

THE EFFECT OF SONIC VIBRATIONS
ON THE RATES OF MASS TRANSFER

by

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INTRODUCTION

Review of Literature

In recent years, there has been a growing interest on the part of chemical engineers in the potentialities of using sonic vibration as a tool to increase the rates or efficiencies on the various fields of unit operations. Bergmann (4) found out that the ultrasonic vibration might help the dispersion of solids in liquids. Wood and Loomis (23) recorded the phenomenon of emulsification in their pioneering paper on the effects of ultrasonics. The rates of crystallization and number of centers formed were found to be increased in an ultrasonic field by Berlaga (5) and Cassady (6). Sollner and Bondy (22) have shown experimentally that accumulation occurs at the nodes or antinodes of standing waves in an ultrasonic field. Hiedemann and Brandt (9) disclosed a method for separating suspended solid and liquid particles from melts and liquids by accumulating these particles in a system of standing waves. All of these showed that the sound wave might cause or increase the relative movements between the phases of solid and liquid or liquid and liquid.

By same reason, the same effects might be expected to be available between the phases of gas and liquid or gas and solid. As early as 1941, a patent was assigned to Mckittrick and Cornish (14) for applying the sonic wave in a fractionating column to increase the plate efficiency. They believed that "the sonic waves increased the fluid movement of at least one of the fluid

phases without a corresponding increase in fluid velocity." And in 1950, Richardson (17) found that it was possible to reduce pressure requirement for the catalytic formation of ammonia from nitrogen and hydrogen from about 1,000 atmospheres to about 10 atmospheres. He believed that the sonic vibration created an relative movement between the catalyst and the gas due to the difference of mass of the catalytic particles and that of gas particles.

All of these previous workers used the sonic waves whose frequencies were within the 'ultrasonic' range, i.e. beyond 16,000 cycle/sec. Although Mckittrick and Cornish (14) claimed that the sonic vibrations of frequencies between 50 cycles and 5 megacycles per second all might have influence on the efficiency of fractionation, they also said that "it is desirable to use ultrasonic waves." Due to the powerful energies the ultrawaves possess, it is no surprise that they might accelerate the motion of molecules therefore increasing the rates or efficiencies of dispersion, emulsification or mass transfer between the phases. But as Auerbach (2) pointed out, the low-frequency range was of economic importance. The audible sounds obviously are easier to produce than ultrasonic waves which can only be created under laboratory-scale by rather complicated equipments until now.

In the technique of using sonic waves to increase the efficiency of fractionating distillation, the importance of selecting suitable intensity and frequency, especially the latter, was recognized by Mckittrick and Cornish (14). They said the efficiency was increased most when the natural period of the

vibration of the zone of contact is such that it is in a state of resonance with respect to the frequency of the sonic waves causing the vibration. But they did not indicate the order of magnitude of the intensities which they used nor did they indicate how critical the resonance effect might have been in obtaining the result. Other factors might also have an effect on sound.

As an ordinary liquid surface is put under the sonic pulsation, its physical shape will be changed due to the vibration caused by sound waves. Mckittrick (14) pointed out this kind of phenomena occurred in his experiment of distillations with glass fractionation columns: "it might be seen that there was rather violent agitation of the liquid phase, with fine drops thrown into the vapor phase." Under this kind of condition, at least a part of increase of fractionating efficiency was due to the increase of conducting area between the liquid and vapor phase. Therefore, before a quantitative study of effect of sonic vibration on the rate of mass transfer is possible, one challenging problem which needs to be solved is that of maintaining a constant area of conducting between phases as they are under the sonic pulsations.

Objectives of Study

To meet the problems mentioned above, the purposes of this investigation were:

1. Preparing a liquid surface whose physical shape would not be altered by the action of the audibly sonic waves.
2. Studying the effect of audibly sonic waves on the rates of mass transfer between liquid phase and gaseous phase.

3. Finding out the factors which might influence the sonic effects.

MATERIAL AND METHODS

While many kinds of systems of mass transfer between liquid and gaseous phase might be selected for study in this investigation, a simplest system, pure water and dry air was chosen. Liquid water was vaporized into air stream, and the effect of sonic pulsation on the rate of vaporization was studied.

To avoid the complication of analyzing all heat and mass transfer action, the rate of vaporization at given conditions without the application of sonic pulsations was compared with the rate under the same conditions but with the application of sound. The difference between these two was assumed due to the effect of sonic pulsation.

The water was vaporized from a thin water layer created on the top of a frittered glass plate¹, one end of which was connected with a water source. Through capillary action, the water would be continuously sucked up to the top of the glass plate to compensate that which had been vaporized off and so maintained the liquid layer at a constant thickness. Since no accumulation occurred in this system, the input should be equal to the output. Therefore, the rate of vaporization could be measured by timing the rate of supplying make-up water to the liquid layer.

¹See "EQUIPMENT AND APPARATUS", Plate III.

The rate of water applied to the liquid layer was measured by the following method: the supply water was contained in a measuring tube laid on a wooden plate.¹ The rate of water being sucked to the frittered glass plate was observed through the movement of the meniscus inside the tube. The time required for the meniscus passing over one mark to another mark as t ; the volume of space between the mark was v ; (for the calibration of v , see Appendix) then v/t was the rate of vaporization. (For details, see Preparation of a Thin Liquid Surface: Experimental Procedures.)

Under such arrangement, the whole experimental process was simplified to just compare the rate of movement of the meniscus inside the measuring tube under the application of sound with that of without sound.

HYPOTHESES

Two Film Theory

Although the real mechanics of mass transfer at the boundary between phases became a debatable ground recently (Bakowski, 3), the traditional two-film theory still was accepted by this paper as a fundamental base to derive the hypotheses for explaining why and how the rates of mass transfer might be influenced by the sonic vibration.

The two-film theory was proposed by Lewis and Whitman (13) in 1924, in which they assumed that there existed at the interface

¹See EQUIPMENT AND APPARATUS: Plate VI and IV.

two thin layers of liquid and gas which remained stagnant no matter how turbulent the flow in the bulk of the gaseous and liquid phase were. These very thin stagnant layers of liquid and gas were the so-called films. Within the films, the mass transfer process could only be carried out by the molecular diffusion, which was a much slower process than distributing through turbulent current which happened in the bulk flow. Therefore, in the process of mass transfer between phases, these films supposedly constituted the major portion of the resistance to encounter the driving force.

Gas Film Control

It was not necessary that these two films, gas film and liquid film, play same important roles in the process of mass transfer. For example, if the liquid phase contained only one component and the components composing the gaseous phase were indissoluble the partial pressure in the main interface, P_i , would be equal to the partial pressure in the main body of liquid phase, P_1 . This meant the resistance of liquid film was negligible. The mass transfer of this kind of system was called under gas film control. The rate of mass transfer of a system of gas film control was determined by the rate of diffusion through the gas film.

The Rate of Gaseous Diffusion

The rate of gaseous diffusion of a two component system might be calculated by the following equation:
$$\frac{N_1}{A} = \frac{D_g P}{RT'x} \frac{(P_1)_i - (P_1)_g}{(P_b)_{lm}} \quad (1)$$

Where N_1 = rate of diffusion of component 1, mole/hr.

A = area of vaporization surface, ft².

D_g = diffusivity, ft²/hr.

P = total pressure, atm.

R = gas-law constant = 0.728 (ft³) (atm)/lb mole °R

$(P_1)_i$ = vapor pressure of component 1 at interface, atm

$(P_1)_g$ = partial pressure of component 1 at gaseous phase, atm.

$(P_2)_{lm}$ = log mean value of partial pressure of component 2 in the gaseous film, atm.

T' = mean temperature in the gaseous film, °R.

x = thickness of stagnant gaseous film, ft.

Thickness of the Gas Film

From the equation (1), it was known that N_1 , rate of diffusion was inversely proportional to the x , thickness of gaseous film. The x was generally believed to be only a function of the properties of gas molecules, and the mass velocity of gas flow, G . The relation between x and G might be expressed as follows:

$$\frac{1}{x} = k(G)^n \quad (2)$$

Hollings and Silver (10), later Gilliland and Sherwood and other workers (7) all believed that n was a constant, but the value they proposed varied from 0.56 to 0.83. Bakowski (3) pointed out that n was a function of G itself. n decreased with the decrease of G and has a higher value as G increased.

By equation (1), the thickness of gaseous film at different gas velocities might be calculated provided that the N_1 , P , and T_1 , temperature at interface were known. The value calculated by Gilliland and Sherwood (7) by the data obtained from a circular absorption, Run No. Sa9c, under the velocity of air of 0.406 lb/ft²sec, While the total pressure was 770 mm Hg. temperature of air was 36°C, The thickness of the stagnant film was 0.128 cm.

An Ideal System

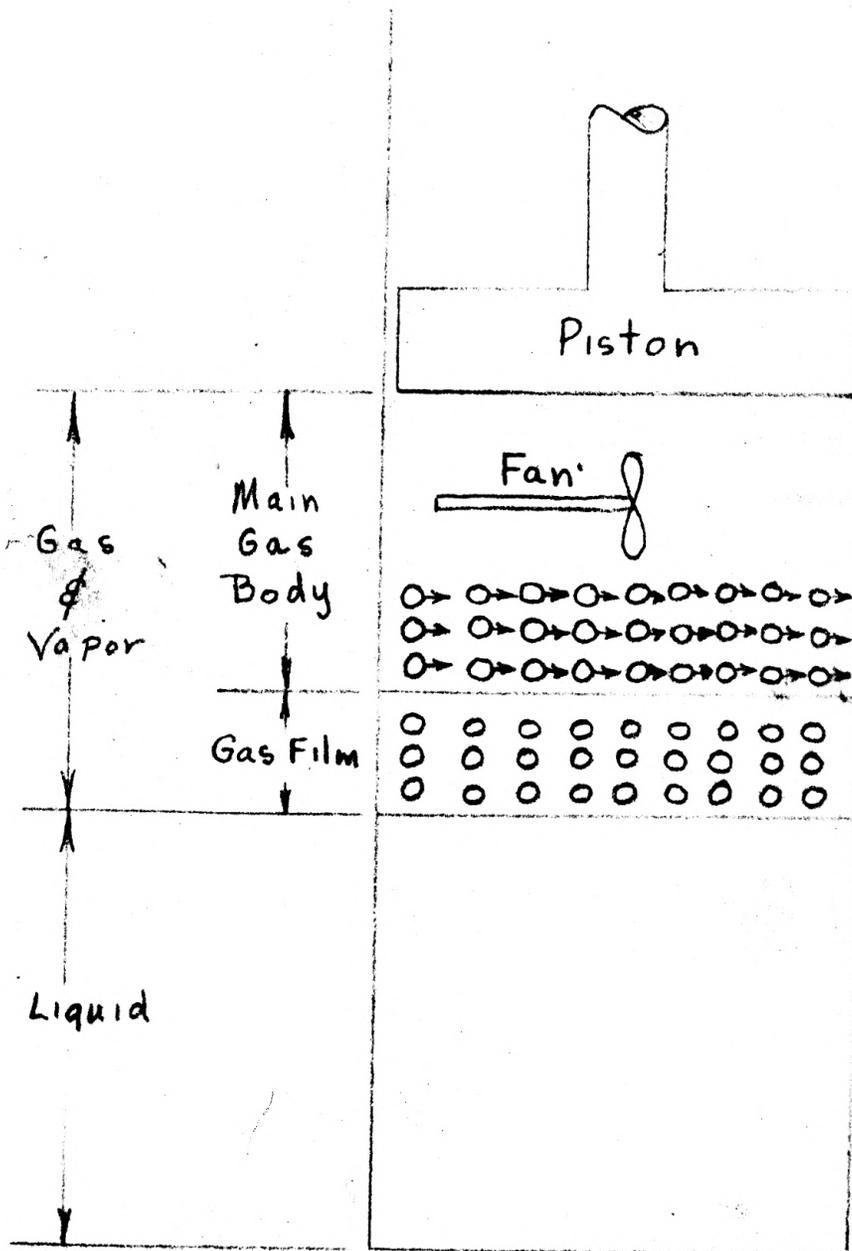
For the convenience of description, an ideal system was assumed as shown on Plate I. The system was composed of an insoluble gas and a pure liquid, contained in a rigid cylinder with a closed bottom and a movable piston as top. The temperature and pressure in the cylinder were so selected that in this system only two phases, liquid and gas, existed. The temperature was kept constant, and pressure was changeable due to the movement of the piston. A fan in the cylinder maintained a uniform ratio of vapor to gas throughout the main body of the gaseous phase. It was assumed that the action of the fan did not create any turbulent motion or unequalized pressure in the main body, so the velocity of the gas passing the liquid surface was constant and kept a uniform horizontal direction.

In this ideal system, if the vibration and rotation of individual molecules were neglected, it would be fair to assume that the molecules in the main gas body all moved along a same direction

EXPLANATION OF PLATE I

An ideal system of pulsation

PLATE I



parallel to the interface, and the molecules in the stagnant gas-film were kept steady.

Effect of a Sudden Pulsation

If the piston was suddenly moved toward the liquid surface, for an instant, the concentration of molecules per unit volume would be greater at the face of the piston than at another point in the gaseous phase. The increase in concentration, or it might also be expressed as the increase of pressure, would transfer from molecule to molecule through the collision between molecules until the pressure was again uniform throughout the whole gaseous phase of the system.

The mechanism of the transmission of the pressure after a pulsation might be assumed as follows: as a pulsation created by a sudden forward movement of the piston traveled through the main body of the gas, the first layer of molecules which received this pulsation would gain a velocity with a direction toward the liquid phase. These molecules started to move downward until they collided against the molecules underneath them. The velocity was thus transferred to the molecules of second layer and made them start moving downward. The same steps were repeated until the front of the pressure pulse reached the stagnant film.

As the last layer of molecules in main gas body started to move down, they would strike the first layer of molecules in the stagnant film. These stagnant molecules which were assumed being kept steady without any motion before the pulsation then gained velocity, not only in vertical direction but also in horizontal direction

which was originally possessed by all molecules in the main gas body. The molecules which gained the new velocity started to move along a direction neither horizontal nor vertical but following the direction by which they were hit. Then they hit other molecules to make them start moving. This kind of chain action formed a turbulent situation in the zone of stagnant layer and reduced its resistance against the mass transfer. (Plate II, Fig. 2)

In deriving the above hypothesis it was assumed that all molecules involved had the same molecular weight. A more complicated situation would occur if the molecules of gas and vapor had different molecular weights. This difference in the mass would make these different kinds of molecules move at different velocities even though they were impacted by the same amount of pressure, that meant there would be a relative motion between vapor and gas molecules. This kind of relative motion increased the tendency of turbulence in the stagnant zone. The same effect would be realized if the vibration and rotation of individual molecules were concerned.

EQUIPMENT AND APPARATUS

The frittered glass plate (Plate III), whose top space served as a vaporization surface, was placed in a wooden tunnel connected to an air steel-pipe line (Plates IV, V and VI). Distilled water was supplied to the frittered plate through capillary tubes and a measuring tube. (Plate VII) Plate VIII shows the dimensions of the wooden tunnel. All of the capillary tubes were connected as shown in the bottom of Plate V. The

EXPLANATION OF PLATE II

Fig. 1. Two film theory

AB = interface between liquid and gaseous phase

$(P_1)_l$ = vapor pressure of component 1 in main liquid phase

$(P_1)_i$ = partial pressure of component 1 at interface

$(P_1)_g$ = vapor pressure of component 1 at main gaseous phase

Fig. 2. The movement of water molecules in the main gas body and stagnant film after a sudden pulsation.

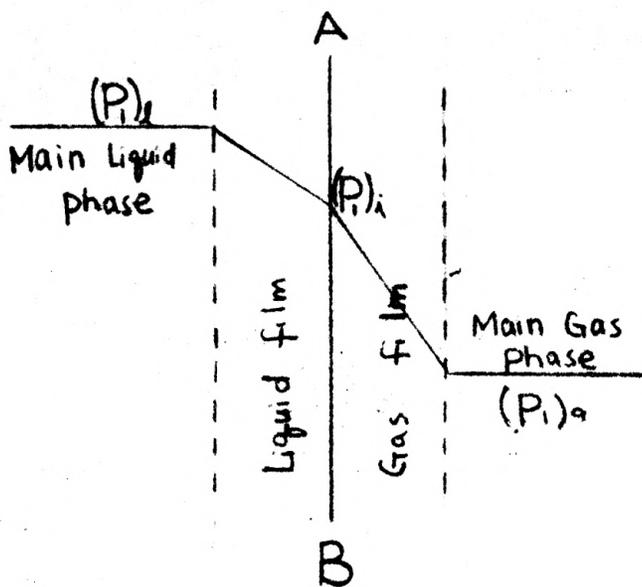


Fig. 1

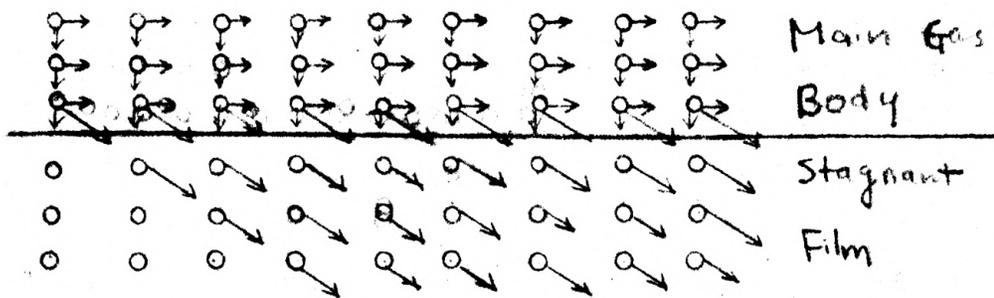
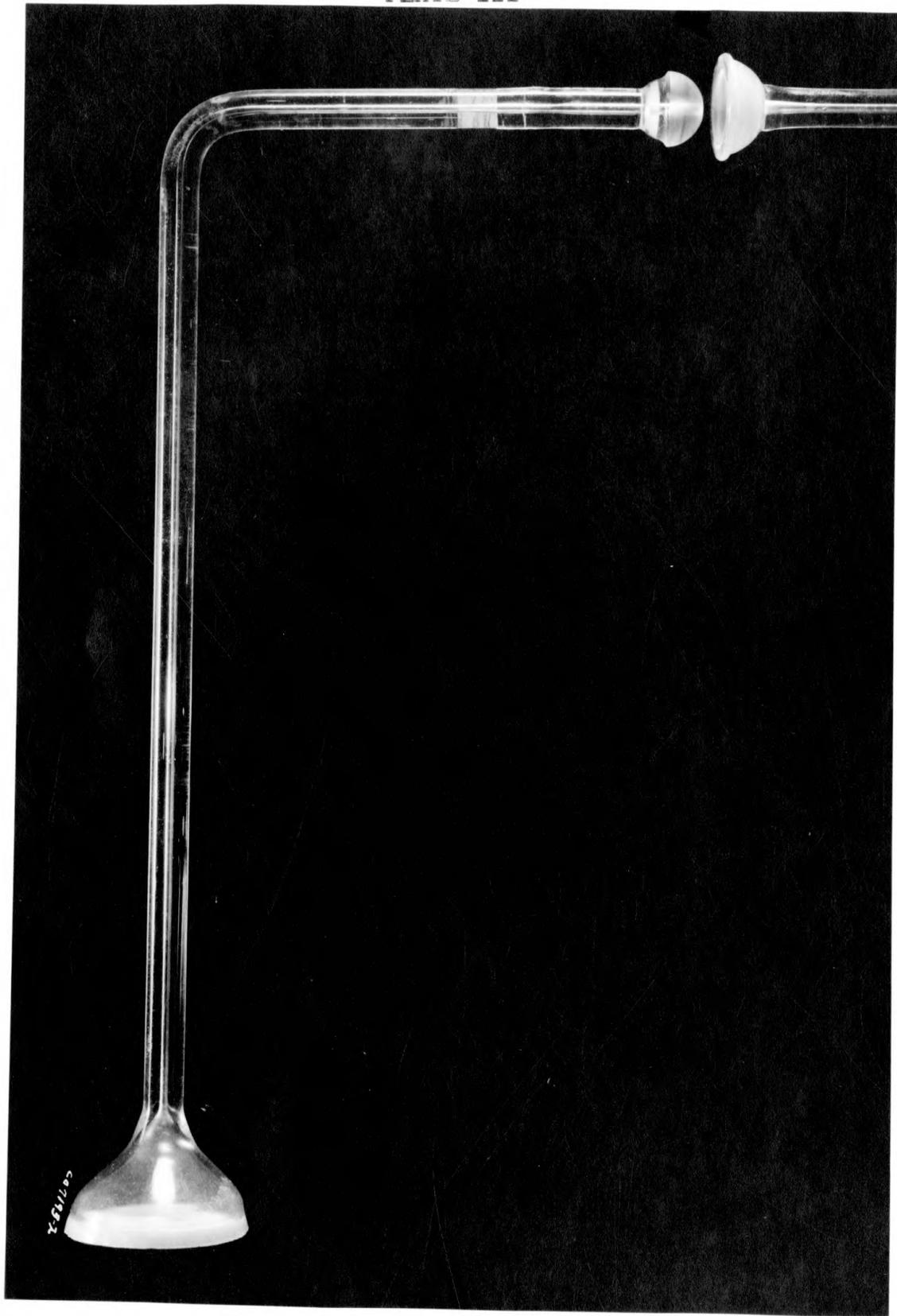


Fig. 2

EXPLANATION OF PLATE III

Frittered glass plate (true size)

PLATE III

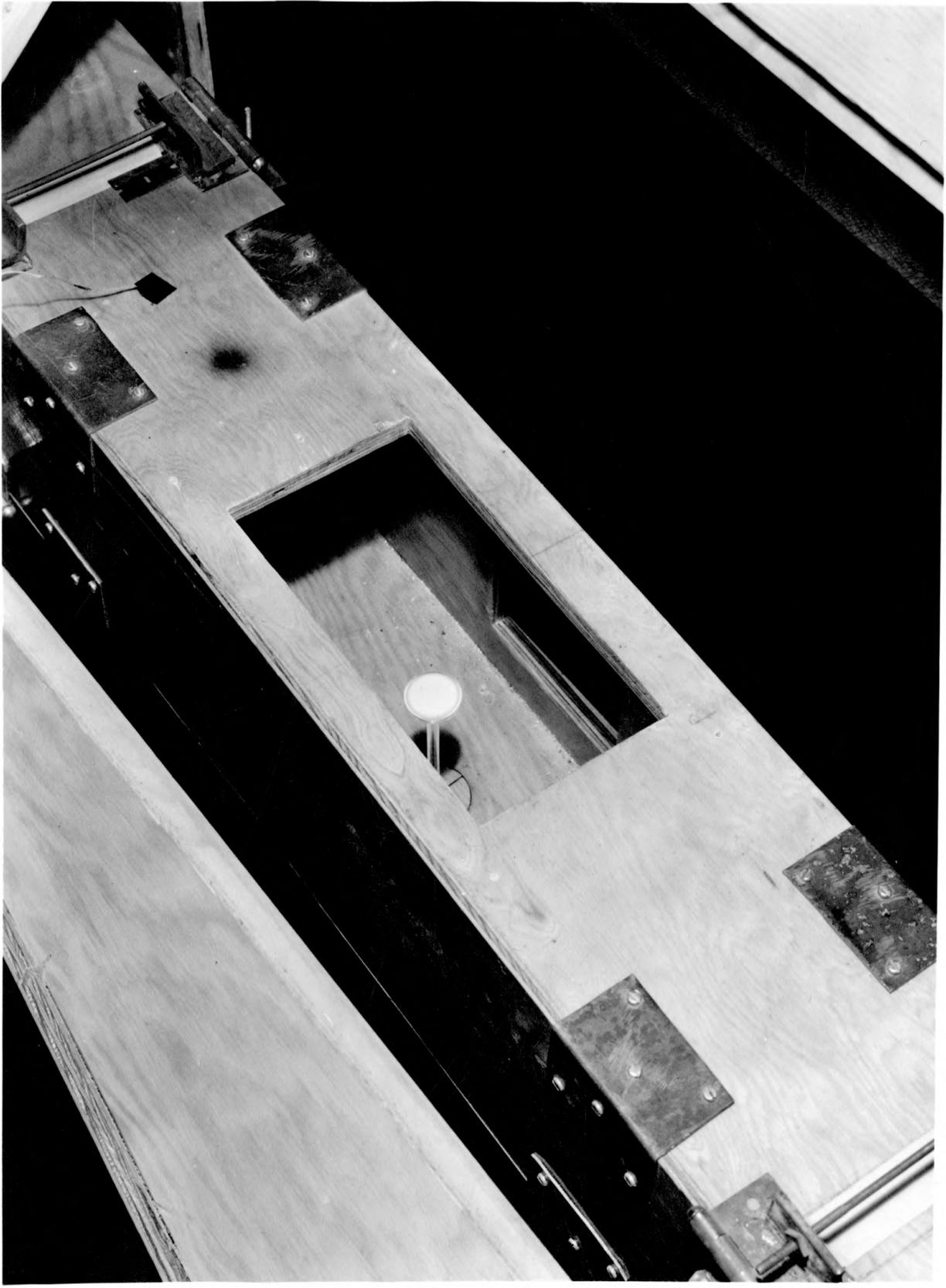


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EXPLANATION OF PLATE IV

A top view of the frittered glass plate
in the wooden tunnel.

