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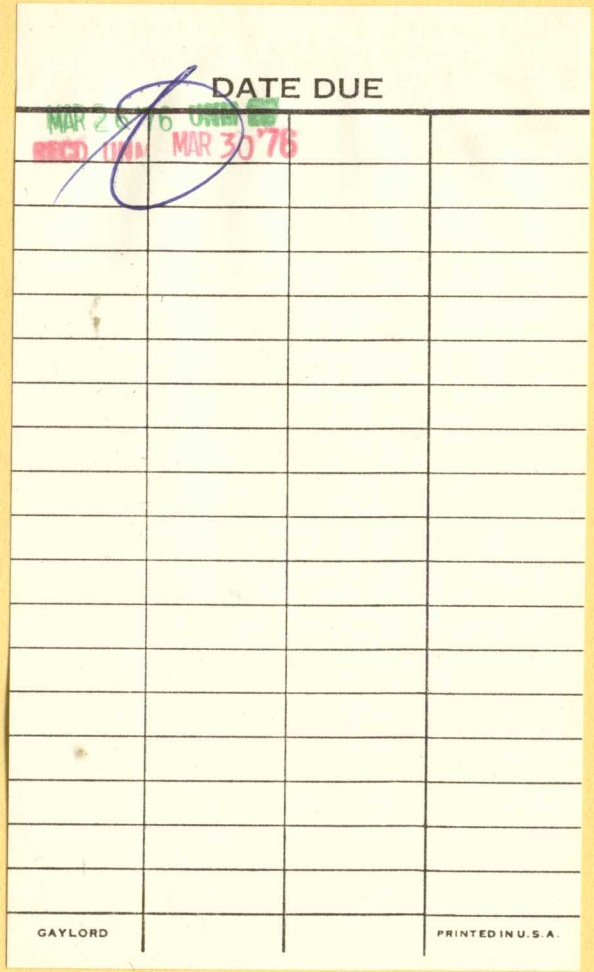
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THE DESIGN, CONSTRUCTION, AND CALIBRATION OF A STATIONARY WAVE DEVICE FOR DETERMINING SOUND ABSORPTION COEFFICIENTS OF ACOUSTIC MATERIALS

By

Douglas W. Ballard

A Thesis

In partial fulfillment of the

Requirements for the Degree of

Master of Science in Mechanical Engineering

The University of New Mexico
1952

This thesis, directed and approved by the candidate's committee, has been accepted by the Graduate Committee of the University of New Mexico in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

E. H. Castetter
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DATE 5/19/52

Thesis committee

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ACKNOWLEDGMENTS

The general scope of the thesis investigation is limited to the engineering design and construction of a stationary-wave device for the experimental determination of the sound absorption coefficients of various building materials, the calibration of the apparatus to give comparisons with results obtained in the more expensive reverberation time method, and to attempt to correlate observed results with generally accepted acoustical standards.

The investigator is indebted in his research to many who have helped by directly contributing to the apparatus construction or by advice and criticisms offered during the design and calibration phase.

A special acknowledgment is due G. V. Lemmon, graduate student, for his invaluable assistance in the construction and calibration stages of the investigation.

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CHAPTER I

INTRODUCTION TO PROBLEM

Acoustics was one of the first sciences and, as a pure science, possesses a unique satisfaction for the researcher because of the concreteness of the fundamental assumptions.[1] However, until the 1870's, acoustics remained a pure science and acoustical considerations by engineers and architects were practically unknown. During the past thirty-five years, however, there has been a rapid growth in the interest, both scientific and popular, in the subject of acoustics. Acoustical treatment of buildings by judicious selection of materials for their sound absorbing characteristics has become a rule rather than an exception. The discovery of the thermionic effect with the resulting development of the vacuum tube has given the researcher a powerful method of amplification and measurement of minute alternating currents involved in the study of sound, and recent experimental data (often conflicting) has given the architect and engineer a mass of data and empirical laws on which to base acoustical design.

---

[1] Sir James Jeans, The Growth of Physical Sciences, The Macmillan Company, New York, 1947, p. 56.

Many early auditoriums were built with very little attention given to the acoustical properties of the building materials. A good example, which is well known throughout the world, is Carnegie Hall which was designed by William Burnet Tuthill in 1891. He used only the lengths and duration of time of sound wave travel, and gave no thought to the acoustical properties of the materials themselves.[2]

Much of the undesirable characteristic of noise, which may be defined as undesirable sound, may be eliminated simply by the proper selection of sound absorbing materials. When a sound source operates, sound waves travel radially from the source. When these waves strike a surface, their direction of travel is changed and, depending upon the ability of the surface to dissipate the energy within the sound wave, the intensity is reduced. Most of the common building materials are notoriously poor sound absorbers, i.e., excellent reflectors as shown in the following list:

Material	Absorbs (%)	Reflects (%)
Plaster	2.5	97.5
Concrete	1.5	98.5
Wood Paneling	3.0	97.0
Glass	2.7	97.3
Carpet	20.0	80.0

2 W. B. Tuthill, "Practical Acoustics," copy of unpublished manuscript secured from John Weil, graduate student.

From this list it is obvious that only a small part of the sound energy is absorbed at each contact and the remainder is reflected back into the room, increasing the overall sound intensity within the room as a first effect. Thus, within a room with a continuous sound source, a listener will receive many reflections from the various surfaces in the room. The total loudness, or intensity, will depend upon the location of the various surfaces and the amount which each surface reflects to the ear, that is, upon the absorptivity of the material.

The acoustical treatment of a room consists of the application of sound absorbing materials in a sufficient quantity and with high absorption coefficients so that the sound will die out quickly after it is produced. It is generally recognized that the reverberation time (time for noise intensity to diminish to 1/1,000,000 of its original value) for an average residence should be approximately one-half second, while auditoriums should have reverberation times in the order of one to one and one-half seconds in order to avoid a flat or dead acoustical quality which is also undesirable. Correct sound treatment will result in a live room with a clarity and distinctness of speech and music which insures easy, effortless hearing.

It is outside the scope of this investigation to go into details concerning physiological acoustics, but it is necessary to include a brief discussion in order to impart an appreciation of the ranges of values of intensity and frequency encountered in acoustic work.[3]

The human ear is a sensitive yet extremely rugged organ. It is capable of responding to a frequency range of ten octaves (twenty cycles per second to twenty thousand cycles per second) and will perceive and tolerate sounds of intensity of the ratio of one to one-trillion. The response of the ear is not proportioned to the intensity; however, it is more nearly proportioned to the logarithm of the intensity. Therefore, a logarithmic scale has been chosen to express acoustic energies and intensities. The basic unit is a decibel (db), which is equal to a noise level of 1×10^{-9} ergs/cm^2-sec.

The list given on the following page indicates the wide range of sound levels perceived by the average human ear.

---

[3] Much of the data in this section has been obtained from H. Fletcher, "Speech and Hearing," D. Van Nostrand Company, Inc., New York, 1929.

Noise Level (db)	Physical Intensity	Example
0	1	Rustle of a leaf
10	10	Whisper at 5 feet
20	100	Very quiet room
30	1,000	Quiet office
40	10,000	Subdued conversation
50	100,000	Business office
60	1,000,000	Ordinary conversation
70	10,000,000	Busy city traffic
80	100,000,000	Boiler factory
90	1,000,000,000	Pneumatic drill at 10'
100	10,000,000,000	Hydraulic press
110	100,000,000,000	Airplane prop at 10'
120	1,000,000,000,000	Air raid siren at 10'
130	10,000,000,000,000	Threshold of painful sound

In order to be able to apply the proper acoustical correction without excessive experimentation it is necessary to know not only the coefficients of absorption for the corrective materials, but also an approximate value for the existing materials in the room to be corrected.

I. THE PROBLEM

Statement of the problem. Sound absorption coefficients of various building materials have generally been determined by the reverberation or sound chamber method which was first devised by Wallace Sabine, Riverbank Laboratories. The reverberation time technique is the only method accepted by Acoustical Materials Association, but there is no question that the technique

Noise Level (db)	Physical Intensity	Example
0	1	Rustle of a leaf
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70	10,000,000	Busy city traffic
80	100,000,000	Heiley factory
90	1,000,000,000	Pneumatic drill at 10'
100	10,000,000,000	Hydraulic press
110	100,000,000,000	Airplane motor at 10'
120	1,000,000,000,000	Air raid siren at 10'
130	10,000,000,000,000	Threshold of painful sound

is subject to considerable error and uncertainty. The period since 1925 has been known as the "battle of the coefficients" because of the variety of absorption coefficients assigned to identical materials by different sound chambers.[4] Absorption coefficients exceeding 1.00 were commonly reported by well designed testing laboratories.[5] The leading manufacturers of acoustical materials wisely declared an armistice and decided to adopt the reverberation time methods and, furthermore, to establish a single testing chamber as the 'official' laboratory for determining absorption coefficients.

The reverberation method utilizes a special chamber with highly reflective walls. Usually the room is completely isolated from building noises and a calibration of the sound chamber amounts simply to determining the total absorbing power of the room in its standard condition for tones within the desired frequency range. The absorbing power of the room is then remeasured using a standard test panel (usually seventy-two square feet) of the material under study within the chamber. If a and b are the total absorbing power of

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[4] F. V. Hunt, Journal of the Acoustical Society of America, 2:38, 1939.

[5] H. J. Sabine, Journal of the Acoustical Society of America, 22:388, 1950.

the room, first empty and then with an area of s square units of absorbing materials introduced, then (b-a)/s is the increase in absorbing power per square unit affected by the material. If the test material replaces a surface of the empty room which has an absorption coefficient of A_1, then the absorption coefficient of the material in question is

$$A_2 = A_1 - \frac{(b-a)}{s}$$

The measurement of A_1 and A_2 may be accomplished in various ways. The early chambers had a person or persons of normal hearing measure the time delay of a sound of known intensity and frequency within the sound chamber. Professor P. E. Sabine found that a pure note from a pipe organ and an average of several human observers produced very accurate results in the reverberation method.[6] Modern laboratories utilize accurate decibel intensity meters and measure the noise level at regular time intervals after a sound is produced. For accurate results, however, the setup can be very elaborate and, consequently, very expensive.

Actually, the commercial tests are run on acoustical materials using the reverberation method

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[6] P. E. Sabine, Acoustics and Architecture, McGraw-Hill Book Company, Inc., New York, p. 98.

because an absorption coefficient is obtained which is usable for all possible angles of sound impingement. Due to the extensive equipment necessary for this method, the investigator decided to concentrate on a second method for determining absorption coefficients--the stationary-wave technique.

The stationary-wave technique utilizes a sound source, a tube to direct the sound waves so that they strike the sample in a normal plane, and a probe to pick up the pressure or velocity of the wave at different points within the tube. This technique has the advantage of simplified and inexpensive equipment, small acoustical sample requirements, plus accurate and reproducible results.

The object of the thesis investigation was to design and make available to the Mechanical Engineering Department of the University of New Mexico a simple and inexpensive method of determining at least the relative absorptivity of different building materials. It was hoped that a thorough investigation would provide some basis of comparison between the stationary-wave method used in the research, and the more commonly accepted reverberation time method.

Importance of the study. It is felt by the investigator that the study has a practical application

as well as a theoretical usefulness. In the first instance, with the rapid growth of the city of Albuquerque, with its attendent growth in building construction and with the lack of an acoustical laboratory of this nature anywhere in the vicinity, it is felt that the equipment will be of much use to local builders and manufacturers. This was borne out by the interest expressed by local builders during the research and by a request for investigative work from a manufacturer of building tile.

In the second instance, the equipment as set up could provide further opportunities for future graduate students in the field of acoustical research which is still relatively unexplored. The question of correlation of thermal conductivity coefficients (U) used in heat transfer and absorption coefficients (α) is still unanswered, as well as many other wave phenomena problems closely allied with acoustical properties of materials.

CHAPTER II

THEORY OF STATIONARY-WAVE TECHNIQUE

As an aid in visualizing the stationary-wave phenomenon, let us consider a string of finite length--in our case, the length of the air column from the loudspeaker to the reflecting or absorbing surface of the plunger.[1] Let us suppose the string is fastened at both ends so that two boundary conditions are imposed. The string can be fastened to rigid supports a distance L cms apart so that the amplitude Y must always be zero at x = o and at x = L. The important effect of the terminating boundary condition is to require that the motion of the string be periodic. A pulse--or a condensation and rarefaction of the air column--started at x = o travels to the second support at x = L in a time (L/C), is reflected or projected. If the supports are rigid or perfect reflectors, the shape of the second reflection is identical to that of the original pulse, and the motion is periodic with a period equal to 2L/C. The simple harmonic motions of the string may be considered as two sinusoidal waves traveling in opposite

---

[1] P. M. Morse, Vibration and Sound, McGraw-Hill Book Company, Inc., New York, 1948, p. 78.

directions. The wave length of these waves is equal to C/f. In the special case where the amplitudes of the two waves are equal (a perfect reflecting surface), the traveling waves combine to form standing or stationary waves. At certain points the two traveling waves just cancel each other, and the amplitude of the string is zero. These points are called the nodes. They are spaced equally along the string a distance C/2f apart, two for each wave length. Halfway between each pair of nodal points is the part of the string with the largest amplitude of motion where the two traveling waves always add their effects. This portion of the wave is called an antinode or loop.

Since we have stated that the amplitude (Y) is zero at x = L, a limited number of frequencies will result in standing waves so long as the length L is fixed. This is true because only those frequencies which have nodal points at x = L will set up standing waves. The distance between node points must be L or L/2, L/3, etc. The allowable frequencies are, therefore, C/2L, 2C/2L, 3C/2L, etc. The lowest stationary-wave frequency (C/2L) is called the fundamental frequency of the string or air column. By varying L or the length of the air column, any number of fundamental frequencies and an infinite number of standing waves

may be established. This is accomplished in the stationary-wave device by moving the acoustic sample plunger to give the fundamental frequency or one of its overtones prior to an actual measurement.

The above discussion was limited to two dimensional analyses, whereas wave motion in air is three dimensional and infinitely more complicated than the waves discussed heretofore. Accordingly, the investigator decided to limit his study to the motion of plane waves of sound and further limited to normal incidence against the acoustical material. Waves traveling inside a tube of uniform cross section will be plane waves as long as the wave length is equal to or longer than 1.707 times the tube diameter.[2]

Application of stationary wave theory. When a train of progressive waves, P (Figure 1), within the tube and of amplitude, p, moves in a positive direction, all points of the medium in the path of the waves move through a distance $2p$ as shown by the shaded portion of Figure 1. When the sound energy within the wave strikes the surface S (Figure 2), the energy is divided into three portions; namely, the incident, reflected, and

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[2] Rayleigh, Theory of Sound II, Cambridge, 1896, 2nd Edition, p. 161.

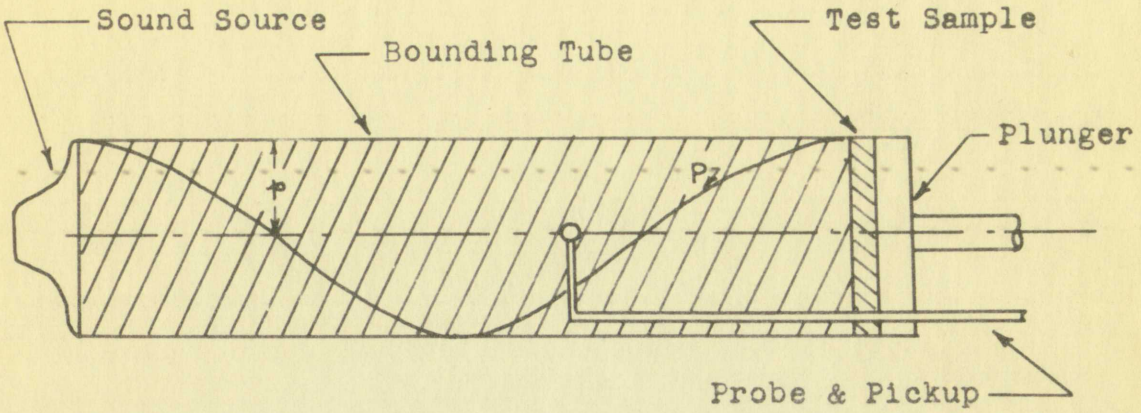

Figure 1: Basic Elements of Stationary-Wave Device

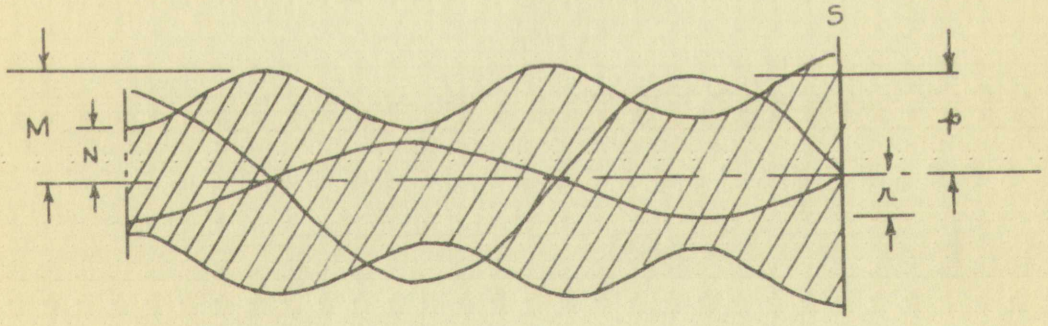

Figure 2: Pressure Variations Within Bounding Tube

absorbed energy. The fraction of absorbed energy is a property solely of the surface exposed to the sound. Actually, the sound energy is dissipated by the friction between the wave and the porous absorbing surface and is changed into heat energy. Additional energy is absorbed by the mechanical vibration of the absorbing surface and its mounting.

