefficients are

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28. G.W. Stewart and R.B. Lindsay. op. cit., p. 293.
29. Some of these are: W.C. Sabine, P.E. Sabine, N.O. Knudsen, F.R. Watson, The National Bureau of Standards, and The Acoustical Materials Association.
30. C.W. Glover. op. cit., p. 90.

recorded in the following table.[31] (Table I, page 21.)

There are a great number of acoustical materials commercially on the market, the surface of which may be decorated without destroying their absorbing property; a number of them are also fireproof.[32] The market for acoustical materials has become so widely diversified that no single product can ideally meet all requirements.

The Acoustical Materials Association annually publishes a bulletin which includes the figures of specification tests for all acoustical products.[33] Mr. John J. Oberle, a staff member of the Celotex Corporation's Acoustical Department, sent the writer a letter on March 4, 1947, to which he attached the most recent copy of this bulletin.

Tables II, III, IV, V, VI, and VII, shown on pages 22-27, list the coefficients of some acoustical products which are manufactured in this country and which are available for installation at the present time. The materials were selected from a great number given in the bulletin as the only materials which are suitable for music room sound conditioning.

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31. C.W. Glover. op. cit., pp. 366-409.
32. Loc. cit.
33. Hale J. Sabine. op. cit., p. 15.

TABLE I

SOUND ABSORPTION COEFFICIENTS FOR FREQUENCY 512 CYCLES OF SOME MATERIALS AND INDIVIDUAL OBJECTS COMMONLY FOUND IN MUSIC ROOMS

Material	Coefficients per sq. ft.
Open window as basis for comparison	1.00
Asphalt tile	0.05
Brick wall, painted	0.017
Brick wall, unpainted	0.032
Carpet, lined	0.20
Carpet, unlined	0.15
Carpet rugs	0.20
Fabrics, light, 10 ozs. per sq.yd. hung straight	0.11
Fabrics, medium, 14 ozs. per sq.yd. hung straight	0.13
Fabrics, heavy, 18 ozs. per sq.yd. in heavy folds	0.50
Glass, single thickness	0.027
Linoleum	0.03
Marble	0.01
Plaster on metal lath	0.033
Plaster on wood lath	0.034
Plaster, acoustical	0.40
Stage opening, depending on stage furnishings	0.25-0.40
Ventilator opening	0.75
Wood paneling	0.06
Wood, plain	0.06
Wood, varnished	0.05
Chairs, metal or wood, not upholstered	0.17
Chairs, wood veneer seat and desk	0.25
Person, adult	4.70
Person, child, high school	3.80
Person, child, junior high school	3.50

TABLE II

SOUND ABSORPTION COEFFICIENTS AND SPECIFICATIONS FOR FREQUENCY 512 CYCLES OF ARMSTRONG ACOUSTICAL PRODUCTS NOW AVAILABLE FOR SOUND CONDITIONING OF MUSIC ROOMS

ARMSTRONG CORK COMPANY

Material	Thickness	Mounting*	Coefficient	Unit size tested	Color	Light reflection	Surface
Corkoustic							
B-5	1 1/2"	1	.72	12"x12"	White	.79	Fissured, painted
B-5	1 1/2"	2	.70	12"x12"	White	.79	Same as above
Cushiontone							
A-1	1/2"	1	.56	12"x12"	Ivory	.73	Perforated, painted**
A-1	1/2"	2	.55	12"x12"	Ivory	.73	Same as above
A-2	5/8"	1	.60	12"x12"	Ivory	.73	Same as above except holes 1/2" deep
A-2	5/8"	2	.55	12"x12"	Ivory	.73	Same as above
A-3	7/8"	1	.74	12"x12"	Ivory	.73	Same as above except holes 3/4" deep
A-3	7/8"	2	.73	12"x12"	Ivory	.73	Same as above
Mineral wool	3/4"	1	.72	12"x12"	Ivory	.73	Fissured, painted
Mineral wool	3/4"	1	.55	12"x12"	Ivory	.73	Perforated, painted***

*Types of mounting:
1. Cemented to plaster board; equivalent to cementing to plaster ceiling.
2. Nailed to 1" x 2" wood furring, 12" on center.

