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UNITED STATES DEPARTMENT OF THE INTERIOR

HAROLD L. ICKES, Secretary

BUREAU OF MINES

R. R. SAYERS, Director

Technical Paper 635

DESIGN OF AIR-BLAST METER AND CALIBRATING EQUIPMENT

By

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UNITED STATES

GOVERNMENT PRINTING OFFICE

WASHINGTON : 1942

For sale by the Superintendent of Documents, Washington, D. C. - - - - Price 10 cents

FOREWORD

For several years the Bureau of Mines has conducted research on seismic waves emanating from quarry blasts and their effects on nearby residential structures. At various times the oscillograph recorded a second vibration following the seismic wave. Investigation showed the arrival time of these delayed waves to be coincident with or close to the speed of sound. They were therefore assumed to be records of disturbances caused by air vibrations.

Tests were made in which explosive charges were detonated in the air without contact with the ground. No seismic wave was produced by this type of blast, but, when set up in houses, the seismometers recorded disturbances, and the time of arrival again closely approximated the speed of sound.

It is common knowledge that mud-capped shots cause air disturbances resulting in the rattling of window sash or loose panes of glass. Tests made with this kind of blasting also gave no record of a seismic wave but did indicate disturbance from an air wave.

A study of photographic records on which vibrations from both seismic and air waves were recorded occasionally showed greater displacement from the latter from the same blast.

It was frequently observed that no complaints were received from residents near a quarry if atmospheric conditions were such that the quarry blast was not heard. Conversely, many complaints were received following blockhole shots from which no appreciable seismic wave was set up.

These observations led to a study of the effect of the air disturbance from quarry blasting paralleling the study of the seismic wave. The seismometers employed to study the ground wave could be used to measure the speed of propagation of the air wave and also the displacement of a house caused by the air wave. A few tests were made to record air-wave speeds, and it was found that at short distances from the blast the speed of the air wave was much faster than the speed of a sound wave, but that it was rapidly damped to the speed of sound and continued at that rate for a considerable distance.

In order that the characteristics of the air wave could be studied quantitatively it was decided to design an air-pressure meter that could be used in place of the seismometer.

The problem of designing such a pressure meter together with the necessary equipment by which the meter could be calibrated was assigned to Andrew T. Ireland in the fall of 1939, following completion of field tests of mechanical agitation of residential structures.

J. R. Thoenen,
Senior Mining Engineer,
Bureau of Mines.

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ILLUSTRATIONS

DESIGN OF AIR-BLAST METER AND CALIBRATING EQUIPMENT[1]

By A. T. Ireland[2]

OBJECT OF THIS PAPER

The object of this paper is to describe the evolution of the design of an air-blast meter to be used for measuring air pressures from quarry blasts and the design and application of equipment required for calibration thereof.

ACKNOWLEDGMENTS

The author wishes to acknowledge his indebtedness to J. R. Thoenen, supervising engineer, Nonmetal Mining Section, for his direction of the work, constructive criticism of the manuscript, and helpful suggestions; to Stephen L. Windes, seismologic observer, Nonmetal Mining Section, for his valuable advice and aid; to Jack T. Donovan, junior physical science aid, Nonmetal Mining Section, for his assistance in calibration; and to Rudolf Kudlich, superintendent, Eastern Experiment Station, C. M. Davis, and M. R. Price for construction of the apparatus.

STUDY OF RELATED PHENOMENA

The fact that the high-pressure impulse of an explosion has a higher density and index of refraction than the undisturbed air is utilized in two methods of photographing (*21, 22, 23, 25*)[3] air waves from explosions. The Schlieren method (*34, p. 342*), by an ingenious arrangement of lenses and mirrors, photographs the wave by means of its changing index of refraction and density. The shadow method of Dvorak (*34, p. 340*) photographs the shadow of the highly compressed pressure wave. With either method, a spark may be used as the source of illumination for an instantaneous picture, or an arc and a moving film may be used to give a continuous record of the progress of the wave. By plotting the position of the wave against time, the velocity of the wave at any distance from the source may be determined. However, neither method directly measures the pressure or energy of the wave. Both methods are designed for the study of the shape and speed of high-pressure waves at short distances from a small explosion, and neither could be adapted easily to determination of lower pressures at greater distances from the source.

Explosions in cannon and engine cylinders also have been recorded by various types of gages (*15, 16, 17, 18, 19*). Such gages have a high

[1] Work on manuscript completed March 20, 1941.
[2] Junior physicist, Nonmetal Mining Section, Mining Division, Bureau of Mines.
[3] Numbers in parentheses refer to references in the bibliography; page numbers are those in the references and not in this publication.

natural frequency so as to respond to the extremely rapid rise in pressure for these confined explosions and must be constructed rigidly to withstand the high pressures. There are three general types of these gages—the piezoelectric, resistance, and condenser. In the piezoelectric type the pressure causes compression of a stack of piezoelectric crystals, the resulting voltage being amplified and recorded by suitable means. In the resistance type, the pressure causes compression of a carbon pile with a resulting change in electrical resistance which is recorded as a pressure-time relationship. In the condenser gage the pressure bends a diaphragm of high natural frequency toward a rigid plate, and the resulting change in electrical capacitance gives the pressure-time relationship. Obviously these gages are designed to measure pressures far above those required to damage a building.

On the other hand, the various types of microphones in common use were designed for sound emanating from such sources as voice, musical instruments, traffic, etc., all of which, as shown by common experience, are harmless to buildings. It was necessary, therefore, to design and calibrate an instrument for the measurement of pressures ranging somewhere between these extremes.

From elementary principles of mechanics, it can be stated that any damage done to a building by the air blast will depend on the construction and condition of the building itself as well as upon the size, distribution, and duration of forces acting upon the structure. These forces at any moment can be computed most easily from a time-pressure record. They could also be computed from the velocity, or amplitude and frequency, of motion of the air particles, but such a computation would require that the velocity, or amplitude and frequency, be used to solve for the pressure, which would then be integrated over the area affected to give the total force. Regardless of the method used, it would be difficult to calculate exactly the minimum force necessary to damage a certain building, but it was thought that this difficulty could be overcome by making observations upon a number of buildings and determining a limit below which an ordinary structure would not be damaged.

To make these observations it was necessary to design an instrument that would measure pressure changes, and it was desired that it should have linear frequency and pressure response over any anticipated range. Further, it should have different sensitivity ranges and should be rugged enough to minimize the danger of being damaged or thrown out of adjustment in the field. The amplifying and recording equipment should not be unduly complicated or require excessive power for field use. Measurements should be reproducible, should be in absolute units, and should be accurate to within 10 percent. Although the desirability of precision measurements was realized, it was felt that, owing to the great differences in the construction and condition of buildings, the added cost necessary for precise measurements would not be justified.