The reflected wave of amplitude r (Figure 2) will travel in a negative direction, and the direct wave and reflected wave will meet and combine as illustrated. Some points in the medium will then move through a greater or lesser distance than originally, as shown by the shaded area in Figure 2. The maximum amplitude at the antinodes (where crest meets crest) will be $p + r$, and the minimum amplitude at the nodes (where the crests of p meet the troughs of r) will be $p - r$.

The coefficient of sound absorption is a function of the intensity of sound and, therefore, of the square of the pressure or amplitude of the waves. If the intensity of sound in the direct wave is $(kp)^2$ and the intensity of the reflected wave is $(kr)^2$, then the coefficient of reflection is $\rho = r^2/p^2$.

If the maximum amplitude or pressure of sound is called M and the minimum pressure is called N,

then:

$$M = p + r$$
$$N = p - r$$

therefore, $p = (M + N)/2$
$r = (M - N)/2$

$$\rho = (M - N)^2 / (M + N)^2$$

The sound absorption coefficient (α) is the fraction of sound not reflected, or:

$$\alpha = 1 - \rho = 1 - (M - N)^2 / (M + N)^2$$
$$\therefore \quad \alpha = 4MN / (M + N)^2$$

Hence, to find the coefficient of absorption of a material, a means must be provided to establish a train of sound waves of constant frequency and amplitude, to cause this train of waves to be reflected from the sample under test, and to accurately measure the maximum and minimum sound pressure of the resultant stationary wave.

Methods within the stationary-wave technique. Within the stationary-wave method there are many different variations of techniques. A rather complete survey of the various possibilities has been given by L. L. Beranek.[3] A few of the most important of these

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[3] L. L. Beranek, Journal of the Acoustical Society of America, 12:4, 1940.

as described by Zwikker and Kosten[4] are:

a) Constant length method, measuring maximum and minimum pressures in the tube;

b) variable length method, measuring maximum and minimum pressures at the sound source;

c) variable length method, measuring curve widths of pressure at the sound source;

d) variable length method, measuring the electrical impedance of the sound source; and

e) short length tube, measuring the pressure and velocity at the source.

The method finally selected for this investigation was the first mentioned. It is a relatively simple setup and is not difficult to operate. From April 1950 to August 1950 the second method, wherein the tube length is varied and the pressures are measured at a constant point in the tube, was attempted. Long experimentation with disappointing results proved that the movement of the sample within the tube to different locations affected the accoustical impedance of the arrangement so that the input amplitude of the sound source could not be kept constant with the signal oscillator available. Since August 1950, all measurements were made by exploring the wave fronts with a movable probe while maintaining a constant tube length. This

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[4] C. Zwikker and C. W. Kosten, "Sound Absorbing Materials," Elsevier Publishing Company, 1949, p. 86.

technique nullified the need for numerous power amplitude corrections to account for differences of the acoustical impedance of the air column.

Definition of terms used. It is felt that a definition of some of the acoustical terms used in this report will be of advantage in understanding the work to follow. Because of the difference in definitions by various researchers, the following definitions are taken from the American Standard Acoustical Terminology, Z24.1-1951, published by the American Standard Association.

Sound. An alteration in pressure, stress, particle displacement, particle velocity, etc., which is propagated in an elastic medium.

Acoustics. The science of sound, including its production, transmission, and effects.

Noise. Noise is any undesired sound.

Wave length. The perpendicular distance between two wave fronts in which the displacements have a difference in phase of one complete period.

Longitudinal wave. A wave in which the direction of displacement at each point of the medium is normal to the wave front.

Transverse wave. A wave in which the direction of displacement at each point of the medium is parallel to the wave front.

Standing waves. Periodic waves having a fixed distribution in space which is the result of interference of progressive waves of the same frequency. Such waves are characterized by the existence of nodes

(zero amplitude) and antinodes (maximum amplitude) that are fixed in space.

Reverberation. The persistence of sound at a given point after direct reception from the source has stopped.

Reverberation time. The time required for the average sound energy density, originally in a steady state, to decrease after the source is stopped to one-millionth (60 db) of its initial value.

Sound intensity. Average rate of sound energy transmitted in a specified direction through a unit area normal to this direction. Commonly used units are the erg per second per square centimeters or watts per square centimeter. (One decibel represents an energy flow of 10^{-16} watts per square centimeter, and doubling the intensity of any sound corresponds to an increase of approximately 3 db). Sound intensity is proportional to the square of the pressure or amplitude.

Sound power of source. The total sound energy radiated by the source per unit of time. Commonly used unit is ergs per second, but the power may be expressed in watts.

Impedance. The complex ratio of a force-like quantity (voltage pressure, temperature, etc.) to a related velocity-like quantity (current, velocity heat flow).

Acoustic impedance. The complex ratio of the sound pressure on a surface to the flux (volume velocity) through the surface. The acoustic impedance is analogous with electrical and mechanical impedance. The commonly used unit is the acoustical ohm.

Fundamental tone. The physical component in a periodic wave corresponding to the fundamental frequency.

Harmonic. A partial component whose frequency is an integral multiple of the fundamental frequency.

Octave. The interval between two sounds having a basic frequency ratio of two.

Sound Absorption. The process by which sound energy is diminished in passing through a medium or in striking a surface. (Practically all sound absorbing surfaces owe their efficiency to a highly porous surface. The air inside the pores of the material is set into vibratory motion by the incident sound waves and a fraction of the sound wave energy is transformed into heat energy by the friction of this motion.)[5]

Sabin. A measure of the sound absorption of a surface. It is the equivalent of one square foot of a perfectly absorptive surface. (Usually considered as one square foot of an open window where no sound would be reflected.)

Sound absorption coefficient. The fraction of incident sound energy absorbed by the surface at each reflection from the material upon which it impinges.

Acoustic interferometer. An instrument or device for measuring the velocity (or pressure) of sound waves by observing the variations of pressure in a standing wave established in the medium between a sound source and a reflector, as the reflector is moved or the frequency is varied.

Sound probe. A device for exploring a sound field without significantly disturbing the field in the region being explored.

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[5] H. J. Sabine, Less Noise, Better Hearing, 5th Edition, Celotex Corporation, 1941, p. 13.

CHAPTER III

REVIEW OF THE LITERATURE

The first person to use the stationary-wave method of measuring sound absorption coefficients was J. Tuma[1] of Vienna in 1902. Tuma's observations were entirely aurel. By means of listening tubes, he observed the relative loudness of sound in the maximum and minimum position in a pipe closed by absorbent materials. His actual results were very meager, but the method has remained relatively unchanged up to this date.

Hawley O. Taylor[2] in 1913 used a tube 115 centimeters long and nine centimeters square. He used an organ pipe with a series of Quincke tubes (branch resonators) to eliminate the harmonics as a sound source. A glass tube was used as the probe for exploring the standing-wave system. This was connected with a delicately balanced Rayleigh disc whose deflections were taken as a measure of relative pressures at

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[1] J. Tuma, "Eine Methode zur Vergleichung von Schallstorkung ---", d. K. Adad. d. Wessenschaften, Vol. III, Pt. 2A, 1902, pp. 402-410.

[2] H. O. Taylor, "A Direct Method of Finding the Value of Materials as Sound Absorbers," Physical Review, 2:270-287, July-December, 1913.

the mouth of the exploring tube and gave the numerical values for M and N (Chapter II, p. 15).

In 1926 a paper was published by Eckhardt and Chrisler[3] covering a modification of Taylor's method. The sound source was a loudspeaker, supplied with alternating current from a vacuum tube oscillator. Their tube was made of brass and the exploring tube was terminated by a telephone receiver. The potential generated in the receiver was amplified, then rectified before being led into a galvanometer. Eckhardt and Chrisler found that due to dissipation of energy along the tube, there was a continuous increase in the values of both the maxima and minima with increasing distance from the closed (sample) end. Thus, the direct wave diminishes in amplitude as it approaches the closed end, while the reflected wave diminishes as it recedes from the reflecting surface. To account for this effect, Eckhardt and Chrisler derived the following expression:

$$\alpha = 1 - \left[\frac{N_1 - N_1 \neq \frac{N_2 - N_1}{2}}{N_1 \neq N_1 - \frac{N_2 - N_1}{2}} \right]^2$$

$N_2 - N_1$ is the difference between the pressures measured at two successive minima.

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[3] E. A. Eckhardt and V. L. Chrisler, "Transmission and Absorption of Sound by Some Building Materials," Bureau of Science Paper 526, Vol. 21, 1926.

The next important work done on the subject was that reported by Dr. E. T. Paris.[4] He carried out investigations on the absorption of sound by acoustical plasters using a hot-wire microphone (EMF, due to slight resistance changes) to measure the intensities.

A. H. Davis and E. J. Evans[5], working together at the National Physical Laboratory in England, obtained some accurate results with a stationary-wave setup quite similar to those already described except for a loudspeaker sound source mounted on their tube. Their work was conducted with great care to experimental details, and revealed the odd phenomena of decrease of absorption coefficients with increases of sample thicknesses beyond a certain point.

Probably the greatest American contribution to the science of acoustics was made by Dr. Paul E. Sabine[6] of Riverbank Laboratory, whose work included studies of both the reverberation time and stationary wave methods.

Recent contributors to the general science of sound absorption measuring include two Dutch scientists,

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[4] E. T. Paris, D. Sc., "On the Stationary Wave Method of Measuring Sound Absorption," Proceedings of the Physical Society, 39:274, 1927.

[5] A. H. Davis and E. J. Evans, Proceedings of the Royal Society of London, Series A, Vol. 127, 1930.

[6] P. E. Sabine, loc. cit.

C. W. Kosten and C. Zwikker. Their work reviewed the efforts which had preceded them and included a very rigorous mathematical approach to the field of acoustics in general, and to sound absorbing materials in particular.[7,8]

An interesting variation of the tube method was devised by E. C. Wente[9] of Bell Telephone Laboratories in 1928. The method has become known as the acoustic impedance technique. Wente's analysis was based upon the analogy between particle velocity and pressure in a standing-wave system and the current and voltage in an electrical transmission line. A tube three inches in diameter and nine feet long was fitted with a movable piston upon which the acoustic sample was mounted. Instead of measuring the maximum and minimum pressures at points in a tube of fixed length, the pressure at a single point near the constant amplitude source was measured for different tube lengths. Wente's method gave the absorption coefficient in terms of the maximum

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[7] Zwikker and Kosten, op. cit.

[8] C. W. Kosten, "Absorption of Sound by Coated Porous Rubber Wallcovering Layers," Journal of the Acoustical Society of America, 18:457-471, 1946.

[9] E. C. Wente, Bell System Technical Journal, 7:1-10, 1928.

and minimum pressures measured near the source as follows:

$$\alpha = \frac{\sqrt{MN}}{M + 2\sqrt{MN} + N}$$

The acoustic impedance method has been utilized by a number of recent experimenters. L. L. Beranek[10] in 1940 made some excellent measurements of the acoustic impedance of various commercial building materials. His work demonstrated the adequacy of the theoretical connection between the acoustic impedance and absorption coefficient as employed in usual practice. R. K. Cook[11] and O. K. Mawardi[12] introduced short-tube acoustical impedance methods in 1947 and 1949, respectively. Their methods indicated a practical procedure for use in the field on acoustical materials for which the absorption is due to the surface and not to mounting effects.

In any acoustic impedance or stationary-wave tube measurement, what is actually measured is the absorption coefficient for normal incidence. Accordingly, a real problem exists in ascertaining the overall

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[10] L. L. Beranek, Journal of the Acoustical Society of America, 12:14, 1940.

[11] R. K. Cook, Journal of the Acoustical Society of America, 19:922, 1947.

[12] O. K. Mawardi, Journal of the Acoustical Society of America, 21:84, 1949.

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[10] L. L. Beranek, Journal of the Acoustical Society of America, 12:14, 1940.

[11] R. K. Cook, Journal of the Acoustical Society of America, 19:952, 1947.

[12] O. K. Mawardi, Journal of the Acoustical Society of America, 21:84, 1949.

reverberant, or random incidence absorption coefficient from the normal incidence coefficient. An ingenious mathematical approach to this problem was devised in 1950 by Albert London[13] of the National Bureau of Standards. His method, which will be discussed in relation to this investigation in a later chapter, yielded results which closely agree with the reverberant coefficients of a number of materials.

The latest published literature on sound absorption reviewed by the investigator was by C. M. Harris and C. T. Molloy in January 1952.[14] They reviewed the general status of the theory of sound absorption with particular attention to the relation between absorption coefficients determined by the tube methods and the sound chamber or reverberation method.

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[13] A. London, "The Determination of Reverberant Sound Absorption Coefficients from Acoustic Impedance Measurements," Journal of the Acoustical Society of America, 22:263, 1950.

[14] C. M. Harris and C. T. Molloy, "The Theory of Sound Absorptive Materials," Journal of the Acoustical Society of America, 24:1, 1952.

CHAPTER IV

DESIGN AND CONSTRUCTION OF APPARATUS

The intent of the investigator was to combine as many of the good points as possible from previous work with the limitations of economy and space enforced by the conditions within the Mechanical Engineering Department. Wherever possible, equipment was designed and constructed on the spot, and where electrical equipment was not available within the Department, the Electrical Engineering Department was in many cases willing to help. Additional assistance was obtained from the Industrial Arts Division which made their facilities available for initial construction and sample preparation.

As in the previous investigations, the principal parts of the apparatus consisted of a sounding tube, sound source, and a pressure pickup. As illustrated in Figures 3 and 4 on the following pages, the sounding tube was constructed from a ten-inch (inside diameter) heavy-duty steam pipe, nine feet and eight inches in length, with flanged connections on each end. The tube was salvaged from pipe removed from the old steam plant at the University of New Mexico. The flanged ends served as supports for the sound source (Figure 5).

