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SOUND ABSORPTION AT THE SURFACES OF SMALL LABORATORY ANIMALS

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FOREWORD

This report was written by Dr. Eugene Ackerman under Contract No. 33(616)-2770 for the Wright Air Development Center under authority of project No. 7210 entitled "Acoustic Energy Control." It was edited by Dr. Adam Anthony and Robert W. Farwell. Technical supervision of the preparation of this report was the responsibility of Dr. Henning E. von Gierke, Aero Medical Laboratory, Directorate of Laboratories, Wright Air Development Center, Wright Patterson Air Force Base.

Dr. E. Ackerman, Mr. R. W. Farwell, Dr. L. Tu, Dr. A. J. Campanella, Mr. F. Oda, and Dr. R. L. Berger were all in the Physics Department of the Pennsylvania State University while working on this contract. Since then, Dr. L. Tu has returned to Red China, Dr. A. J. Campanella is now working for Topp Industries, Inc., and Dr. Berger is doing post-doctoral research in England.

Dr. A. Anthony, Dr. H. W. Frings, and Mrs. P. A. Danner were all members of the Department of Zoology and Entomology when active in the research described in this report. Since then Mrs. Danner has left the Pennsylvania State University.

ABSTRACT

This report describes the theory, equipment and experimental results of the measurement of the acoustic absorption coefficients for the surfaces of rats, guinea pigs, and haired and hairless mice. These coefficients were measured at The Pennsylvania State University by various methods in the frequency band from one to twenty kilocycles per second. All experiments showed that the absorption coefficients rise between six and twenty kc. Those for the haired animals approached 100%. Hairless mice, on the other hand, had lower absorption coefficients. These were still appreciably higher than corresponding absorption coefficients for humans. The data for haired rats are consistently higher but in reasonable agreement with those obtained by others. The acoustic absorption coefficients for both haired and hairless animals in a randomly oriented sound field appear to be due at least in part to the excitation of surface waves.

PUBLICATION REVIEW

This report has been reviewed and is approved.

FOR THE COMMANDER:

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INTRODUCTION

One approach to the investigation of possible damage of sound to man and animals is to determine the amount of energy entering the body through the skin. This report summarizes the results of sonic absorption studies using laboratory animals at The Pennsylvania State University from 1951 through 1957. The results are compared with the few similar measurements made elsewhere.

Animals used at The Pennsylvania State University for these studies of the absorption of sound energy include rats, guinea pigs, haired mice and hairless mice. It was originally felt that the haired animals might be a reasonable analog to the hair-covered surfaces of the human head, whereas the hairless mice would be an approximation to the bare skin of humans. In view of data presented here and in a following report, the last assumption appears particularly unlikely.

In general, several methods are available for a study of absorption coefficients. In one, the substance studied is placed at the end of an impedance tube and a standing wave pattern is set up. This method has the following advantages: the entire theoretical treatment is exact involving no approximations; the equipment used is relatively simple; and the complex impedance of the surface is actually measured. A measurement method of this general type was used at Wright Field for several studies. (1). Unfortunately the impedance tube measurement has a number of disadvantages. Most pronounced of these is the lack of correspondence between the impedance for sound waves of normal incidence and those of random incidence. In the design of noise reduction installations it is well known that these two types of absorption may differ widely in an unpredictable fashion. Another disadvantage of the impedance tube method is that the surface must be accurately plane and parallel to the plane wave front of the incident sound wave. In order to achieve a plane wave it is necessary to have a tube that is several wavelengths long, and narrow enough to propagate only the plane wave mode. Although a tube of this nature is used in our laboratory (2), it was not felt to be of value for experiments with laboratory animals due to the difficulty of achieving a truly plane surface.

The most direct method is to observe the rate of heating of an animal in a sound field; this method is described in an earlier paper (3); it is reviewed briefly in the next section. The principle disadvantages of this method are: the irreversible skin changes during the experiment; the large number of animals needed; and the length of time per experiment. In addition these heating experiments could only be done in the siren sound field with its complicated shape distorted by the mouse.

A third way of measuring absorption coefficients is to measure reflections from a plane surface in an anechoic chamber. This method had been used successfully at Penn State (3) for insulating materials. It can only be used with a plane area which is large compared to the sound beam. This is not possible with mice and rats if experiments are conducted at frequencies audible to humans.

Instead of using an anechoic chamber, studies can also be carried out in a reverberant chamber. Here one may measure the added energy necessary to maintain the sound level after adding a mouse; or one may measure the change in decay time after the sound field has been turned off. We chose the latter alternative as easier equipment wise and capable of greater precision. Its greatest disadvantage is that pure tone measurements set up particular standing wave patterns whose interpretation is not clear. We have avoided this by using one third octave bands of noise centered at the reported frequencies. The use of random noise demands a large number of measurements, but once the equipment is set up, a measurement takes only five seconds. Its repetition even 100 times takes only six minutes.

An additional method which was used at WADC (4), is to place a vibrating rod against the surface and then observe the damping introduced. Essentially this method depends on a number of questionable assumptions. The worst of these is that the animal (or human) surface follows the rod. It seems reasonable that at a sufficiently high frequency this is not likely to happen. This in effect would cause the apparent absorption to decrease as the frequency is raised due to poor skin-rod coupling even if the absorption of sound waves from air remained constant. The same would be true of the impedance tube. There is also the problem of the reaction of the damper on the vibrating rod. If this is much lower than the effective impedance of the rod it is not important. On the other hand, if it is comparable, it could become very critical. The numerical evaluation of this effect is difficult.

The rod, impedance tube and reflection methods are limited by exposing only a part of the animal surface. In this case, surface waves will spread out over the rest of the animal. This was illustrated dramatically at low frequencies by work at WADC (5). These surface waves would make the absorption coefficient decrease as the exposed area increases. This has been observed in detail for the rod and modified impedance tube methods (4). Here the sound pressure is constant and in phase over the area concerned, which is not so with the reverberation chamber.

This report discusses the theory briefly in Section II, along with a definition of the pertinent symbols. In Section III, the siren work is reviewed. Absorption data using a cylindrical reverberant chamber and a sound level recorder are discussed in Section IV. Similar data on more animals and with a somewhat greater precision are presented in Section V. These results are discussed, compared with other results, and summarized in Section VI. In each appropriate section the equipment used is described.

SECTION II

SYMBOLS AND THEORY

A. Table of Symbols

Throughout this report the following symbols and units are used.

a	absorption in cm^2 (cross-section)
α	absorption coefficient in percentage
p	pressure in μ bars
p_o	reference sound pressure $p_o = 2 \times 10^{-4}$ μ bars
ρ	density in gm/cm^3
v	velocity of particle in cm/sec
c	velocity of wave in cm/sec
$z = p/v$	specific acoustic impedance in cgs units
$(\rho c)_o$	value for air = 42 cgs units
$\zeta = \frac{z}{c\zeta}$	impedance ratio
$\zeta_o = \frac{z}{(\rho c)_o}$	normalized impedance ratio
t	time in seconds
τ	reverberation time - the length of time for the sound pressure level to fall 60 db
L	sound pressure level in db $L = 20 \log p/p_o$
E	electric potential difference in volts
A	area
V	volume
υ	frequency
N	number
l	length
r	radius
Λ	length of parameter

τ_c	reverberation time of empty chamber
τ_{c+m}	reverberation time of chamber plus mouse (or other small animal)
Π	power in ergs/sec or cal/sec
Υ	intensity in ergs/cm^2/sec
σ	standard deviation
s	standard error of the mean
T	temperature in $^{\circ}$C
T_A	air temperature
T_B	body temperature
T_F	fur temperature
p_{ff}	free field pressure
C_B	heat capacity of animal body
β	coefficient of heat transfer in cal/cm^2/sec/$^{\circ}$C
β_A	β for fur to air
β_B	β for body to fur
β_C	β for body to air
M	metabolic rate

B. Theory

When an incident sound field falls on an animal some of the sound energy will be absorbed. In order for this to be meaningful, we will initially consider a free field of intensity Υ_{ff}. If one denotes the power absorbed by Π , then the acoustic absorption (or cross-section), a, is defined by

$$a = \frac{\Pi}{\Upsilon_{ff}} \qquad (1)$$

The term, a, has the dimensions of an area; it represents the area of a completely absorbing material, which would absorb the same power as the actual object. In atomic and nuclear physics, this ratio is referred to as the cross-section. In the case of electromagnetic waves, geometries arise in which the effective cross-section, a, defined as above, is greater than the physical cross-section . In acoustics it is usually assumed that this is not the case, although it can be. It is customary to call the ratio

$$\alpha = \frac{a}{A}\ 100\% \qquad (2)$$

the acoustic absorption coefficient.

Many restrictions must be placed on this concept. As defined above, Υ_{ff} must be uniform over σ. If a standing wave pattern is used it must be treated as the sum of two progressive waves. In general α will depend on the frequency, υ, as well as on the angle of incidence of the plane wave. Moreover, we must distinguish, as in nuclear physics, between scattered energy and absorbed energy.

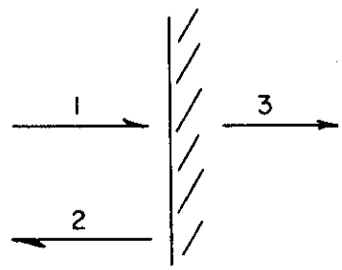
We can relate α to the normalized acoustic impedance ratio ζ_o, where

$$\zeta_o = \frac{z}{(\rho c)_o} \quad . \qquad (3)$$

In this last formula, $(\rho c)_o$ is the characteristic impedance of air, and z is the specific acoustic impedance defined by

$$z = p/v \qquad (4)$$

where p is the acoustic pressure and v the particle velocity. Consider now a plane wave, denoted by subscript 1, incident in air on a surface of the material. A reflected wave, denoted by subscript 2, and a transmitted wave, denoted by subscript 3, can be diagrammed as follows:



Using the equations of motion within the media, and the continuity of pressure and particle velocity at the boundaries, one may write for a simple harmonic wave:

$$p_1 = (\rho c)_o \, v_1 \qquad p_1 + p_2 = p_3$$
$$p_2 = -(\rho c)_o \, v_2 \qquad v_1 + v_2 = v_3 \qquad (5)$$
$$p_3 = (\rho c)_o \, \zeta_o \, v_3$$

Solving for p_3, one obtains

$$p_3 = p_1 \cdot \frac{2\zeta_o}{1 + \zeta_o}$$

or recalling that

$$\Upsilon = \frac{|p|^2}{2\,|z|}$$

$$\frac{\Upsilon_3}{\Upsilon} = \frac{4\,|\zeta_o|}{|1 + \zeta_o|^2}$$

If no energy is returned after entering the absorbing medium then

$$\alpha = 100\,\frac{\Upsilon_3}{\Upsilon_1} = 100\,\frac{4|\zeta_o|}{|1 + \zeta_o^2|} \qquad (6)$$

This expression is exact and involves no approximations if the plane, sinusoidal wave is normal to the interface and no special boundary effects occur. The sinusoidal aspect can be taken into account by dealing only with the Fourier transform of the pressure.

If the wavefront is not normal to the interface the same basic equations can be used as equation (5) except that now an angle of incidence θ_1 and of refraction θ_3 must be included. This introduces the additional equation

$$\frac{\sin \theta_3}{\sin \theta_1} = \frac{c}{c_o}$$

where c is the wave velocity in the medium and c_o the wave velocity in air. In addition, the equation expressing the continuity of particle velocity, $v_1 + v_2 = v_3$ must be replaced by a similar equation for the normal velocity component

$$\cos \theta_1 \; (v_1 + v_2) = v_3 \cos \theta_2 \; .$$

This, of course, complicates the above expressions. Little advantage can be seen in solving these here except to point out that the absorption coefficient will depend quite markedly on the angle of incidence.

The above considerations are known to make it possible to compute the transmission of sound from one fluid, as water, to another as air (or water to oil), and to form a reliable basis for discussing the properties of an absorbing material such as Fiberglas. For such porous materials the actual absorption can be computed by a variety of techniques all leading to the essentially correct answer.

On the other hand, the absorption of acoustic waves from air, by non-porous materials is less amenable to theoretical calculations. It is known that a solid panel at a suitable angle to a sound field may transmit as much energy as air would. This is due to surface or shear waves in the panel of wavelengths that are easily excited by the air waves. In this case, or any other case in which surface, shear, or bending modes are important due to finite dimensions of material, the use of the above formulas for the absorption is not justified and will lead to numbers far below those observed experimentally. Fig. 1 shows the values of ζ_o for steel and brass with "effective values" computed from reverberant chamber and impedance tube data. A review of the literature has not led us to any similar data to contradict these measurements; some architectural acoustics tables quote values similar to ours. The impedance tube data appear particularly reliable having been obtained by different observers at different times and with equipment which should respond to an

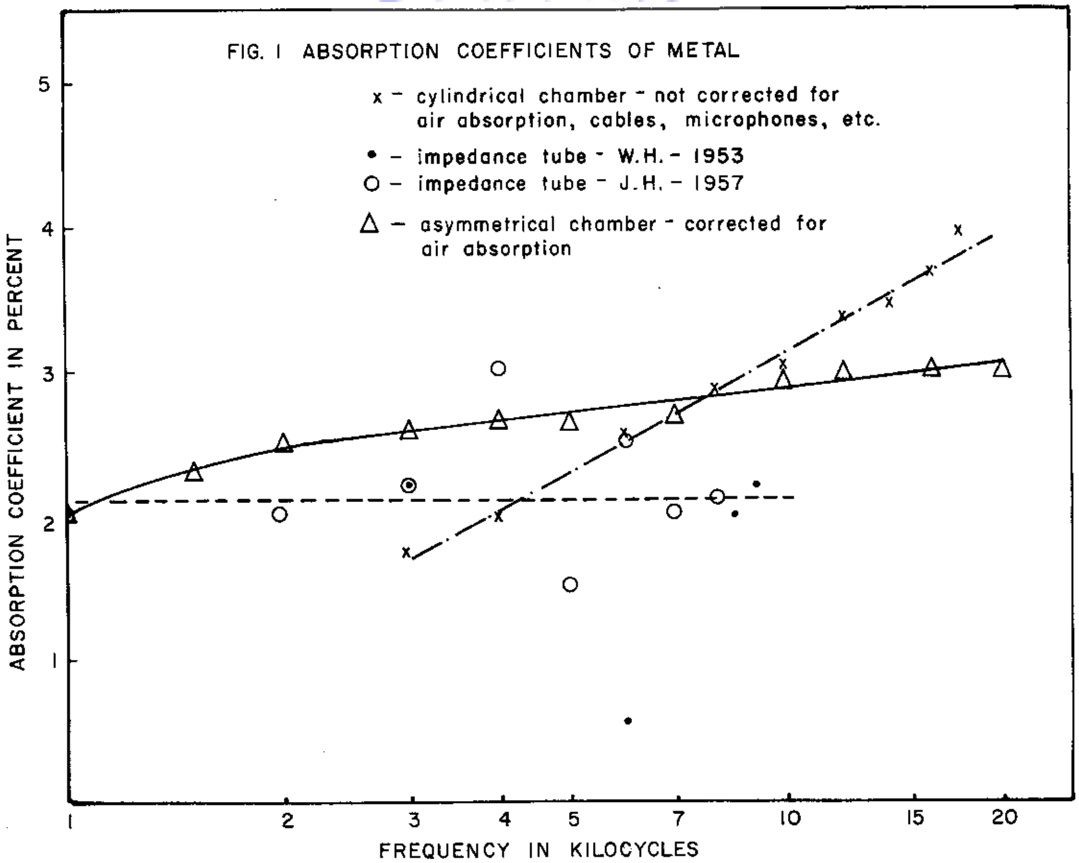


Fig. 1. Absorption Coefficients of Metal

absorption less than one tenth of this. The data on which these are based will be discussed in a future report.

