INVESTIGATION OF ACOUSTICS IN RELATION TO STRUCTURES WITH SPECIFIC APPLICATION TO LABORATORIES AND CLASSROOMS USED FOR TECHNICAL INSTRUCTIONAL PURPOSES

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PREFACE

It is the purpose of this thesis to extend the understanding and use of acoustical knowledge and materials in relation to structures and to increase the awareness of the importance of architectural acoustics in our present day environment.

General principles of architectural acoustics, requirements and methods for proper sound control and economic aspects of acoustical construction are included in this study. These principles and methods are applied to a structure with particular emphasis on acoustical analysis of laboratory and classrooms used for technical instructional purposes. Measured sound levels for traffic noise, laboratory equipment, classroom and corridor are incorporated into the analysis.

The author wishes to express sincere appreciation to his thesis adviser, Professor F. C. Salmon, for his guidance in the preparation of this paper and to Professor Dean W. Irby for his making available certain materials and sound measuring instruments used in the investigation. Appreciation is also expressed for the encouragement and excellent instruction received from Professors W. G. Chamberlain, John R. Cunningham, Alec Notaras, Dwight E. Stevens and Professors Emeritus John E. Lothers and Ray E. Means, all of the Faculty of the School of Architecture.

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NOMENCLATURE

α	Coefficient of absorption.
a	Units (sabins) of absorption.
cps	Cycles per second.
db	Decibel.
f	Frequency of a sound wave in cycles per second.
λ	Length of a sound wave in feet.
NR	Noise reduction in decibels.
R	A ratio of $\frac{T_f}{T_{500}}$.
S	Area of a surface in square feet.
τ	Coefficient of transmission.
TL	Transmission loss in decibels.
TL eff.	Effective transmission loss in decibels.
T_R	Reverberation time in seconds.
T_f	Reverberation time at a given frequency.
T_{500}	Reverberation time at a frequency of 500 cps.
V	Volume in cubic feet.

CHAPTER I

INTRODUCTION

Sound control in human environment became a significant problem with the advent of the mechanized age and the clustering together of society.

In this century, outdoor noises have become greater because of vehicular traffic and aircraft. In addition, the use of electrical and mechanical equipment has increased the noise produced within a structure.

Continuity of structure and the architectural concept of transparency have increased the use of lightweight, thin construction in recent years thus creating a more complex problem for acoustical control.

The complexity and magnitude of these outdoor and indoor noises today render sound control as necessary to the proper functioning of a building as other considerations such as lighting and air conditioning.

The field of architectural acoustics has developed rapidly since the early years of this century when Professor Wallace C. Sabine published his original quantitative study of reverberation in the Fogg Lecture Hall at Harvard University (1). Many papers and textbooks have been written since then, which provide both theory and application for either the consultant or the student of architectural acoustics (2, 3, 4, 5, 6).

Test data is available on sound insulation of many types of wall, floor and ceiling constructions; on sound absorption of building materials and on impact noises (7, 8).

The author's contribution is the investigation of sound levels produced by laboratory equipment, as well as vehicular traffic at the building site and the application of this information to a proposed building to be used for instructional purposes. It also includes an economic study of various types of wall, floor and ceiling constructions acoustically applicable for the proposed building.

CHAPTER II

PRINCIPLES OF ARCHITECTURAL ACOUSTICS

The following discussion does not investigate in depth the physics of acoustics but gives the necessary information for a practical understanding and approach to the solution of problems in the field of architectural acoustics.

General Nature of Sound

Sound is the pulsation of pressure waves in an elastic medium. It consists of back and forth motions of molecules in the air which create a series of compressions and rarefactions.

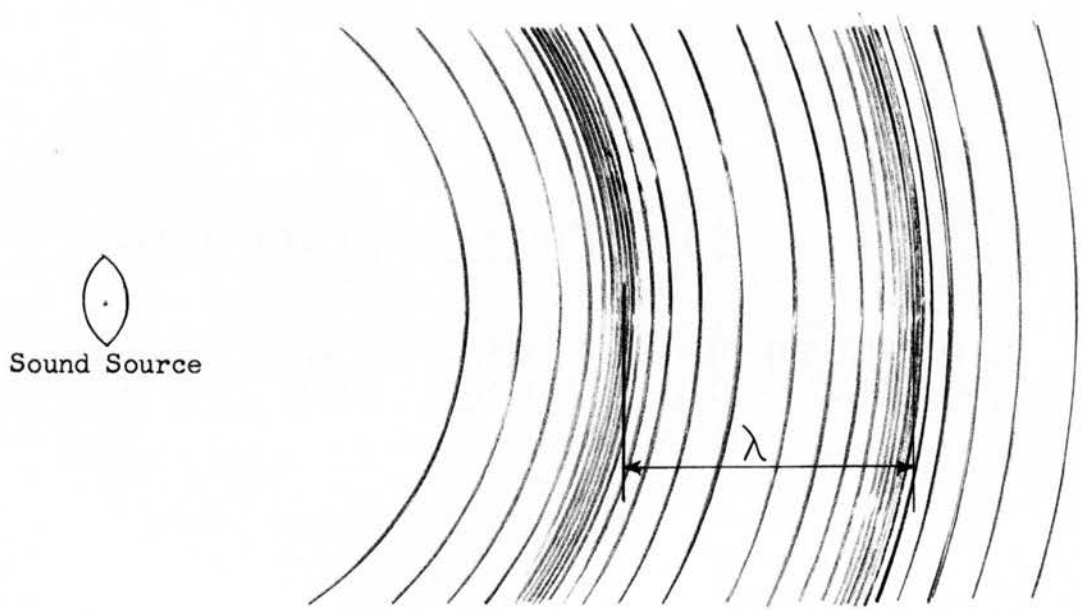


Figure 1. Propagation of a sound wave.

Sound waves spread outward from the source in all directions, if not restricted, and diminish in intensity inversely as the square of the distance from the source. This is a reduction of approximately six decibels for each doubling of the distance from the source.

The speed of sound is approximately 1,130 feet per second in air and faster in denser media such as wood, plaster, concrete and steel (1).

The number of pressure waves per second is the frequency of the sound. Most sounds consist of numerous frequencies at different intensities. In architectural acoustics, the most common set of frequencies is 125, 250, 500, 1,000, 2,000 and 4,000 cycles per second. The human ear responds to frequencies from about 16 to near 20,000 cps, being most senstivie in the middle frequency range, around 2,000 cps (1).

The length of a sound wave is equal to the speed of sound divided by the frequency of the wave, $\lambda = \frac{1130}{f}$. From this relationship it can be seen that the wave length varies inversely as the frequency.

The intensity of sound energy is measured in decibels and is generally spoken of as sound level or sound pressure level. The intensity which the human ear can tolerate depends upon the frequency and duration of the sound. Low frequency noise is tolerable at higher intensity than is high frequency noise (2). The ear does not respond in proportion to the energy of the sound. As the energy of a sound increases steadily, the sensation of loudness fails to keep pace with it. The loudness sensation or sound level in decibels, shown in Figure 2, is approximately proportional to the logarithm of the sound energy when related to some reference energy representing zero decibels. In other words the sound energy at a sound level of 60 db is a million times the sound energy at 0 db and at a sound level of 120 db the sound energy is a million-million

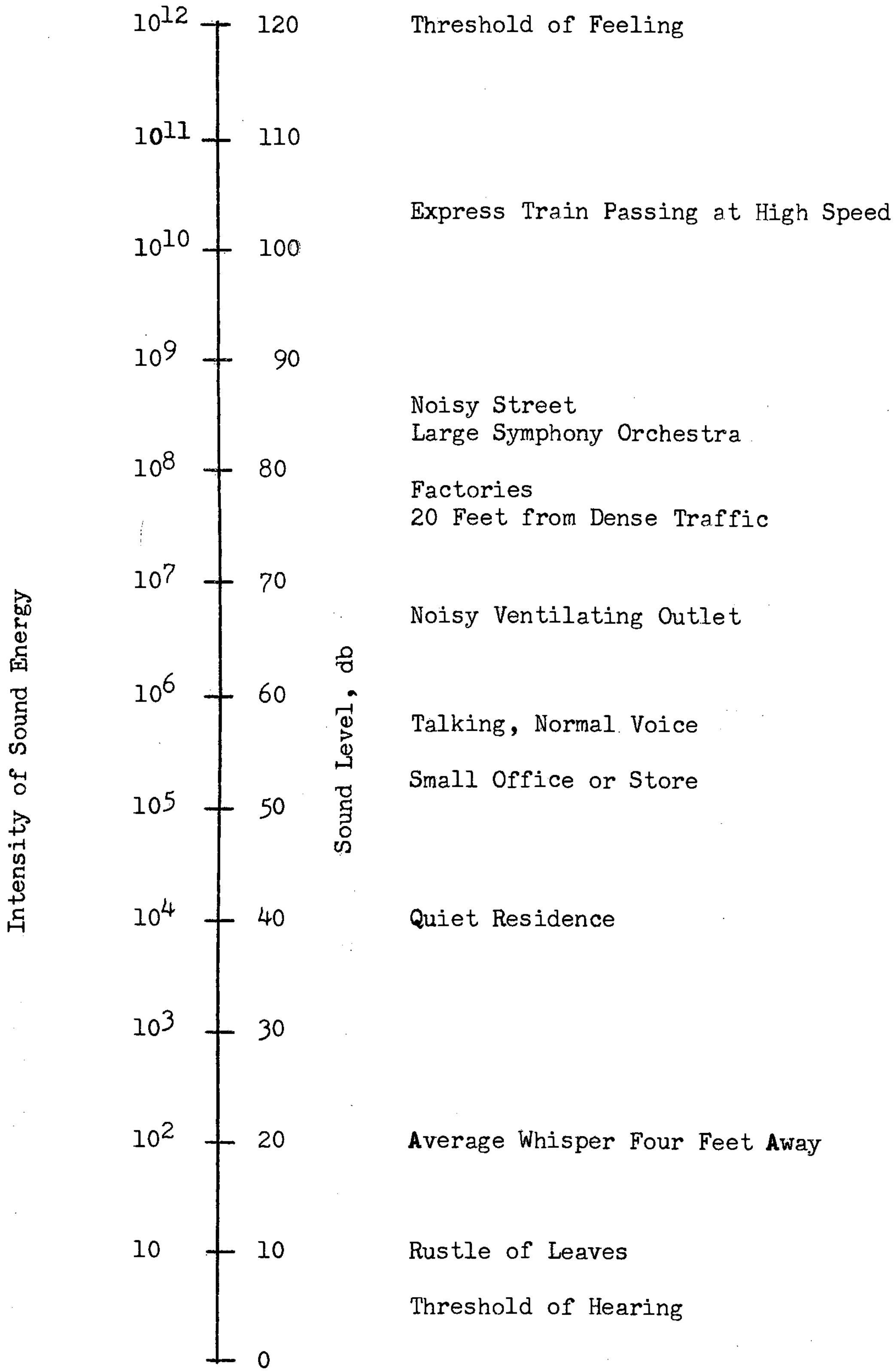


Figure 2. Relationship between the intensity of sound energy, the sound level in decibels and typical noises.

times the sound energy at 0 db. Average sound levels for typical noises are also shown in Figure 2.

When a sound wave in air comes in contact with the surface of a structural material, part of the sound energy is reflected, part is transmitted by the material and part is absorbed by the material; see Figure 3.