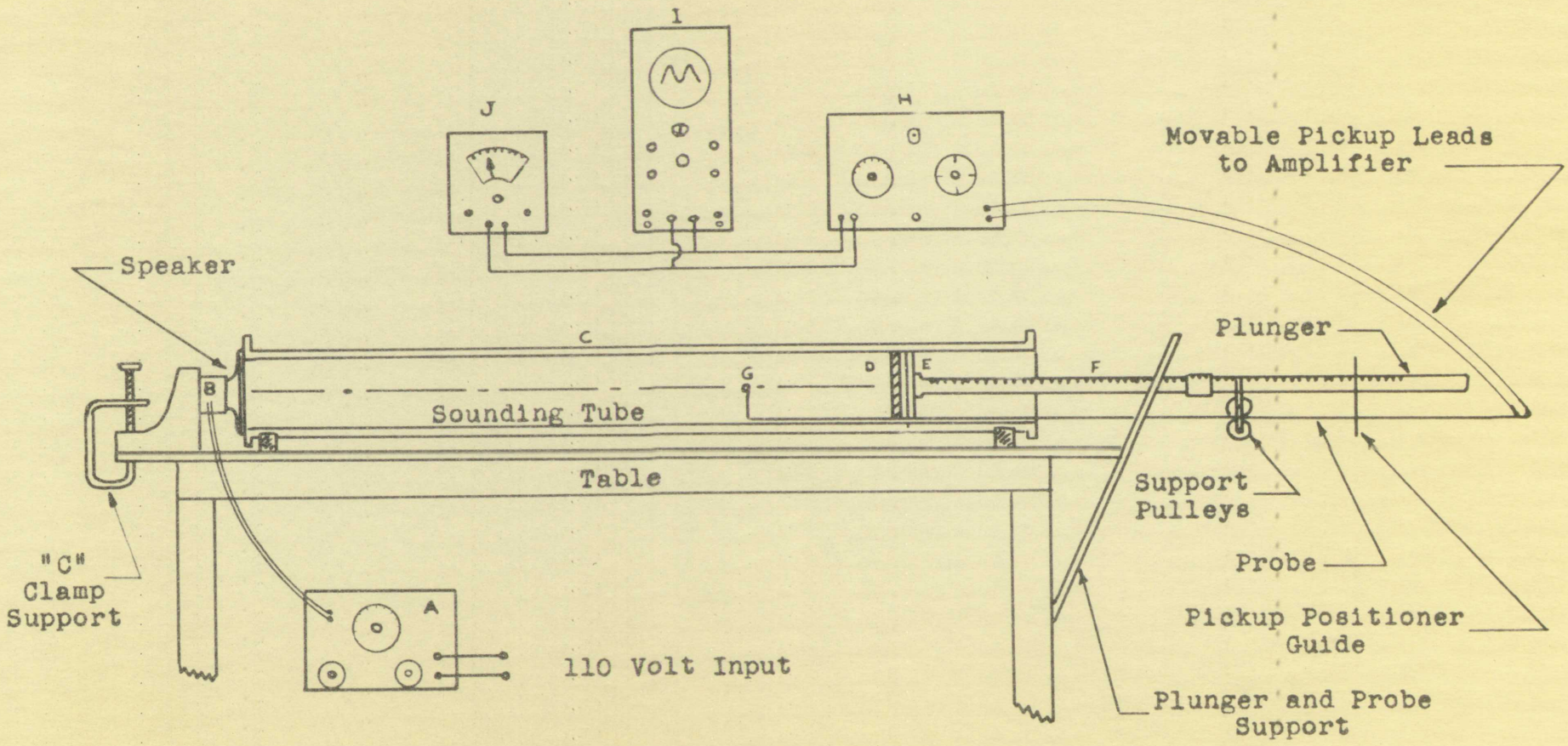

Figure 3: Schematic of Stationary-Wave Setup

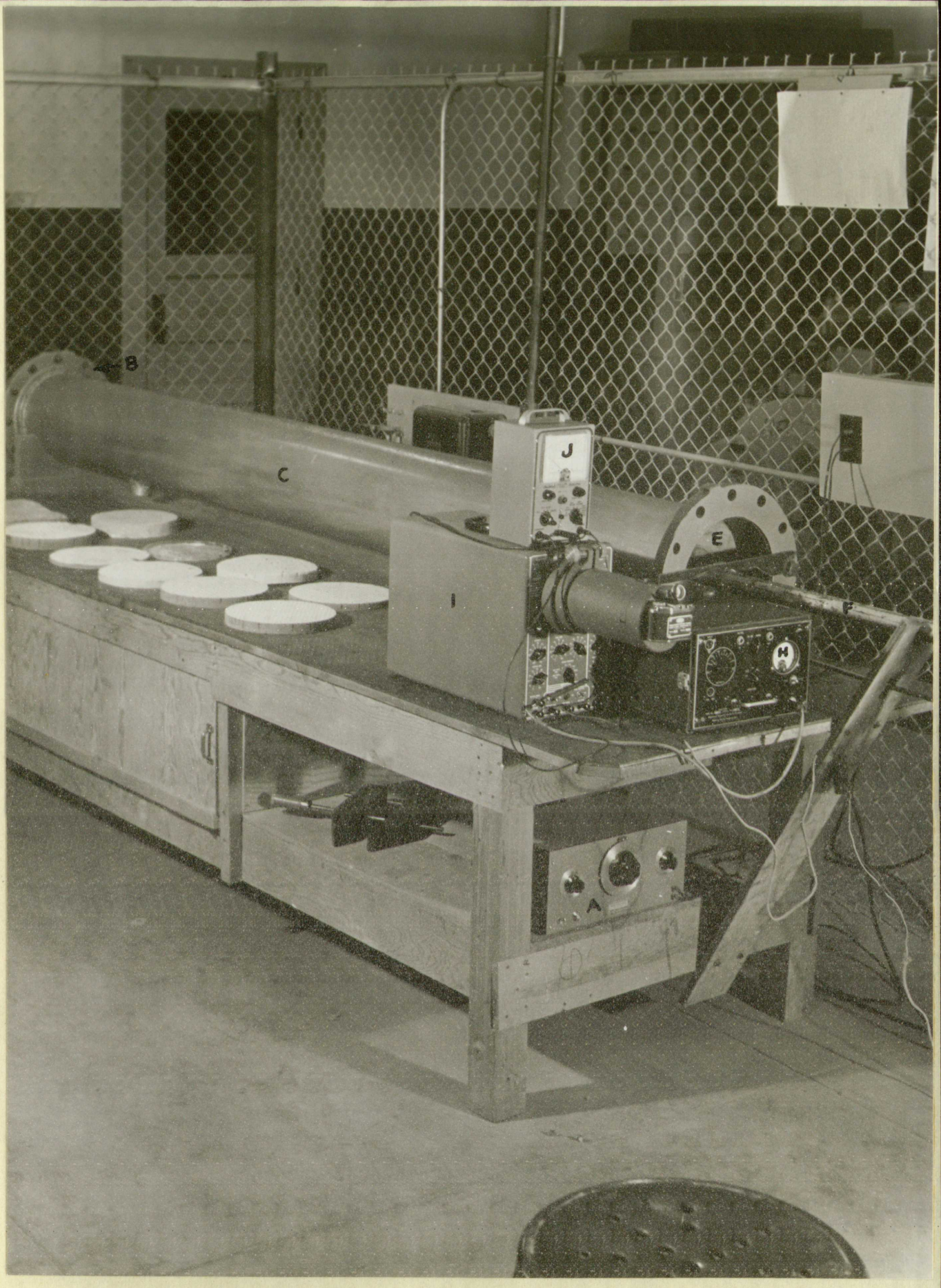

Figure 4 - - Complete Stationary-Wave Setup

Figure 4 - - Complete Stationary-Wave Setup

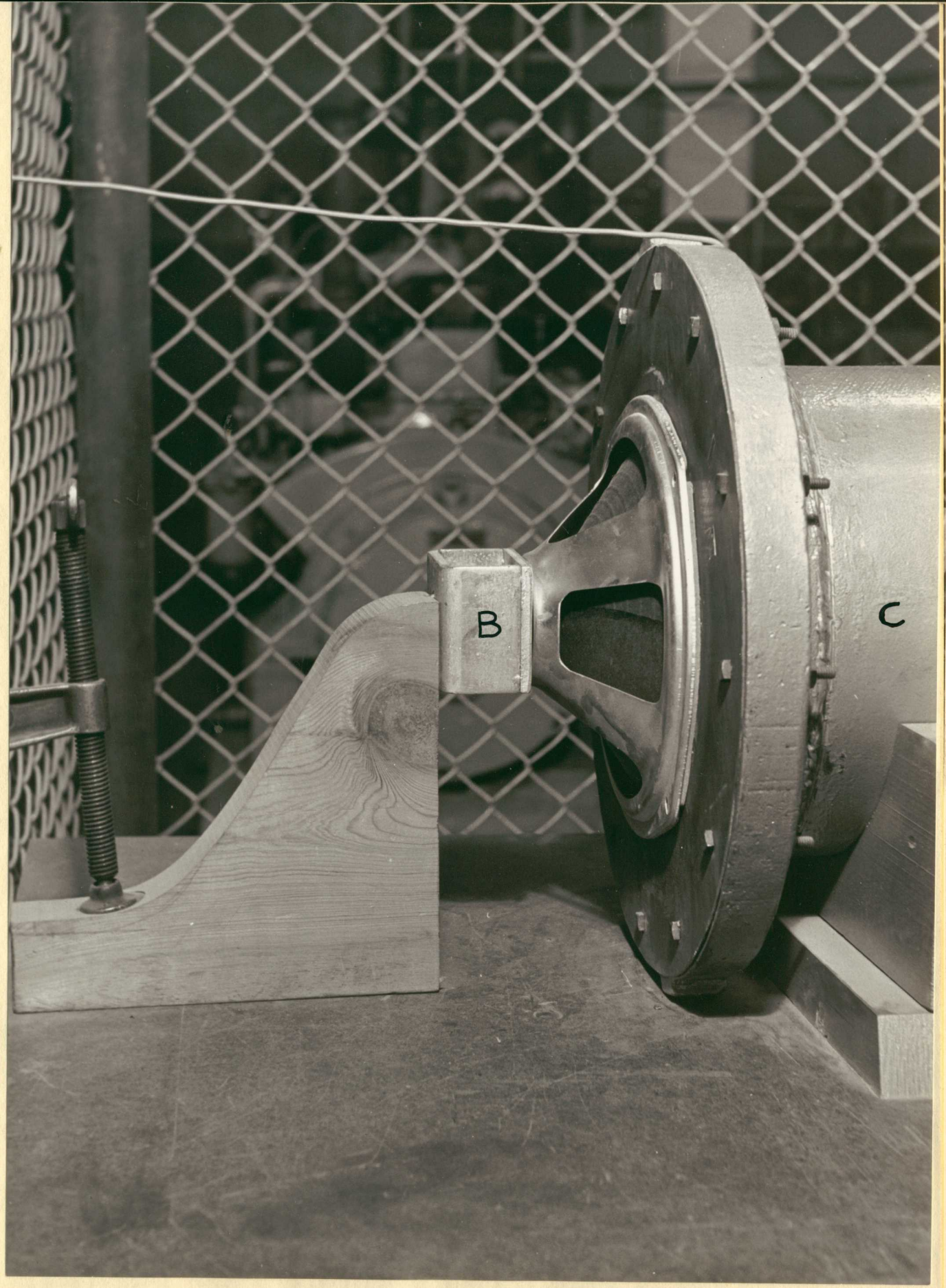

Figure 5 - - Loudspeaker Mounting Details

Figure 5 - - Loudspeaker Mounting Details

The tube was supported by wooden blocks which carried the load to a specially constructed support table. The tube had two imperfections; namely, a fairly rough inside surface and a two-inch branch connection near the source which was sealed off by a block of solder. Undoubtedly, these flaws contributed to some extent to a distortion of the original sound signal.

A Hewlett-Packard audio oscillator, Model 200B, was used as a variable amplitude, variable frequency sound source. The maximum power output of the oscillator (one watt) was fed to a ten-inch permanent magnet speaker used to minimize distortion and 60 cycle hum. The oscillator had a frequency range from 20 cps to 20,000 cps with a calibration accuracy of two per cent. The speaker was mounted on one end of the tube with the use of a "C" clamp and a wooden support so that the speaker could be removed for inspection of the tube.

The sample was mounted on a movable plunger constructed as shown in Figures 6 and 7. Two six-foot sections of 1-1/2 inch pipe served as the plunger rod. The sections were connected with a coupling and an accurate inch and centimeter scale was scribed on the pipe to indicate the distance to the face of the plunger. The closely-fitting plunger consisted of two one-inch thick plywood discs, ten inches in diameter,

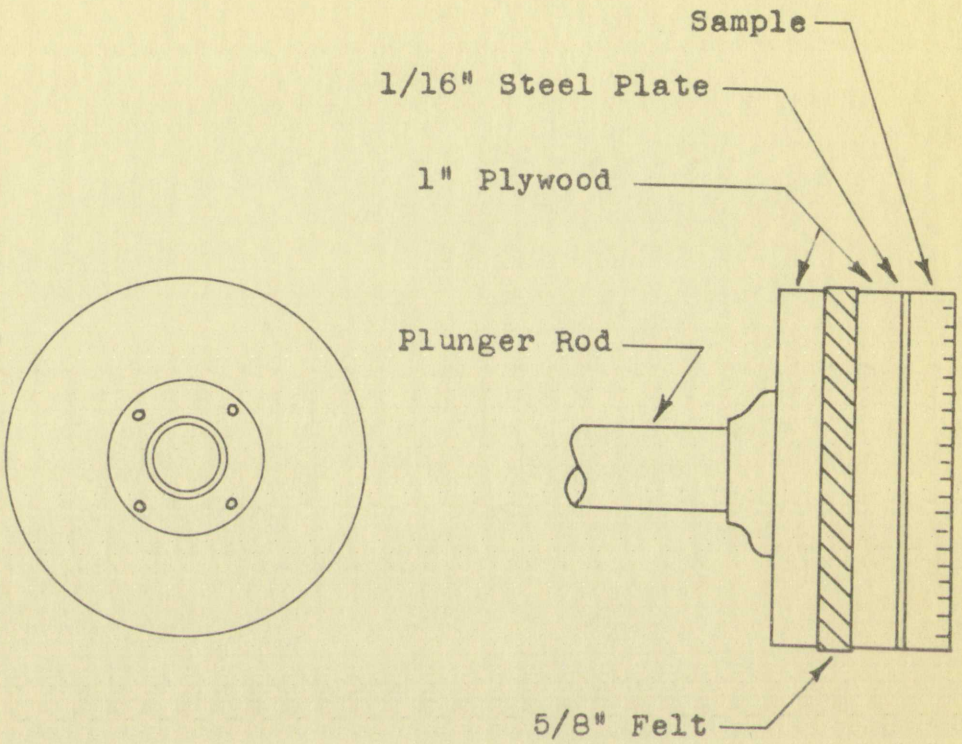

Figure 6: Sample Mounting Details

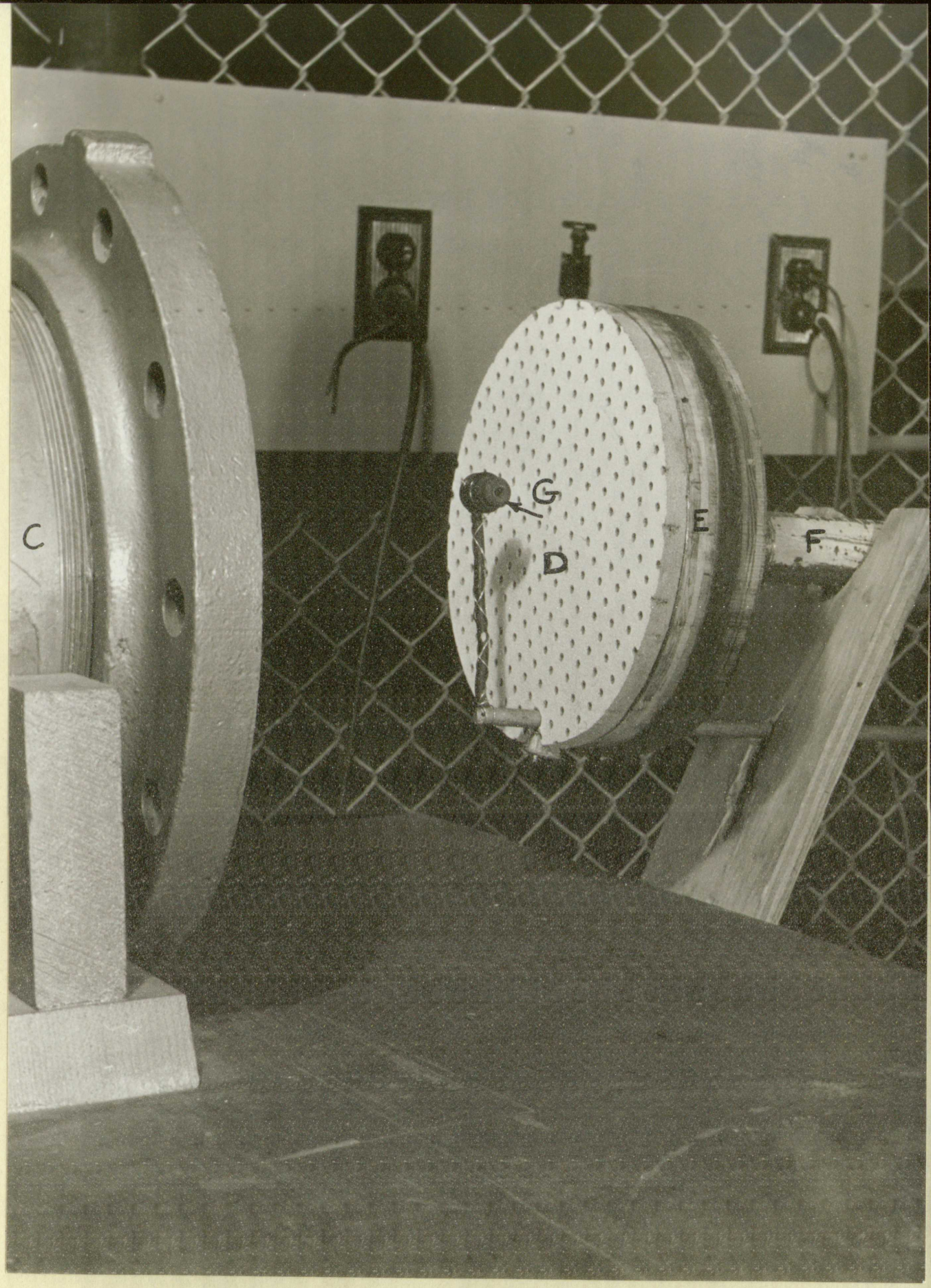

Figure 7 - - Plunger and Pickup Details

Figure 7 - - Plunger and Pickup Details

separated by a 5/8-inch thickness of hair felt. A 1/16-inch steel plate was screwed onto the inside face of the plunger to serve as a mounting plate and a perfect reflective surface for apparatus calibration.