**Perforated 484 holes per sq.ft., 3/16" diam., 7/16" deep; painted two coats.

***Perforated 484 holes per sq.ft., 5/32" diam., 5/8" deep.

TABLE III

SOUND ABSORPTION COEFFICIENTS AND SPECIFICATIONS FOR FREQUENCY 512 CYCLES OF CELOTEX ACOUSTICAL PRODUCTS NOW AVAILABLE FOR SOUND CONDITIONING OF MUSIC ROOMS

THE CELOTEX CORPORATION

Material	Thick-ness	Mount-ing*	Coeffi-cient	Unit size tested	Color	Light reflec-tion	Surface
Acousti-Celotex							
C-4	1 1/4"	1	.99	12"x12"	Ivory	.78	Perforated,painted**
C-4	1 1/4"	2	.99	12"x12"	Ivory	.78	Same as above
C-6	1 1/4"	1	.99	12"x12"	White	.76	Perforated,painted***
C-6	1 1/4"	2	.91	12"x12"	White	.76	Same as above
C-8	1"	2	.69	24"x24"	White	.81	Perforated,painted**
C-9	3/4"	1	.80	12"x12"	Ivory	.78	Same as above
C-9	3/4"	2	.79	12"x12"	Ivory	.78	Same as above
M-1	5/8"	1	.64	12"x12"	White	.80	Perforated,painted****
M-1	5/8"	2	.50	12"x12"	White	.80	Same as above
M-2	1"	1	.92	12"x12"	White	.80	Same as above
Muffeltone							
Standard	1"	1	.74	12"x12"	---	---	Integrally colored
Fissured	1"	1	.83	12"x12"	---	---	Same as above

*See Table II, p. 22.
**Perforated 441 holes per sq.ft., 3/16" in diam., 17/32" on center.
***Perforated 441 holes per sq.ft., 1/4" in diam., 17/32" on center.
****Perforated 676 holes per sq.ft., 5/32" in diam., 7/16" on center.

TABLE IV

SOUND ABSORPTION COEFFICIENTS AND SPECIFICATIONS FOR FREQUENCY 512 CYCLES OF JOHNS-MANVILLE ACOUSTICAL PRODUCTS NOW AVAILABLE FOR SOUND CONDITIONING OF MUSIC ROOMS

JOHNS-MANVILLE SALES CORPORATION

Material	Thick-ness	Mount-ing*	Coeffi-cient	Unit size tested	Color	Light reflec-tion	Surface
Fibracoustic	1"	2	.83	12"x12"	White	.58	Painted
Fibracoustic	1"	2	.72	12"x12"	White	.58	Painted
Fibretex	13/16"	1	.63	12"x12"	White	.68	Slotted,painted**
Fibretex	13/16"	2	.56	12"x12"	White	.68	Same as above
Fibretone	1/2"	1	.52	12"x12"	White	.71	Perforated,painted***
Fibretone	13/16"	1	.80	12"x12"	White	.71	Same as above
Fibretone	13/16"	2	.72	12"x12"	White	.71	Same as above

*See Table II, p. 22.
**Slotted at 1" intervals, vertically and horizontally. Slots are 1/8" wide.
***Holes are 3/16" in diam., 3/8" deep; 484 per sq. ft.

TABLE V

SOUND ABSORPTION COEFFICIENTS AND SPECIFICATIONS FOR FREQUENCY 512 CYCLES OF NATIONAL GYPSUM ACOUSTICAL PRODUCTS NOW AVAILABLE FOR SOUND CONDITIONING OF MUSIC ROOMS

NATIONAL GYPSUM COMPANY							
Material	Thick-ness	Mount-ing*	Coeffi-cient	Unit size tested	Color	Light reflec-tion	Surface
Acoustic 40R	3/4"	2	.59	12"x12"	---	---	Painted
Acoustifibre	5/8"	1	.62	12"x12"	---	---	Painted, perforated**
Acoustifibre	5/8"	2	.72	12"x12"	---	---	Same as above
Econacoustic	1/2"	1	.62	12"x12"	---	---	Painted
Econacoustic	1/2"	2	.75	12"x12"	---	---	Painted
Econacoustic	1"	1	.80	12"x12"	---	---	Painted

*See Table II, p. 22.
**Perforated with holes 3/16" in diam., 6/16" deep, 441 per sq. ft.