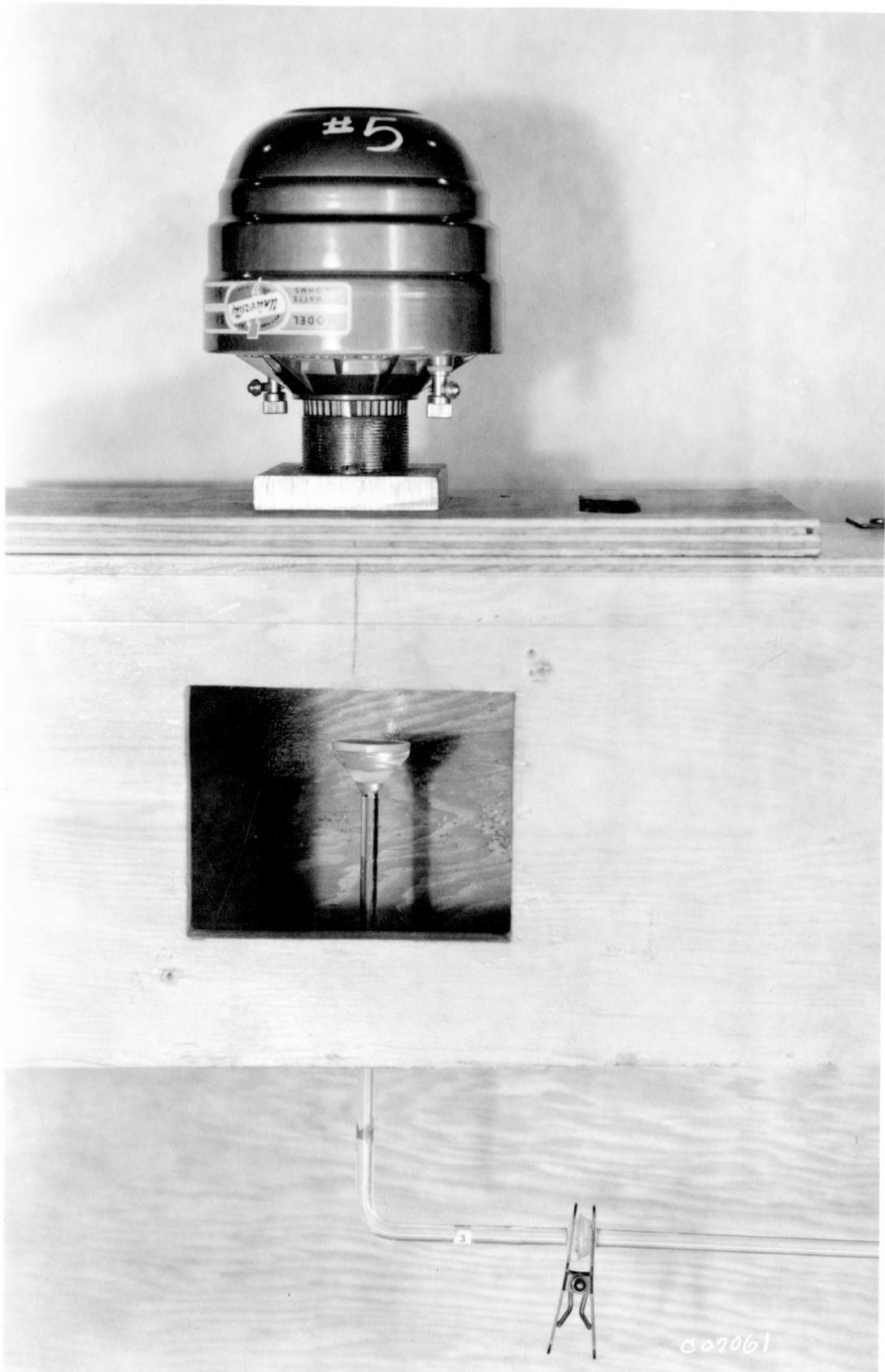
PLATE IV



EXPLANATION OF PLATE V

A front view of the frittered glass
plate in the wooden tunnel. Above it is
a Universal Model SA-HF sound driver.

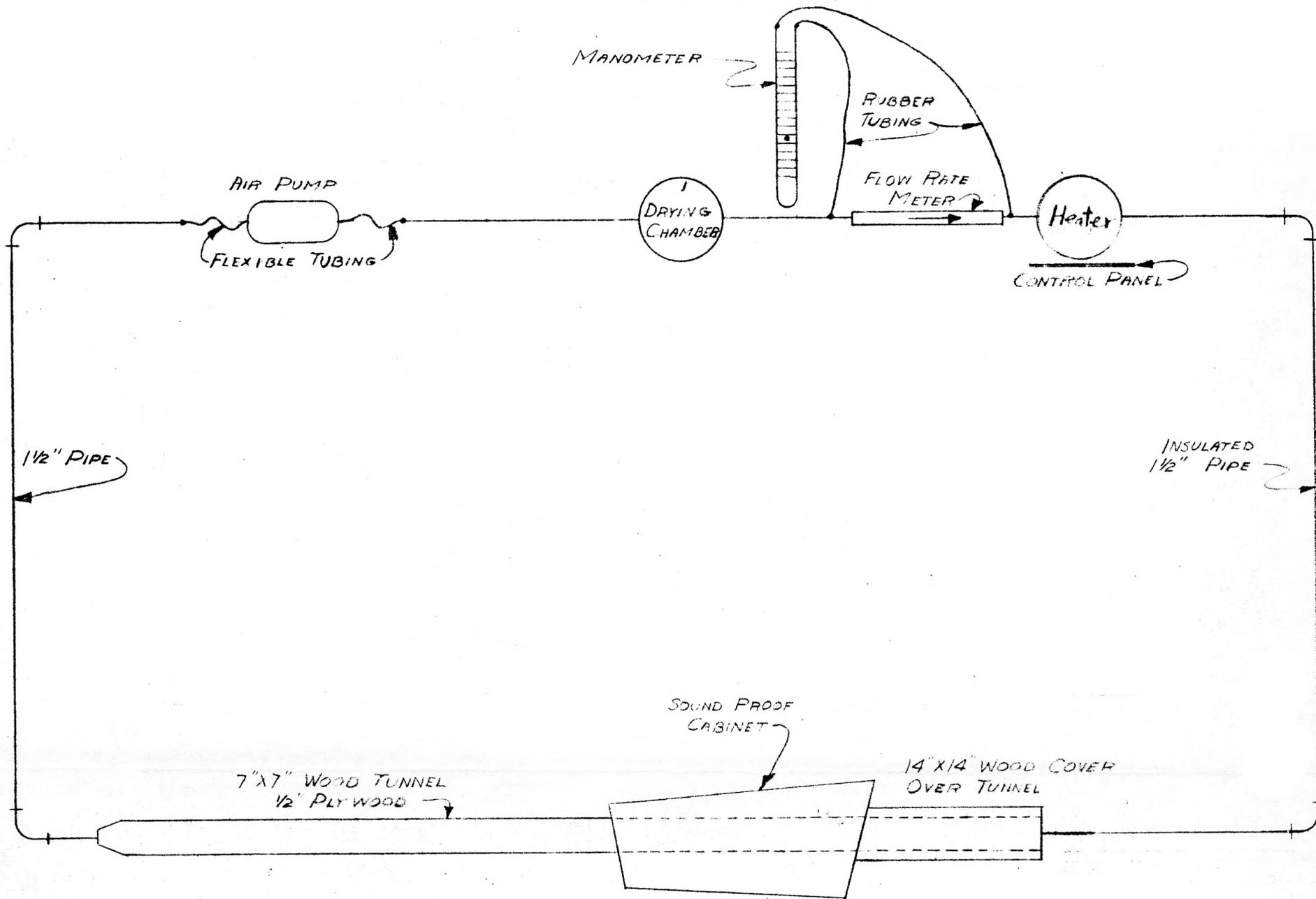
PLATE V



EXPLANATION OF PLATE VI

Schematic layout of equipment

PLATE VI



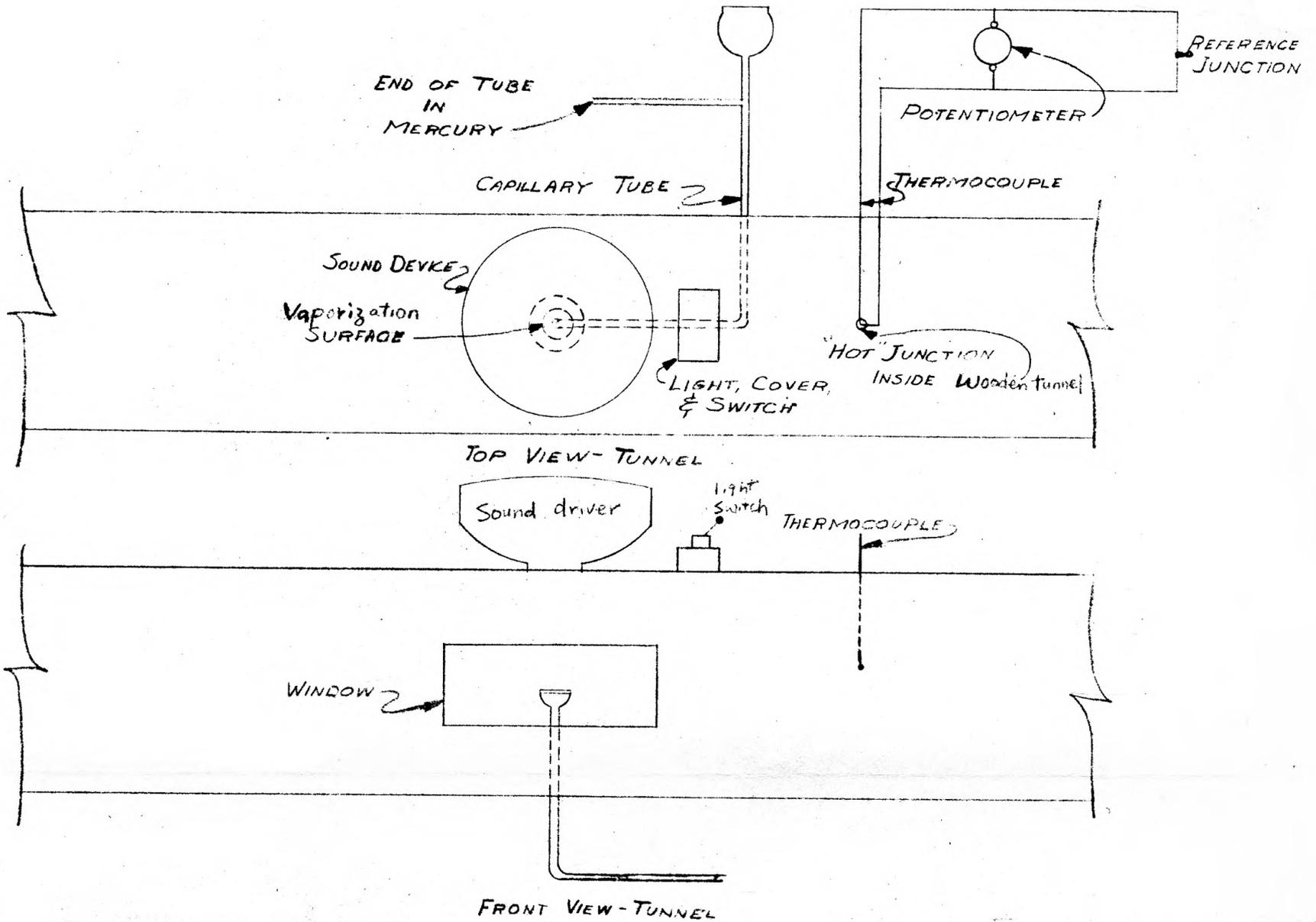
EXPLANATION OF PLATE VII

Wooden tunnel and its inside

Upper: top view

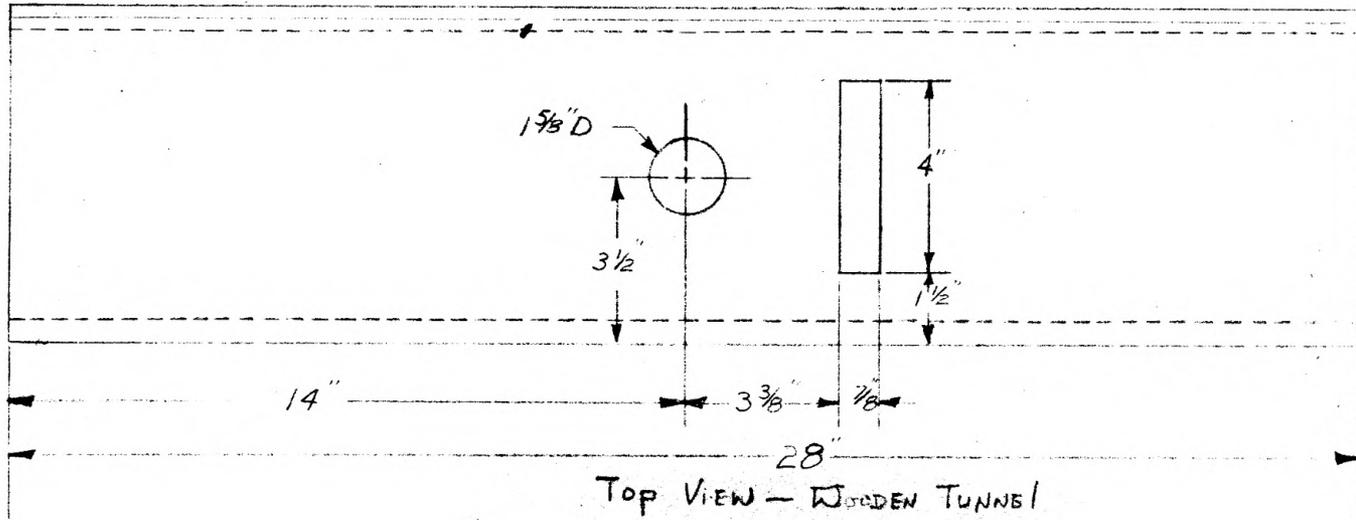
Lower: front view

PLATE VII

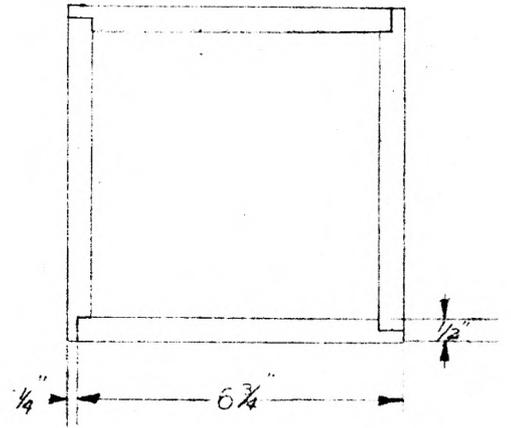


EXPLANATION OF PLATE VIII

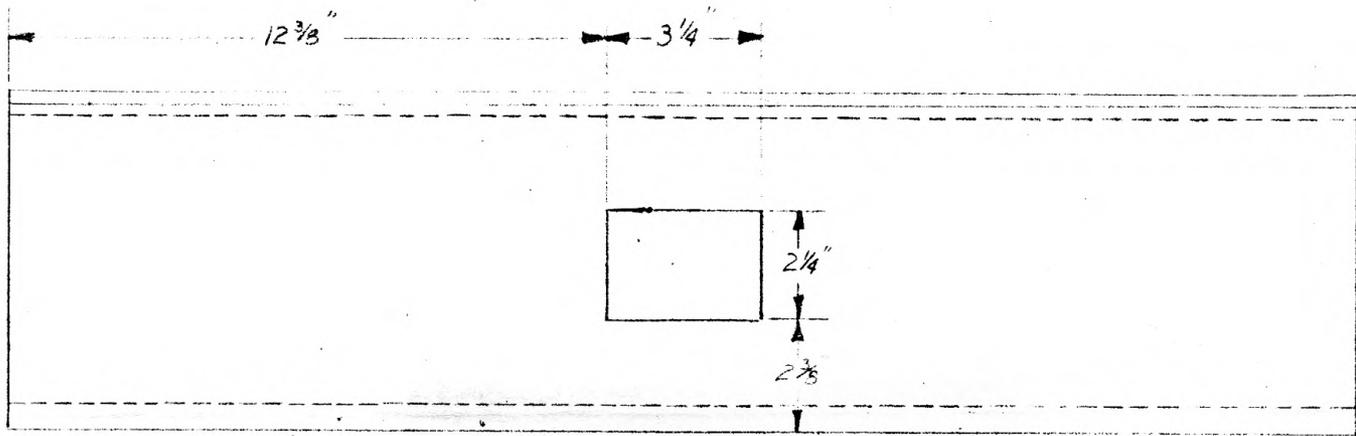
Dimensions of wooden tunnel



Top View - WOODEN TUNNEL



Side View - WOODEN TUNNEL



FRONT VIEW - WOODEN TUNNEL

measuring tube was attached to a hinged wooden plate (Plate IX). The height of water column supported by the frittered glass plate, h , might be adjusted by simply changing the inclined angle of the plate¹. The value of h was measured with a transit and a meter stick, (Plate IX).

Dry air: humidity and temperature were controlled by a dryer-heater combination (Plate X; for detailed construction of heater see Appendix Plate XXXI) and was circulated through the wooden tunnel by an air pump (Plate XII). The velocity of air was controlled by adjusting the input voltage to the air pump through a variable transformer as shown on E of Plate X, and measured by a flow meter as shown on A of Plate X. The inlet part of the air line from heater to the wooden tunnel was insulated by zonolite. A thermostat and a pair of relays mounted on the heater (Plate XI and Appendix Plate XXXI) kept the air temperature constant at a desired level. The temperature of air was measured by an iron-constant thermocouple and a Leeds and Northrup Precision Potentiometer (Plates VII and IX).

The vaporization rate was measured by timing the rate of movement of the meniscus in the measuring tube.

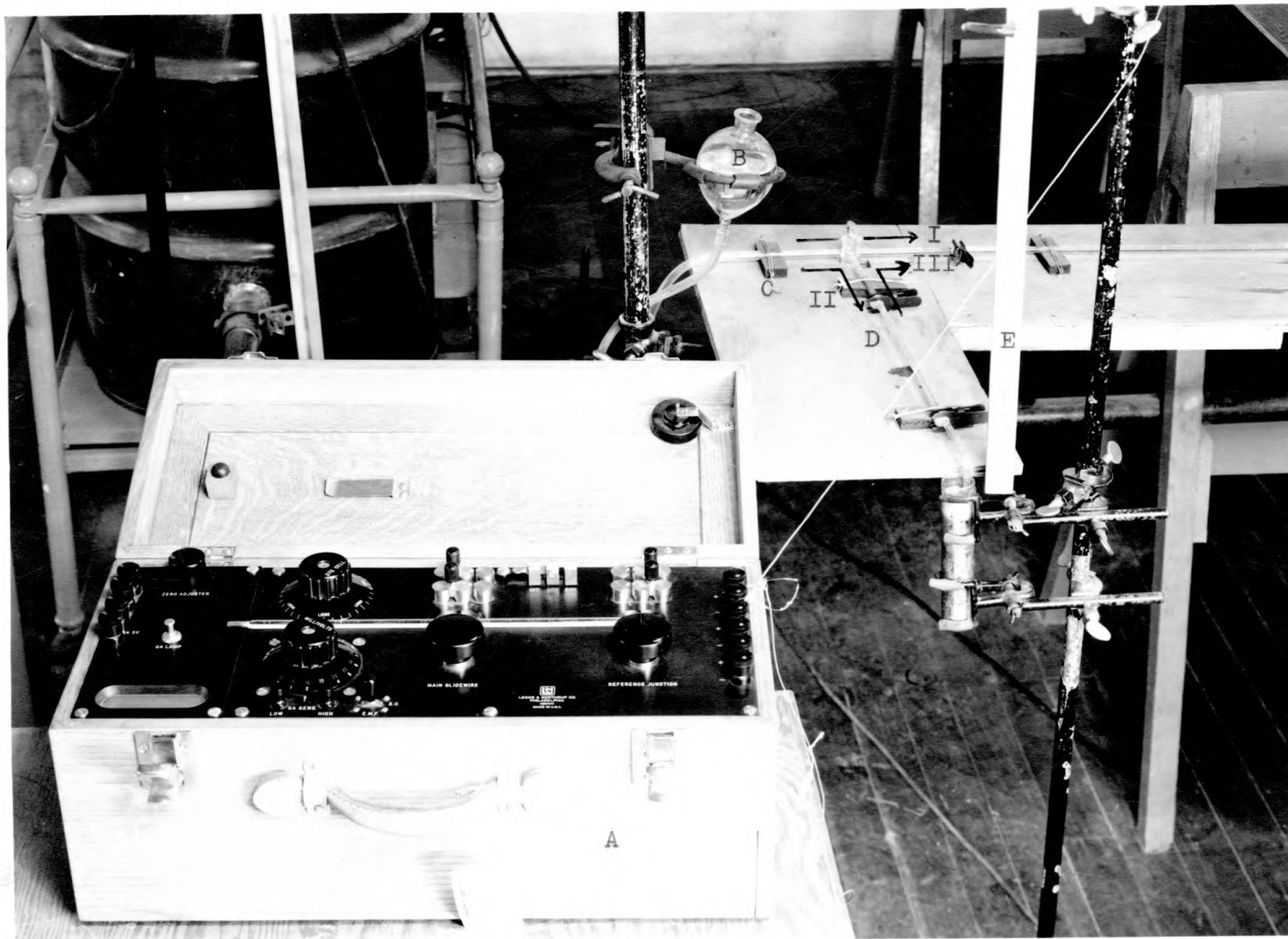
The sounds were generated by an A-C current sound generating system which contained a Heathkit audio generator, a Bell model 2200C High Fidelity amplifier and a Universal Model SA-H_F driver which was mounted on the top of the wooden tunnel as shown in Plate V. Another D-C sound generating system which contained a

¹For meaning of h , see PREPARATION OF A THIN LIQUID SURFACE, Plate XVI, Fig. 1

EXPLANATION OF PLATE IX

- A. Leeds and Northrup Potentiometer
- B. distilled water flask
- C. wooden plate
- D. measuring tube
- E. metric stick
- F. mercury container

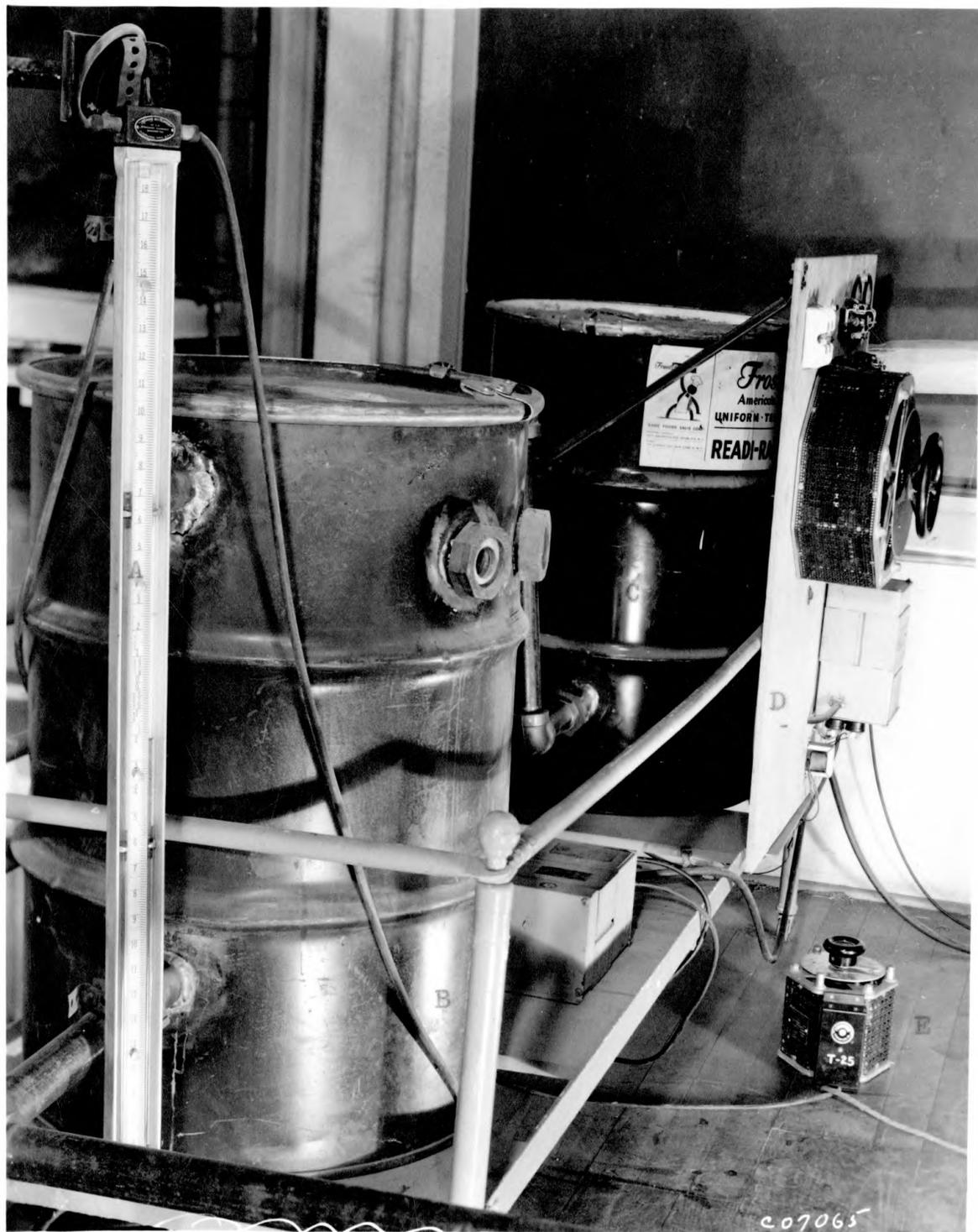
PLATE IX



EXPLANATION OF PLATE X

- A. flow meter
- B. dryer
- C. heater
- D. control board of heater
- E. variable transformer for
adjusting the "input voltage"
to the air pump.

PLATE X

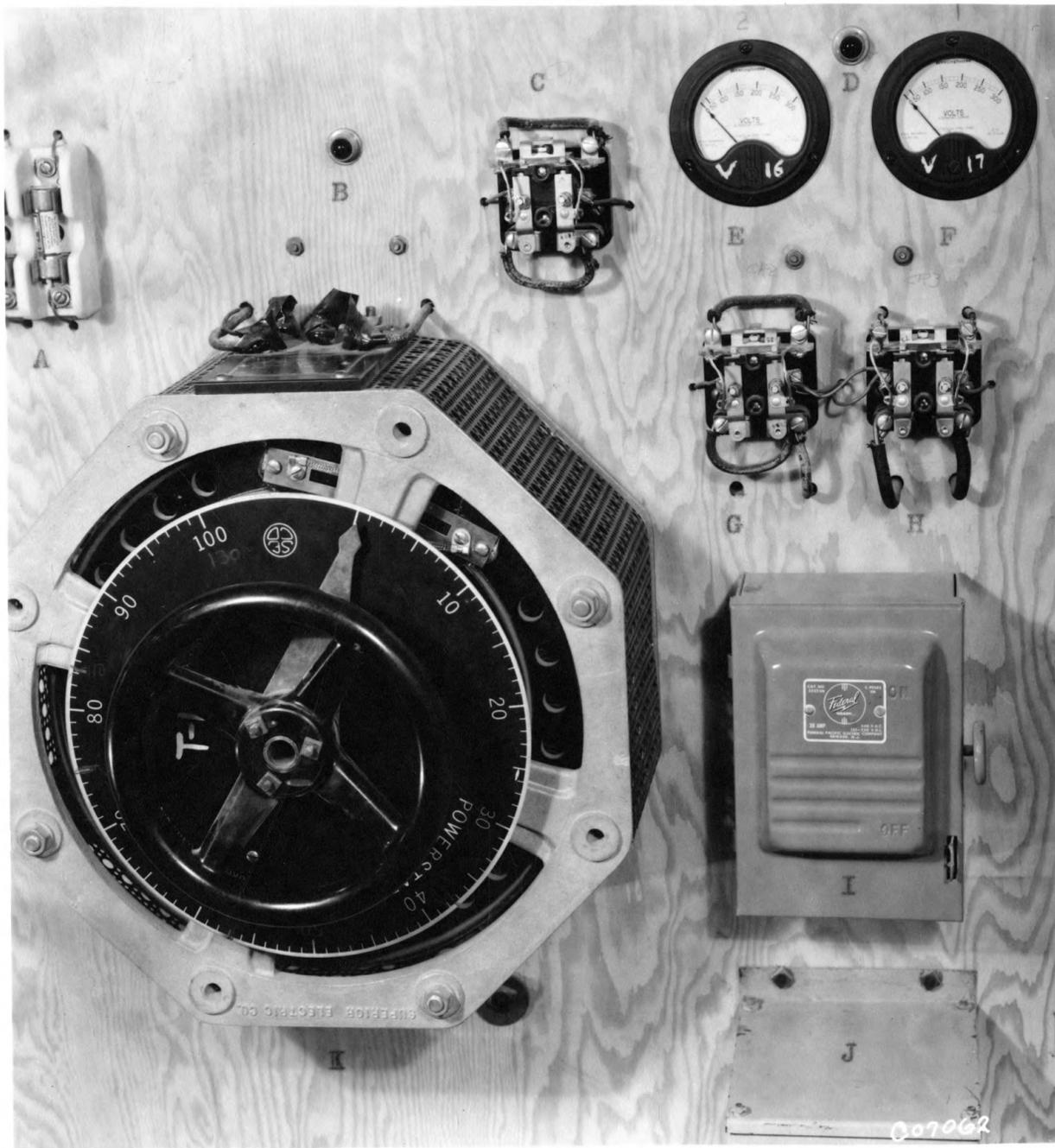


EXPLANATION OF PLATE XI

Control panel of heater

- A. 2 - 3.2 ampere fuse
- B. indicating light (lighting as 110 v heaters on)
- C. condenser - CRI
- D. indicating light (lighting as 220 v heaters on)
- E. and F. voltage meters
- G. and H. condenser, CR2 and CR3
- I. 3 pole 30 ampere safety switch
- J. auto transformer, 240/120 v, 2 KVA
60 cycle/sec. 16.6 second ampere
- K. variable transformer, 0-270 v out,
7.5 KVA out, 28 ampere max. output.