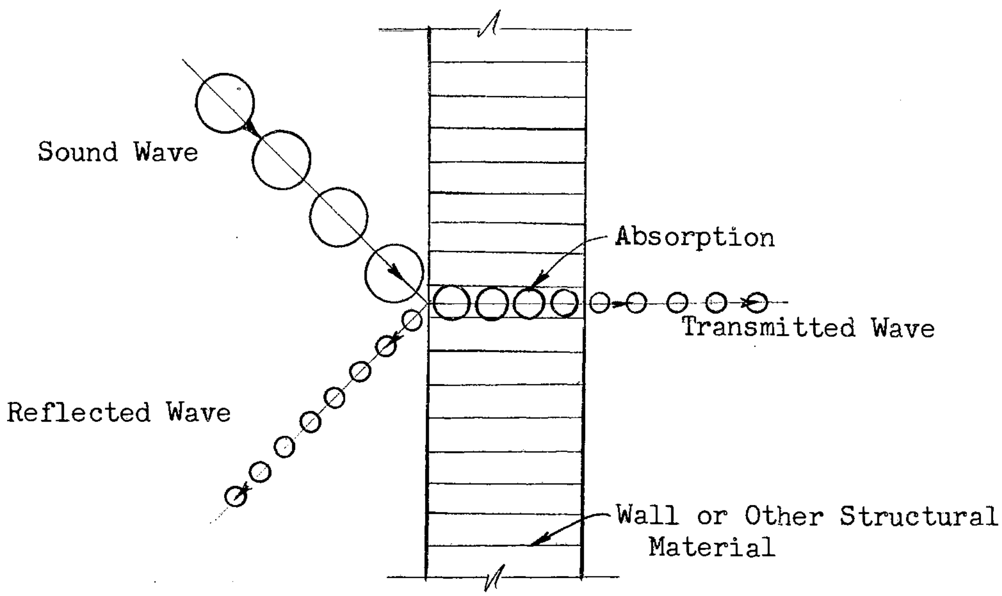


Figure 3. The dispersion of sound when it encounters a solid material.

The relative magnitude of these three parts of the original sound is determined by the physical properties of the material. A dense, hard surfaced material will reflect a great deal of the sound which strikes it, while a soft, porous surface will reflect very little. If one is concerned with only the space in which the sound originates, absorption and reflection may be the only consideration. More often, however, one is also concerned with the part that is transmitted into an adjacent space.

The mechanisms governing absorption, reflection and transmission are quite different and must be clearly understood in order to determine accurately the acoustical environment in a finished building.

Absorption

Absorption is the conversion of sound energy into heat energy by frictional and viscous resistance within the pores and by vibration of the small fibers of the material. Materials such as carpets, draperies, upholstered furniture and specially designed acoustical blankets and tiles provide significant sound absorption. Flexural vibration of thin floor, wall and ceiling components also provides some absorption depending on the stiffness of the structural element. Absorption by structural vibration is small at high frequencies but may be large at low frequencies, while absorption by porous materials normally is large at high frequencies and small at low frequencies. The fractional part of the energy of an incident sound wave that is absorbed by a given material is called the absorption coeficient (2). Its value depends upon the nature of the material, its thickness, the way it is mounted and the depth of the air space behind it, as well as the frequency of the impinging sound. For example, the coeficient of absorption for concrete is 0.01 at 250 cps while the coeficient of absorption for perforated cement asbestos panel with three-inch glass or mineral wool backing is 0.99 at 1,000 cps. The absorption coeficient times the number of square feet of surface of a given material equals the number of units (sabins) of absorption supplied by that surface; $\alpha S = a$.

Sound absorbers, because they are porous and admit moving molecules in the sound wave, will also transmit sound. A good sound absorber is almost always a good sound transmitter.

Transmission

Sound is transmitted from one space to another by one or more of the following means: (a) as airborne sound through openings such as open windows or doors; through cracks around doors, windows and piping; and through ducts of ventilating equipment; (b) by vibration of the structure (impact) and (c) as airborne sound through wall structures. The first means of sound transmission can be practically eliminated by proper detailing, sealing all cracks, using fixed window sash and using a properly designed acoustic filter in duct work. The second means of sound transmission can often be controlled by the use of a nonhomogeneous structure or when possible by the complete separation of two parts of a structure; also by the use of properly designed mounts and foundations for vibrating machinery. The third means of sound transmission is the result of diaphragm action; the wall being activated by sound waves on one side of it creates new sound waves on the other side. The amount of transmission through the wall depends upon the amplitude of vibration of the material making up the wall. This in turn depends upon the initial energy striking the wall and the mass and stiffness of the wall. The heavier the wall per unit area the less sound will be transmitted; however, this is not a direct relationship. The sound-insulation factor (transmission loss in decibels) for homogeneous walls is proportional to the logarithm of the weight per unit area (3). The insulating value of a wall of given weight can be increased considerably if the wall is broken up into two or more layers; in other words, made nonhomogeneous. The fraction of incident sound energy that is transmitted through a barrier (wall, floor, window, etc.) is called the transmission coefficient and the number of decibels the sound level is reduced in the process of transmission through each square foot of the structure at a given frequency is the transmission loss for that particular structure.

Reflection

The part of the sound wave which is reflected behaves in optical fashion; that is, the angle of reflection will equal the angle of incidence. This is true provided the reflecting surface is larger than the sound wave striking it. For example, at a frequency of 125 cps the wave length is about nine feet; therefore, the reflective surface would need to be larger, in least dimension, than nine feet. Small obstructions such as columns, mullions and trim have little effect on sound waves except at frequencies above 4,000 cps. Inside a room or building reflecting surfaces are often used to control the direction of sound. On the other hand if the spread of sound needs to be reduced the surfaces are treated to reduce the reflected sound energy. Reflected sound from domed or concave surfaces will tend to focus as it moves away from the surface rather than continuing to spread as it does from flat or convex surfaces.

Diffraction

Sound waves that pass through openings such as windows, doors or cracks under doors diffract or bend as they pass through and spread outward to fill the space. Diffraction is more efficient in the low frequencies than in the higher frequencies.

CHAPTER III

FACTORS AFFECTING NOISE CONTROL

The basic reasons for acoustical design are to provide a satisfactory acoustic environment and to provide good hearing conditions.

Environmental

A satisfactory acoustic environment is one in which the character and magnitude of all noises are compatible with the satisfactory use of the space for its intended purpose (4).

Environmental factors to be considered are (a) site location; (b) existing sound levels; (c) sound level desired for a given activity or use and (d) quality of noise.

Site location and location of the building on the site should be part of the basic planning. Since sound diminishes with distance, the farther a building is from a noise source such as traffic the less isolation the structure will need to provide. Foliage located as near the noise source as possible will attenuate many sounds especially in the middle and higher frequencies.

Existing sound levels on the noise source side of the walls, floor and ceiling of the room under investigation should be measured with a sound level meter and an octave-band noise analyzer for all frequency bands in accordance with recognized procedures (5, 6). These values in addition to the sound level desired in the room are used to determine the acoustical construction of the room.

There is a wide range of acceptable background noise levels in rooms as indicated by Table I. It is also important to consider the sound reflecting properties of a room because an extremely reverberant space can be annoying for some purposes such as speech, even with relatively low noise levels.

TABLE I

DESIGN CRITERIA FOR ACCEPTABLE BACKGROUND NOISE LEVELS

Type of Space	Cycles per Second					
	125	250	500	1000	2000	4000
Apartment or Dwelling	47	39	32	28	25	22
Church	51	43	37	32	30	28
Convention Hall	55	47	41	37	35	33
Factory	59	52	46	42	40	38
Hospital	51	43	37	32	30	28
Hotel	47	39	32	28	25	22
Library	49	41	35	30	28	26
Motel	51	43	37	32	30	28
Night Club	62	56	50	47	45	43
Office Building	51	43	37	32	30	28
Opera House	43	35	28	23	20	17
Radio and Television Studio	38	30	23	18	15	12
Restaurant	59	52	46	42	40	38
School Classroom	47	39	32	28	25	22
Sports Arena	66	60	55	52	50	48
Theatre	51	43	37	32	30	28

The tolerance to noise depends also on its quality (high pitched, low pitched, sharp, etc.) and on its dynamic characteristics (continuous, intermittant or rhythmic); the more unexpected a noise, the more likely it is to be disturbing.

Hearing Conditions

A room satisfying the conditions for environmental control must still meet the requirements for good hearing. Factors to be considered for good hearing are (a) background noise; (b) loudness; (c) reverberation characteristics and (d) proper distribution of sound.

Background noise is an important factor in both the environmental aspects and the hearing properties of the room. Background noise must be lower than the desired sounds of speech or music yet loud enough to mask out undesirable sounds from the next room or outdoors that have not been isolated by the structure. Steady noises such as continuous traffic, diffused ventilating air or piped-in music are often used for masking effects. Providing adequate background noise can be particularly troublesome in quiet locations where there is very little traffic. In any case the background noise must be soothing and continuous so that people will scarcely notice it.

Adequate loudness of speech is not a problem in small rooms (less than 25,000 cubic feet in volume) provided the other conditions for good hearing are satisfied. In very large rooms (250,000 cubic feet or more in volume) sound amplification is usually needed. In rooms varying between these two sizes, sound amplification may or may not be needed depending on the skill with which the other conditions for good hearing can be controlled.

Sound inside a room continues to travel and reflect from surface to surface until it is either transmitted to another space or absorbed by the surrounding enclosure and furnishings. The support of sound by successive reflections is called reverberation. The time required for the sound to decrease to one millionth of its original intensity (60 db) after the source has stopped is called the reverberation time. The reverberation time that exists in a room is determined by the volume, absorptive qualities of the surface finishes and the occupancy of the room. The reverberation time for a given room is equal to the volume times the value 0.05 divided by the total number of absorptive units provided; $T_R = \frac{0.05\ V}{a}$. The optimum reverberation time for variously occupied rooms is shown in Figure 4. These values are for a frequency of 500 cps. To obtain the optimum reverberation time at any other frequency, multiply the value from Figure 4 by the appropriate ratio for that frequency from Figure 5. For example, $T_f = T_{500}\ R$, where T_{500} is the reverberation time at 500 cps given in Figure 4.

The reverberation time must be satisfactory over a wide range of frequencies. A common form of frequency unbalance is excessive reverberation at low frequencies (below 250 cps) and inadequate reverberation at high frequencies (above 2,000 cps). The resulting "boomy" effect is due to inadequate low frequency absorption (3). Increased low frequency absorption can be obtained by using thick absorptive materials, deep air spaces behind porous materials, thin panels such as plywood or acoustic resonators. All of these measures require greater depth than usually allowed for normal construction.

