THE EFFECT OF SONIC VIBRATIONS ON THE RATES OF MASS TRANSFER

by

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INTRODUCTION

Review of Literature

In reviewing the literature on the use of sonic energy or vibrations as a tool to aid mass transfer, it was apparent that opinions differed regarding the mechanics or theory of how sonic energy aided in mass transfer. Work has been done in the high frequency range, ultra-sonic, and work has also been done in the low frequency range, audible range. Possibly the work was done in the low frequency range of sound because the audible sound was easier and less complicated to handle. However, Auerbauch (1) felt that the low frequency range of mechanical vibrations were of more economic importance in process engineering than the high frequency range of vibrations.

As examples of differences in proposed mechanics, consider the works of McKittrick and Garnish (8), of Richardson (10) and of Chueh (4). McKittrick and Garnish received a patent in 1941 for a distillation process which used sonic vibrations of frequencies between 50 and 5,000 cycles per second. 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. In 1950 Richardson introduced sonic vibrations into a reaction chamber and found that it was possible to reduce pressure requirements for the catalytic formation of ammonia from nitrogen and hydrogen from about 1,000 to about 10 atmospheres. He believed that the sonic vibrations created a mixing effect between the catalyst and the gas; this was due to the difference of mass between the catalyst and gas particles.

Mirsky (9) studied the effects of ultra-sonic energy on the evaporation of single liquid drops. He found that the evaporation rate was affected and that this effect was dependent upon both the field intensity and frequency of the ultra-sonic energy. Mirsky was unable to correlate between normal evaporation and evaporation in the ultra-sonic field because of the complex nature by which the field effects were dependent upon such parameters as relative air velocity, field frequency and intensity.

In 1957 Chun-fei Chueh (4) found that by applying sound at a frequency of 1,150 cycles per second and a strong intensity of 129 decibels, rate of vaporization of liquid water was increased up to 210 per cent when compared with the rate without sound. Chueh felt that the frequency of sound was a very sensitive factor and that it was possible that the rate of mass transfer could be affected only when a resonance frequency was applied. McKittrick and Garnish shared Chueh's opinion that sonic vibrations should be selected so that the vibrations would be in a state of resonance with the volume and shape of the equipment employed.

The reporting investigators (4, 8, 9, 10) showed that sonic vibrations increased the rate of mass transfer. They were not, however, able to agree on the optimum ranges of frequencies and intensities employed.

Objectives of Study

The objectives of this study were:

1. to correlate the effects of sonic vibrations on the rate of mass transfer.

2. to completely define, eg., place limits on, frequencies and intensities of the sonic vibrations.

3. to submit an explanation relating the sensitivity of mass transfer to the frequency and intensity of the sonic vibrations.

This work was limited to the range of frequencies 240 to 1,200 cycles per second.

Summary of Previous Investigations

Prior to this investigation, Chun-fei Chueh studied the effects of sonic vibration on the rate of mass transfer (Chueh, 4). The equipment used in this present study was basically the same as the equipment which Chueh employed. The following 3 basic assumptions were made by Chueh:

The thin water layer which was created on the top of a frittered glass plate was not altered by the action of audibly sonic waves of intensity up to 130 decibles (about 13 pounds per square foot).

The vapor pressure of the thin water layer was effectively the same as that of a free water layer.

The increase in the rate of vaporization was not caused by a "wind effect" created by the transducer.

Chueh presented experimental evidence to substantiate these assumptions and, accordingly, they were accepted as valid for the work reported herein.

THEORETICAL CONSIDERATIONS

The two film theory, prepared by Lewis and Whitman (7), was employed to explain why and how the rate of mass transfer was influenced by gas phase sonic pulsations. Lewis and Whitman's theory was based on an assumption that two thin films or layers of fluid existed at the interface between a liquid and gaseous phase. One was a liquid layer and the other was a gaseous layer. Both layers of fluid remained stagnant regardless of how turbulent the flow became in the bulk of the liquid and/or the gas phases.

Within these thin layers mass transfer can only take place by molecular diffusion. Also, within these films or layers, the major portion of resistance to mass transfer is encountered.

If the liquid phase contained one component and the components of the gaseous phase were insoluble in the liquid, the partial pressure at the interface, $(p_1)i$, Plate I, would equal the partial pressure in the main body of liquid phase, $(p_1)l$. This would mean that the resistance to mass transfer in the liquid layer or film was negligible. This type of system was called mass transfer under gas film control.

Under gas film control, the rate of steady state diffusion of one gas through a second stagnant gas layer or film was given by Sherwood (11):

$$\frac{N_A}{A} = \frac{D_G \ P \ (pA_1 - pA_2)}{R \ T \ X \ (pB) \ lm} \qquad (1)$$

where N_A = rate of diffusion of component A, mol/hour

A = area of mass transfer surface, $feet^2$

D_G = diffusion coefficient

P = pressure in atmospheres

R = gas law constant

pA_1 = vapor pressure component A in gas phase

pA_2 = vapor pressure component A in liquid phase

T = absolute temperature (°K.)

X = thickness of stagnant gaseous film

$(pB)lm$ = $\log_e$ mean value of pB_1 and pB_2

The relationship between the thickness of the stagnant layer, and the mass velocity of gas flow in the gaseous phase, G, was expressed as:

$$\frac{1}{X} = K(G)^n \qquad (2)$$

Investigators (5, 6) believed that n was constant but the values which were experimentally determined varied from 0.56 to 0.83. Bakowski (2) felt that n was a function of G and varied directly as G was varied. The thickness of the stagnant layer, X, played an important part in all mass transfer operations which involved a gaseous phase.

Diffusivity of gas systems was given by Gilliland (5):

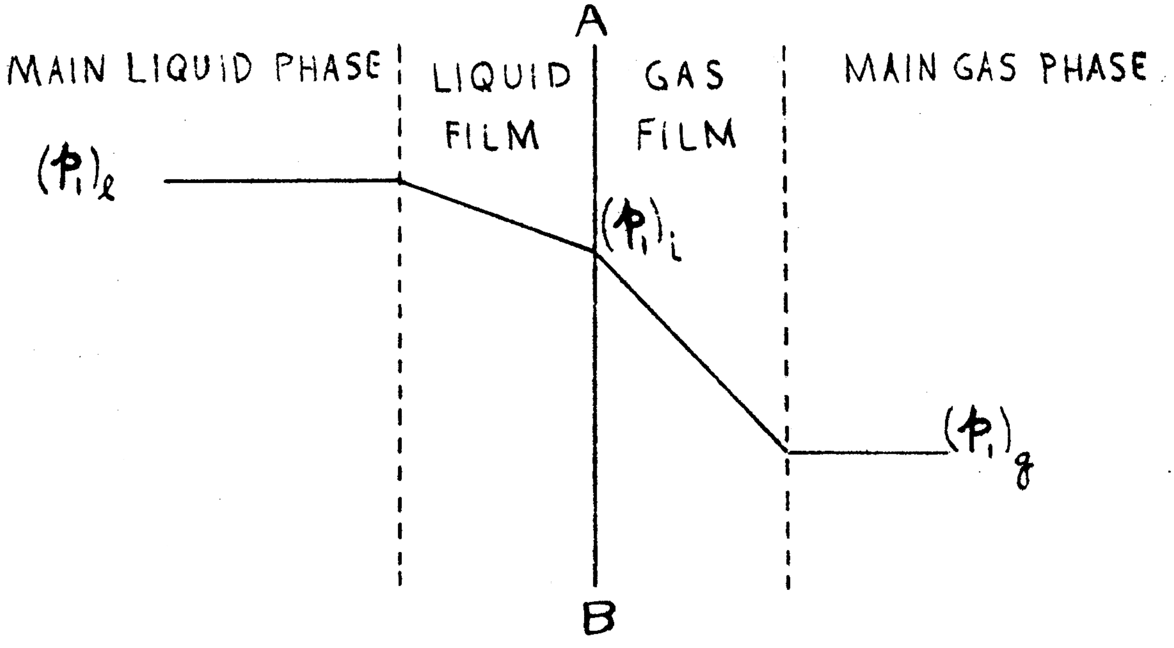
$$D_G = 0.0166 \frac{T^{3/2}}{P(V_A^{1/3} \quad V_B^{1/3})^2} \quad \frac{1}{M_A} \quad \frac{1}{M_B} \qquad (3)$$

EXPLANATION OF PLATE I

Diagram of the two film theory

AB	interface between a liquid and a gaseous phase
(p_1)	vapor pressure of component one in main liquid phase
$(p_1)i$	vapor pressure of component one at interface
$(p_1)_g$	vapor pressure of component one at main gaseous phase

PLATE I


A
MAIN LIQUID PHASE
LIQUID FILM
GAS FILM
MAIN GAS PHASE
$(p_1)_l$
$(p_1)_i$
$(p_1)_g$
B

where T = absolute temperature

P = pressure

V_A, V_B = molecular volumes of gases A and B

M_A, M_B = molecular weights of gases A and B

This relation, according to Brown (3), appeared to be the most satisfactory correlation of the diffusivities of gas systems.

MATERIALS AND METHODS

Pure water and dry air were chosen for study in this investigation of mass transfer between liquid and gaseous phase. Liquid water was vaporized into an air stream. The effect of sonic vibrations on the rates of vaporization was studied. The rate of vaporization at given conditions without application of sound was compared with the rate of vaporization under the same conditions but with the application of sound. The resulting differences in the rates of mass transfer were assumed to be due to the effect of sonic energy or pulsations (see Chueh (4) MATERIAL AND METHODS).

EQUIPMENT AND APPARATUS[1, 2]

Equipment and apparatus employed for these investigations were essentially the same as those which were described by Chueh (4) (EQUIPMENT AND APPARATUS, pages 12-42, Plates III-XI, XIII-

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[1] For preparation of a thin liquid surface whose physical shape was not altered by the action of sonic pulsations, see Chueh (4), pages 43-52.

[2] For calibrations of measuring tubes, see Chueh (4), pages 95-97.

XV). The blower described on Plate XII of Chueh was replaced by a type AF, 2 lobe, number 47, Roots-Connersville, rotary positive blower and two surge tanks were located up-stream from the blower. Air rate was controlled by a valve in the recycle loop of the blower and by a second valve down-stream from the blower.

The blower speed was regulated by a Reeves, gear reducer. The gear reducer was powered by a General Electric, 1- horse power motor (see Plate II).

FREQUENCY AND INTENSITY RELATIONSHIPS FOR A PARTICULAR SURROUNDING

In these calibrations, the object was to determine the frequency and intensity relationships for the particular surroundings in which the mass transfer experiments were made. The equipment or surroundings consisted of a 20-foot-long, wooden tunnel which was constructed of ½ inch plywood. Geometry of the tunnel was square shaped with inside dimensions of six inches on a side. Mounted on top of the tunnel was a SA-HF university sonic driver unit, the driver unit to be referred to as a transducer. Receiving the impulses was a type 1551 A sound level meter[1] made by General Radio Company. The microphone was a Rochelle-Salt crystal diaphram type which was supplied with the sound level meter. A 25 foot extension cable plus a 9-inch-long, 3/4 inch diameter extension joint was used between the microphone and the sound level meter. (See Plate XIV of appendix for arrangement of the meter, microphone and transducer.

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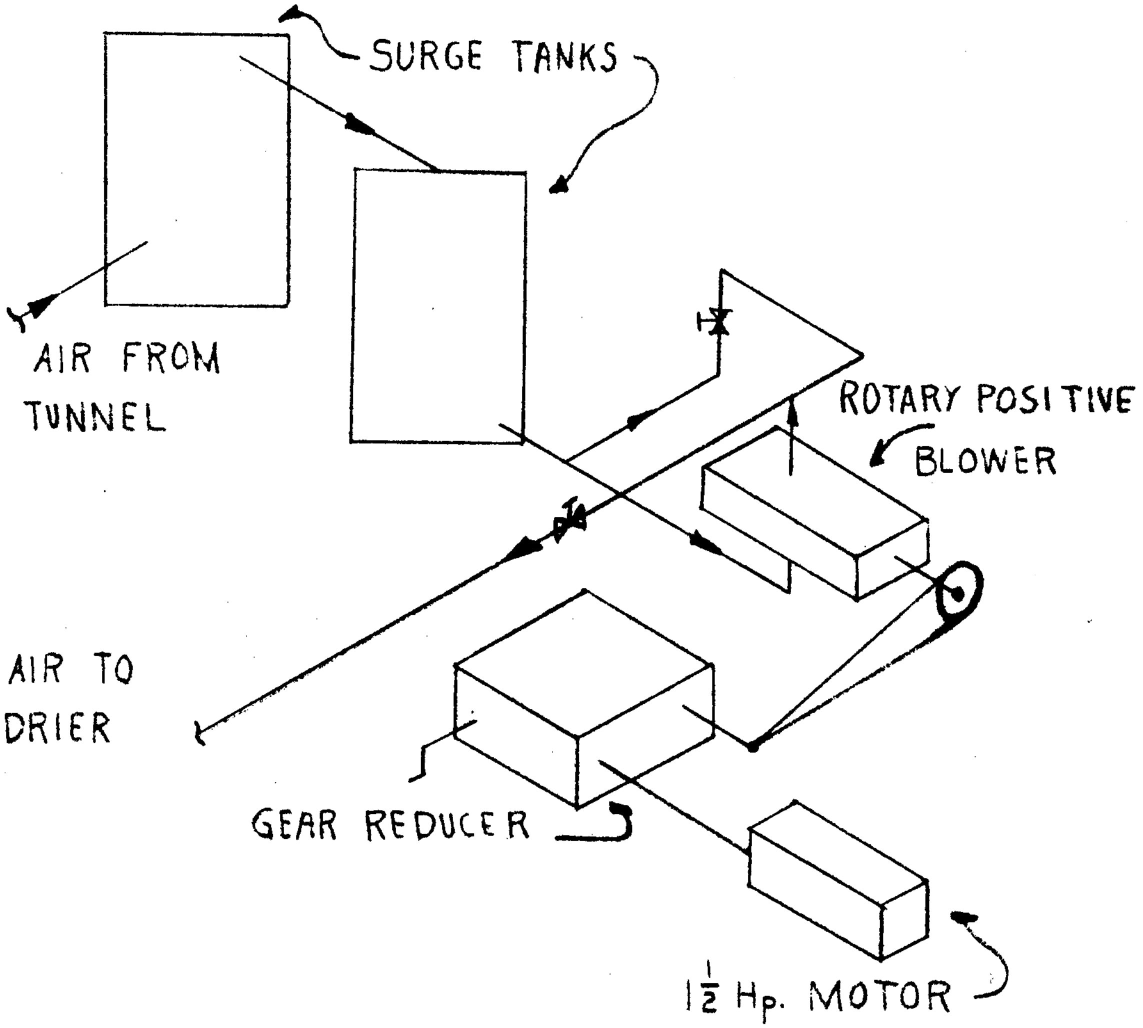
[1] For calibration of meter, see APPENDIX.