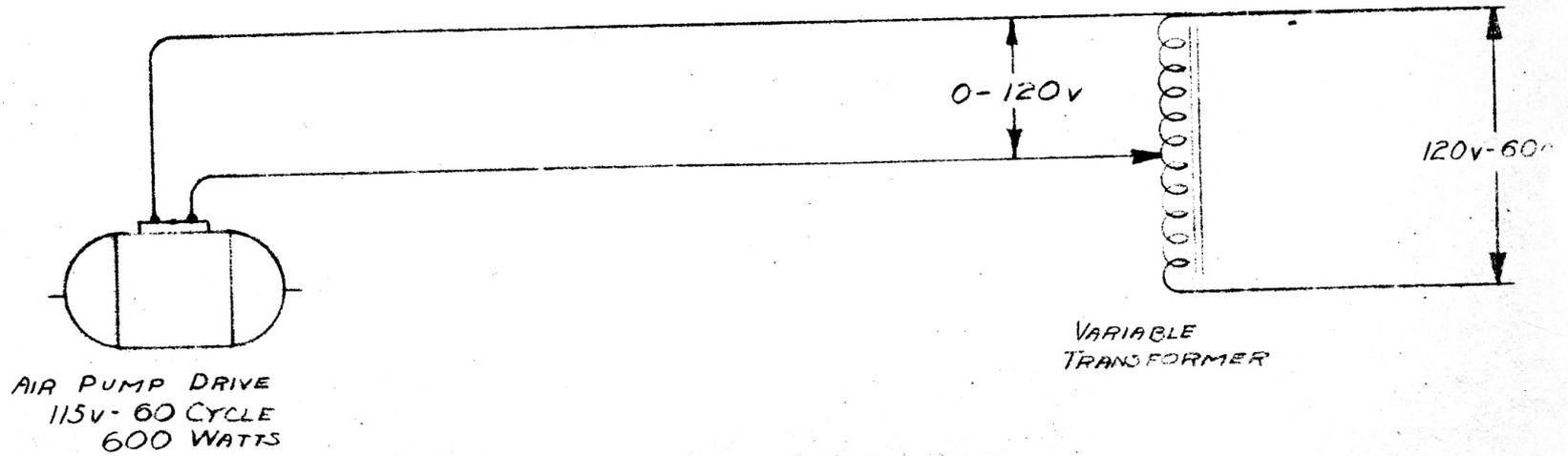
PLATE XI



EXPLANATION OF PLATE XII

Air Pump

PLATE XII



Superior Electric Co. Type H3 horn or Benjamin Electric Co. Type H-8 horn, (Plate XIII) was occasionally used in the preliminary runs.

The input voltage to the driver, V , was measured by a Weston Model 769 electronic volt milliammeter; such readings would be converted to I , the intensity of the sound applied on the vaporization surface, through an I vs. V calibration curve. (For details of calibration, see Appendix).

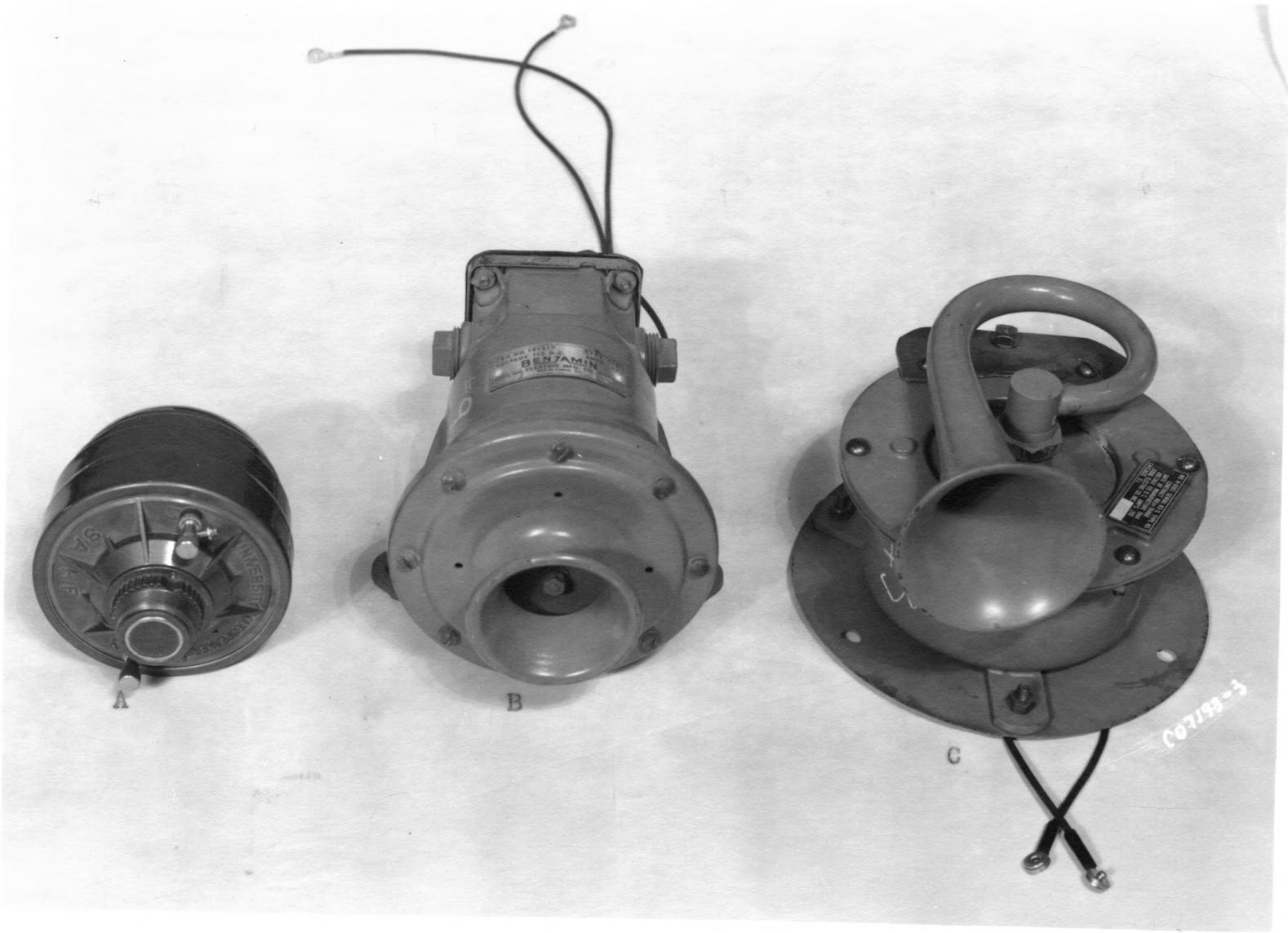
For calibrating the I vs. V , the intensity of sound was measured directly by a General Radio Co. Type 1551-A sound level calibrator. A Model 76B lapel crystal microphone, whose geometrical shape and dimensions were similar to those of the frittered glass plate, was often used instead of the Altec Type 21-BR-150 condenser-microphone which was a standard microphone for the Type 1552-B sound level meter. The advantage of using lapel microphone was that it might be set into the wooden tunnel in the exact same place the frittered glass plate had been, without the need of disconnecting the water supply line. The db readings obtained by the lapel microphone were calibrated against that obtained by the Altec Type microphone.

The frequency dial of the audio generator was calibrated by a Heathkit Laboratory Oscilloscope; the oscillations created by a General Radio Type 1037-A transistor oscillator and the line frequency were used as standards (for details of calibration, see Appendix).

EXPLANATION OF PLATE XIII

- A. Universal Model SA-HF driver.
- B. Benjamin Electric Co. Type
H-8 horn.
- C. Federal Electric Co. Type
H-3 horn.

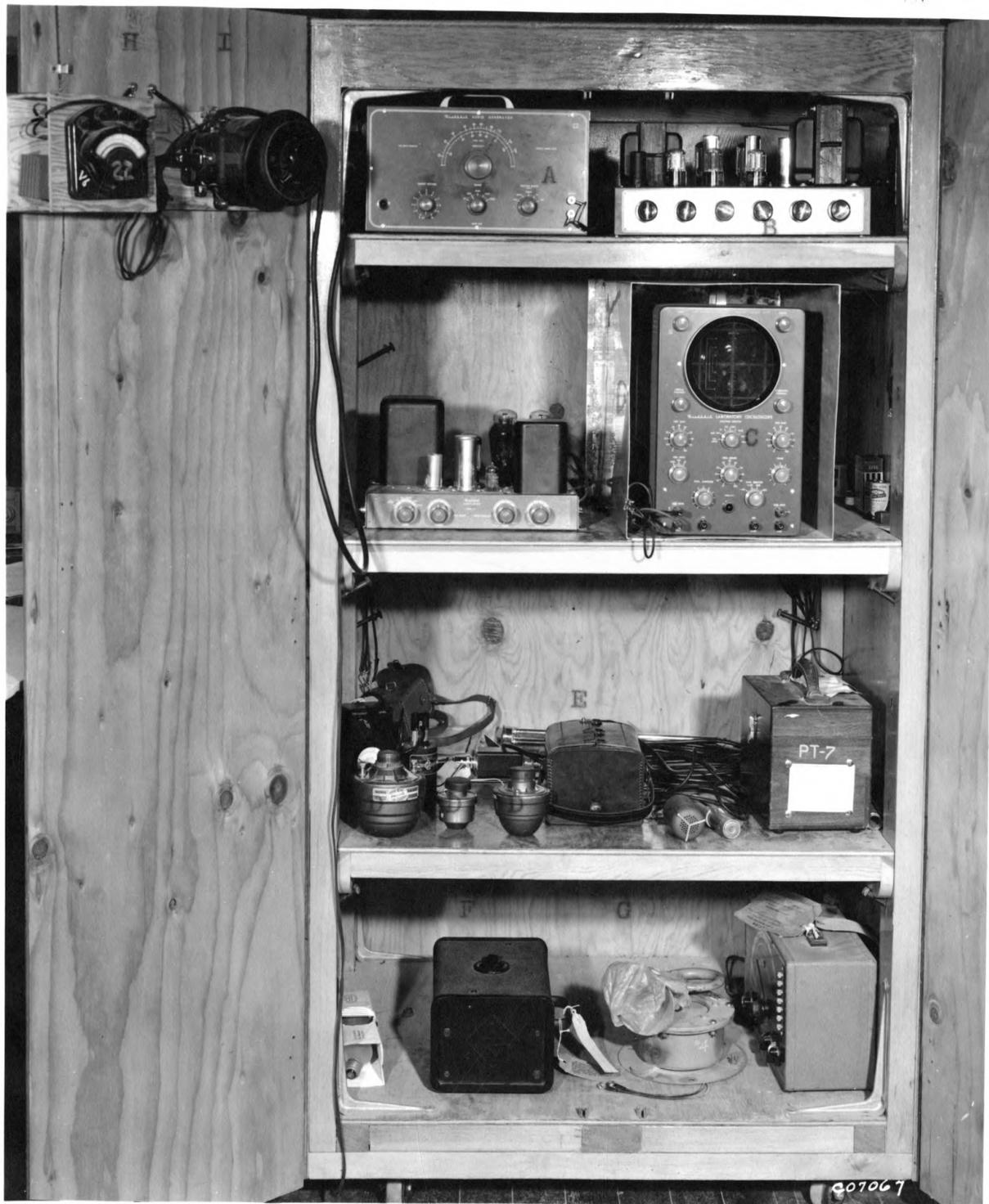
PLATE XIII



EXPLANATION OF PLATE XIV

- A. Heathkit audio generator
- B. Bell H-F amplifier
- C. Heathkit Laboratory oscilloscope
- D. H-F sound drivers
- E. Voltage meter
- F. Type 1552B Sound level meter
- G. Type H-3 horn
- H. D-C voltage meter
- I. Powerstat

PLATE XIV

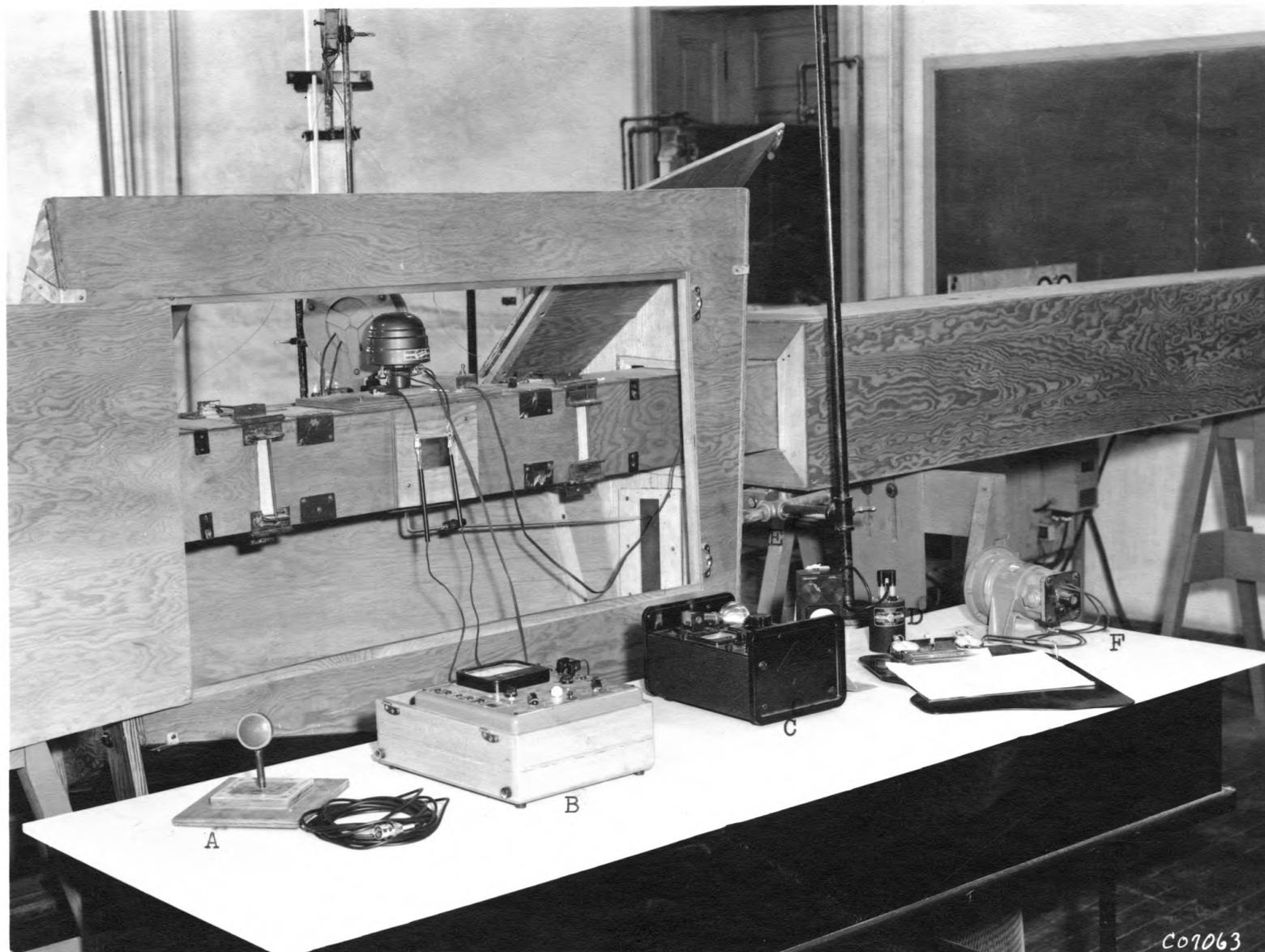


EXPLANATION OF PLATE XV

Side view of wooden tunnel as sounds were applied.

- A. Model 76B lapel microphone
- B. Weston Model 769 electronic analyzer
- C. General Radio Co. Type 1551-A sound level meter
- D. General Radio Co. Type 1552-B sound level calibrator
- E. Type 1307-A Transistor (behind the calibrator)
- F. Benjamin Electric Co. Type H-8 horn

PLATE XV



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PREPARATION OF A THIN LIQUID SURFACE

Theory

As has been mentioned in the Introduction, before a quantitative study of the effect of sonic vibration on the mass transfer as applied to the stagnant layer is possible, one challenging problem which must be solved is how to prepare a liquid surface which will not be altered in its physical shape by the action of sonic pulsations. To prepare such a surface, a method has been proposed by Hall (8). He assumed that the disturbance in physical shape of a liquid surface created by the moderately intense sonic pulsations would have the nature of simple harmonic motion, and the maximum amplitude of the wave motion would not be greater than twice that of the depth of the liquid layer. For a very thin liquid layer, the amplitudes of the wave motions were assumed to be so small that it might not cause any sensible area change. And the surface tension of such a thin layer would also tend to minimize the disturbing effect of wave motion.

In order to increase the reproductivity of the measurement of the evaporation rate, it is necessary that the physical shape of evaporation surface be kept as constant as possible. Consequently, the liquid layer to be used is desired to be as thin as possible. But the following calculation shows that due to the compensated effect of the surface tension, a sound wave with the intensity of 130 db will not cause more than one per cent area change upon a water layer with a depth of less than 1×10^{-3} cm.

To increase the area of a liquid surface with one per cent of the original area, the energy consumed to overcome the surface tension is:

$$W_1 = 0.01A \delta \quad (3)$$

Where W_1 = energy consumed, erg.

A = original area of liquid surface, cm^2 .

δ = specific surface tension of liquid,
dyne/ cm^2 .

For a pressure pulsation, with a displacement amplitude of 1×10^{-3} cm., the work done is:

$$W_2 = AP_s \times 1 \times 10^{-3} \quad (4)$$

Where P_s is the intensity of the pressure needed for this pulsation, dyne/ cm^2 .

The displacement of the liquid layer is so small that the gravity gradient may be neglected. Because no other energy is involved, by energy balance:

$$W_1 = W_2 \quad (5)$$

$$\text{Therefore } 0.01 A \delta = AP_s \times 1 \times 10^{-3} \quad (6)$$

$$\text{And } P_s = 10 \delta \text{ dyne/cm}^2 \quad (7)$$

For water at room temperature (25°C)

$$\delta = 71.97 \text{ dyne/cm} \quad (8)$$

$$\text{Therefore, } P_s = 720 \text{ dyne/cm}^2 \quad (9)$$

The pressure amplitude of sound wave with the intensity of 130 db may be calculated by the following equation:

$$130 = 20 \log_{10}(P_s)(2 \times 10^{-4}) \quad (10)$$

$$\text{Therefore, } P_s = 780 \text{ dyne/cm}^2 \quad (11)$$

This value is in reasonable agreement with that of equation (9), thus demonstrating that a sound wave with the intensity of 130 db will not cause more than one per cent area change on a thin water layer whose depth is less than 1×10^3 cm.

Creation of a Thin Liquid Layer. Liquid will rise within a certain limit in a capillary tube which the liquid will wet. Thus, if it were possible to place a large number of capillary holes side by side and to connect the tops of the sides of the holes to each other with a wettable surface, it would be possible to place the lower end of the holes in a free liquid layer, and liquid would then rise in the capillaries and would pass on through to wet the surface between the tops of the capillaries, and a thin liquid layer will be formed. The equipment designed by Hall (8) is a frittered glass plate containing many tiny holes serving as capillaries which raise the liquid to the top of the plate and form a liquid layer there. The depth of the liquid layer on the top of the plate may be estimated in this manner: From Fig. 1 of Plate XVI it appeared evident that the maximum thickness of the liquid layer on the top of the plate will not be greater than the radii of the capillary tubes. That is:

$$d_{\max} = r \quad (12)$$

Where

d_{\max} = the maximum depth of the liquid layer

r = the average radius of the porous holes of the frittered glass plate.

According to the equations developed by Adams (1), the radius of a capillary tube may be calculated from the value to the maximum

EXPLANATION OF PLATE XVI

Fig. 1. Formation of a thin liquid layer on a solid surface which contains a large number of capillary pores.

d_1 and d_2 = the thickness of liquid layer formed on the various positions of solid surface.

d_{max} = the maximum thickness of liquid layer might be created on the top of the plate while its capillary pores support a liquid column of the height of h .

h = the distance between the solid surface and free liquid surface = the height of water columns supported by the capillary pores through capillary action.

r = radius of capillary pore

Fig. 2. The liquid surface inside a capillary tube

r = radius of capillary tube

θ = stable contact angle.

PLATE XVI

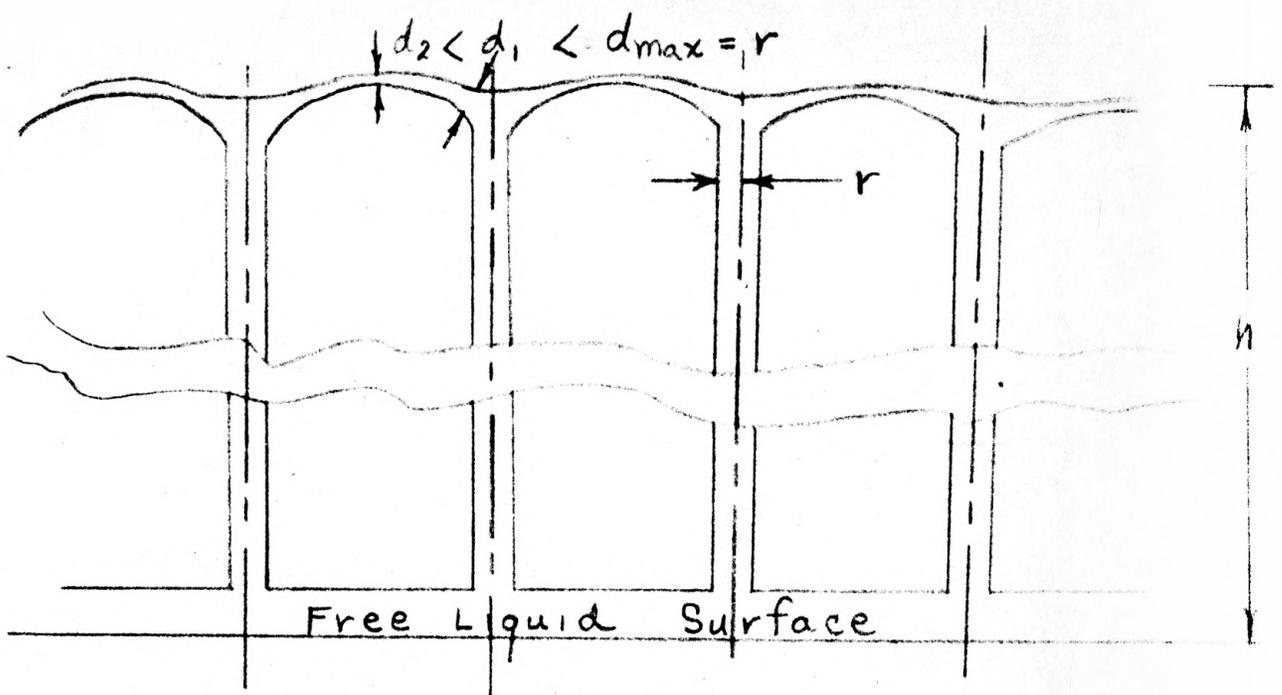


Fig. 1

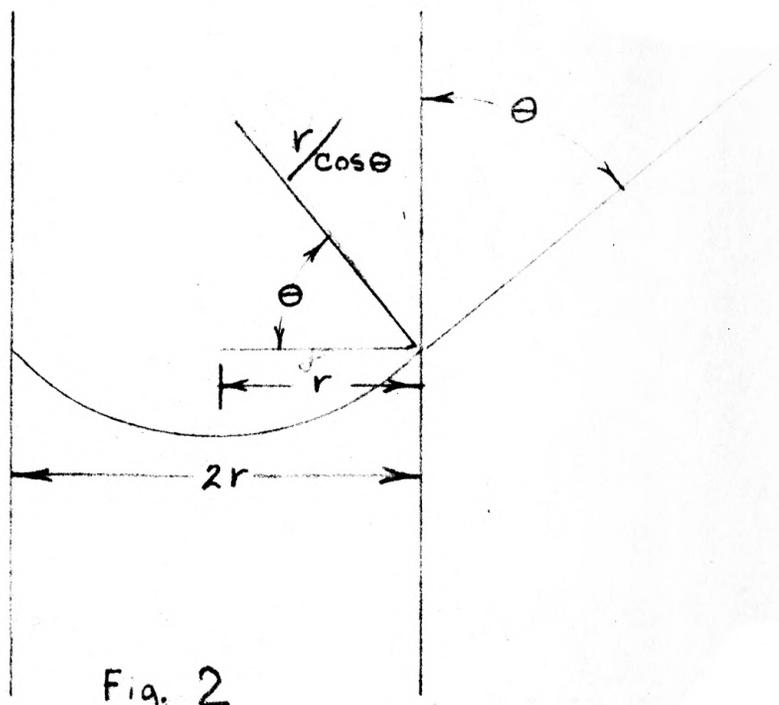


Fig. 2

height of the liquid column to which the tube can raise. As shown on Fig. 2, Plate XVI, let r be the radius of a cylindrical tube, so small that the liquid meniscus does not depart appreciably from the spherical form, while θ is the contact angle between the liquid and glass. Then the radius of curvature of the meniscus is $r/\cos\theta$, and the pressure under the meniscus becomes less than that at the same height, in a liquid with a plane surface, by $(\gamma \cos\theta)/r$. This produces a driving pressure, tending to force the liquid up the tube, and the meniscus will rise to a height h , such that the weight of the column of liquid elevated above the plane surface outside the tube just balances the pressure deficiency under the curved meniscus. If $D_1 - D_2$ is the difference between the densities of the liquid rising in the tube and the surrounding fluid, h must be given by

$$2\gamma \cos \theta r = gh(D_1 - D_2)$$

$$r = \frac{2\gamma \cos \theta}{gh(D_1 - D_2)} \quad (13)$$

For water rising in a glass tube under acceleration of gravity, with air above, at 25°C

$$\cos \theta = 1.0$$

$$D_1 = \text{Density of water} = 1.0 \text{ g/cm}^3$$

$$D_2 = \text{Density of Air} \doteq 0$$

$$g = 980 \text{ cm/sec}^2$$

$$\gamma = 71.97 \text{ dyne/cm}$$

Above values are substituted into equation (13), then,

$$r = 0.1463 (1/h) \quad (14)$$

Since $r = d_{\max}^2 d$

$$\text{Therefore, } d = 0.1463 (1/h) \quad (15)$$

This relationship is graphically expressed in Plate XVII, Fig. 1.

