ACOUSTICS OF BUILDINGS

With Applications in the Pentagon

By FLOYD R. WATSON

INTRODUCTION

Acoustics of buildings is that part of the science of physics which deals with the control of sound in buildings. Since the purpose of this control is to create conditions by which people can hear with comfort, it is necessary to consider not only the principles of sound but to take into account also the phenomena of hearing.

SOUND AND ITS ACTION

Sound is similar to light in many of its actions; it is reflected, refracted, diffracted, etc., as light is, but it should be realized that it is entirely different fundamentally. Sound is a mechanical wave motion in a material medium, while light is an electro-magnetic phenomenon in the fictitious ether. Another difference which is important in the acoustics of buildings, is that the average wavelength of sound is about one million times greater than the average wavelength of light, so that objects that are optically "large" are acoustically "small." Thus, a rough plaster wall acts as a polished mirror for sounds of moderate frequency; a partly opened window diffracts sound in about the same proportion that the fine lines on a grating diffract light.

Sound originates when a vibrating body pushes and pulls on the air particles about it, thus generating compressions and rarefactions that travel out in the surrounding air with a large velocity of about 1100 feet per second. These waves enter the ear canal and push and pull on the ear drum, which transmits the motion through an effective arrangement of three small bones to the inner ear, where the mechanical energy is transformed into nervous energy and the person hears.

Sounds in a building are of two kinds: those that are wanted and those that are objectionable (noise). The unwanted sounds should be eliminated as far as possible, while the wanted sounds should be adjusted for comfortable hearing. Sound is a form of energy, and energy cannot be destroyed. To eliminate sound, therefore, requires a transformation to some other form of energy, ultimately heat. Thus, sound waves impinging on a porous structure are absorbed when they set up a friction between thin layers of air and the adjacent solid material to which the layer adheres, with a consequent creation of heat. Sound energy is also used up when it generates vibrations in windows, doors, partitions, etc. The amount of energy in sound is small, an average voice having only about one-millionth of the energy needed to operate an ordinary electric lamp, which means that but little heat is generated when sound is absorbed.

HEARING

The limits of sound that can be perceived by the normal ear are shown by the diagram in *Fig. 1.* The lower heavy line (threshold of hearing) shows the faintest sounds that can be perceived, while the upper curve locates the loudest sounds that can be endured without harmful effects. Ordinary speech sounds lie between the frequencies of 100 and 8000 cycles per second, but musical sounds cover a greater range. The intensity range that can be tolerated lies between zero decibels (threshold) and 120 decibels, the latter sound being very loud, as explained later.

Many people are hard-of-hearing, a fact that must be remembered in adjusting the acoustical conditions in rooms. For a hard-of-hearing person, the threshold of hearing curve lies above the one shown in *Fig. 1*, indicating that the fainter sounds, including some of the sounds of speech and music, cannot be heard by the person, and that some sort of hearing aid may be needed.

APPLICATIONS IN ACOUSTICS OF BUILDINGS

The procedure followed by acoustical engineers in designing acoustical treatment is, first, to anticipate the possibilities of noise before a building is started and to make provision to reduce the disturbances. The second procedure is to adjust conditions so that the wanted sound will be loud enough and undistorted.

A detailed account of acoustical treatment is not possible in a brief article, but some general principles may be discussed. Consider the disturbances set up by a typewriter in an office. It generates a "click" when a type

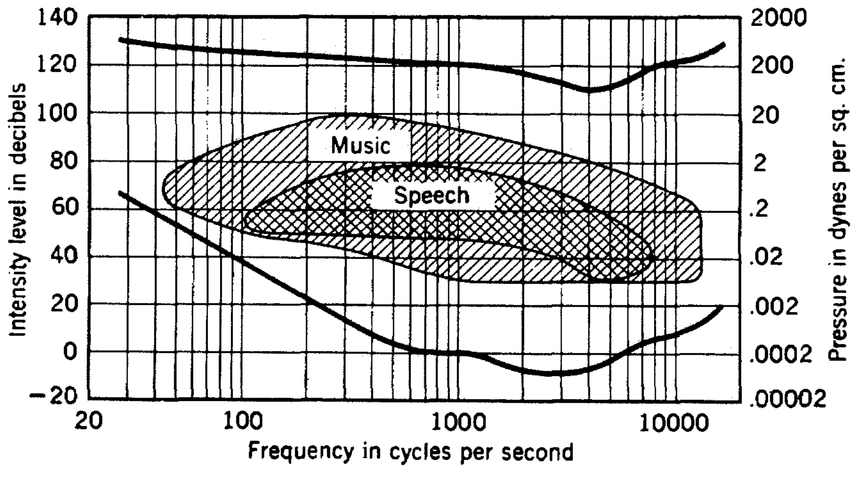

FIG. 1. (Left) Limit of sound that can be perceived by the normal ear.