AIR-BLAST METER

HISTORY

Of the pressure-response instruments in common use, the condenser- and crystal-type microphones give the most nearly linear frequency response below their resonant frequencies. The condenser microphone (see fig. 1) was chosen instead of the crystal type because it is easily constructed and its response is independent of atmospheric conditions.

E. C. Wente's condenser microphone (*13*) has the notable characteristic that its sensitivity is comparatively constant over a wide frequency range. It consists of a steel diaphragm stretched in front of a rigid plate. The plate does not cover the entire area of the diaphragm and is separated from it by an air space of about 0.0025 cm. (0.001 inch). This air space is connected by grooves and holes in the plate and holes at the side of the plate to a larger air chamber behind the plate. The large air chamber is connected to the outside by a small hole or by means of a compensating diaphragm to allow for changes of atmospheric pressure. The thin air space between the diaphragm and plate overdamps the diaphragm at low frequencies; at higher frequencies it adds stiffness to the diaphragm and raises

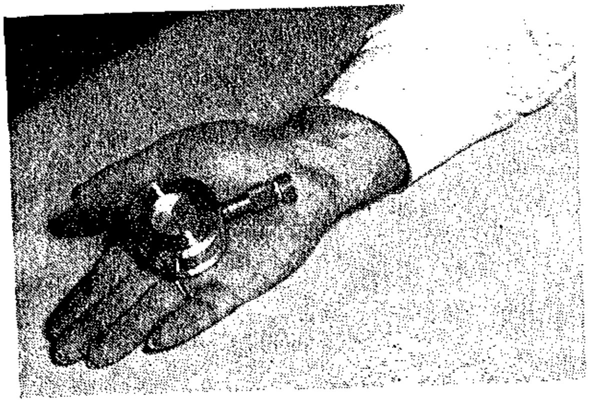

FIGURE 1.—Air-blast meter.

the natural frequency of the system. The pressure response of the microphone can be held comparatively constant from frequencies of a few hundred cycles per second to frequencies above the natural frequency of the diaphragm.

CONSTRUCTION

As the air-blast meter must be taken apart, the sensitivity changed, and the meter reassembled in the field, a clamped plate instead of a stretched membrane was used as the diaphragm. This resulted in some loss of sensitivity, as a plate is less sensitive than a membrane of the same resonant frequency; but this was not considered a serious disadvantage.

Different sensitivities are obtained by using diaphragms of different thickness (0.01 ± cm., 0.03 ± cm., and 0.05 ± cm.) and by varying the spacing between the plate and diaphragm (fig. 2). Duraluminum was chosen for the diaphragm because its low density and high modulus of elasticity insure high sensitivity for a given resonant frequency. Other metal parts also were made of duraluminum to avoid any distortion due to temperature changes. The diameter of the unclamped portion of the diaphragm is 2.5 cm. (1 inch), and the resonant frequency of the thinnest diaphragm is about 1,400 cycles per second, slightly above the highest resonant frequencies of the elements used in the oscillograph. A dielectric washer (*b*) holds rigid inside plate (*d*) away from case (*i*) and diaphragm (*a*). The case and diaphragm completely enclose and electrically shield this plate, which is the only part not at ground potential. This prevents any interference from near-by electrical circuits or any change in capacitance caused by the movement of one's hand near the air-blast meter. The separation between the diaphragm and the inside plate is varied by means of one to four spacer washers (*c*) of 0.0025 cm. (0.001 inch) thickness, the number used depending on the sensitivity desired. Since the thin air space between the diaphragm and inside plate would ordinarily cause the diaphragm to be overdamped, holes and grooves are cut in the plate, connecting with a larger air chamber (*g*) formed by a bakelite

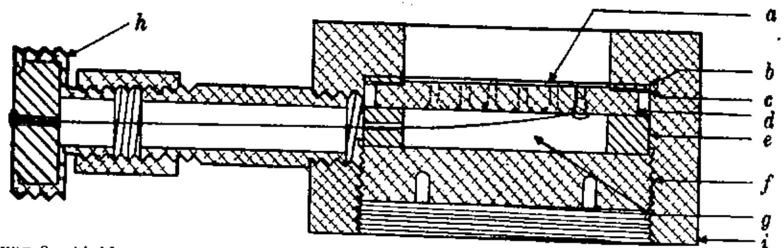

FIGURE 2.—Air-blast meter: *a*, Plate diaphragm; *b*, dielectric washer; *c*, spacing washer; *d*, inside plate; *e*, bakelite ring; *f*, rear metal plate; *g*, air chamber; *h*, miniature cable connector; *i*, case.

ring (*e*) pressed against the inside plate by the rear metal plate (*f*). The diaphragm therefore acts as an underdamped vibrating system. The electrical connection to the inside plate is made by a small wire from the miniature microphone cable connector (*h*) through the bakelite ring to the inside plate.

CHARACTERISTICS

As the diaphragm is underdamped, its deflection for a certain force is the same at all frequencies that are small compared to its resonant frequency. It therefore has a "linear frequency response" over this range. The force exerted upon the diaphragm is due to the difference in pressure of the outside air and the pressure in the air chamber. Some leakage must be allowed to compensate for changes in temperature and atmospheric pressure. This leakage is through the threaded portion of the back plate and causes a loss in sensitivity at low frequencies. Tests (described under "Pistonphone") have shown this error to be less than 2 percent at 20 cycles on one air meter and increasing from 4 percent at 20 cycles to 8 percent at 10 cycles and 15 percent at 5 cycles on another. It can be assumed that the air meter would record waves of even lower frequency with some further loss in sensitivity. As no indication of infra-audio (below 15 cycles per second) waves (such as Esclangon (*20*) found) have yet been obtained in the tests, calibration below 5 cycles has not been made.

The response of a condenser microphone at high frequencies not only depends on the natural frequency and damping of the diaphragm but also on the size and shape of the microphone and the cavity in front of the diaphragm. These factors influence the response due to cavity resonance, directivity, and diffraction (*2*, *4*, *5*), as the dimensions of the microphone become an appreciable fraction of the wave length of the sound and usually necessitate separate field and laboratory calibrations. In a laboratory calibration, the sound waves are produced in a chamber that is relatively small when compared to the wave length of the sound. In a field calibration the sound waves are produced in a chamber so large, or with walls so sound-absorbent, that any reflections are negligible compared to the source. It would obviously require great power to produce sounds with pressures as great as those produced by explosions. The investigations of others (*2*) with similar condenser microphones showed close agreement between field and laboratory calibration and negligible errors up to 500 cycles. The dimensions of the meter were made smaller than those used by other investigators to avoid the necessity of field calibration.