With reference to Fig. 1 of Plate XVI, it may be noted that $d_2 < d_1$. If the porous surface is very rough, if the pores are small in relation to the distance between pores, and if h is of adequate value then $d_2 < d_1$; d_2 may approach zero. When $d_2 = 0$, portions of the evaporation surface will be dry. A reduction in the rate of drying would result because of the reduction in area available for evaporation. This relationship is graphically expressed in Plate XVII, Fig. 2.

Point B in Plate XVII, Fig. 2 represents the h_{\max} . Beyond this point, the water on the free liquid layer can no longer be drawn to the top of the porous plate. The vaporization process may still continue within the pores, but the water is not drawn from below to replace that which has evaporated.

If the porous surface is smooth enough and if the pores are side by side, a complete thin liquid layer will be maintained on the top of the plate regardless of the increase of h until the h_{\max} is reached. Then, as it reaches the point of h_{\max} , the thin liquid layer will suddenly disappear due to the fact that the liquid cannot be supplied from the free liquid surface. The relation between \bar{R} and h can be expressed as shown on Plate XVII, Fig. 3.

The actual distribution of liquid on the top of the porous plate may be detected by plotting an \bar{R} vs h curve from experimental data; if the shape of the curve is the same as that of Plate XVI, Fig. 3, it follows that the liquid layer covers the

EXPLANATION OF PLATE XVII

Fig. 1. Relation between d_{\max} and h .

Fig. 2. The relation between the vaporization rate and the height of water column if the vaporization surface is partially dried due to the increase of h .

R. The rate of liquid being risen from free liquid surface to the top of porous plate. As the whole system is full of water and no air bubble exists, the value is equal to the rate of vaporization from the porous plate.

Fig. 3. The relation between the vaporization rate and the height of water column if a complete thin liquid is maintained on the top of the plate regardless of the increase of h until the h_{\max} is reached.

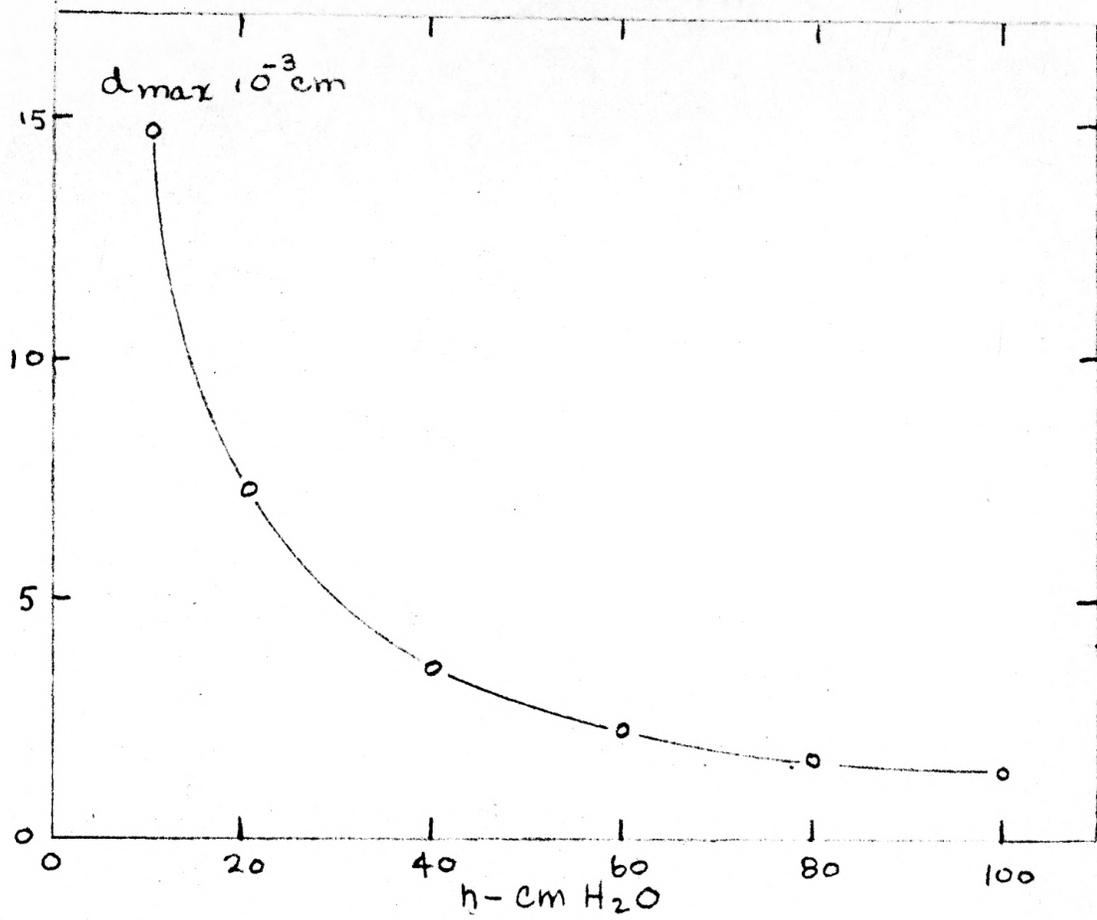


Fig. 1

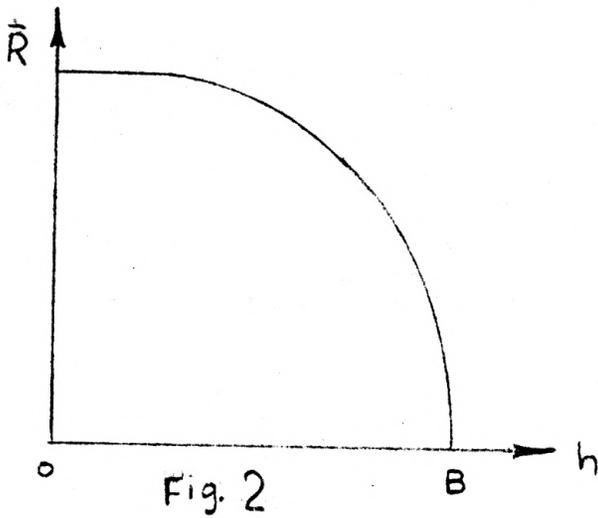


Fig. 2

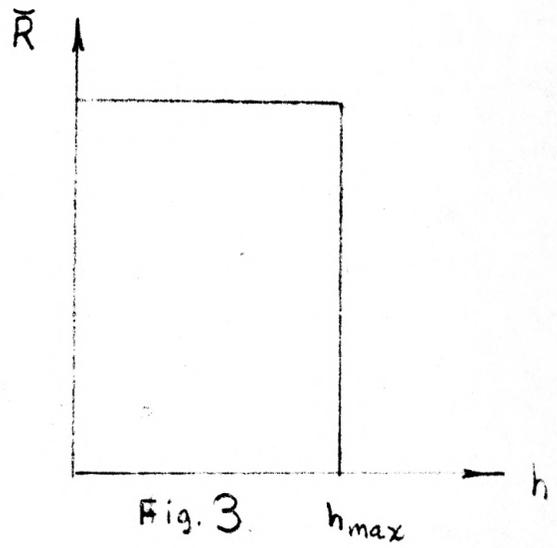


Fig. 3

entire area over the porous plate and the evaporation area is independent of h until h_{\max} is reached.

The Vapor Pressure Difference Between a Free Liquid Surface and a Liquid Surface on Top of a Porous Plate When the Latter Surface is Supporting a Column of Liquid. This problem has been studied and worked out by investigators who are interested in soil moisture (16, 18, 20) and summarized by Hall (8).

According to the principles of thermodynamics

$$\frac{-\Delta G^{\circ}}{T} = R \ln K \quad (16)$$

Where G° is the difference of free energy between the free liquid surface and a liquid surface on the top of a porous plate,

and
$$K = \frac{f_1}{f_2} = \frac{\gamma_1 P_1}{\gamma_2 P_2} \quad (17)$$

Where f_1 = fugacity of liquid surface on the porous plate.

f_2 = fugacity of free liquid surface.

P_1 = vapor pressure of liquid surface on the porous plate.

P_2 = vapor pressure of free liquid surface.

γ_1 = fugacity coefficient of liquid surface on the porous plate.

γ_2 = fugacity coefficient of free liquid surface.

Under atmospherical pressure, $\gamma_1 \doteq \gamma_2 \doteq 1$

then
$$K = \frac{P_1}{P_2} = \frac{H_1}{H_2} = \frac{H_1}{100} \quad (18)$$

Where H_1 = % relative humidity over porous plate

H_2 = % relative humidity over free liquid surface =
100%

Therefore from Equ. (16), $\frac{\Delta G^{\circ}}{T} = R \ln \frac{H_1}{100} = R(\ln H_1 - \ln 100)$

$$\Delta G^{\circ} = RT \cdot 2.303 (\log 100 - \log H)$$

$$= RT \cdot 2.303 (2 - \log H)$$

Let ΔG° is expressed on the basis of cm H₂O column (Assume water density = 1.00 g/cm).

Then R = 82.05 c.c. atom

$$= 4700 \frac{\text{cmH}_2\text{O}}{\text{OK}}$$

$$\Delta G^{\circ} = (2.303) (4700) (T^{\circ}\text{K}) (2 - \log H)$$

At 25°C, T = 298°K

$$\Delta G^{\circ} = 3.23 \times 10^6 (2 - \log H) \text{ cm H}_2\text{O}$$

$$\text{Since } G^{\circ} = \int_1^2 \bar{v}_{\text{vap}} = V \Delta P = \frac{\Delta P}{\rho} = h$$

Where ΔP is the pressure head of water column; \bar{v} is the specific volume of water; ρ is the density of water; h is the height of water column supported by the porous plate. Therefore, $h = 3.23 \times 10^6 (2 - \log H_1) \text{ cm H}_2\text{O}$.

A study of this equation demonstrates that the humidities are influenced very little by the height of water column being supported. To reduce H₂ from 100% to 90%, a column of water about 1480 meters would be required; at 99 per cent humidity a column 141 meters and at 99.9 per cent a column about 14 meters high would be necessary.

The calculation shown above may be proved by the experiments: the rates of evaporation of the liquid layer over the top of a porous plate are compared with that of a free liquid with the exact same area and under the same conditions. If they are the

same, that means the vapor pressure over these two liquid surfaces are the same. But if the rates of evaporation are different, that does not necessarily mean that the vapor pressures of these two liquid surfaces are unequal, because it may be caused by the decrease of the effective vaporization area (partially dried) of the liquid layer which supports a water column of considerable height, as it has been discussed.

Experimental Procedures

Before a run was started, the frittered glass plate and water lines were connected as shown in Plates V and VII. The spaces inside the frittered glass plate and capillary tubes were filled with distilled water, which was continuously supplied from a flask through a three-way stopcock along the direction I as marked on wooden plate of Plate IX. The presence of air bubbles in the entire water lines was carefully avoided.

The zero end of a metric stick was placed on the top of the frittered glass plate. The vertical distance from the surface of the frittered plate to a datum line was measured with a transit, and recorded as h^0 .

The heater and air pump were started. The thermostat on the heater and input voltage of the vacuum pump were adjusted to achieve a desired temperature and a certain flow velocity of air.

The inclined angle of wooden plate on which the measuring tube was attached was adjusted until a desired distance between the center line of the measuring tube to the top surface of the glass plate was achieved. The altitude of the measuring tube

related to the same datum line was read by the transit by setting the zero end of metric stick to coincide with the center line of the measuring tube, the value obtained was recorded as h' . The net distance between the center line of measuring tube and top surface of the glass plate, h , which also was the height of the water column supported by the porous surface of the frittered glass plate due to the capillary action, was calculated by h' minus h^0 .

Before this step was carried out, warm air should have been circulated at least four to five hours to make sure that the temperature difference between the air and the vaporization surface of the frittered glass plate had reached an equilibrium state. Then the stopcock was turned from direction I to direction II as marked on Plate IX to let the water flow into the measuring tube. The stopcock was then turned to direction III. The water inside the measuring tube began to be drawn to the glass plate. The rate of movement of meniscus inside the measuring tube was noted. This reading, after being multiplied by the cross section area of the measuring tube, was the rate of decrease of volume of water inside the measuring tube, which in turn was equal to the rate of vaporization from the top surface of the frittered glass plate.

Before the water inside the measuring tube was emptied, the stopcock was turned back to direction II, and the measuring tube again was refilled.

The distance between the center line of the measuring tube and the vaporization surface, h , was changed to another value by adjusting the inclined angle of the wooden plate.

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Repeat step five.

In some runs, a mercury column was added to the water column to get a greater value of the equivalent height of water column. Its connection was shown on Plate IX.

The value of h was gradually increased for each subsequent run, until a critical point was reached where the water layer on the top of the porous plate was broken and air bubbles came into the glass plate. The value of h at this point was considered as h_{\max} .

Results and Discussion

Summary of Data. The rates of vaporization were observed with various heights of water column supported by the frittered glass plate. The variation of h covered a range from 0.4 cm positive water head to 145 cm negative water head which was achieved by adding a mercury column. Within this range no change of rate of vaporization due to the change of the value of h was found. The temperature and velocity of dry air used were around 55°C and 0.108 lb/ft² sec. corresponding to 1.53 ft/sec. Under such conditions, the 145 cm negative water head was found to be the maximum height of water column which the frittered glass plate might support; the liquid surface was broken and air came in as the value of h was increased beyond this point. (The data were plotted on Plate XVIII. For original data, see Appendix, Run No. U-10-01 to U-10-24, M-18-01 to M-18-19, and M-16-01 to M-16-38).

Discussion. The first problem encountered in carrying out the experiments was the determination of the temperature of the

EXPLANATION OF PLATE XVIII

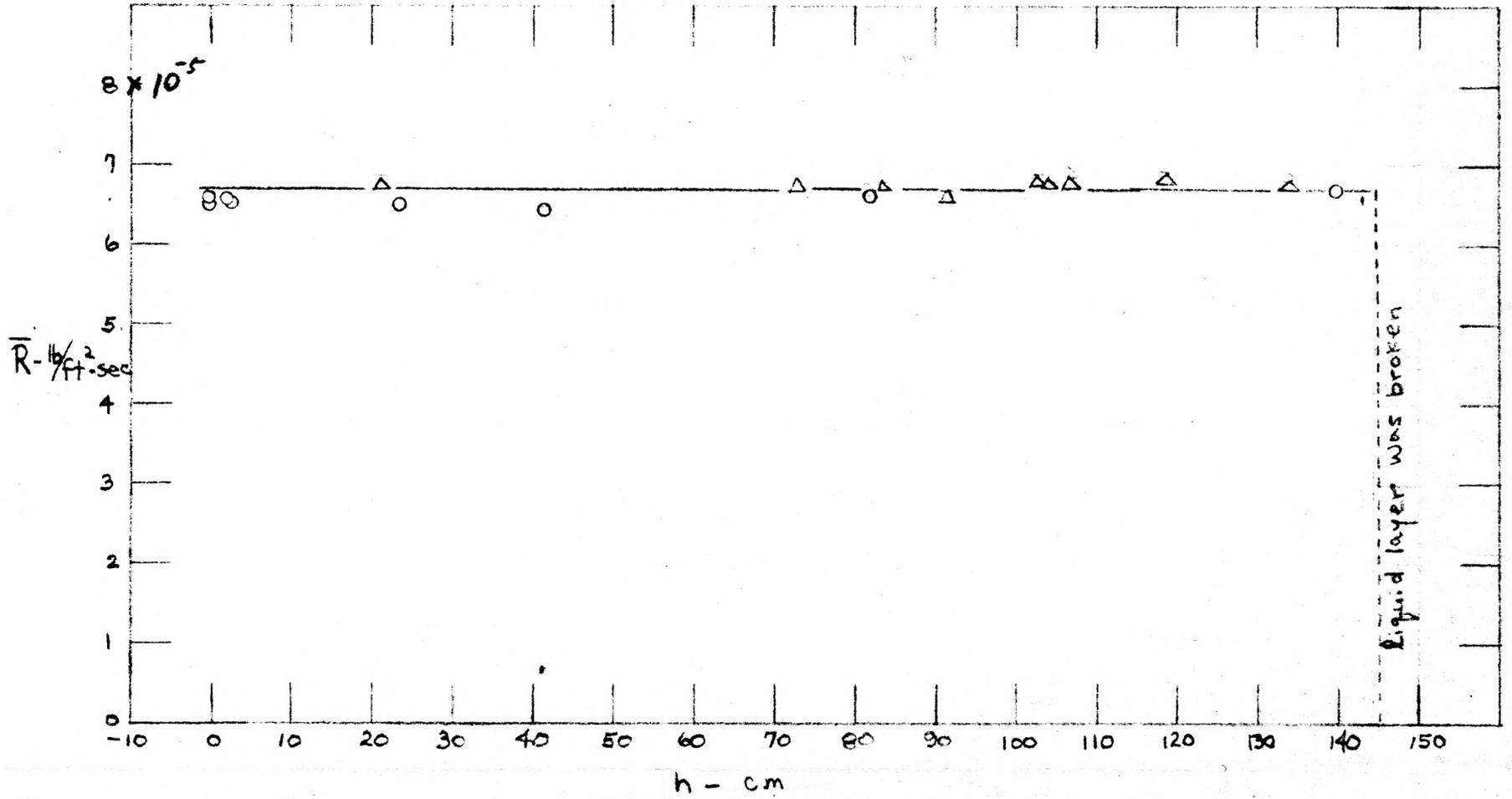
\bar{R} versus h at T = 55°C

○ G = 0.108 lb/ft²sec
(May 16, 18, 1956)

△ G = 0.112 lb/ft²sec
(June 10, 1956)

No sound applied

PLATE XVIII



vaporization surface. The dry air temperature was measured by a thermocouple, but no satisfactory measurements or estimations of surface film temperature were obtained. The temperature readings obtained from a thermocouple which was in contact with the vaporization surface might not be considered as real surface temperature due to the influence of hotter air layer above the surface. Since not the absolute value but the constancy of surface temperature was essentially important in the experiment, the obstruction was by-passed by circulating the warm air for more than four hours before any readings of rates of vaporization were taken to assure that the temperature of air and of vaporization surface had reached a state of equilibrium. The temperature of air was kept constant with a fluctuation of less than 1°C through the aid of a pair of relays and thermostat circuit on the heater, (Appendix, Plate XXXI). The experimental data showed that such small variations of air temperature had no appreciable effect on the rates of vaporization. That meant the surface temperature was practically kept constant.

Another problem encountered was the presence of air bubbles inside the frittered glass plate. Sometimes these bubbles had little or no effect upon vaporization rates measured, but in most cases their presence caused unreproducible results.

Improved laboratory techniques and careful operation gained with experience help keep air bubbles out of the system. The data plotted on Plate XVIII were free from air bubbles.

In runs M-18-18 and M-18-19 (Appendix, Original data), the water level of the measuring tube was 0.4 cm higher than that of

frittered glass plate surface. This positive water head assured the existence of a complete liquid layer over the top of porous surface, which might be confirmed by visual observation. The vaporization rates of these two runs were compared with that of other runs which had negative water head. Plate XVIII shows obviously that the rate of vaporization was practically independent of the variation of h and identical with that of positive water head as long as the values of h were within the limitation of 145 cm. As a result, a conclusion might be drawn that for a water column up to 145 cm. in height the top of the porous plate was as completely wetted as when it was under 0.4 cm positive head.

From Plate XVII, Fig. 1, it was found that as $h = 80$ cm, $d_{\max} \doteq 1.0 \times 10^{-3}$ cm. As it had been pointed out that the sonic pulsation would not cause more than one per cent area changes in a water layer whose depth was less than 1.0×10^{-3} cm, therefore the water layer being created on a porous plate which supported a water column higher than 80 cm was considered satisfactory to be used as a vaporization surface for study quantitatively the effect of sonic wave on the rate of vaporization.

THE EFFECT OF SONIC PULSATION

Experimental Procedures

In this exploratory investigation which dealt with the combination effects of three motions: the wave motion created by the sonic pulsation, the flow motion of air stream, and the

transfer of material between phase, the required information for making a theoretical analysis was lacking. Hundreds of preliminary runs were made before a reproducible condition was established. The effect of frequency was noted to be so sensitive that a slight movement of the frequency control dial on the audio generator which could not be distinguished from the dial marks might cause quite different result. The position of glass plate located in the wooden tunnel and the angle of vaporization surface against the air stream were found to be critical. These variables had to be carefully specified in order to get reproducible data even without the application of sound. Some small holes drilled to set in the thermocouples on the wall of wooden channel were found responsible for the fluctuated data obtained during the preliminary runs. The contamination of vaporization surface of the frittered glass plate might weaken the surface tension of liquid, in turn cause the top surface of the glass plate not to be completely wetted.

Reproducible results were achieved after efforts had been made to keep all experimental conditions, except the variables investigated, as constant as possible. The glass plate which had been carefully cleaned by sulfuric-sodium dichromate cleaning solution¹, was located in the wooden channel such that the vaporization surface was almost on the center line of the wooden channel, directly under the mouth of the sound driver and parallel to the

¹The cleaning solution was prepared by adding 250 ml conc. H_2SO_4 (96% c.p.) to 10 ml saturated sodium dichromate water solution.

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direction of the air stream (Appendix, Plate XXVIII). The position was never changed throughout all the runs. The wooden channel, especially the section where the glass plate was located was well sealed by plastic wood to make sure no leakage occurred to cause undesirable air current flow. For experimental procedures, the same steps as listed on PREPARATION OF A THIN LIQUID SURFACE from one to eight were followed, except that on step five, in most runs, the sound waves were applied.

The sounds were usually applied for only two to ten minutes. The rates of vaporization were measured in the same manner as described in steps five and six on PREPARATION OF A THIN LIQUID SURFACE. The readings obtained before and after the sonic applications were compared with that measured when the sound was applied. Their difference would be assumed as the result of the sonic effect.

Results and Interpretations of Data

Influence of Frequency. Thirty-three runs were carried out for a brief observation of the influence of frequency on the effect of sonic pulsation. Input voltages to the driver were adjusted to produce the sounds at the same level of intensity while the frequencies were varied. Two different levels of intensity were observed. Intensity of 130 db was tested with three different frequencies while the air at 20°C was circulated at a mass velocity of $0.017 \text{ lb/ft}^2\text{sec}$. (almost corresponding to 0.23 ft/sec). Data were plotted on Plate XIX as separate lines since the arbitrary change of \bar{R} with respect to f . It was noted that the sonic wave with the frequency of $1,160 \text{ cycle/sec}$ increased

EXPLANATION OF PLATE XIX

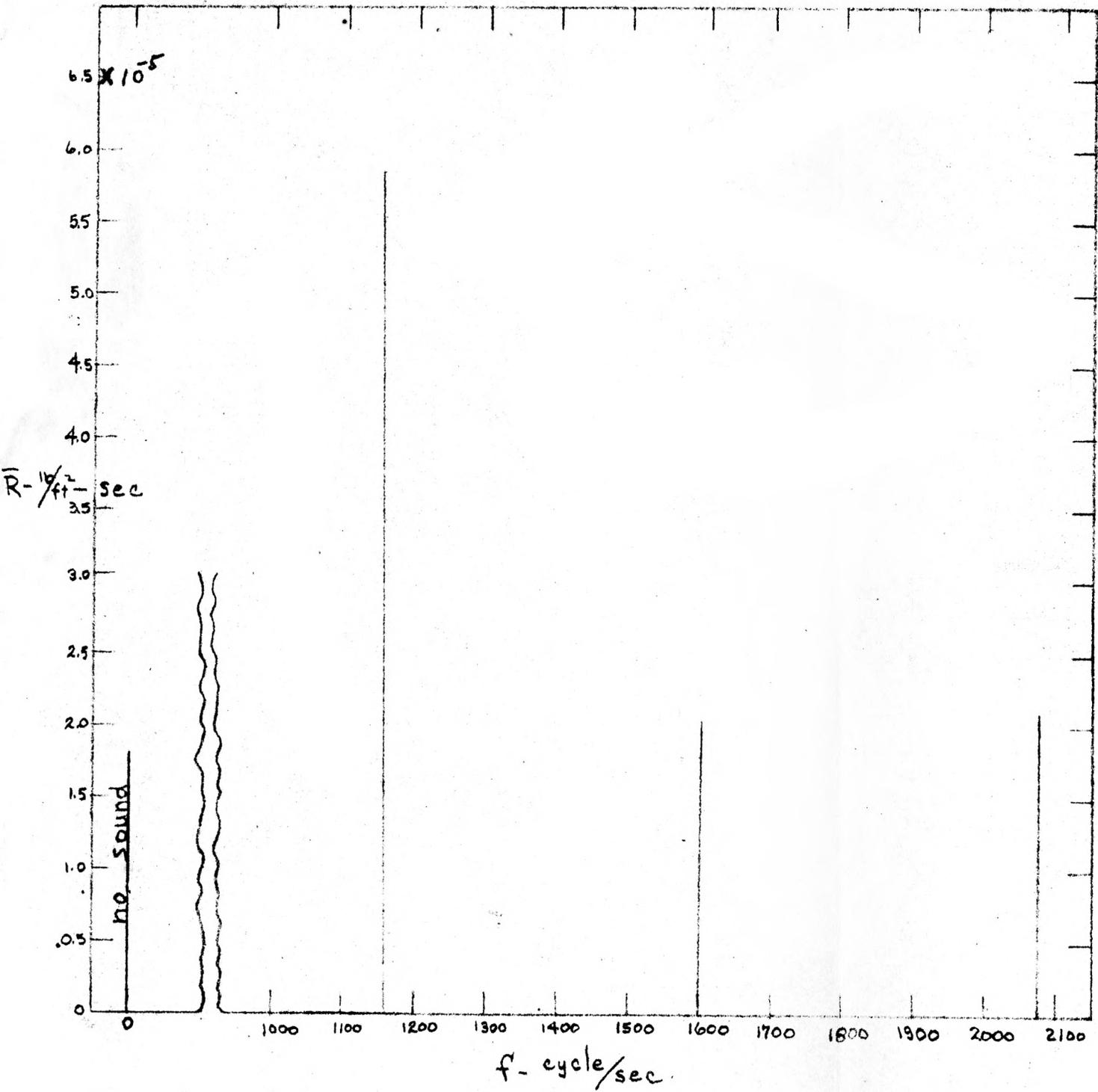
\bar{R} versus f as $I = 130$ db

$G = 0.017$ lb/secft²

$T = 32^{\circ}\text{C}$

$h = 86$ cm

PLATE XIX



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the rate of vaporization up to 300 per cent while almost no effect might be found with frequency of 1,600 cycle/sec and 2,350 cycle/sec. Another phenomenon worthy of mention is that the rates of vaporization right after the sound stopped, as Run D-4-1, D-4-12, and D-4-14, were faster than that before the application of sound. (Ref. to Original data, Appendix).