TABLE VI

SOUND ABSORPTION COEFFICIENTS AND SPECIFICATIONS FOR FREQUENCY 512 CYCLES OF OWENS-CORNING ACOUSTICAL PRODUCTS NOW AVAILABLE FOR SOUND CONDITIONING OF MUSIC ROOMS

OWENS-CORNING FIBERGLASS CORPORATION

Material	Thick-ness	Mount-ing*	Coeffi-cient	Unit size tested	Color	Light reflec-tion	Surface
Fiberglass Acoustical Tile							
A	3/4"	1	.72	12"x12"	White	.80	Painted, fiber and mineral
A	3/4"	2	.79	12"x12"	White	.80	Same as above
A	1"	1	.85	12"x12"	White	.80	Same as above
A	1"	2	.91	12"x12"	White	.80	Same as above

*See Table II, p. 22.

TABLE VII

SOUND ABSORPTION COEFFICIENTS AND SPECIFICATIONS FOR FREQUENCY 512 CYCLES OF UNITED STATES GYPSUM ACOUSTICAL PRODUCTS NOW AVAILABLE FOR SOUND CONDITIONING OF MUSIC ROOMS

UNITED STATES GYPSUM COMPANY

Material	Thickness	Mounting*	Coefficient	Unit size tested	Color	Light reflection	Surface
Acoustone							
F	11/16"	1	.76	12"x12"	White	.80	Fissured, painted
F	13/16"	1	.85	12"x12"	White	.80	Same as above
Auditone							
B	1"	1	.79	12"x12"	White	.74	Slotted, painted
B	1"	2	.64	12"x24"	White	.74	Same as above
Auditone							
C	3/4"	1	.68	12"x12"	White	.72	Slotted, painted
C	3/4"	2	.60	12"x24"	White	.72	Same as above

*See Table II, p. 22.

The total absorption of an empty room may be easily determined by utilizing the figures given in the previous tables. The area of each material is multiplied by its coefficient; to the sum of these figures, 50 units are added. These miscellaneous units include the small amount of absorption of office-type desks, pianos, blackboards, and articles which may not be readily apparent but which are "almost always present in a room and which should be allowed for in calculations."[34] The sum total, given in "open window units," will be the total absorption of the empty room.

Measuring Reverberation Time of a Room

Bearing in mind that sound waves, both direct and reflected, travel at a fixed speed and that they lose energy only by absorption, it is apparent that (1) the longer the average distance between reflections, the more slowly will the sound be absorbed, and (2) the greater the average absorption coefficient and the larger the area of the room surfaces, the more rapidly will the sound become inaudible. These two factors can be reduced, respectively, to the volume of the room, "V," and the total absorption in the room, "a," which are related to the reverberation time,

34. Hale J. Sabine. op. cit., p. 51.

"T," by the simple formula:

$$T = \frac{.05V}{a}$$

This is known as the Sabine formula, which was derived by Wallace C. Sabine from the results of a carefully controlled investigation which he carried out at the beginning of the century.[35]

The same formula has subsequently been derived by others from a purely theoretical approach.[36] The formula implies that (1) the reverberation time measured in seconds is a basic acoustical characteristic of a room, and depends only on the volume and on the total absorption of the room, and not on the position of either the source or the observer; and that (2) if the reverberation time is lowered by introducing additional sound absorbing materials into the room, the amount of reduction will be determined only by the number of sound absorbing units introduced and not by the area, coefficient, location, or method of distributing the absorptive materials. The accuracy with which these predictions are realized in actual cases depends on how closely the conditions in an individual room approach the theoretical assumptions and the experimental conditions on which the formula is based. Fortunately, this

35. Floyd R. Watson. Acoustics of Buildings, pp. 27-28.
36. Harry F. Olson and Frank Massa, Applied Acoustics, pp. 352-356.

agreement is sufficiently close in the majority of cases that the Sabine formula may be used to calculate the reverberation time of rooms with satisfactory accuracy.[37]

In view of the above factors, it may be seen that the formula may not only be applied to the correction of rooms, but also the formula serves to determine the acoustical efficiency of a room in advance of construction. An architect's plans and specifications will provide the figures for calculating the volume and, from the area and absorption coefficient of each material used, the total absorption may be obtained. Therefore the reverberation time becomes a simple mathematical calculation; and if adjustments are necessary, they can be made on the drawings instead of on the completed building.