Variations of air pressure within the tube were picked up by a midget earphone-type dynamic pickup mounted on the upright end of a 1/4-inch probe, ten feet in length, which was inserted through a 3/8-inch hole in the sample and plunger. The wires from the pickup were pulled through the pipe and connected to the input side of an amplifier located outside the tube. The midget pickup selected for the investigation was manufactured by Sonotone Corporation[1] for military use in World War II and has the following characteristics:

1. Resistance - - 256 ohms
2. Matching Impedance - - 6000 ohms
3. Frequency Response - - 100 to 3500 cps
4. Diaphragm Opening Width - - 1/8 inch
5. Overall Size - - 1/2 x 1/2 inch

The pickup was permanently mounted on the centerline of the tube with the 1/8-inch diaphragm opening facing the wall of the tube to record consistent static pressures.

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[1] H. A. Pearson, et al., "Development of Midget Earphones for Military Use," Journal of the Acoustical Society of America, 18:348, October, 1946.

Probably the most difficult and persistent problem in the construction of the apparatus was the provision for a simple but accurate amplification system to make the extremely small voltages supplied by the pickup readable on a voltmeter. Initial attempts to use the amplifier built into a laboratory oscilloscope failed, and an amplifier built by Professor G. B. Bliss and loaned by the Electrical Engineering Department proved to be unsatisfactory due to high distortion and insufficient amplification.

An attempt was made to measure the sound intensities directly by use of a sensitive decibel meter manufactured by the Western Electric Corporation. The amplifier stages of the meter proved to have adequate amplification and accurate step selection, but the decibel meter stage indicated uncertain results due to the logarithmic scale. The method was discarded in favor of a more successful technique described below.

A sensitive amplifier which had been constructed by two graduate students for their own thesis investigation was used next in the investigation. The pickup leads were connected directly to the amplifier, and the output leads from the amplifier were connected to an RCA vacuum-tube voltmeter. This method proved to be very satisfactory, but before the apparatus calibration

could be completed the amplifier ceased to function and, despite extensive repairs, no further satisfactory results were obtained from it.

The most successful sound pressure instrumentation resulted from a use of the amplifier stages of the Western Electric decibel meter in conjunction with a Heathkit vacuum-tube voltmeter as shown in Figure 8. This method proved very satisfactory because of the great sensitivity of the amplifier and its freedom from external hum or background noises. Several ranges of amplification were available, and they were used to advantage in keeping the voltage generated by the sound pressure level in the tube on a readable section of the voltmeter scale.

A DuMont cathode-ray oscilloscope was wired in parallel with the voltmeter and proved a great aid in determining the maximum and minimum pressure points within the standing-wave front. A visual observation of the amplitude of the wave form on the oscilloscope greatly reduced the operational time of the investigation.

In summary, the apparatus could best be described by reference to the coded components shown in Figures 3, 4, 5, 7, and 8, and by the code key shown on the following page.

A. Sound Source - Audio oscillator, 20 - 20,000 cps

B. Loudspeaker - Permanent magnet, 10-inch

C. Sounding Tube - Heavy-duty steam pipe, 10-inch

D. Sample - Acoustic material under test

E. Movable Piston - Steel and plywood mounting platform

F. Piston Plunger - 1-1/2 inch steel pipe, calibrated

G. Pressure Pickup - Midget earphone

H. Pressure Amplifier - Amplifier stages, decibel meter

I. Monitoring Oscilloscope - DuMont Model #274-A

J. Vacuum-tube Voltmeter - Heathkit, 1.5, 15, 30, 150 volts full scale.

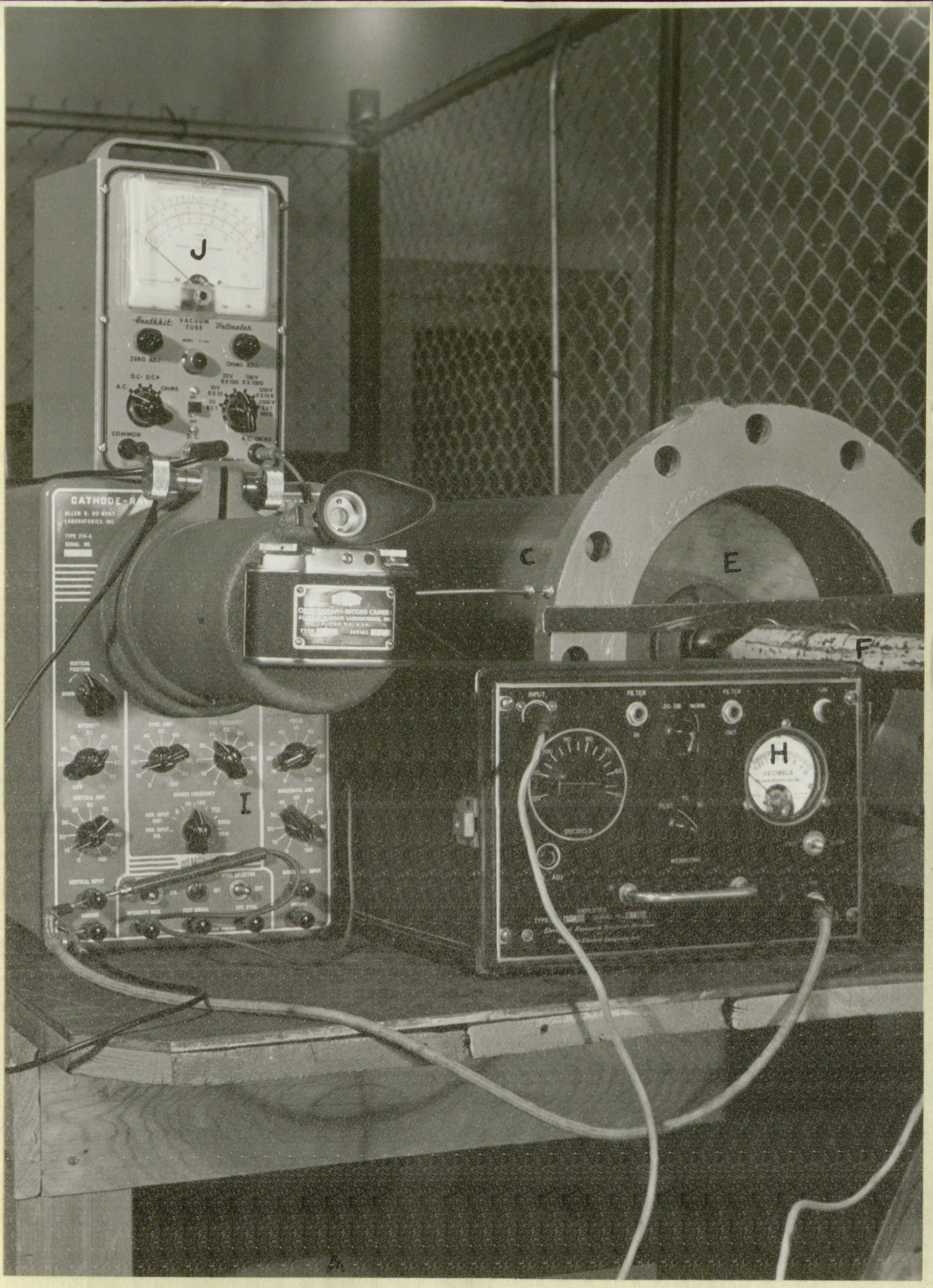

Figure 8 - - Instrumentation Details

Figure 8 - - Instrumentation Details

CHAPTER V

CALIBRATION OF APPARATUS

The original intention, as previously mentioned, was to base the investigation on the fixed-pickup length, variable-plunger length; therefore, much of the original calibration was done on this basis also. With the pick-up located thirteen inches from the sound source, the plunger was moved into and out of the tube, and the amplitude of pressure was measured within the tube. When these amplitudes were plotted against the plunger position, a variety of curves were produced which were very irregular. Even at the lower frequencies, succeeding sets of maxima and minima were not regular in their amplitudes. It was later deduced that as the plunger was forced into or out of the tube, the acoustical impedance varied so that the oscillator which operated at constant power output could not maintain the same sound level within the tube. It is quite possible that this first method could have been even more convenient than the one actually used if a method of varying the input power could have been secured in order that the sound level within the tube could have been kept constant.

Materials and samples used for calibration. The test materials used for the calibration of the stationary

wave device were all secured from the Celotex Corporation through Mr. Jay Grear, local distributor. The materials included three of their perforated Accoustic-Celotex products (types C-1, C-4, and C-9) and two accoustic plasters bearing the trade names Muffletone and Fissuretone. Complete information, including accepted absorption coefficients by the reverberant method, was available through the Accoustical Materials Association which represents major manufacturers of accoustic materials for the purpose of furnishing architects and engineers with reliable technical data on accoustics.

Investigation of sound pattern. The next step was the exploration with the use of a probe, the plunger having been set at a constant distance from the source of the sound. The recommended frequencies of calibration, according to the Accoustical Materials Association[1], are 128, 256, 512, 1024, and 2048 cps which correspond to frequencies one octave lower to three octaves higher than middle C on the musical scale (256 cps). Therefore, a complete exploration of the tube was made for

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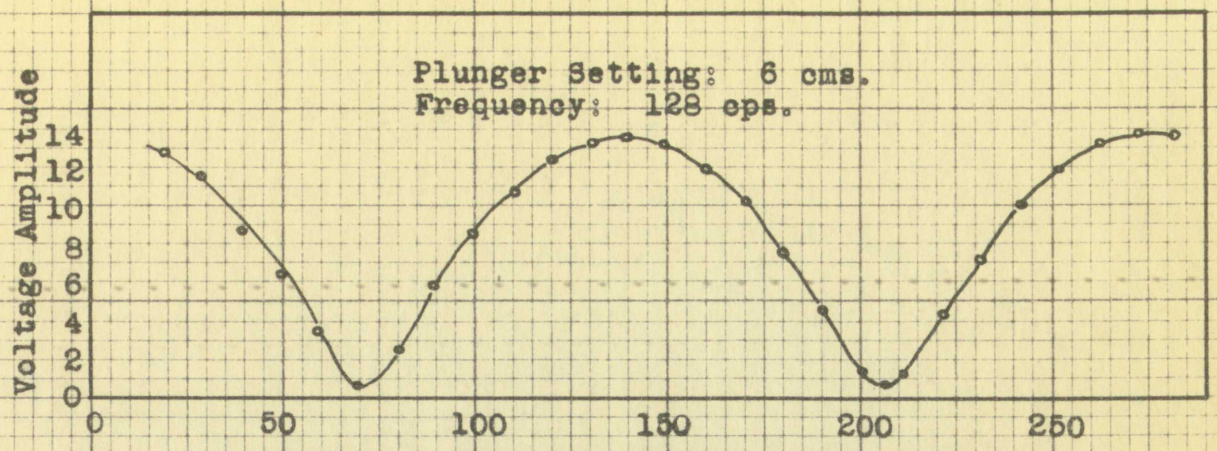
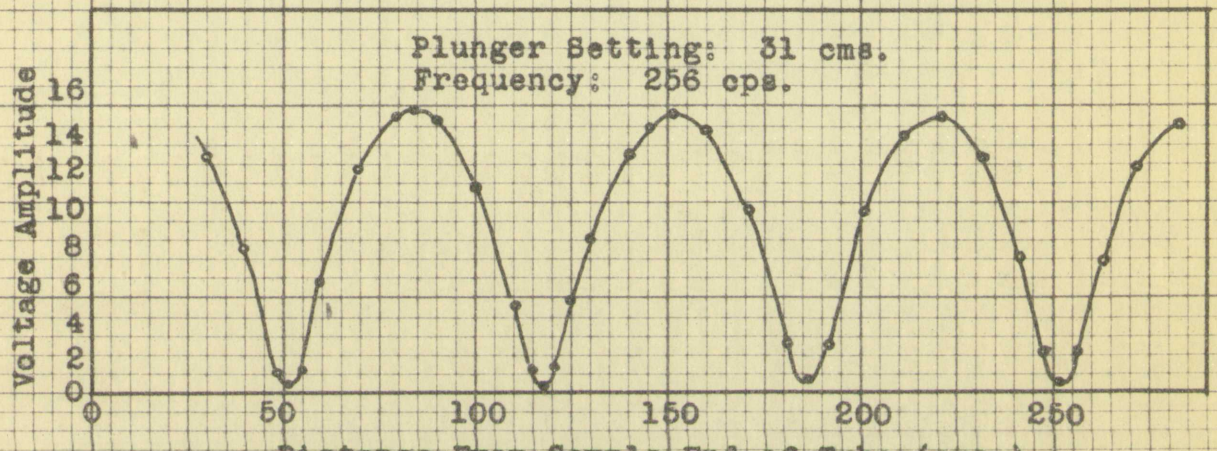
[1] Accoustical Materials Association, "Sound Absorption Coefficients of Architectural Accoustical Materials," Bulletin XI, Published by the Accoustical Materials Association, 1949.

each of these frequencies with the plunger reset for each frequency change to a point of tube resonance, and with a sample of Celotex C-9 mounted on the end of the plunger. The results from this test are shown on the following pages on Graphs 1 through 5. In each case the plunger setting was noted, and the voltage amplitude was plotted against the plunger distance measured from the sample end of the tube. Before each run was made, the voltage measuring apparatus was carefully set to zero with the oscillator on, but with the amplitude gain turned to zero. A study of the graphs revealed a picture of the pressure variation within the tube after the standing wave was established, but more important, it revealed the uniformity of that variation within the length of the tube. For the most part, the variation up to 1024 cps was very regular with uniform sets of maximum and minimum, but this was certainly not true of the test run at 2048 cps where the curves were very irregular and there could be computed from the data listed an almost innumerable group of absorption coefficients.

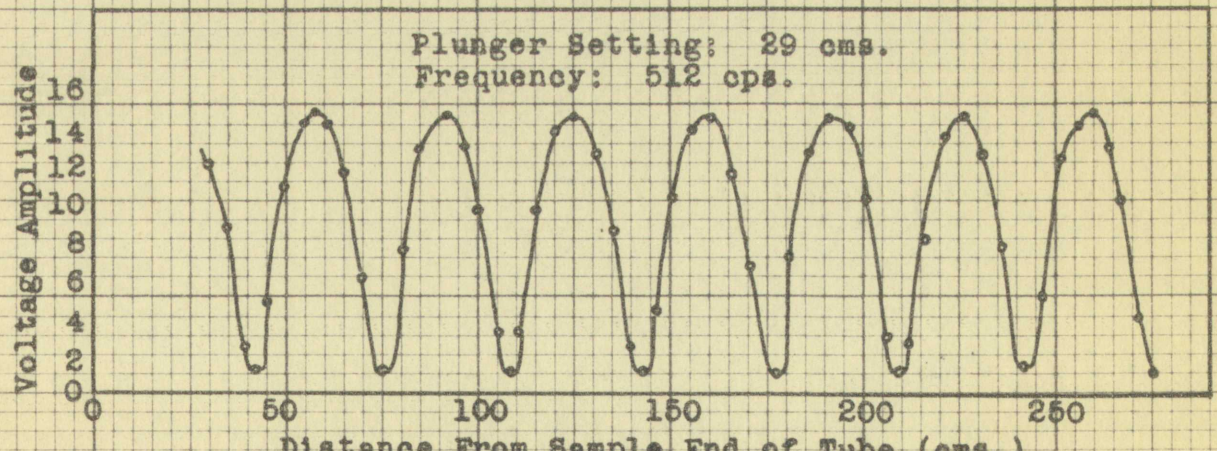
This break in continuity was higher than it seemed it should have been according to Zwikker and Kosten who referred directly to the work of Rayleigh in stating, "If the sound source operates at such a low frequency that the wave length is greater than 1.707