The distribution of sound in a room is determined principally by the shape of the enclosure and the smaller scale breakup of the

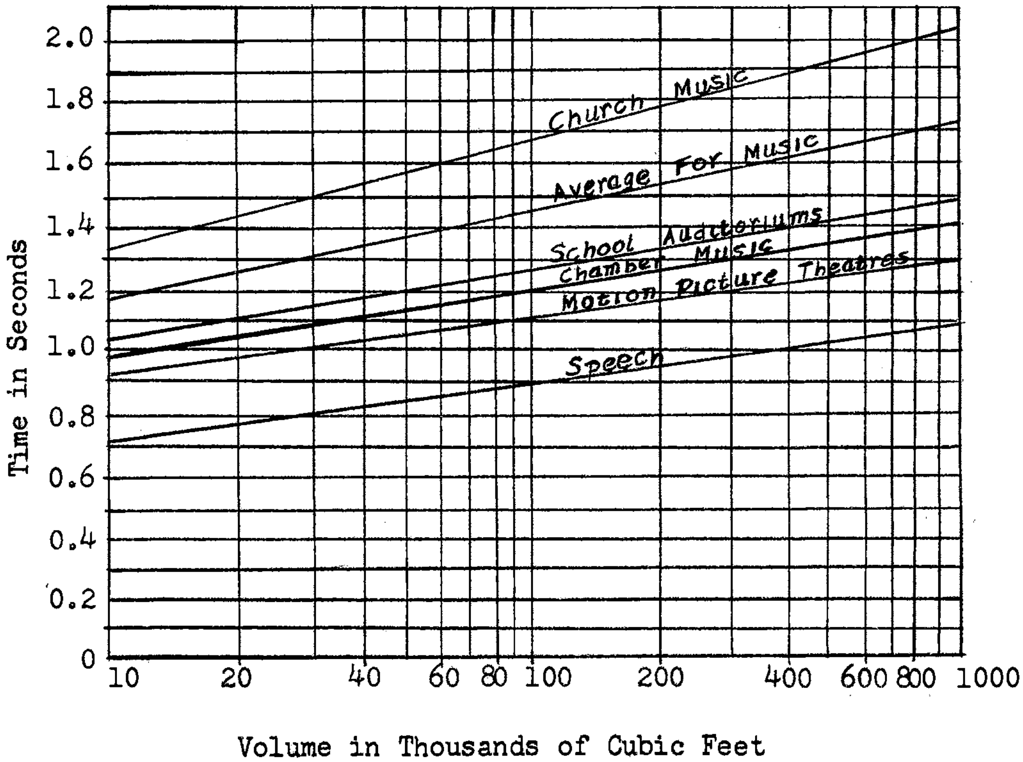


Figure 4. Optimum reverberation time at 500 cps for different types of rooms as a function of room volume.

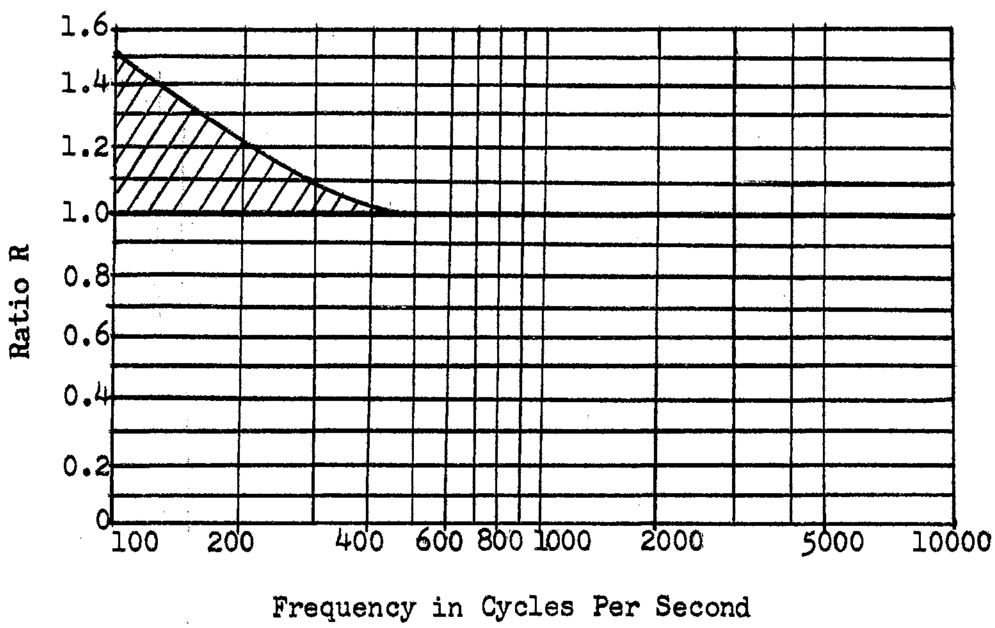


Figure 5. Optimum reverberation time as a function of frequency.

surfaces. Sound should be distributed uniformly to all parts of the room for good listening. There should be no distinct echoes due to reflected components of a sound wave. An echo will result when there is a difference of 1/17 second or more between the time the direct ray and a reflected component of the ray reaches the listener. This time delay represents a travel distance of approximately 65 feet; see Figure 6.

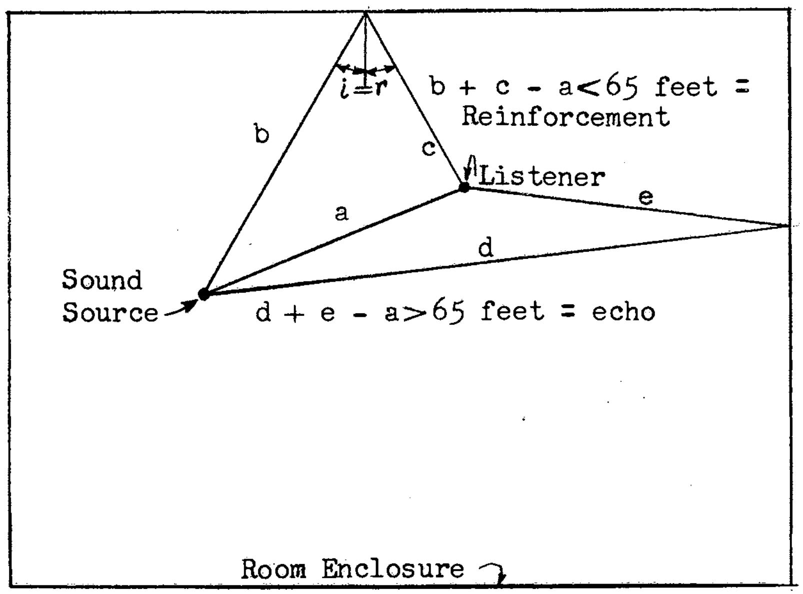


Figure 6. Ray diagram of sound wave components. Ray d plus e will result in an echo while ray b plus c will provide useful reinforcement.

Reflections which follow the direct sound in less time than 1/17 second contribute useful reinforcement if they are not stronger than the direct component. They will not generally be stronger if they reflect from a flat, convex or irregular surface. But if they reflect from a large concave surface they will focus into excessively strong components; see Figure 7. Echoes can be eliminated by using sound absorbing material on the surface that reflects the echo, by breaking up the surface into irregular surfaces or by sloping the surface to reflect the sound away.

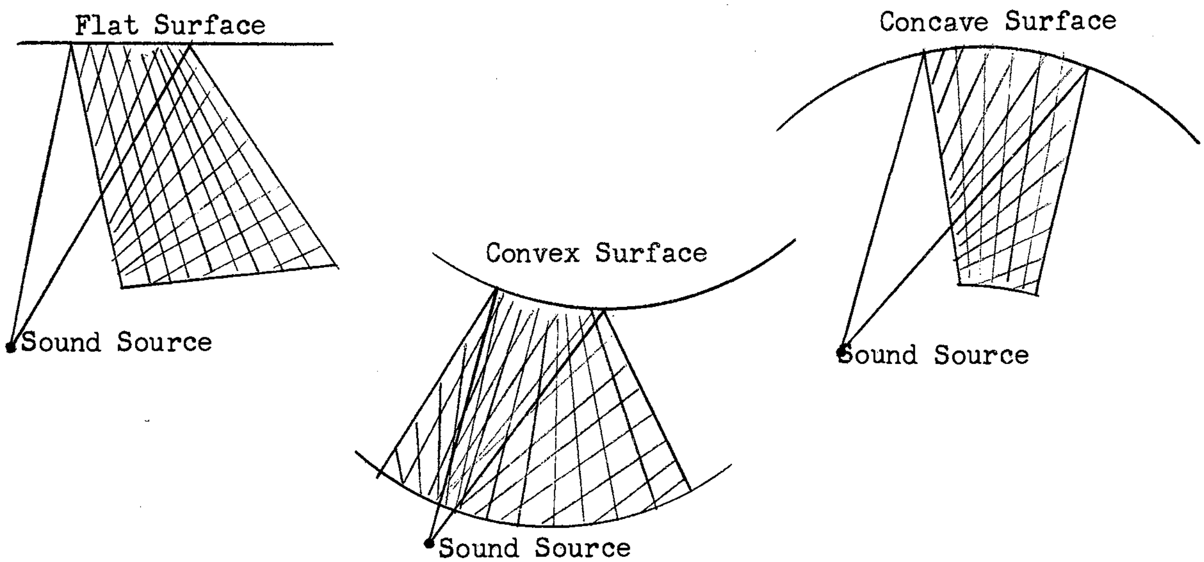


Figure 7. Reflection of sound by various surface shapes. A flat surface diffuses sound slightly, a convex surface diffuses sound over a wide area, while a concave surface concentrates sound.

The direct sound and the first few reflections are the important ones in providing loudness, definition and articulation. Ray diagrams, both in plan and section, will aid in determining the distribution of these wave components.

As was stated in Chapter II, if a particular reflection has traveled twice as far as the direct ray it will be lower by six decibels; therefore, if the listener is to hear as well at the back of a room as at the front, the reflections should increase in density towards the back of the room to compensate for the falling off of the direct component.

Parallel, opposing surfaces often result in multiple back and forth reflections called flutter echoes. Flutter is particularly noticeable if surfaces other than the reflecting pair are sound absorptive. Flutter can be eliminated by sloping the walls, in plan or section, so that they are out from parallel by one foot in twenty feet or steeper (4). Wall irregularities also reduce flutter as well as provide diffusion, and highly absorbing material on one of the wall surfaces can adequately control flutter.

CHAPTER IV

MATERIALS AND METHODS OF CONSTRUCTION

While proper distribution of sound and reverberation control are necessary for noise control, the isolation of sound from a space and the control of sound within a space also depends upon the components of the enclosing structure, the continuity or discontinuity of the structure, details of construction and the absorptive materials and finishes used.

Structure

A structure is composed of various construction components such as foundation, frame, walls, ceiling, floor, doors and windows.

The foundation of a structure can transmit vibrations from the surrounding soil mass to the structure. If vibration of the soil is present or anticipated, the foundation must be isolated from it. Where foundation vibration cannot be overcome, the frame of the building may be isolated from the foundation by the use of resilient members between the structural supports and the foundation. Vibrations and noise arising within the structure are transferred to the foundation. The greater the mass of the foundation the more effectively will these vibrations be dissipated. Individual foundations are required for machinery that imparts vibration of any consequence to the structure.

Continuity of structure results in the transmission of sound from one part of the structure to another. Rigidly connected walls and floors transmit vibration to the frame and in turn the rigid frame of concrete or steel transmits this vibration throughout the structure. Complete structural breaks, sealed with mastic or other soft expansion material, will eliminate the transmission of sound from one portion of the structure to another. Also, light structural members, walls and ceilings may be supported or attached to the frame with resilient supports and clips to provide additional isolation. For example, finish materials may be attached to load-bearing walls by resilient clips and joined only to the suspended ceiling thus preventing the transfer of vibrations.

The degree of noise isolation of a homogeneous wall increases with weight. Composite walls, particularly if they include air spaces, are generally superior to homogeneous walls of the same weight. Regardless of weight, however, a wall must be highly impervious to air flow through it if it is to provide adequate sound isolation.