Other data support the proposition that similar special surface effects are the primary agents responsible for absorption of sound by biological surfaces. For instance, when the fingers are held close together in the siren field the sound absorption causes local heating whereas when they are spread apart no local heating can be detected (6). Also Anthony and Danner (7) showed that damage to hairless mice exposed to the siren sound fields could be associated with skin damage. In other words, these data on absorption are not well correlated with the specific acoustic impedance of the bulk of the tissue. (This statement assumes that the sound energy is not rapidly absorbed within the tissue; experiments at higher frequencies reviewed by Goldman and Heuter (8) as well as our own at lower frequencies (9), and those of Franke, von Gierke et al (5), strongly support this assumption. Thus the acoustic absorption discussed throughout this report must be interpreted as some complex type of surface phenomenon.

The irregularities in all the surfaces concerned (i.e. metal, hairless mice, and haired animals) are small compared to the wavelengths of either the incident or the transmitted waves. The irregularity then cannot be a major cause of the absorption. On the other hand, small pores which are shallow compared to a wavelength, as in Fiberglas, or between the fingers, can absorb appreciable amounts of sound energy. This may be one of the contributing factors to the absorption of metals and tissues. Large numbers of types of surface waves, and mixed shear and compressional waves can be set up within solid materials and tissues. These are hard to analyze completely but they may contribute to the effects described in this report. It was our original hope to relate the properties of animal surface and tissues to the observed absorption coefficient. In this we have been completely unsuccessful. Accordingly, the data are presented in this report as empirical results; no attempt is made to explain them other than the trivial observation that fur absorbs much more than bare skin.

SECTION III

SIREN DATA

This material was reported in detail in an article by Danner, Ackerman, and Frings (3). A brief resume of our findings is included here. Most of the following is quoted directly from the above article. Only the portions directly related to absorption coefficient have been used.

In 1948 Frings, Allen, and Rudnick (10 and 11), using a high powered siren built by Allen and Rudnick (12), reported experiments which showed profound physical effects of high-intensity air-borne sound waves on animals. These studies emphasized the importance of thermal phenomena in killing white mice by sonic irradiation. Frings and Senkovits (13) showed that heating of the fur of mice is the major factor in destruction of the pinnae in a high-intensity air-borne sound field. In 1951 Pimonow (14) and Grognot (15) also reported killing rats and mice by air-borne sound with heating probably the major cause of death. Von Gierke studied sound absorption of the body surface of man and animals, and von Gierke, Parrack and Eldredge (16) presented a theoretical explanation for the heating of animals by absorbed sound energy.

It seemed desirable, therefore, to study the effects of high-intensity sound fields on hairless animals. The experiments reported in this section were designed to find threshold intensities for systemic heating of haired and hairless mice and to determine the effect of frequency of the sound on heating of the mice.

A. Materials and Methods

The sound source for this work was the high-powered siren built by Allen and Rudnick (12). This siren produces air-borne sound of great intensity in both sonic and ultrasonic ranges. Intensity readings were made with Hewlett-Packard and Ballantine voltmeters and a calibrated probe microphone having a ceramic element. Frequency was determined by the same microphone and a Hewlett-Packard wave analyzer for the frequency range 0-15 kc. A Benham analyzer was used for frequencies above 15 kc.

The hairless strain of mice used in these experiments was obtained from the Jackson Memorial Laboratory at Bar Harbor, Maine, and is maintained by breeding hairless males to heterozygous haired females. Hairless females do not produce enough milk to care for their young and therefore are not satisfactory for breeding. Litters thus obtained have on the average 1/2 haired and 1/2 hairless animals. Comparisons can thus be made within a given litter, if desired.

Approximately 220 animals were subjected to sound in these experiments. Mice of both sexes, from 50 to 56 days of age, were anesthetized by subcutaneous injections of Nembutal. As shown in Figure 2, animals were bound "spread eagle" fashion to a piece of coarse mesh wire screening which was clamped 6 cm above the siren opening, exposing the dorsal surface of the mouse. The probe microphone, which could be moved freely across the field was used to measure the free field sound pressure 4 cm below the mouse. Four thermocouples were used to measure temperature; these were placed in the rectum, skin, and muscle of the rear of the animal, and in the air near the mouse, respectively. In conjunction with the thermocouples, a d.c. chopper-type amplifier and an Esterline-Angus recorder were used to permanently record the temperatures of each animal. A switching device was designed so that the emf's of the thermocouples could be recorded at successive 15 sec intervals. Thus, within one minute, a 15 sec temperature measurement was obtained from each of the four thermocouples. The thermocouples were calibrated twice a day.

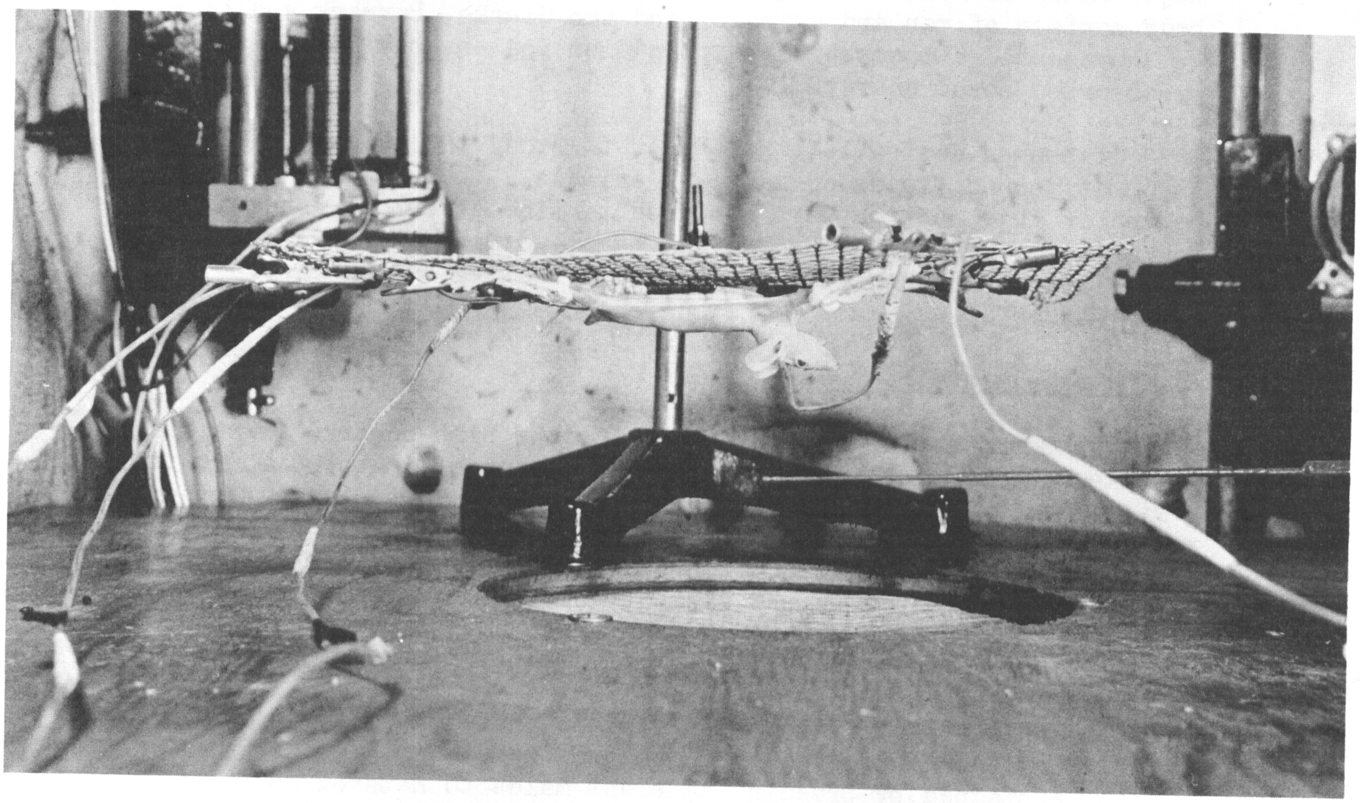


Fig. 2. Anesthetized hairless mouse mounted on a wire screening and placed in a siren chamber above baffle board.

B. Experiments and Results

Preliminary experiments showed that the threshold at 18-20 kc for heating of hairless mice was 155 ± 3 db and for haired mice 144 ± 2 db. Other tests showed that at 163 db the rate of heating of haired mice was independent of the frequency, being controlled primarily by the rate of conduction through the animal. Therefore constant (peak) intensities of 155 db for haired mice and 162 db for hairless mice were used in the following experiments.

Twenty-eight hairless mice were treated at 162 db and frequencies of 6, 12, 18, and 22 kc. Twenty-one haired mice were tested at 155 db and frequencies of 6, 12, and 18 kc. Figures 3 and 4 show the effects of treatment on rectal temperatures of the mice. At all frequencies the sound fields were probed to be certain that the mice were receiving the correct peak free field intensity. It can be seen from these graphs that higher frequencies accelerate and intensify heating of animals, haired or hairless. Hairless mice tested at 6 kc had an average rectal temperature of 33.5°C after 45 minutes. At 18 kc the animals had rectal temperatures of 42.5-46.5°C and died in an average time of 48 minutes.

The effect of different frequencies on heating of a single animal was also studied. One haired and three hairless animals were used in this experiment. An individual mouse was tested at one frequency for four minutes, was allowed to cool to starting temperature, and then was tested at another frequency for four minutes. Frequencies of 6, 12, and 18 kc were used at 162 db for hairless and at 155 db for haired mice. The frequency effect was also evident in these tests, since the animals heated faster the higher the frequency. In this study the mouse was left in a fixed position in the anechoic chamber, in spite of the fact that the sound field was known to shift slightly with changes of frequency. The effect of a change in frequency on a hairless mouse is also shown in Figure 5. The mouse was treated for 25 minutes at 5.5 kc at which time the frequency was changed to 19 kc with the peak intensity maintained at 162 db. Two other hairless mice were tested similarly at 162 db and frequencies of 7 kc and 21 kc. Results were like those shown in Fig. 5. The results obtained here, though a direct demonstration of the frequency effect, were not as significant as those in the previous study, in which the same part of the mouse was at the point of peak free field intensity at each frequency.

At higher frequencies of 18 and 22 kc localized burns were observed on hairless mice, but one could see little evidence of such burning on haired animals. To investigate the variation in temperature obtained over the surface of the mouse and relate it to the rectal

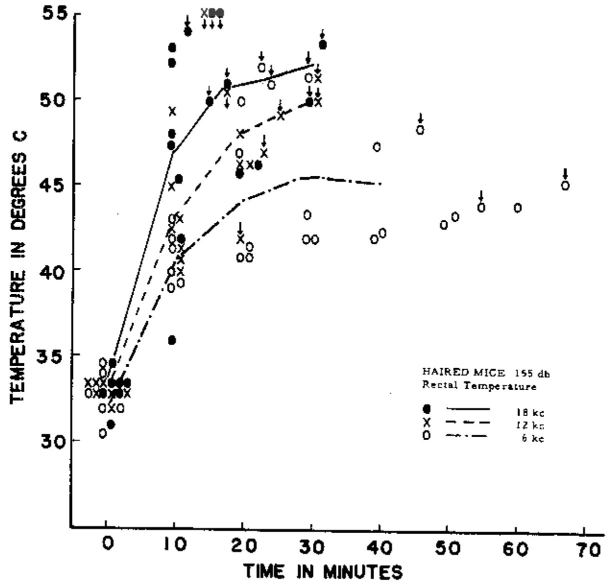


Fig. 3. Effect of frequency and time of treatment on temperatures of hairless mice in sound fields of 162 db, peak f. f. intensity (arrows indicate deaths).

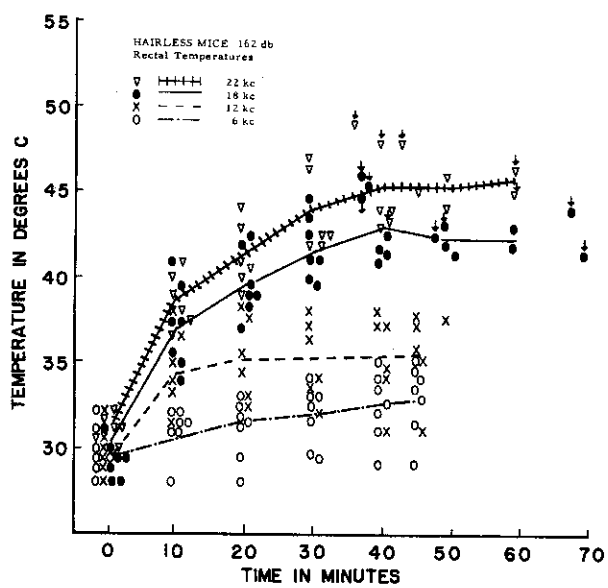


Fig. 4. Effect of frequency and time of treatment on temperatures of haired mice in sound fields of 155 db, peak f. f. intensity.