Although an explosion has a very steep wave front, which would show large components of high-frequency waves if subjected to Fourier analysis (*34*, *p. 27*), the damping is so much greater on the

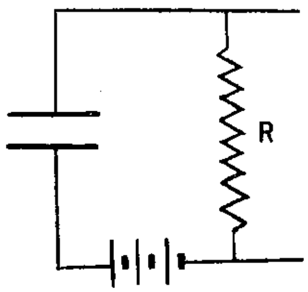

FIGURE 3.—Wente's circuit.

high-frequency components that the steepness of the wave front rapidly decreases with distance except very close to the source, where the pressure is great enough to increase the velocity appreciably. Within this range, that part of the wave having the greatest pressure also has the greatest velocity and consequently gains on less highly compressed parts of the wave leading to a steeper wave front. As the air-blast meter was intended to be used at distances from about 100 feet to several thousand feet from the explosion, the calibration was carried only to 500 cycles. The thicker diaphragm, used nearer the shot, would have linear response to higher frequencies, but the calibration was not carried higher owing to limitations of the oscillograph elements being used.

CIRCUIT

Wente's circuit (*13*) consists of the condenser microphone in series with a large resistance and a polarizing voltage, as shown in figure 3. This circuit gives a certain change in voltage for a given change in capacitance at any frequency sufficiently high that R (resistance) is large compared to $\frac{1}{2\pi fC}$, where C is the capacitance of the condenser microphone in farads and f the frequency in cycles per second. Below this frequency the sensitivity of the circuit decreases.

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The disadvantages of this system for low frequencies are obvious. Moreover, the first stage of the amplifier usually is kept close to the microphone to avoid adding capacitance in parallel with the microphone and decreasing the sensitivity. For high-pressure work this would expose the amplifier to severe shocks. Furthermore, this circuit requires several stages of amplification, which are difficult to calibrate and maintain in calibration.

A slightly modified form of the transducer circuit (*26*) used by the Bureau of Mines in its seismic research work was adapted in the form shown in figure 4 and gives linear frequency response from static to

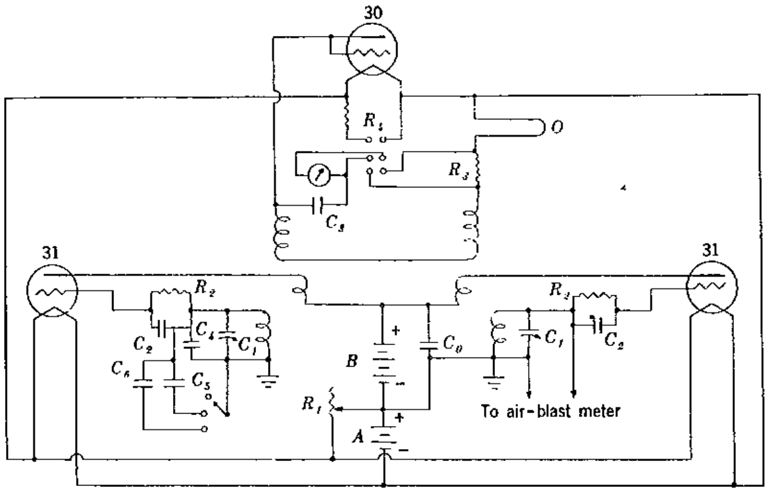

FIGURE 4.—Transducer circuit: C_0, 0.01 mfd.; C_1, 100 mmfd.; C_2, 0.002 mfd.; C_3, 50 mmfd.; C_4, 300 mmfd.; C_5, 200 mmfd.; O, oscillograph element; R_1, 6 ohms; R_2, 50,000 ohms; R_3, shunt for milliammeter; R_4, 500 ohms; 30 and 31 are vacuum tubes.

supersonic frequencies. Two A batteries are used for the filament supply, and up to four B batteries (180 volts) are used for plate voltage. Its sensitivity is slightly more than 1 milliampere per micromicrofarad of change in capacitance. The transducer is built in a small aluminum case, which completely shields the system from electrical interference. The case and batteries are protected from the weather and the air blast by a heavy wooden box. The transducer case is suspended within the wooden box by elastic cords to minimize shocks. A shielded cable 6 to 10 feet in length connects the air-blast meter and transducer. Tests were made with the air-blast meter disconnected. These showed no vibration due to the transducer circuit itself. Figure 5 shows transducer box, shielded cable, and air-meter assembly, the air meter mounted on window frame.

FIGURE 5.—Transducer box, shielded cable, and air-meter assembly.

ELECTROSTATIC ACTUATOR

THEORY

From the theory of electrostatic forces we find that two parallel plates, whose dimensions are large compared to the distance separating them, will, according to Pender (*33*), exert a force upon each other of

$$f=\frac{V^2kA}{8\pi x^2}, \tag{1}$$

where

f = force, in dynes;
V = potential drop between the plates, in electrostatic volts (practical volts divided by 300);
A = area of the plate, in square centimeters;
k = the dielectric constant;
x = the separation, in centimeters.

It is also shown that

$$C=\frac{kA}{4\pi x},$$

where C is the capacity of the condenser; hence, equation 1 may be written

$$f=\frac{V^2C}{2x}. \qquad (2)$$

If plates *1* and *2* of the system shown in figure 6 are separated by a dielectric of constant k, and plates *2* and *3* are separated by air

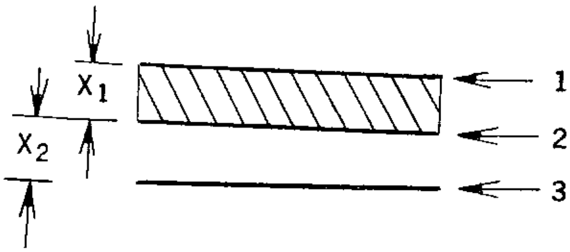

FIGURE 6.—Three-plate condensor.

(dielectric constant 1), the capacitance, C, between plates *1* and *3* may be found from the equation

$$\frac{1}{C}=\frac{1}{C_1}+\frac{1}{C_2},$$

or

$$\frac{1}{C}=\frac{4\pi x_1}{kA}+\frac{4\pi x_2}{A}. \qquad C=\frac{A}{4\pi\left(\frac{x_1}{k}+x_2\right)}=\frac{A}{4\pi x},$$

where

x = the effective separation,
C_1 = capacitance between plates *1* and *2*,
C_2 = capacitance between plates *2* and *3*,
C = capacitance between plates *1* and *3*.