The use of the Sabine formula is further justified since reverberation is a fundamental acoustical property of the room and does not depend on any human element. This eliminates any possible inaccuracies which are sure to result if the duration of a sound is also dependent on the power of a sound source, the hearing acuteness of the particular observer, and on the deafening effect of whatever extraneous noise happens to be present at the time of testing.

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37. C.A. Culver. op. cit., p. 180.

Summary of Criteria for the Installation of Acoustical Materials

Band and orchestra rooms as well as rooms which are used for vocal music were shown to have acceptable reverberation times of .75 to 1.2 seconds and 1.0 to 1.5 seconds, respectively, for the empty rooms. It was further shown that the preferred reverberation times are indicated by experience, and that these reverberation times have proven their validity through the remarkable sensitivity and accuracy of musical taste.

It is evident, therefore, that by measuring the reverberation time of a given music room, having previously calculated the volume of the room and the total absorption present, it is possible to determine whether or not the room is properly reverberant. If the room is excessively reverberant, acoustical materials should be added; if the room is too absorptive, reflective surfaces should be introduced. If the measured reverberation time falls within the acceptable limits, no further acoustical treatment is necessary.

CHAPTER III

THE ACOUSTICAL ANALYSIS OF MUSIC ROOMS IN THE TUCSON PUBLIC SCHOOLS

Method of Analysis

Seven of the Tucson Public Schools which have rooms used specifically for music classes were selected for acoustical analysis. In order to illustrate the principles discussed thus far, the auditorium of the Catalina Junior High School will serve as an example of the method used in determining the acoustical efficiency of the respective seven rooms.

This room is a comparatively small auditorium, and serves as the only music room in the school. Because of the small stage the auditorium proper is used as the classroom. The room is rectangular in shape; the floor is of linoleum; the walls and ceiling are of plaster on metal (or wire) lath; the stage is furnished with a heavy velours curtain; and the 250 seats are made of metal and are collapsible.

The measurements of the room are: length, 65 feet; width, 40 feet; and height, 14 feet. From these figures the volume of the room, inclusive of the stage, is calculated to be 36,400 cubic feet. (In the case of a small

stage, the volume and absorption of the stage are included with that of the auditorium proper.)[1]

The next step after determining the materials of the interior surfaces and the volume was to determine the total absorption in the empty room. The total number of "open window units" is an important factor, since it must be known in order to use the Sabine formula. This was done by multiplying the area of each material by its coefficient, as follows:[2]

Chairs, metal, collapsible.....	250	sq.ft. at	.17	= 42.5	units
Curtain, velours, in heavy folds.....	207	" "	.5	= 103.5	"
Floor, linoleum.....	2000	" "	.03	= 60	"
Glass.....	205	" "	.027	= 5.535	"
Plaster on metal lath...	4679	" "	.033	= 154.407	"
Wood, varnished.....	461	" "	.05	= 23.05	"
Miscellaneous				= 50	"

Total absorption in empty room..... 438.992 units

The coefficients shown in this tabulation have been taken from Table I. It will be noted that the absorption of chairs is not figured on a square foot basis, but is given as .25 units per seat.

Using the Sabine formula, $T = \frac{.05V}{a}$, it is now possible to calculate the reverberation time of the empty room.

$$T = \frac{.05 \times 36{,}400 \text{ cubic feet}}{439 \text{ OWU}} = \frac{1820}{439} = 4.1 \text{ seconds}$$

1. Hale J. Sabine. op. cit., p. 15.
2. See Table I, p. 21.

Since the auditorium is used as a classroom for vocal music, and bearing in mind that the acceptable reverberation time is between 1.0 and 1.5 seconds, it will be seen that the reverberation time is excessively long. It is advisable, therefore, to install enough acoustical treatment so that the reverberation will fall within the proper limits. By selecting a time in the middle of the range, 1.3 seconds, the absorption units required to produce this time may now be determined.