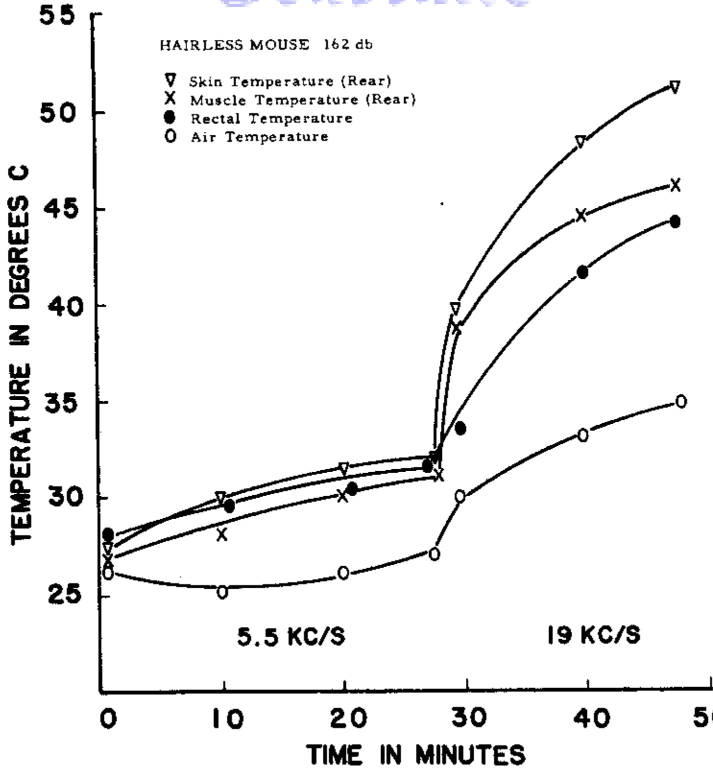


Fig. 5. Effect of a change in frequency at a constant peak free-field intensity on a hairless mouse.

temperature a hairless mouse was placed in the siren chamber with thermocouples in the rectum, skin of the right rear leg, skin of the neck, and skin of the center of the back. It was treated at 18 kc and 163 db, and the temperatures, when death occurred (after 37 minutes), were as follows: rectum 46°C, skin of leg 46°C, skin of neck 45°C, and skin of back 53°C. By testing the field with the probe microphone in the area where the mouse had been exposed, it was discovered that there was a peak free field intensity of 163 db in the region and a variation of about 10 db over the surface of the mouse. The position of the peak intensity corresponded to the area on the back where very high temperatures and burning were evident.

It was desired to make some comparison between the acoustic power to which the experimental mice were exposed and the power actually being absorbed by them. Using the equations of von Gierke et al (16) and information obtained by temperature measurements on the mice, it is possible to determine the approximate power absorbed by the haired and hairless mice at the frequencies used in these studies.

The major factors tending to decrease the temperature of an experimental mouse are radiation to the surroundings and conduction to the air. Measurements on anesthetized animals after treatment in the sound field at various frequencies showed that, when their surface temperatures were the same, there was little difference in radiation rates of the two kinds of animals. Thus differences in radiation to the surroundings by the two types of animals do not contribute appreciably to the differences in heating observed at a fixed frequency.

The remaining factors - conduction to the air, metabolic rate, and absorption - can be described mathematically, allowing one to compute from the observed heating rates the energy absorbed from the sound field. Von Gierke et al (16) in discussing the equations for the heating of haired rats in a siren field assume that the metabolic rate is approximately constant. Their final equation has the form

$$\Pi = C_B \left(1 + \frac{\beta_A}{\beta_B}\right) \frac{dT_B}{dt} + A\beta_A (T_B - T_A) - M \qquad (7)$$

where Π = power absorbed from the sound field, C_B = heat capacity of the animal body = specific heat of the body times the weight of the animal, A = surface area of the animal body, β_A = coefficient of heat transfer from fur to air, β_B = coefficient of heat transfer from body to fur, T_B = body temperature, T_A = air temperature, M = metabolic rate of heat production, and t = exposure time. For the mice the same equation should apply when C_B = 17 cal/°C, A = 60 cm², M = 0.06 cal/sec (from Herrington (17)), $\beta_A = 1.7 \times 10^{-4}$ cal/cm²/sec/°C, and $\beta_B = 3.4 \times 10^{-4}$ cal/cm²/sec/°C. As time progresses, the terms $A\beta_A(T_B - T_A)$ must predominate and the rectal temperature will become approximately constant. This will be due to the increase of $T_B - T_A$ (we have assumed that M is approximately constant). The most significant time interval for calculating the power absorbed is just after the siren has been turned on. An interval of six minutes was used, during which the animals' temperature increases somewhat linearly, and the metabolic rate may be more legitimately assumed to be constant during this period. This interval is the most useful for computing the power absorbed from the sound field, because its linear nature shows that terms $A\beta_A (T_B - T_A) - M$ are unimportant. In the middle of this interval, at the end of three minutes, the formula for Π in cal/sec can be simplified to:

$$\Pi = 25 \frac{dT_B}{dt} + 0.02$$

This was used to compute the average energy absorbed by the haired mice in sound fields of 155 db peak intensity and 6, 12, and 18 kc (Table I).

For hairless mice, by reasoning similar to that of von Gierke, one can derive an analogous equation. Let Π, C_B, T_A, A and M have the same values as above and β_C be the coefficient of heat transfer from hairless mouse to air. This leads to the equation

$$\Pi = C_B \frac{dT_B}{dt} + A\beta_C (T_B - T_A). \qquad (8)$$

The term T_A has been included since the air temperature increased during the time the siren was in operation.

There is no information available concerning the value of β_C for hairless mice. However, $\beta_C = 5.8 \times 10^{-4}$ cal/cm²/sec/°C for a nude man in a wind of 10 miles per hour (18). Since the exact value of β_C does not play an important role in the calculations, this number was assumed to be approximately correct for the hairless mouse. Using numerical values in the equation (8) given above:

$$\Pi = 17 \frac{dT_B}{dt} + \frac{1}{30} (T_B - T_A) \text{ in cal/sec.}$$

This formula was used to compute the values in Table I for hairless mice.

It would be simpler to compute the coefficient of absorption if one could treat the siren sound field as a plane wave. Two tests were applied to determine the validity of treating the measured fields as if they were plane waves striking a large area: (1) the variation of the measured free field pressures with height and (2) a comparison of L_{ff} and L' the sound pressure levels at the mouse holder in a free field and at the mouse, respectively. Although the sound field is divergent, the decrease in free field intensity with height above the siren is negligible over a distance as small as the thickness of a mouse. Thus the incident sound field is effectively a plane wave for use with an animal of this thickness. It was observed that L_{ff} and L' were very different at some places. However, since total body heating was observed, the total power striking the mouse was the important factor. The corresponding intensities, I_{ff} and I' were each integrated over the bottom surface of the mouse to give the total powers striking the animal, Π_{ff} and Π' respectively. The difference between Π_{ff} and Π' were less than the estimated $\pm$ 15 per cent limits of error. This agreement indicates that the diffraction pattern could be ignored for the purpose of computing α. The average of Π_{ff} and Π' was used for the incident power.

The values for the power striking the mouse, the rate of absorption of energy, Π, and the absorption coefficient, α, are given in

Table I for hairless mice, temperatures of which are shown in Fig. 3, and for haired mice, temperatures of which are shown in Fig. 4. The haired mice were exposed at 155 db which is lower in intensity than 162 db by a factor of 5. Therefore intensities measured at 162 db were divided by 5 to determine the power striking the haired mice. The table shows that hairless mice absorb about 1 per cent of the incident sound energy at 6 kc, and about 10 per cent at 22 kc. Haired mice absorb about 50 per cent of the free field sound power striking them at 6 kc and about 100 per cent at 18 kc. Death times for haired mice were in satisfactory agreement with those observed by von Gierke for haired rats. Wide variations in death times, however, as much at 100 per cent, and in death temperatures, 10°C or more, led to the conclusion that initial heating rates should be more significant in determining absorption than death times and temperatures.

The above figures may be compared with those of von Gierke et al, who measured with an impedance tube 0.6 per cent for the absorption of an area of a shaved rat at 3.5 kc, and 12 per cent at 6 kc for the absorption of an area of a haired rat. Since absorption coefficients vary widely (up to 100 per cent) on haired animals even of the same species (16) and considering the limits of error involved, the absorption coefficients obtained for haired rats and haired mice are comparable. Absorption by haired mice increases with frequency, as was shown for haired rats and predicted by calculations (16). At 6 kc heating of hairless mice provides an absorption figure which is in the range of the figure obtained for absorption of an area of a shaved rat at 3.5 kc. An extrapolation of the curve for shaved rats at 6 kc, however, leads to a smaller absorption coefficient which would not compare favorably to that for hairless mice at the same frequency. At higher frequencies hairless mice were found to heat more rapidly, die in shorter time, and produce α values which showed an increase with an increase in frequency.

TABLE I

Variation of power striking the animals and the absorption coefficients of haired and hairless mice with frequency. All errors are probable errors. 100α = per cent of incident sound absorbed. dT/dt = average time rate of increase of rectal temperature during first six minutes. P max = maximum free field pressure striking mouse. Power absorbed from sound field. ff = free field. M = mouse present.

	Frequency kc		Total Incident Power in Watts	Rectal dT/dt in °C/min	Absorbed Power in Watts	α
Hairless mice P max = 162 db	6	ff	19	0.2	0.24	0.012±0.009
		M	18			
	12	ff	15	0.75	0.98	0.06±0.015
		M	12			
	18	ff	13	1.0	1.30	0.10±0.02
		M	12			
	22	ff	12	1.1	1.40	0.13±0.04
		M	9			
Haired mice P max = 155 db	6		3.7	1.1	2.0	0.5±0.10
	12		3.3	1.2	2.2	0.65±0.1
	18		2.5	1.5	2.7	1.1±0.25

C. Summary of Siren Data

These data will be discussed later in this report. This entire set of siren experiments was summarized as follows. The threshold intensity at 18–20 kc for heating of haired mice is approximately 144 ± 2 db, while that of hairless mice at the same frequencies is approximately 155 ± 2 db. The effectiveness of high-intensity air-borne sound in heating haired and hairless mice increased as the frequency of the sound waves increased, i.e. a sound source of 18 kc heated an animal more rapidly than a source of like intensity at 6 kc. At higher frequencies, 18 and 22 kc, localized regions on the mice were badly burned and the animals died after less than an hour in the sound chamber. The death time was apparently dependent upon the portion of the animal exposed to the intense part of the sound field.

The configuration of the field was found to change with a change in frequency, the peak intensity of the sound beam becoming narrower as the frequency increased. Measurements made with and without a hairless mouse demonstrated the effect of the animal's body on the sound field immediately below the animal. At higher frequencies, the pattern obtained just beneath the mouse showed the effect of the presence of the body much more graphically than those obtained at lower frequencies. Absorption coefficients were computed from these data for haired and hairless mice; these co-efficients increased with frequency over the entire range investigated.

SECTION IV

CYLINDRICAL REVERBERATION CHAMBER

A. Theory and Experiment

It was desired to determine the acoustic absorption coefficient by a method other than those previously employed; i.e. the rod, impedance tube, and siren, in order to avoid their inherent difficulties. The first attempt of this nature was carried out by Farwell and Ackerman; the data formed the basis for Farwell's thesis (19) for the degree of Master of Science. Most of the material in this section is quoted from his thesis.

The technique selected for the experiments reported in this section utilizes the relationship between the total absorption and the reverberation time in a reverberant chamber. The relation is given by the well-known Sabine formula (20):

$$\tau = 1.45 \ \frac{V}{\alpha A} \ . \qquad (9)$$

Here, τ is the reverberation time in seconds; i.e. the time required for the steady-state sound energy to decrease by 60 db; V is the volume of the reverberation chamber in milliliters; A is the area of the absorbing material in square centimeters; and α is the absorption coefficient (absorption per unit area) of the absorbing surface. If more than one absorbing material is present, the total absorption αA is represented by the sum of the products of the individual absorption coefficients and their respective surface areas.

The derivation of the Sabine formula can be found in texts on acoustics. The chief assumptions made in the derivation are that the sound energy be uniformly distributed throughout the volume of space and that the absorption be continuous. If this is the case, then the Sabine formula is found to hold very well for live rooms having high reverberation times. For "dead" rooms, however, the Sabine formula does not hold. The modifications to this formula may be found in the texts on acoustics (21). One such modification due to Eyring assumes a uniform distribution of sound, but assumes a discontinuous absorption at the boundaries of a room or chamber. In the present work it is assumed that the absorption within the chamber is kept small enough that the Sabine formula may be used.

Essentially the determination of the absorption coefficients in this work was made by first measuring the reverberation time of the empty chamber and then repeating the process with a known number of mice in the chamber.

From equation (9) the second step in the procedure gives

$$\tau_{c+m} = 1.45 \frac{V}{\alpha_c A_c + \alpha_m A_m} \qquad (10)$$

where τ_{c+m} is the reverberation time of the chamber with the mice; α_c and α_m are the absorption coefficients of the chamber walls and the mice, respectively; and A_c and A_m are the absorbing surfaces of the chamber and mice, respectively.

Solving equation (9) for $\alpha_c A_c$ from the first measurement of the reverberation time of the empty chamber and substituting the value into equation (10), the total absorption of the mice, a_m, is found to be

$$a_m = \alpha_m A_m = 1.45 V \left(\frac{1}{\tau_{c+m}} - \frac{1}{\tau_c}\right) . \qquad (11)$$

τ_c is the reverberation time of the empty chamber. If the volume of the mice is appreciable compared to V, then the volume V should be corrected to account for the decreased volume of the chamber. By a separate measurement A_m can be determined and the absorption coefficient α_m obtained.

The absorption coefficient measured in this manner is an average coefficient determined by the total absorption of a single mouse or of a known number of mice. Hence, different values of the absorption coefficient for different parts of the animals or for different areas of body surface are not encountered. Only an average over the entire body is determined.

Fig. 6 is a photograph of the equipment used to perform the measurements of the acoustic absorption coefficients of haired and hairless mice in the frequency range from 3 to 22 kc. The block diagram of the equipment as it was used to obtain the reverberation time data is presented in Fig. 7.