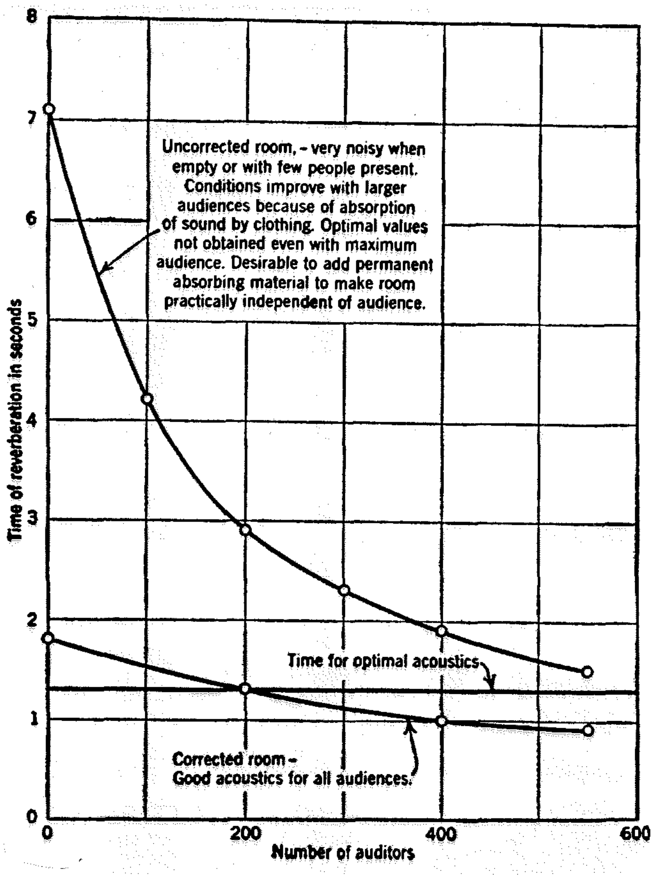

FIG. 2. (Right) Reverberation time for auditorium as a function of the size of the audience.

hits the paper and a "thump" when the carriage is stopped abruptly after each click. The click sound is effectively stopped (reflected) when it meets a solid boundary of the room, and if this boundary is lined with sound-absorbing material, much of the click sound disappears. The thump creates a vibration that is communicated to the table, then through the table legs to the floor, where it spreads out through the solid structure of the building and may be heard, usually in the room below. An elastic felt cushion under the machine presents an effective reduction in the transmission of the disturbance. This same procedure applies also to other machines, such as calculating machines, motors, etc., but more drastic action must be taken for these more intense disturbances. Grouping noisy machines in separate rooms allows a better control of the sound by mounting each machine on an elastic support and by installing sound-absorbing material on sound-proof walls.

The theory and practice of insulating machines is a large subject in itself. The resonance frequency of the elastic support is an important factor compared with the frequency of the machine that is supported. If the two frequencies are the same, a resulting motion is set up with a large amplitude that may result in damage. Gen-