The Sabine formula has been given as $T = \frac{.05V}{a}$, but it may be written as $a = \frac{.05V}{T}$.

If for "T" the acceptable average reverberation time be substituted, the required number of absorption units may be calculated as follows:

$$a = \frac{1820}{1.3} = 1400 \text{ units.}$$

Through a previous calculation it was found that the absorption already present in the empty room is approximately 439 units. Subtracting this from the number required for acceptable acoustical conditions, 1400 units, the result shows that 961 additional units are needed in the form of acoustical treatment.

Using this method of analysis for the remaining six music rooms, the respective acoustical characteristics are compiled in the following tables. The acoustical analysis

of the Catalina Junior High School (which was used as the example of the method of analysis) will also be tabulated as a basis for comparison. The dimensions given were obtained with the use of a measuring tape.

In summarizing the acoustical efficiency of the seven music rooms which were analyzed, two tables were prepared. In Table XV (page 43) the respective reverberation times now present are compared with the theoretical reverberation times. It should be noted that Catalina, Dunbar, Mansfeld, Roskruge, and Safford Junior High Schools have reverberation in excess of the average desired time; and that the vocal and instrumental classrooms of Tucson Senior High School have reverberation times below the lower limit of accceptability. Since the instrumental music room of the Senior High School has a reverberation time which is deficient by only .01 seconds, an acoustical correction would not appreciably affect the final acoustical results.[3]

A correlation of the respective absorption units is presented in Table XVI (page 44). The five Junior High Schools are shown to be in need of comparatively large amounts of absorptive units; and it is further apparent that the vocal room of Tucson Senior High School contains an excess absorption of approximately two-thirds above the amount required.

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3. Hale J. Sabine. op. cit., p. 52.

TABLE VIII

ACOUSTICAL ANALYSIS OF THE VOCAL MUSIC ROOM OF CATALINA JUNIOR HIGH SCHOOL

Dimensions in sq. ft.	65 x 40 x 14
Volume in cu. ft.	36,400

Materials	Area	Coefficient*	Absorption in OWU
Chairs, metal, collapsible	250	.17	42.5
Curtain, velours in heavy folds	207 sq.ft.	.5	103.5
Floor, linoleum	2,000 sq.ft.	.03	60.0
Glass	205 sq.ft.	.027	5.535
Plaster on metal lath	4,679 sq.ft.	.033	154.407
Wood, varnished	461 sq.ft.	.05	23.05
Miscellaneous			50.0
Total absorption in OWU			438.992

Measured reverberation time	4.1 seconds
Acceptable reverberation time	1.0 to 1.5 seconds
Required OWU for average acceptable reverberation time	1,400 units
Additional OWU needed	961 units

*Coefficients are taken from Table I, p. 21.

TABLE IX

ACOUSTICAL ANALYSIS OF THE VOCAL MUSIC ROOM OF DUNBAR JUNIOR HIGH SCHOOL

Dimensions in sq. ft.	57 x 30 x 12
Volume in cu. ft.	20,520

Materials	Area	Coefficient*	Absorption in OWU
Chairs, desk type	54	.25	13.5
Floor, linoleum	1,703 sq.ft.	.03	51.09
Glass	162 sq.ft.	.027	4.374
Plaster on wood lath	3,791 sq.ft.	.034	128.894
Wood, varnished	24½ sq.ft.	.05	1.225
Miscellaneous			50.0
Total absorption in OWU			249.083

Measured reverberation time	4.1 seconds
Acceptable reverberation time	1.0 to 1.5 seconds
Required OWU for average acceptable reverberation time	789 units
Additional OWU needed	540 units

*Coefficients are taken from Table I, p. 21.