The source of acoustic energy is a Type 422 Noise Generator developed by the Psycho-Acoustic Laboratory at Harvard University. The selection of a random-noise source in preference to a pure-tone signal generator is discussed later in this section. The output of the noise generator is amplified by a Model E-14 Bogen power amplifier and fed to an Altec 633A microphone. It has a frequency response which reaches a maximum at about 10 kc and drops off at the higher

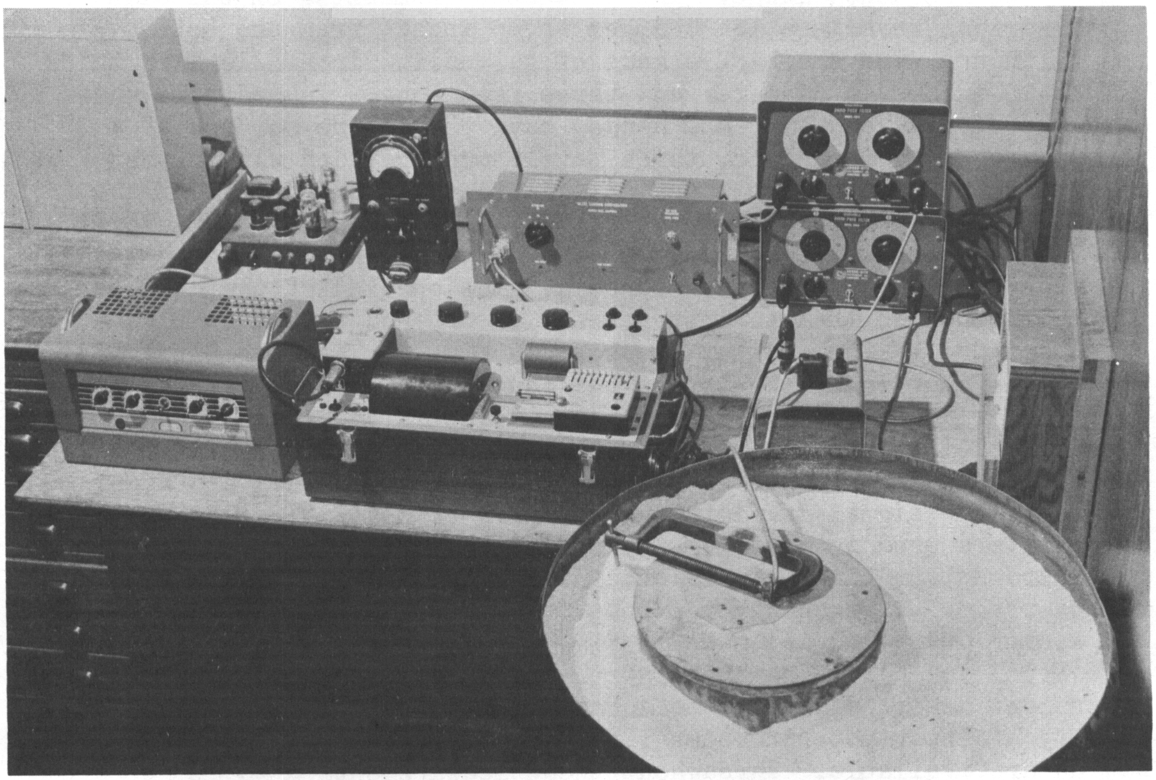


Fig. 6. The apparatus

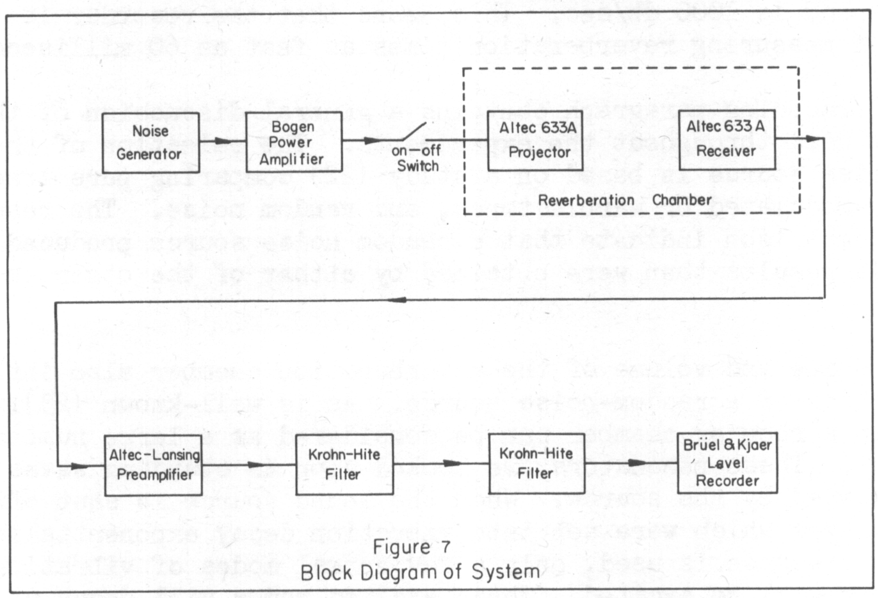


Fig. 7. Block diagram of system

end of the frequency range. The projector is mounted on the side of a cylindrical reverberation chamber seven inches from the bottom of the cylinder. The chamber is made of galvanized iron 1/16 inch thick and is 10 inches in diameter and three feet long. In order to suspend the mice in mid-air, and hence, have the entire surface of a mouse exposed to the sound, three levels are provided within the chamber. Two of the levels are at a distance of one foot from the top and bottom of the cylinder, respectively, while the third level is at the center of the cylinder. The platforms for all three levels are made of wide-opening mesh screens. The opening of the mesh is about 1/4 inch so that no interference is offered to the sound. A cross-section of the chamber is shown in Fig. 8. Another Altec 633A microphone mounted at the top of the chamber is used to receive the sound. The output of this microphone is amplified by an Altec-Lansing Model A 408B low noise preamplifier capable of amplifying the signal by 80 db. Before being recorded by the Bruel and Kjaer Recorder, the signal is filtered by a pair of Model 310 A Krohn-Hite filters used in tandem. Employed in this fashion a constant one-third octave band pass is obtained throughout the entire frequency range. A frequency response curve for the filters used in the manner described is shown in Fig. 9. The recorder is a Type 2301 Bruel and Kjaer Level Recorder. It is a high-speed recording instrument designed for the measurement of reverberation times. A variety of input potentiometers, pen writing speeds, and paper chart speeds are available. Throughout these measurements a 50 db logarithmic potentiometer was used. In this manner an exponential decay curve appears as a straight line on the chart paper. The 50 db potentiometer is accurate to ± 0.5 db. The fastest pen writing speed is 1000 db/sec. This means that the recorder is capable of measuring reverberation times as fast as 60 milliseconds.

The preceding paragraph contains a general discussion of the equipment used throughout the experiments. The selection of the random noise source is based on a study (22) comparing pure tones, frequency-modulated or warble tones, and random noise. The results of this comparison indicate that a random noise source produced more repeatable results than were obtained by either of the other two sources.

The shape and volume of the reverberation chamber also influenced the selection of a random-noise source. As is well-known (23), the air within a room or chamber can be considered as a large number of resonators. These resonators are looked upon as standing waves which can be excited by the source. When the sound source is shut off, the standing waves which were set into vibration decay exponentially. If a pure-tone source is used, only a few normal modes of vibration of the chamber will be excited. These excited modes will decay at

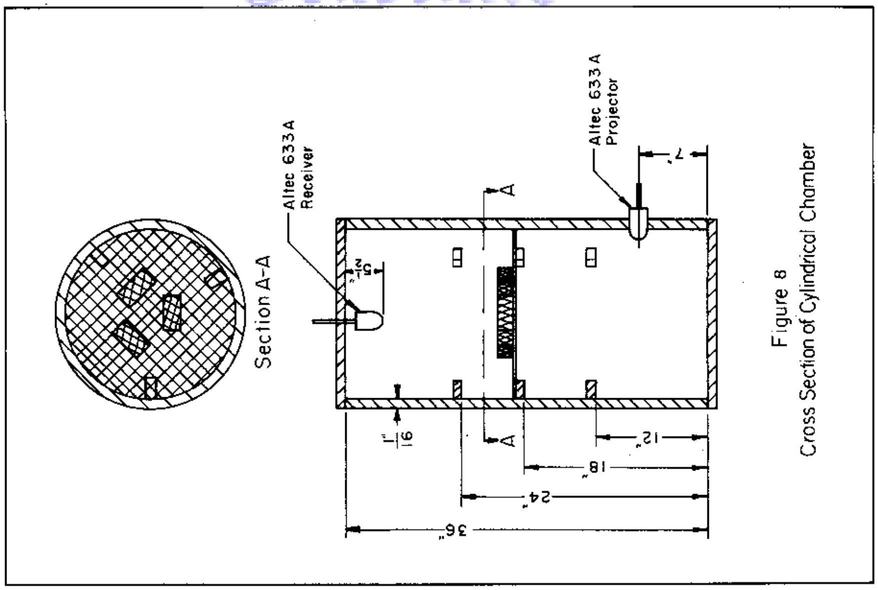


Fig. 8. Cross section of cylindrical chamber

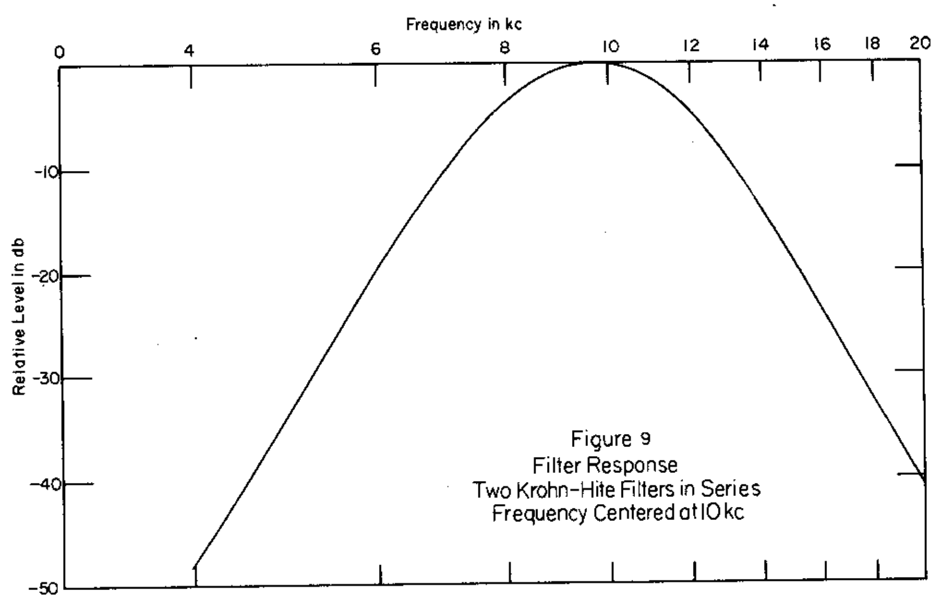


Fig. 9. Filter response two Krohn-Hite filters in series frequency centered at 10 kc.

different rates and will perhaps interfere with each other producing beats. The appearance of beats makes the interpretation of the results difficult.

If, however, a random-noise source is employed, a large number of standing waves are created. Then when the source is shut off, the sound energy will decay uniformly. Thus, by employing a noise generator and a band-pass filter, the number of normal modes of vibration can be controlled.

For a cylindrical room the number of normal modes of vibration (24), dN, in a frequency band, $d\upsilon$, is given by

$$dN = \left[\left(\frac{4 \pi \upsilon^2 V}{c^3} \right) + \left(\frac{\pi \upsilon A}{2c^2} \right) + \left(\frac{\Lambda}{8c} \right) \right] d\upsilon$$

where V is the volume of the room, A is the surface area, and Λ is found from

$$\Lambda = 4 \pi r + 4 \ell$$

ℓ being the length of the cylinder and r the radius of the cylinder.

The number of modes in a one-third octave bandwith as a function of frequency from 1 to 20 kc is shown in Fig. 10 for the cylindrical chamber being used in this experiment.

In order to decrease the possibility of wall vibrations of the chamber, the cylinder was placed in a large oil drum, open at the top, and encased in sand.

For the collection of the data a switch located between the projecting microphone and the power amplifier was used to turn the sound source on and off. The sound was always turned on for a time long enough to ensure that a steady-state condition was attained inside the cylinder. This could be determined by observing visually the amplitude of the sound on the chart paper of the Bruel and Kjaer recorder. When the amplitude was constant, the source was shut off and the decay curve resulted. This procedure was repeated about ten times at each frequency of interest. In most cases the decay curve proved to be approximately a straight line. This made it relatively simple to measure the slope over a 20 db drop. Since the chart paper was moving at the rate of 30 mm/sec, the time for the sound to diminish 60 db from the steady-state value could be calculated. Thus, an average reverberation time was found for each frequency from 3 to 20 kc centered in a one-third octave pass band.

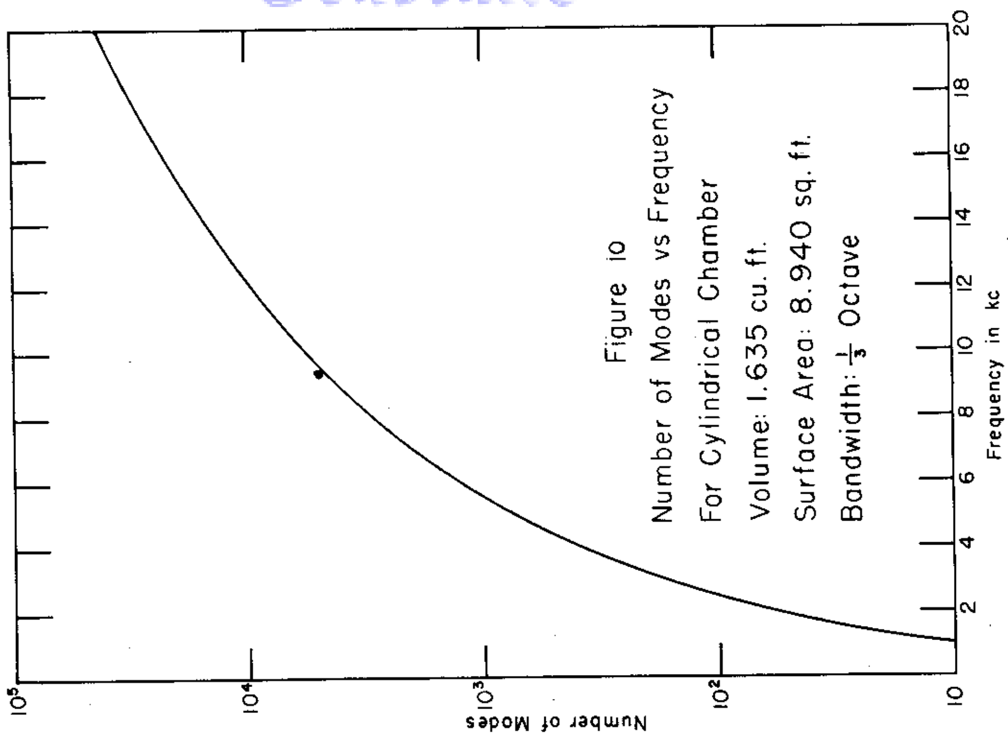


Fig. 10. Number of modes vs frequency for cylindrical chamber

The mice used were obtained at the Jackson Memorial Laboratory, Bar Harbor, Maine. Two varieties of hairless mice were used: C57 black hairless mice and albino white hairless mice. Only one variety of haired mice was used - the albino white haired mice. Photographs of a haired and hairless mouse are shown in Figs. 11 and 12, respectively.