Sound isolation provided by floors and ceilings should correspond to that provided by the walls. If the sound passing between two adjacent rooms through the floor or ceiling exceeds the amount transmitted through the common wall a limit of isolation will be reached regardless of the effectiveness of the wall. Figure 8, view a, shows a common type of construction which permits the transmission of sound through the ceiling, over the partition and down through the ceiling in the next room as well as transmission through the joint between wall and ceiling; also impacts on the floor caused by walking or equipment will cause the floor to vibrate thus transferring sound to other spaces. Figure 8, view b, shows a type of construction that will greatly reduce the transmission of airborne and solid-borne sounds indicated in view a. Another method of floor construction is to support wood sleepers in flexible chairs or on a resilient blanket over the structural floor system. The sound isolating floor and the furred plaster ceiling are one means of preventing sound from being transmitted through floor and ceiling in either direction. If vibration is present, the ceiling should be suspended by flexible mechanical hangers.

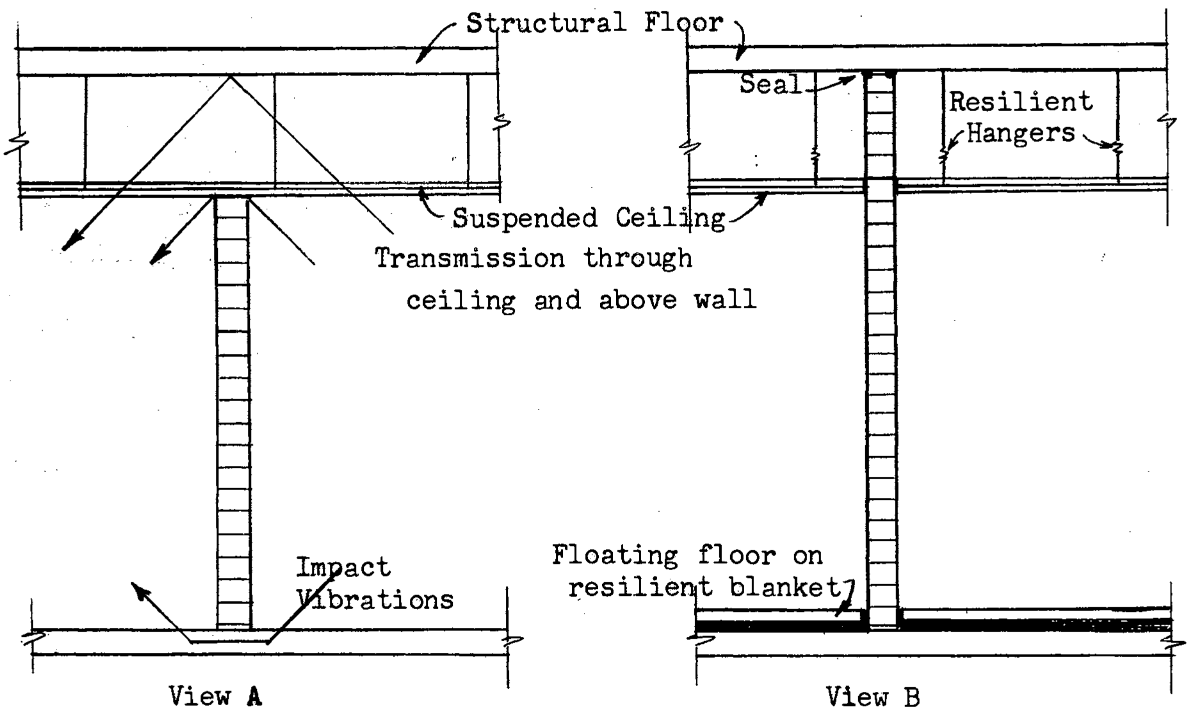


Figure 8. Sectional views of construction pertaining to the transmission of airborne and solid-borne sounds.

Windows and doors located in a wall usually contribute more to the passage of sound between spaces than any other construction element. It is essential for good sound isolation that doors and windows fit tightly in their openings. The transmission loss of a door increases with increased weight and as the frequency of sound increases. Doors that close tightly against a neoprene or rubber gasket all around the door, including a seal at the threshold, should provide adequate isolation; however, if this is not adequate a double set of doors with a small vestibule between them, that has been treated heavily with absorptive material, should be used. The isolation provided by a window depends to a great extent on the thickness of the pane; the heavier the glass the more isolation it provides. Isolation can be increased by using double or triple panes. The space between panes should not be less than one inch and preferably three or four inches. The panes should not be rigidly joined at the edges and should be encased in felt, neoprene or rubber. The periphery of the space between panes should be lined with sound absorptive material. Tilting one pane with respect to another and varying the thickness of the panes will difuse the sound and cause the panes to have different resonant frequencies.

The design of an enclosure to decrease the transmission of sound involves more than the choice of a wall structure with adequate transmission loss. Proper detailing of all joints, divisions and penetrating elements must also be considered.

Details of Construction

Detailing is the essance of good sound isolation. Joints formed by the intersection of walls with floors, ceiling or other walls, and small openings around ducts, conduit, pipes and outlet boxes which penetrate into or through a construction must be sealed against the passage of airborne sound. Air conditioning ducts should be lined with sound absorbent material at the fan end and at the room outlet end to prevent the transmission of mechanical noises and the transmission of sound between spaces. Rooms should not be served by a common duct with wall outlets back to back. Other sources contributing to the transmission of airborne sound between spaces are louvered doors and electric or other outlet boxes back to back in a thin partition.

To prevent solid borne sound, pipes, conduit or ducts penetrating a wall or other construction should be isolated from the construction by rubber, neoprene, felt or other pliable materials; also they should be suspended from the floor above by resilient supports. Connection between supply ducts and the fan housing must be flexible and at other branch locations where required. Service connections for piping and conduit must also be flexible and limp. If the connections are in tension they will still transmit vibrations.

Operating machinery sets up vibrations which travel through the supporting construction to other parts of the structure thus creating noise. Control of the noise consists of breaking the vibratory path of travel. This can be done by setting the machinery on a foundation isolated from the rest of the structure. If the machinery must be placed on a floor above grade and a separate foundation cannot be provided, vibration isolators may be used between the machine and the supporting floor. Vibration isolators may be composed of springs, rubber and other resilient materials. When noisy machinery must be located close to a quiet space every quieting technique should be used including machinery enclosures if possible. Machinery enclosures made from sound proofing panels can be used to quiet single sources of noise which may otherwise require extensive acoustical treatment of the surrounding construction.

Materials and Furnishings

Materials and furnishings of buildings may serve only to reduce sound transmission, may serve only as sound absorbers or may be a combination of these to varying degrees.)

Most structural materials reduce the transmission of sounds, as discussed earlier in this chapter, and have been tested and rated according to their transmission loss values for a given frequency (7).

(All materials used in the construction of buildings absorb some sound; however, it is usually necessary for proper acoustical control of a space to use some materials that have been designed to function primarily as sound absorbers.) Many different acoustical materials are manufactured for use in buildings and many more have been and can be devised by a combination of existing materials. (Many of these materials and combinations have been tested and rated according to their absorption coefficient (8) which is the efficiency of a material in absorbing acoustical energy at a specified frequency. Most acoustical materials used in buildings to absorb sound can be included in one of three categories:) ((a) prefabricated units including acoustical tile, mechanically perforated units backed with absorbent material, tile boards, absorbent sheets and certain wall boards; (b) acoustical plaster and sprayed-on materials including plastic and porous materials applied with a trowel and fibrous materials applied with an air gun; and (c) acoustical blankets of mineral wool, glass fibers, kapok batts and hair felt. In addition to their ability to absorb sound, acoustical materials are selected on the basis of appearance, economy and maintenance.) One acoustical material may cost twice as much as another yet have three times the absorptive value, thus the more costly material would in this case be more economical for a given absorptive requirement. Acoustical materials such as acoustical tile, cloth covered blankets and other soft acoustical materials should not be used on an area subject to wear and tear, such as that portion of wall below door height. It would be better, for instance, to use an absorptive blanket covered by perforated metal, plywood or fiberboard on this area. Acoustical materials may be painted repeatedly without impairing their absorption provided the holes or fissures in the material are not filled or bridged with paint. Holes one-eighth inch in diameter or larger will normally not become bridged by painting.

Most absorptive materials are satisfactory over a wide frequency range, being more absorptive as the frequency increases and providing little absorption in the low frequencies, below 250 cps. The combination of thin panels, such as plywood or masonite, with an air space and a blanket of rock wool or fiberglass provides high absorption at low frequencies and progressively less absorption at higher frequencies. For most applications, one-eighth inch holes not to exceed one-half inch on center both ways is satisfactory. The perforated covering does not reduce absorption in proportion to the area covered due to diffraction of sound through the perforations. Panel action of the perforated covering also contributes to the low frequency absorption. Acoustical blankets are more absorptive in the low frequencies depending upon their density and thickness. Absorption increases with increasing thickness and density. A density of four pounds per cubic foot is often specified. An air space between the blanket and wall will generally increase absorption at low frequencies.

The method of mounting acoustical materials influences, to some extent, their absorptive properties. For example, acoustical tile mounted on furring strips will generally have higher absorption at low frequencies than will the same tile mounted directly to the wall or ceiling construction.

Other methods of mounting acoustical material, such as suspending acoustical tile from the floor above by rigid or flexible hangers, influences sound control, as noted previously, in the transmission of vibrations.

Furnishings and people are important elements of absorption in a space. A room with draperies, carpeting and filled with people may provide all the absorption required. The seating in such a room should be upholstered to provide approximately equal absorption per seat to that of a person, since the room may be only partially filled at times. Draperies are absorptive principally in the higher frequencies. Carpeting is a very useful sound absorber especially in relation to impact type noises. Other floor coverings such as cork and rubber tile are also useful in absorbing impact noises.

The types of acoustical materials vary widely and are great in number. Therefore the ultimate selection for a particular space depends not only on the acoustical properties of the materials but also on economy and function of the space.

CHAPTER V

NOISE REDUCTION

Noise reduction in buildings is achieved by means of (a) proper planning to segregate sounds, (b) proper design and detailing of structures to block effectively the passage of sounds; and (c) proper utilization of materials and furnishings to absorb sound.

Segregation reduces noise by placing the source farther from the listener and should be an important consideration in the basic planning stage. Many times a building must be located near a noise source and adequate spatial separation within a building cannot always be achieved because of other functional considerations. If either or both conditions exist, the required noise reduction must be provided by sound-insulative and absorptive construction.

The noise pressure level at any point in a space is related to the absorptivity of the surfaces as it affects sound within the space, the effective transmission loss of the various kinds of enclosing construction which impede the flow of sound into a space, and the reverberant quality of the space.

The effect of absorptivity on noise reduction will be considered first. If a room has various surface areas, S_1, S_2, S_3, etc., such as walls, ceilings, doors and windows, having corresponding absorption coefficients $\alpha_1, \alpha_2, \alpha_3$ etc., the total units of absorption of the room may be found from

$$a = \alpha_1 S_1 + \alpha_2 S_2 + \alpha_3 S_3 + \ldots \alpha_n S_n$$

Let this value equal a_1. For a reflective room the value would be small and the space would support sound. If absorptive material was applied to reflective surfaces, such as the ceiling, floor or walls, the units of absorption would increase and reflected sounds would die out at a faster rate. Let the increased value of total absorption units equal a_2. Now, if the room contained a noise source of known intensity or sound level under the conditions represented by a_1, it is possible to determine the noise reduction due to the addition of absorptive material represented by condition a_2 from

$$NR = 10 \log_{10} \frac{a_2}{a_1} \text{ db}$$

The amount of noise reduction by the use of absorptive materials applies to sound levels within a space and not between spaces. Absorptive materials reduce only reflected sound energy.