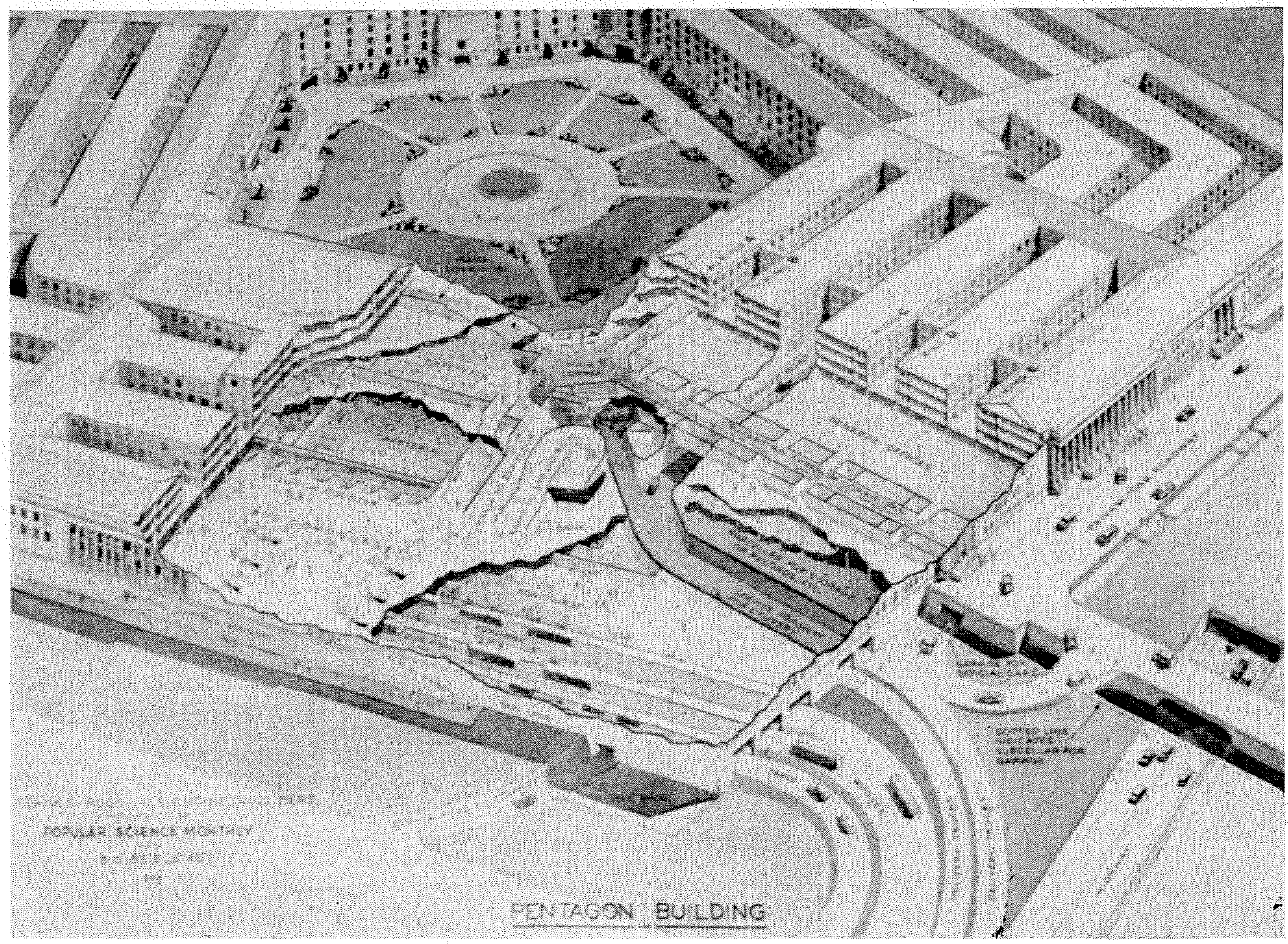

FIG. 3. Pentagon Building.