Nine different frequencies with a constant intensity of 124 db were observed under the condition of natural convection. ($G = 0$). The air was circulated for four hours through the drier to reduce its humidity before the data were taken. After each run the air was circulated for two minutes to blow out the water vapor accumulating above the vaporization plate, a waiting period of 15 minutes was allowed to let the air settle. The data of D-5-01 and D-5-09 (Original data, Appendix) were a little higher than the average value due to the fact that these two runs were carried out right after the stop of the air pump.

Plate XX shows that under the conditions specified, 1,150 cycle/sec is an optimum frequency.

Influence of Intensity. The influence of sound intensity was studied intensively under five different levels of velocity of air. The height of water column and the frequency of sound applied were fixed at 86 cm and 1,150 cycle/sec respectively while the intensities of sound varied from 98 db to 129 db.

The noise background of the room was 80 db. Since db is a logarithmic function, the intensity of 80 db expressed as pressure amplitude, is only about 0.2 per cent of that of 110 db, the weakest sound applied.

EXPLANATION OF PLATE XX

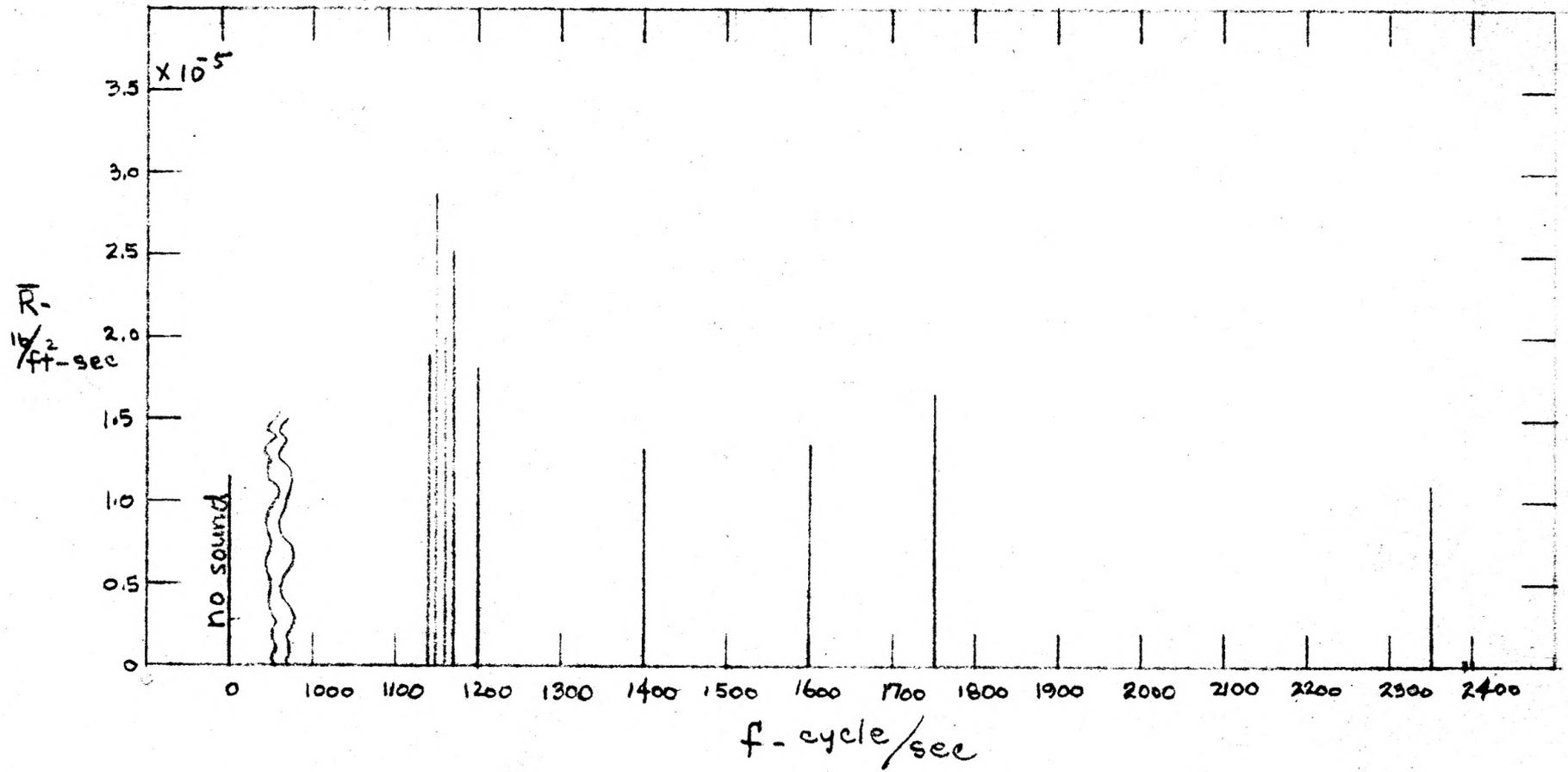
\bar{R} versus f at $I = 124$ db

$T = 30^{\circ}\text{C}$

$h = 86$ cm

$G = 0$ lb/secft²

PLATE XX



The data (Appendix, Original data, Run N-25-01 to N-29-51) were plotted on Plate XXI. $I = 80$ db meant no sound was applied. In general, the rates of vaporization increased with the increase of intensity. It was noted that the effect of sonic pulsation was prominent on the range of lower velocity of air and decreases with the increase of velocity of air. Under the high intensity of sound, the rates of vaporization almost approached to a common point regardless of the difference of velocity of air.

Influence of Air Velocity. To confirm the tendency shown on Plate XXI that under the sonic pulsation of suitable frequency and strong intensity, the rate of vaporization practically would be independent of the velocity of air stream, 35 runs were carried out under the sound wave with the frequency of 1,150 cycle/sec and intensity of 129 db/sec while the velocity of air was varied from the zero (natural convection) to 0.12 lb/ft²sec. The height of water column and temperature of air were fixed at 86 cm and 27-29°C.

The data (Appendix, Original data Run N-29-03 to N-29-35) were plotted on Plate XXII as \bar{R} vs G . They checked well with those of Plate XXI. \bar{R} under the sound wave of 129 db appeared independent of G from $G = 0$ up to $G = 0.70$ lb/ft²sec, while \bar{R} of no sound changed from 1.1×10^{-5} lb/ft²sec. to 3.25×10^{-5} lb/ft²sec. (The small reduction of \bar{R} at $G = 0$ as sound applied might be caused by the accumulation of water vapor over the vaporization surface.) For higher air velocity, the rate of vaporization increased with the increase of air velocity, but slower than the correspondent increase if no sound were applied.

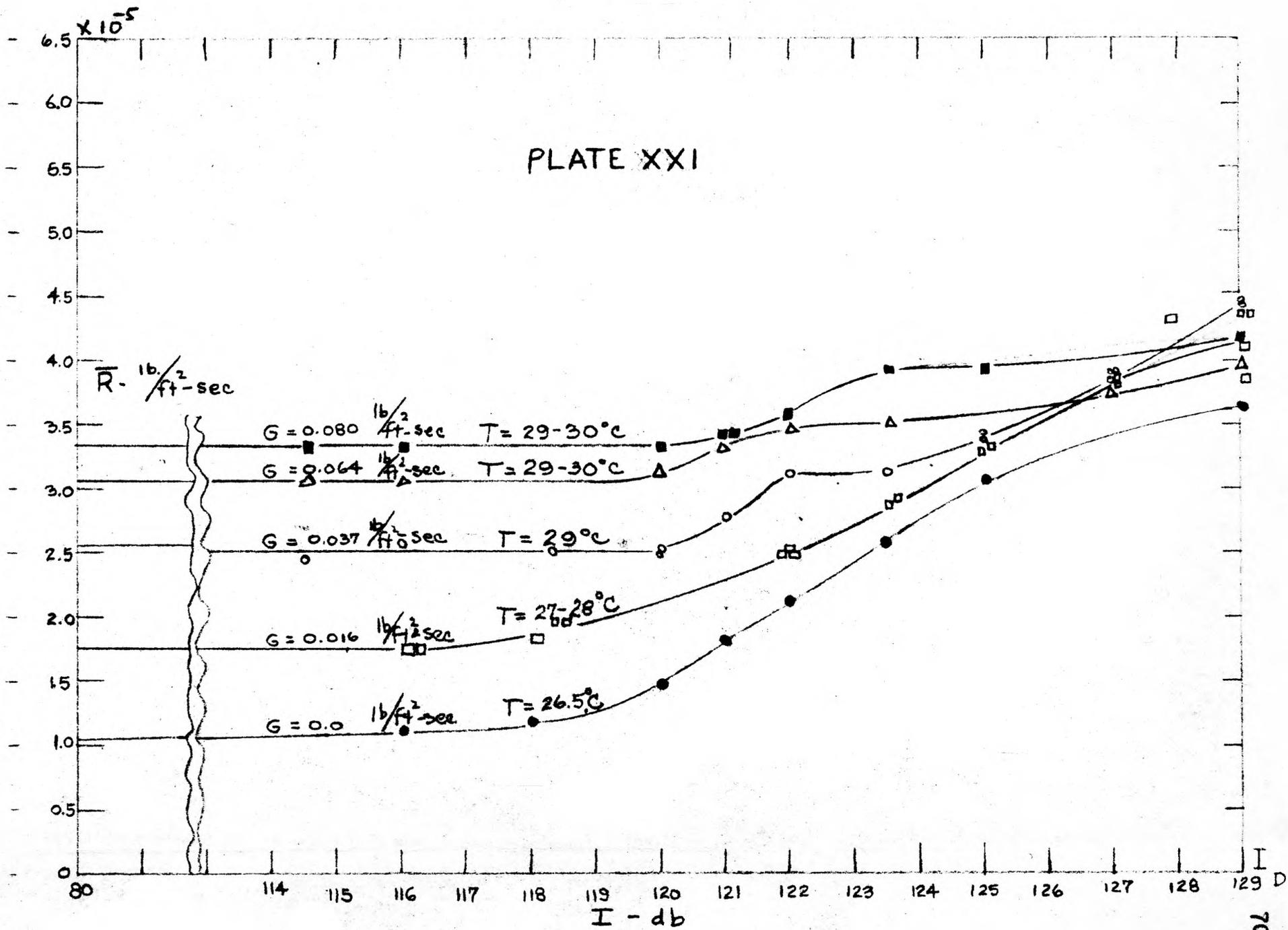
EXPLANATION OF PLATE XXI

\bar{R} versus I at various G levels

f = 1,150 cycle/sec

h = 86 cm

PLATE XXI



EXPLANATION OF PLATE XXII

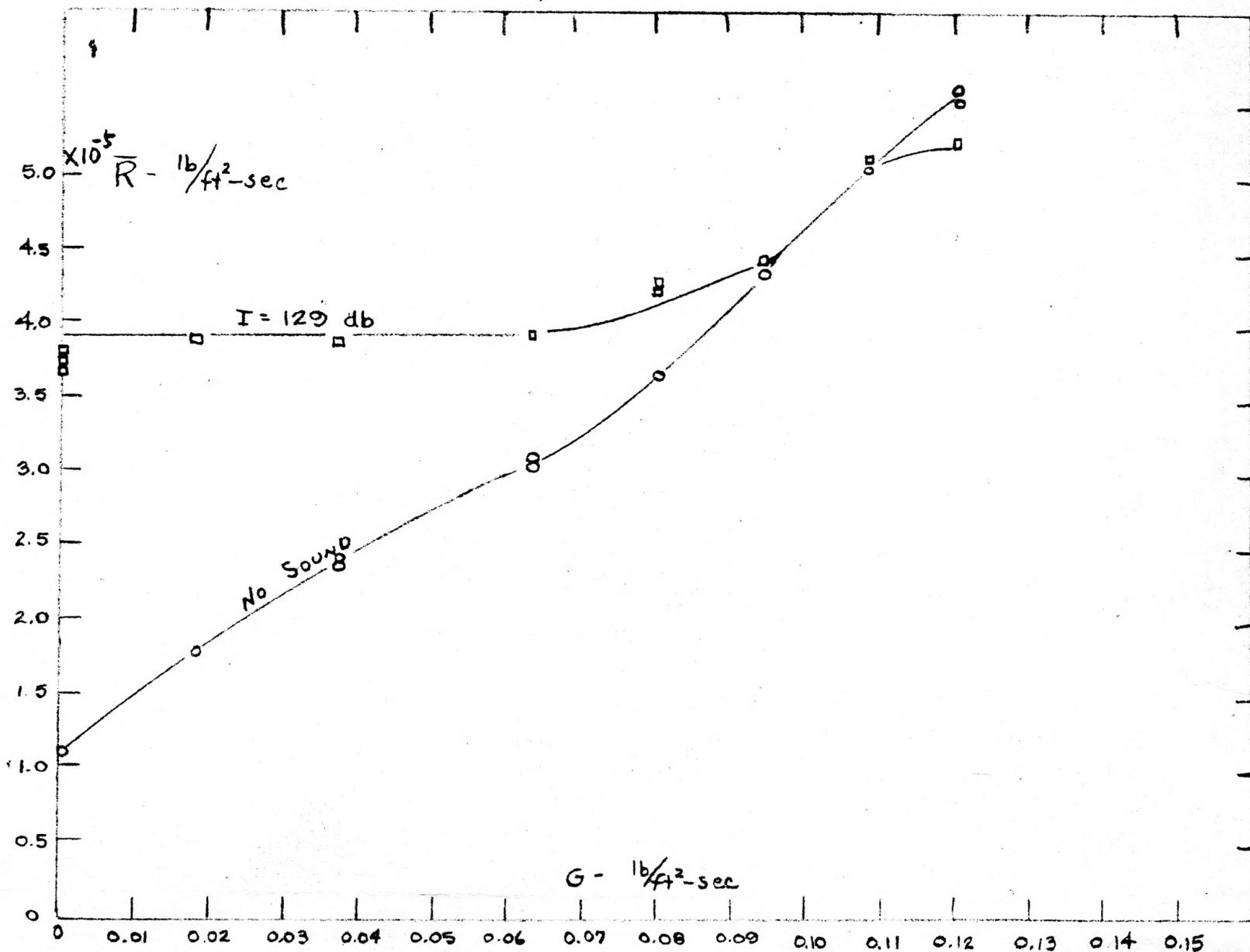
\bar{R} versus G at I = 129 db

f = 1,150 cycle/sec

h = 86 cm

T = 27°C - 29°C

PLATE XXII



At the point of $G = 0.108 \text{ lb/ft}^2\text{sec}$, the vaporization rate with sound applied and that without sound were identical, no effect due to the application of sound was observed. For the air velocity higher than that point, the \bar{R} 's under the application of sound were less than those without; the application of sonic pulsation resulted in a negative effect.

The highest air velocity investigated was $0.12 \text{ lb/ft}^2\text{sec}$. which was the maximum capacity of the air pump used.

Influence of h. To avoid the complexity of introducing one more variable, all runs except a few were carried out at a constant h of 86 cm. The data (Appendix, Original data Run N-19-01 to N-19-11) of few runs carried at $h = 0$ were plotted on Plate XXIII to compare with those obtained at the same condition but $h = 86$ cm. Deviations between these two lines were found in the range of $I = 122 \text{ db}$ to $I = 125 \text{ db}$. These two series of experiments were run completely independently; the frequency dial of audio generator might not have been set at exactly the same position. Since a small change of the position of the frequency dial might introduce considerable error in frequency as well as intensity of the sound applied, such relative small difference between two series of runs should be considered as experimental error rather than due to the change of h.

Discussion

Wind Effect¹. While the results of hundreds of runs at least

¹The "wind effect" is defined as the disturbances caused by the "wind current" created by the movement of the diaphragm of sound driver. The difference between "wind current" and "sound wave" is that the former is a flow motion and the latter is transmitted through molecular motion.

EXPLANATION OF PLATE XXIII

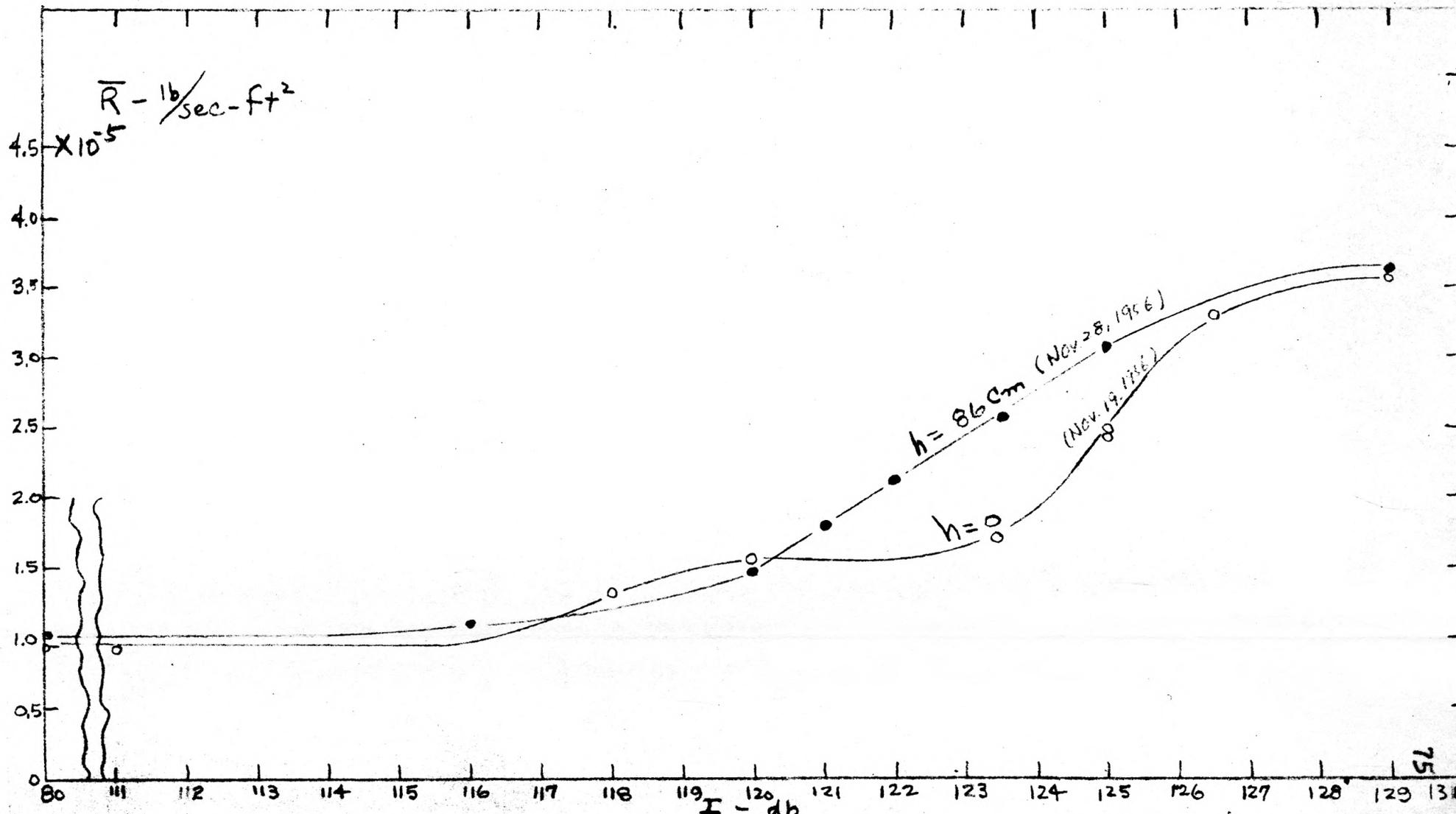
\bar{R} versus I at $h = 86$ and $h = 0$

As $f = 1,150$ cycle/sec

$T = 26.5^{\circ}\text{C}$

$G = 0$ lb/ft²sec

PLATE XXIII



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established the fact that the rates of vaporization might be increased by operating a sound driver set above the vaporization surface, the data still might be questioned whether or not such an increase was caused by the "wind effect" created by sound driver rather than the "sonic effect" of sound wave. To answer that question, smoke created by an E. Vernon Hill and Co. smoke gun was introduced into the wooden tunnel. Its distribution pattern with or without the application of sound was observed. It was found that even under the sonic of 129 db and 1,150 cycle/sec, which caused great increase of rate of vaporization, no appreciable change of smoke pattern was found. This fact should be considered as sufficient evidence that no such strong wind which would increase the rate of vaporization up to 210 per cent had been created by the sound driver. Another fact might support this point of view is that the driver should cause same degree of wind effect whether it was operated at 1,160 cycle/sec or 1,600 cycle/sec., but the rate of vaporization under the sonic pulsation with former frequency is three times that under the latter as shown on Plate XIX.

Resonance. The abrupt change of \bar{R} vs. f , as shown on the Plates XIX and XX, might be assumed to be the result of the existence of a state of resonance; only at the resonance frequency would the sound pulsation be expected to give significant effect on the \bar{R} . The resonance is a function of boundary condition of the medium where the waves travel, from the sound that the \bar{R} was independent of h under the sound pulsation with a frequency of 1,150' cycle/sec., (see Influence of h). Such kind of

resonance should be the sound wave in the medium of air rather than of water (otherwise, the \bar{R} had to be a function of h since the latter was a function of the thickness of water layer, in other words, the function of the boundary condition of the medium of water.) As a result, the condition of resonance was a function of the geometric shape of the wooden tunnel in which the sound was applied. No method has been developed to predicate the resonance frequencies; the knowledge available is only enough to say that for the special geometric shape of the wooden tunnel used in this investigation, (for dimensions see Plate VIII) 1,150 cycle/sec seems to be one of the resonance frequencies. It is believed that some other resonance frequencies might be found in the range of hundreds cycle per sec. No systematic tests had been carried over that region to prove this assumption since the A-C audio generator used in this investigation could not generate sounds strong enough with such low frequency. However, in some preliminary runs, by using another D-C current horn, the sounds of 320 cycle/sec. with the intensity of 124 db had been successfully generated, the data (Appendix, Original data, Run U-23-01 to U-23-30) plotted on Plate XXIV shows that even under air flow of velocity as high as 0.11 lb/ft²sec, ten per cent to fifty per cent increase of vaporization rates were found. However, it was also noted on Plate XXIV that \bar{R} appears as a function of h ; that meant as the frequency being 320 cycle/sec, a resonance of sound wave in water layer might occur.

Liquid Layer. The liquid layer serving as a vaporization surface in this investigation was supporting a water column of 86

EXPLANATION OF PLATE XXIV

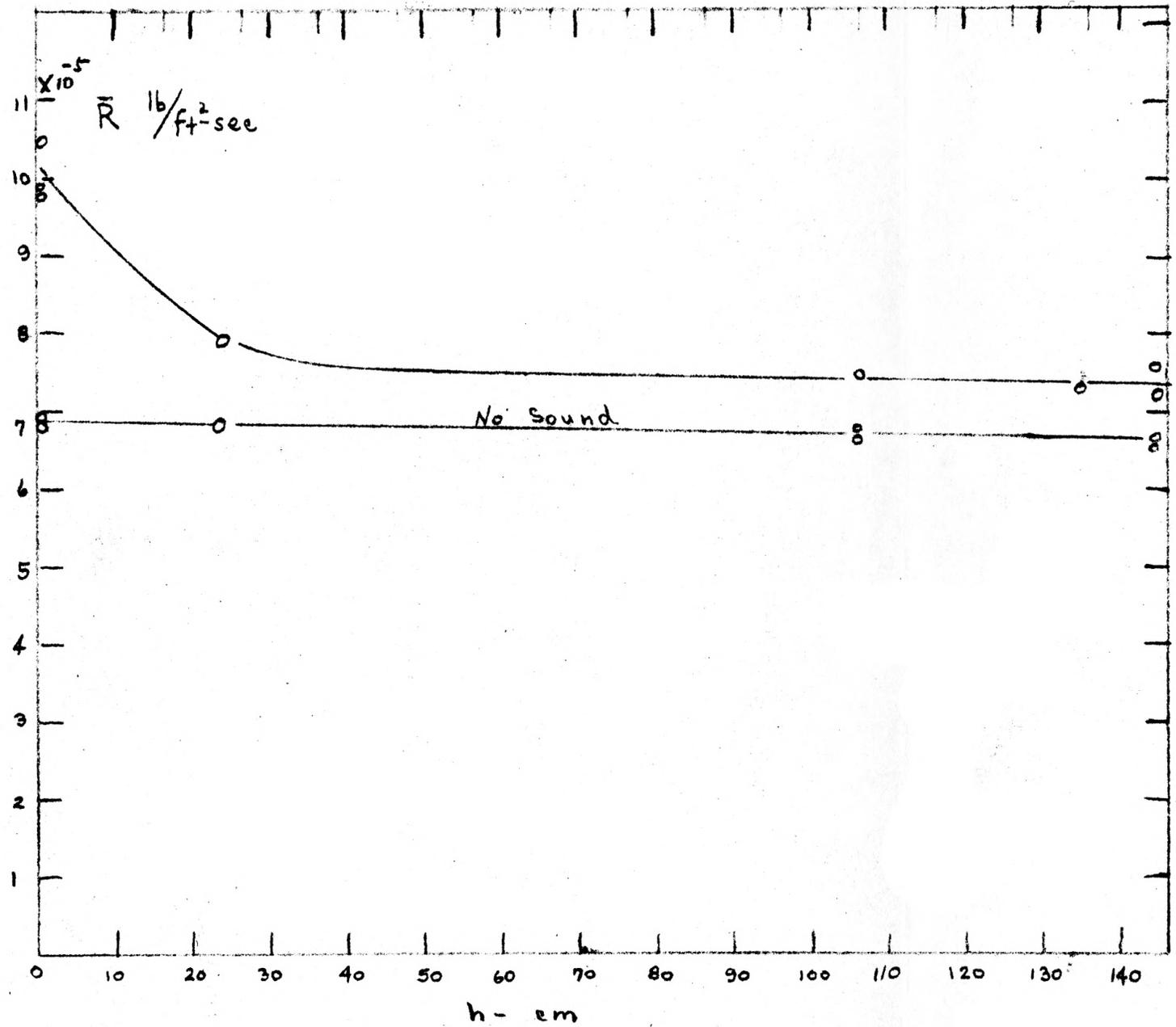
\bar{R} versus h as $F = 320$ cycle/sec

$T = 55^{\circ}\text{C}$

$I = 124$ db

$G = 0.113$ lb/ft²sec

PLATE XXIV



cm. Plate XVII, Fig. 1 showed that the d_{max} of such water layer was in the order of 1.0×10^{-3} cm, which was supposed to be thin enough to prevent the alternation of physical shape due to the sonic pulsation according to the calculation presented on "PREPARATION OF A THIN LIQUID SURFACE."