Next, noise reduction between spaces or through a construction will be considered. The sound insulative value of a given construction is measured by the reduction in sound level as sound energy passes from one side of the construction to the other side. The drop in sound level is the transmission loss for a given type of construction. Transmission loss values at various frequencies have been determined and published for many different constructions of walls, floors, ceilings, doors and windows (7). The transmission loss value is given by

$$TL = 10 \log_{10} \frac{1}{\tau} \text{ db}$$

also the value of the transmission coefficient can be determined from the above equation as

$$\tau = \frac{1}{\text{antilog } (TL/10)}$$

Since a space or room is usually enclosed by different types of construction it is possible to determine the effective transmission loss for these various components from

$$TL_{eff} = 10 \log_{10} \frac{\sum S}{\sum \tau S} \text{ db}$$

The total noise reduction between rooms or from outside to inside depends then upon absorptive surfaces in the room where noise is to be reduced and upon sound transmission losses through the enclosing structure and can be stated as

$$NR = 10 \log_{10} \frac{a}{\sum \tau S} \text{ db}$$

With the above information, noise reduction values can be determined for a given space and construction. These values can then be compared with the desired noise criteria. Or starting with a criteria and basic data on surface areas and room finishes, the required transmission loss values can be calculated for each type of construction. The constructions to satisfy the transmission loss requirements can then be chosen.

Noise reduction calculations can be determined for a construction at any frequency by using the corresponding values for the coefficient of absorption and for transmission loss. Determining the noise reduction a construction furnishes at several or all of the standard frequencies can be quite important in specific cases such as broadcasting studios and music studios, or in situations involving unusual frequency characteristics. However, it is normal practice to use the arithmetic average of the transmission loss values, in decibels, at the frequencies of 125, 250, 500, 1,000, 2,000 and 4,000 cps as the transmission loss value for a given construction. It is also normal practice to average the absorption coefficients at frequencies of 250, 500, 1,000 and 2,000 cps to the nearest 0.05 and use this value (called the noise reduction coefficient) as the coefficient of absorption of a given material.

CHAPTER VI

APPLICATION

The information contained in the preceding chapters together with observed sound level measurements will now be used for a solution to a particular problem in architectural acoustics. The problem simply stated, consists of the acoustical analysis of a building to be used for the instruction of engineering technologies. Special consideration is given to noises created by equipment used in the laboratories. In addition, economies of the various constructions that could be used in the solution are included.

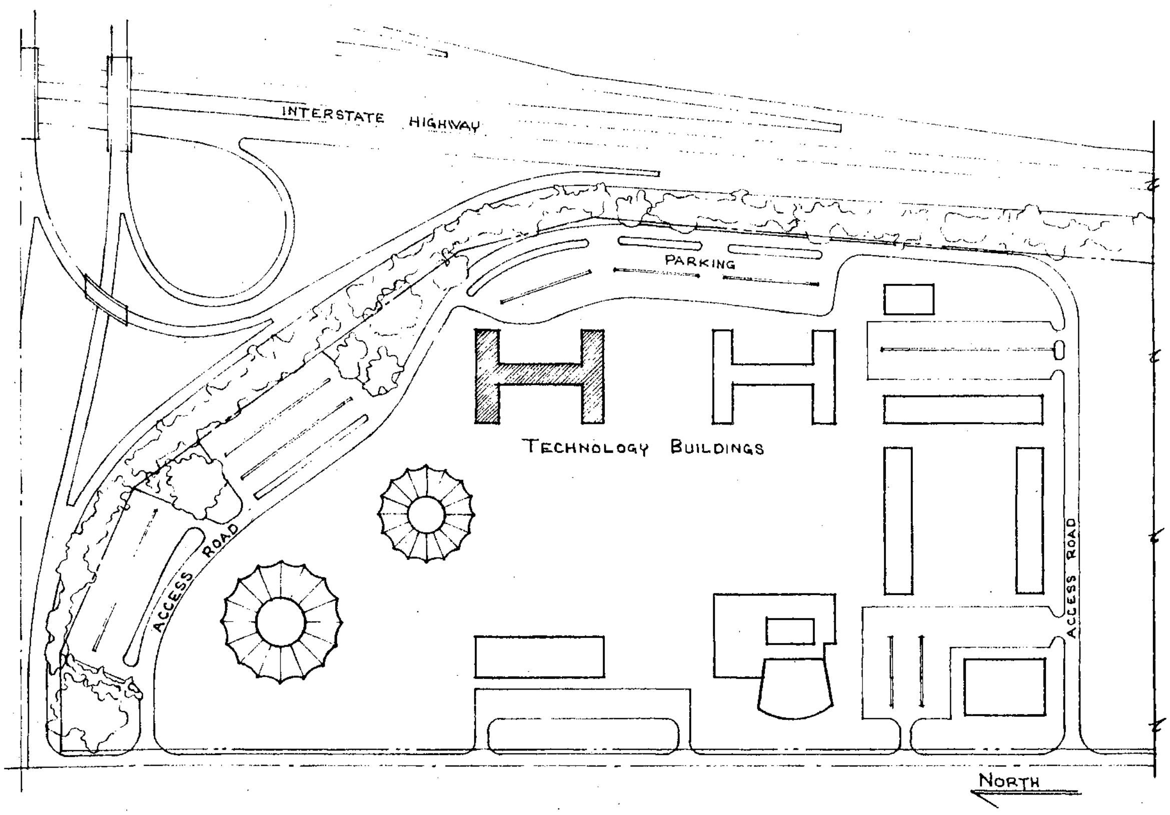


FIGURE 9 PLOT PLAN

The plot plan, Figure 9, shows the location of the proposed building (cross-hatched) and its relation to highways, access roads, parking areas, foliage and other buildings. Although there are other locations on the plot more secluded from traffic noises, the indicated location was dictated by the overall aspects of the campus development. The interstate highway along the east boundry of the plot is approximately 400 feet away from the building. This distance plus the continuous screen of foliage located close to the highway will be very helpful in reducing the highway traffic noise. From a study made at a building located in similar surroundings it was found that noises from traffic and pedestrians on the access road and parking areas created noises that were far more disturbing than was the traffic noise from the highway.

The architects preliminary layout of the building is shown in Figure 10. This arrangement of space is to be desired if economically and acoustically feasible since it provides complete separation of the instructional area from the office and conference areas.

Although the entire building must be considered for proper acoustic treatment the area considered in this analysis will be limited to the multipurpose space and surrounding rooms which are located in the north instructional wing on the first floor. This particular area is critical from an acoustical standpoint because of the relationship between the multipurpose room, which will often be used as a classroom requiring a quiet environment, and the materials testing laboratory which produces considerable noise. In addition, the multipurpose room will need to be shielded against noises from outdoors, interior noises from corridor and classroom and noises from the multipurpose room above. Since there is little or no spatial separation between the rooms, all noise reduction

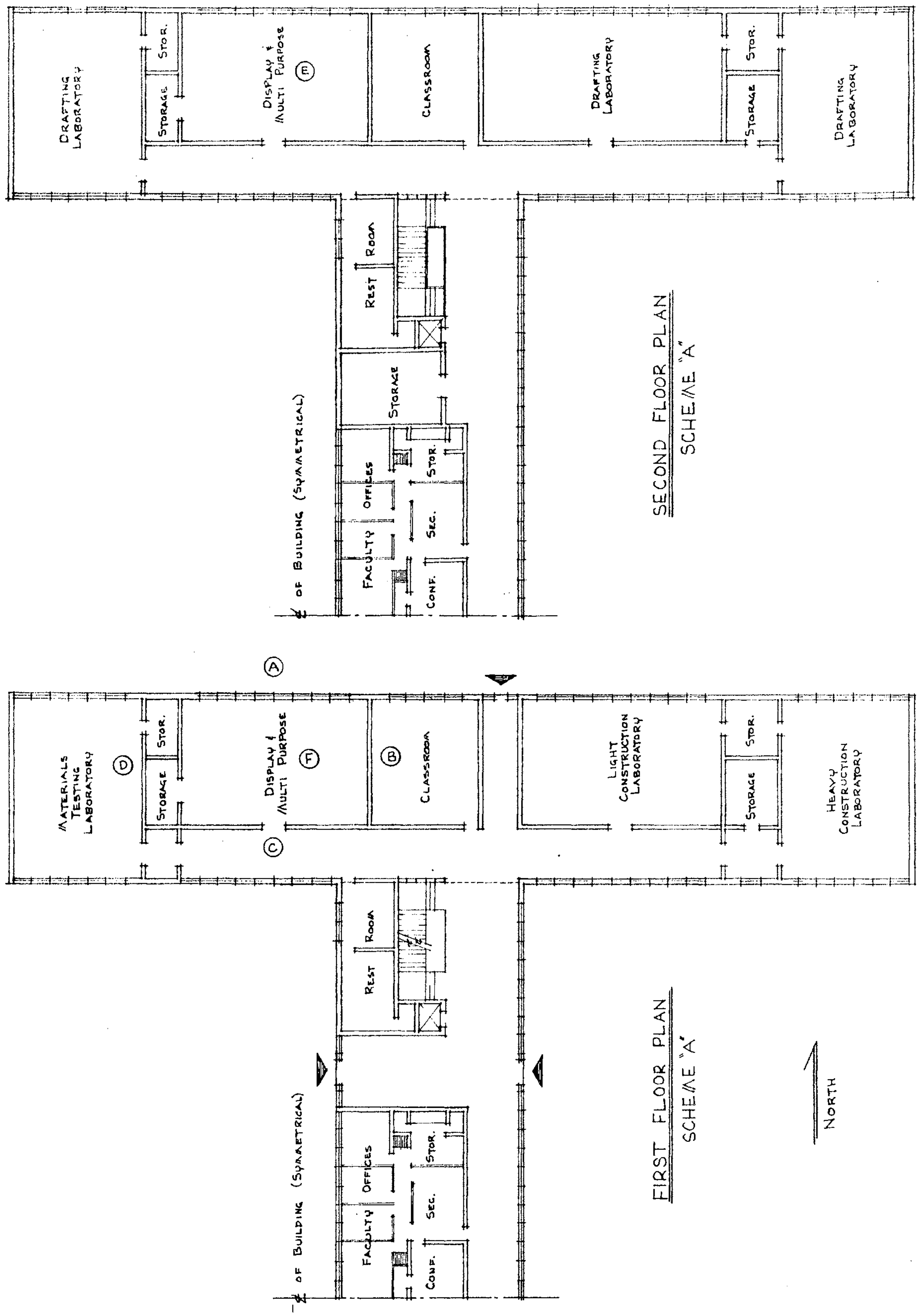


Figure 10. Floor Plans

must be provided by the insulative and absorptive construction surrounding the space.

It has been determined that the structural frame of the building will be reinforced concrete on pier and grade beam foundation. Piers and grade beams that are structurally adequate will be sufficient to dissipate the small amount of soil vibration anticipated in this location. The first floor of the instructional wings will be a concrete slab on grade, structurally separated from the foundation and walls, thus eliminating the transmission of vibrations between these elements.

The building has been planned so that all heavy operating machinery will be located on the ground floor and each machine will have a foundation isolated from the floor slab by resiliant material.

The second floor and roof will be reinforced concrete slabs integral with their supports; therefore, any vibration of these slabs will be transferred through the frame to the foundation and soil. The exterior walls will be non-loadbearing masonry and glass of such dimension and composition as required for acoustics. The interior partitions will also be non-loadbearing masonry as required for sound transmission loss and will extend from the floor to the underside of the structural slab above thus restricting the passage of sound between rooms via the suspended ceiling plenum.