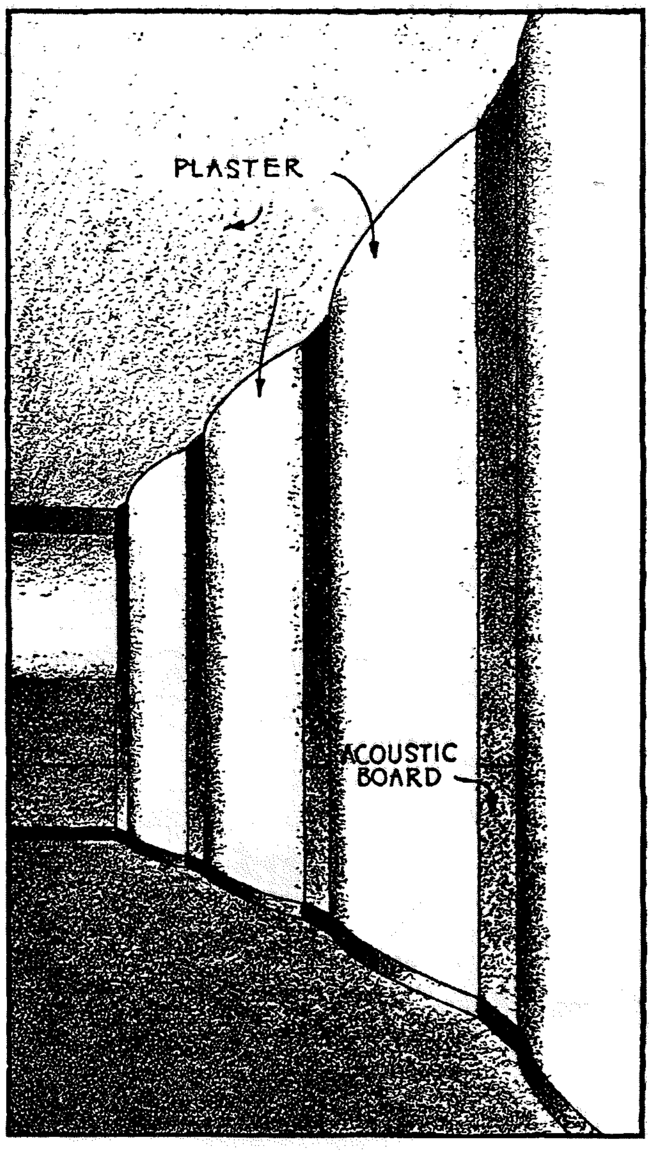

FIG. 4. Acoustic treatment of walls with convex panels—Pentagon Building.

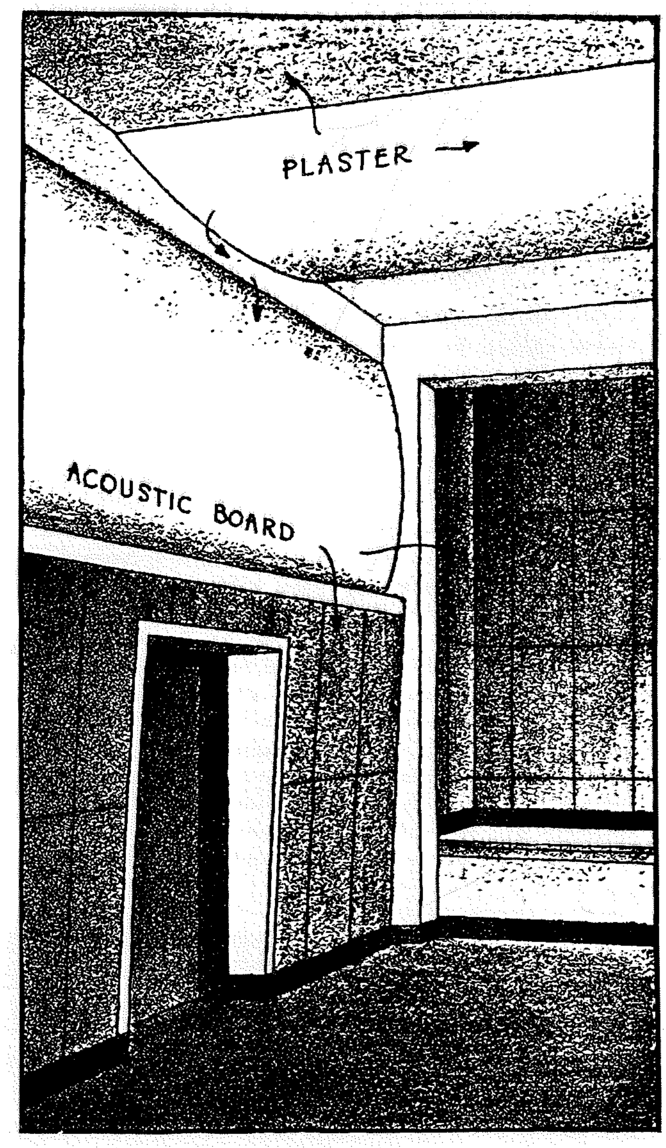

FIG. 5. Acoustic treatment of ceiling with convex panels—Pentagon Building.

erally, high-frequency machine vibrations require an elastic mounting of low frequency and without friction, but low frequency or impulsive vibrations should have an elastic mounting *with* damping. (See *Mechanical Vibrations*, by J. P. den Hartog, and other texts.)

Air openings between rooms, such as ventilators, transoms, cracks under and around doors, etc., allow easy transfer of sound. Doors and windows transmit more sound than the adjacent thicker and more massive walls. Unless these defects are corrected, it will be a waste of effort to construct sound-proof walls. Ventilators can be equipped with baffles and lined with sound-absorbing materials; doors and windows can be made tight-fitting. When effective insulation is wanted, double doors and windows should be installed. Generally, the objective is to make all the boundaries of the room equal in stopping sound.