TABLE X

ACOUSTICAL ANALYSIS OF THE VOCAL MUSIC ROOM OF MANSFELD JUNIOR HIGH SCHOOL

Dimensions in sq. ft.	30.75 x 30 x 12.5
Volume in cu. ft.	11,532

Materials	Area	Coefficient*	Absorption in OWU
Chairs, desk type	50	.25	12.5
Floor, linoleum	922½ sq.ft.	.03	27.675
Glass	151 sq.ft.	.027	4.077
Plaster on wire lath	2,359 sq.ft.	.033	77.847
Wood, varnished	70½ sq.ft.	.05	3.525
Miscellaneous			50.0
Total absorption in OWU			175.624

Measured reverberation time	3.27 seconds
Acceptable reverberation time	1.0 to 1.5 seconds
Required OWU for average acceptable reverberation time	444 units
Additional OWU needed	268 units

*Coefficients are taken from Table I, p. 21.

TABLE XI

ACOUSTICAL ANALYSIS OF THE VOCAL MUSIC ROOM OF ROSKRUGE JUNIOR HIGH SCHOOL

Dimensions in sq. ft.	28 x 23 x 12
Volume in cu. ft.	7,728

Materials	Area	Coefficient*	Absorption in OWU
Chairs, desk type	40	.25	10.0
Floor, asphalt tile	644 sq.ft.	.05	32.2
Glass	72 sq.ft.	.027	1.944
Plaster on wood lath	1142 sq.ft.	.034	38.828
Wood, varnished	10 sq.ft.	.05	.50
Miscellaneous			50.0
Total absorption in OWU			133.472

Measured reverberation time	2.9 seconds
Acceptable reverberation time	1.0 to 1.5 seconds
Required OWU for average acceptable reverberation time	297 units
Additional OWU needed	164 units

*Coefficients are taken from Table I, p. 21.

TABLE XII

ACOUSTICAL ANALYSIS OF THE VOCAL MUSIC ROOM OF SAFFORD JUNIOR HIGH SCHOOL

Dimensions in sq. ft.	53½ x 33 x 12
Volume in cu. ft.	21,186

Materials	Area	Coefficient*	Absorption in OWU
Chairs, desk type	63	.25	15.75
Floor, linoleum	1,436 sq.ft.	.03	43.08
Glass	261 sq.ft.	.027	7.047
Plaster on wood lath	2,561 sq.ft.	.034	87.074
Ventilator opening	12 sq.ft.	.75	9.0
Wood paneling	220 sq.ft.	.06	13.2
Wood, varnished	403 sq.ft.	.05	20.15
Miscellaneous			50.0
Total absorption in OWU			245.301

Measured reverberation time	4.3 seconds
Acceptable reverberation time	1.0 to 1.5 seconds
Required OWU for average acceptable reverberation time	815 units
Additional OWU needed	570 units

*Coefficients are taken from Table I, p. 21.

TABLE XIII

ACOUSTICAL ANALYSIS OF THE VOCAL MUSIC ROOM OF TUCSON SENIOR HIGH SCHOOL

Dimensions in sq. ft.	42½ x 25 x 14
Volume in cu. ft.	14,875

Materials	Area	Coefficient*	Absorption in OWU
Chairs	60	.17	10.2
Floor, linoleum	1,016½ sq.ft.	.03	30.495
Glass	147 sq.ft.	.027	3.969
Plaster, acoustical	2,850 sq.ft.	.4	1,140.0
Wood, varnished	285 sq.ft.	.05	14.25
Miscellaneous			50.0
Total absorption in OWU			1,248.914

Measured reverberation time	.59 seconds
Acceptable reverberation time	1.0 to 1.5 seconds
Required OWU for minimum acceptable reverberation time**	744 units
Fewer OWU needed	505 units

* Coefficients are taken from Table I, p. 21.
** Economy justifies use of minimum rather than average acceptable reverberation time.