EXPLANATION OF PLATE II

Iso-metric drawing of blower assembly

PLATE II



NOTE: TWO LOBE TYPE
BLOWER WAS USED

Intensity as a Function of Voltage for Given Frequencies

At each of the following frequencies (cycles per second):

200	400	500	600	700	800	1,000
300	450	550	650	750	900	1,050

the voltage to the transducer was varied and the corresponding intensity was recorded. (See Plate XV for conversion chart, decibels to dynes per square centimeter). At each of the above frequencies, intensity readings were made with voltages of:

6	10	14
8	12	18

For frequencies of 1,100 and 1,200 cycles per second the intensities were determined from voltage readings to the transducer of 1, 2, 3 and 4 volts. The transducer was unable to operate effectively at frequencies of 1,100 and 1,200 cycles per second when more than four volts were applied because of equipment limitations.

The original data for these readings are presented in Table 1 of appendix. The results which show intensity as a function of voltage are shown graphically in Plate XVII of appendix. The results showed that for every frequency which was investigated an increase in voltage gave an increase in intensity.

Intensity as a Function of Frequency at a Constant Voltage to Transducer (10 Volts)

Range of frequencies studied was 240 to 1,020 cycles per second. Starting at 240 cycles per second, frequency was increased slowly. High and low points of sonic intensity were noted. Where high or low intensity points uccurred, the frequency was interpolated from established frequency points on the frequency generator. The frequencies which were multiples of 60: 240, 300, 360, etc., to 1,020, were established by use of an oscilloscope. The magnitude of these intensities and the interpolated frequencies at which they occurred were then recorded.

The original data of this series of runs are tabulated in Table 2 and are shown graphically on Plate XVIII of the appendix. The results showed that the relationship between intensity and frequency was extremely complex. At frequencies of 720 to 1,020 cycles per second there appeared to be a gradual increase in intensity along with the increase in frequency. Between 240 and 720 cycles per second it was difficult to detect, much less to locate, all of the maximum and minimum intensities. Because of the limitations on accuracy and sensitivity of the sound level meter, it was suspected that some of the maximum and minimum intensity points were passed by undetected. In all of these investigations the maximum and minimum intensity points appeared to have no set pattern of occurrence.

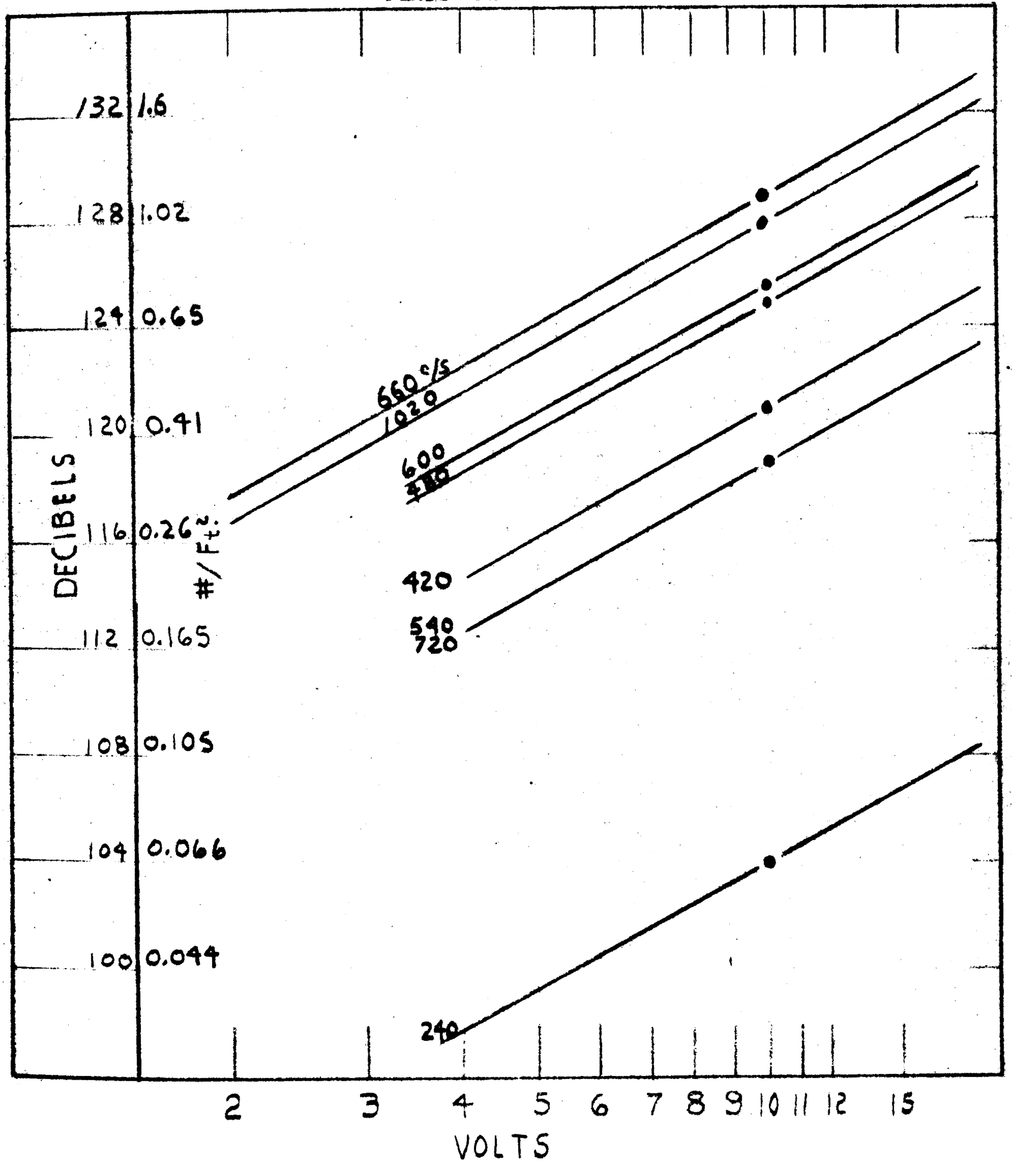
It is hypothesized that, if it were possible to connect the points representing the maximum and minimum intensities by a curve, there would be cusps and inverted cusps at the maximum and minimum intensity points, as indicated on Plate XIX of appendix.

The results of frequency and intensity relationship studies for a particular transducer and surrounding are presented in graphical form on Plate III. These relationships, at different

EXPLANATION OF PLATE III

Intensity as a function of volts applied to the transducer. Parameter is frequency in cycles per second. The slopes of these curves were assumed to be the same as the slopes on Plate XVII.

PLATE III


DECIBELS
#/Ft²
132
1.6
128
1.02
124
0.65
120
0.41
116
0.26
112
0.165
108
0.105
104
0.066
100
0.044
660 c/s
1020
600
480
420
540
720
240
2
3
4
5
6
7
8
9
10
11
12
15
VOLTS

frequencies, showed intensity as a function of voltage and were employed in this study through the voltage range indicated on Plate III. The curves on Plate III were established to be used in studying the effects of sonic vibrations on the rate of mass transfer.

THE EFFECT OF SONIC VIBRATIONS

Experimental Procedures

All experimental runs were carried out with evaporative head at one level (see Plate XVI of appendix). The height of the water column was maintained at 3 feet or about 90 centimeters; the water column was supported by capillary action of the evaporative head or porous frittered glass plate (Chueh 4, p. 60). All runs were carried out at room temperature, which varied from 67°F. to 84°F.

The independent variables of this experiment were: intensity of sonic vibrations, frequency of sonic vibrations and the mass flow of air which was passed over the evaporative surface and parallel to the evaporative surface.

Results and Interpretations of Data

Search Number One. The purpose of this series of runs was to study the rates of vaporization at different frequencies. Frequencies varied from 240 to 1,020 cycles per second and only those frequencies which were divisible by 60 were investigated. Those frequencies divisible by 60 were determined by use of an oscilloscope. Intensity was not held constant but the voltage to the transducer was held at ten volts. Air flow across the evaporative surface was varied.

The results of search number one are shown graphically on Plate IV. It was seen that the vaporization rate was affected by the application of sound. The results of search number one indicated an increase in the rate of vaporization in the frequency range of 240 to 720 cycles per second.

A second series of runs were made using the same procedure as was used above, however, a different vaporization head of the same nominal size was used. The results of the second series of runs agreed with results shown on Plate IV. This was evidence that the increase in rate of evaporation was not due to any peculariaty or characteristic of the evaporative head.

Search Number Two. In search number two the rates of vaporization were studied at the frequencies of 420, 480, 540, 600, 660, 720 and 1,020 cycles per second. Intensity was a variable. Intensities were determined graphically, (see Plate III), from corresponding voltages which were applied to the transducer. Air flow across the vaporizing surface was also varied from 0.008 to 0.034 pounds per square feet per second.

The results of search number two are shown graphically on Plates V, VI and VII. These results showed that the rate of vaporization or the rate of mass transfer was affected by the sonic vibration. The rate of mass transfer, however, was affected differently at different frequencies. At the higher frequencies, 720 and 1,020 cycles per second, it appeared that the rate of mass transfer was retarded by the action of sonic

EXPLANATION OF PLATE IV

Evaporation rate as a function of frequency

Frequency is in cycles per second.

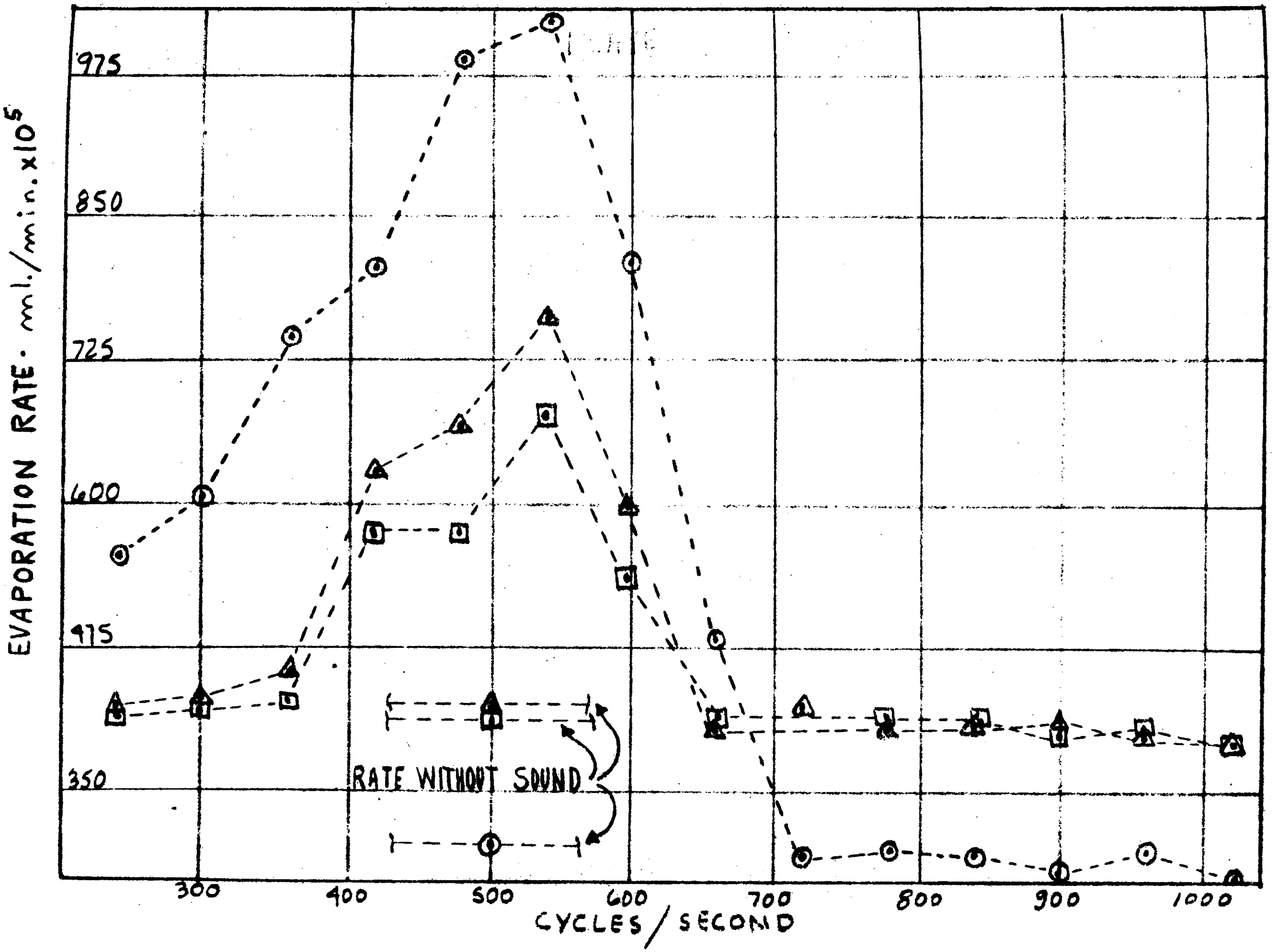
Rate is in ml/min. of water evaporating from the wetted surface.

Parameter is gas flow rate.

	inches of water	lb./sq.ft.per sec.
⊙	1.5	0.0228
◬	6.0	0.0488
⊡	9.0	0.0611

Evaporation rate is not necessarily restricted by the dotted lines. Dotted lines connecting points are to aid interpretation of data.