Noise is measured in units called decibels. The intensities of sounds that the ear can tolerate range from a threshold sound—one that can barely be perceived—to that of a very loud sound, such as a nearby airplane, that may be as much as 1,000,000,000,000 times greater than the threshold. Such large numbers were found to be awkward to use in practice, so that smaller numbers were obtained by taking logarithms of the intensities. The decibel difference between two sounds of intensities I_1 and I_2 is given by the equation:

$$db = 10 \times \log_{10} (I_2/I_1)$$

where *db* is the usual abbreviation of decibel. For example, if I_1 and I_2 represent respectively the intensities of one musical instrument and 10 similar instruments, the *db* difference between them is: $db = 10 \times \log (10/1) = 10 \times 1 = 10\ db$. It might be remarked further that the 10 instruments would appear to be only about *twice as loud* as one instrument.[1]

ACOUSTICAL ADJUSTMENT OF ROOMS

A sound in a room proceeds rapidly outward in spherical waves with but little absorption until a surface is reached. Here the sound suffers some absorption and is reflected to another surface for more absorption and reflection, and so on until it becomes inaudible. For example, in a room with a volume of 100,000 cubic feet, bounded by 20,000 square feet of hard plaster walls and wooden floor that absorb an average of three per cent of

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[1] Fletcher and Munson, *Jour. Acous. Soc. Amer.*, 9, 1, 1937.

the sound at each reflection, calculations show that while the sound is decreasing in energy to one-millionth of its initial value it will be reflected 461 times and will travel a distance of 9,220 feet in a "time of reverberation" of 8.22 seconds.[2] Under these conditions, the acoustics will be very unsatisfactory. Before one word of a speech dies out, several later words will have been uttered and will have been mixed with the earlier ones, thus producing a confusion that makes it almost hopeless for an auditor to understand what is being said. The obvious improvement is to make the sounds die out quicker by making the room more absorptive.

The correction is brought about by installing sound-absorbing materials on the boundaries of the room. The amount of absorption needed is calculated from the simplified form of the general reverberation equation:

$$t = 0.05V/a$$

where t is the time taken for a sound to decrease to one-millionth of its initial value, V is the volume of the room in cubic feet, and a is the total amount of sound absorption. For satisfactory acoustics the time should be reduced to about two seconds for a large auditorium of 1,000,000 cubic feet, with greater reductions for smaller rooms. Details of calculation may be found in texts on the subject.[3] *Fig. 2* illustrates graphically how a reverberant school room may be corrected.

RESONANCES

The action of sound in a room as just described is modified by what are called normal modes of vibration. That is, sound proceeding in certain directions is amplified when successively reflections cause the waves to unite so as to make these particular sounds louder. This result is noticeable in a bath room which has highly reflecting surfaces whereby sounds of appropriate frequency are increased in volume. The equation for the frequencies, f, of these "normal modes," as they are called, is as follows:

$$f = \frac{c}{2}\left[\left(\frac{p}{l}\right)^2 + \left(\frac{q}{w}\right)^2 + \left(\frac{r}{h}\right)^2\right]^{\frac{1}{2}}$$

where p, q, and r are numbers, 0, 1, 2, 3, etc., for different modes; l, w, and h are respectively the length, width, and height of the room; and c is the velocity of sound. As an example, if $q = 0$, $r = 0$, then $f = cp/(21)$, which gives the normal vibrations parallel to the length of the room. If the length of the room is 10 feet, the velocity of sound 1,120 feet per second, and $p = 1$, then $f = 1{,}120/(2\text{x}10) = 56$ cycles per second. For $p = 2$, $f = 112$ cycles per second, etc. Similar vibrations can be set up parallel to the width and height of the room. Diagonal vibrations can also take place as for example, when $p = 1$, $q = 1$, and $r = 0$.

Resonances are objectionable because they amplify some frequencies more than others, thus interfering with a uniform distribution of sound in a room. What is desired are conditions that will allow all auditors wherever they may be located to get satisfactory hearing. One method for correcting the difficulty is to modify the walls and ceiling by convex panels which diverge the reflected waves, thus reducing the possibilities of resonance and increasing the uniform distribution sound. Sound-absorbing materials installed between the convex panels serve to control the reverberation and also to reduce the noise level in the room.

PUBLIC ADDRESS SYSTEMS

A very important new development in the acoustics of rooms has been brought about by the use of public address systems, which might be designated more appropriately as sound-amplifying systems. These consist of a microphone that "picks up" the sound of speech or music and converts the sound energy into an electric current, which is amplified and reconverted back into a louder sound that is emitted from an electric loud-speaker directly to the audience. Thus, instead of the comparatively weak sound of the speaker's voice that spreads out in spherical waves to all parts of a room, the loud-speaker emits a powerful beam of sound that is sent directly to the area occupied by the audience. This arrangement is comparable to the action of an automobile headlight on a foggy day that serves to reveal the presence of the automobile to oncoming cars. The loud-speaker may be regarded as an acoustic headlight that pierces the "fog" or reverberant sound in the room and "shines" on the auditor, thus allowing him to "see" (hear) the sound. A satisfactory sound-amplifying system allows all the auditors in the room to get sufficient sound, those in the rear seats getting just as loud sounds as those in the front seats near the speaker. The system also raises the sound level, which tends to hold the attention of listeners more effectively than the usual weaker sounds of speaking—a feature that is welcomed particularly by the hard-of-hearing.