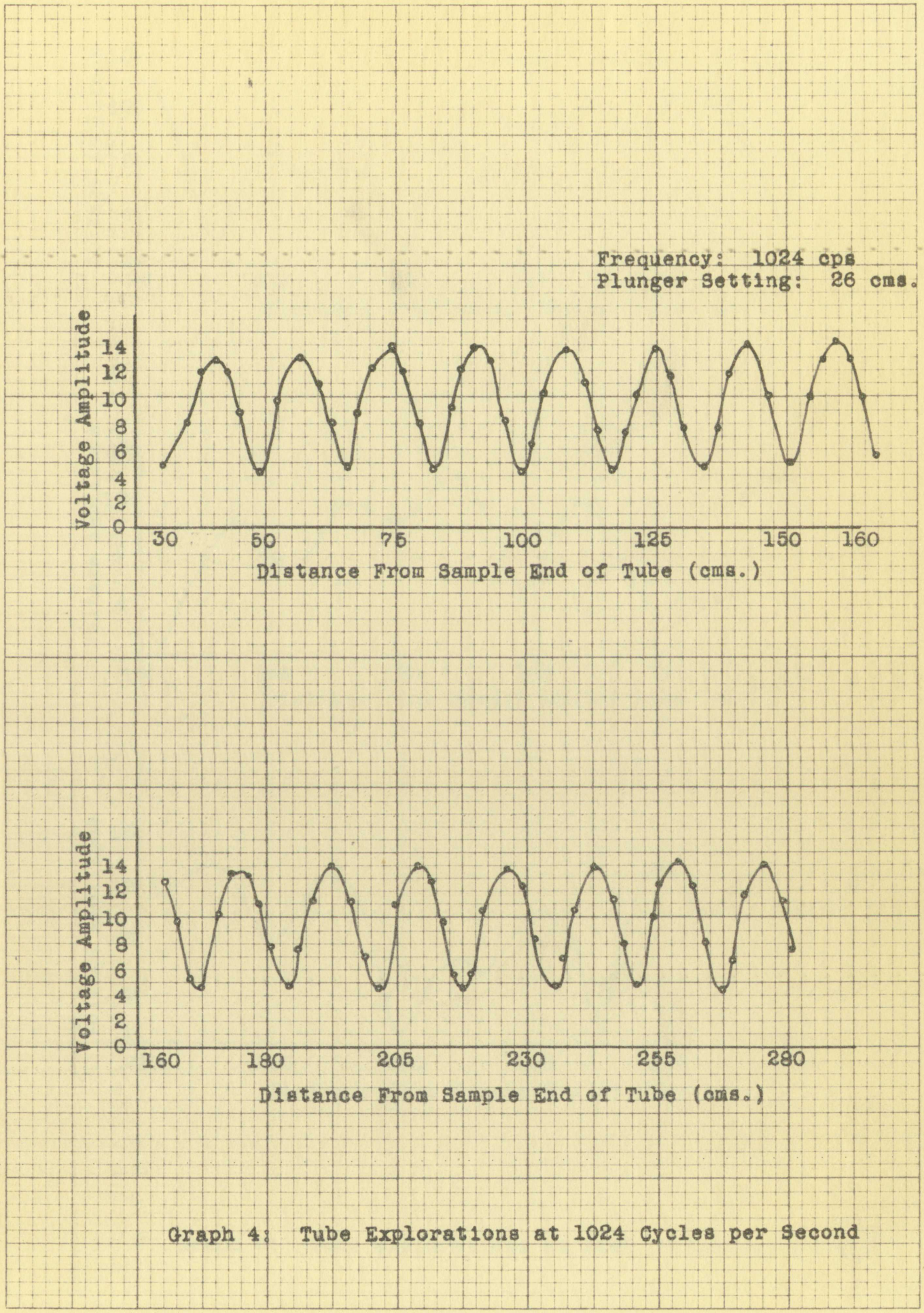
Graph 1: Tube Explorations at 128 Cycles per Second



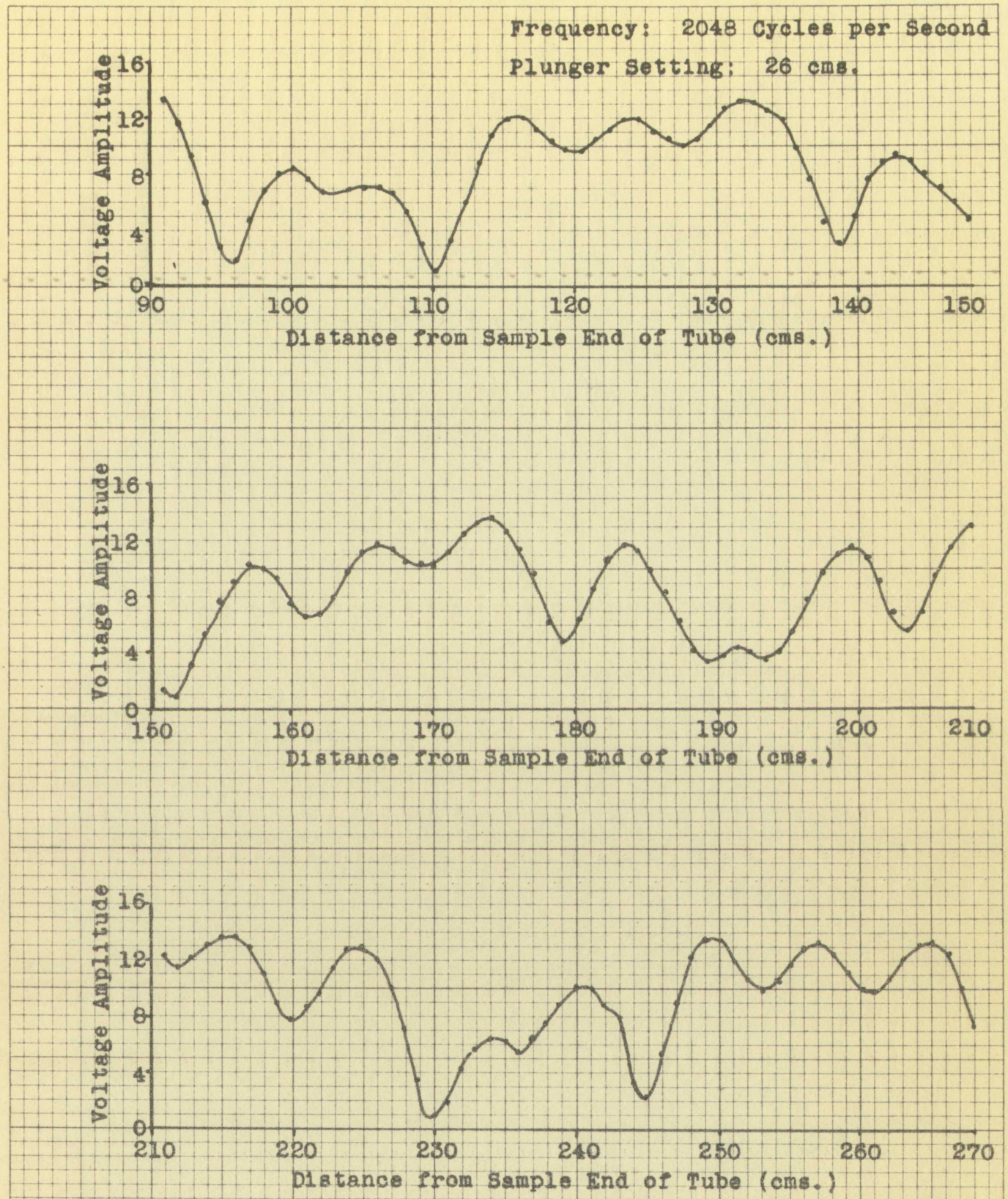
Graph 2: Tube Explorations at 256 Cycles per Second



Graph 3: Tube Explorations at 512 Cycles per Second



Graph 4: Tube Explorations at 1024 Cycles per Second



Graph 5: Tube Explorations at 2048 Cycles per Second

times the diameter D of the tube, only plane waves can travel in the tube."[2] With a tube diameter of 25.4 centimeters and a wave length of sound at room temperature of 343 meters, this should limit the usable frequency to about 800 cps. This was borne out somewhat better in subsequent tests.

Investigation of effect of pickup position variation. At the higher frequencies several points of maximum and minimum pressures were picked up by moving the position of the probe to different points throughout the tube, and it was thought well to investigate the effect of such a variation upon the absorption coefficients involved. Graph 6 on page 45 indicates this variation for Celotex C-4 measurements. Up to the third frequency--512 cps--there was no noticeable variation. From this point on, however, the average of five different sets of maximum and minimum showed some variation. The width of the band was not excessive until it reached a frequency of around 2000 cps although, obviously, limited accuracy could be counted on for the frequencies from 800 cps up to 2000 cps.

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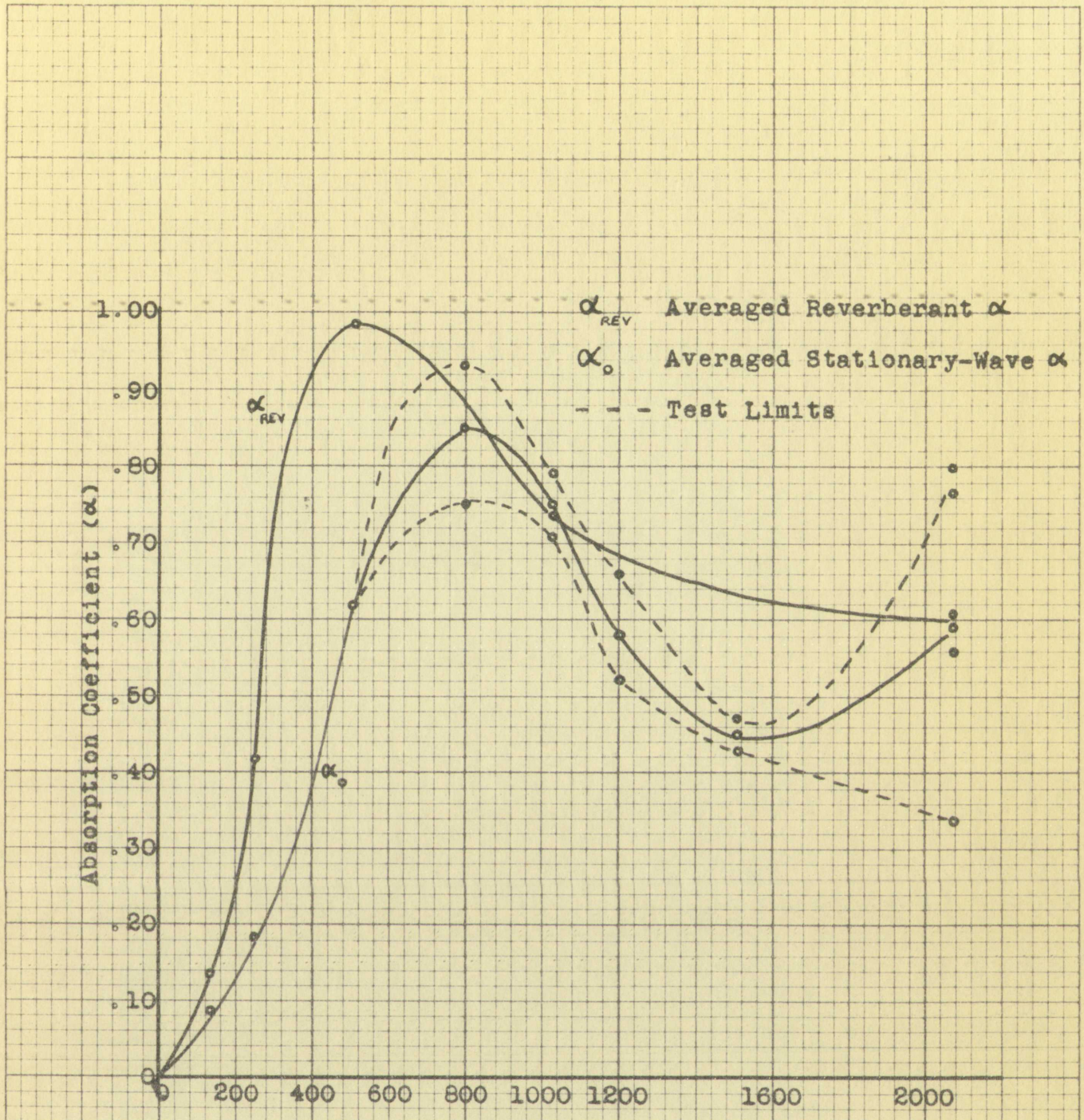
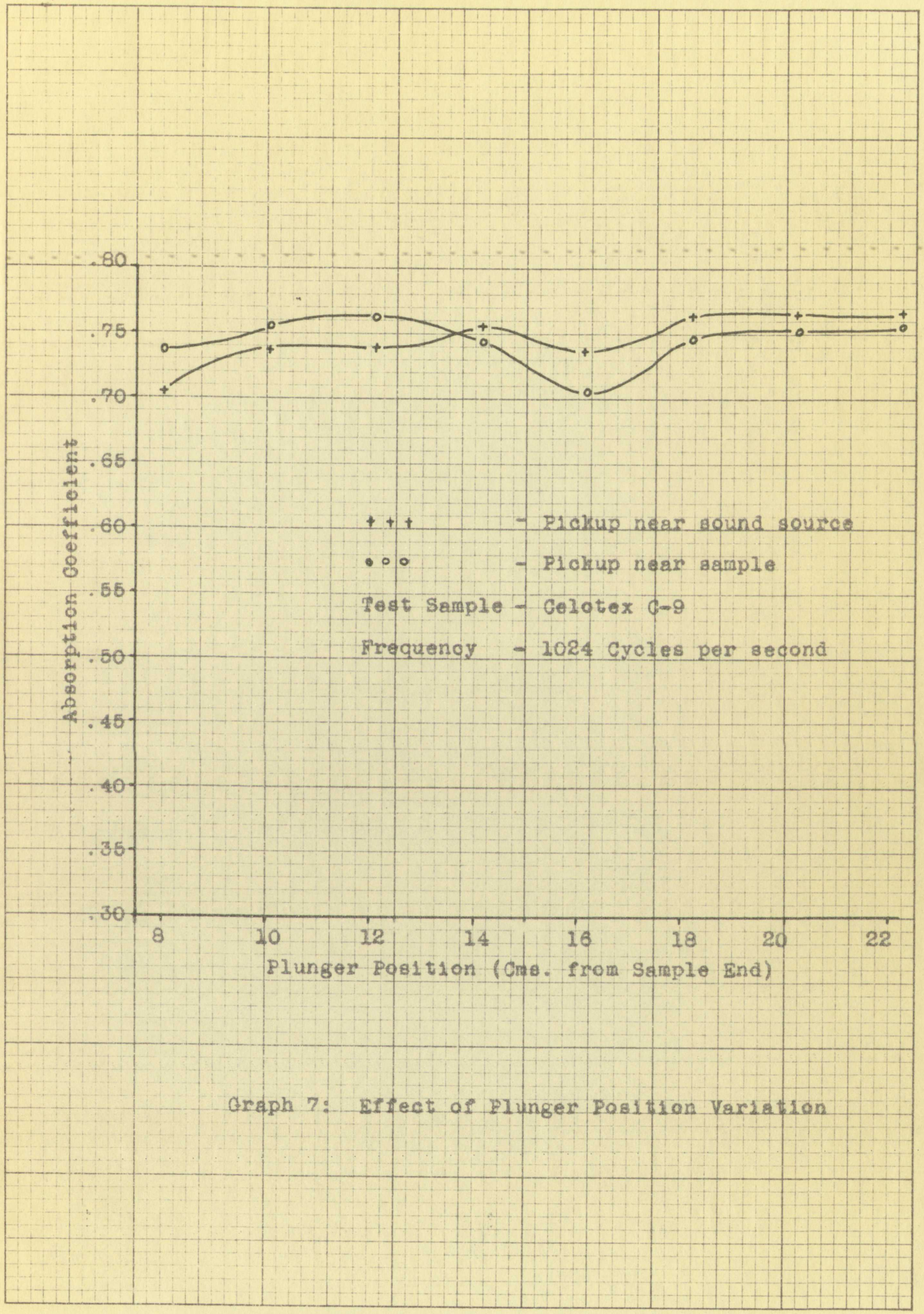
[2] C. Zwikker and C. W. Kosten, op. cit., p. 86.



Graph 6: Calibration Curve--Celotex C-4 ($1\frac{1}{4}$")

Similar tests were run with different samples but Celotex C-4 was representative of all of them; therefore, no others are included in this report.

Study of effect of plunger position. With the pickup probe set at any fixed position, the plunger could be changed in position with a considerable change in the pressure amplitude reading at the pickup position. For this reason it was thought advisable to investigate the effect that the original plunger (and, thereby, the sample position) would have on the coefficients calculated. A frequency of oscillation of 1024 cps was selected, and the plunger position varied by two centimeter intervals, and the effect was studied with the pickup near the sound source in the first case, and near the sample in the second. To insure more uniformity, after the plunger had been set correctly, the maximum amplitude was found by movement of the pickup probe, and then brought up to a value of 12.45 volts. These values have been plotted on Graph 7. A study of this graph indicated that the variation was very small, on the order of about 6% and, considering the other errors inherent in the method, almost negligible. This amount was reduced, however, by setting the plunger at the same relative point for each sample tested. It is



Graph 7: Effect of Plunger Position Variation

recommended that this plunger location be one at which the tube will be in resonance; that is, so that a maximum pressure will exist at any fixed probe position.

Effect of microphone pickup on results. The stationary-wave technique was derived on the assumption that the sound pressure along the tube could be accurately measured at discrete points. Actually, the pressure pickup diaphragm covered a finite length of tube. Its output was the integral of the response over its entire surface to sound pressure along the finite tube length. This pressure varied both in magnitude and in phase. Theoretical considerations and investigation revealed that only an insignificant error was introduced by this situation. The only effect was to decrease the sensitivity of the measuring system as the wave length became comparable with the width of the microphone. This effect was not important because transverse waves would be present in the ten-inch diameter tube at the high frequencies where the wave length would approach the width of the microphone, and the distorted sound field from the transverse waves would make the sensitivity loss even more insignificant. Furthermore, as only the ratios of pressures were used in the measurements and calculations, no error results.