TABLE XIV

ACOUSTICAL ANALYSIS OF INSTRUMENTAL MUSIC ROOM OF TUCSON SENIOR HIGH SCHOOL

Dimensions in sq. ft.	50 x 36 x 14
Volume in cu. ft.	25,200

Materials	Area	Coefficient*	Absorption in OWU
Chairs	75	.17	12.75
Floor linoleum	1,800 sq.ft.	.03	54.0
Glass	157½ sq.ft.	.027	4.252
Plaster, acoustical	3,932 sq.ft.	.4	1,572.8
Wood, varnished	84 sq.ft.	.05	4.2
Miscellaneous			50.0
Total absorption in OWU			1,698.0

Measured reverberation time	.74 seconds
Acceptable reverberation time	.75 to 1.2 seconds
Required OWU for minimum acceptable reverberation time**	1,680 units
Fewer OWU needed	18 units

* Coefficients are taken from Table I, p. 21.
** Economy justifies use of minimum rather than average acceptable reverberation time.

TABLE XV

EXISTING REVERBERATION TIMES AS COMPARED WITH THE THEORETICAL REVERBERATION TIMES OF SEVEN MUSIC ROOMS

Description		Reverberation time in seconds			
School	Type of room	Existing	Theoretical	Excessive	Deficient
Catalina Junior High	Vocal	4.1	1.3	2.8	---
Dunbar Junior High	Vocal	4.1	1.3	2.8	---
Mansfeld Junior High	Vocal	3.27	1.3	1.97	---
Roskruge Junior High	Vocal	2.9	1.3	1.6	---
Safford Junior High	Vocal	4.3	1.3	3.0	---
Tucson Senior High	Vocal	.59	1.0*	---	.41
Tucson Senior High	Instrumental	.74	.75*	---	.01

* Lower limit of acceptable reverberation time.

TABLE XVI

CORRELATION OF SOUND ABSORPTION UNITS OF SEVEN MUSIC ROOMS SELECTED FOR ACOUSTICAL ANALYSES

Description		Total absorption in OWU		Acoustical treatment necessary	
School	Type	Existing	Required for acceptable average reverberation time	OWU to be added	OWU to be eliminated
Catalina Junior High	Vocal	439	1,400	961	---
Dunbar Junior High	Vocal	249	789	540	---
Mansfeld Junior High	Vocal	176	444	268	---
Roskruge Junior High	Vocal	133	297	164	---
Safford Junior High	Vocal	245	815	570	---
Tucson Senior High	Vocal	1249	744*	---	505
Tucson Senior High	Instrumental	1698	1680*	---	18

* The dictates of economy necessitate a computation on the basis of the minimum acceptable reverberation time.

Location and Distribution of Acoustical Materials

In Chapter II it was shown that through the use of the Sabine formula the change in the reverberation time produced by the introduction of a given number of sound absorption units in the form of acoustical treatment should be the same regardless of the location or distribution of the material. Furthermore, the change in reverberation time should be the same whether the added absorption is supplied by a small area of high absorption efficiency or by a larger area of less efficient materials. This permits considerable flexibility in adapting acoustical treatment to the architectural design of a room.

The choice of location of the necessary treatment will be governed to a considerable extent by the areas which are available for treatment. From the architectural point of view, the ceiling is generally the most suitable surface for the application of acoustical materials.

Although accurate retail prices of acoustical products were not available, it was learned that the cost of installation usually is proportional to the thickness of absorptive materials. On the basis of a thousand square feet, the prices range from approximately thirty-eight to forty-two cents per square foot. The figures given in Table XVII were obtained from Mr. Richard K. Warren, Tucson representative of the J.B. Matz, Incorporated.

TABLE XVII

APPROXIMATE COST OF ACOUSTICAL INSTALLATION ON THE BASIS OF ONE THOUSAND SQUARE FEET

Thickness of material	Cost per sq.ft.
1/2 inch	$ .31 - .33
3/4 inch	.33 - .36
1 inch	.36 - .38
1 1/4 inch	.38 - .42

Selection and Application of Acoustical Materials

The selection of a specific commercial material for the acoustical treatment of a music room depends on many factors. Some thought must be given to availability, cost, color, efficiency of absorption, light reflection value, geometric design of material, effect of paint, and effect of water. However, once the material has been chosen, it is easily possible to determine how many square feet need to be applied in order to give the room an average acceptable time. Following is an illustration.