B. Experimental Data

The data were obtained first on one mouse, then on two mice, and then on three mice. The mice were placed in the chamber one at a time. They were confined to small cages to restrict their motion. The reverberation time of the chamber was obtained with the cages arranged in the form of a triangle on the second level of the chamber. The procedure described in this section was adhered to for all the measurements. By averaging the values of absorption

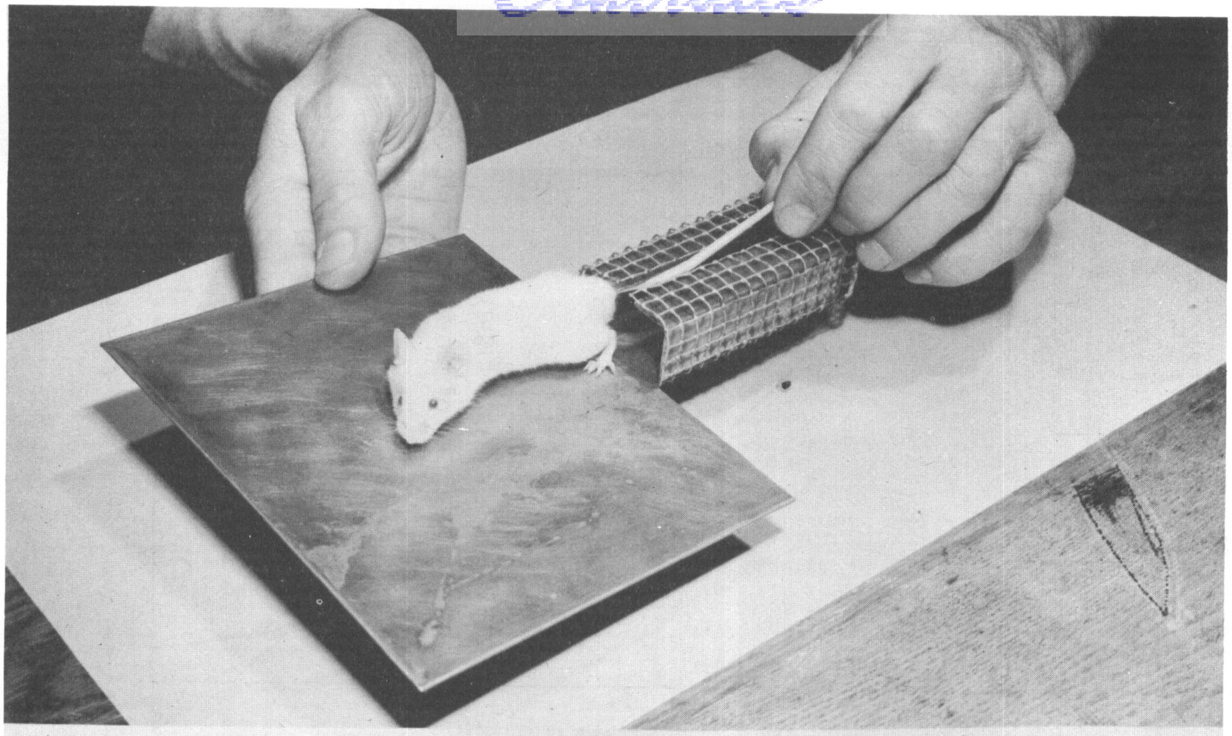


Fig. 11. Haired Mouse

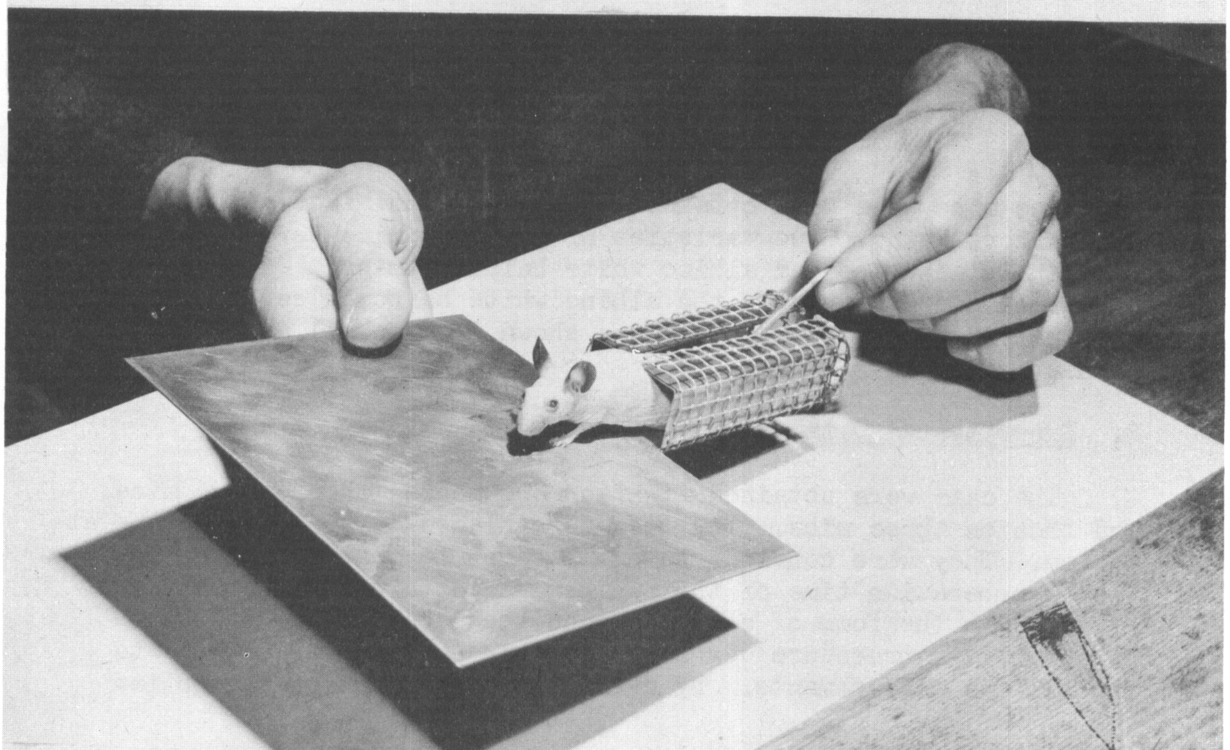


Fig. 12. Hairless Mouse

obtained for the three cases, a total absorption per mouse was calculated for an average haired mouse. Dividing the absorption per mouse by the total surface area of an average haired mouse results in the absorption coefficient.

The haired mice used in these experiments had weights of 39.9 gm, 32.5 gm, and 31.5 gm for one set of measurements; 33.3 gm, 34.3 gm and 34.6 gm for another set; and 30.0 gm, 31.8 gm, and 29.4 gm for the last set of measurements.

In order to find the surface area, a mouse was sacrificed and cast in paraffin. When the cast had dried, it was stripped off the dead mouse and broken into pieces, The pieces were assembled and their outlines drawn on a piece of paper. These areas were then measured with a planimeter. Two or three measurements on the same mouse repeated within 2%. The variation of surface between two mice of comparable weight was within 5%. The body, tail and total surface areas of a haired mouse weighing 31.5 gm and a hairless mouse weighing 28.0 gm are given below in Table II.

TABLE II

Mouse Type	Weight (gm)	Body (cm^2)	Tail (cm^2)	Total (cm^2)
Haired	30.5	81.0	7.0	88.0
Hairless	28.0	60.0	7.0	67.0

The hairless mice data were obtained in the same way that the haired mice data were taken except that the mice were not placed inside the chamber one at a time, but rather four at a time. A total of eight mice were used for each group of measurements, and a total of four groups of measurements taken. The average weight of the mice used was 27.8 gm. To preclude the possibility of mice on one level from casting a shadow on the mice located on another level, care was taken to insure that the mice were not directly above one another.

During the last set of data the temperature inside the chamber was measured to see whether the body temperatures of the mice appreciably changed the original temperature of the chamber without mice. As can be seen from the table following only small variations were recorded.

TABLE III

No. of Mice	Temperature (°C)
0	24.2
4	25.2
8	26.0

Figs. 13 and 14 show the variations of the acoustic absorption coefficients as a function of frequency for the haired and hairless mice, respectively. The significance of the confidence limits and the average curves shown are discussed fully in the next section.

C. Discussion and Conclusions

The acoustic absorption coefficients shown in Figs. 13 and 14 represent the percentage of the incident energy absorbed per unit area by either a haired or hairless mouse at a frequency centered in a one-third octave pass band. For both the haired and hairless mice there is a rather large variation of the absorption coefficient at any one frequency. However, due to the nature of the measurements, these variations are not entirely surprising. Such factors as skin texture and hair length vary from one mouse to another. Although the average weight of a group of mice used for a measurement remained almost constant for the hairless mice, the same mice were not always used. Hence, skin texture, for instance, could play a leading role in the variation of the measurements. Von Gierke, Parrack, and Eldredge (16) report that for furred rats the absorption coefficient was as much as 30% higher for ruffled fur than for fur which had been smoothed down.

Another factor which has been mentioned briefly is the movement of the mice. Even though the mice were placed in cages, they were still able to move about quite freely in a limited region, and also to curl up somewhat. Coupled with the physical variations in the mice, the movement and the curling could easily be responsible for the variations obtained.

In spite of the scattering of the absorption coefficients throughout the frequency range, there is a general increase in the absorption as the frequency increases. To investigate this dependence more thoroughly a statistical process was applied to the data. As described above, a measurement of the reverberation time of either the empty chamber or of the chamber with the mice included, consisted of averaging about ten single measurements. By the usual methods of statistics the square root of the variance, σ, was calculated. If σ

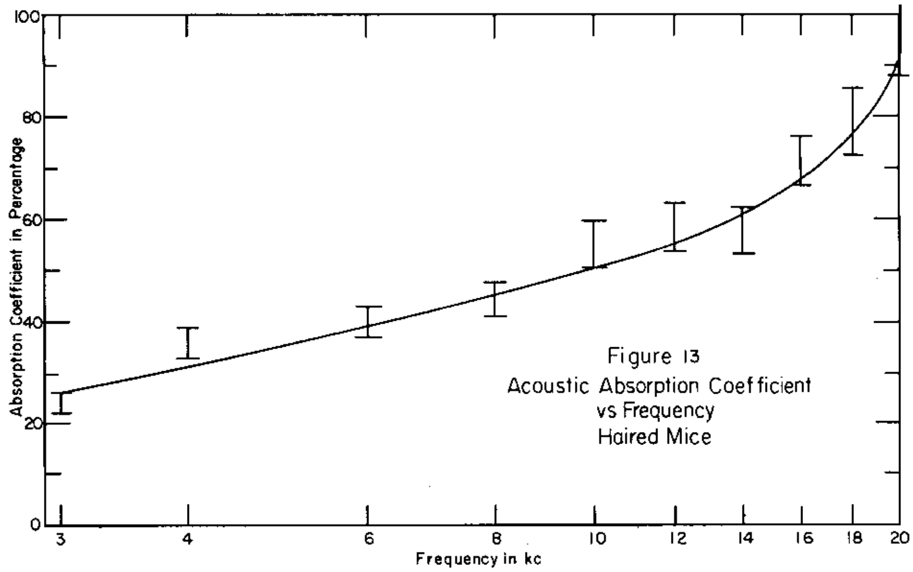


Fig. 13. Acoustic absorption coefficient vs frequency haired mice

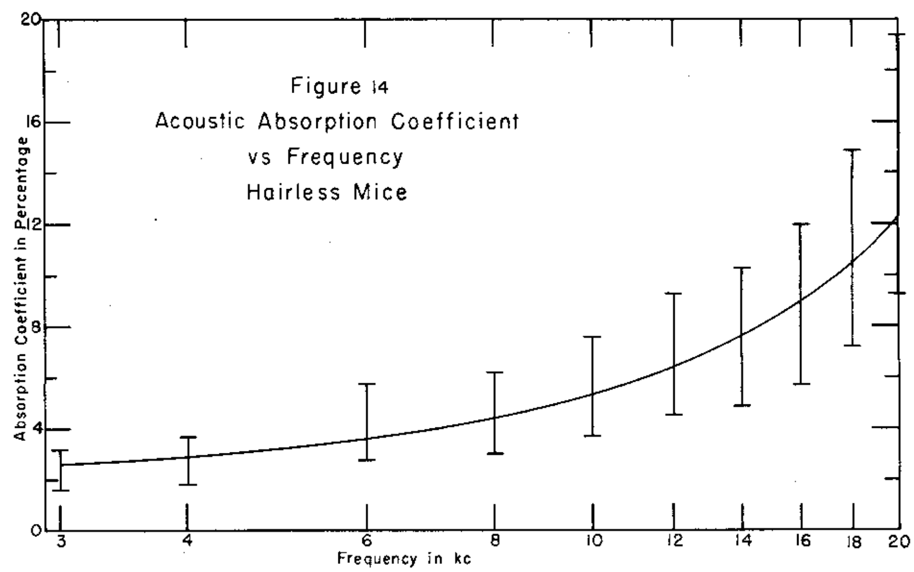


Fig. 14. Acoustic absorption vs frequency hairless mice

is divided by the square root of the number of measurements (in this case ten) the standard deviation from the mean is obtained. This value has the meaning that if one hundred sets of ten measurements are taken, sixty-seven will fall within the limits defined by the standard deviation from the mean. Several such determinations of the standard deviation from the mean were made and the results averaged. The value found and used was 2.25% of the reverberation time. Armed with this value, the confidence limits shown in Figs. 13 and 14 were determined for the haired and hairless mice. A smooth curve is shown for both varieties of mice. The standard error for the haired mice was calculated to be 8%, while for the hairless mice it was 35%. The large percentage error for the hairless mice is to be expected since their absorption coefficients are very small and, hence, are more difficult to determine.

The confidence limits show a definite increase in sonic absorption with increasing frequency for both the haired and hairless mice. An especially sharp rise is observed in both cases from about 16 to 20 kc. These results are in agreement with those reported by Danner, Ackerman and Frings (3) for haired and hairless mice. A comparison of a few values of the acoustic absorption coefficient with the values mentioned above are given in Table IV. Very good agreement has been attained.

TABLE IV

Freq. (kc)	Acoustic Absorption Coefficient			
	Reverberation Time Method		Danner, Ackerman, Frings	
	Haired Mice	Hairless Mice	Haired Mice	Hairless Mice
6	0.40 ± .03	0.042 ± .015	0.50 ± .10	0.012 ± .009
12	0.58 ± .05	0.069 ± .024	0.65 ± .10	0.060 ± .015
18	0.80 ± .06	0.110 ± .039	1.10 ± .25	0.100 ± .020

A comparison of the standard errors recorded in Table IV is very interesting. The values of the acoustic absorption coefficients of hairless mice quoted by Danner, Ackerman, and Frings are more accurate than those found by the reverberation time method. On the other hand, the values found by the reverberation time method for the haired mouse are more accurate. This information seems to indicate that the reverberation chamber used is well suited for measuring absorptions in excess of 20%, providing that not too many mice are measured at a time. Hence, there is some ratio of the chamber volume to mouse volume or chamber surface to mouse surface above which fairly good accuracy is attained. In addition a certain minimum absorption must be provided to obtain satisfactory accuracy. In order to determine more accurately the absorption coefficient for eight hairless mice, a different chamber geometry would be needed.

D. Summary

The acoustic absorption coefficients for haired and hairless mice have been measured in the frequency range from 3 to 20 kc using a reverberation time technique. The average absorption coefficients for both haired and hairless mice increase with increasing frequency. For the haired mice the average absorption coefficient rises from about 24% at 3 kc to about 96% at 20 kc, while for the hairless mice it rises from about 2% at 3 kc to about 14% at 20 kc. The standard error for the measurements on the haired mice is 8% of the average absorption coefficient and 35% in the case of the hairless mice.

A reverberation time method appears to be well suited for absorption measurements of larger animals with small absorptions if the equipment used in the present study is modified.