This factor is one of the real advantages of the stationary-wave method, the practical significance being that accurate measurements can be made with other noisy laboratory equipment in operation--impossible in the sound chamber or reverberant method.

Calibration curves for several samples. To compare the results obtained by the stationary-wave method and the reverberation method, several samples of known acoustical properties were prepared and run at standard test frequencies of 128, 256, 512, 1024, 2048 cps and for 800 cps, a frequency which was of interest because of Rayleigh's prediction of the usable frequencies for the ten-inch diameter tube. All of these samples were mounted on the steel plunger face by the use of a transparent rubber cement around the edges of the sample as much in accordance with the recommendations of the Acoustical Materials Association as possible.[3]

Graph 6 on page 45 and Graphs 8, 9, and 10 on the following pages illustrate the results of this investigation. On each graph there is a plot of averaged test values of "stationary α" (a minimum of three measurements was made at each frequency for each sample) versus the test frequency. For comparison purposes, a

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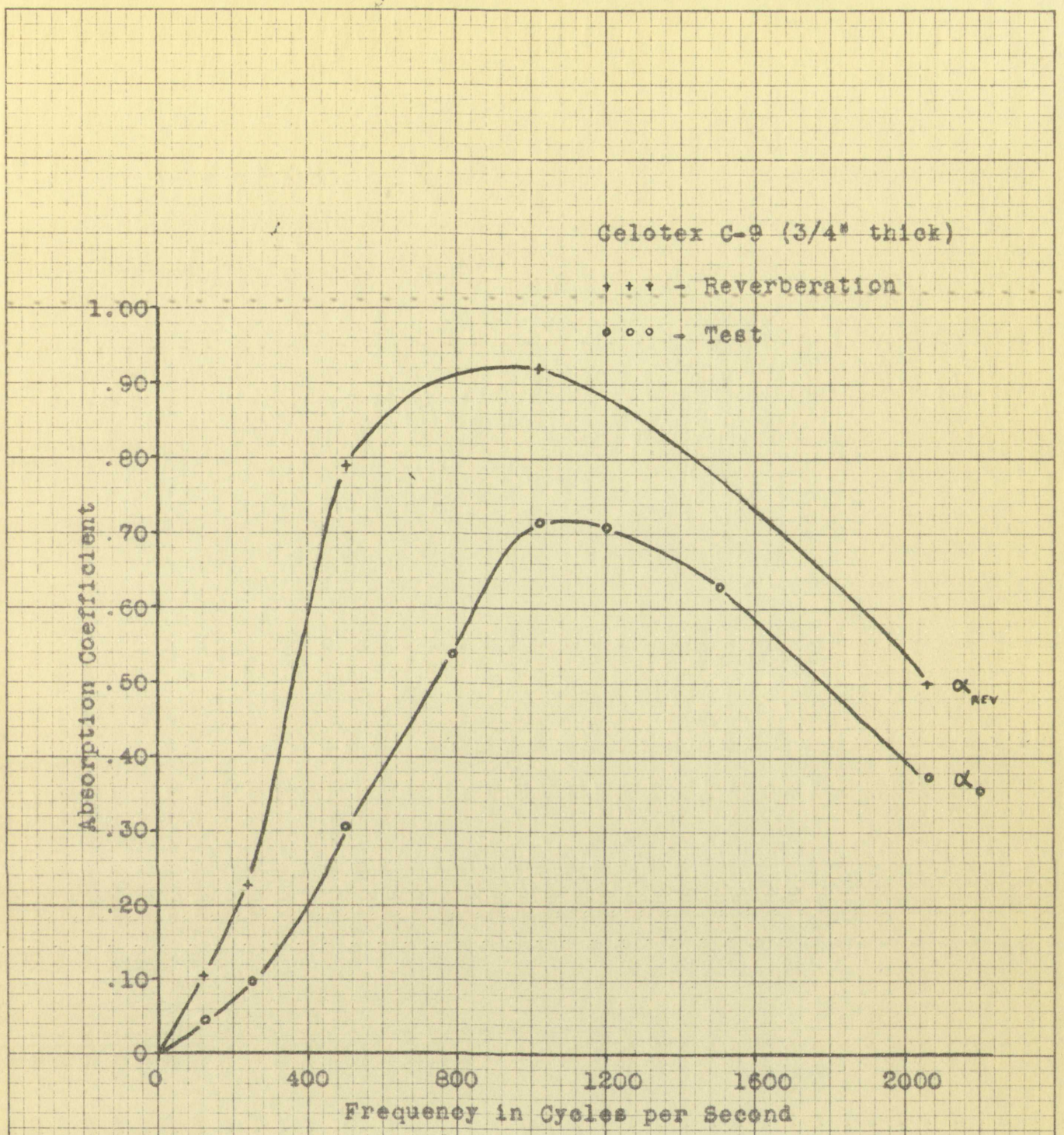
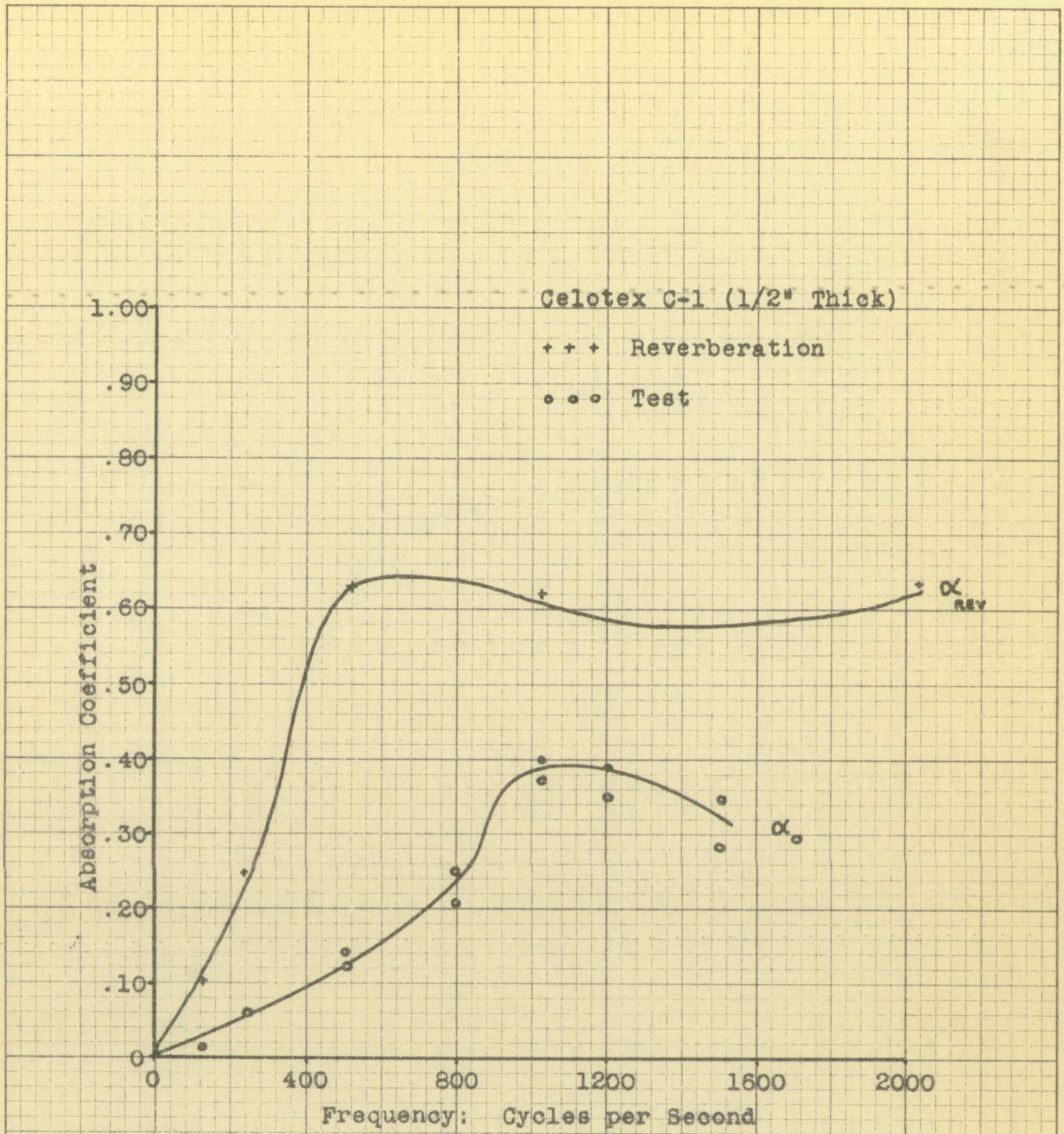
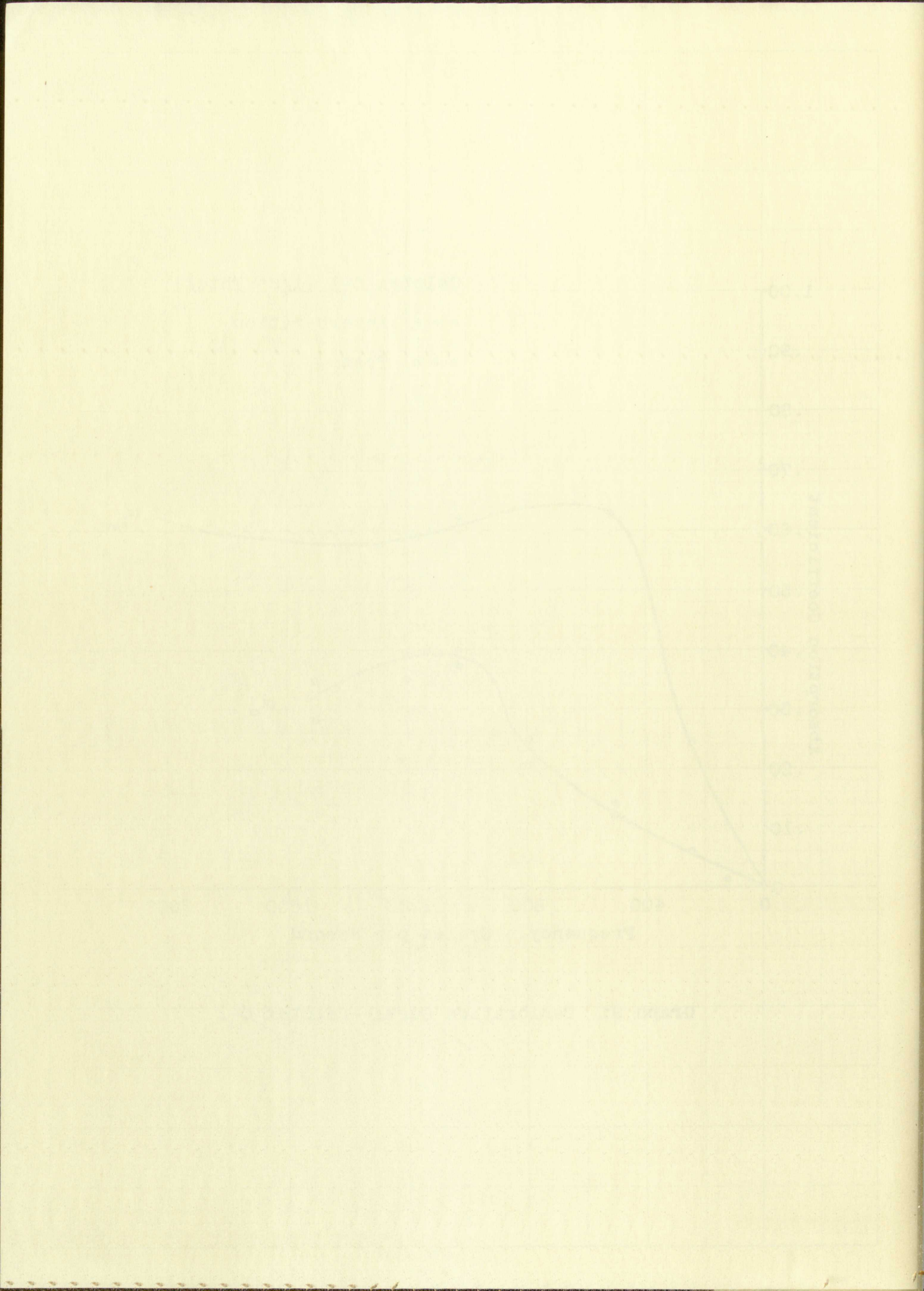
[3] Acoustical Materials Association, loc. cit.