PLATE IV


975
850
725
600
475
350
EVAPORATION RATE · ml./min. x10^5
RATE WITHOUT SOUND
300
400
500
600
700
800
900
1000
CYCLES / SECOND

vibrations. Greatest rates of mass transfer were observed at the frequency of 540 cycles per second. Of all frequencies studied in search number two, 600 and 660 cycles per second contributed the most workable or consistent data. The frequencies of 420, 480 and 540 cycles per second contributed the least workable or most inconsistent data.

Search Number Three. The rates of mass transfer at frequencies of 600 and 660 cycles per second were studied because of the consistency of the data obtained in search number two.

The intensity was varied over the range set by the limitations of the transducer. For 600 cycles per second the range of intensity was 0.58 to 0.94 pounds per square foot; for 660 cycles per second the range of intensity was 0.32 to 1.32 pounds per square foot. The air flow across the vaporizing surface was varied from 0.008 to 0.092 pounds per square foot per second.

The runs were made in semi-random order. The intensities which were applied were chosen at random for a given air flow rate and a given frequency.

The results of search number three are shown graphically on Plate VIII and Plate XI. The data are presented in Table 4 of the appendix.

Treatment of Data from Search Number Three. The data of search number three were replotted and the curves were smoothed by eye judgments. It was felt that smoothing by eye was justifiable because of the limitations in obtaining the original

EXPLANATION OF PLATE V

Evaporation rate as a function of sonic intensity

Rate is in ml./min. of water leaving the evaporative surface.

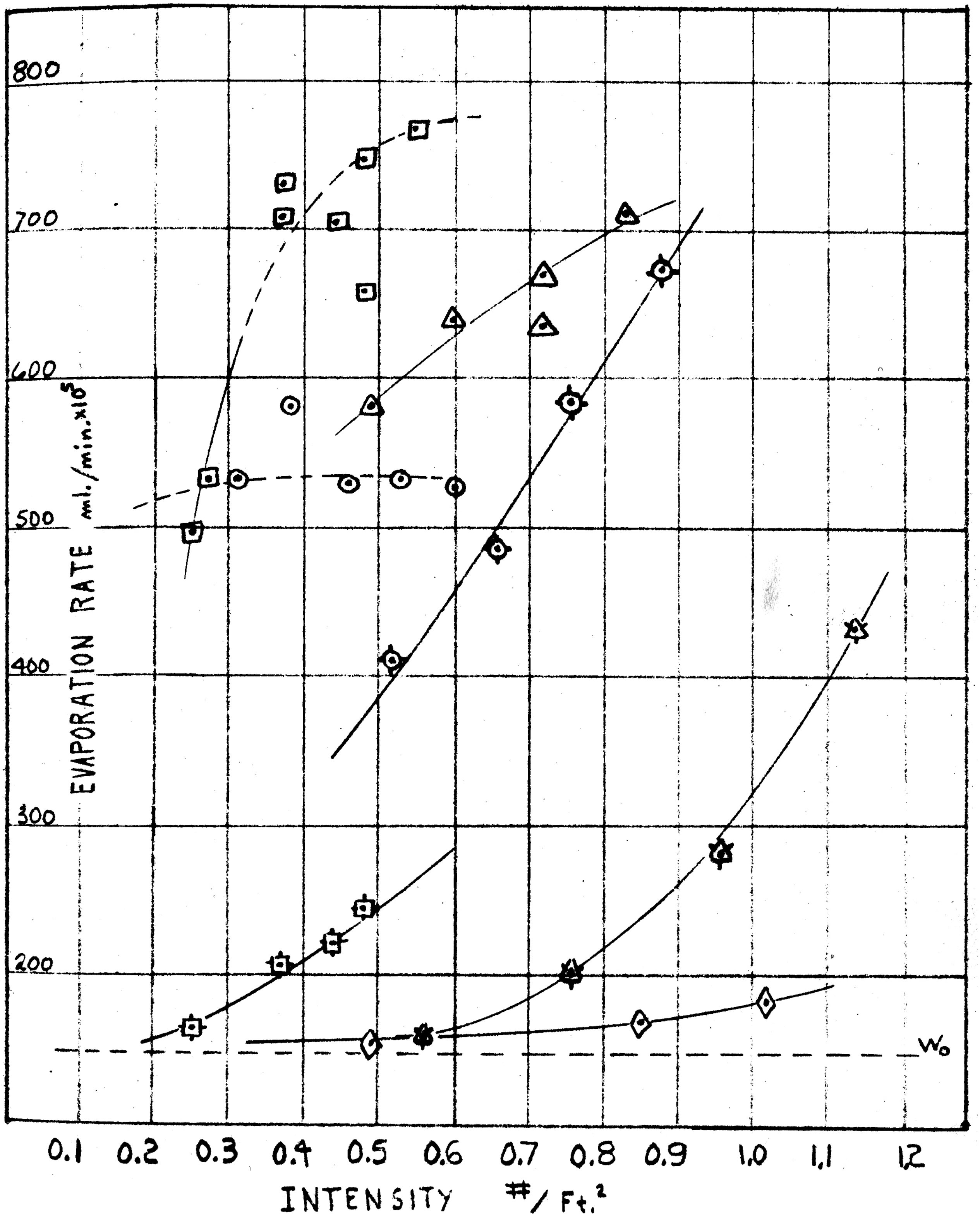
Parameter is frequency.

	cycles per second
⊙	420
◬	480
⊡	520
⌖	600
⟁	660
⊞	720
◈	1,020

Gas flow rate was 0.3 inches of water or 0.008 lb./sq. ft. sec.

W_o gives rate of evaporation with no sound applied.

PLATE V


800
700
600
500
400
300
200
EVAPORATION RATE ml./min.x10^5
W$_0$
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.1
1.2
INTENSITY #/Ft.^{2}

EXPLANATION OF PLATE VI

Evaporation rate as a function of sonic intensity

Rate is in ml./min. of water leaving the evaporative surface.

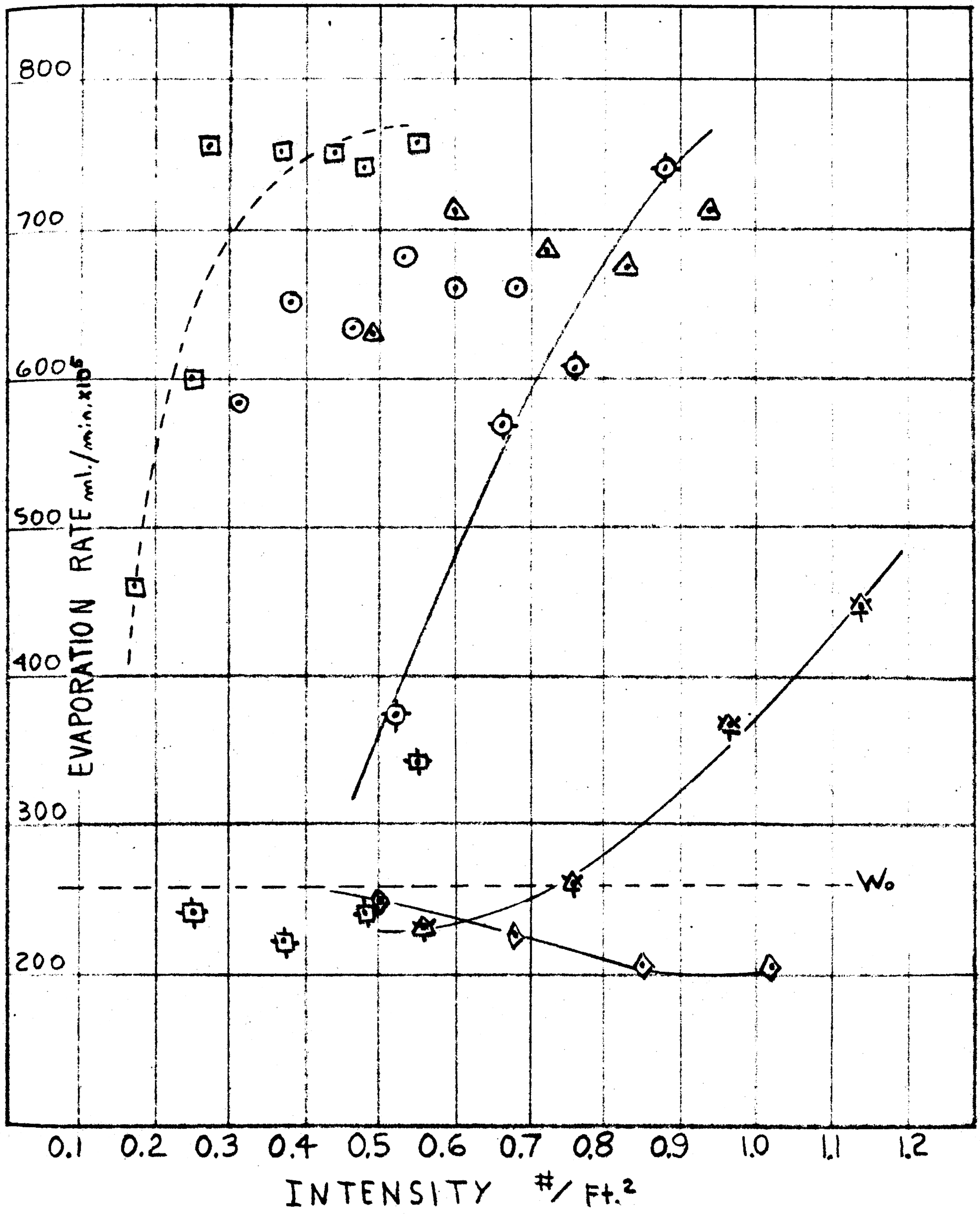
Parameter is frequency.

	cycles per second
⊙	420
◬	480
⊡	520
⌖	600
⟁	660
⊞	720
◈	1,020

Gas flow rate was 1.5 inches of water or 0.0228 lb./sq.ft. per sec.

W_o gives rate of evaporation with no sound applied.

PLATE VI


800
700
600
500
400
300
200
EVAPORATION RATE ml./min.x10⁶
W₀
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.1
1.2
INTENSITY #/Ft.²

EXPLANATION OF PLATE VII

Evaporation rate as a function of sonic intensity

Rate is in ml./min. of water leaving the evaporative surface.

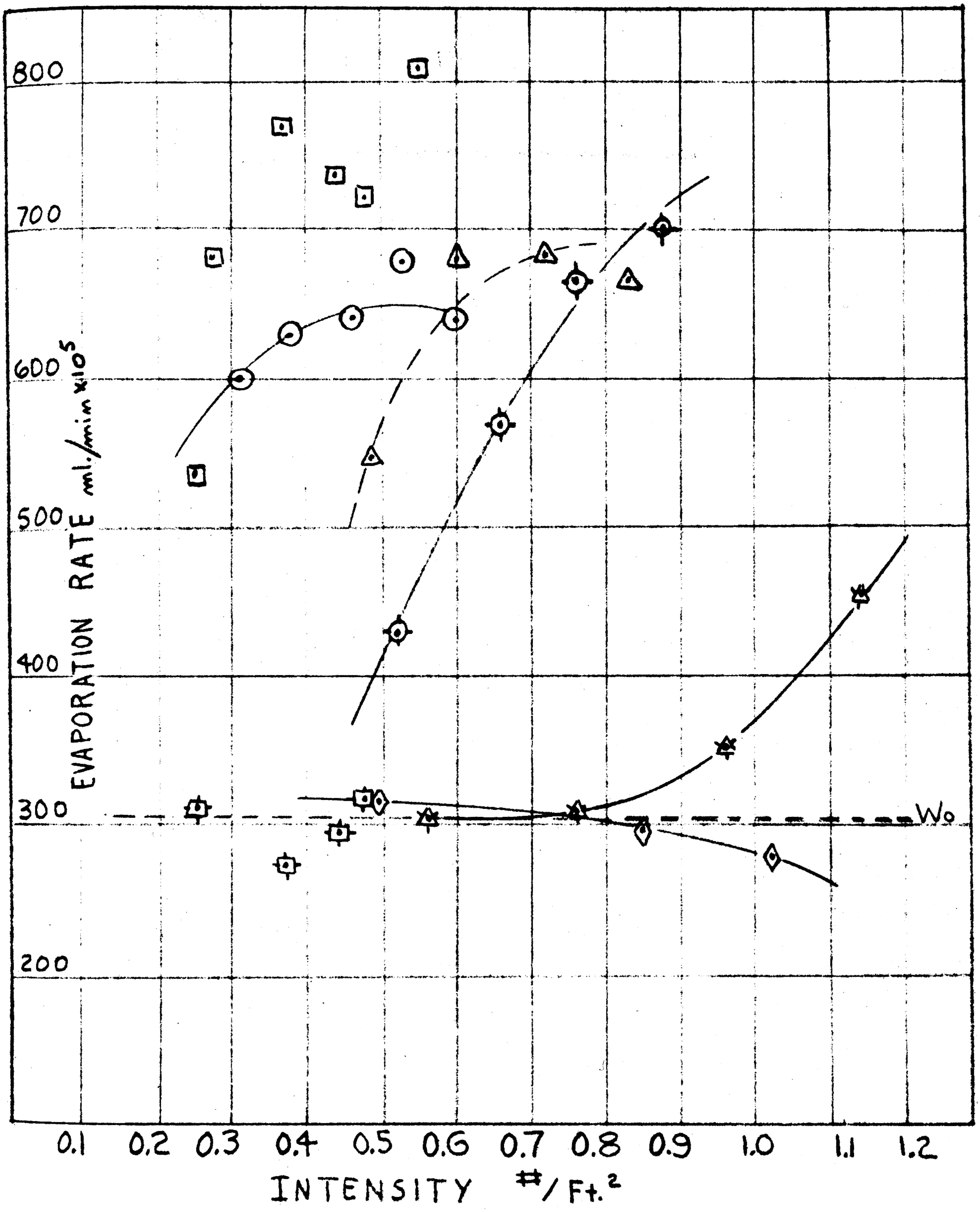
Parameter is frequency.

	cycles per second
⊙	420
◬	480
⊡	520
⌖	600
◬	660
⊡	720
◈	1,020

Gas flow rate was 3.0 inches of water or 0.0338 lb./sq.ft. per sec.