There will be a complete structural break between the instructional wing and the central section of the building in order to eliminate the transmission of vibratory sounds from one section of the building to the other.

The mechanical systems, duct work, electrical equipment, pipe supports, outlet boxes and other devices will be considered properly designed acoustically and will not be considered further in this analysis.

Before an accurate analysis can be made of the required noise reduction to be provided by the enclosing walls, floor and ceiling, it will be necessary to first determine the existing sounds outside the multipurpose room and the acceptable sound level inside the multipurpose room, hereafter referred to as Room F. Sound level measurements are required outside Room F at the locations indicated by A, B, C, D, and E in Figure 10. Since the building is in the design stage it was necessary to make sound level measurements at similar locations and under similar conditions as those proposed in the design. Sound level measurements were made in accordance with recommended procedures using a type 1551-B sound level meter and a type 1558-A octave-band noise analyzer. To furnish more accurate values, at least three complete sound level measurements were taken and recorded for the existing noise sources over a period of approximately four months and at different times of the day to allow for the changes in foliage, wind, temperature, atmosphere and other surroundings which have some effect on sound levels. These values, shown in Table II, were then averaged for each frequency band. The Los Angeles abrasion machine and the Gilson screen shaker were bolted to the floor on rubber mounts and enclosed in an accessable housing composed of three layers of one-half inch fiberboard separated ty two, three-fourths inch air spaces. The portable Tyler sieve shaker was bolted to the floor but not enclosed.

Although all three of the machines would not always be operating simultaneously it is very probable that they would be operating together occasionally; therefore, the values for the machines operating simultaneously will be used in the noise reduction calculations. Also the back-

TABLE II

OBSERVED SOUND LEVEL MEASUREMENTS

Source of Noise	Conditions	All Pass	Frequency Band cps (C weighting) 75 150	150 300	300 600	600 1200	1200 2400	2400 4800
Location A - traffic and other outdoor noises	5 p.m., calm, clear	89	82	75	77	74	71	66
	noon, windy, clear	85	80	78	75	73	68	61
	8 a.m., calm, cloudy	82	82	74	73	71	66	60
	8 a.m., clam, clear	88	83	77	77	81	75	68
	Average	86	82	76	76	75	70	64
Location B (classroom) - students and instructor	Microphone	69	54	62	64	58	57	62
	12 to 20 ft. from	71	61	64	64	60	57	58
	speaker	72	68	66	67	64	60	58
	Average	71	61	64	65	61	58	59
Location C (corridor) - students	Between classes	76	74	77	80	81	79	78
	During class	64	54	58	61	62	60	58
	Noon	66	59	60	65	67	67	61
	Average	69	62	65	69	70	69	66
Location D (materials testing laboratory) - Los Angeles Abrasion Machine	Microphone	92	60	58	72	87	90	88
	5 to 12 feet	87	62	64	68	76	80	76
	from source	89	62	63	69	82	88	85
	Average	89	61	62	70	82	86	83
Gilson Screen Shaker	Same as above	93	89	80	79	82	84	84
		88	82	74	76	78	79	81
		89	87	78	78	80	82	82
	Average	90	86	78	78	80	82	82

(continued)

TABLE II (continued)

Source of Noise	Conditions	All Pass	Frequency Band cps (C weighting) 75–150	150–300	300–600	600–1200	1200–2400	2400–4800
Tyler Portable Sieve Shaker	Same as Above	87	74	67	68	76	77	80
		85	71	70	73	75	79	81
		87	73	69	70	76	80	81
	Average	86	73	69	70	76	79	81
All of the machines operating simultaneously	Same as Above	98	88	80	85	87	99	89
		94	83	79	82	83	85	83
		97	85	80	84	85	89	86
	Average	96	85	80	84	85	91	86

ground noise will be included since it is a part of normal laboratory operations. Due to the fact the machinery in the materials testing laboratory and traffic produce rather high low frequency sounds, calculations throughout will be based on absorption, transmission loss and measured sound level values at 125 cps and 500 cps. These calculations will determine not only the usual requirements for proper control of absorption and transmission of sounds for the average decibel levels represented by the values at 500 cps, but they will also determine the requirements for proper control of absorption and transmission of low frequency sounds.

The most critical usage for Room F, pertaining to the need for isolation, will be as a classroom. The acceptable sound levels for a classroom selected from Table I are 47 db at 125 cps and 32 db at 500 cps. The difference between the acceptable level in Room F and the existing levels outside the walls and ceiling of Room F is the number of decibels of noise reduction that each must provide. These values along with the existing and acceptable sound levels are listed in Table III.

TABLE III

NOISE LEVELS, db

Existing and Acceptable Noise Levels				Required Noise Reduction		
Location	Type	125 cps	500 cps		125 cps	500 cps
A	Existing	82	76	A-F	35	44
B	"	61	65	B-F	14	33
C	"	62	69	C-F	15	37
D	"	85	84	D-F	38	52
E	"	74	80	E-F	27	48
F	Acceptable	47	32			

It will be noted that the anticipated levels for location E are the same as those obtained between classes for location C in Table II. This is due to the fact that the multipurpose room above Room F will be used at times for purposes other than a classroom; such as student meetings, construction materials display and demonstration, and as a drafting laboratory.

From published data on transmission losses for various types of construction (1, 7) selections can now be made for the walls, floor, ceiling, windows and doors. Table IV indicates various wall, floor and ceiling components in current usage along with an estimated in place cost per square foot and their transmission loss values. The estimated costs are based on local labor and material costs furnished by material suppliers and general contractors in the Oklahoma City, Oklahoma, area.

Based upon the above data and architectural preference, the preliminary selection of materials will be as follows: The exterior walls will be eight-inch lightweight concrete blocks, painted, and three-inch precast concrete panels for the facing; the windows will be double glazed as shown in Table IV; the interior partition between Room F and the materials testing laboratory will be composed of two, four-inch lightweight concrete block walls separated by a two-inch air space and painted on exposed sides; all other interior partitions will be eight-inch lightweight concrete blocks, painted; interior doors will be one and three-fourths-inch hollow core, flush, with rubber gaskets around sides and top, and door felt at the bottom. The ceiling and floor system for the second floor will be a concrete slab with a suspended ceiling on resilient hangers.

Having made a preliminary selection of the enclosing construction it will now be necessary to determine and provide the absorption required for optimum reverberation. Room F, shown in Figure 11, is 28 feet by 40 feet in plan with a ceiling height of nine feet, and has a volume of 10,480 cubic feet. From the optimum reverberation charts, Figures 4

TABLE IV

COST AND TRANSMISSION LOSS VALUES FOR VARIOUS
WALL, FLOOR AND CEILING COMPONENTS

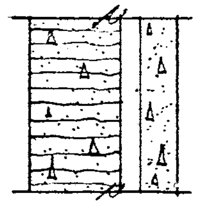
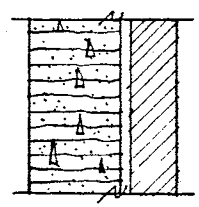
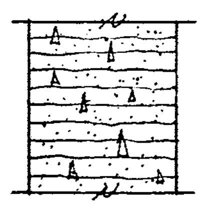
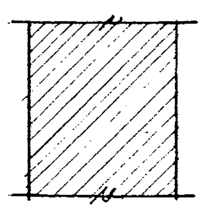
Construction	Section	Estimated Cost in Place per sq. ft.	Transmission Loss, db 125 cps	500 cps
8 in. lightweight concrete block back-up, painted; 3 in. precast concrete panels, broomed finish.		$2.85	43	52
8 in. lightweight concrete block back-up, painted; 4 in. face brick.		2.05	45	53
12 in. concrete block homogenous wall, built up of 8 in. and 4 in. blocks; painted both sides.		1.60	50	49
12 in. solid brick wall, combination of common and face brick.		2.50	45	53

TABLE IV (Continued)

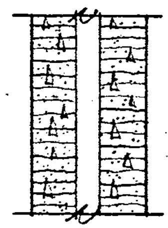
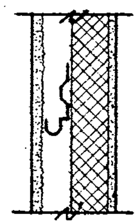
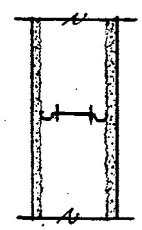
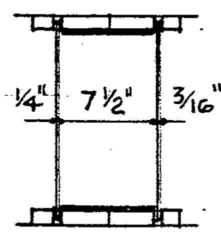
Construction	Section	Estimated Cost in Place per sq. ft.	Transmission Loss, db 125 cps	500 cps
Two 4 in. lightweight concrete block walls, painted both sides and separated by 2 in. air space.		$1.25	39	55
3 in. gypsum tile; on one side 1/2" gypsum plaster; on the other side, spring clips attached to expanded metal lath with 7/8" gypsum plaster.		1.45	45	55
3-1/4" steel truss studs 16 in. o.c.; on each side spring clips 16 in. o.c. fastened to studs, 1/4" metal rods wire-tied to clips, metal lath wire-tied to metal rods, and 3/4" gypsum plaster.		1.50	50	55
Double glazed with 1/4" and 3/16" plate glass; sealed with resilient material at edges; absorbent lined interior.		3.25	33	45

TABLE IV (Continued)

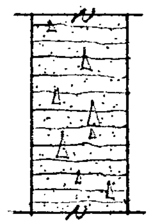
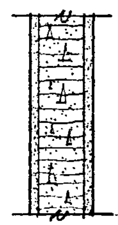
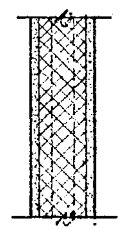
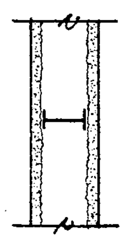
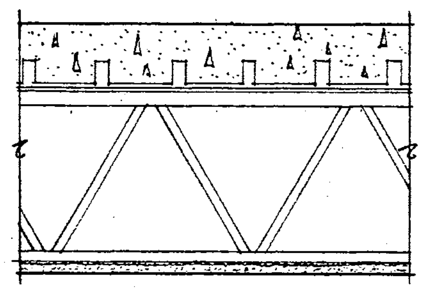
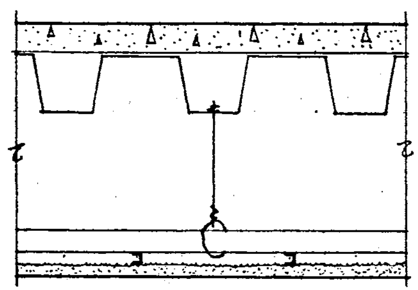
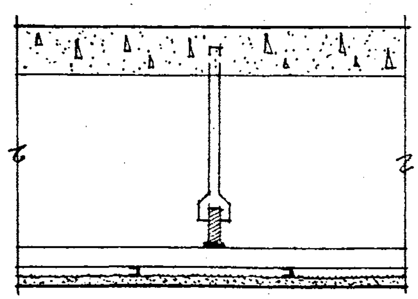
Construction	Section	Estimated Cost in Place per sq. ft.	Transmission Loss, db 125 cps	500 cps
8 in. lightweight concrete block, painted.		$0.90	24	43
4 in. lightweight concrete block with 1/2" gypsum plaster each side.		0.95	37	38
4 in. hollow gypsum blocks with 1/2" gypsum plaster each side.		0.95	37	38
3-1/4" steel trusses 16 in. o.c. for studs; on each side expanded metal lath wire-tied to studs, and 3/4" gypsum plaster.		1.05	40	37