If the plate *2* has no electrical connections and is of negligible thickness, it may be removed without affecting the capacitance C of the system. Substituting in equation 2, we have the force between two plates, one of which is covered by a dielectric, as

$$f=\frac{V^2A}{8\pi x^2}. \qquad (3)$$

To give the force per unit area (F) in dynes per square centimeter we divide by A, and equation 3 becomes

$$F=\frac{V^2}{8\pi x^2}. \qquad (4)$$

If the potential applied is an alternating voltage,

$$V=V_o \sin \omega t,$$

where

t = the time,
ω = 2π times the frequency, in cycles per second,
V_o = the peak voltage,

we have

$$F = \frac{V_0^2 \sin^2 \omega t}{8\pi x^2}. \tag{5}$$

The force is one of attraction, since opposite charges attract; it has twice the frequency of the impressed voltage and is inversely proportional to the square of the effective separation.

If a rigid plate is placed near and parallel to the diaphragm of the air-blast meter and a voltage is impressed across them, the air meter can be calibrated if the voltage and effective separation are known. Such a calibrating device is called an electrostatic actuator.

CONSTRUCTION

In calibrating the air-blast meter one must be careful that the calibrating instrument does not affect the meter's response. The chief danger in the use of the electrostatic actuator in calibrating the meter is the damping effect of the thin air space between actuator plate and meter diaphragm.

For this reason the plate of the electrostatic actuator must be kept at such distance from the diaphragm that the air space between them will not be thin enough to add appreciable damping or take the form of a grill or stretched-wire screen closer to the diaphragm.

Both methods reduce the sensitivity and maximum pressures obtainable with the actuator.

The former method was adopted to avoid the necessity of precise separation and parallelism between grill and diaphragm.

The actuator plate, as shown at *b*, figure 7, was covered with a dielectric (*c*). This protected the equipment in case of an electrical break-down across the air gap and added only $\frac{1}{k}$ of its thickness (k=the dielectric constant) to the effective separation. As high potentials (several thousand volts) are used in calibrating, the plate is entirely enclosed by insulating material while the diaphragm and case of the air-blast meter are kept at ground potential.

Alternating voltage was supplied by either of two Ward-Leonard control systems through a *pi*-type, low-pass filter of variable inductance to a 400-to-1 voltage step-up transformer (fig. 8). The generators could supply frequencies from 20 to 500 cycles per second, which could be used for calibrations of 40 to 1,000 cycles per second (see electrostatic actuator theory). Thus, if the frequency of the voltage was 20, the frequency of the force would be 40 cycles per second. The voltage across the electrostatic actuator was recorded on a Duddell-type oscillograph. The oscillograph element was in series with a resistance, *R* (fig. 8), of several megohms, depending on the voltage being used. Potentials up to 9,000 volts were used. A resistance, *r* (fig. 8), of 2,000 ohms was connected in parallel with the oscillograph element (approximately 1 ohm resistance) to prevent having a high potential on the oscillograph if the element circuit were opened accidentally. All high-potential parts of the circuit were kept in a cabinet, where they could not be touched accidentally. A cable with an insulation capable of withstanding 15,000 volts led to the electrostatic actuator plate.

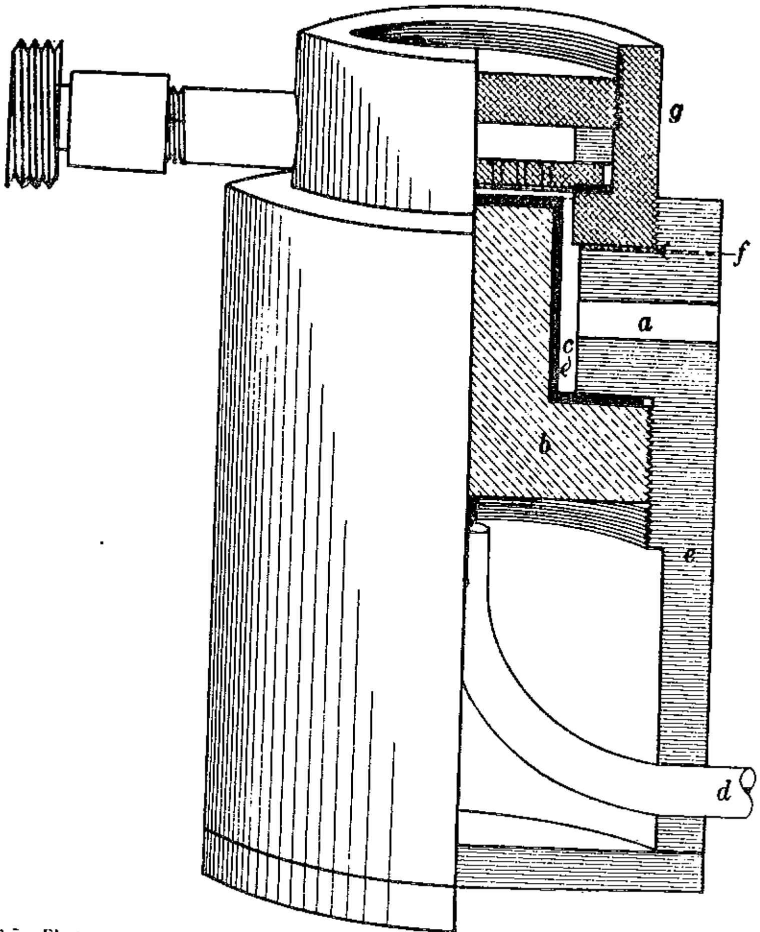

FIGURE 7.—Electrostatic actuator: *a*, Air outlet; *b*, electrostatic actuator plate; *c*, dielectric covering plate *d*, insulated cable to plate; *e*, bakelite case; *f*, spacing washers; *g*, air-blast meter in place for calibration.

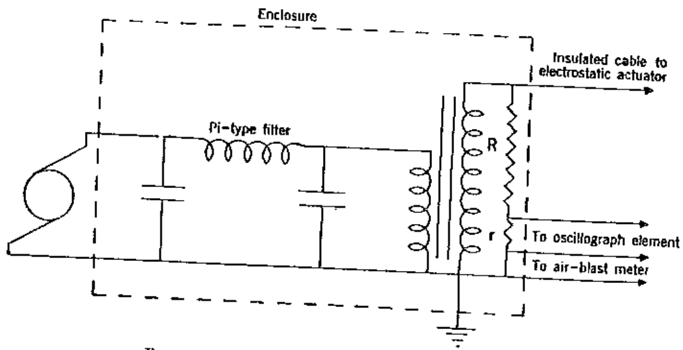

FIGURE 8.—Electrostatic-actuator voltage supply.