W_o gives rate of evaporation with no sound applied.

PLATE VII


800
700
600
500
400
300
200
EVAPORATION RATE ml./min x10⁵
Wo
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.1
1.2
INTENSITY #/Ft.²

intensity levels or readings which were presented on Plate IX and XII. The smoothed curves were, however, more than qualitative explanations of the effect of sonic vibrations on the rate of mass transfer because of the quantity and consistency of the original data. A cross plot of the curves which appear on Plates IX and XII showed rate of vaporization as a function of mass flow rate of air across the evaporative surface with intensity as a parameter (Plates X and XIII).

An empirical equation which showed the rate of vaporization as a function of intensity and as a function of mass flow rate of air across evaporative surface was obtained from plots of:

$$\frac{\text{Rate of evaporation with sonic vibrations}}{\text{Rate of evaporation without sonic vibration}} \quad \text{versus}$$

intensity with mass flow rate of air across vaporization surface as a parameter, (see Table 3 and Plates XX and XXI of appendix), or

$$R/R_o = f(I,G) \tag{5}$$

for a given frequency. The empirical equations were of the forms:

$$R/R_o = aI + bIG + cG + d \tag{6}$$

where a, b, c and d were constants. At a frequency of 600 cycles per second and within the bounds $0.6 < I < 0.9$ pounds per square foot and $0.01 < G < 0.09$ pounds per square foot per second, the equation was found to be:

$$R/R_o = 5I - 50GI + 15.5G - 0.65 \tag{7}$$

At a frequency of 660 cycles per second and within the bounds $0.1 < I < 1.2$ pounds per square foot and $0.01 < G < 0.035$ pounds per square foot per second, the equation was found to be:

EXPLANATION OF PLATE VIII

Evaporation rate as a function of sonic
intensity with gas flow rate as a parameter

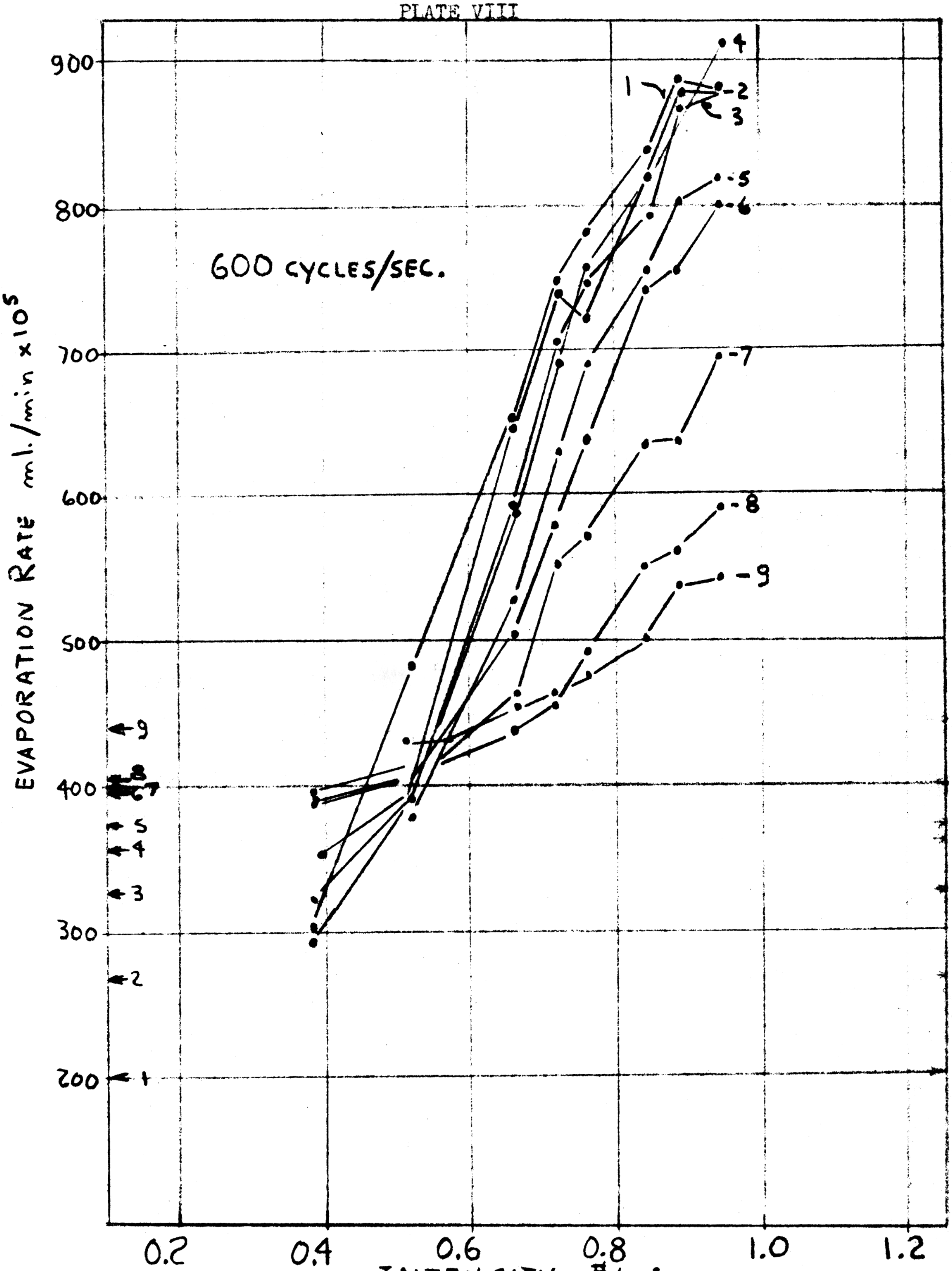
Frequency is 600 cycles per second.

Rate is in ml./min. of water leaving the evaporative surface.

	inches of water	lb./sq. ft. per sec.
1	0.3	0.008
2	0.9	0.0168
3	1.5	0.0228
4	2.1	0.0274
5	3.0	0.0338
6	4.5	0.0418
7	6.0	0.0488
8	9.0	0.0611
9	15.0	0.0785

Arrows indicate rate of evaporation without sound

PLATE VIII


600 CYCLES/SEC.
EVAPORATION RATE ml./min x10⁵
INTENSITY #/Ft.²
900
800
700
600
500
400
300
200
0.2
0.4
0.6
0.8
1.0
1.2
1
2
3
4
5
6
7
8
9

EXPLANATION OF PLATE IX

Evaporation rate as a function of sonic intensity with gas flow rate as a parameter

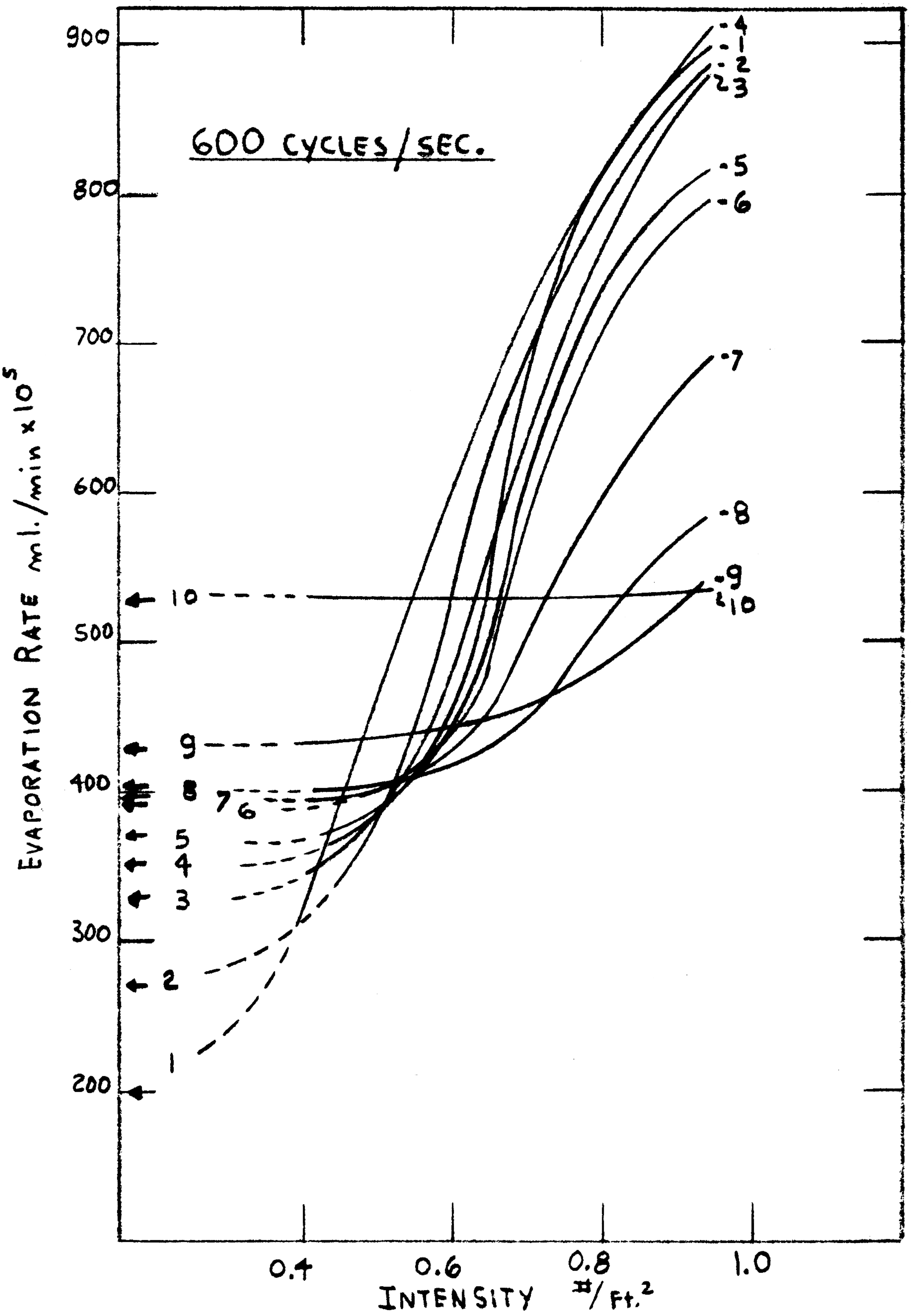
Frequency is 600 cycles per second.

Rate is in ml./min. of water leaving the evaporative surface.

	inches of water	lb./sq. ft. per sec.
1	0.3	0.008
2	0.9	0.0168
3	1.5	0.0228
4	2.1	0.0274
5	3.0	0.0338
6	4.5	0.0418
7	6.0	0.0488
8	9.0	0.0611
9	15.0	0.0785
10	30.0	0.112

Arrows indicate rate of evaporation without sound.

PLATE IX


600 CYCLES/SEC.
EVAPORATION RATE ml./min x 10^5
900
800
700
600
500
400
300
200
INTENSITY #/Ft.²
0.4
0.6
0.8
1.0
10
9
8
7
6
5
4
3
2
1
4
1
2
3
5
6
7
8
9
10

EXPLANATION OF PLATE X

Rate of evaporation as a function of air flow rate

Frequency is 600 cycles per second.

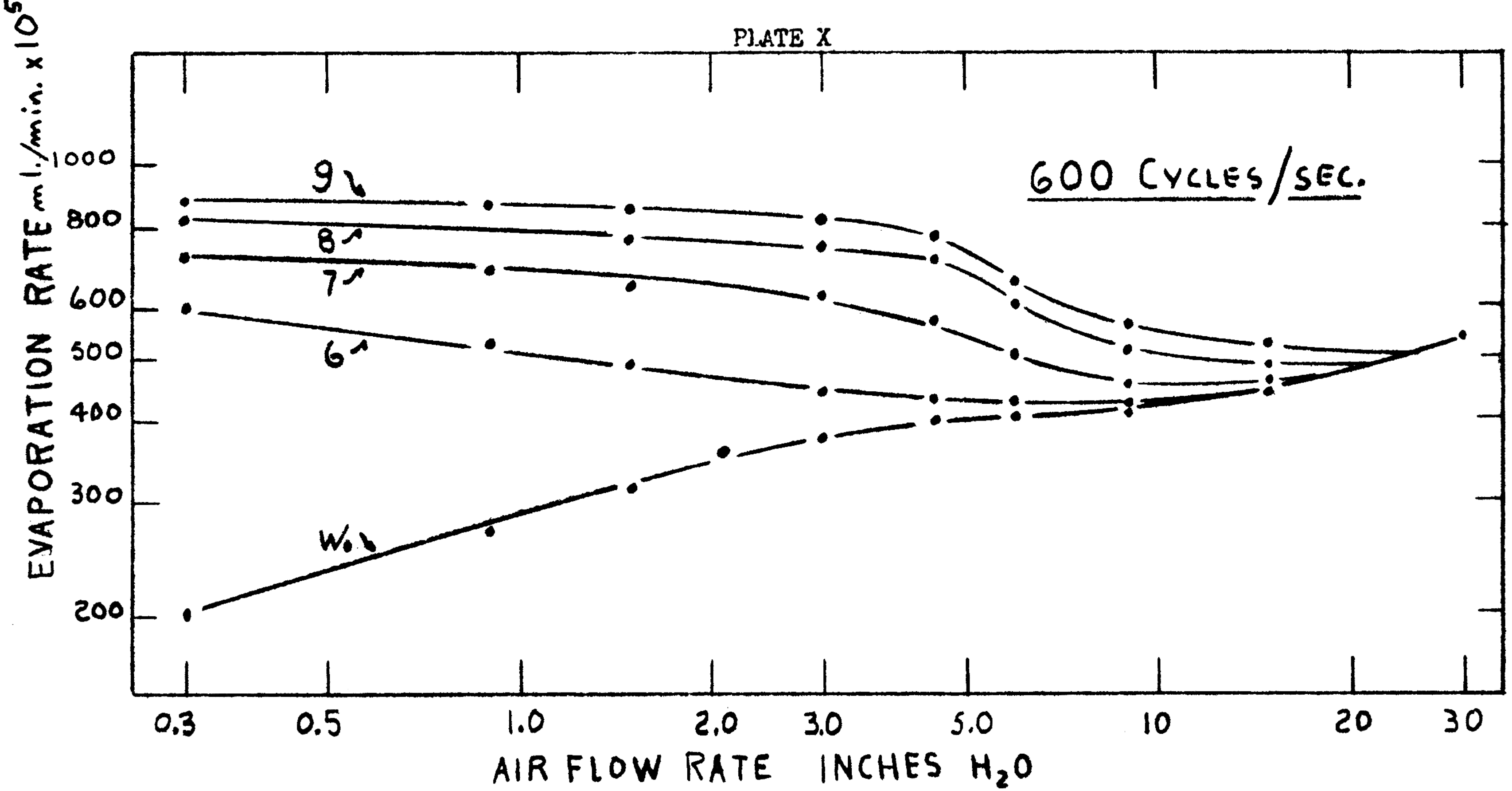
Rate is ml./min. of water leaving the evaporative surface.