SECTION V

ASYMMETRICAL CHAMBER - INITIAL EQUIPMENT

One of the limitations of the cylindrical reverberation chamber was that only certain regions could be used. In these, the calculated absorption coefficient for porous Fiberglas was close to one, and the calculated absorption coefficient for two mice was twice that for one mouse. However, it appeared desirable to check these reverberation measurements with a chamber not limited in this fashion. Another drawback of the previous work was the necessity of using a paper tape record. Considerable practice was necessary to be able to read the tape and even then the process was very slow. Accordingly a new apparatus was constructed to avoid these restrictions.

The initial form of the chamber was not altered after construction. It is shown in Fig. 15. Its volume was determined to be 48.9 $\pm$ 0.1 liters by filling it with water after lining it with plastic.

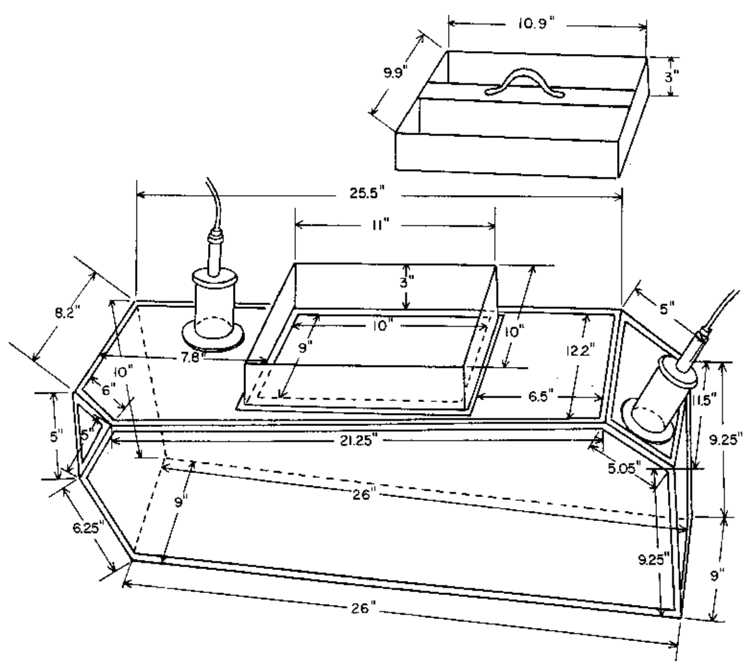


FIG. 15 REVERBERANT CHAMBER

Fig. 15. Asymmetrical chamber shape

Two types of electronic systems were used initially with this chamber. The first method used a Kay Laboratory Model 511C logaten and a persistent vision oscilloscope. Fig. 16 is a block diagram showing the arrangement of the different apparatus. The output of the logaten is proportional to the log of the input. Fig. 17 is a plot of the logaten output against the log of the input voltage. Within a specified range the curve is practically a straight line and can be expressed by the following equation:

$$E_o = \beta_1 + \beta_2 \log_{10} E_i$$

where β_1 and β_2 are constants and E_o, E_i the output and input voltages respectively. For the logaten used here, β_1 is 0.110 and β_2 is 0.120.

The output from the logaten was fed into the vertical deflection plates of the oscilloscope. The horizontal sweep was set to the driven sweep position and synchronized with the key which opened the circuit of the microphone that generated the noise. Therefore, if the sound field in the chamber decreased exponentially, the output from the logaten decreased linearly. This is illustrated in Fig. 18.

The amplitude and the sweeping time were calibrated by feeding signals of known amplitude and frequency into the oscilloscope. Fig. 19 is a picture of the response to input signals of 0.05, 0.10, 0.15, 0.20, and 0.25 volts rms and Fig. 20 is the trace of a 100 cps signal. Using Figs. 19 and 20 as references, it is possible to determine the time used for the sound field inside the chamber to drop from one level to another. Fig. 21 shows that the reverberation time is different when different frequencies are used. Fig. 22 shows the measured results of the coefficient of absorption of haired mice at different frequencies.

The second method used an electronic switch and a Hewlett-Packard Model 522B electronic counter instead of the oscilloscope. The output from the logaten was amplified by a three stage amplifier. The amplifier output was rectified by a twin diode and these rectified dc voltages used to bias the two grids of two separate thyratrons. One of the thyratrons was biased more than the other by connecting a battery in the cathode circuit. As the sound field in the chamber dropped in intensity, the output from the logaten also dropped. This reduced the bias voltages on the grid of the thyratrons. At a certain level the first thyratron (the one without battery bias) fired and generated a pulse. As the sound field intensity inside the chamber continued to decrease, the second thyratron fired at a level which was ΔE below the first one, where ΔE was the voltage of the battery. These two pulses were used to

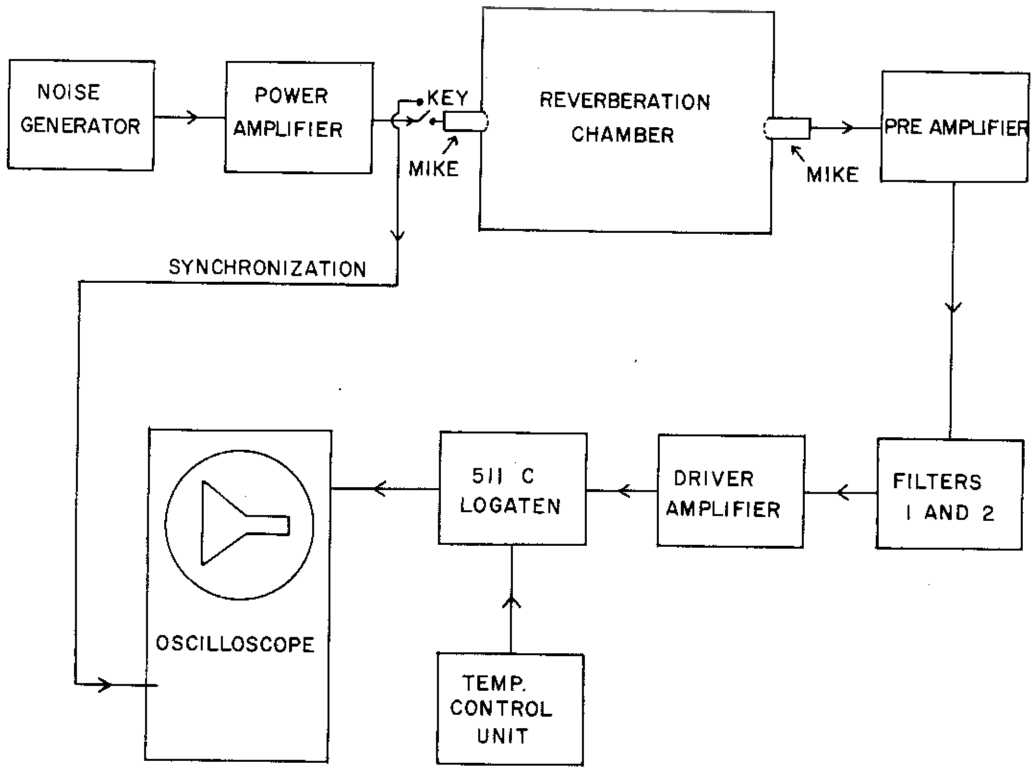


Fig. 16. Block diagram - oscilloscope and logaten method

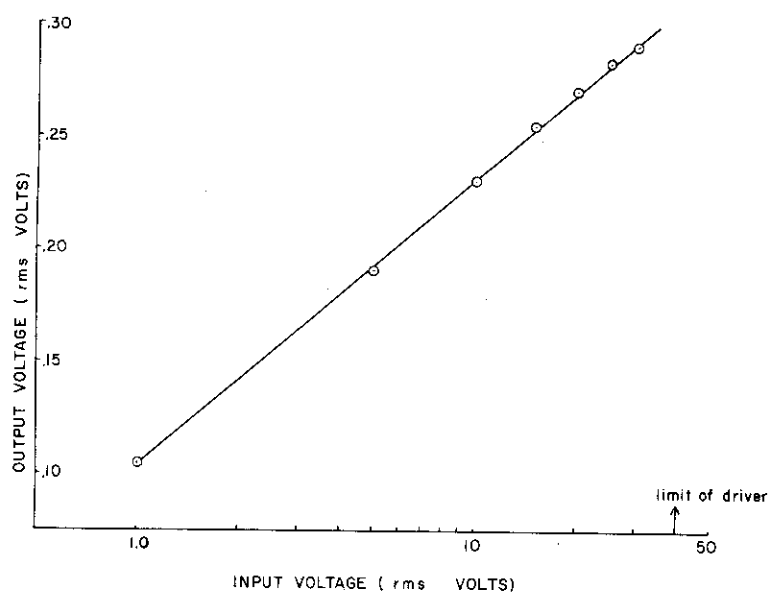


Fig. 17. Logaten response curve

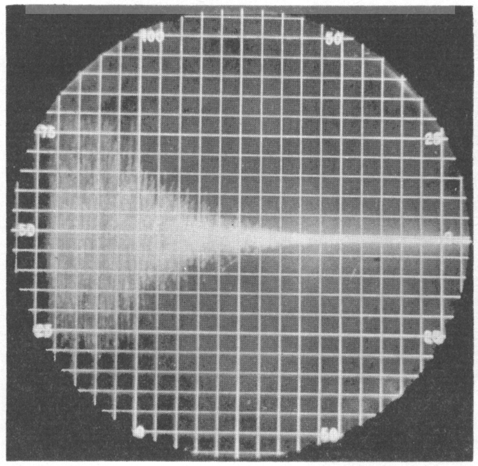


Fig. 18. Decay Curve using logaten

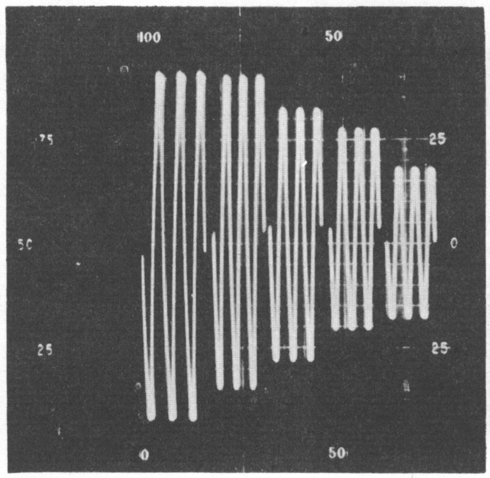


Fig. 19. Oscilloscope calibration vertical axis

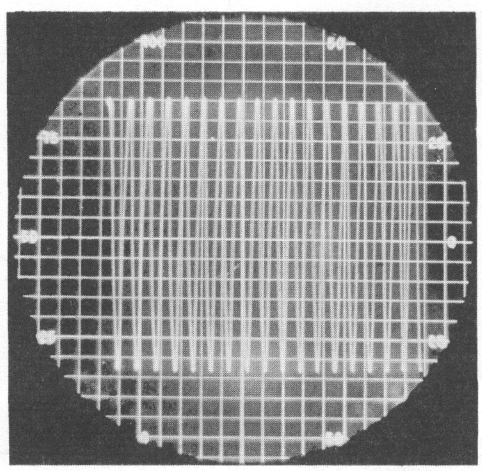


Fig. 20. Oscilloscope calibration horizontal axis

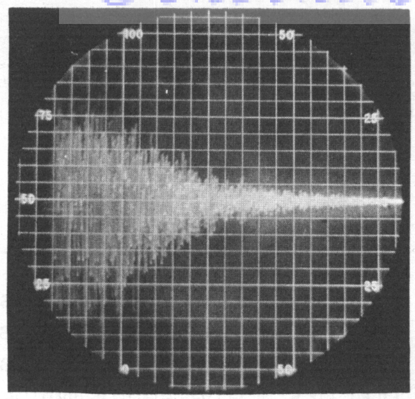


Figure 21A . Reverberation time curves

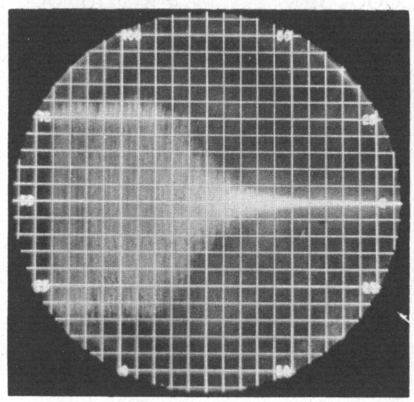


Figure 21 B. Reverberation time curves

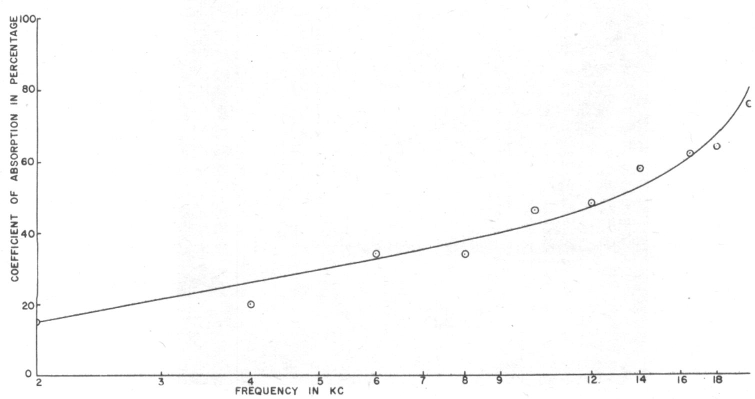


Figure 22. Absorption vs frequency of haired mice - Method I

operate the electronic counter. The counter measured time to an accuracy of 0.01 millisecond which was more accurate than needed in this experiment. Extra pulses from the thyratron occurred which were smaller in magnitude than the initial ones. These were eliminated by diodes, biased to pass the first pulse only.

In the experiments using the cylindrical chamber the mice were always unanesthetized. As noted, this necessitated special small cages. To check the effect of anesthesia, mice were used with and without anesthesia by the second method. The measured coefficients of absorption for haired mice is shown in Fig. 23. There seems to be no systematic difference between the anesthetized and unanesthetized mice.