Plate XXIII shows that at a frequency of 1,150 cycle/sec the \bar{R} were almost the same either $h = 0$ or $h = 86$ cm. That might mean the liquid layer created on the top of the porous plate regardless of its thickness would not be changed in its physical shape by a sonic pulsation with the frequency of 1,150 cycle/sec., although it shows a different effect as being pulsed by sonic wave with lower frequency as shown on Plate XXIV.

Time. Experiments proved that the rate of vaporization responded to the sonic pulsation immediately after it was applied, and returned back to the original rate right after the audio generator was turned off. In many runs strong sounds had been continuously applied for ten or fifteen minutes. No evidence showed the \bar{R} would be the function of length of time the sound being applied. To test whether the increase of time of application might improve the effect of weak sound, a run was carried out by applying the sound of 118 db for more than one hour. The result (Appendix, Original data Run No. N-25-13 to N-25-18) plotted on Plate XXV shows negative answer.

Velocity of Air Stream. The data plotted on Plate XXI and XXII show that the velocity of air is an essential factor of sonic effect. It should be emphasized that the G was an average mass velocity, while the local velocity around the vaporization

EXPLANATION OF PLATE XXV

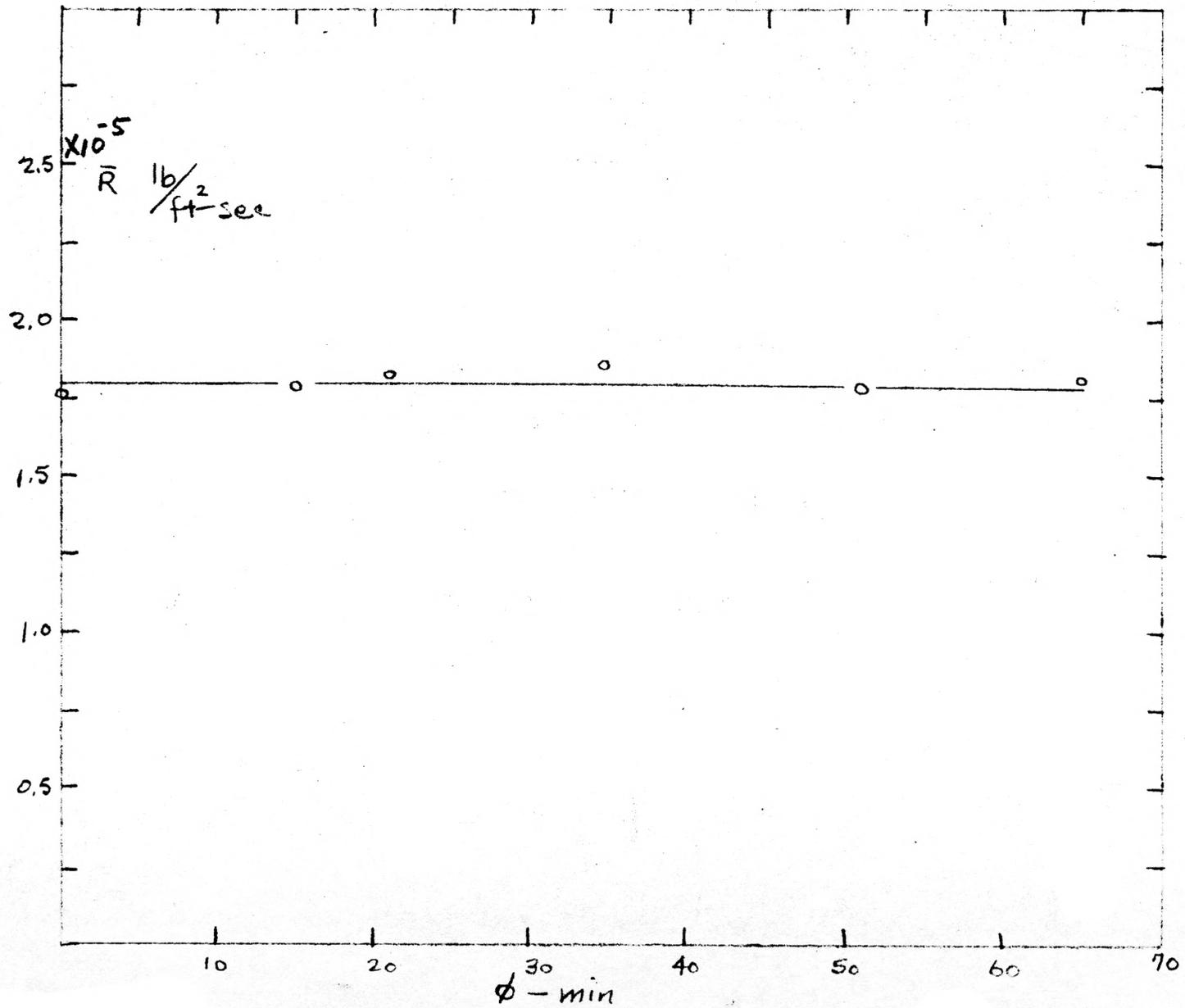
h versus ϕ as $f = 1,150$ cycle/sec

I = 118 db

G = 0.016 lb/secft²

T = 27°C

PLATE XXV



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surface, which is a function of the geometric shape of the glass plate as well as its position and angle against the air stream, might be quite a different value. The smoke showed that in the region of six inches up stream from the glass plate, the critical point for the stream changing from laminar flow to turbulent flow was $Re = 1,250$, ($G = 0.031 \text{ lb/ft}^2\text{sec}$ as $T = 30^\circ\text{C}$) while the region around the glass plate was turbulent even as $Re = 850$. ($G = 0.022/\text{ft}^2\text{sec}$ as $T = 30^\circ\text{C}$).

A Hypothesis. The conclusion that the sonic pulsation will "fix" the rates of vaporization while the mass velocity of air stream is varied seems strange enough at first glance, but it is not contrary to reason if the concept of stagnant film is adopted.

According to the two film theory suggested by Lewis and Whitman (13), the resistance to the mass transfer between phases was assumed to be concentrated on the two films adhered to both sides of the interface. In the case of vaporization of pure water into the air stream, the resistance of liquid film may be neglected and the rate of mass transfer was solely controlled by the resistance of the stagnant air film. As shown by equation (2), the thickness of the stagnant film is a function of the velocity of the gas stream, so that \bar{R} becomes a function of G as shown on the no sound line of Plate XXII.

As it is suggested on HYPOTHESES, the effect of sonic pulsation is supposed to disturb the stagnant film. It is assumed that under a sonic pulsation with suitable frequency and strong enough intensity the gas molecules of stagnant layer might all be disturbed into a turbulent state, and as a result the stagnant

film disappears. It certainly does not mean that under such conditions the water will be vaporized at infinitive rate, because even in a vacuum chamber such a thing will not occur due to the molecular attraction forces in the water layer. As a matter of fact, the effect of sonic pulsation which converts the stagnant film into a kind of turbulent state is far away from eliminating all resistance to the mass transfer since, even in turbulent state, there still exists a significant amount of resistance to the eddy diffusion as pointed out by many investigators (Sherwood, 21). But all such kinds of resistances, being different to that of stagnant film, are more or less independent of the velocity of gas, consequently under such a condition the rate of vaporization will no longer be a function of G .

A further assumption might be made to take into account the negative effect of sonic pulsation which occurred when the velocity of air was increased up to $0.12 \text{ lb/ft}^2\text{sec}$. Under the sonic pulsation with a resonant frequency, the molecules of air in the duct might all be brought into a kind of periodic motion. This phenomenon will be more predominant in the region close to the liquid layer, because first the air velocity is slower in that region than that in the main stream, the molecules which are less turbulent are easier to be forced to move in some certain directions; and second, the sonic energy reflected from the liquid layer will reinforce the periodic motion. It might be reasonable to suppose that in the region of the gas phase close to the liquid layer, no matter whether it is stagnant layer or turbulent layer before the application of sound, a new layer will be formed by

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the sonic pulsation. In this new "wave layer" the molecules of air are guided by the sonic wave and are more or less moved in some specific directions. The resistance of such new layer is between that of stagnant layer and turbulent layer. Therefore, for low velocity of air, the formation of this layer will increase the rate of vaporization because it takes place of the region originally occupied by stagnant film. For high velocity air stream, while the stagnant layer over the liquid layer is thinner, the new "wave layer" not only takes the place of the stagnant layer but the region which originally was turbulent. This kind of converting the turbulent layer into "wave layer" apparently will increase the resistance and in turn decrease the rate of vaporization; if it cannot be balanced by the positive effect it made through disturbing the stagnant film, the total negative effect appears as that shown on Plate XXI when G is higher than 0.11 lb/secft^2 .

It should be emphasized that all statements on the foregoing page are just some kind of assumptions; a complete theory to explain the combination effect of wave motion and flow motion can only be developed after more data are available.

CONCLUSIONS

A thin water layer with the thickness in the order of 10^{-3} cm., whose physical shape was believed not to be altered by the action of the audibly sonic waves, with the intensity up to 130 db was created on the top of a frittered glass plate. The vapor pressure of such a water layer was shown to be effectively the

same as that of a free water layer.

Under the sonic pulsations with the frequency of 1,150 cycle/sec and intensity of 129 db, the rate of the vaporization of water from a thin water layer such as described in preceding paragraph, to still air at 26.5°C was found to be increased up to 210 per cent above the rate when no sound was applied.

Under the air stream of low velocity (0.018 lb/ft²sec to 0.063 lb/ft²sec, approximately 0.25 to 0.80 ft/sec) with other identical conditions the rate of vaporization might be increased from 25 per cent to 175 per cent. The sonic effect on vaporization rate was reduced as the velocity of air was increased. For the velocity of air up to 0.12 lb/ft²sec., the sonic pulsation might even cause the decrease of the vaporization rate.

Frequency of sound wave applied was found to be a most essential factor of the sonic effect. Significant effect of sonic pulsation to the rates of vaporization could only be noted at specific frequencies. Up to 130 db, the strongest intensity which was employed, the sonic effect gave increase in the vaporization rate as intensity was increased.

RECOMMENDATIONS

For further investigation, the following ideas are recommended.

Investigation in the region of higher intensity of sound should be made. In every case studied so far, the rates of vaporization have been increasing sharply as maximum available intensities were applied. For such an investigation, a powerful sound source is required.

A thorough scan of the sonic frequency spectrum at a constant intensity should be conducted. Investigation to date suggests that effective frequencies may be a function of resonance conditions. It is reasonable to presume that the dimensions of the evaporation chamber, frittered glass plate, and perhaps even the stagnant layer, may be factors which contributed to the resonance conditions.

Only cursory observations on the flow pattern in the region of vaporization surface were made. Specific point velocity measurement over various regions of vaporization surface, more complete information on Reynolds' number and nature of flow around the vaporization surface, should be obtained.

Only the variables of intensity, frequency, air velocity have been studied. The variable temperature undoubtedly will contribute a great deal to the sonic pulsation and should be studied. A method of precisely measuring the surface temperature of vaporization surface should be developed.

Systems other than water and air should be studied in order to find out the influence of molecular weights on the sonic effect.

TABLE OF NOMENCLATURE

- A = area of vaporization surface, ft²
- D = equivalent diameter of wooden tunnel = 0.5 ft.
- D_g = diffusivity, ft²/hr
- d = thickness of water layer, cm.
- d_{max} = the possible maximum thickness of water layer = r, cm.
- db = unit of intensity of sound = $20 \log \frac{P_s}{0.0002}$
- f₁ = fugacity of water surface on the porous plate, cm. of water head.
- f₂ = fugacity of water surface on the free liquid surface, cm. of water head
- g = acceleration due to gravity, cm/sec²
- G⁰ = free energy at equilibrium condition, cm. of water head
- H₁ = relative humidity over porous plate, %
- H₂ = relative humidity over free liquid surface, %
- h = height of water column supported by the porous frittered glass plate by the capillary action, cm.
- h⁰ = altitude of the vaporization surface, cm.
- h¹ = altitude of the measuring tube, cm.
- h_{max} = the maximum height of water column might be risen by a porous plate through capillary action
- I = intensity of sound, db.
- K = equilibrium constant for vapor over a free liquid surface and over a liquid surface supported by a certain height of water column through capillary action
- k = constant

- l = length of distance between marks on measuring tube, inch
 l' = length of mercury column inside the measuring tube, inch
 n = exponent value for the relation between x and G .
 N_1 = rate of diffusion of component 1, mol/hr.
 P = total pressure, atmosphere
 P_s = sound pressure, dyne/cm².
 P_g = partial pressure of water in the main body of gaseous phase, atmosphere
 P_i = partial pressure of water in the interface between phases, atmosphere
 P_l = vapor pressure of water in the main body of liquid phase, atmosphere
 R = gas-law constant = 0.728 (ft³)/(atm)/(lb.mole)(OR).
 \bar{R} = rate of vaporization of water, lb/(sec)(ft²).
 r = radius of capillary tube, cm.
 Re = Reynolds' number = $\frac{(DG)}{\mu}$
 T = temperature of air stream in the wooden tunnel, °C
 T' = mean temperature in the gas film, OR.
 T_i = temperature in the interface between phases, °F.
 t = time of meniscus taken moving from mark 1 to mark 2 inside the measuring tube, seconds.
 V = input voltage of the sound driver or horn.
 v = space inside measuring tube between marks, ml.
 \bar{v} = specific volume of mercury, m/g.
 w_1 = energy required to increase the one per cent of the area of liquid surface.
 w_2 = the work done by a sonic pulsation, erg.

- x = thickness of stagnant film, ft.
- γ = specific surface tension of water, dyne/cm².
- ρ = density of water, lb/ft³.
- γ_1 = fugacity coefficient of water surface on the porous plate.
- γ_2 = fugacity coefficient of free liquid surface.
- μ = viscosity of water, English unit.
- ϕ = length of the time the sound being applied, minute.

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REFERENCES

- (1) Adam, N. K.
The physics and chemistry of surfaces. London:
Oxford University Press. 1941. 10 p.
- (2) Auerbauch, R.
Mechanical vibrations in process engineering. Chem.
Eng. Tech. 24: 259. 1952.
- (3) Bakowski, S.
A new approach to the problem of mass transfer in the
gas phase. Trans. Inst. Chem. Eng. Symposium on the
Gas Absorption. 32: supplement No. 1. 537. 1954.
- (4) Bergmann, L.
Der ultraschall and seine anwendung in wissenschaft
und technik. Berlin: VDI-Verlag GMBH. 3d ed. 1942.
- (5) Berlage, R.
J. Exp. and Theor. Phys. 16: 646. 1954.
- (6) Cassady, J. J., Jr.
B. S. Thesis. Dept. of Chem. Eng., Virginia Poly-
technic Institute, 1949.
- (7) Gilliland, E. R. and T. K. Sherwood
Diffusion of vapors into air streams. Ind. Eng. Chem.
26: 516. 1934.
- (8) Hall, R. C.
Preparation of a liquid surface which will not be altered
in its physical shape by the action of sonic pulsations.
Unpublished paper. Dept. of Chem. Eng., Kansas State
College. 1954.
- (9) Hiedemann, E., and O. Brandt
British Patent 508,675. 1936.
- (10) Hollings, H. and L. Silver
Trans. Inst. Chem. Engrs. London: 1934.
- (11) Hucter, T. F. and H. B. Bolt
Sonics. New York: John Willey and Sons, 1955.
- (12) Lange, N. A.
Handbook of chemistry, 8th ed. Sandusky, Ohio: Hand-
book Publishers. 1952. 1219 p.
- (13) Lewis, W. K. and W. C. Whiteman
Principles of gas absorption. Ind. Eng. Chem. 16:
1215, 1924.

- 93
- (14) Mckittrick, S. C., and R. Cornish
U. S. Patent 2,263,762; 1951.
 - (15) Peterson, P. G. Arnold, and L. L. Beranek
Handbook of noise measurement. Cambridge, Massachusetts:
General Radio Co. 1954.
 - (16) Richards, L. A.
The usefulness of capillary potential to soil moisture
and plant investigations. J. Agr. Research. 37: 719.
1928.
 - (17) Richardson, C. N.
U. S. Patent 2,500,008. 1950.
 - (18) Richards, L. A., and W. Gardner
Tensiometers for measuring the capillary tension of
soil water. J. Am. Soc. Agron. 28: 352. 1936.
 - (19) Ruitter, J. H.
Modern oscilloscopes and their uses, Rev. ed. New York:
Rinehart. 1955.
 - (20) Schofield, R. K.
The Pf of water in soil. Trans. 3d. Intern. Cong.
Soil Sci. 2: 37-48. 1935.
 - (21) Sherwood, T. K.
Absorption and extraction. New York: McGraw-Hill,
1952. 53 p.
 - (22) Sollner, K., and C. Bondy
Trans. Faraday Soc. 32: 616. 1936.
 - (23) Wood, R. W. and A. L. Loomis
The physical and biological effects of high-frequency
sound-waves of great intensity. Philosophy Magazine. 4
(7): 417. 1927.

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APPENDIX

Calibrations of Instruments

Calibrating the Measuring Tubes.

Purposes. Determining v , the spaces inside the measuring tubes between marks.

Procedure. A small amount of mercury (chemically pure) was introduced into a measuring tube; the length of mercury column inside the tube, l' , and the length between marks on the tube, l , were measured by a Vernier Caliper, then the mercury was poured out and weighed by a chemical balance, recorded as w .

Calculation. $\frac{w}{l'}$, = weight of mercury per unit length column.

$$l\left(\frac{w}{l'}\right) = \text{weight of mercury between marks}$$

$$l\left(\frac{w}{l'}\right) \cdot \bar{v} = v = \text{space inside tube between marks.}$$

Where \bar{v} was specific volume of mercury at the temperature the calibration being performed; its value was taken from Lange's (12) Handbook of Chemistry.

Results. Five tubes had been calibrated, lengths and spaces between each mark expressed as inches and milliliters respectively were described diagrammatically in Plate XXVI.

Discussion. The two ends of the mercury column were set as close as possible to the marks being measured to eliminate the error caused by the un-uniformity of the diameter of the capillary column inside the tubes with the help of Vernier calipers. For each measuring several readings were taken. Their deviations from the mean value were found to be less than one per cent.

EXPLANATION OF PLATE YXVI

Diagrammatic description of the capillary
tubes

l stands for length between the marks in inches.

V stands for the space inside the tube between
the marks in milliliters.

PLATE XXVI

Tube I) /-----/ D
 A 1 = 7.979 B
 v = 0.0927

Tube II) /-----/ D
 A 1 = 3.962 B 1 = 3.982 C
 v = 0.0421 v = 0.0464

Tube III) /-----/ D
 A 1 = 3.614 B 1 = 1.379 C 1 = 3.614 D
 v = 0.0421 v = 0.01127 v = 0.0421

Tube IV) /-----/ D
 A 1 = 8.01 B
 v = 0.0933

Tube V) /-----/ D
 A B C D E F G H I J

l = 0.960 0.974 0.975 0.956 0.956 0.990 0.932
 1.008 0.980

v = 0.01124 0.01141 0.01142 0.01120 0.01120 0.01160
 0.1091 0.01181 0.01148

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Calibrating the Intensity of Sound vs. Input Voltage to the Sound Driver. The Altee Type 21-BR-150 Condenser measuring microphone connected with sound level meter was located inside the wooden tunnel in the place where the frittered glass plate had occupied as shown on Plate V. The sound was generated by the sound generator after the frequency dial was set at a specified frequency. The intensities of sound at a specified position, where the frittered glass plate had been and the condenser was, were read by the sound level meter against various V, input voltage of the sound driver, which was measured by a Weston model 769 electronic volt milliammeter as shown on Plate XV. A calibration curve of I vs V for a specific frequency of 1,150 cycle/sec was obtained as shown on Plate XXVII.

The input voltages were also calibrated against various frequencies at constant intensity. Table I shows such calibrated data for the intensities of 124 db and 130 db.

With the help of this curve and table, the intensity of sound applying on the vaporization surface could be read from V measured by a voltage meter.

The calibrations were carried out under such air condition that $T = 30^{\circ}\text{C.}$, the same temperature under which the sonic effect experiments carried, and $G = 0$. The experiments proved that the G had no effect on the calibration curve.

Since the intensity was a function of the distance between the sound source and the place where it was measured, to measure the intensity of sound applying on the vaporization surface, the importance of setting the distance between the measuring microphone

EXPLANATION OF PLATE XXVII

The calibrating curve of I vs. V

while $f = 1,150$ cycle/sec.

$T = 30^{\circ}\text{C}$

$G = 0$

PLATE XXVII

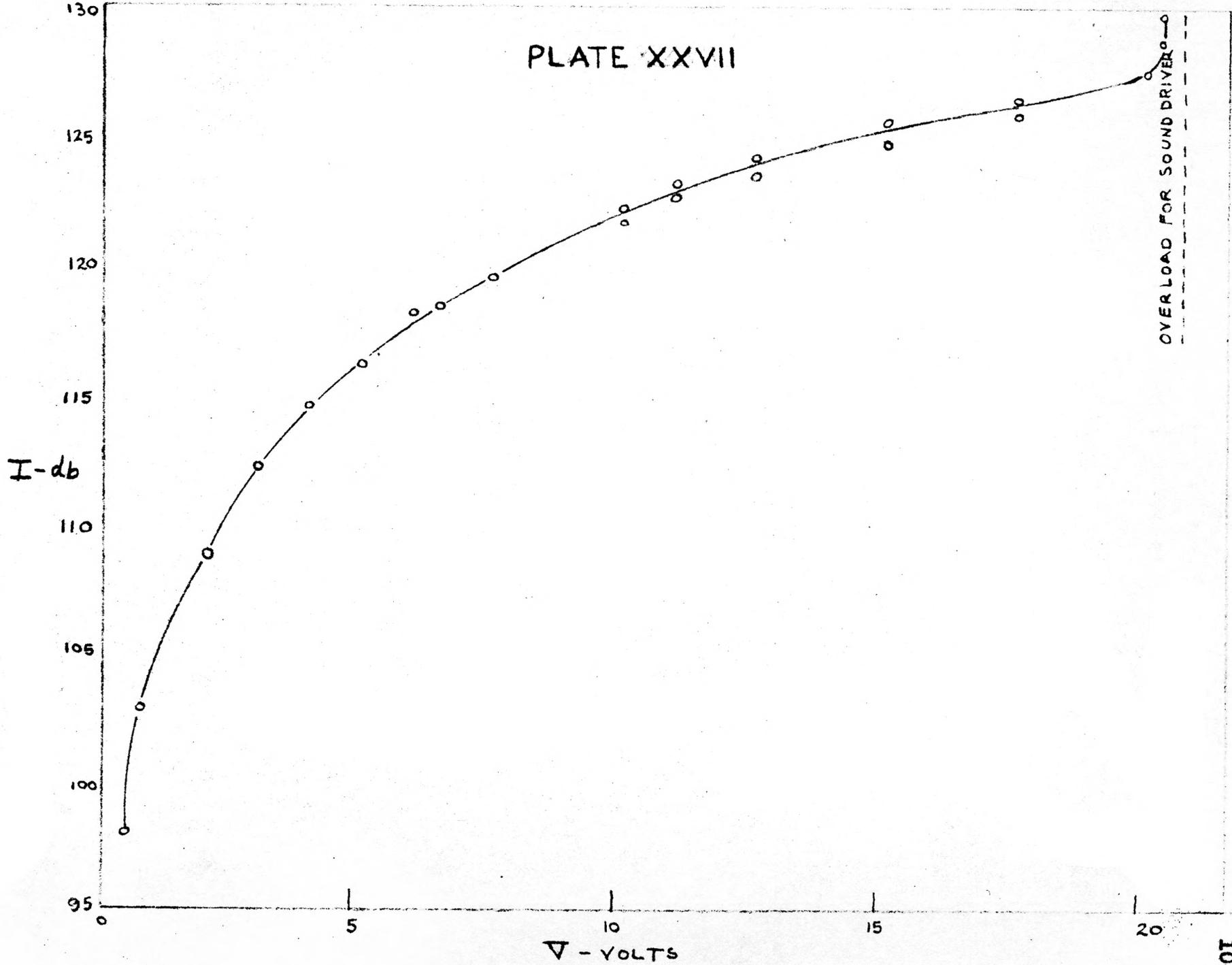


Table 1. Calibration of intensity of sound vs. input voltage.

Frequency cycle/sec :	Input Voltage: volt :	Intensity db
1160	23.2	130
1600	18.5	130
2350	13.2	130
1140	17.0	124
1150	13.0	124
1170	10.5	124
1198	12.2	124
1200	15.5	124
1400	11.5	124
1600	7.5	124
2350	8.5	124

and mouth of sound driver exactly the same as that of vaporization surface and mouth of sound driver was recognized. The microphone, due to its spherical shape, was calibrated by a Type 1552-A-Sound-Level Calibrator whose loudspeaker mounted in an enclosure which fitted over the microphone and delivered a uniform intensity of sound wave over the spherical surface. As a result, it was difficult to determine what was the effective distance between microphone and sound source if the latter was a point instead of an enclosure.

In Plate XXVIII, effective distance was taken as 2.68 inches, which was equal to $2.38 \text{ inches} \times \frac{1}{3} (0.908 \text{ inches})$. Considerable error might be introduced due to such choice of effective distance. Since the space inside the wooden tunnel was far away from a free sound field, and the really reposing mechanic of microphone was unknown, no analytic method has been developed to check the error.