Parameter is intensity

	pounds per square foot
6	0.6
7	0.7
8	0.8
9	0.9

W_o is rate of evaporation without sound.

PLATE X


600 CYCLES/SEC.
EVAPORATION RATE ml./min. x 10^5
1000
800
600
500
400
300
200
9
8
7
6
W.
0.3
0.5
1.0
2.0
3.0
5.0
10
20
30
AIR FLOW RATE INCHES H_2O

EXPLANATION OF PLATE XI

Evaporation rate as a function of sonic intensity with gas flow rate as a parameter

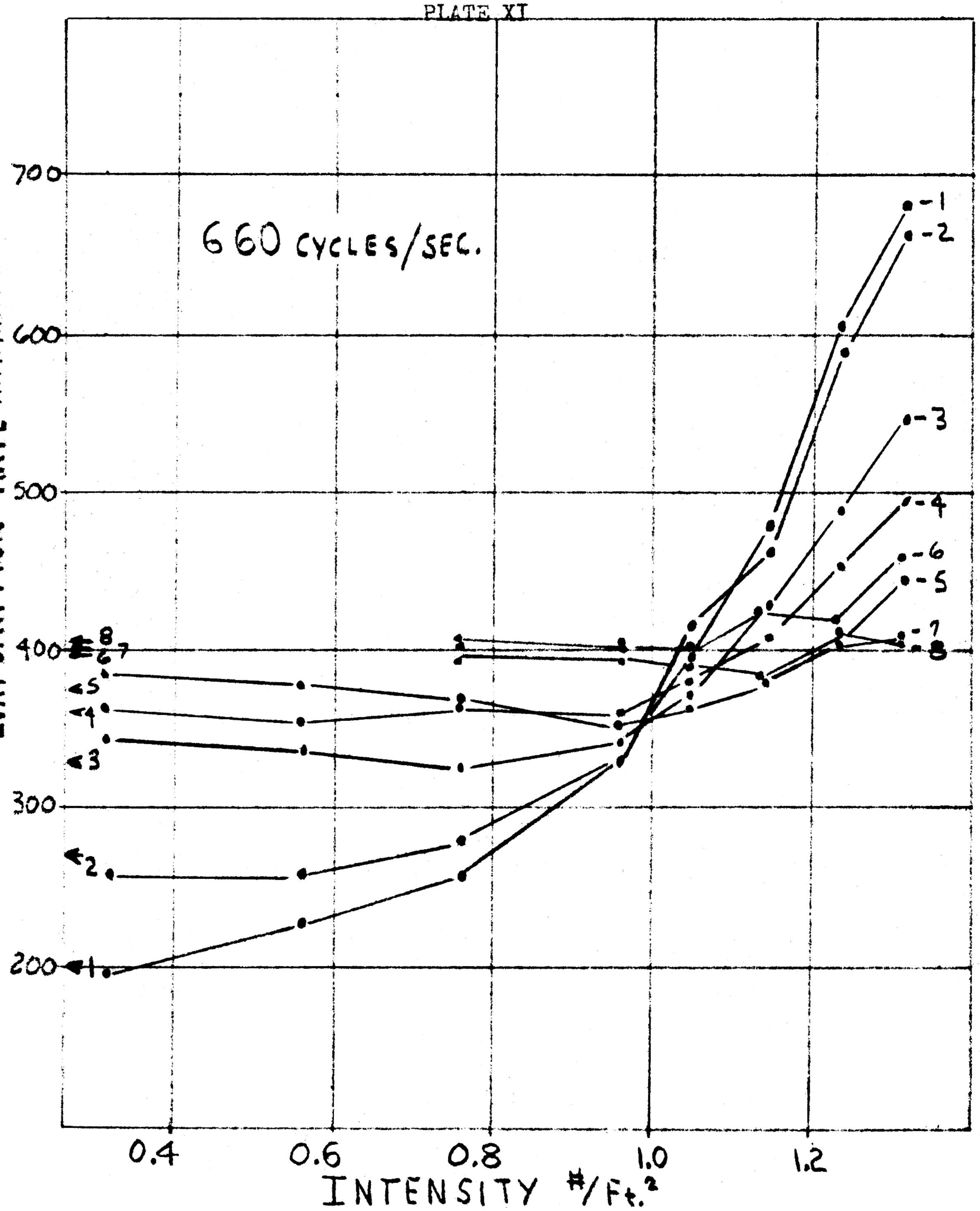
Frequency is 660 cycles per second.

Rate is in ml./min. of water leaving the evaporative surface.

	inches of water	lb./sq. ft. per sec.
1	0.3	0.008
2	0.9	0.0168
3	1.5	0.0228
4	2.1	0.0274
5	3.0	0.0338
6	4.5	0.0418
7	6.0	0.0488
8	9.0	0.0611

Arrows indicate rate of evaporation without sound.

PLATE XI


660 CYCLES/SEC.
EVAPORATION RATE ml./min. x10⁵
INTENSITY #/Ft.²
700
600
500
400
300
200
0.4
0.6
0.8
1.0
1.2
1
2
3
4
5
6
7
8

EXPLANATION OF PLATE XII

Evaporation rate as a function of sonic intensity with gas flow rate as a parameter

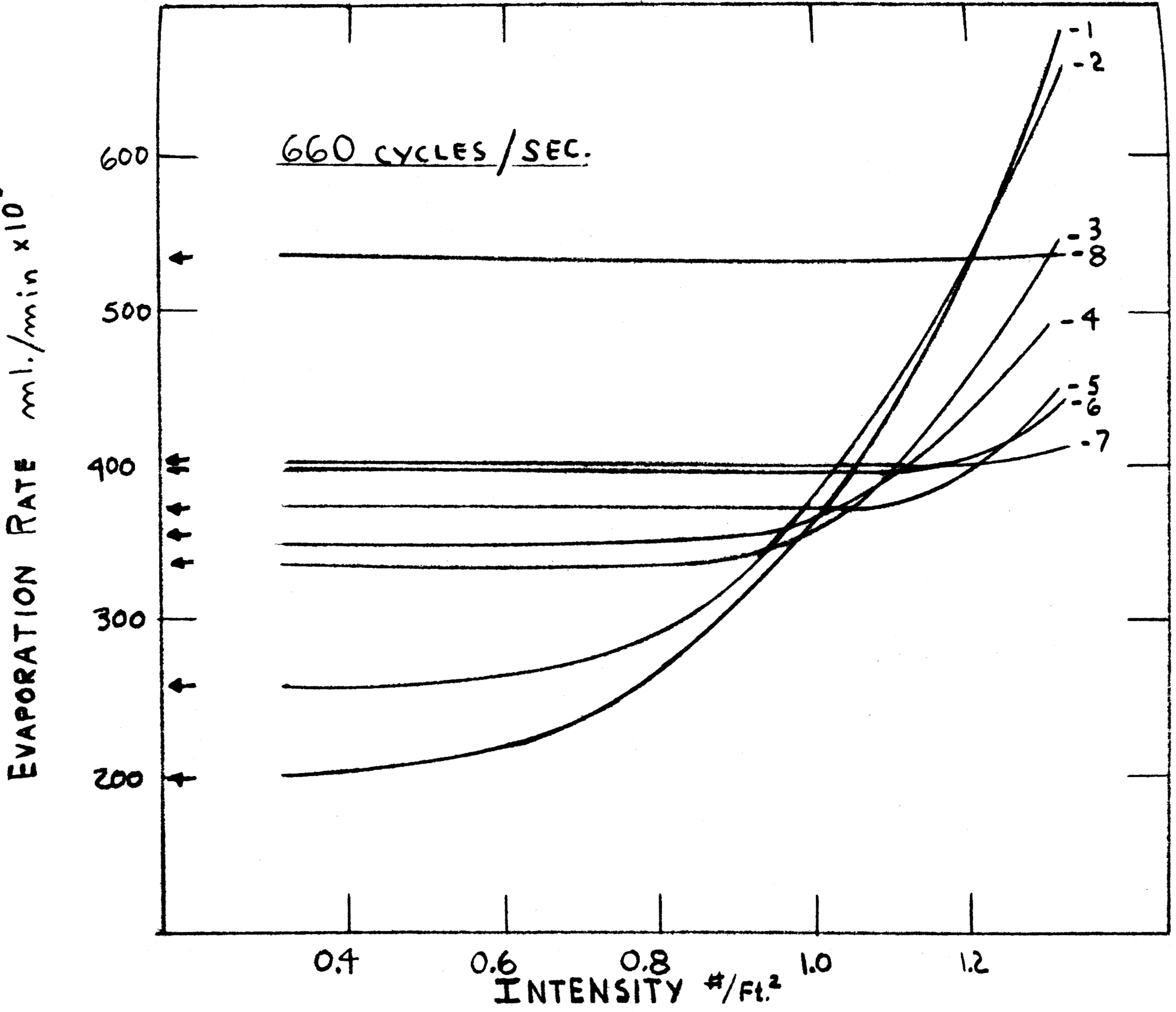
Frequency is 660 cycles per second.

Rate is in ml./min. of water leaving the evaporative surface.

	inches of water	lb./sq. ft. per sec.
1	0.3	0.008
2	0.9	0.0168
3	1.5	0.0228
4	2.1	0.0274
5	3.0	0.0338
6	4.5	0.0418
7	6.0	0.0488
8	30.0	0.112

Arrows indicate rate of evaporation without sound.

PLATE XII


660 CYCLES/SEC.
EVAPORATION RATE ml./min x10^5
600
500
400
300
200
0.4
0.6
0.8
1.0
1.2
INTENSITY #/Ft.²
-1
-2
-3
-8
-4
-5
-6
-7

EXPLANATION OF PLATE XIII

Rate of evaporation as a function of air flow rate

Frequency is 660 cycles per second.

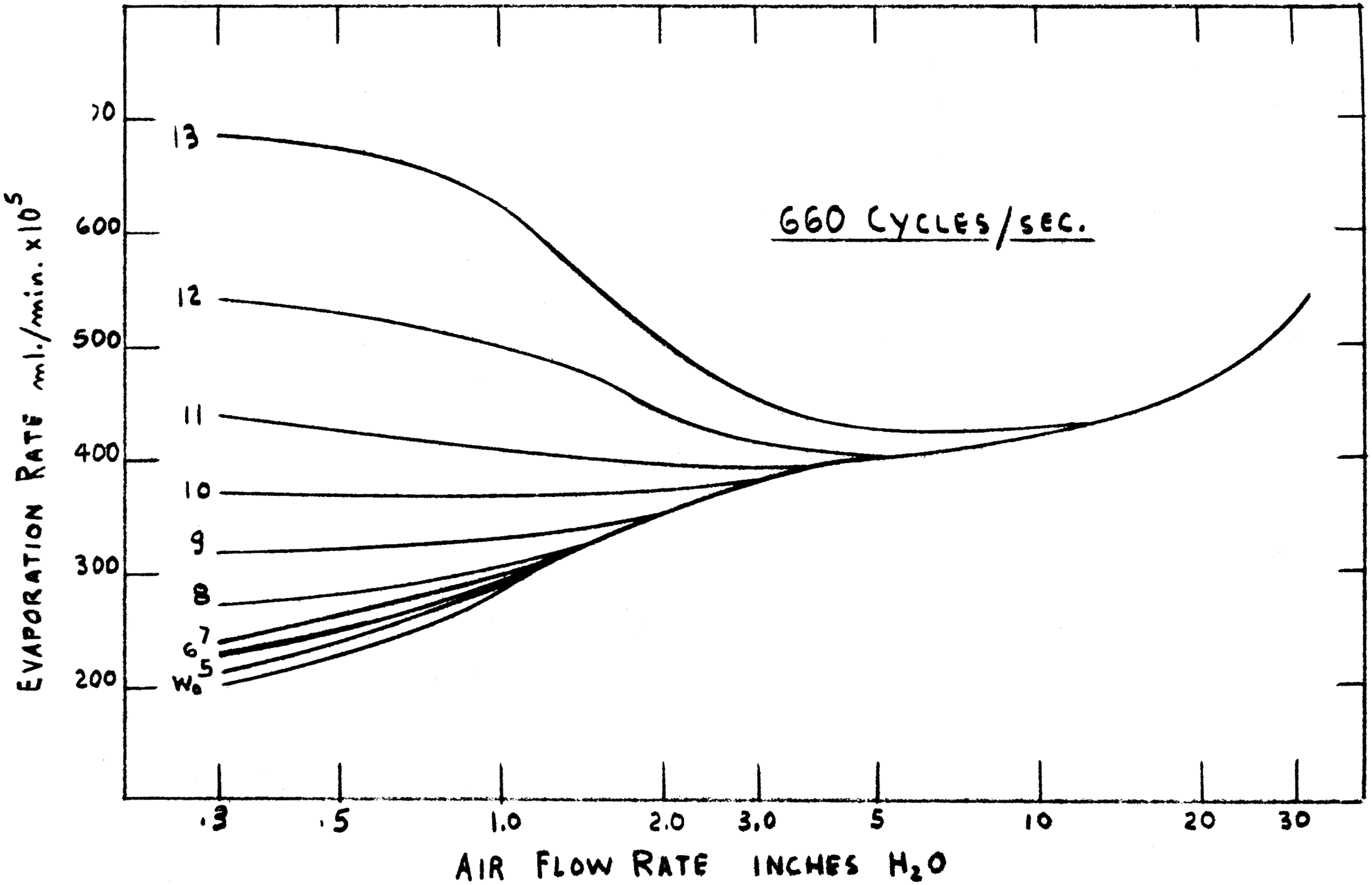
Rate is ml./min. of water leaving the evaporative surface.