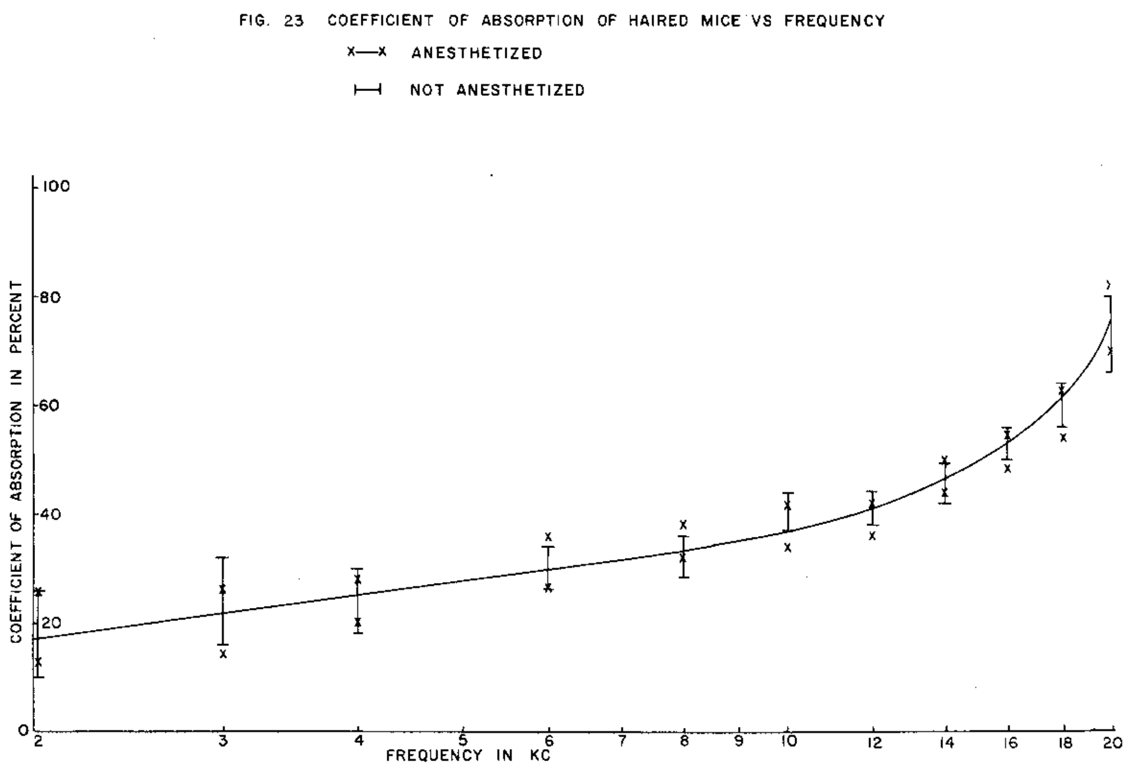


Fig. 23. Absorption vs frequency of haired mice - Method II

The two methods described above needed further improvement. In the first method the slope of the envelope of the noise amplitude did not change sufficiently with the change of reverberation time. Precise measurement was comparatively difficult, although this might have been improved by making the sweep faster. This would have expanded the time axis and increased the accuracy of measurement.

The second method appeared more promising. However, there were several things which needed improvement. The two thyratrons had to be carefully matched. With fixed plate voltage, it was found that some thyratrons, although of the same type, did not fire at the same grid voltage consistently. It was therefore necessary to choose those thyratrons which were consistent. Finally, the rectified voltage from the diode was smoothed by an RC filter circuit. The time constant of this circuit had to be small or the rectified bias voltage would not follow the decay of the sound field inside the chamber. Of course corrections could be made to the measured reverberation time. This is especially important for short reverberation times. However, the time constant could not be made too small otherwise it no longer would function as a filter.

Conclusions

The measured results may be summarized as follows: The acoustical coefficient of absorption of the haired mice measured in these fashions increased as the frequency was increased. This is in agreement with the results described in the last section. However, it should be pointed out that the values obtained by the present experiment are systematically smaller than those of the last section. The coefficient of absorption for the anesthetized mice does not seem to differ from that of the unanesthetized mice.

The results given in this section were preliminary measurements. They showed that the electric counter method was potentially useful but that the electronic apparatus had to be completely rebuilt.

SECTION VI

ASYMMETRICAL CHAMBER - DETAILED STUDIES

Following the plans suggested in the previous section the electronic equipment was completely redesigned and rebuilt. Its final form is shown in the accompanying block diagram and photograph (Fig. 24). The details of the circuits used are shown in five diagrams which follow (Figs. 25 through 29). This equipment has proven satisfactory for all of our animal measurements. In practice, the equipment is set so that the counter is activated during the time that the signal falls 30 db. It is necessary to be careful that none of the circuits are overloaded; in that case one observes an electronic rather than an acoustic decay time.

The standard oscillator was set at 20 kc. The counter added successive decay times. By doing five experiments and dividing by 10^5, one had the average time for the sound to decay 30 db expressed in seconds. The reverberation time was exactly twice this amount. The equipment could in theory be set to measure the time for the signal to fall 60 db. However, our previous experiments with the logaten output fed into an oscillograph, as well as later experiments, all indicated the equipment noise determined the signal before the sound pressure level fell 60 db below the peak useful value. Thus 30 db appeared a more practical range.

As in the studies reported in the previous sections, a pure tone noise signal was felt to be unsatisfactory due to the creation of distinct standing wave patterns. The use of noise, however, introduces a random variation into the decay times measured. As described above, five decay times can be easily averaged by the equipment. This is always repeated at least five times, and when dealing with lower absorptions, at least 10 times. When measuring haired animals it was possible to measure the reverberation time of the empty chamber at all frequencies used; and then to repeat with the animal in the chamber. With hairless animals it was necessary to run the equipment at one frequency and take successive measurements on the empty chamber and then on the chamber with the animals in place.

In almost all the experiments reported here the animals were anesthetized and placed on a wire screen in the middle of the chamber. The experiments in the last section indicated that this should not alter the observed absorption. In one experiment, using the equipment described here, the mice recovered from anesthesia and started

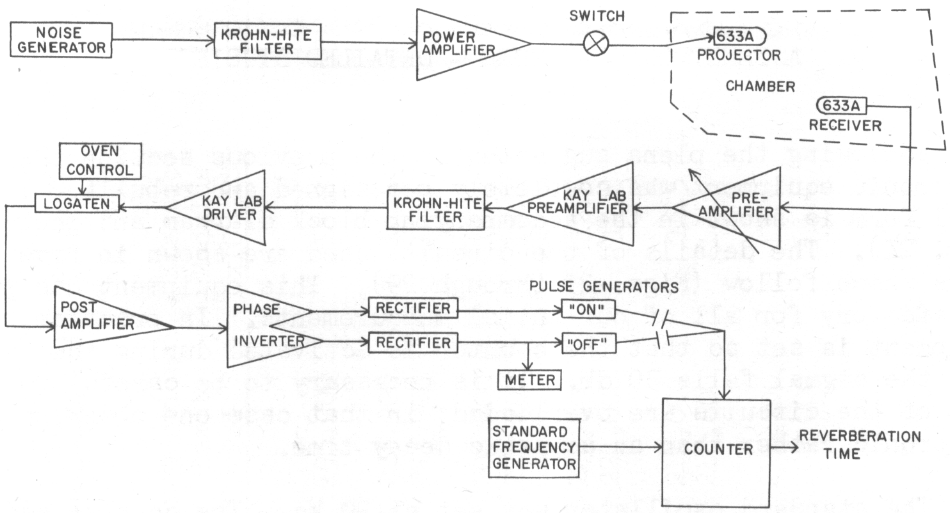


Fig. 24A. A block diagram of reverberation time counter

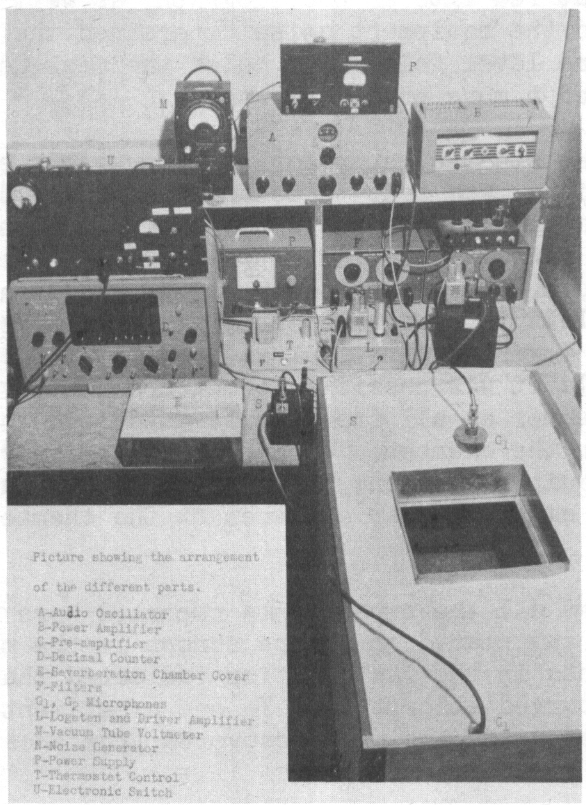


Fig. 24B. Photo of original form of reverberation time counter

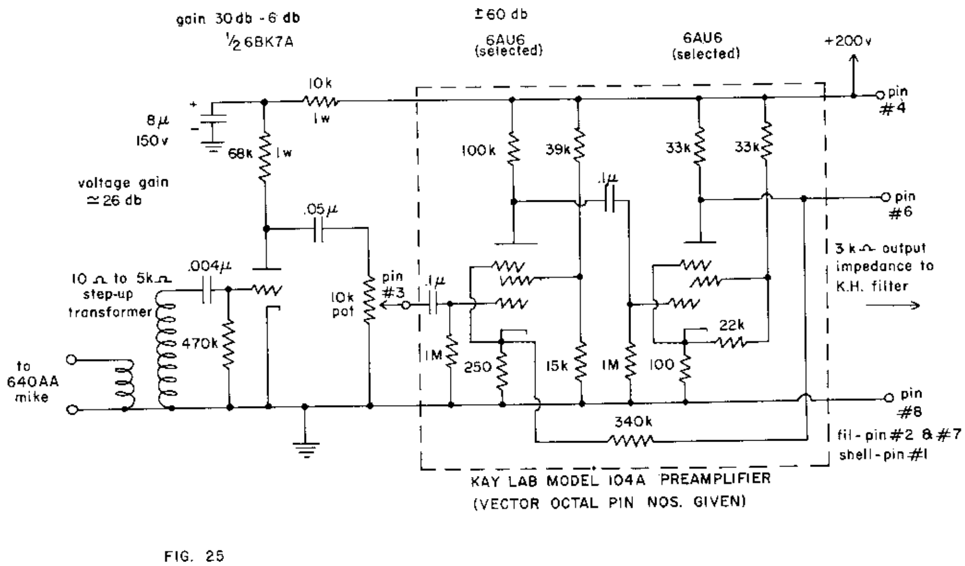


Fig. 25. Pre-amplifier of reverberation time counter

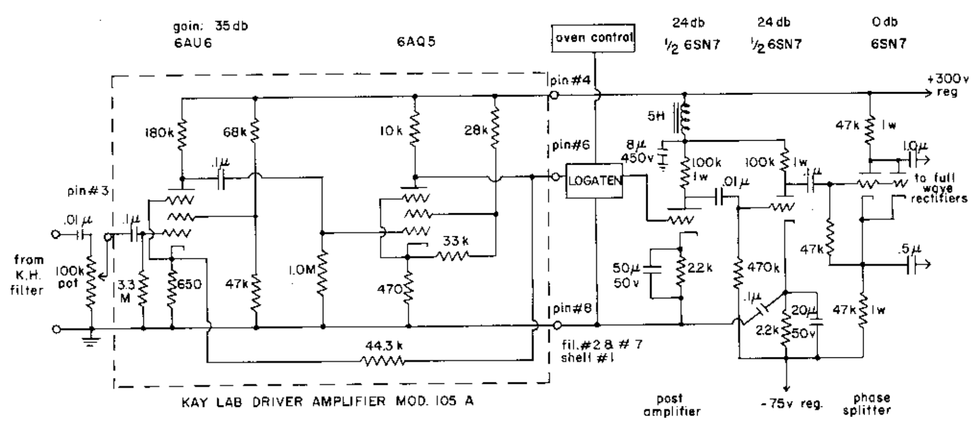


Fig. 26. Logaten, post amplifier and phase splitter of reverberation time counter

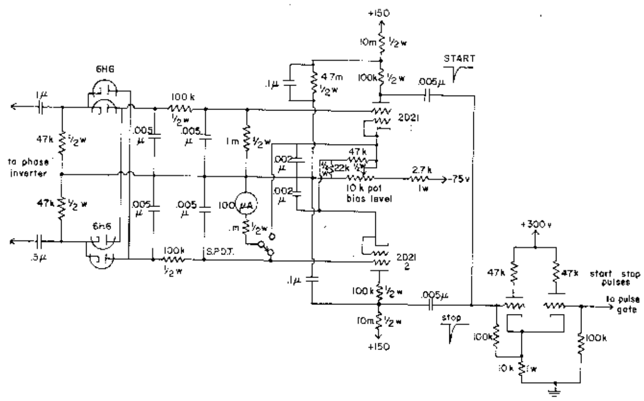


Fig. 27. Rectifier and coincidence circuit of reverberation time counter

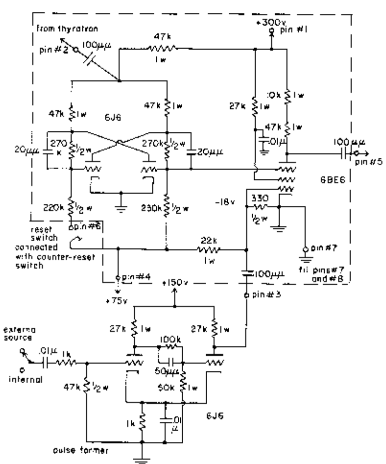


Fig. 28. Counter gate and pulse former of reverberation time counter

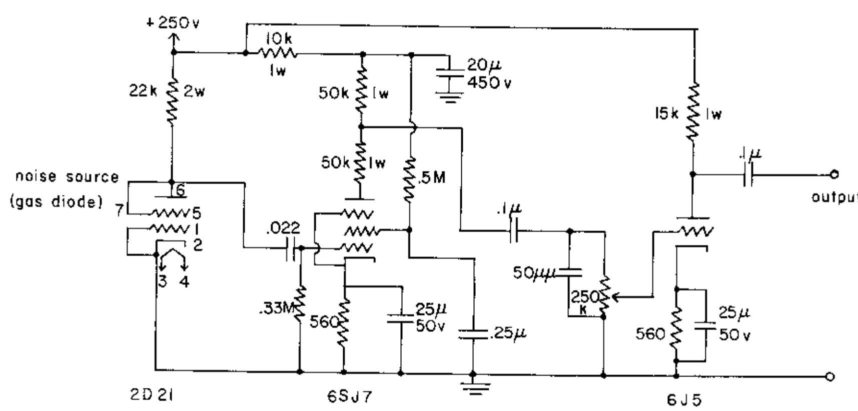


Fig. 29. Noise generation of reverberation time counter

running around the chamber. Repeat experiments showed that this did not alter the observed decay times except to increase the random error.

Likewise placing the animals in different parts of the box did not alter the reverberation time. In fact, somewhat to our surprise, we found the same reverberation time if the animal, or a Fiberglas dummy, were on the screen or on the floor. This could only be the case if the walls (or floor at any rate) were vibrating. Further experiments did indeed confirm that the chamber floor was vibrating, thereby increasing the effective chamber volume. Accordingly, Fiberglas was used to calibrate the chamber. A change in decay time was treated as equivalent to a certain area of Fiberglas. By using a light weight Fiberglas with an absorption coefficient close to 100%, the equivalent Fiberglas area was identical to the absorption.