EXPLANATION OF PLATE XXVIII

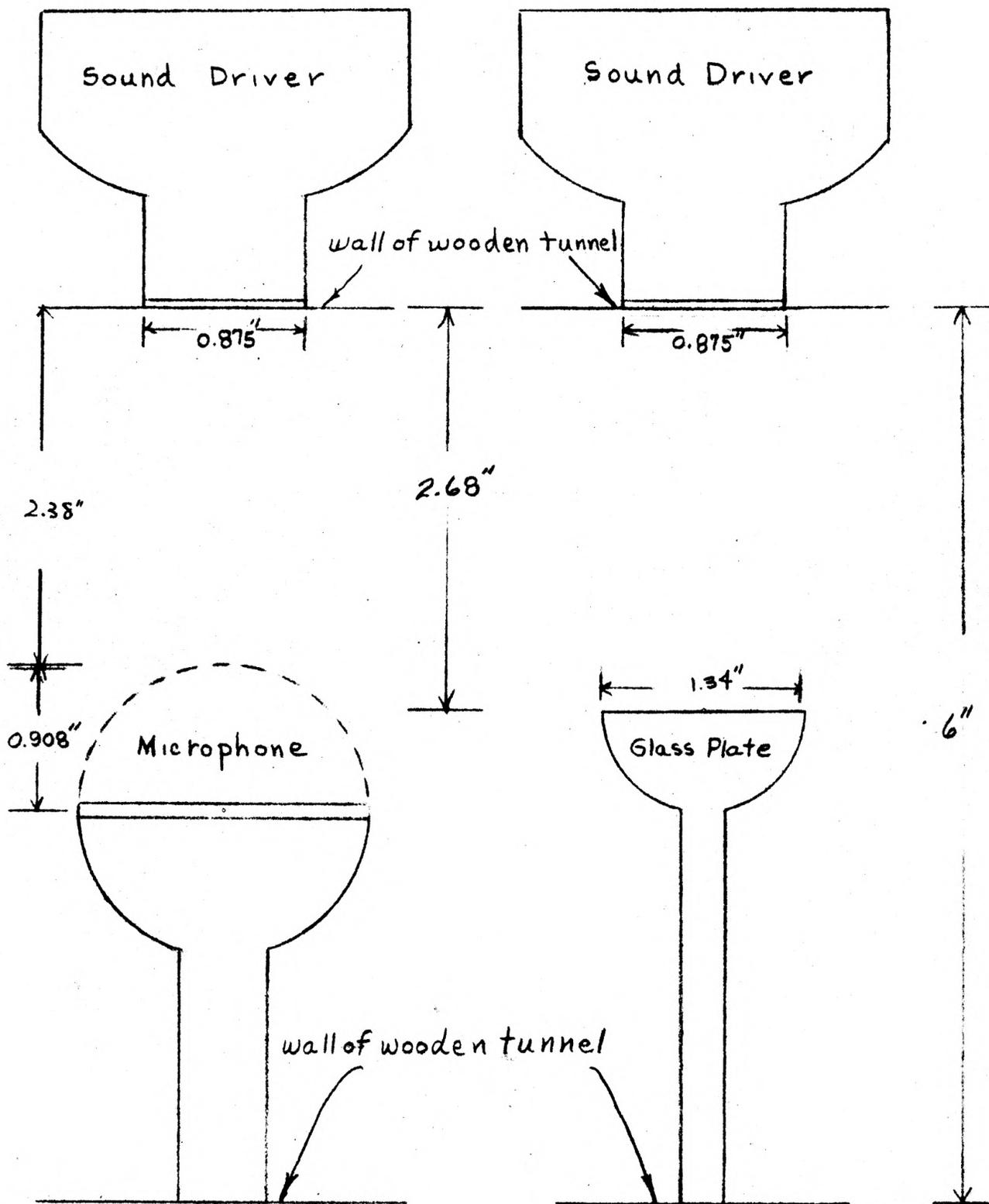
The positions of the Altee Type

21-BR-150 Condenser microphone and

the frittered glass plate inside the

wooden tunnel.

PLATE XXVIII



Calibrating the Frequency Dial of Audio Generator.

Purpose. Correcting the reading of the frequency dial of audio generator.

Procedures¹. The frequency dial was calibrated by a Heath-kit Laboratory Oscilloscope. The standard signal generated by a General Radio Co. Type 1307-A Transistor Oscillator with the frequency of 1000 cycle/sec. was applied to the horizontal channel while the signal generated by the audio generator was applied to the vertical channel; the wave pattern formed on the screen of oscilloscope was observed. The frequency of signal generated by the audio generator was calculated according to the following equation:

$$\frac{\text{Frequency applied to the vertical channel}}{\text{Frequency applied to the horizontal channel}} = \frac{\text{number of loops tangent to a horizontal line}}{\text{number of loops tangent to a vertical line}}$$

Another signal of 400 cycle/sec. generated by same transistor oscillator and the line signal of 60 cycle/sec. also were used as standard signal. The results on Plate XXIX show the data obtained by these three different kinds of standards were well checked.

Sample Calculation

Run No. U-10-01

t = 170.0 sec
v = 0.0464 ml

$$\text{Therefore } v/t = \frac{0.0464}{170.0} = 2.73 \times 10^{-4} \text{ ml/sec.}$$

¹For details of the procedures see Ruiter's (19) "Modern Oscilloscopes and Their Uses"., page 140.

EXPLANATION OF PLATE XXIX

Calibration curve of frequency

dial of audio generator.

f_d = dial reading

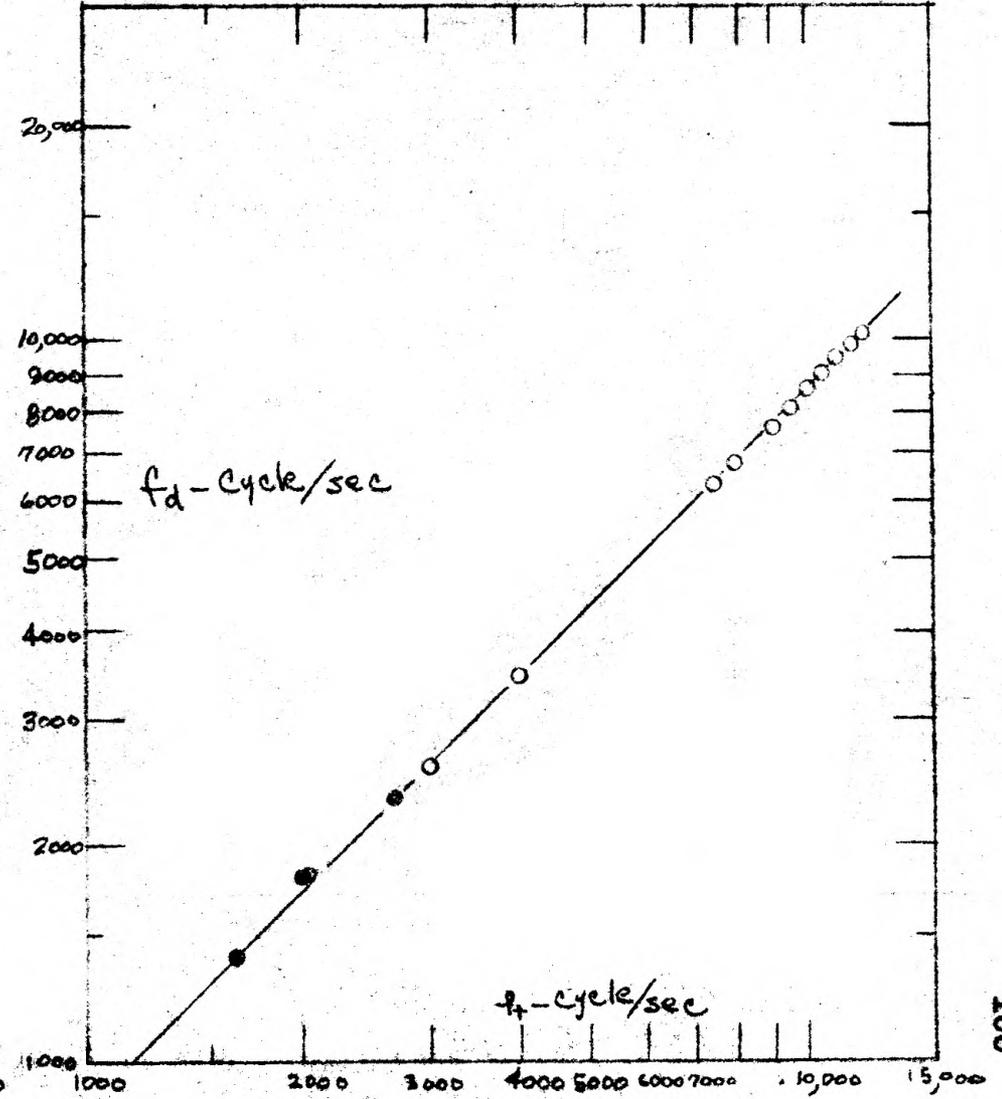
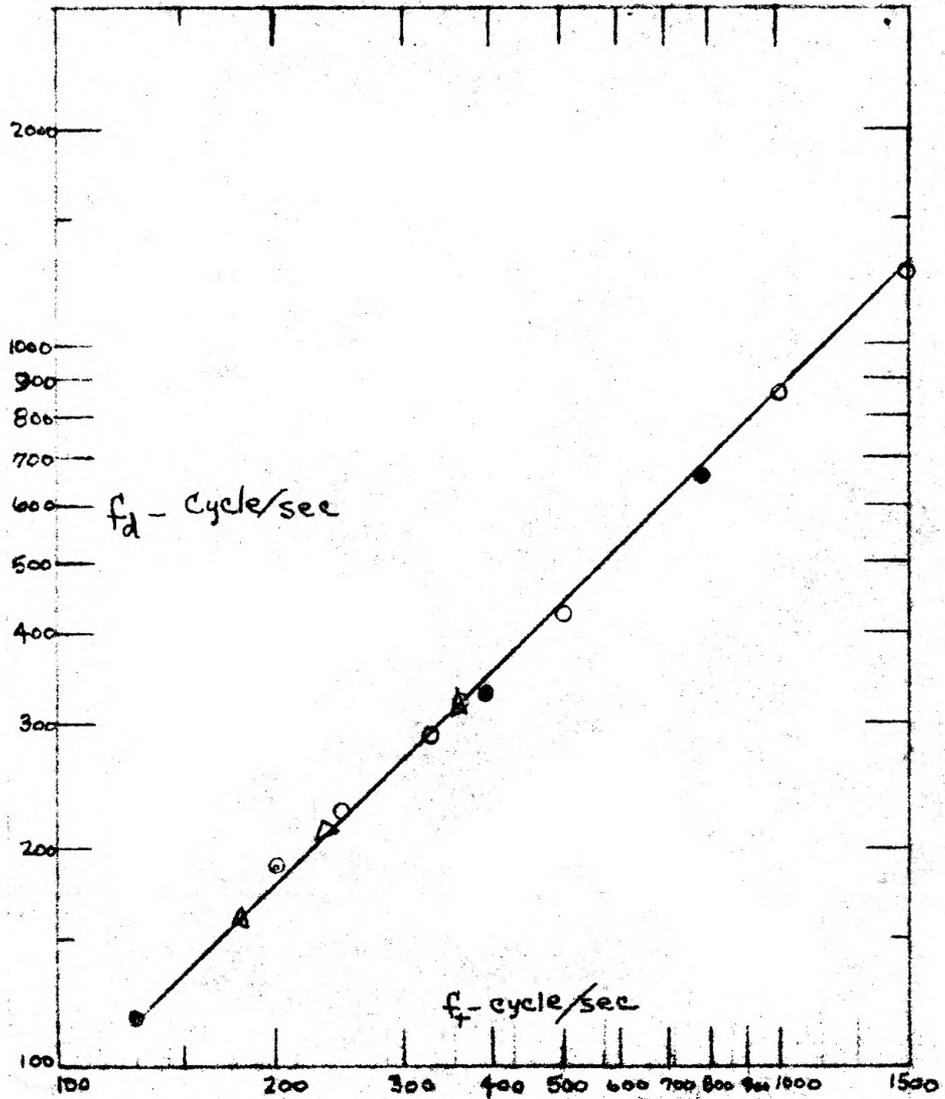
f_t = true frequency

○ = using signal of 1000 cycle/sec
generated by transistor oscillator
as standard frequency

● = using signal of 400 cycle/sec
generated by transistor oscillator
as standard frequency

△ = using line-frequency of 60 cycle/sec
as standard frequency

PLATE XXIX



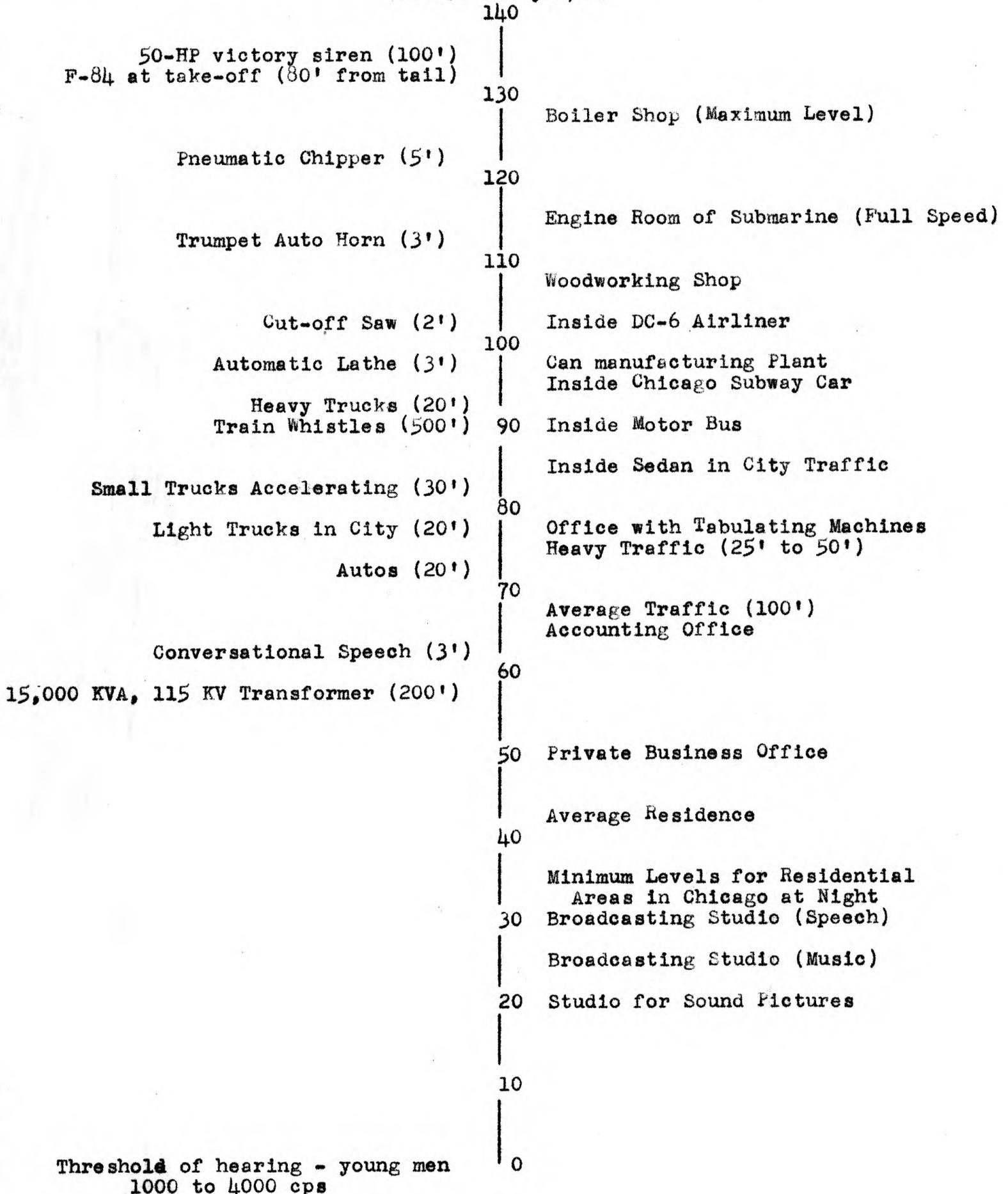
EXPLANATION OF PLATE XXX

Typical sound levels measured
with a sound-level meter. (15)

At a given distance from noise source

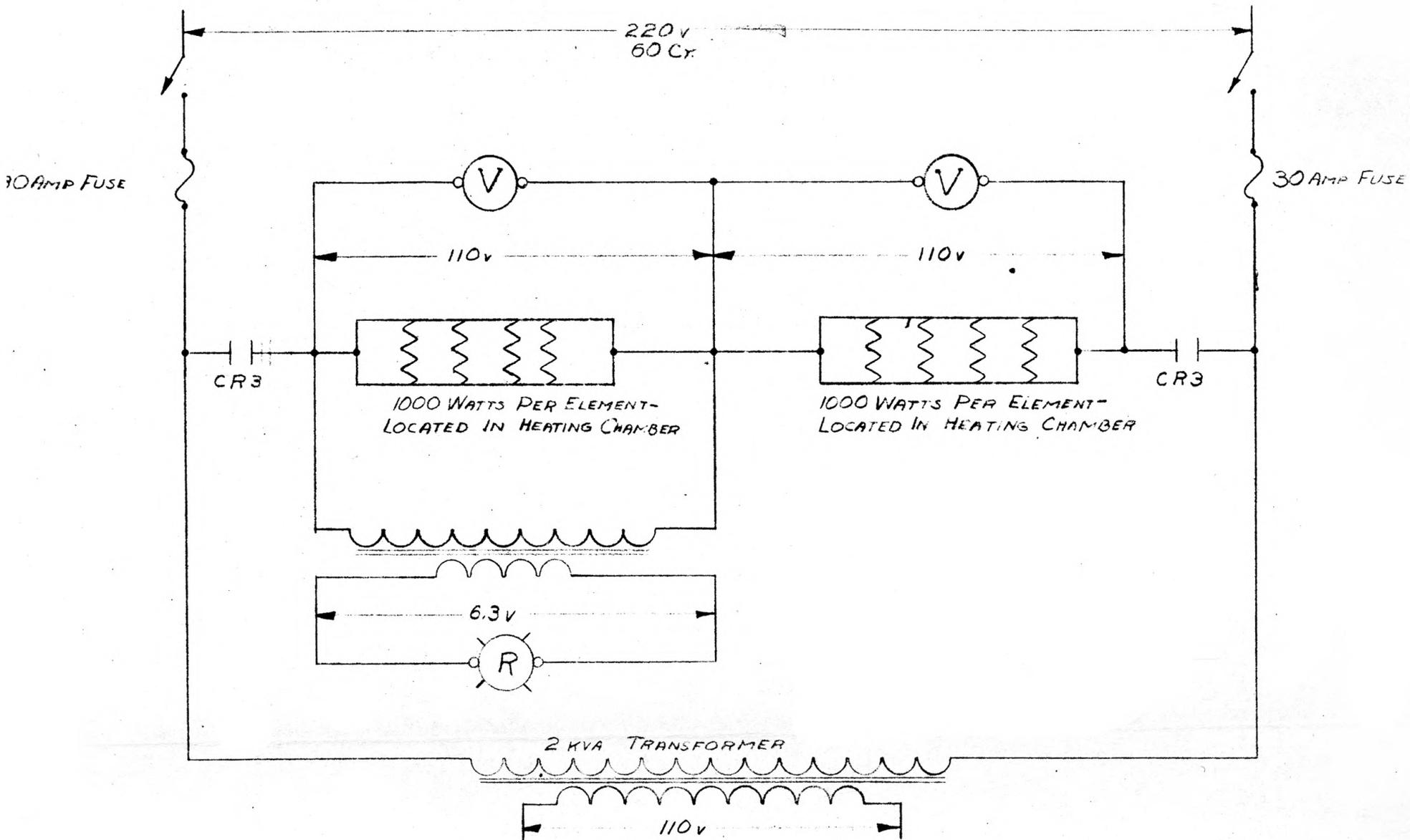
Environmental

decibels
re 0.0002 dyne/cm²



EXPLANATION OF PLATE XXXI

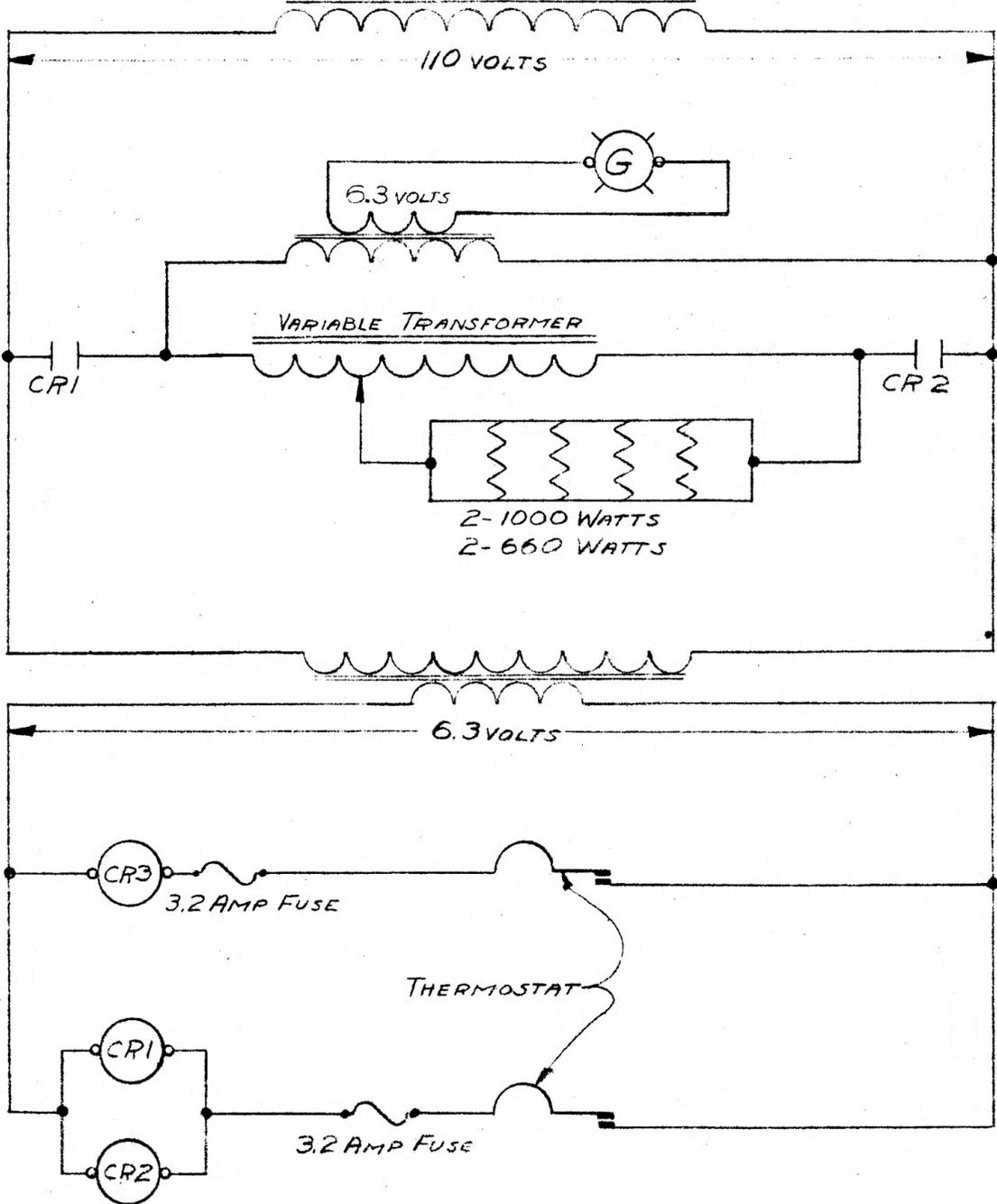
Heating circuit of heater



FOR CONTINUATION - SEE NEXT page

PLATE XXXI (CONT.)

FOR CONTINUATION SEE Last Page



Since the measuring tube was always at room temperature,
the density of water = 1 gm/ml.

Therefore $v/t = 2.73 \times 10^{-4}$ g/sec.

The area of vaporization surface was 8.4 cm².

$$\begin{aligned} \text{Therefore } \bar{R} &= v/tA = \frac{2.73}{8.4} = \overset{3.25}{6.83} \times 10^{-5} \frac{\text{g}}{\text{sec. cm}^2} \\ &= (0.334) \frac{(1)}{(454)} (30.48)^2 = 6.83 \times 10^{-5} \text{ lb/sec.ft}^2 \end{aligned}$$

Table 2. Original data.

A = 8.4 cm²

Run No.:	G lb secft ²	T C	h cm	f cycle/sec	V volt	I db	t sec	V ml	V/t x 10 ⁴ ml/sec	R x 10 ⁵ lb/secft ²
D-4-01	0.017	31	86	--*	--*	--*	157.6	0.01148	0.729	1.82
02	"	"	"	1170	10.5	124	109.0	"	1.05	2.63
03	"	"	"	1160	6.5	124	138.8	"	0.837	2.06
04	"	"	"	--	--	--	164.7	"	0.698	1.74
05	"	"	"	1160	23.2	130	50.8	"	2.26	5.65
06	"	"	"	1160	23.2	130	51.0	"	2.25	5.65
07	"	"	"	1160	20.5	129	76.4	"	1.50	3.76
08	"	"	"	2350	22	132	175.0	"	0.656	1.64
09	"	"	"	1000	18.5	130	145	"	0.792	1.98
10	"	"	"	2350	22	132	164	"	0.700	1.75
11	"	"	"	--	--	--	136.5	"	0.843	2.10
12	"	"	"	--	--	--	142.0	"	0.809	2.02
13	"	"	"	1600	18	130	140.0	"	0.820	2.05
14	"	"	"	--	--	--	132.4	"	0.867	2.16
15	"	"	"	2350	20	130	154.3	"	0.744	1.85
16	"	"	"	"	"	"	152.0	"	0.755	1.89
D-5-01	0	30.5	"	--	--	--	236.0	"	0.486	1.21
02	0	"	"	1140	17	124	163.0	"	0.705	1.76
04	0	"	"	1150	13	124	104.0	"	1.10	2.75
05	0	"	"	1170	10.5	124	113.7	"	1.01	2.51
06	0	"	"	1200	15.5	124	178.4	"	0.644	1.61
07	0	"	"	1750	12	124	174.5	"	0.659	1.65
08	0	"	"	1600	7.5	124	212.5	"	0.540	1.35
09	0	"	"	--	--	--	215.5	"	0.533	1.44
10	0	"	"	--	--	--	256.7	"	0.447	1.12
11	0	"	"	1400	11.5	124	235.0	"	0.489	1.22
12	0	30	"	1150	13	124	104.2	"	1.10	2.75

* No sound applied

Table 2. (cont.) Original data.