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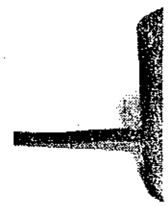

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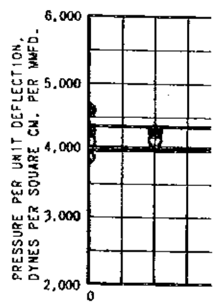

FIGURE 10.- Calibration of the
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TESTS

The electrostatic actuator (see fig. 9) was most useful for determining the frequency-response curves of the more sensitive air-blast-meter settings. Care had to be taken that the separation between the electrostatic actuator plate and the meter diaphragm was enough to reduce the damping effect to a point where it would not change the frequency response. A separation of 0.025 cm. was found to be sufficient for most air-meter settings. The upper curve on figure 10 shows the effect of this added damping on the frequency-response curve. The pressure (dynes per square centimeter) required to give a deflection of the diaphragm sufficient to change the capacitance of

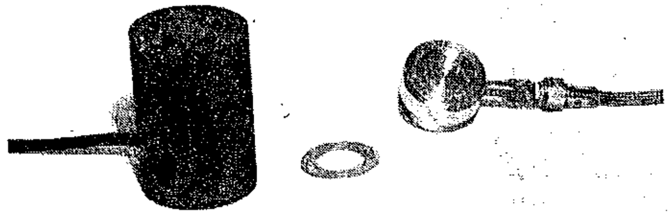

Figure 9.—Electrostatic actuator with air-blast meter and spacing washer ready to mount for calibration.

the air-blast meter 1 micro-microfarad is plotted against the frequency. The pressure required for this deflection is calculated from the voltage and distance of separation (equation 5, Electrostatic Actuator Theory). The bottom curve was taken with a greater separation between the electrostatic actuator plate and the diaphragm of the meter. A comparison of the curves shows how added damping increases the pressure necessary at higher frequencies.

The deflections at zero frequency on figure 10 were obtained by putting a D. C. voltage on the electrostatic actuator. The D. C.

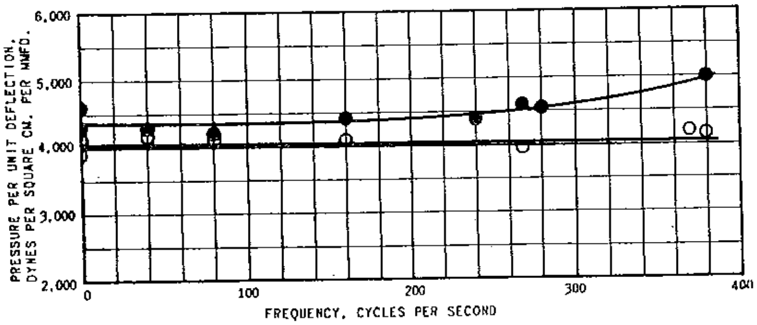

Figure 10.—Calibration of the electrostatic actuator. Upper curve shows effect of added damping when plate is too close to diaphragm. Lower curve is correct calibration and can be duplicated for different distances of separation between plate and diaphragm.

voltage was obtained by means of the circuit shown in figure 11. The voltmeter had a resistance of 62.5 megohms. As the current drawn was quite small, the rectifier and filter gave a D. C. voltage with negligible ripple for an input frequency of 100 cycles or higher.

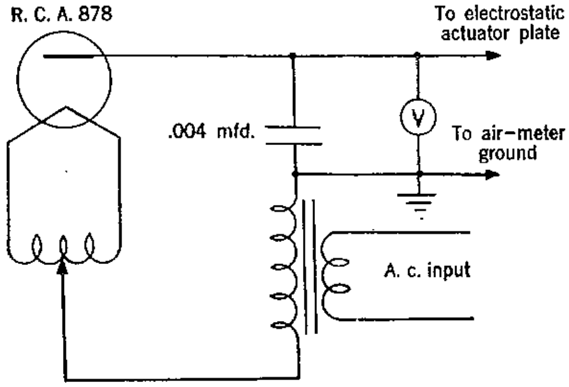

FIGURE 11.—High-voltage rectifier.

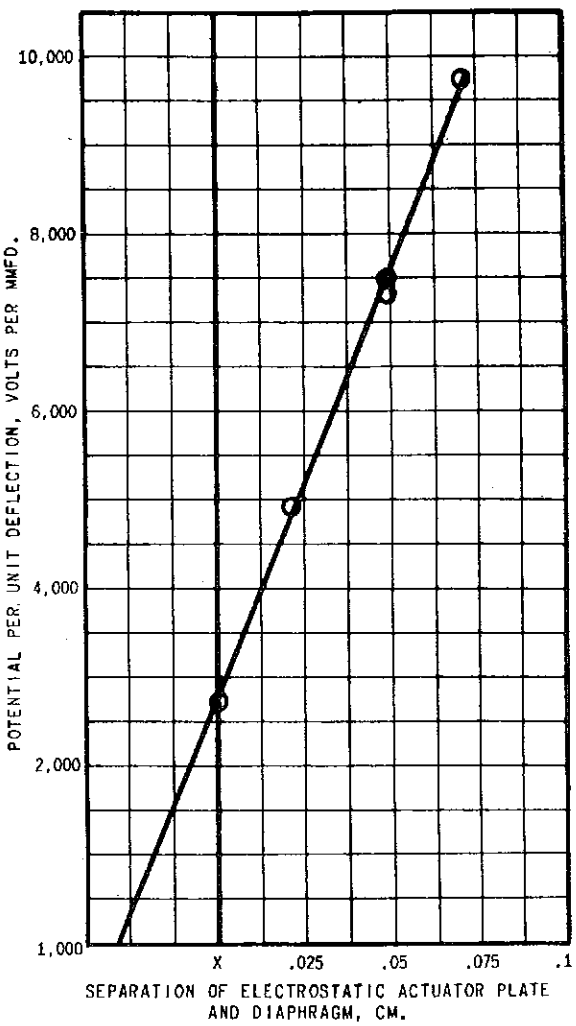

FIGURE 12.—Voltage-separation graph and electrostatic actuator.