Measurements of this type were carried out on rats, mice and guinea pigs. Both haired and hairless mice were used. The graphs in Figs. 30 and 31 show the absorption coefficients computed for rats and guinea pigs. Note that both are similar in that the absorption coefficient rises with increasing frequency as one approaches twenty kilocycles. The rat surface areas were measured by an approximate formula, and by sewing a dead rat in a tight-fitting plastic sheet coat and then planimetering the area of the coat. This showed that a 344 gm male rat had a total surface area of 403 cm^2 of which 44 cm^2 was tail and the remainder body. Since the tail is not covered, it appeared debatable whether the tail should be included in the surface area. In one series of experiments a rat's tail was amputated. The anesthetized animal, its detached tail lying in place, was used in the reverberation chamber; then similar experiments were performed with the tail removed. Since the area of the tail was only ten per cent of the total, it had a small effect. However, the average absorption at the frequencies used, was decreased by the absence of the tail. Therefore, the tail was included in the surface areas used.

Fig. 32 shows the absorption coefficients for haired mice obtained by all the techniques mentioned in this report. Note that there is reasonable agreement among all of them. Similar (but fewer) data for hairless mice are shown in Fig. 33. This confirms the idea that principal absorption in the haired animals is related to the fur. Unlike data for humans, to be presented in a future report, these show that the absorption coefficient increases with frequency for hairless mice.

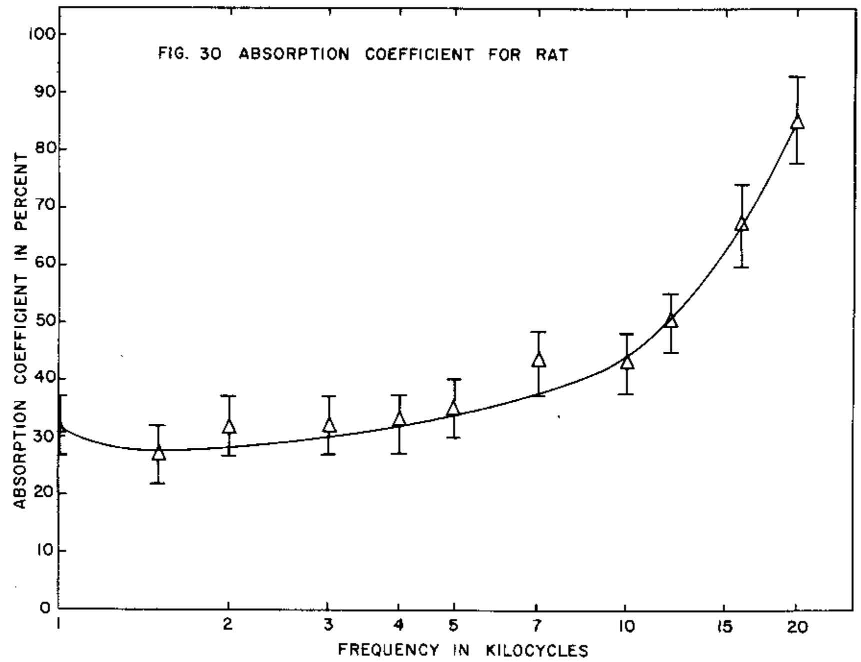


Fig. 30. Absorption coefficient for rats

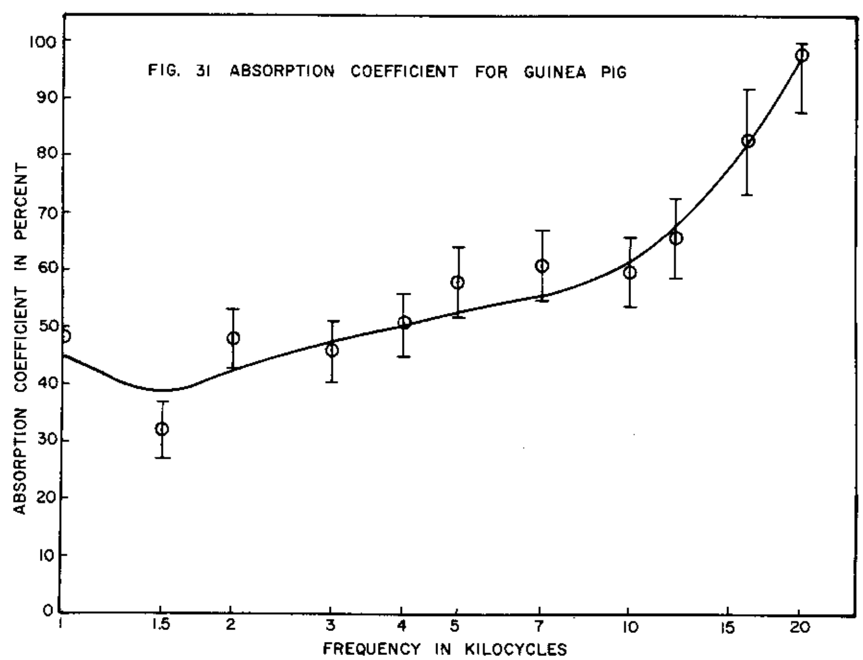


Fig. 31. Absorption coefficients for guinea pigs

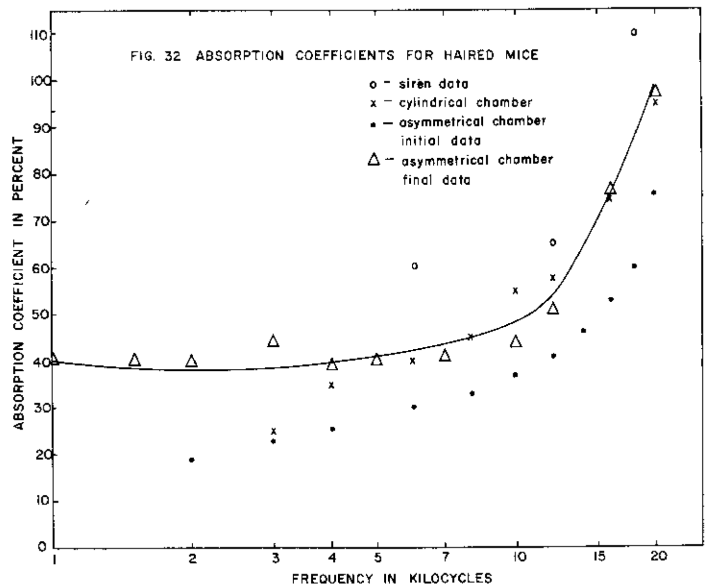


Fig. 32. Absorption coefficient for haired mice by various methods

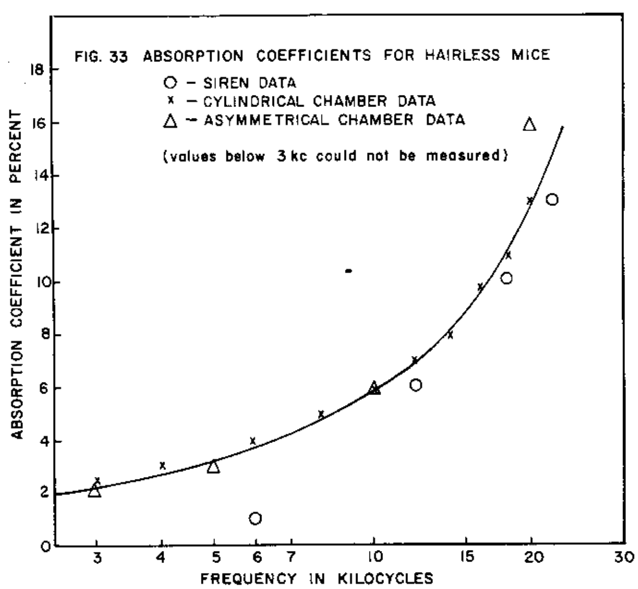


Fig. 33. Absorption coefficient for hairless mice by various methods

SECTION VII

DISCUSSION AND SUMMARY

The data presented in this report show the acoustic absorption coefficient for small laboratory animals. Two essentially different techniques are used. One involved the direct absorption of sound energy in high intensity (ca 160 db sound pressure level) fields. The other measured the absorptions in terms of an increase in the reverberation time of a chamber. Two different reverberant chambers were used, and two different types of methods were used with the last chamber. The sound pressure levels in the reverberant chambers were 100 db and fell from about 95 db to 65 db during the observation. The good agreement between all of these measurements indicates that the absorption coefficients do not depend on the intensity of the sound waves.

Measurements on haired mice, rats and guinea pigs all showed a similar increase in absorption coefficient from 1-20 kc. These were very different from values either for hairless mice or human surfaces. In all cases the acoustic absorption coefficient of the haired animals approached 100% at 20 kc.

While the above increase in acoustic absorption coefficient with frequency is undoubtedly due primarily to the fur, it is possible that the skin may also contribute to this. Measurements on hairless mice showed that their absorption increased with frequency above 5 kc. Other observations showed that most of the energy absorbed is converted to heat directly at the skin; i.e. this absorption is an interface phenomenon which might be masked or largely absent when using the impedance tube method.

The measured absorption coefficients for hairless mice differed very markedly from coefficients for humans. If the absorption were due to the propagation of sound waves through the tissues, the human and hairless mouse data should have been similar. The marked differences emphasize that these coefficients for the hairless animals are due to surface absorption. Since the skin of humans and hairless mice is histologically very different, i.e. hairless mouse skin is keratinized and full of lipoidal cysts, it is not surprising in retrospect that the two absorption coefficients are not the same.

In all of these experiments, a large standard error of the mean was found. This is due to a variety of causes. First, but probably not most important, is the inherent variation of biological materials. Superimposed on this are a number of physical factors. In the given experiments it was not possible to reproduce the same harmonic content of the sound field from day to day. Moreover a variation of only 3 db would have caused an error of a factor of two in the incident power; it was almost impossible to regulate the sound field closer than a few tenths of a decibel. In addition, it was impossible to know the probe microphone calibration any closer than this. Thus physical uncertainties were sufficient to produce the observed scatter in the siren not given.

The inaccuracy in the reverberation time measurements was in part inherent in the method. Either one used a few well determined modes in which case the absorption of an irregular object was almost impossible to compute, or one had to use a band of noise. We chose the latter alternative as being more reasonable for animal experiments. This meant that at any given instant the actual modes present were different than a short time before. The modes actually present at the opening of the switch determined the observed reverberation time. Maximum differences as great as 30 per cent were obtained between successive readings. This meant that with twenty-five determinations (five sets of five) the standard error of the mean was reduced to less than one per cent. However, between one day and the next considerably greater variations were found. Their exact cause was not determined although it was clear that room temperature, line voltage, ambient acoustic and electric noise levels all contributed. By and large, these were not important if measurements of the reverberation times with and without the animals were made sufficiently closely in time.

The Sabine formula used (or the Norris-Eyring modification which led to the same absorption coefficients) assumes that the modes throughout the chamber are of such a nature that absorption occurs continuously at all surfaces. In the asymmetric chamber this was the case since the reverberation time was not affected by the location of the absorber. If this is true, it is equally valid to consider absorption in the air as equivalent to increasing the effective absorption of the chamber. When computing the added absorption due to the animals, that due both to the walls and to the air cancel when τ_c^{-1} is subtracted from τ_{c+m}^{-1}. To express this mathematically, we may note that the Sabine formula comes from the expression

$$\frac{d}{dt}\left(\frac{4V\Upsilon}{c}\right) = \Pi - \Upsilon a \ .$$

For symbols, see Section II; for justification see Morse (23). If Π is set to zero one may solve for the reverberation time. In this uniform distribution case, the pressure amplitude, p_o, is shown by Morse to be given by

$$p_o^2 = \frac{2\rho c}{\pi} \Upsilon$$

If α' is the rate of attenuation of p_o^2 per centimeter, then $\alpha' c$ is the rate of attenuation per second of p_o^2 as well as . Hence,

$$\frac{d}{dt}\left(\frac{4V\Upsilon}{c}\right) = -\Upsilon a - 4\alpha' V$$

is as good an approximation as the Sabine formula. Thus the air absorption increases the apparent wall absorption; but both of these are cancelled out when the animal absorption is computed. The values of the acoustic absorption coefficients of the wall will be discussed in the following report.

Our measurements on the absorption coefficients of rats can be compared with the work of von Gierke et al (16). He used the rod and impedance tube methods to measure the absorption coefficient of furred and shaved rats from 1-17 kc. The data for both showed that his measured absorption coefficients depended on the area tested, as did the exact shape of the curve obtained. Depending upon the area and the method used, they found a dip or flat region in the absorption coefficient curve as the frequency was raised from one to four kc. Above four kc the curve rose, although its exact shape depended on the method and area used. These shapes are in agreement with our data. Our measured absorption coefficients are higher than those of von Gierke and his coworkers. However, the differences between his highest value and ours are comparable to the spread of his values using 4.9 cm^2 and 17.6 cm^2 areas. Considering the differences in the methods and rat strains used, our values can be considered in good agreement with theirs.

As pointed out earlier, if a solid object is placed in a randomly oriented sound field (as opposed to a normally incident plane wave), surface waves are excited. Thus one would expect our results to be closer to those of von Gierke et al for their smaller area. Smaller areas are more likely to excite surface type waves. The data do indicate this better agreement between the 4.9 cm^2 values and ours, than the 17.6 cm^2 values and ours.

On the other hand, our data for hairless mice bear little or no resemblance to those of von Gierke. As noted in Section II, we suspect that this difference is due to the much greater importance of surface waves in our experiments. In addition, the hairless mouse skin is quite different than shaved rat skin, both physically and histologically.

In summary, values of acoustic absorption coefficients have been measured from 1-20 kc for rats, guinea pigs, and both haired and hairless mice. These all show an increase as the frequency is raised from six to 20 kc which is large compared to the experimental errors. The latter are inherent in the various methods used and appear to result primarily from physical factors. The furred animals all had similar absorption coefficients which approached 100% at 20 kc. The hairless mice had an increasing absorption as the frequency approached 20 kc; but its value was about one-fifth that of the furred animals. The data for furred rats are in general agreement with those of von Gierke et al (16).

It would seem of interest to extend these measurements to higher frequencies to see if the acoustic absorption coefficients again decreased. For hairless mice it is quite possible that the absorption coefficients will continue to rise above 20 kc. At lower frequencies the results obtained at WADC make it apparent that the absorption coefficient will rise as the frequency is lowered. But the higher frequency end of the acoustic spectra associated with jet engine and industrial noise, from 20 kc up, has not been explored. Values for inanimate objects obtained at Penn State indicate that in some a rising absorption curve is found in this region; in others a flat curve is obtained, and in still others a curve which falls with increasing frequency. We do not know of any data indicating what the absorption coefficient curve for laboratory animals or humans does in the frequency range from 20 kc to 100 kc.

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