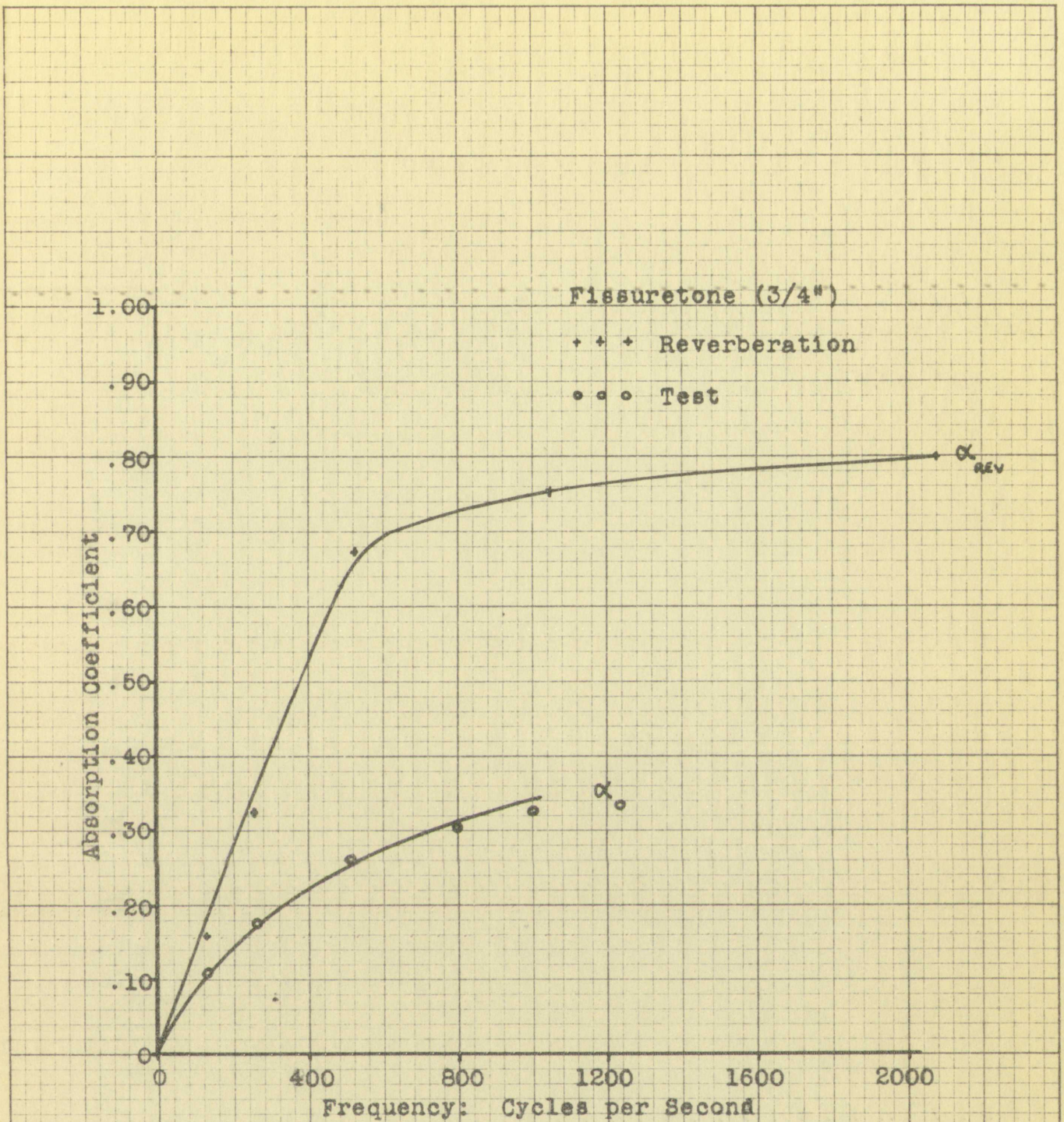


Graph 8: Calibration Curve for Celotex C-9



Graph 9: Calibration Curve--Celotex C-1



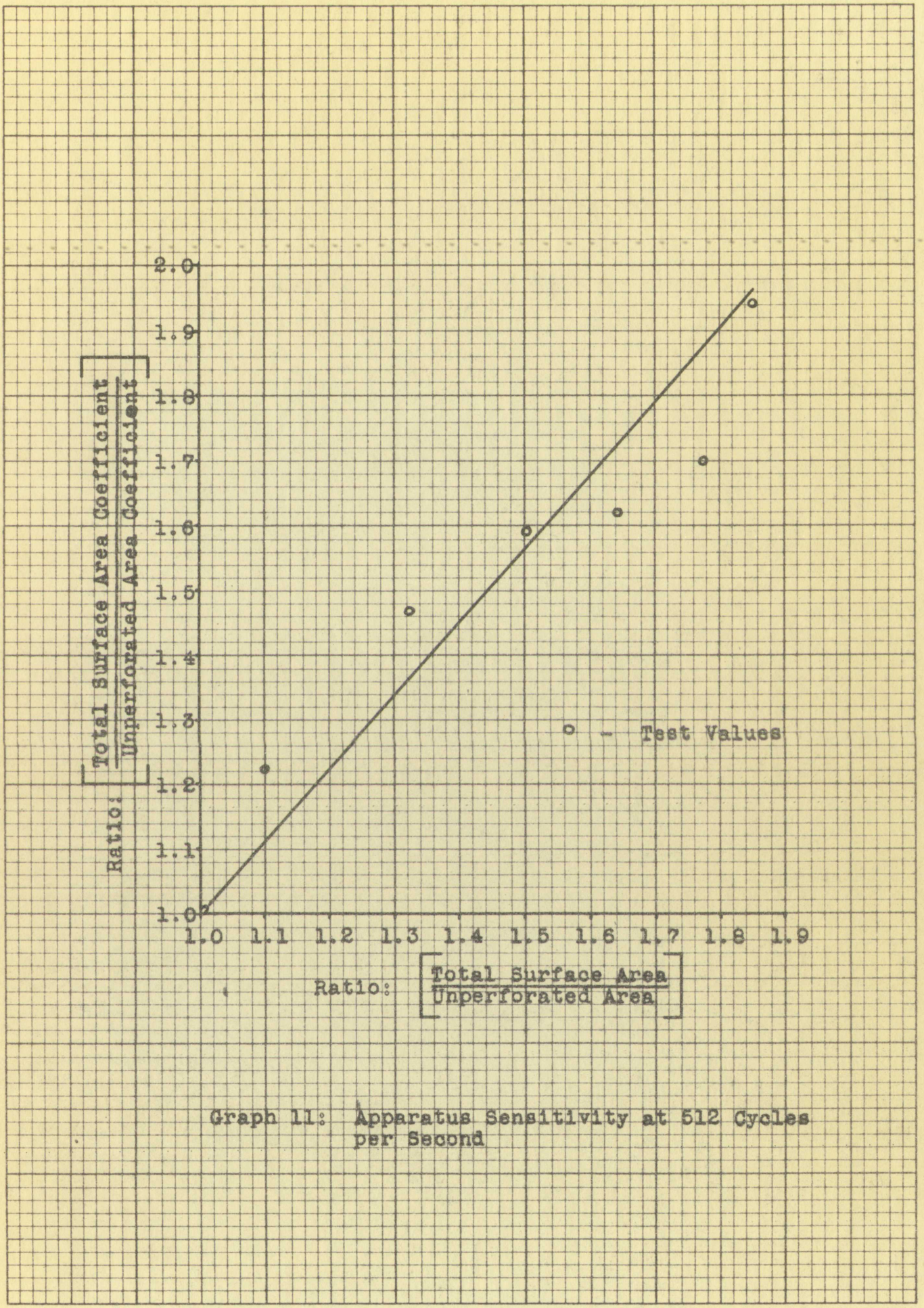


Graph 10: Calibration Curve--Fissuretone

plot of the latest accepted "reverberation α" was also included. As indicated in Graph 10, measurements on Fissuretone were discontinued at 1024 cps because of erratic results which were obtained at higher frequencies.

Study of apparatus sensitivity. An extensive calibration was undertaken to determine the sensitivity of the apparatus by artificially introducing porosity to a plain unperforated sample of 1/2-inch Celotex. This was accomplished by drilling increasingly larger numbers of 3/16-inch diameter holes, 3/8-inch deep, in regular geometric patterns and measuring the increase in absorption coefficients at various test frequencies. The perforated area of the test sample was determined by adding the lateral area of the drilled holes (πdh) to the original or unperforated area. Graph 11 shows the results of this phase of the investigation for a single test frequency of 512 cps. The plot indicates that the absorption coefficient increased linearly and almost directly with increased sample surface area. Hence, the increase in α was due to surface absorption of sound only, and the absorption due to the vibration of the plunger and tube could be neglected.

General conclusions on calibration tests. In general, the results of the calibration were better



Graph 11: Apparatus Sensitivity at 512 Cycles per Second

than anticipated, and agreement with work of previous stationary-wave experimenters was good. Specifically, the following conclusions were drawn.

1. The apparatus, as judged by the calibration and sensitivity tests, was capable of determining accurate values of absorption coefficients for normal incidence reflection. The results were reproducible and as accurate as more elaborate and expensive stationary-wave setups used heretofore.

2. Because of the massive walls of the heavy-duty steam pipe bounding tube which practically eliminated dissipation along the tube, results at low frequencies (less than 800 cps) were more accurate than previous setups.

3. For most of the samples tested, satisfactory results cannot be expected for test frequencies in excess of 800 cps.

4. The stationary-wave absorption coefficients as measured were always less than the reverberation time coefficients. This was expected because theoretical considerations indicated that the mean value of the absorption coefficient, if all angles and directions were taken in account, would always exceed that for normal incidence.

5. The thicker Celotex samples gave results which were more consistently close to the coefficients determined by the reverberant method.

6. Sensitivity measurements indicated that the absorption coefficients measured by the apparatus increased almost linearly with the increased surface area induced by drilling holes in plain specimens.

CHAPTER VI

RECOMMENDED TEST METHODS

One of the advantages of the stationary-wave method of acoustical testing was the small size of the sample of material tested. For the apparatus herein described, however, the tester chose a sample which was representative of the material in question, and of a size sufficient to allow the cutting-out of a ten-inch diameter flat cylinder. In the cutting operation it was found better to cut a little oversize (approximately 1/8-inch) to assure close fitting around the inside of the tube.

Preparation. To properly mount the specimen, the steel face of the plunger was thoroughly cleaned and a thin layer of transparent rubber cement was spread uniformly two inches wide on the steel face from the outer circumference inward. A small hole (3/8-inch) was previously drilled in the test sample to match the hole through the plunger for the pickup probe. By experimentation, it was found that if the hole was notched to the outside of the specimen to allow assembly over the probe, disassembly of the probe would be eliminated and the test greatly expedited. The precut specimen was placed

over the probe and held against the freshly cemented face of the plunger by two wooden "C" clamps. The sample was normally allowed to set overnight; however, some tests were run after two hours drying. After the drying period a wood rasp file and sandpaper were used to bring the specimen down to the diameter of the steel mounting plate.

The amplifier and oscillator were allowed about twenty minutes to warm up completely, although only a small error was introduced if it was necessary to begin testing before the full twenty minute warm-up period was completed. With the oscillator turned on and the amplitude gain turned to zero, the voltmeter was zeroed with the decibel meter range scale set at 60 db.

Test procedure. To eliminate some of the error due to the variation in readings with plunger location variation, the plunger was first set in a position for the frequency of the test run which would give a maximum reading for any position of the pickup. This placed the tube in resonance for the frequency selected.

The maximum pressure point was then secured by running the probe swiftly through the length of the tube and, with the voltmeter reading at the upper end of its range (the 15 volt range was found best), the probe was

carefully located at a maximum pressure point as close to the sound source as was convenient. The amplitude dial on the oscillator was then set at the maximum reading (15 volts).

Sets of maxima and minima were obtained by slowly pulling the probe out of the tube, being very careful that the exact values of these two points were obtained.

Sample test of Firtex. Graph 12 on the following page illustrates the results of a test run on a sample of Firtex, using the procedure indicated above.[1] The sample was obtained from the Alba Building Company which was building the new Beverlywood Addition in the Northeastern section of the city of Albuquerque. Firtex was used as a heat insulating board around the exterior of their frame-stucco buildings.

The sample showed consistent and regular results up to about 800 cps, after which succeeding sets of maxima and minima showed wide variations. Although the average of from five to ten sets were plotted and connected with a dotted line on the graph, they were viewed with suspicion because of the breakdown of the normal

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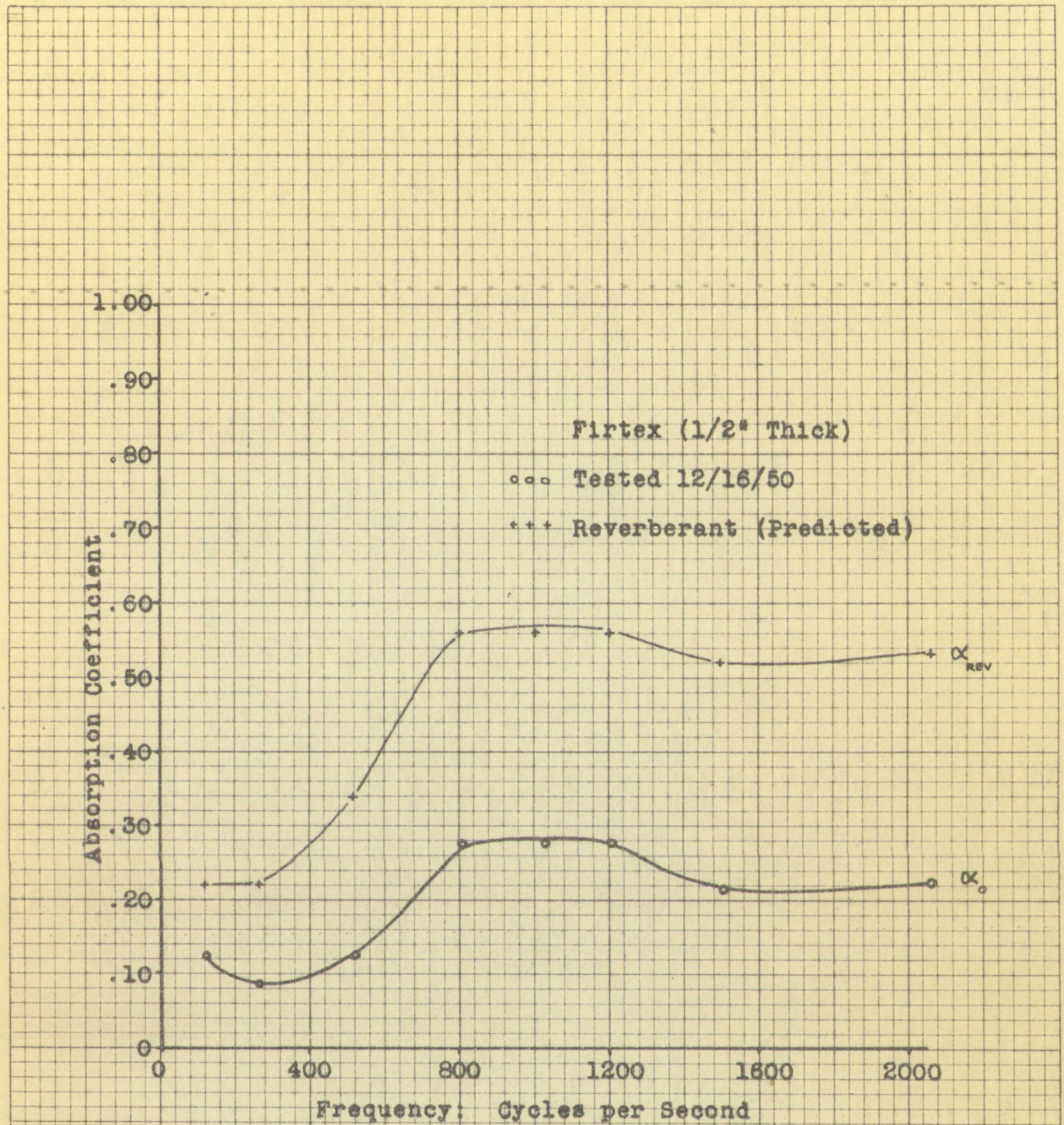
[1] Apparatus was operated by G. V. Lemmon, graduate student, for the Firtex tests.



Graph 12: Test of 1/2 inch Firtex Building Board

wave pattern which must have occurred within the tube at these higher frequencies.

The general shape of the curve did not agree well with the samples of Celotex used as calibration specimens, but the absorption coefficients as determined by the reverberation method are shown in the table below for comparison. These were approximated by a study of the relationships between the two coefficients as determined for the calibration specimens.

1/2 Inch Thick Firtex Specimen

Frequency	St. Wave Coefficient	Predicted Reverberation Coefficient
128	.12	.22
256	.09	.22
512	.13	.34
800	.28	.56
1024	.28	-
2048	.22	-

CHAPTER VII

CORRELATION OF STATIONARY-WAVE AND REVERBERANT ABSORPTION COEFFICIENTS

Early sound absorption investigators[1,2,3] recognized that it would be of considerable technological importance if it would be possible to determine from laboratory measurements on small accustical samples the sound absorption coefficients one might expect to measure on large samples placed in a reverberant sound chamber. Hence, the stationary-wave or tube method of determining the absorption coefficient has received intensive theoretical and empirical study in an attempt to determine an accurate correlation between small tube and large sound chamber absorption coefficients. Unfortunately, the correlation did not lend itself to either a straightforward mathematical or experimental solution. The solution to this problem was one of the subjects that received intensive study at the Tenth

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[1] H. C. Taylor, loc. cit.

[2] E. A. Eckhardt and V. L. Chrisler, loc. cit.

[3] A. H. Davis and E. J. Evans, loc. cit.

Anniversary Meeting of the Accustical Society of America in May, 1939.[4]

A. H. Davis[5] in his book Modern Accustics discussed the relationship between the reverberant and stationary-wave absorption coefficients. Graph 13 is a reproduction of a graph from his book in which is shown the experimental relationship between the ratio of reverberant to stationary-wave coefficient as a function of stationary-wave coefficients at a test frequency of 500 cps. The best smooth curve was drawn through eleven test measurements. It should be noted that the experimental points were deduced from published values of reverberant coefficients while stationary-wave values were measured by Davis and Evans.[6]

In general, the agreement between data obtained by the stationary-wave device at the University of New Mexico and the Davis and Evans curve was closer than expected. Averaged values of measurements on Celotex materials at 512 cps by this investigator are indicated

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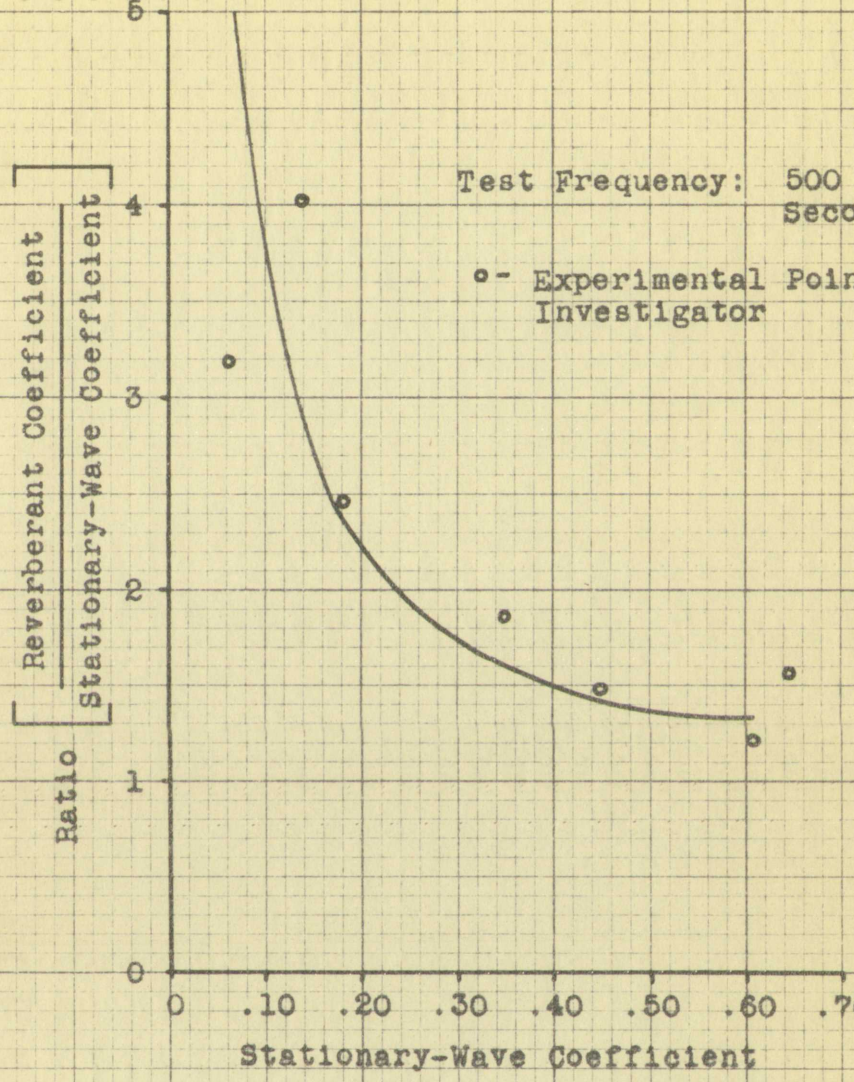
[4] V. L. Chrisler, et al., "Symposium Discussion on Sound Absorption Coefficient Problems," Journal of the Accustical Society of America, 11:38-47,96-105, July 1939.