A = 8.4 cm²

Run No. : G lb : T C : h cm : f cycle/sec : V volt : I db : t sec : V ml : V/t x 10⁴ ml/sec : R x 10⁵ lb/sect²

D-5-13	0	30	86	--*	--*	--*	245.0	0.01148	0.460	1.15
14	0	"	"	1200	15.5	124	177.5	"	0.647	1.65
15	0	"	"	1600	7.5	124	198.4	"	0.579	1.45
16	0	"	"	1198	12.2	124	176.0	"	0.661	1.65
17	0	"	"	2350	8.5	124	246	"	0.466	1.16
18	0	"	"	--	--	--	353	"	0.454	1.12
M-16-01	0.098	51.8	41.5	--	--	--	167.3	"	2.52	6.30
02	"	52.2	"	--	--	--	167.3	"	2.52	6.30
03	"	51.9	21.3	--	--	--	167.3	"	2.52	6.30
04	"	52.0	"	--	--	--	166.5	"	2.53	6.33
05	"	51.8	"	--	--	--	166.6	"	2.53	6.33
06	"	53.6	"	--	--	--	166.4	"	2.53	6.33
07	"	52.0	"	--	--	--	166.5	0.0421	2.53	6.33
08	"	52.0	"	--	--	--	165.0	"	2.55	6.37
09	"	52.0	"	--	--	--	165.0	"	2.55	6.37
10	"	51.8	41.5	--	--	--	164.2	"	2.56	6.40
11	"	51.7	"	--	--	--	163.0	"	2.58	6.45
12	"	52.0	"	--	--	--	163.5	"	2.57	6.44
13	"	52.0	"	--	--	--	164.0	"	2.56	6.40
14	"	51.9	"	--	--	--	163.0	"	2.58	6.45
15	"	51.8	"	--	--	--	163.2	"	2.58	6.45
16	"	51.8	0.9	--	--	--	161.2	"	2.61	6.52
17	"	51.7	"	--	--	--	162.9	"	2.58	6.45
18	"	52.0	"	--	--	--	162.0	"	2.60	6.50
19	"	51.7	"	--	--	--	162.0	"	2.60	6.50
20	"	51.7	"	--	--	--	161.0	"	2.62	6.55
21	"	51.7	0.4**	--	--	--	161.0	"	2.62	6.55

* No sound applied

** The minus sign means positive water head

Table 2. (cont.) Original data.

A = 8.4 cm²

Run No.:	G lb : secft ²	T C	h cm	f : cycle/sec	V : volt	I : db	t sec	V ml	V/t x 10 ⁴ : ml/sec	\bar{R} x 10 ⁵ : lb/secft ²
M-16-22	0.098	52.0	-0.4*	---	---	---	163.0	0.0421	2.58	6.45
23	"	52.0	"	---	---	---	160.0	"	2.63	6.58
24	"	51.8	"	---	---	---	163.2	"	2.58	6.45
25	"	52.0	"	---	---	---	163.5	"	2.58	6.45
28	"	52.0	2.0	---	---	---	161.0	"	2.62	6.54
29	"	52.0	"	---	---	---	161.0	"	2.62	6.54
30	"	52.0	"	---	---	---	162.8	"	2.59	6.47
31	"	52.0	"	---	---	---	163.0	"	2.58	6.45
32	"	"	3.0	---	---	---	158.5	"	2.66	6.65
33	"	"	"	---	---	---	159.2	"	2.64	6.60
34	"	"	"	---	---	---	160.8	"	2.62	6.55
37	"	"	"	---	---	---	163.0	"	2.59	6.58
38	"	"	"	---	---	---	161.5	"	2.60	6.50
M-18-01	"	53.9	21.3	---	---	---	163.6	"	2.58	6.46
02	"	53.8	"	---	---	---	163.4	"	2.58	6.45
03	"	53.9	"	---	---	---	160.0	"	2.63	6.57
04	"	53.9	"	---	---	---	161.0	"	2.62	6.55
05	"	53.9	"	---	---	---	160.8	"	2.62	6.55
06	"	53.9	82	---	---	---	159.6	"	2.64	6.55
07	"	54.1	"	---	---	---	158.6	"	2.66	6.60
08	"	54.6	"	---	---	---	160.6	"	2.62	6.55
09	"	54.0	"	---	---	---	159.0	"	2.65	6.63
10	"	54.3	"	---	---	---	156.2	"	2.70	6.75
11	"	54.4	"	---	---	---	159.0	"	2.65	6.62
12	"	54.2	"	---	---	---	160.4	"	2.63	6.47
13	"	54.5	"	---	---	---	159.0	"	2.65	6.62
14	"	54.2	2.7	---	---	---	159.0	"	2.65	6.62

* The minus sign means positive water head

** No sound applied

Table 2. (cont.) Original data.

A = 8.4 cm²

Run No.:	G lb secft ²	T C	h cm	f cycle/sec	V volt	I db	t sec	V ml	V/t x 10 ⁴ ml/sec	H x 10 ⁵ lb/secft ²
M-18-15	0.098	54.0	2.7	---	---	---	158.8	0.0021	2.65	6.62
16	"	54.2	"	---	---	---	158.5	"	2.66	6.65
17	"	54.1	"	---	---	---	159.5	"	2.64	6.60
18	"	54.2	-0.4**	---	---	---	159.3	"	2.64	6.60
19	"	54.1	"	---	---	---	159.0	"	2.65	6.62
N-19-01	0	26.5	0	---	---	---	307.3	"	0.374	0.935
02	0	"	0	1150	15	125	116.4	"	0.986	2.48
03	0	"	0	---	---	---	314.4	"	0.366	0.912
04	0	"	0	1150	15	125	119.8	"	0.961	2.40
05	0	26.5	0	1150	8.0	120	186.2	0.01148	0.616	1.55
06	0	"	0	"	12.5	123.5	168.5	"	0.681	1.71
07	0	"	0	"	3	112	317.8	"	0.362	0.905
08	0	"	0	"	0.5	118	215.6	"	0.533	1.33
09	0	"	0	"	20.5	129	81.2	"	1.41	3.51
10	0	"	0	---	---	---	32.8	"	0.350	0.875
11	0	"	0	1150	20	126	86.8	"	1.32	3.30
N-25-01	0.016	28	86	---	---	---	166.2	"	0.691	1.73
02	"	"	"	---	---	---	162.0	"	0.710	1.78
03	"	"	"	1150	20.5	129	65.2	"	1.76	4.0
04	"	"	"	"	20.5	129	70.4	"	1.63	4.08
05	"	"	"	"	22	128	66.5	"	1.73	4.32
06	"	"	"	"	22	128	66.0	"	1.74	4.35
07	"	"	"	"	15	125	96.4	"	1.19	2.98
08	"	"	"	"	14	125	89.0	"	1.29	3.22
09	"	"	"	"	15	125	88.0	"	1.31	3.28
10	"	"	"	"	10	122	116.4	"	0.986	2.47
11	"	"	"	---	---	---	170.0	"	0.675	1.69

* No sound applied

** The minus sign means positive water head

Table 2. (cont.) Original data.

A = 8.4 cm²

Run No.:	G lb secft ²	T C	H cm	f cycle/sec	V volt	I db	t sec	V ml	V/t x 10 ⁴ ml/sec	R x 10 ⁵ lb/secft ²
N-25-12	0.016	28	86	---	---	---	168.0	0.01148	0.684	1.71
13**	"	"	"	1150	5	116	163.0	"	0.705	1.76
14**	"	"	"	"	5	116	161.6	"	0.711	1.78
15**	"	"	"	"	5	116	153.4	"	0.730	1.83
16**	"	"	"	"	5	116	154.6	"	0.743	1.85
17**	"	"	"	"	5	116	160.5	"	0.716	1.78
18**	"	"	"	"	5	116	156.2	"	0.737	1.84
19	"	"	"	---	---	---	158.4	"	0.725	1.81
20	"	"	"	---	---	---	159.2	"	0.721	1.80
21	"	"	"	---	---	---	158.3	"	0.725	1.81
22	"	"	"	1150	12.5	123.5	100.8	"	1.14	2.85
23	"	"	"	"	"	"	101.8	"	1.13	2.82
24	"	"	"	"	17.5	126	74.8	"	1.53	3.86
25	"	"	"	"	17.5	126	74.8	"	1.53	3.86
26	"	"	"	"	20.5	129	77.8	"	1.48	3.69
27	"	"	"	"	20.5	129	79.4	"	1.45	3.62
28	"	"	"	"	3	112	167.0	"	0.688	1.72
29	"	"	"	"	20.5	129	73.2	"	1.57	3.92
30	"	"	"	"	20.5	129	76.0	"	1.51	3.78
31	"	"	"	"	8	120	135.8	"	0.846	2.11
32	"	"	"	"	8	120	136.2	"	0.844	2.10
33	"	"	"	"	6	118	158.4	"	0.726	1.81
34	"	"	"	"	7	119	146.0	"	0.787	1.97
36	"	"	"	---	---	---	87.2	"	1.31	3.28
37	"	"	"	1150	8	120	83.3	"	1.38	3.45
38	"	"	"	"	20.5	129	67.8	"	1.69	4.21
39	"	"	"	"	6.5	118.3	84.0	"	1.37	3.42
40	"	"	"	---	---	---	85.6	"	1.33	3.32

* No sound applied

** The sound was applied continuously during these six runs. The data were taken 2, 17, 24, 41, 53, and 67 minutes after starting the sound driver respectively.

Table 2. (cont.) Original data.

A = 8.4 cm²

Run No.:	G lb: secft ² :	T C :	h cm:	f cycle/sec:	V : volt:	I : db :	t sep:	V ml:	V/t x 10 ⁴ : ml/sec :	\bar{R} x 10 ⁵ : lb/secft ²
N-25-41	0.064	28.5	86	--*	--*	--*	73.1	0.01148	1.57	3.92
42	"	"	"	--	--	--	88.3	"	1.30	3.25
43	"	"	"	"	6.5	118.3	86.2	"	1.33	3.32
44	"	"	"	"	"	"	84.8	"	1.35	3.38
45	"	"	"	"	8	120	85.6	"	1.34	3.35
46	"	"	"	"	9	121	85.3	"	1.35	3.38
47	0.037	29.2	"	--	--	--	110.2	"	1.04	2.60
49	"	"	"	"	20.5	129	68.2	"	1.68	4.20
50	"	29.5	"	"	"	"	69.2	"	1.66	4.15
51	"	29.0	"	"	5	116	111.5	"	1.03	2.58
52	"	"	"	"	"	"	111.0	"	1.03	2.58
53	"	"	"	"	17.5	126	74.6	"	1.54	3.85
54	"	"	"	"	"	"	74	"	1.55	3.88
55	"	"	"	"	8	120	115	"	1.00	2.50
56	"	"	"	"	9	121	104	"	1.10	2.75
57	"	"	"	--	--	--	109	"	1.05	2.62
58	"	"	"	"	15	125	85.7	"	1.34	3.35
59	"	"	"	"	"	"	84.7	"	1.36	3.40
60	"	"	"	"	8	120	117.3	"	0.98	2.46
61	"	"	"	--	--	--	109.2	"	1.05	2.62
62	"	"	"	"	6.5	118.3	113.0	"	1.01	2.75
63	"	"	"	"	12.5	123.5	93.6	"	1.13	2.82
64	"	"	"	"	10	122	103.0	"	1.11	2.52
65	"	"	"	"	4	114.5	117.0	"	0.98	2.45
66	"	"	"	"	2	108.5	112.0	"	1.02	2.55
67	"	"	"	"	1	103	105.55	"	1.09	2.72
68	"	"	"	--	--	--	111.6	"	1.03	2.58
N-26-01	0.064	28.5	"	--	--	--	97.8	"	1.17	2.92
02	"	"	"	1150	22	128	74.2	"	1.55	3.88

* No sound applied

Table 2. (cont.) Original data.

A = 8.4 cm²

Run No.:	G lb secft ²	T C	h cm	f cycle/sec	V volt	I db	t sec	V ml	V/t x 10 ⁴ ml/sec	R x 10 ⁵ lb/secft ²
N-26-03	0.064	28.5	86	1150	17.5	126	76.8	0.01148	1.50	3.75
04	"	"	"	"	17.5	126	76.2	"	1.51	3.78
05	"	"	"	"	17.5	126	76.0	"	1.51	3.78
06	"	"	"	"	5	116	93.4	"	1.23	3.08
07	"	"	"	"	10	122	83.2	"	1.38	3.45
08	"	"	"	"	8	120	91.6	"	1.25	3.12
09	"	"	"	"	12.5	123.5	81.8	"	1.40	3.50
10	"	"	"	"	9	121	84.0	"	1.37	3.42
11	"	"	"	"	4	114.5	92.8	"	1.24	3.10
12	"	"	"	"	14	125	75.5	"	1.52	3.80
13	"	"	"	"	17.5	126	70.4	"	1.63	4.07
14	"	"	"	"	20.5	129	70.8	"	1.62	4.05
15	"	"	"	"	17.5	126	69.6	"	1.65	4.12
16	"	"	"	"	20.5	129	64.0	"	1.80	4.50
17	"	"	"	"	20.5	129	63.5	"	1.81	4.52
18	"	"	"	---	---	---	92.4	"	1.27	3.18
19	"	"	"	1150	10	122	83.8	"	1.37	3.42
20	"	"	"	"	10	122	84.0	"	1.36	3.40
21	"	"	"	"	10	122	84.5	"	1.36	3.40
22	"	"	"	"	20.5	129	68.0	"	1.69	4.22
23	"	"	"	"	20.5	129	68.3	"	1.68	4.20
24	"	"	"	"	9**	121	86.2	"	1.33	3.32
25	"	"	"	"	"	121	83.2	"	1.38	3.45
26	"	"	"	"	"	121	82.0	"	1.40	3.50
27	"	"	"	"	"	121	80.0	"	1.43	3.32
28	"	"	"	"	"	121	80.6	"	1.42	3.55
29	"	"	"	"	"	121	81.2	"	1.41	3.52
30	"	"	"	"	"	121	78.7	"	1.46	3.55

* No sound applied

** The sound was applied continuously during these runs. The data were taken 1, 10, 17, 22, 30, 35, 45 minutes after starting the sound driver respectively.

Table 2. (cont.) Original data.

A = 8.4 cm²

Run No.:	G lb : sacft ²	T C	h cm	f : cycle/sec	V : volt	I : db	t sec	V ml : ml	V/t x 10 ⁴ : ml/sec	R _x 10 ⁵ : lb/sacft ²
N-26-31	0.064	28.5	86	1150	9**	121	80.2	0.01148	1.43	3.58
32	"	"	"	"	"	121	78.9	"	1.46	3.55
33	"	"	"	"	"	121	80.0	"	1.43	3.58
34	"	"	"	"	8	120	86.0	"	1.33	3.33
35	"	"	"	"	8	120	84.7	"	1.36	3.40
N-27-01	0.037	29	"	"	6.5	118.3	122.0	"	0.943	2.36
02	"	"	"	---	---	---	122.0	"	0.943	2.36
03	"	"	"	1150	8.0	120	118.0	"	0.975	2.44
04	"	"	"	"	20.5	129	74.0	"	1.55	3.88
05	"	"	"	"	"	129	75.0	"	1.57	3.92
06	0.080	"	"	"	--	--	84.0	"	1.37	3.42
07	"	"	"	"	"	129	73.3	"	1.57	3.92
08	"	"	"	"	5	116	87.7	"	1.31	3.28
09	"	"	"	"	"	"	87.0	"	1.32	3.30
10	"	"	"	---	---	---	82.2	"	1.40	3.50
11	"	"	"	"	15	118.5	73.4	"	1.56	3.90
12	"	"	"	"	8	120	87.0	"	1.32	3.30
13	"	30	"	"	9	121	84.4	"	1.36	3.40
14	"	"	"	"	2	108.5	87.3	"	1.31	3.28
15	"	"	"	---	---	---	83.0	"	1.38	3.45
16	"	"	"	1150	2	108.5	87.0	"	1.32	3.30
17	"	"	"	"	1	103	85.6	"	1.34	3.35
18	"	"	"	"	10	122	80.5	"	1.43	3.56
19	"	"	"	"	0.5	97	78.6	"	1.46	3.65
20	"	"	"	"	"	"	78.8	"	1.46	3.65
21	"	"	"	"	1.25	106	86	"	1.33	3.32
22	"	"	"	"	5	116	88	"	1.30	3.25
23	"	"	"	"	12.5	123.5	74.8	"	1.53	3.82

* No sound applied

** The sound was applied continuously during these runs. The data were taken 45, 57, and 63 minutes after starting the sound driver respectively.

Table 2. (cont.) Original data.

A = 8.4 cm²

Run No.:	G lb : secft ²	C : h cm:	f : cycle/sec:	V : volt:	I : db :	t sec:	V ml:	:v/t x 10 ⁴ : ml/sec	\bar{R} x 10 ⁵ : lb/secft ²	
N-27-24	0.080	30	86	1150	10	122	83.0	0.01148	1.38	3.45
25	"	"	"	"	0.5	100	78.5	"	1.46	3.65
26	"	"	"	"	9	121	86.0	"	1.33	3.33
N-29-03	"	28.4	"	---	---	---	78.2	"	1.45	3.62
04	"	"	"	---	---	---	78.8	"	1.47	3.68
05	"	"	"	---	---	---	78.8	"	1.46	3.65
06	0.037	"	"	---	---	---	119.3	"	0.952	2.38
07	"	"	"	---	---	---	119.6	"	0.96	2.40
08	0.064	28.3	"	---	---	---	85.4	"	1.21	3.02
09	"	"	"	---	---	---	92.0	"	1.25	3.13
10	"	"	"	1150	20.5	129	73.2	"	1.57	3.92
11	0.012	"	"	---	---	---	51.2	"	2.24	5.60
12	"	"	"	"	20.5	129	55.2	"	2.09	5.04
13	"	"	"	"	"	"	54.2	"	2.11	5.28
14	"	"	"	---	---	---	51.8	"	2.21	5.52
15	"	"	"	---	---	---	52.2	"	2.20	5.05
16	"	"	"	1150	0.5	97	56.8	"	2.02	5.05
17	"	"	"	---	---	---	53.4	"	2.15	5.38
18	0.118	28.4	86	---	---	---	57.2	"	2.02	5.05
19	"	"	"	1150	20.5	129	56.2	"	2.04	5.10
20	"	"	"	"	0.5	97	66.4	"	1.73	4.32
21	"	"	"	---	---	---	66.2	"	1.74	4.35
22	0.094	27.4	"	1150	20.5	129	65.4	"	1.76	4.40
23	"	"	"	"	0.5	97	67.0	"	1.72	4.30
24	"	"	"	---	---	---	65.0	"	1.77	4.42
25	"	"	"	1150	0.5	97	65.8	"	1.75	4.38
26	0.017	"	"	---	---	---	160.3	"	0.715	1.79
27	"	"	"	1150	20.5	129	74.5	"	1.55	3.87
28	0.080	"	"	"	20.5	129	78.2	"	1.47	3.68
29	"	"	"	"	20.5	129	67.0	"	1.71	4.28

* No sound applied

Table 2. (cont.) Original data.

A = 8.4 cm²

Run No.:	G lb secft ²	T C	h cm	f cycle/sec	V volt	I db	t sec	V ml	V/t x 10 ⁴ ml/sec	R x 10 ⁵ lb/secft ²
N-29-30	0.037	27.4	86	1150	20.5	129	68.0	0.01148	1.69	4.22
31	"	"	"	--*	--*	--*	112.0	"	1.02	2.55
32	"	26.4	"	1150	20.5	129	74.0	"	1.55	3.87
33	-	"	"	"	20.5	129	83.0	"	1.40	3.50
34	-	"	"	--	--	--	277	"	0.415	1.04
35	0	"	"	1150	20.5	129	82	"	1.47	3.67
36	"	26.5	"	--	--	--	83.3	"	1.38	3.45
37	"	"	"	--	--	--	83.5	"	1.37	3.43
38	"	"	"	--	--	--	331.0	"	0.347	0.868
39	"	"	"	--	--	--	317.8	"	0.362	0.905
40	"	"	"	1150	20.5	129	79.8	"	1.45	3.62
41	"	"	"	"	15	125	93.8	"	1.22	3.05
42	"	"	"	"	12.5	123.5	111.4	"	1.03	2.58
43	"	"	"	"	10	122	135.0	"	0.850	2.13
44	"	"	"	"	8	120	197.3	"	0.582	1.46
45	"	"	"	"	9	121	157.0	"	0.732	1.83
46	"	"	"	"	6.5	118.3	244.5	"	0.470	1.18
47	"	"	"	"	0.5	97	276.0	"	0.416	1.04
48	"	"	"	"	--	--	274.0	"	0.420	1.05
49	"	"	"	"	5	116	301.5	"	0.381	0.954
50	"	"	"	"	4	114	307.0	"	0.374	0.936
51	"	"	"	"	10	122	116.0	"	0.986	2.47
U-10-01	0.112	55.0	21.3	--	--	--	170.0	0.0464	2.73	6.83
02	"	"	"	--	--	--	170.3	"	2.73	6.83
03	"	"	72.6	--	--	--	170.3	"	2.73	6.83
04	"	"	72.6	--	--	--	170.7	"	2.72	6.80
05	"	"	83.6	--	--	--	172.0	"	2.70	6.75
06	"	"	83.6	--	--	--	170.4	"	2.73	6.83
07	"	"	91.3	--	--	--	171.5	"	2.70	6.75

* No sound applied

Table 2. (cont.) Original data.

A = 8.4 cm²

Run No. : G lb : : : f : V : I : : : V/t x 10⁴ : \bar{R} x 10⁵
 : secft² : T C : h cm : cycle/sec : volt : db : t sec : V ml : ml/sec : lb/secft²

U-10-08	0.112	55.0	91.3	---	*	---	*	---	*	173.5	0.0464	2.73	6.83
09	"	"	91.3	---	---	---	---	---	---	172.5	"	2.69	6.73
10	"	"	91.3	---	---	---	---	---	---	171.5	"	2.70	6.75
11	"	"	105.0	---	---	---	---	---	---	173.8	"	2.68	6.70
12	"	"	105.0	---	---	---	---	---	---	171.5	"	2.70	6.75
13	"	"	107.0	---	---	---	---	---	---	172.2	"	2.70	6.75
14	"	"	107.0	---	---	---	---	---	---	176.0	"	2.64	6.60
15	"	54.5	107.0	---	---	---	---	---	---	170.7	"	2.72	6.80
16	"	"	107.0	---	---	---	---	---	---	173.5	"	2.67	6.68
17	"	"	107.0	---	---	---	---	---	---	170.8	"	2.72	6.80
18	"	55.0	103.4	---	---	---	---	---	---	168.7	"	2.75	6.88
19	"	"	103.4	---	---	---	---	---	---	169.0	"	2.74	6.85
20	"	"	119.4	---	---	---	---	---	---	170.5	"	2.72	6.80
21	"	"	126.4	---	---	---	---	---	---	171.5	"	2.70	6.75
22	"	"	134.4	---	---	---	---	---	---	171.5	"	2.70	6.75
23	"	54.8	134.4	---	---	---	---	---	---	172.0	"	2.70	6.75
24	"	"	145.0	---	---	---	---	---	---	The liquid layer broke			
U-23-01	0.114	55.0	23.3	---	---	---	---	---	---	170.6	0.0464	2.72	6.80
02	"	"	"	---	---	---	---	---	---	169.6	"	2.74	6.85
03	"	"	"	320	150**	124	---	---	---	146.8	"	3.16	7.90
04	"	"	"	"	"	"	---	---	---	"	"	"	"
05	"	"	106	---	---	---	---	---	---	172.0	"	2.69	6.62
06	"	"	"	---	---	---	---	---	---	172.5	"	2.69	6.62
07	"	"	"	320	150**	124	---	---	---	155.6	"	2.98	7.45
08	"	"	"	"	"	"	---	---	---	154.4	"	3.00	7.50
09	"	"	"	"	"	"	---	---	---	152.4	"	3.04	7.60
10	"	"	"	"	"	"	---	---	---	155.6	"	2.98	7.45
11	"	"	"	---	---	---	---	---	---	168.4	"	2.75	6.88
12	"	"	"	---	---	---	---	---	---	172.0	"	2.70	6.75

* No sound applied
 ** D. C. current

Table 2. (concl.) Original data.

A = 8.4 cm²

Run No.: G lb : T C : h cm: f cycle/sec: V : I : db : t sec: V ml: ml/sec : V/t x 10⁴: R x 10⁵ : lb/sect²

U-23-13	0.114	55.0	0.4	---	---	---	167.5	0.0464	2.77	6.82
14	"	"	"	--	--	--	167.0	"	2.78	6.95
15	"	"	"	--	--	--	167.0	"	2.78	6.95
16	"	"	"	320	150**124	"	110.0	"	4.21	10.5
17	"	"	"	"	"	"	116.0	"	4.00	10.0
18	"	"	"	"	"	"	119.5	"	3.88	9.70
19	"	"	"	"	"	"	118.5	"	3.92	9.80
20	"	"	135	--	--	--	174.6	"	2.76	6.90
21	"	"	"	320	150**124	"	159.5	"	2.91	7.28
22	"	"	"	--	--	--	175.2	"	2.65	6.62
23	"	"	"	320	150**124	"	158.5	"	2.93	7.33
24	"	"	144	"	"	"	161.0	"	2.88	7.20
25	"	"	"	--	--	--	177.5	"	2.65	6.62
26	"	"	"	320	150 124	"	153.0	"	3.03	7.57
27	"	"	"	"	"	"	152.4	"	3.04	7.60
28	"	"	"	"	150/ 124/	"	148.0	"	3.13	7.82
29	"	"	"	"	"	"	150	"	3.09	7.74
30	"	"	"	--	--	--	177.5	"	2.61	6.53

* No sound applied

** D. A. current

THE EFFECT OF SONIC VIBRATIONS
ON THE RATES OF MASS TRANSFER

by

CHUN-FEI CHUEH

B. S., National Taiwan University, China, 1955

AN ABSTRACT OF A THESIS

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In this investigation, the audio sonic waves were used as a tool to increase the rate of mass transfer between phases. The experimental data indicated that the sonic pulsations with suitable frequency (1,150 cycle/sec) and strong intensity (129 db), might increase the rates of vaporizing liquid water (into air under natural convection and 80°F) up to 210 per cent compared with that without sound. Such effect was in general increased with the increase of intensity of sound applied and reduced under force convection with high velocity of air. The frequency of sound was found to be a very sensitive factor and it is possible that the rates of mass transfer can only be affected when a resonance frequency is applied. The water was vaporized from a thin liquid layer with the thickness in the order of 10^{-3} cm; an equation which was developed showed the surface tension of such thin layer was enough to prevent the significant area change of liquid surface due to the sonic pulsation with the intensity of 130 db. Therefore, such increases of rates of mass transfer were supposedly due to the disturbance of stagnant gas film caused by the sonic pulsation.