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The effective distance for separation between the electrostatic actuator plate and the diaphragm of the air-blast meter was found by increasing the separation by known amounts (by means of spacing washers shown in fig. 7) and plotting the voltages required to give a certain deflection (measured in micro-microfarads capacitance change) against the distance of separation. From equation 5 we see that if F is constant, V_o is proportional to x, the distance of separation. Figure 12 is such a graph with all points taken at a frequency of 80 cycles per second. The graph in figure 12 has a slope of 96,500 practical volts per centimeter, or 322 electrostatic volts per centimeter. From equation 5 we have

$$F=\frac{1}{8\pi}\left(\frac{V_o}{x}\right)^2=\frac{1}{8\pi}(322)^2=4{,}100$$

dynes per square centimeter per micro-microfarad deflection.

The electrostatic actuator could only be used for sensitive settings of the air-blast meter, as high voltages would cause an electrical break-down across the air gap between the dielectric covering the plate of the electrostatic actuator and the diaphragm of the air meter. Although these break-downs passed negligible current (less than 10^{-4} amperes) and did not damage any equipment, they made it impossible to obtain pressures greater than 1,400 dynes per square centimeter. The maximum pressures obtainable decreased as the separation of the electrostatic actuator plate and the diaphragm increased. Since a deflection of 1 micro-microfarad change in capacitance could not always be obtained, graphs such as figure 12 had to be corrected for smaller deflections. From equation 5 it is evident that if a ¼-micro-microfarad deflection was produced by a potential of 2,500 volts, a deflection of 1 micro-microfarad would require 5,000 volts—that is, if the distance of separation is constant, the pressure is proportional to the square of the voltage.

PISTONPHONE

THEORY

From elementary thermodynamics we know that if a perfect gas is compressed isothermally, the relation between the volume, v, and the pressure, p, may be expressed by the equation

$$pv=C, \tag{6}$$

where C=a constant. If we change the volume by a small amount, Δv, the pressure changes a small amount Δp, so that

$$(v+\Delta v)(p+\Delta p)=C, \tag{7}$$

or

$$vp+p\Delta v+v\Delta p+\Delta v\Delta p=C, \tag{8}$$

subtracting equation 6,

$$p\Delta v+v\Delta p+\Delta v\Delta p=O, \tag{9}$$

neglecting $\Delta v\Delta p$ as an infinitesimal of the second order, this becomes

$$\frac{\Delta p}{p}=-\frac{\Delta v}{v}. \tag{10}$$

If the compression is adiabatic, the relation between the pressure and volume is expressed by

$$pv^\gamma=C, \tag{11}$$

where γ is the ratio of the specific heats at constant volume. Its value for air at normal temperature is 1.40. Again, changing the volume by a small amount, Δv, and neglecting infinitesimals of the second or higher order, we have

$$\frac{\Delta p}{p} = -\gamma \frac{\Delta v}{v} \tag{12}$$

by a similar development.

If a perfect gas is compressed rapidly in a metal container, it will not lose any appreciable amount of heat, and the compression will be adiabatic. If it is compressed slowly, the gas will remain at the temperature of the containing walls, and the compression will be isothermal. If a piston alternately expands and compresses the gas in a cylinder, it is evident that the pressure obtained will depend on the rate of compression and expansion as well as on the change in volume. Ballantine (*2*) has calculated this correction and shown how it depends on the frequency, area of the enclosing walls, and volume of the chamber. Figure 13 is a graph of this correction as applicable

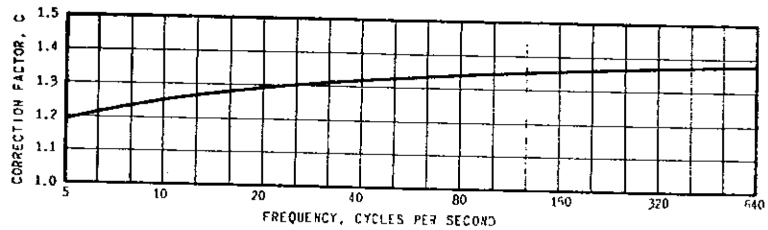

FIGURE 13. Correction curve for pistonphone. Ratio of change in pressure to change in volume for pistonphone plotted against frequency $\frac{\Delta p}{p} = -C\frac{\Delta v}{v}$.

to the Bureau of Mines pistonphone. From the graph it is evident that between 40 and 600 cycles per second a factor of 1.35 can be used without more than 2 percent error. However, at lower frequencies the correction factor changes rapidly with frequency, area of walls, and volume, and therefore the expected error will be larger than at the higher frequencies.

CONSTRUCTION

The pistonphone (fig. 14) consists of two closed cylindrical chambers 2.54 cm. (1 inch) long and 2.54 cm. (1 inch) in diameter separated by the piston, 0.0025 cm. (0.001 inch) less in diameter. The air meter (*G*), screwed tightly into place for calibration, formed one end of the front air chamber (*F*), and the piston (*E*) formed the other end. The piston was driven electromagnetically by an alternating-current driving coil (*B*) operating in the field of a permanent magnet (*A*) and connected to the piston by a light rod (*D*), which passed through the rear air chamber (*I*). A steel band (*C*) held the piston and driving coil to their zero settings. The tension of the steel band was adjustable so as to vary the natural frequency of the system. The moving parts (piston, connecting rod, driving coil, and steel band) formed a system analogous to a string loaded in the center and vibrated by a force acting at the center. To get as high natural frequencies as possible, great tension and a light load are necessary. The piston and driving rod were made of duraluminum for strength and lightness and the driving coil, taken from a 25-watt magnetic speaker, was also

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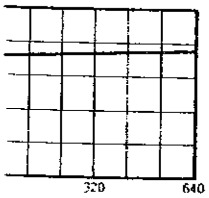

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very light. The steel band, which is 30 cm. (12 inches) long, 1.8 cm. (¾ inch) wide, and 0.025 cm. (0.01 inch) thick, is of high tensile strength for maximum tension.