Parameter is intensity.

Curve Number	sonic intensity, lb./sq. ft.
5	0.5
6	0.6
7	0.7
8	0.8
9	0.9
10	1.0
11	1.1
12	1.2
13	1.3

W_o is rate of evaporation without sound.

PLATE XIII


660 Cycles/sec.
Evaporation Rate ml./min. x10^5
00
600
500
400
300
200
13
12
11
10
9
8
7
6
5
W_0
.3
.5
1.0
2.0
3.0
5
10
20
30
Air Flow Rate inches H_2O

$$R/R_o = 5I - 165\ GI + 55\ G - 2.75 \qquad (8)$$

Discussion

Search number one, which was a preliminary series of investigations, revealed several interesting phenomena. The frequency range of 300 to 720 cycles per second, where the greatest change or effect on the rate of vaporization occurred, was also the range where the greatest number of maximum and minimum intensity points were observed. This was seen by comparing Plates IV and XVIII. In the frequency range of 720 to 1,020 there appeared to be decreases in the rate of evaporation when sound was applied to the system.

Search number two again indicated that at higher frequencies the rate of evaporation was decreased when sound was applied to the system. The per cent of decrease in the rate of vaporization was in the neighborhood of 4 to 5 per cent; the per cent increases at other frequencies, however, was as great as 400 per cent. In search number two it was difficult to reproduce results or obtain consistent readings for frequencies of 420, 480, 540 cycles per second. However, in search number two the results from the readings at 600 and 660 cycles per second were consistent and reproducable. It was because of this consistency of data obtained from runs at 600 and 660 cycles per second that frequencies of 600 and 660 cycles per second were chosen for closer study in search number three.

It was from the results of search number three that this author intended to show and explain the effects of sonic vibrations on the rate of mass transfer. For miscellaneous observations, see APPENDIX.

The curves, rate of evaporation versus mass flow rate of air across the evaporative surface, represented as inches of water, with intensity as a parameter, demonstrated that a range existed when the rate of evaporation was independent of the mass flow rate of air across the evaporative surface (Plate X and Plate XIII). These curves agreed well with a curve of a former investigator, (Chueh (4) Plate XXII).

From the equation, $R/R_o = aI + bIG + cG + d$, it can be seen that, if G were sufficiently small and the constants a, b, c and d were of proper sign and of sufficient magnitude, R/R_o, for a given frequency, would essentially be a function of intensity. This was in agreement with the hypothesis that the diffusivity coefficient was a function of intensity; thus, rate of mass transfer became a function of sonic intensity. From the equation, $R/R_o = aI + bGI + cG + d$, it was evident that the rate of mass transfer was dependent primarily upon intensity when G was such that the last three terms of the equation were insignificant.

The curves of Plate X showed the rate of evaporation was a function of sonic intensity and of mass flow rate of air across the evaporative surface. In agreement with the concept of Lewis and Whitman (7) the thickness of the stagnant gaseous layer decreased as the mass flow rate of air increased. At high mass flow rates of 0.09 pounds per square foot per second, the thickness of the stagnant layer or film was controlling the rate of evaporation. Intensity was controlling the rate of evaporation at low mass flow rates of air, eg., 0.02 pounds per square foot per second.

In search number three the emphasis was on intensity. Frequency was constant at 600 and 660 cycles per second. It was mentioned that at frequencies of 600 and 660 cycles per second the data obtained was consistent. In search number two it was observed that at the frequencies of 420, 480, and 540 cycles per second the data would not readily fit a curve or, as previously stated, the data was not consistent. It was seen from the plot of intensity versus frequency, on Plate XVIII, that the frequency range around 420, 480 and 540 cycles per second was where the majority of maximum and minimum intensity points were detected. The area or range of 600 and 660 cycles per second of the same plot showed only two such maximum and minimum intensity points. Certainly, sound intensity was an important variable in the studies of the effects of sonic vibrations on the rate of mass transfer. However, frequency on sonic vibration must be considered with equal and possibly with more care in the studies of sonic vibrations and their effect on the rates of mass transfer.

CONCLUSIONS

The conclusions of this series of investigations were:

The relationship between frequency and intensity was quite complex (Plate XVIII). There will be disagreement among investigators of sonic energies as to the optimum frequencies to be employed because of this "complex relationship" between frequency and intensity and because of the difficulty in reproducing identical frequencies.

Simple empirical equations which showed the rate of evaporation as a function of intensity and mass flow rate of air across the evaporative surface were:

$$R/R_o = 5I - 50IG + 15.5G - 0.65$$

with the restrictions:

frequency = 600 cycles per second

$0.6 < I < 0.9$ pounds per square foot
$0.01 < G < 0.09$ pounds per square foot per second

$$R/R_o = 5I - 165\,IG + 55G - 2.75$$

with the restrictions:

frequency = 660 cycles per second

$0.9 < I < 1.2$ pounds per square foot
$0.01 < G < 0.035$ pounds per square foot per second

where I = intensity in pounds per square foot

G = mass flow rate of air in pounds per square foot per second

R = rate of evaporation with sound applied to the system

R_o = rate of evaporation without sound applied to the system.

It was noted that the coefficient of the intensity term was the same in both equations, eg., 5.0. This seemed to indicate that the term, 5I, was independent of the frequency of the sonic vibrations.

RECOMMENDATIONS

The following are recommended for further investigations:

1. Systems other than water and air should be studied. It is quite possible that, by using different atmospheres above the evaporating liquid, much can be learned about mass transfer through the stagnant gaseous layer.

2. The influence of temperature on the effects of sonic vibrations should be more clearly analyzed. This type of study is highly technical and is quite involved. Studying the effects of sonic vibrations on the rate of mass transfer at different controllable temperatures should, however, contribute a great deal toward the understanding of temperature effects on sonic vibrations.

3. This work indicated that sonic vibrations caused a decrease in the rate of mass transfer. It is recommended that work be continued to search for a negative effect on the rate of mass transfer.

4. The equations obtained are presented as being applicable only under restrictions in which they were obtained. With additional equipment, this work could be repeated and quantitative

equations, relating rate of mass transfer, sonic vibrations, geometrical environments and other similar variables could be obtained. Specifically, a more sensitive sound level meter should be employed for this work. If additional equipment were available, frequencies other than those divisible by 60 could be investigated.

ACKNOWLEDGMENTS

Acknowledgment is given to professor Raymond C. Hall, major instructor and advisor. Professor Hall's interest, experience and consultation made possible the success of this investigation.

Acknowledgment is given to Dr. Henry T. Ward, professor and head of the chemical engineering department.

Acknowledgment is given to Jim Gates and John Rhodes, students of Kansas State College, for their assistance in the laboratory.

Funds were made available through the Engineering Experiment Station of Kansas State College.

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Absorption and extraction. New York: McGraw-Hill, 1952. 53 p.

APPENDIX

HYPOTHESIS

Sonic energy is transmitted through air in the form of longitudinal compressional waves. The physical characteristics of sound are frequency and intensity. The psychological characteristics of sound are pitch and loudness. Frequency is cycles per time, eg., cycles per second and is analogous to pitch. Intensity, measured in decibles, is analogous to loudness. Intensity is also measured in units of pressure.

If sonic energy were to affect the rate of mass transfer in a system under gas film control, then, sonic energy may have affected or altered some property of the gas molecules in the gaseous layer or film. Suppose sound intensity or pressure were able to alter or change the "effective densities" of the gases in the gaseous layer or film, this would in turn alter the molecular volume of the gases in the film. By "effective densities" it is meant that under the influence of sonic pulse or vibrations the densities of the gases in the gaseous layer are constantly changing with each compressional wave of sound; therefore, the average of "effective densities" differ from the densities of the gas in the gaseous layer when no sound is applied to the system.

Molecular volume by definition is:

$$V_A = \frac{M_A}{D_A} = \frac{\text{molecular weight } A}{\text{density of } A} \qquad (4)$$

If the densities of the gases in the gaseous layer or film were altered or changed, the molecular volumes of the gases in the layer would also have been changed. Since diffusivity was a function of molecular volumes, (see equation 3 of THEORETICAL CONSIDERATIONS), then, if the molecular volumes of the gases in the gaseous layer or film were altered or changed, the diffusivity, D_G, was also changed.

For example, a liquid surface was exposed to sonic vibrations. Because of the sonic vibrations or energy there was an increase in the "effective densities" of the gases in the gaseous layer. This increase in "effective densities" caused a decrease in the molecular volumes of the gases in the film or gaseous layer. The decrease in molecular volume caused the coefficient of diffusivity to become larger. Finally, the larger diffusivity coefficient caused an increase in the rate of mass transfer.

This author's hypothesis was that sonic energy or vibrations altered the effective densities of the gases in the gaseous layer or film which, in turn, caused an increase in the rate of mass transfer.

DISCUSSION OF SONIC EFFECT ON THE DIFFUSIVITY COEFFICIENT

By rewriting the equation, $\frac{N_A}{A} = \frac{D_G P}{RTX} \frac{(pA_1 - pA_2)}{(pB)lm}$, (see equation 1 of THEORETICAL CONSIDERATIONS), into the form, $N_A = K_1 \frac{D_G}{X}$, it was assumed that:

$$A, R, T, P, pA_1, pA_2 \text{ and } (pB)\,lm$$

were constants and were included in the new constant, K_1. It can now be shown that the rate of mass transfer is a function of D_G

and X. In agreement with Lewis and Whitman (7), X is a function of the mass flow of air across the evaporative surface.

The curves on Plate X showed that the rate of evaporation was a function of sonic intensity and mass flow rate of air. From Plate X, it was made evident that the thickness of the stagnant gaseous layer was controlling the rate of evaporation at high mass flow rates, eg., 0.09 pounds per square foot per second. However, intensity was controlling the rate of evaporation at low mass flow rates of air, eg., 0.02 pounds per square foot per second.

The observations of the above paragraph are used as evidence that DG is a function of sonic vibrations and is the controlling factor in the rate of evaporation at low mass flow rates of air.

This author feels that the thicker stagnant gaseous layer is more susceptible to the sonic vibrations or that the thicker gaseous layer is more easily affected by sonic vibrations.

There was no evidence obtained from this work that the molecular volumes of the gases in the gaseous layer were a function of sonic intensity. Nor was there evidence that densities of the gases in the stagnant layer were being altered by the sonic vibrations. There was, however, evidence that would support a hypothesis that the diffusivity coefficient was a function of sonic energy.

Miscellaneous Observations

A piece of thin tissue paper was placed over the evaporative surface. Runs were made to determine if the sonic vibrations would still affect the rate of evaporation. The results were comparable to those when the tissue paper was not present. Sonic vibrations increased the rate of evaporation of the water from the surface of the wet tissue paper.

An attempt was made to eliminate some of the turbulence created by the evaporation head. A piece of balsa wood was shaped so that the evaporation head fit into the balsa wood. (See Plate XXII). Thus, the surface of the evaporation head was smooth with the top surface of the balsa wood.

The rate of evaporation without sound being applied was less than the observed rate without the balsa. The rate of evaporation with sound applied was comparable to the results obtained with sound and without the balsa wood.

Calibration of Sound Level Meter

The sound level meter was calibrated by using a type 1552-B sound level calibrator and a type 1307-A transistor oscillator according to directions given in the operating instruction manual Form 719-E.[1] Calibration oscillator and manual are all products of General Radio Company.

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[1] Operating Instructions, type 1552-B sound level calibrator, form 719-E, May 1956, General Radio Company, 275 Massachusetts Avenue, Cambridge 39, Massachusetts.

Sound Level Readings in decibels, 1 db.

	with 25' ext. cord and 9" ext. joint	without	difference
400 cps.	98	110	12
1000 cps.	93	105	12

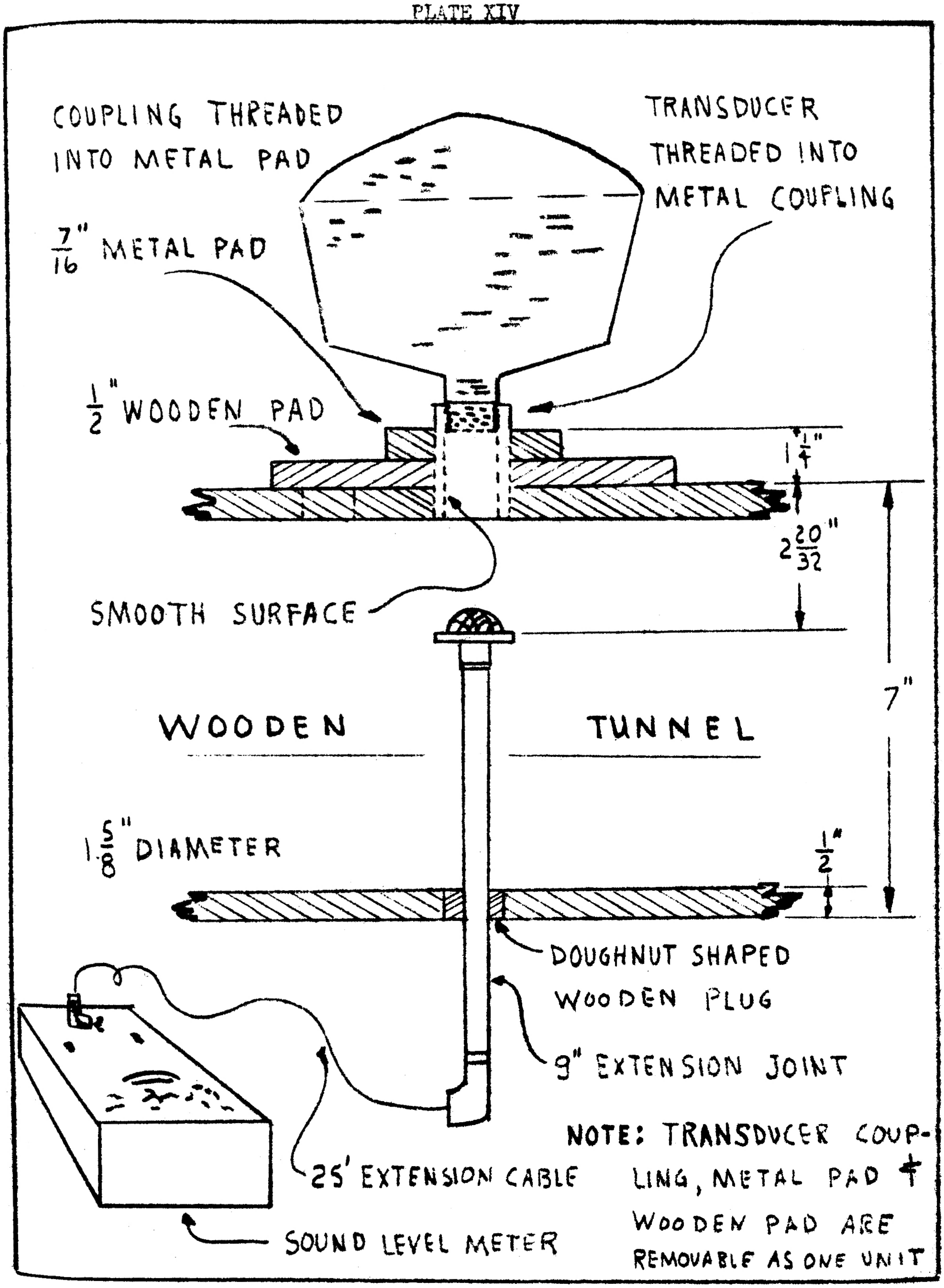
By using an extension cord and joint there occurred a loss of 12, plus or minus 2 decibels.