IN THE PENTAGON BUILDING

An opportunity for the application of the acoustical procedures just described was given in The Pentagon. First of all, a noise survey was conducted in various public buildings in Washington to obtain information about the disturbances to be expected in The Pentagon Building, which was then in the process of construction. Sound-level readings were taken of the noises of calculating machine rooms, elevators, air-conditioning machinery, cafeterias and the Union Depot. An investigation was also made to get information about available sound-absorbing materials. Large samples of these materials were mounted for inspection, and detailed data were collected concerning the qualities of the products and the cost of installation.

Fig. 3 gives a perspective of The Pentagon. It reveals a large variety of rooms and spaces, starting with the bus terminal on the ground floor, the large concourse over it, cafeterias, lunch rooms, a multitude of offices, miles of corridors, etc. The perspective shows five concentric pentagonal buildings about the central court, connected by radiating corridors. The building covers 32 acres, including the 6-acre court, and is expected to accommodate as many as 40,000 people.

The chief features of the acoustical treatment are given as follows: Machinery for the air-conditioning system and for other purposes was placed on the top floor, remote from the main activities of the building, in rooms that were sound-deadened and that were equipped with sound-proof walls when they were adjacent to offices. The machines selected were chosen from the "quiet-running" types and were mounted on elastic supports. On the ground floor, the bus terminal ceiling was covered with a material (metal-clad rockwool) that was highly absorptive, fireproof, and could be cleaned or painted without acoustic loss. In the hundreds of office rooms, the ceilings were deadened with various types of materials. The noise of the Lamson tube system was reduced by a special device for minimizing the explosive sound when packets left the tubes, and by deadening material in the central control room and in the outlets in different parts of the building. A small auditorium and several review rooms received special study. Convex panels in the walls and ceiling were used to promote uniform dis-

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[2] F. R. Watson, *Acoustics of Buildings*, 31.

[3] V. O. Knudsen, *Architectural Acoustics*; P. E. Sabine, *Acoustics and Architecture*; F. R. Watson, *Acoustics of Buildings*.