A microscope with a filar micrometer eyepiece is mounted above a mark on the driving rod to measure the movement of the piston (see

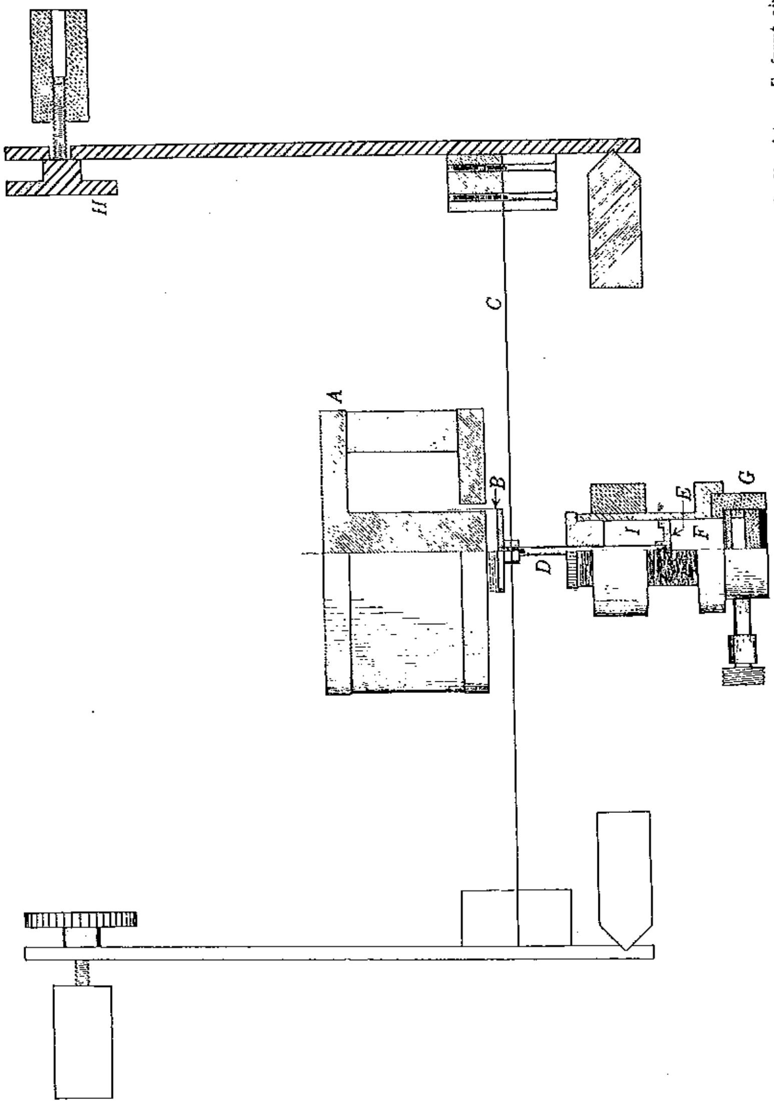

FIGURE 14.—Pistonphone assembly. *A*, Permanent magnet; *B*, driving coil; *C*, steel band; *D*, piston rod; *E*, piston; *F*, front air chamber; *G*, air-blast meter mounted for calibration; *H*, screws for adjusting tension on steel band; *I*, rear air chamber.

fig. 15). Accuracy of measurement depended mainly on maintenance of a steady state of vibration.

For obtaining higher pressures with the same movement of the piston, the front chamber can be shortened to 1.25 cm. (½ inch), at the same time increasing the rear chamber to 3.7 cm. (1½ inches). Maximum double amplitude of the piston that can be measured by the microscope is slightly over 1 mm. (0.04 inch).

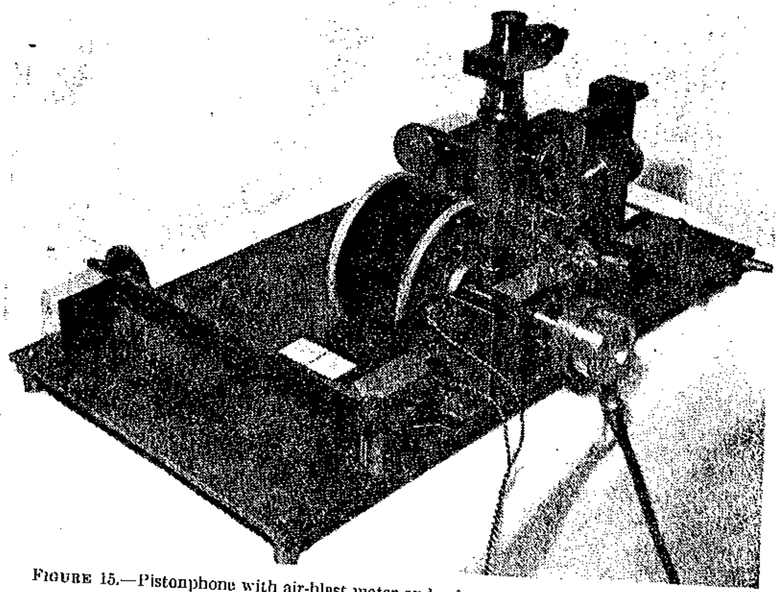

FIGURE 15.—Pistonphone with air-blast meter and microscope mounted for calibration.

TESTS

The pistonphone was used for calibrating the air-blast meters at all settings but was most satisfactory for high-pressure calibrations, being difficult to maintain in a steady state of vibration for low pressures (less than 5,000 dynes per square centimeter) at low frequencies. Maximum pressure differences of over 100,000 dynes per square centimeter were obtained at low frequencies, and their measurement was limited to this figure only by the field of vision of the microscope used. Maximum pressure differences at high frequencies were limited by heating of the 25-watt driving coil (100 percent overloads were not injurious for short periods of time); consequently, at 500 cycles per second the pressure was limited to approximately 6,000 dynes per square centimeter. Frequencies as low as 5 cycles per second were obtained and were limited by the voltage available from the alternating-current generator.

At frequencies below 40 cycles per second the correction becomes larger because of nonadiabatic compression and expansion. As it was difficult to eliminate friction and obtain sine waves at frequencies as low as 5 cycles per second, more friction was introduced and, by tightening the adjusting screws (part *H*, fig. 14) unevenly, virtually square wave shapes were obtained. This would increase the error to be expected from nonadiabatic compression. However, the pressure response, as calculated from Ballantine's formula, was virtually the same as at higher frequencies. Figure 16 shows the pressure response plotted against the frequency.

These tests with the pistonphone checked the electrostatic-actuator results within 10 percent for sensitivities from static pressures to frequencies of approximately 500 cycles per second for the sensitive settings where both methods could be used. The high-pressure settings of the air-blast meter were calibrated only by the pistonphone.

Although the deflection of the diaphragm is the same for a certain force at any frequency from zero to 500 cycles per second, the sensitivity of the air meter (as discussed under Air Meter Characteristics) will be influenced by any leakage between the air chamber and the atmosphere. Leakage around the diaphragm would show on the frequency sensitivity calibrations. Possibility of leakage through the cable connector is made negligible by sealing the connections with metal glue. The remaining possibility for leakage through the rear of the air-blast meter is tested by reversing it in the pistonphone and measuring the deflection from known pressures. Results vary with different units but have not exceeded 15 percent error at 5 cycles per second. For accurate measurement of lower frequencies the back could be sealed to eliminate this error.