The purpose of this calibration was to determine the effect of using an extension cord and joint. Because of ranges of intensities to be explored, eg., 100-130 decibels, and in order to remain consistent and, at the same time, somewhat conservative it was here defined that 10 decibels shall be added to meter readings taken with the above mentioned 25 foot long cable and 9 inch joint.

EXPLANATION OF PLATE XIV

Sketch of transducer and microphone arrangement

PLATE XIV


COUPLING THREADED INTO METAL PAD
TRANSDUCER THREADED INTO METAL COUPLING
7/16" METAL PAD
1/2" WOODEN PAD
1 1/4"
2 20/32"
SMOOTH SURFACE
7"
WOODEN TUNNEL
1 5/8" DIAMETER
1/2"
DOUGHNUT SHAPED WOODEN PLUG
9" EXTENSION JOINT
NOTE: TRANSDUCER COUPLING, METAL PAD + WOODEN PAD ARE REMOVABLE AS ONE UNIT
25' EXTENSION CABLE
SOUND LEVEL METER

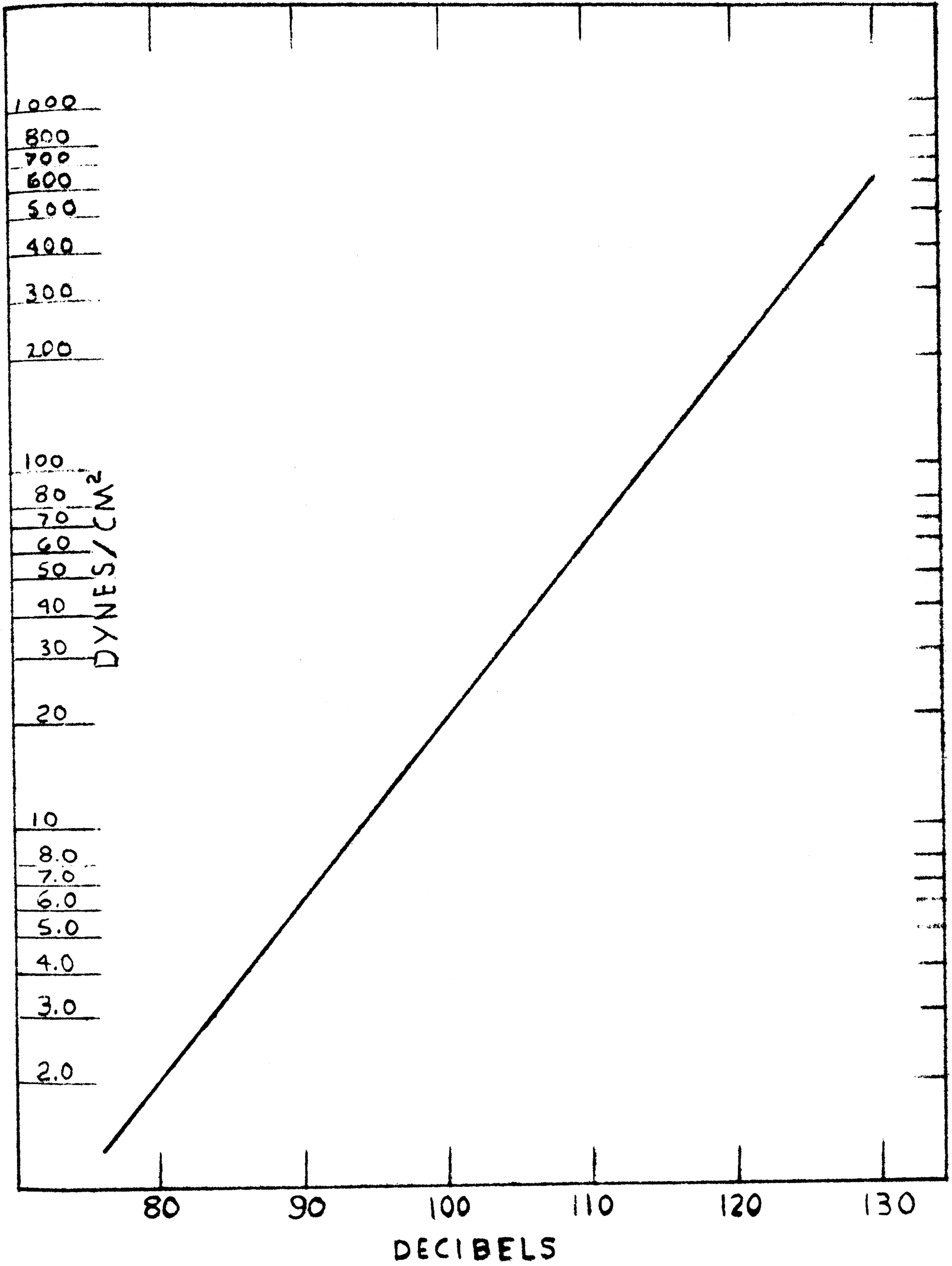
EXPLANATION OF PLATE XV

Conversion chart for decibels to
dynes per square centimeter

Values recalled from:

Weber, R. L. and White, M. W. and Manning, K. W., College Physics, McGraw-Hill Book Co., 1947, N. Y., fig. 6, p. 349.

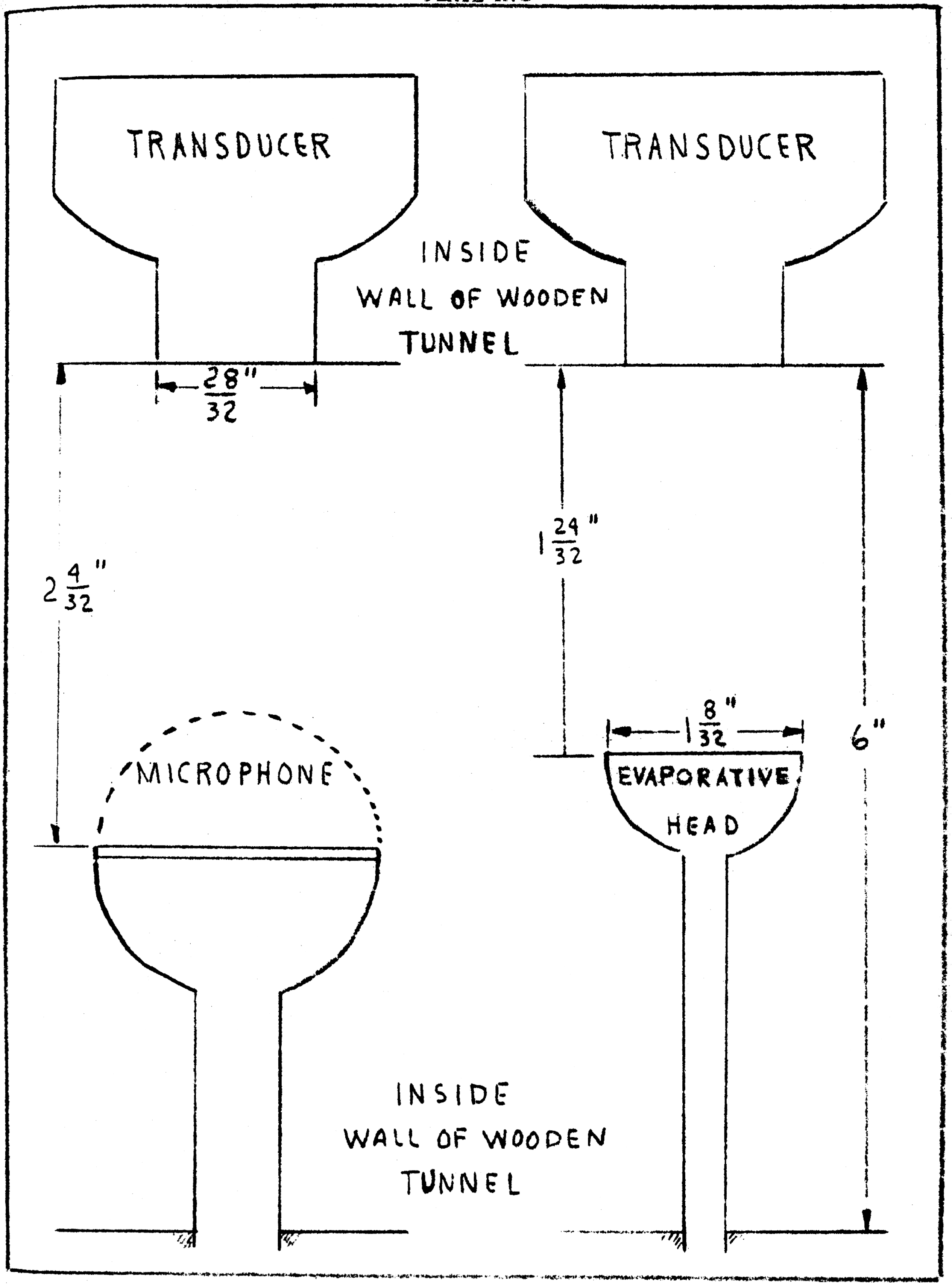
PLATE XV


1000
800
700
600
500
400
300
200
100
80
70
60
50
40
30
20
10
8.0
7.0
6.0
5.0
4.0
3.0
2.0
DYNES/CM²
80
90
100
110
120
130
DECIBELS

EXPLANATION OF PLATE XVI

Transducer and evaporative head arrangement compared with transducer and microphone arrangement

PLATE XVI

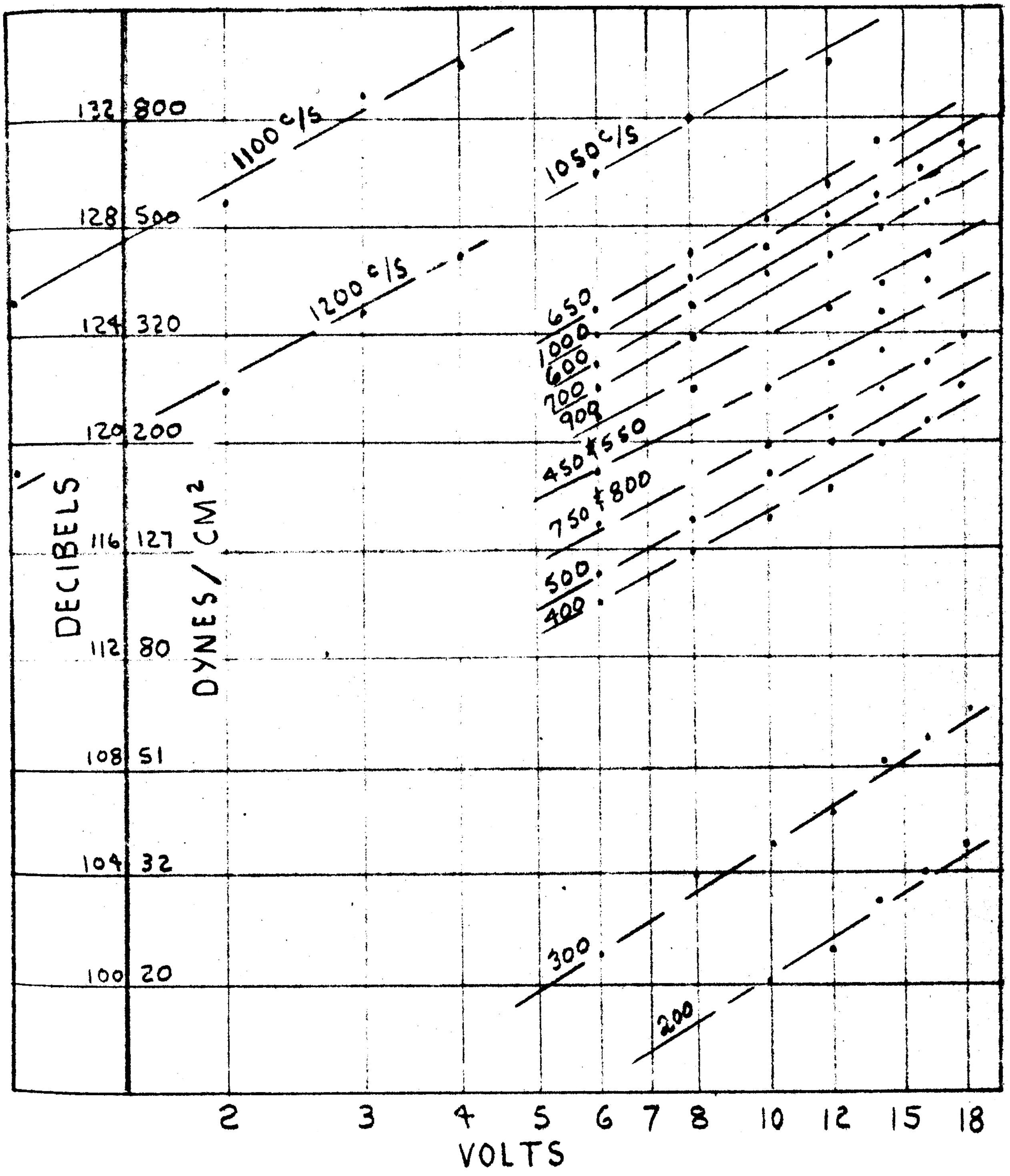

TRANSDUCER
TRANSDUCER
INSIDE
WALL OF WOODEN
TUNNEL
28"
32
$1\frac{24}{32}$"
$2\frac{4}{32}$"
$1\frac{8}{32}$"
6"
MICROPHONE
EVAPORATIVE
HEAD
INSIDE
WALL OF WOODEN
TUNNEL