Name	Class	Rank	Service	Location
Llewellyn, F. E.	'38	Lt. (j.g.)	U.S.N.R.	Washington, D. C.
Loeffler, D. E.	'40	*	U.S.A.	California
Losey, R. M.	'35	*	U.S.A.	Killed in Norway, 1940
Lownes, E. D.	'24	Lt.	U.S.A.	Canada
Macartney, E. J.	'43	Ensign	U.S.N.R.	Connecticut
MacDonald, J. H.	'30	Lt.	U.S.N.R.	*
MacDonald, R. G.	'33	Capt.	U.S.A.	Overseas
MacKenzie, D. C.	'22	Lt. Col.	U.S.A.	Georgia
Maier, M. P.	'44	Lt.	U.S.A.	*
Maloney, F. V.	'35	Lt. (j.g.)	U.S.N.R.	Overseas
Manchee, V.	ex-'24	Capt.	U.S.A.	Alabama
Marshall, R. W., Jr.	'44	*	U.S.N.R.	*
Martin, J. S.	'44	*	U.S.N.R.	*
Maurer, F. A.	'22	Lt.	U.S.A.	Ohio
Mayer, A.	'42	*	U.S.A.	Illinois
McClung, R. M.	'39	2nd Lt.	U.S.A.	Illinois
McDougall, C. H.	ex-'43	Ensign	U.S.N.R.	North Carolina
McKillip, J. C. S.	'36	Lt.	U.S.N.	New York
McNaughton, J. B.	'44	Lt.	U.S.N.R.	*
Mercereau, J. T.	'24	Lt. Col.	U.S.A.	Fort Belvoir, Va.
Meyer, G. F.	'42	Lt. (j.g.)	U.S.N.R.	Overseas
Mitchel, T. S.	'33	Lt. (j.g.)	U.S.N.R.	Florida
Mitchell, G. S.	ex-'30	Major	U.S.A.	Overseas
Mitchell, R. K.	'44	*	U.S.N.R.	*
Mohr, W. H.	'29	Lt. Col.	U.S.A.	Mississippi
Monning, J. C., Jr.	'33	Lt. Col.	U.S.A.	Overseas
Moore, C. K.	'37	*	U.S.A.	Dayton, Ohio
Morris, L. P.	'34	Lt. Cmdr.	U.S.N.R.	California
Morse, C.	'36	Capt.	U.S.A.	Overseas
Munk, W. H.	'40	*	U.S.A.	Washington
Murphy, J. N.	'37	Lt.	U.S.N.R.	San Pedro, Calif.
Nestler, W. W.	'36	Capt.	U.S.A.	Florida
Nevis, A. H.	'36	Lt.	U.S.N.	Hawaii
Newby, C. T.	'41	Lt.	U.S.N.R.	Virginia
Nichols, R. M.	'36	*	U.S.A.	Overseas
Olson, C. W.	'44	*	U.S.N.R.	*
Osborn, J. E.	'39	Ensign	U.S.N.R.	Overseas
Osborne, J. B.	ex-'31	Sgt.	U.S.A.	Missouri
Osborne, L. S.	'44	*	U.S.N.R.	*
Ours, S. R.	'44	Comdr.	U.S.N.	*
Parker, J. E.	'38	Lt.	U.S.A.	*
Parker, R. G.	ex-'37	Major	U.S.M.C.	Overseas
Parker, T. B.	'44	Lt.	U.S.A.	*
Pearce, R. B., Jr.	'44	Lt.	U.S.A.	*
Pearne, J. F.	'34	Lt. (j.g.)	U.S.N.R.	*
Philleo, R. A.	'27	Major	U.S.A.	California
Pilorz, B. H.	'44	*	U.S.N.R.	*
Potter, W. T.	'35	Ensign	U.S.N.R.	*
Powlesland, K. L.	'43	Ensign	U.S.N.R.	Virginia
Proctor, H., Jr.	'44	*	U.S.N.R.	*
Putt, D. L.	'38	Lt.	U.S.A.	*
Radford, J. C.	'34	Lt. Cmdr.	U.S.N.R.	Washington, D. C.
Rambo, L.	'43	Ensign	U.S.N.R.	New Jersey
Ramey, R. C.	ex-'26	Lt. (j.g.)	U.S.N.R.	Overseas
Rattray, M., Jr.	'44	*	U.S.N.R.	*
Reid, D. C.	'43	Ensign	U.S.N.R.	Overseas
Reimers, G. I.	'41	Ensign	U.S.N.R.	Washington, D. C.
Rempel, J. R.	'44	*	U.S.N.R.	*
Reynolds, R. W.	'27	*	U.S.A.	*
Rhoades, R.	'43	Ensign	U.S.N.R.	New Jersey
Richards, R. T.	'17	Lt. Col.	U.S.A.	Overseas
Richardson, O. B.	'30	Lt. Cmdr.	U.S.N.R.	California
Ridenour, C. H.	'18	Brig. Gen.	U.S.A.	New York
Riggs, E. H.	'27	Major	U.S.A.	California
Ritter, J.	'35	Lt.	U.S.N.R.	Overseas
Roese, H. V.	'42	*	U.S.M.C.	*
Rogers, W. V.	'27	Major	U.S.A.	*
Rupert, C. S., Jr.	'41	Lt. (j.g.)	U.S.N.R.	Washington, D.C.
Schneider, A.	'43	Cadet	U.S.N.R.	*
Schneider, C. L.	'34	Capt.	U.S.A.	*
Schrader, C. G.	'40	*	U.S.N.R.	Washington, D.C.
Schroder, L. D.	'32	*	U.S.A.	Fort Douglas, Utah
Schubert, Wm.	'41	Lt. (j.g.)	U.S.N.R.	Annapolis, Md.
Schultz, W. F.	'32	Capt.	U.S.A.	Overseas
Scott, W. R., Jr.	'44	*	U.S.N.R.	*
Scribner, O.	'42	Lt.	U.S.A.	Overseas
Seed, R. W.	'44	*	U.S.N.R.	*