TABLE IV (Continued)

Construction	Section	Estimated Cost in Place per sq. ft.	Transmission Loss, db 125 cps	500 cps
Steel joists 20 in. o.c.; on floor side high-rib metal deck attached to joists, 2-1/2" of concrete; on ceiling side, high-rib metal lath attached to joists and 3/4" gypsum plaster.		$1.10	40	54
Steel floor section with flat top; on floor side, 2" of concrete; on ceiling side a suspended ceiling of expanded metal lath and 7/8" gypsum plaster.		1.65	34	52
4 in. concrete slab; on ceiling side a suspended ceiling of channels, metal lath and 3/4" plaster. The ceiling is suspended by metal hangers imbedded in the concrete slab and attached to the channels by a coiled spring and pieces of felt.		1.80	37	51

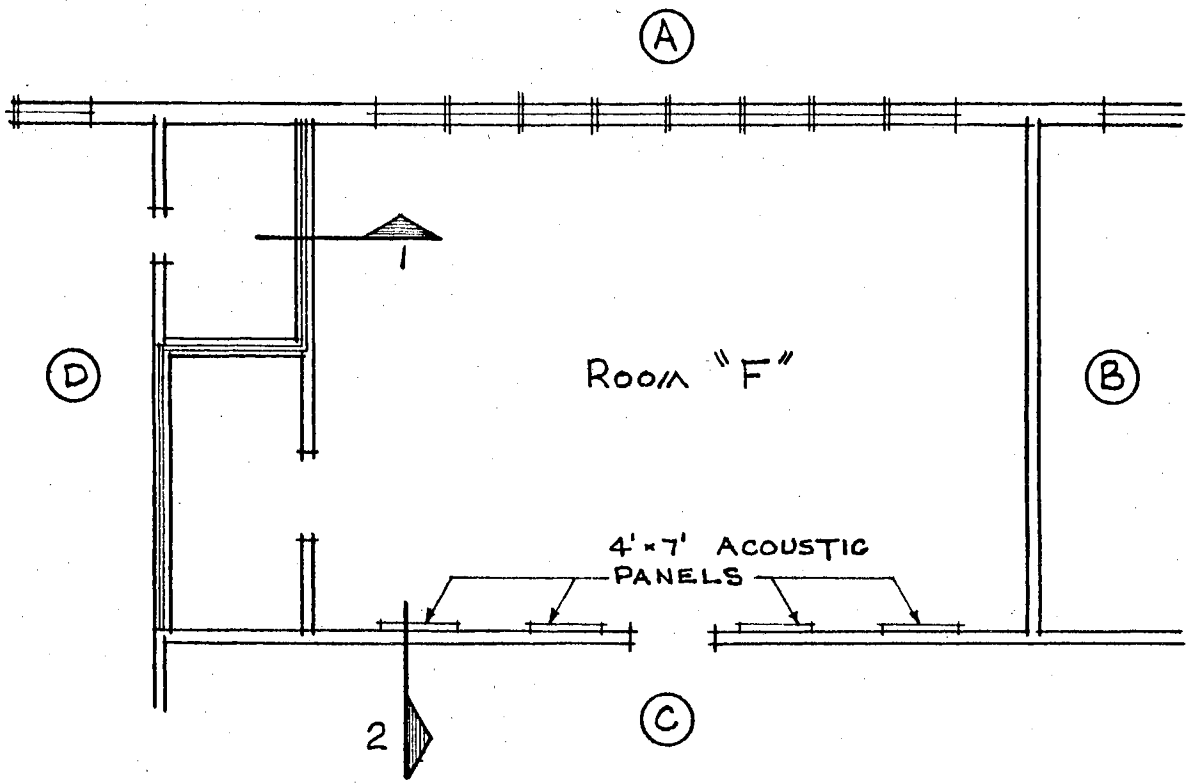


Figure 11 Floor plan

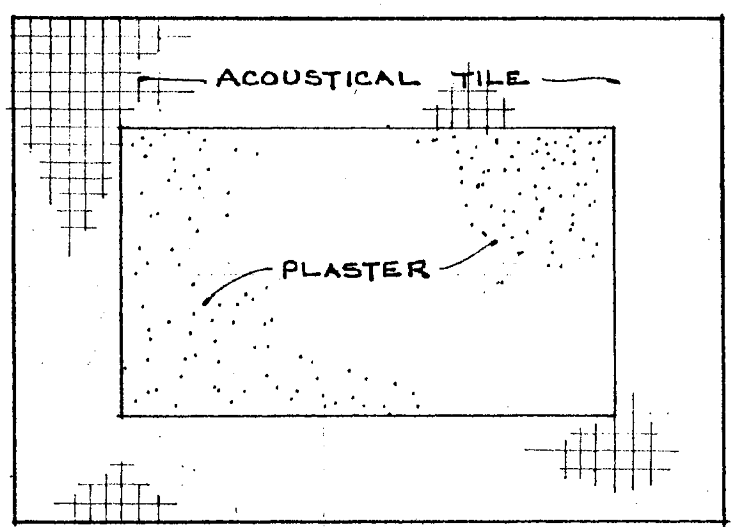


Figure 12 Reflected ceiling plan

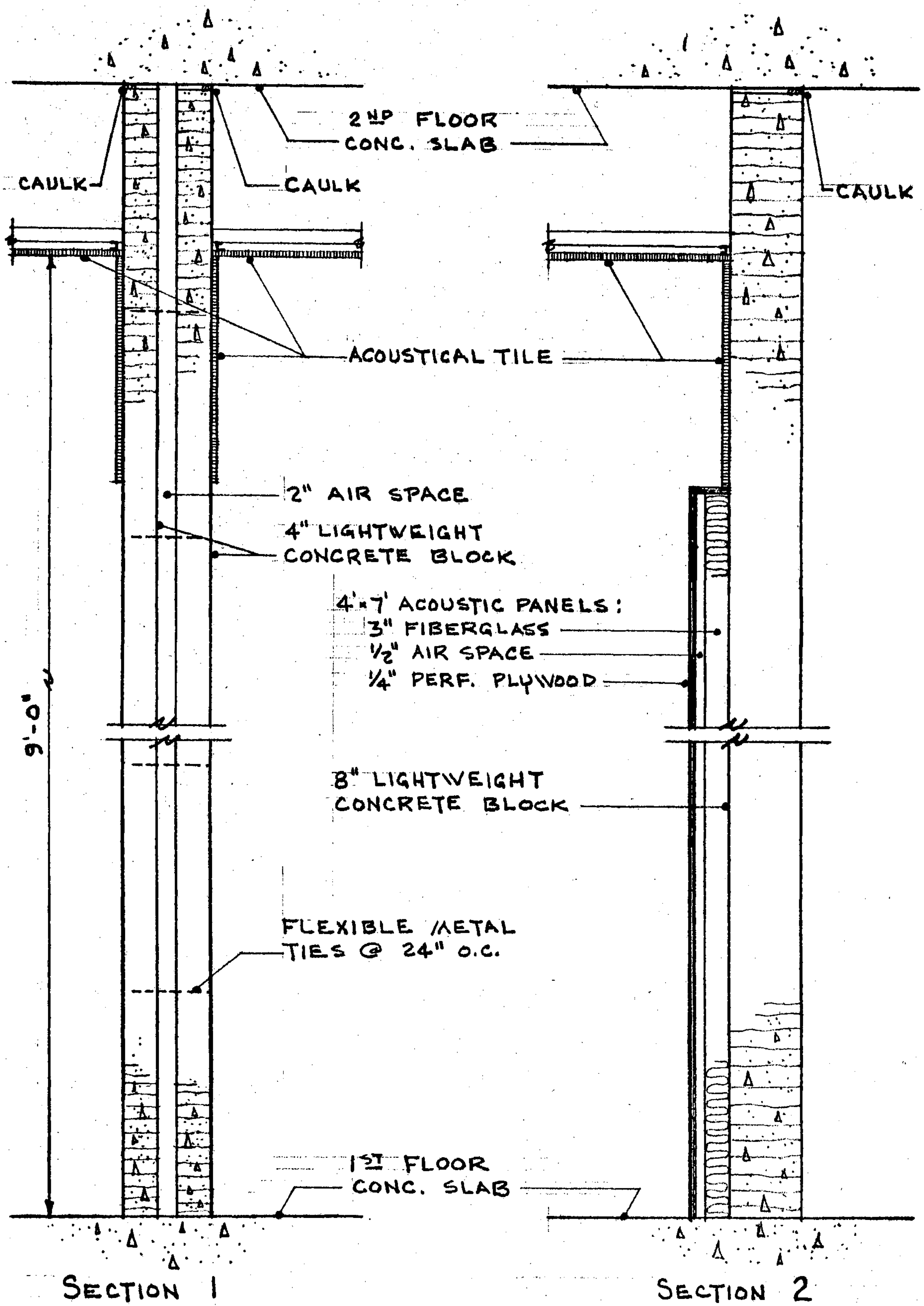


Figure 13 Wall and ceiling details

and 5, T_{500} = 0.72 seconds and T_{125} = 0.72 x 1.4 = 1.0 second for speech usage; therefore, $A_{125} = \frac{.05 \times 10,480}{1.0} = 524$ units of absorption required at 125 cps and $A_{500} = \frac{.05 \times 10,480}{0.72} = 728$ units of absorption required at 500 cps. A preliminary investigation showed the absorption furnished by the surface finishes of the enclosing structure to be inadequate; therefore, highly absorptive material was added to the ceiling and walls. In order to provide some reflection from the ceiling, acoustic tile was used only around the outer edges of the ceiling and the upper part of the walls; also absorptive panels were placed along one side wall to control flutter echoes. These details are shown in Figures 12 and 13. The additional absorptive material increased the total absorption units in Room F to near the optimum as seen in Table V.

TABLE V

ABSORPTION CALCULATIONS FOR ROOM F

		Area	125 cps		500 cps	
		Sq. Ft.	Coef.	Units	Coef.	Units
Floor:	Rubber Tile	1120	.02	22	.03	34
Walls:	Painted block	828	.10	83	.06	49
	Acoustic tile	136	.19	26	.68	93
	Plate glass	128	.18	23	.04	5
	Flush panel door	20	.09	2	.10	2
	Acoustic panels	112	.22	22	.62	69
Ceiling:	Plaster	448	.02	9	.03	13
	Acoustic tile	672	.48	322	.57	383
Upholstered Seats		30	.15	5	.22	7
People		15	2.5	38	4.5	68
TOTAL UNITS				552		723

TABLE VI

NOISE REDUCTION CALCULATIONS

Construction		Area(s) Sq. Ft.	125 cps.				500 cps.			
			TL	τ	τS	NR	TL	τ	τS	NR
A to F	Concrete wall panels + 8" block, painted.	232	43	0.00005	0.01160		52	0.0000063	0.001461	
	Double plate glass sealed at edges	128	33	0.00050	0.06400		45	0.0000320	0.004096	
					0.07560	38.4			0.005557	51.2
B to F	8" L.W. concrete block wall, painted	252	24	0.00398	1.00296		43	0.0000500	0.012600	
					1.00296	27.2			0.012600	47.6
C to F	8" L.W. concrete block wall, painted	340	24	0.00398	1.35320		43	0.0000500	0.017000	
	Wood door, rubber gasket around all edges	20	28	0.00160	0.03200		29	0.0013000	0.026000	
					1.38520	25.7			0.043000	42.3
D to F	Two 4" L.W. concrete block walls with 2" air space between, exposed sides painted	252	39	0.00013	0.03276		55	0.0000032	0.000806	
					0.03276	42.0			0.000806	59.5
E to F	Concrete slab with ceiling suspended on resilient hangers	1120	37	0.00020	0.22400		51	0.0000079	0.008848	
					0.22400	33.7			0.008848	49.2

It will be noticed that seats and people are included in the absorption calculations. The room will accomodate more than fifteen people; therefore, when a greater number is present the absorption will increase. This will not affect the reverberation time to any great extent because the noise will usually increase proportionately.