The air meter was taken apart, reassembled, and recalibrated several times for all settings with both the pistonphone and the electrostatic actuator to determine whether such changes would appreciably affect the sensitivity. All calibrations could be duplicated within the 10-per-

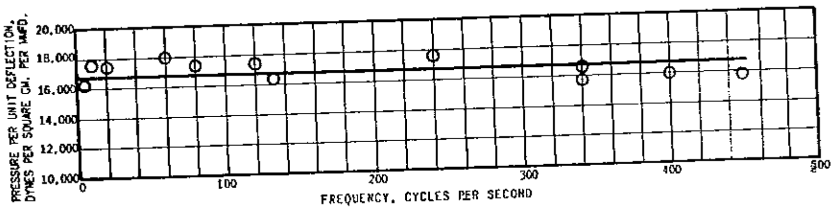

FIGURE 16.—Calibration of pistonphone.

cent limit of error. All parts were marked so that they could be reassembled in the same positions relative to each other, thus decreasing any change in sensitivity due to small mechanical defects of the parts.

RESULTS OF PRELIMINARY FIELD TESTS

The damage ascribed to the air blast of an explosion by most complainants is broken window glass. It was decided to find the approximate pressure at which window glass would break and at the same time test the operation of the air meter in the field.

Rather than risk damaging a building in these preliminary tests, it was decided to simulate conditions by mounting panes of glass in one side of a closed wooden box. The force exerted on the glass will depend on the area exposed and the difference in pressure on the two sides of the glass. The pressure on the outside will depend on the pressure in free space, reflection from the house, and possibly other factors as well. The pressure inside the house will not remain exactly at atmospheric because of leakage and slight bending of the walls. As the duration times of the pressure wave and the following vacuum wave are short, the change in pressure inside the house probably will be small compared to the change in pressure on the outside. As the walls are much denser than the air it is evident that their amplitude of motion and, consequently, the pressure change within the house will be small compared to the amplitude of motion of the air particles on the outside. For these reasons, it was thought that the pressure necessary to break the glass mounted in the box would approximately equal that necessary to break windows in a house.

The box (fig. 17) was built of 0.6-cm. (¼-inch) plywood and was of tight construction to minimize leaking. Various-size panels of glass

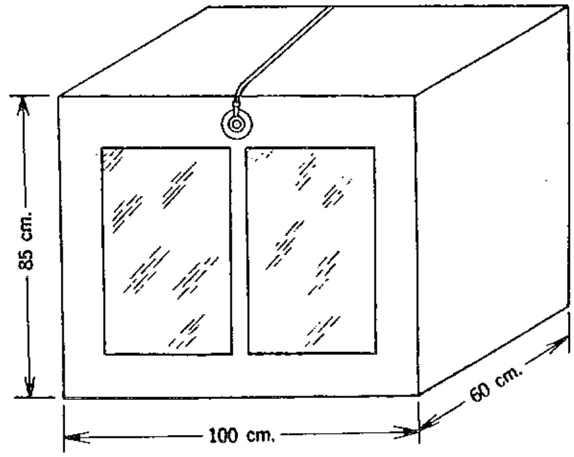

FIGURE 17.—Window box.

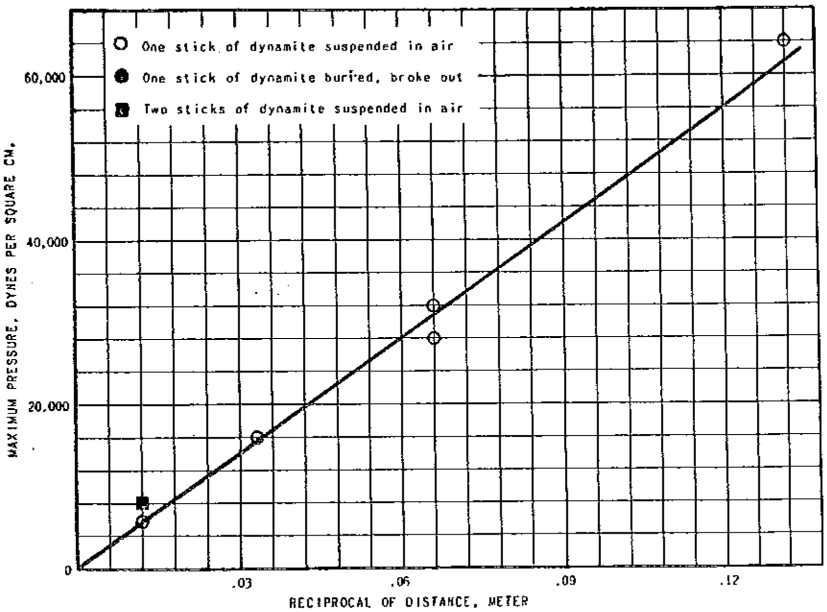

FIGURE 18.—Observed pressure-distance relationship.

could be mounted in the front and were fastened with glazier points (no putty being used) to expedite these tests. The air meter was in the center of the box above the glass. Dynamite hanging about 1.2 meters (4 feet) from the ground was exploded at measured distances in front of the sash. Under these conditions, one stick (3 cm. (1¼ inches) by 20 cm. (8 inches)) of 40-percent gelatin dynamite gave a

maximum pressure per square inch) a glazier points on a area of 60.5 cm. (2 were tightened ar shattered, glass f pressure on two s area of 37.5 cm. but did not dama ciably influenced by the glazier poi

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maximum pressure of 60,000 dynes per square centimeter (0.9 pound per square inch) at 7.5 meters (25 feet). This test first loosened the glazier points on a pane of double-strength glass having an unsupported area of 60.5 cm. (23 13/16 inches) by 77.5 cm. (30½ inches). When these were tightened and the test was repeated, the pane was completely shattered, glass falling both inside and outside the box. The same pressure on two smaller, single-strength panes having an unsupported area of 37.5 cm. (14¾ inches) by 60.5 cm. (23⅞ inches) shattered one but did not damage the other. It is thought that breakage is appreciably influenced by inhomogeneities in the glass and strains caused by the glazier points, but tests for these factors were not conducted.

Although one object of these tests was to determine whether the oscillograph elements and the air meter could accurately follow the steep wave front resulting from exploding dynamite in air, adverse conditions prevented accurate analysis of the wave front. However, the fact that the maximum pressures measured were approximately inversely proportional to the distance, as shown by figure 18, supports the accuracy of the measurements, since, neglecting damping, the intensity of the wave should vary inversely as the square of the distance and the intensity is proportional to the square of the pressure. It is proposed to use crystal elements in the oscillograph for further experimentation with the steep wave front found close to explosions.

A stick of dynamite exploded in the air gave about six times the pressure and a steeper wave front than a like amount which was buried about 1 foot underground at the same distance and broke out upon explosion.

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