[5] A. H. Davis, Modern Accustics, G. Bell and Sons, London, 1934, p. 216.

[6] A. H. Davis and E. J. Evans, Proceedings of the Royal Society of London, 117:89, 1930.



Graph 13: Stationary-Wave α Versus Reverberant α as Plotted From Experimental Data by Davis and Evans

on Graph 13 for comparison purposes. A limitation in utilizing the relationship plotted on this graph exists because the experimental values of stationary-wave coefficients determined by Davis and Evans did not exceed 0.60; therefore, it was not possible to check the extent of agreement of test data for larger values of absorption coefficients.

Probably the best mathematical approach to the correlation problem was recently devised by Albert London[7] of the National Bureau of Standards. His solution took cognizance of the fact that stationary-wave or tube measurements give coefficients for normal incidence only, whereas sound chamber measurements give coefficients for random incidence. His solution involved a complex integration of the normal incidence relationship over all angles from 0° to 180°. He devised an equivalent acoustic impedance (Ze) from normal incidence coefficients (α_o) as follows:

(1). $$Ze = \frac{1 + (1 - \alpha_o)^{\frac{1}{2}}}{1 - (1 - \alpha_o)^{\frac{1}{2}}}$$

whence, after setting up a complex integral and integrating, the following random incidence coefficient * was established

(2). $$\alpha^* = \frac{4}{Ze}\left[\ln (1 + Ze) - \frac{Ze}{1 + Ze}\right]$$

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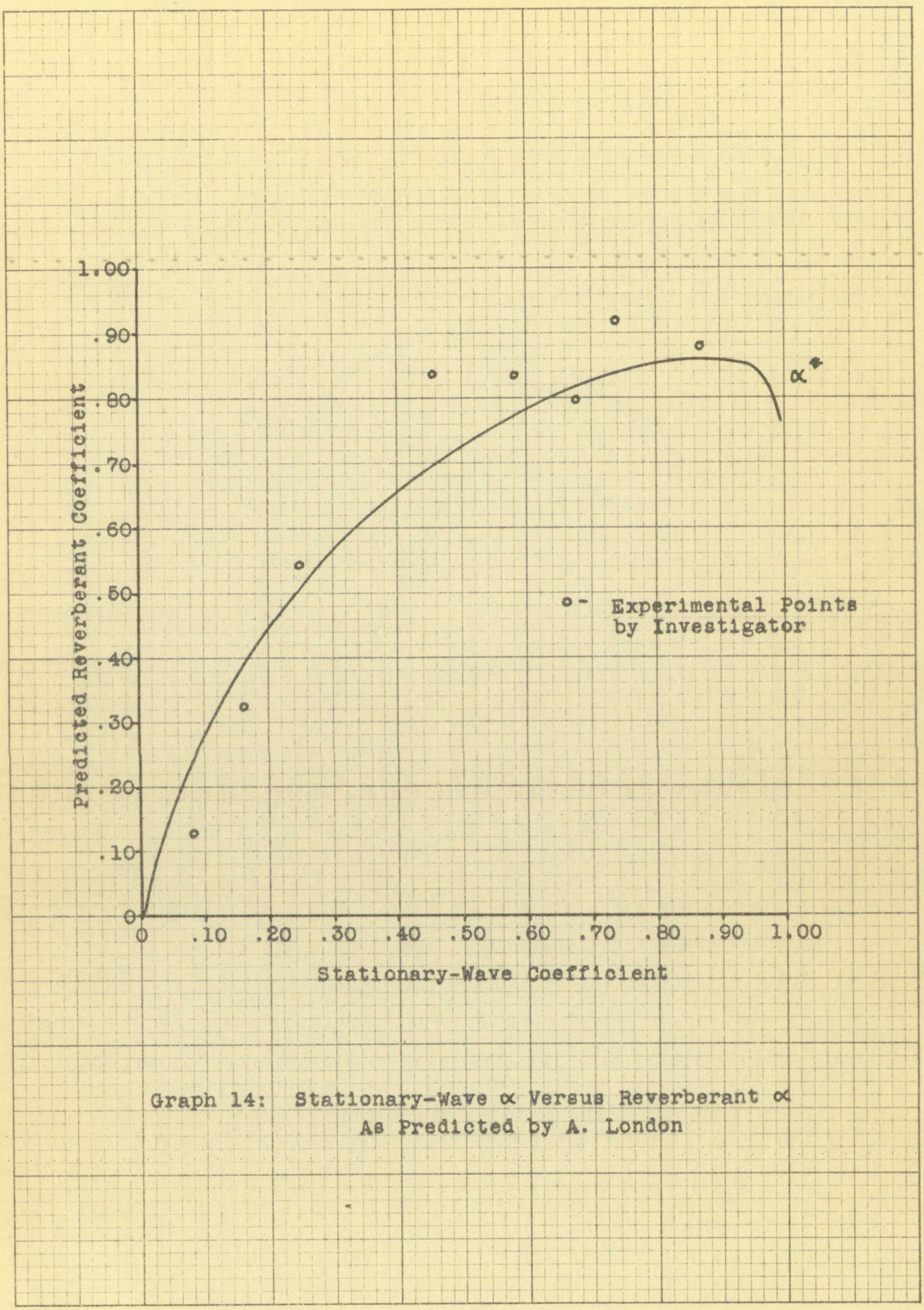
[7] A. London, loc. cit., pp. 263-269.

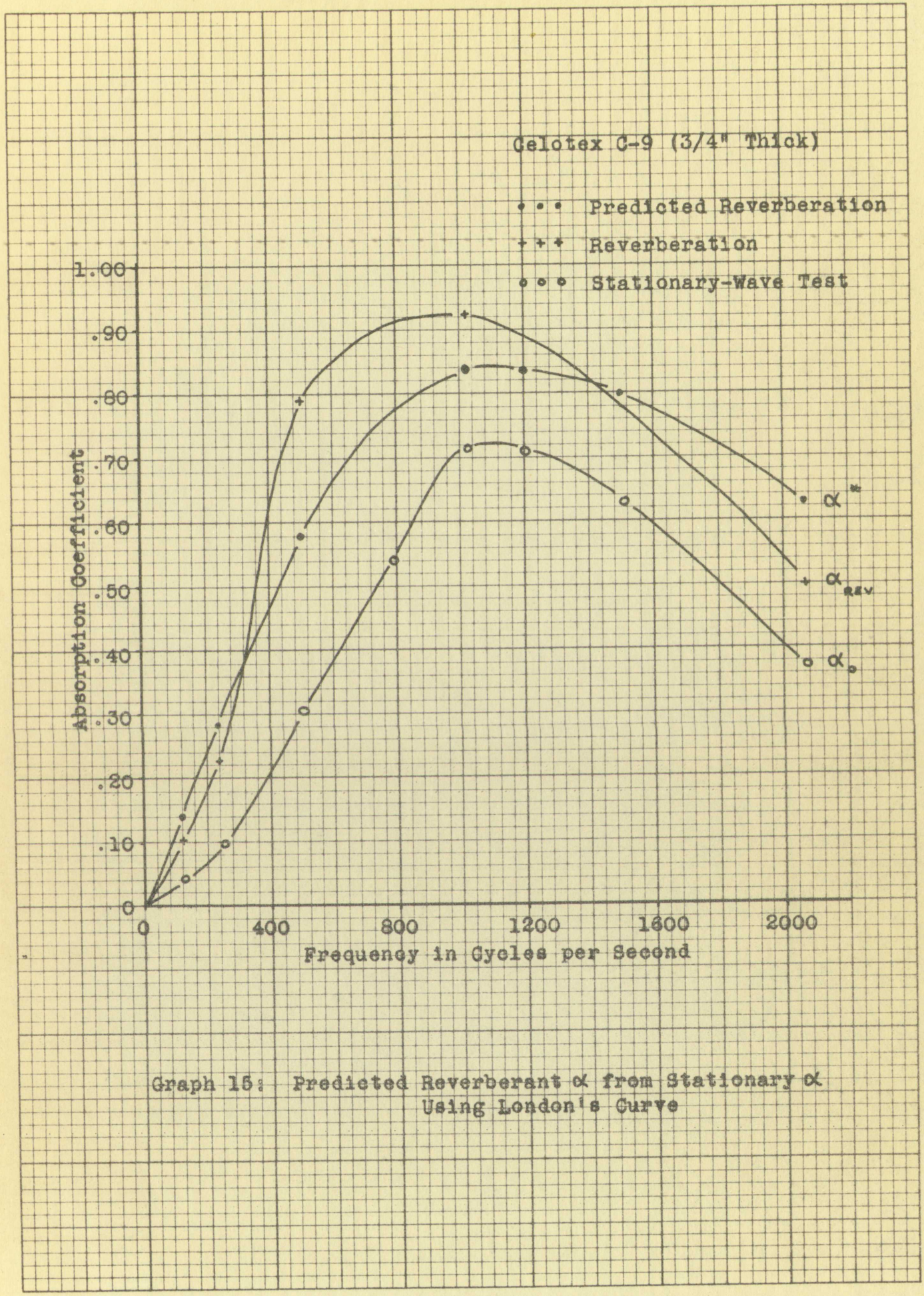
Graph 14 represents a plot of stationary α_o versus predicted reverberant α^* as determined by Equations (1) and (2). London observed that close agreement with chamber data was obtained for measured reverberant coefficients up to 0.85, but because the solution to Equation (2) has an upper limit of 0.86 for reverberant α, errors of ten per cent were found for highly absorbent materials whose α approached 1.00. Again, for comparison, the observed stationary α versus accepted reverberant α (as determined from Bulletin XI, Acoustical Materials Association) was plotted in Graph 14.

Graph 14 may be used to advantage in predicting random reverberant α coefficients from observed stationary-wave data. Graph 15 illustrates the usefulness of London's curve for predicting reverberant α for Celotex C-9 (3/4" thick) from stationary-wave measurements made by the investigator. Close agreement between predicted values and recognized sound chamber data is indicated for low and high test frequencies with the maximum deviation at the intermediate frequencies.

The extent of agreement between London's work and this investigation is also shown in the tabulation on page 68 for one of the Celotex materials investigated by both experimenters.



Graph 14: Stationary-Wave α Versus Reverberant α As Predicted by A. London



Graph 15: Predicted Reverberant α from Stationary α
Using London's Curve

Celotex C-4 (1-1/4 inches)

(cps)	(1) α_o	(2) α_o	(3) αRev.	(4) α^*
128	0.07	0.08	0.14	0.25
256	0.20	0.18	0.42	0.43
512	0.64	0.62	0.99	0.81
1024	0.61	0.70	0.74	0.83
2048	0.33	0.39	0.61	0.64
Average	0.370	0.394	0.580	0.592

(1) - Measurements of stationary α by L. L. Beranek

(2) - Measurements by the investigator

(3) - Reverberant α per Accoustical Materials Association

(4) - Predicted reverberant α from stationary α of this investigation using London's curve (Graph 14)

From the above evidence, it was the studied opinion of the investigator that the results of this thesis research closely corroborated and supplemented the mathematical work of London. By supplying accurate experimental data that supported the theoretical work of London, the answer to the problem of correlation of stationary-wave and reverberation-time absorption coefficients was brought closer to a practical solution.

CHAPTER VIII

SUMMARY AND CONCLUSIONS

This final chapter summarizes all of the work which has been mentioned in the preceding chapters and draws specific conclusions relating to the apparatus herein described, and the samples which were tested by the investigator. In addition, other conclusions of a more general nature are given in the hope that they will be of further use to future investigators of the same or related subjects.

Summary. In pursuance of the object of the problem solution, the investigator, after a thorough search of the literature available, set about to design and construct a stationary-wave setup for the measuring of acoustical sound absorption coefficients for various building materials. It was well realized that the reverberation method is the standard method in use because of its ability to measure the effect of sound waves incident upon the surface from all angles of approach.

Within the limits of space and finances, it was felt that the stationary-wave method would prove satisfactory for a means of testing local building materials

and for providing a worthwhile apparatus for research to the Department for future use of Graduate Students and Faculty.

The method originally suggested by H. C. Taylor was used as the basis of the work and, by a process of purchasing, borrowing, and making on the spot, the equipment necessary was assembled in the research laboratory of the Department of Mechanical Engineering. This included a steam pipe to act as a bounding tube for the sound waves to assure a normal angle of incidence upon the sample; a source of sound which was provided by an oscillator and permanent magnet speaker attached to one end of the tube by the use of a "C" clamp and block of wood; a plunger constructed of plywood, felt pads, and steel attached to a long pipe in two sections to provide a handle for the plunger, and; an earphone type of microphone for a pressure pickup within the tube, plus the needed amplification and measuring equipment to make it possible to read and interpret the small variations in sound pressure existing. All of this equipment was used with the accompanying accessories such as electrical connections, power supply, oscilloscope for studying the wave forms within the tube, tools, etc., in a small section within the fenced-in research laboratory in the Mechanical Engineering Department.

Since it was desired to arrange a comparison between the results obtained from the method at hand and the coefficients of absorption normally given for acoustical materials by the use of the reverberation method, tests were run on four samples of acoustical material provided by the Celotex Company. The results obtained were compared with the data which the Acoustical Materials Association recommends in their Bulletin M.

Other calibration studies included an investigation of the sound patterns set up within the tube by a range of frequencies upon a sample of Celotex C-9, a study of the effect of the pickup position upon the absorption coefficient at various test frequencies, and an investigation of the effect of plunger position on the test results. The effect of the pickup size on the stationary-wave patterns and observed results was also investigated, both theoretically and experimentally. An extensive calibration was undertaken to determine the sensitivity of the apparatus by increasing the absorbing surface area of the test sample by drilling holes in regular geometric patterns and measuring the increase in absorption coefficients.

The extent of correlation between accepted reverberant and measured stationary-wave coefficients was investigated in an attempt to corroborate recent

mathematical approaches to the correlation problem. Measurements of absorption coefficients by previous investigations were compared to the results of this research and predicted reverberant coefficients were determined by mathematical treatment of the observed stationary-wave data.

A recommended test procedure was then proposed from the experience of the investigator as one which would give the best results in the most efficient manner with the available apparatus. A complete test of a local building material was made to illustrate the test method and to indicate the procedure for predicting reverberant coefficients from the results of a laboratory measurement.

General conclusions. It was the studied opinion of the investigator that the scope of the work undertaken was too large for the drawing of a large number of specific and reliable conclusions. However, from the experimental data to date, the following general conclusions were drawn.

1. The apparatus was capable of determining accurate values of absorption coefficients for normal incidence. The results were reproducible and compared favorably with the reported values obtained by more

elaborate stationary-wave setups used by other investigators as shown by the tabulation on page 67.

2. Higher accuracy for measurements below 800 cps was obtained because of the massive, non-absorbing walls of the bounding tube.

3. The present apparatus had a definite frequency limitation because of the large diameter of the tube, and this limitation varied with the sample under test. In general, confidence of reliability of results was limited to frequencies below 800 cps. For each individual sample, however, the sound pattern should be explored for discontinuities and irregularities to obtain more conclusive knowledge of this limitation.

4. Correlation studies between reverberant coefficients and coefficients determined by this investigator closely checked theoretical and mathematical predictions of the relationship between random and normal incidence absorption.

5. The method of operation as discussed in Chapter VI was found to be satisfactory, and future experimentation should carefully follow the procedure to insure comparable accuracy.

6. Reproducible test results were obtained only when the amplitude dial on the Hewlett-Packard oscillator was positioned between numbers 8 and 25.

7. The position of the plunger during the test did not significantly affect the measurements but, for ease of operation and highest sensitivity, the tube was tuned to resonance before tests were begun.

Recommendations for future investigation. The investigation revealed certain adaptations and improvements that would give more accurate results from the stationary-wave apparatus. The following recommendations for future modification were drawn on the basis of the belief that the equipment has a definite value to the University of New Mexico and to the building industries of Albuquerque and surrounding territory.

1. Since the usual test frequencies used in determining the sound absorption coefficient includes values up to 4096 cps, the first recommendation is that another smaller tube be constructed to supplement the effectiveness of the present equipment. The smaller tube would allow higher frequency waves within the apparatus without disturbing the plane wave pattern necessary for the accurate operation of the apparatus.

2. The new tube should be carefully selected to avoid irregularities and roughness of the inner surfaces that distort the wave pattern. For the same reason, the internal surface of the present tube should be ground or buffed to reduce the surface roughness.

3. More experimental data should be taken, and it is believed that if the proper approach is made to the eight members of the Acoustical Materials Association for samples, enough material would be provided to construct calibration curves for the majority of acoustical materials which might come to the laboratory for testing.

4. Local and regional manufacturers of building materials and local architects and engineers should be made cognizant of the equipment available within the Mechanical Engineering Laboratory for performing acoustical tests on all types of building materials.

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