The actual noise reduction provided by the materials making up each wall, floor and ceiling can now be determined using the equations of Chapter V. The contributing information and results are shown in Table VI. The noise level in Room F caused by the sound level at **A** is equal to the sound level at **A** minus the noise reduction provided by the construction between noise source **A** and Room F. For example, at 125 cps the sound level at **A** equals 82 db and from Table VI the noise reduction provided by the exterior wall is 38.4 db; therefore, the noise level in Room F due to the sound level at **A** equals 82.0 - 38.4 = 43.6 db. The noise level in Room F caused by any one of the noise sources can be determined in like manner for any frequency as shown in Table VII.

TABLE VII

NOISE LEVELS IN ROOM F

	125 cps			500 cps		
Noise Source	Sound Level	NR Provided	Noise Level Room F	Sound Level	NR Provided	Noise Level Room F
A	82	38.4	43.6	76	51.2	24.8
B	61	27.2	33.8	65	47.6	17.4
C	62	25.7	36.3	69	42.3	26.7
D	85	42.0	43.0	84	59.5	24.5
E	74	33.7	40.3	80	49.2	30.8

The peak noise level that could occur in Room F is not the sum of the noise levels shown in Table VII, but can be calculated as follows:

At 125 cps

$$\text{Antilog}_{10}\ (43.6/10) = 22{,}910$$
$$\text{Antilog}_{10}\ (33.8/10) = 2{,}399$$
$$\text{Antilog}_{10}\ (36.3/10) = 4{,}266$$
$$\text{Antilog}_{10}\ (43.0/10) = 19{,}950$$
$$\text{Antilog}_{10}\ (40.3/10) = \underline{10{,}715}$$
$$60{,}240$$

$$10\ \text{Log}_{10}\ 60{,}240 = 47.8\ \text{db}$$

At 500 cps

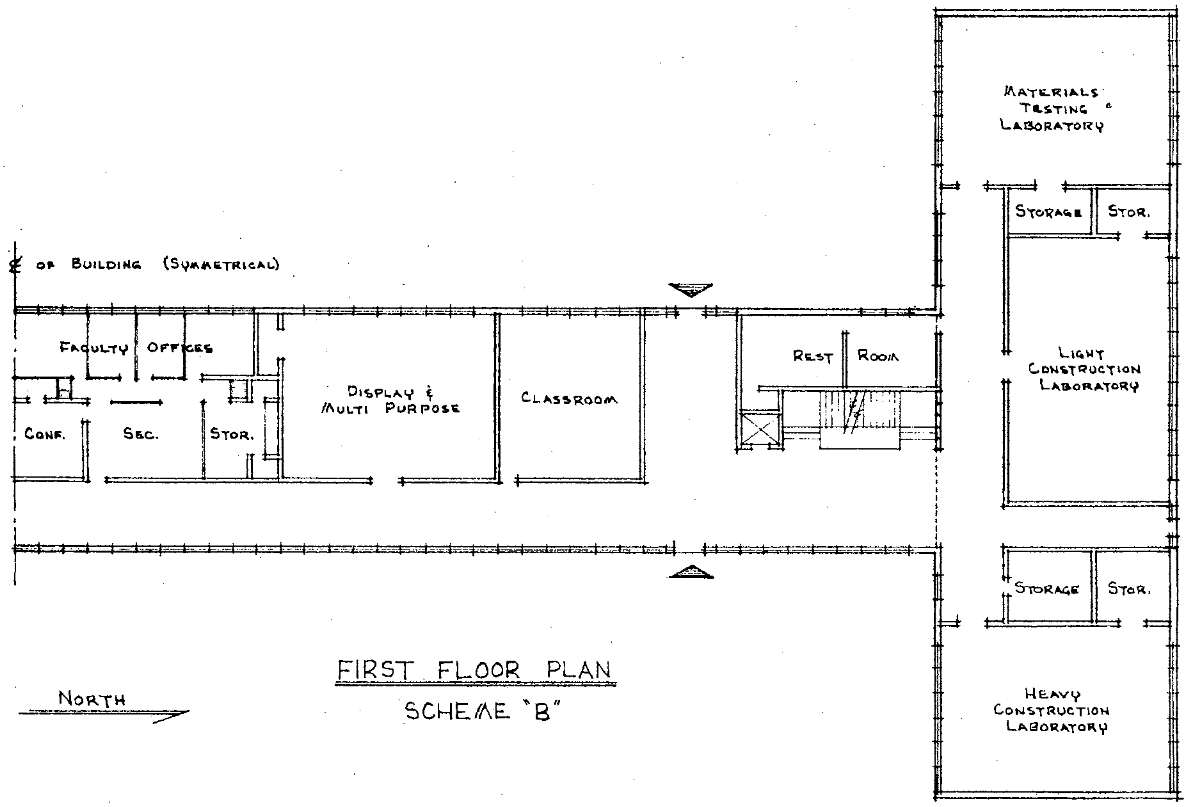
$$\text{Antilog}_{10}\ (24.8/10) = 302$$
$$\text{Antilog}_{10}\ (17.4/10) = 55$$
$$\text{Antilog}_{10}\ (26.7/10) = 468$$
$$\text{Antilog}_{10}\ (24.5/10) = 282$$
$$\text{Antilog}_{10}\ (30.8/10) = \underline{1{,}203}$$
$$2{,}310$$

$$10\ \text{Log}_{10}\ 2{,}310 = 33.6\ \text{db}$$

These values compare favorably with the acceptable noise levels for a classroom as indicated in Table I; that is, 47 db at 125 cps and 32 db at 500 cps.

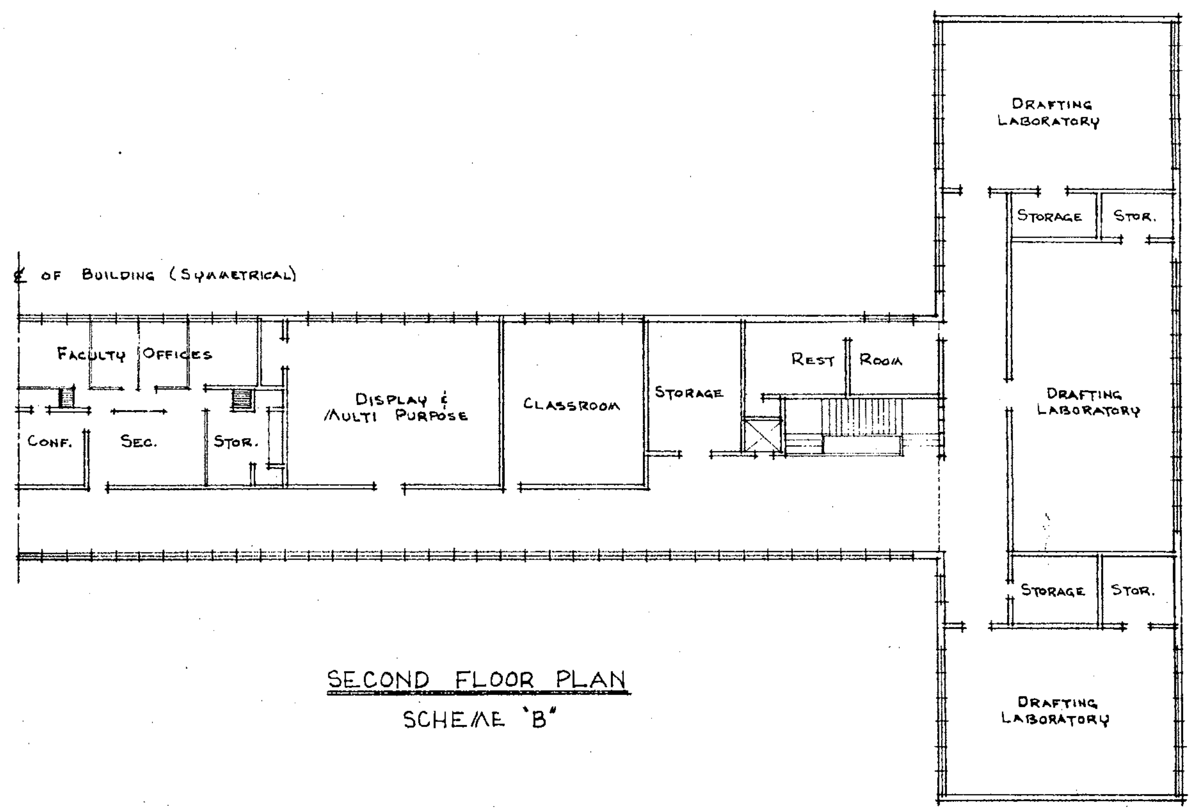
Based upon the above analysis, the construction elements and the absorptive material preliminarily selected for Room F would provide satisfactory acoustics. Similar construction could be used for the remainder of the building; however, each area would need to be checked for proper reverberation and distribution and any area or sound level of unusual nature must be investigated thoroughly.

From an acoustical and an economical viewpoint it would appear advantageous to move the classroom and the multipurpose room in each wing into the center office section as shown in Figure 14. This change would eliminate the need for the double wall between the noisey laboratories and the multipurpose rooms and would probably eliminate the



FIRST FLOOR PLAN

SCHEME "B"



SECOND FLOOR PLAN

SCHEME "B"

FIGURE 14 FLOOR PLANS

double doorways into the laboratories; however, there would still need to be a very good door at this location since doors are a major contributor to the transmission of sound. The decision as to which plan would function best would ultimately be made by the architect, based upon acoustic requirements as well as all the other aspects of design.

CHAPTER VII

SUMMARY AND CONCLUSIONS

In this study an investigation of the principles, methods and materials of architectural acoustics is made and the resulting knowledge is used to acoustically analyze a structure to be used for instructional purposes. Particular attention is given to noises produced in classrooms and corridors and by laboratory equipment and vehicular traffic. A cost comparison of various wall, floor and ceiling constructions that are acoustically adequate for the analysis are included.

Architectural acoustics, though not an exact science, has shown rapid progress in this century and has gained wide acceptance as a necessary environmental aspect for all types of buildings. Functional planning for proper acoustics is very basic in the preliminary design of a building. The separation of quiet and noisy areas in the layout of a building is essential for an economical solution to sound control. Site selection and the location of a building on the site determines the type and magnitude of outdoor noises to be controlled. Proper detailing of a structure is necessary to prevent the passage of airborne sound through openings and solid-borne sound between rigidly connected elements.

From the sound level measurements taken in connection with the investigation it was observed that there was considerable variation between the sound levels for the different frequency bands as well as within a given frequency band. This indicates that several measurements would need to be made to determine the proper magnitude of a sound to be used in any analysis. It was also observed that the type and frequency of a sound rather than the magnitude often dictates the criteria for noise control.

Additional investigation of existing sounds for varying conditions and seasonal changes needs to be conducted and the results made available to practicing architects and engineers for their use in acoustical designing.

The need for proper sound control in buildings is presently evident and will continue to increase as the population increases and the environment becomes more complex.

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