Cushiontone, 1/2 inch in thickness and used with a No. 1 mounting, was selected as an absorbing agent for the acoustical correction of the Catalina Junior High School music room. From Table II, page 22, it will be seen that

the material has an absorption coefficient of .56 OWU at 512 cycles. Since its application renders ineffective the coefficient of the plaster which it covers, the coefficient of the plaster must be subtracted from that of the treatment (.56 - .033) and the net coefficient (.527) should be used in the necessary calculations. In Table XVI, page 44, it was shown that 961 additional units of acoustical treatment are essential. The total area to be covered with this material may be computed by dividing 961 by .527, which is approximately 1,824 square feet. Inasmuch as the ceiling has an area of 2,600 square feet, the entire ceiling will not require treatment.

Nevertheless, due to architectural and aesthetic considerations, it is assumed that the ceiling should be completely covered with acoustical material. Whether or not this would result in a reverberation time below the lower acceptable limit (1 second) may be determined prior to the treatment, as follows:

2,600 sq. ft. of ceiling
x .527 net coefficient
= 1,370 absorption of ceiling after treatment
+ 439 absorption already present
= 1,809 total absorption of treated room

$$T = \frac{.05V}{a} = \frac{1820}{1809} = 1.006 \text{ sec.}$$

The reverberation period is still within the acceptable limit, and treatment of the whole ceiling with the selected

material is therefore valid. If the calculated time of reverberation were too short, a material with a coefficient of less absorption should be installed.

Elimination of Absorptive Materials

Although it is unusual for a music room to have a reverberation period of less than the acceptable value, such was the case of the music rooms of Tucson Senior High School. Therefore a discussion is here given of the method used in calculating the acoustical correction. The vocal classroom will serve to illustrate the method.

According to Tables XV and XVI (pages 43 and 44, respectively), it may be seen that the reverberation was deficient by .41 seconds and that 505 OWU should be eliminated. Most of the absorption is due to the high coefficient of acoustical plaster, and it is only reasonable to assume that some area of acoustical plaster be removed; in its place a material with a low coefficient should be substituted. Suppose that plaster to be applied on a metal lath is the material selected as a substitute. The coefficient of this substance per square foot is known to be .033; acoustical plaster is equal to .4 OWU per square foot. By dividing the net coefficient into the total number of absorptive units to be eliminated, the result will specify the number of square feet of acoustical plaster to be removed. In other words, the answer will ascertain the

area of plaster which is to be applied to metal lath. Accordingly, the amount of this material required will be

$$\frac{505}{.367} = 1,376 \text{ sq. ft.}$$

Summary of Analyses

In order to determine their acoustical characteristics, the music rooms of Catalina, Dunbar, Mansfeld, Roskruge, and Safford Junior High Schools and of Tucson Senior High School were analyzed. It was found that the Sabine formula serves as a basis for calculating existing characteristics as well as for corrective measures. The music rooms of the five Junior High Schools were shown to have excessive reverberation times, and the vocal and instrumental classrooms of the Senior High School have reverberation periods below the acceptable range. It was further shown that after the acoustical characteristics of the rooms were determined, simple mathematical calculations indicated the necessary corrective measures.

CHAPTER IV

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

Some of the more important facts in regard to the acoustics of music rooms of the Tucson Public Schools are:

1. Satisfactory acoustical conditions are necessary for effective instruction.

2. Acoustical characteristics of music rooms may be determined by mathematical calculations.

3. The reverberation time is the important factor in determining the acoustical efficiency of a music room.

4. The music rooms of Catalina, Dunbar, Mansfeld, Rockruge, and Safford Junior High Schools have reverberation times above the acceptable range. The music classrooms of Tucson Senior High School have reverberation times below the lower limit of acceptability.

5. Of the seven music rooms analyzed, all except the instrumental room in Tucson Senior High School require acoustical correction.

Recommendations

The following are recommendations for future practice:

1. The six music rooms which are acoustically inefficient should be corrected.

2. Similar studies could be made of music rooms in other schools.

3. Tucson schools erected in the future should be planned to include music rooms scientifically designed for acoustical efficiency.

4. It is recommended that a further study of sound conditioning of entire school buildings be made. This would involve the problems of noise reduction, rather than those of sound conditioning for satisfactory musical conditions.

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