Seekins, C. W.	'42	*	U.S.N.R.	Annapolis, Md.
Seiler, D. D.	'44	Lt.	U.S.N.	*
Seymour, S.	'26	Lt. Col.	U.S.A.	California
Shalecky, F. H.	'40	Ensign	U.S.N.R.	Overseas
Sharp, R. P.	'34	Capt.	U.S.A.	New York
Shields, J. E.	'22	Major	U.S.A.	Missouri
Shor, G., Jr.	'44	Ensign	U.S.N.R.	New York, N.Y.
Sigworth, H. W.	ex-'44	Ensign	U.S.N.R.	Overseas
Silberstein, R. F.	'41	Sgt.	U.S.A.	Overseas
Sinclair, C.	ex-'45	Cpl.	U.S.A.	Georgia
Skinner, M. J.	'42	*	U.S.N.R.	San Pedro, Calif.
Slawsky, M. M.	'35	*	U.S.N.R.	Washington, D.C.
Small, J. G.	'41	*	U.S.M.C.	*
Smith, F., Jr.	'44	*	U.S.N.R.	*
Smith, J. C.	'42	*	U.S.N.R.	Maryland
Smith, R. C.	'20	Major	U.S.A.	Denver, Colo.
Smith, W. H.	ex-'36	Lt.	U.S.N.R.	Massachusetts
Snyder, W. M.	'39	Cadet	U.S.N.R.	Texas
Soike, R. J.	'44	*	U.S.N.R.	*
Southwick, T. S.	'29	Capt.	U.S.A.	Virginia
Spaulding, A. T., Jr.	'44	*	U.S.N.R.	*
Sperling, M. H.	'29	*	U.S.N.R.	*
Spooner, W. A.	'40	Ensign	U.S.N.R.	Overseas
Staatz, D. S.	'40	Lt.	U.S.A.	*
Strickland, C. P., Jr.	'43	Ensign	U.S.N.R.	Overseas
Stroud, S. G.	'41	*	U.S.N.R.	Ft. Schuyler, N. Y.
Sutton, R. A.	'43	Ensign	U.S.N.R.	Overseas
Swift, F. T.	'30	Lt.	U.S.N.R.	Overseas
Taylor, R. M.	'39	*	U.S.N.R.	*
Tenney, F. H.	'43	Ensign	U.S.N.R.	*
Thayer, E. M.	'33	*	U.S.N.R.	*
Thompson, F. W.	'29	Lt.	U.S.N.R.	*
Thompson, W. C., Jr.	'43	Cpl.	U.S.A.	Florida
Tickner, A. J.	'32	*	U.S.A.	Washington, D.C.
Tiemann, C. F.	'41	*	U.S.A.	*
Titzler, H. N.	'44	Lt.	U.S.A.	*
Tuedio, J.	'44	*	U.S.N.R.	*
Tyler, R. M.	'39	Lt.	U.S.N.R.	Overseas
Urgin, N.	'34	Lt. (j.g.)	U.S.N.R.	*
Van Dyke, G. R.	'40	Capt.	U.S.A.	Montana
Van Dusen, C. A.	ex-'37	Lt.	U.S.N.R.	Florida
Van Reed, M.	'35	Capt.	U.S.A.	Ft. Belvoir, Va.
Veronda, C. M.	'42	Ensign	U.S.N.R.	Massachusetts
Wadsworth, J. F., Jr.	'44	Capt.	U.S.A.	*
Walkowicz, T. F.	'44	Capt.	U.S.A.	*
Warfel, J. S.	'33	Lt. Cmdr.	U.S.N.R.	Washington, D.C.
Wayne, J. C.	'44	Capt.	U.S.A.	*
Weaver, F. E.	'44	*	U.S.N.R.	Rhode Island
Webster, G. M.	'22	Major	U.S.A.	Oregon
Wheeler, F. A.	'29	Lt. Cmdr.	U.S.N.R.	Overseas
Widdoes, L. C.	'41	Lt.	U.S.N.R.	Washington
Williams, R. S.	'44	Capt.	U.S.A.	*
Wilson, J. H.	'44	*	U.S.N.R.	*
Winchell, Robert	'44	Major	U.S.A.	Florida
Winter, P. H.	'44	Ensign	U.S.N.R.	Rhode Island
Wolf, P. L.	'44	*	U.S.N.R.	*
Wolfe, S.	'41	*	U.S.A.	*
Wood, F. W.	'42	Lt.	U.S.A.	Idaho
Woodard, G. E.	'34	Ensign	U.S.N.R.	*
Wychoff, P. H.	'37	Major	U.S.A.	Ohio
Zipser, S.	'30	Lt.	U.S.A.	Overseas
Zivic, J. A.	'44	Lt.	U.S.N.R.	*

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tribution of sound, while absorbing material was installed in selected locations to reduce the reverberation and noise. *Figs. 4* and *5* give sketches of the constructions used.

CONCLUSION

The decision to provide acoustical treatment for the entire Pentagon Building is in accord with the modern trend of adjustment of large buildings. Statistics show that office workers are more efficient under quiet conditions; they are not so nervous, they get more work done, and absences are reduced. The Pentagon has the reputation of being the world's largest and best equipped office building, a reputation which is based in part on the quiet conditions.