EXPLANATION OF PLATE XVII

Intensity as a function of voltage to transducer

Parameter is frequency in cycles per second

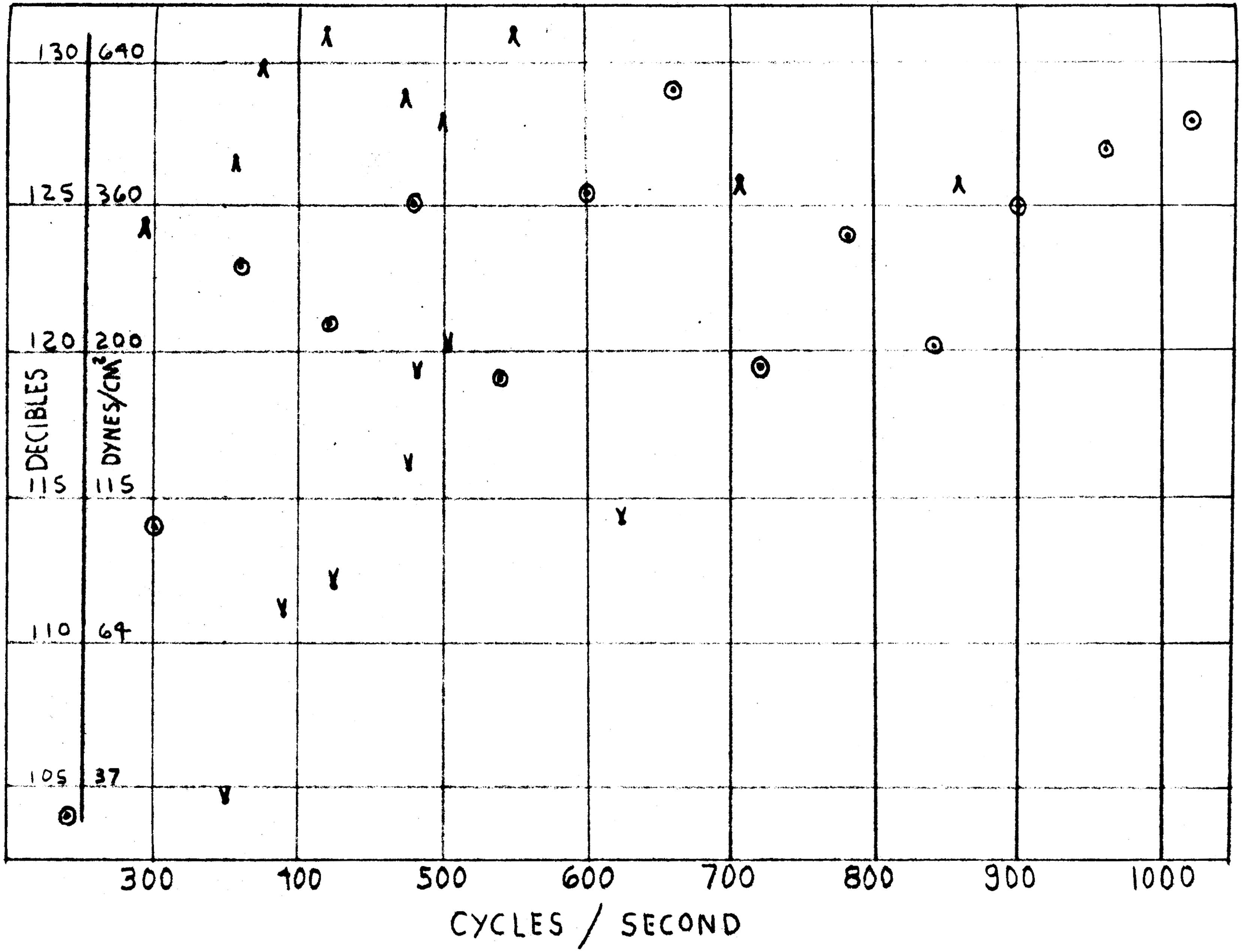
PLATE XVII


132 800
128 500
124 320
120 200
116 127
112 80
108 51
104 32
100 20
DECIBELS
DYNES/CM²
1100 c/s
1200 c/s
1050 c/s
650
1000
600
700
909
450 & 550
750 & 800
500
400
300
200
2
3
4
5
6
7
8
10
12
15
18
VOLTS

EXPLANATION OF PLATE XVIII

Plot is of intensity versus frequency in cycles per second. Fish tails represent maximum and minimum intensity points. Voltage to transducer was held at 10 volts.

PLATE XVIII



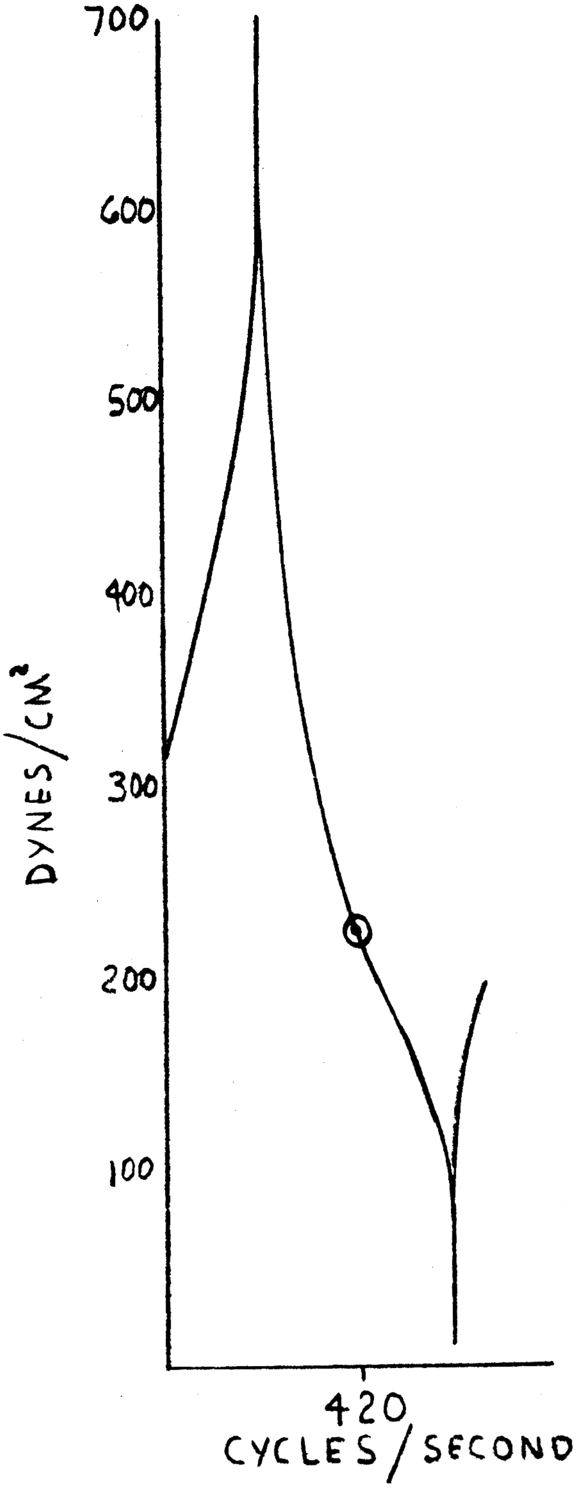
130
640
125
360
120
200
115
115
110
64
105
37
DECIBLES
DYNES/CM²
300
400
500
600
700
800
900
1000
CYCLES / SECOND

EXPLANATION OF PLATE XIX

Author's concept of intensity versus frequency

Cusps represent maximum and minimum intensity points.

PLATE XIX



EXPLANATION OF PLATE XX

Method used in calculating empirical equation

$R/R_o = aI + bIG + cG + d$ at 600 cycles per second

where a, b, c and d are constants

$R =$ rate of evaporation with sound

$R_o =$ rate of evaporation without sound

$I =$ intensity in pounds per square foot

$G =$ mass flow rate of air in pounds per square foot per second

$R/R_o = mI + b$ where m and b are functions of G

$m = -50G + 5$

$b = 15.5G - 0.65$

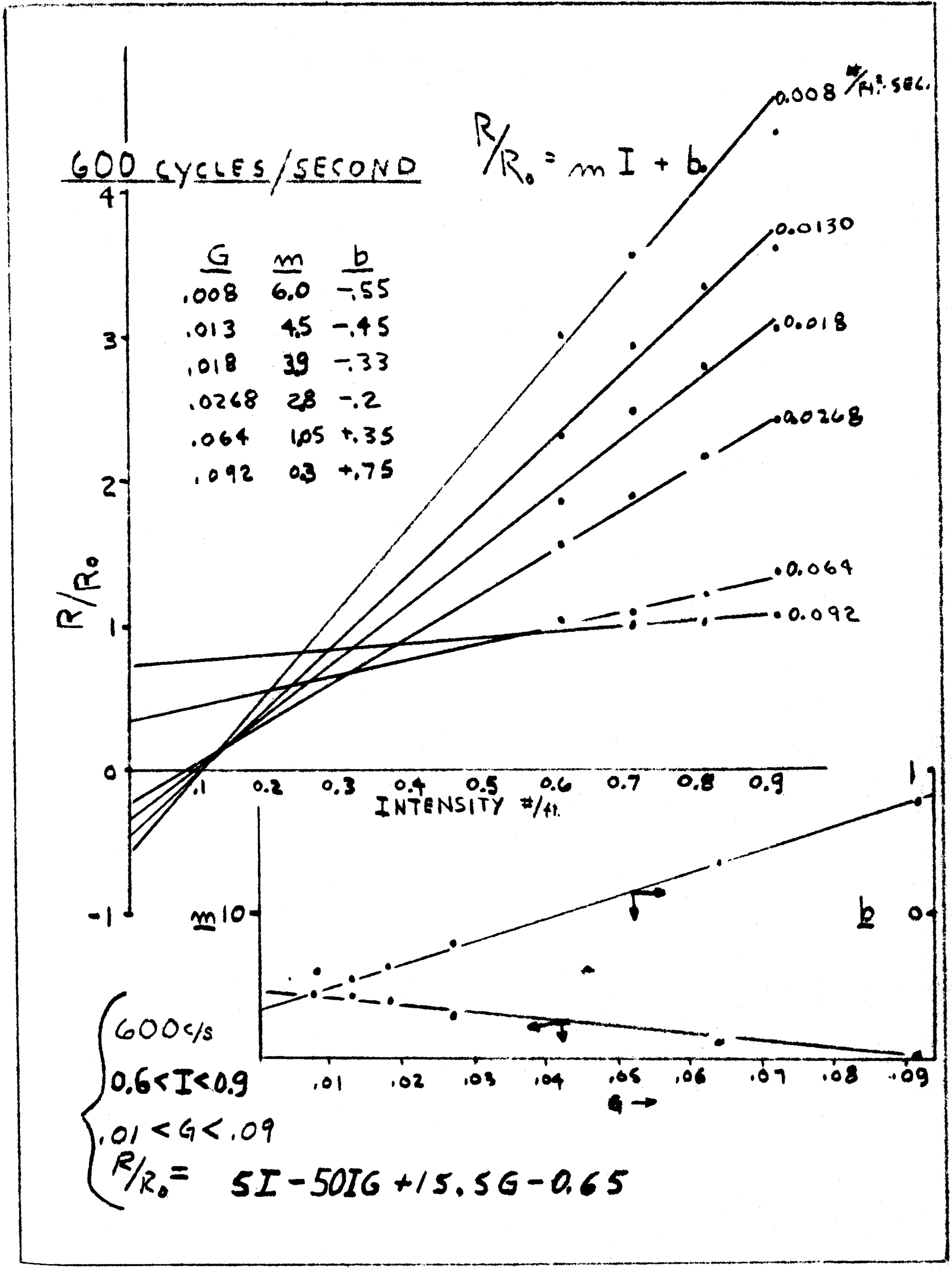
These are simple straight line relationships and apply only the ranges indicated.

$R/R_o = 5I - 50IG + 15.5G - 0.65$

$0.6 < I < 0.9$

$0.01 < G < 0.09$

PLATE XX



$R/R_0 = mI + b$

G	m	b
.008	6.0	-.55
.013	4.5	-.45
.018	3.9	-.33
.0268	2.8	-.2
.064	1.05	+.35
.092	0.3	+.75

600 c/s

$0.6 < I < 0.9$

$.01 < G < .09$

$$R/R_0 = 5I - 50IG + 15.5G - 0.65$$

EXPLANATION OF PLATE XXI

Method used in calculating empirical equation

$R/R_o = aI + bIG + cG + d$ at 660 cycles per second

where a, b, c and d are constants

R = rate of evaporation with sound

R_o = rate of evaporation without sound

I = intensity in pounds per square foot

G = mass flow rate of air in pounds per square foot per second

$R/R_o = mI + b$ where m and b are functions of G

$m = -165G + 5$

$b = 55.0G - 2.75$

These are simple straight line relationships and apply only to the ranges indicated.

$R/R_o = 5I - 165IG + 55G - 2.75$

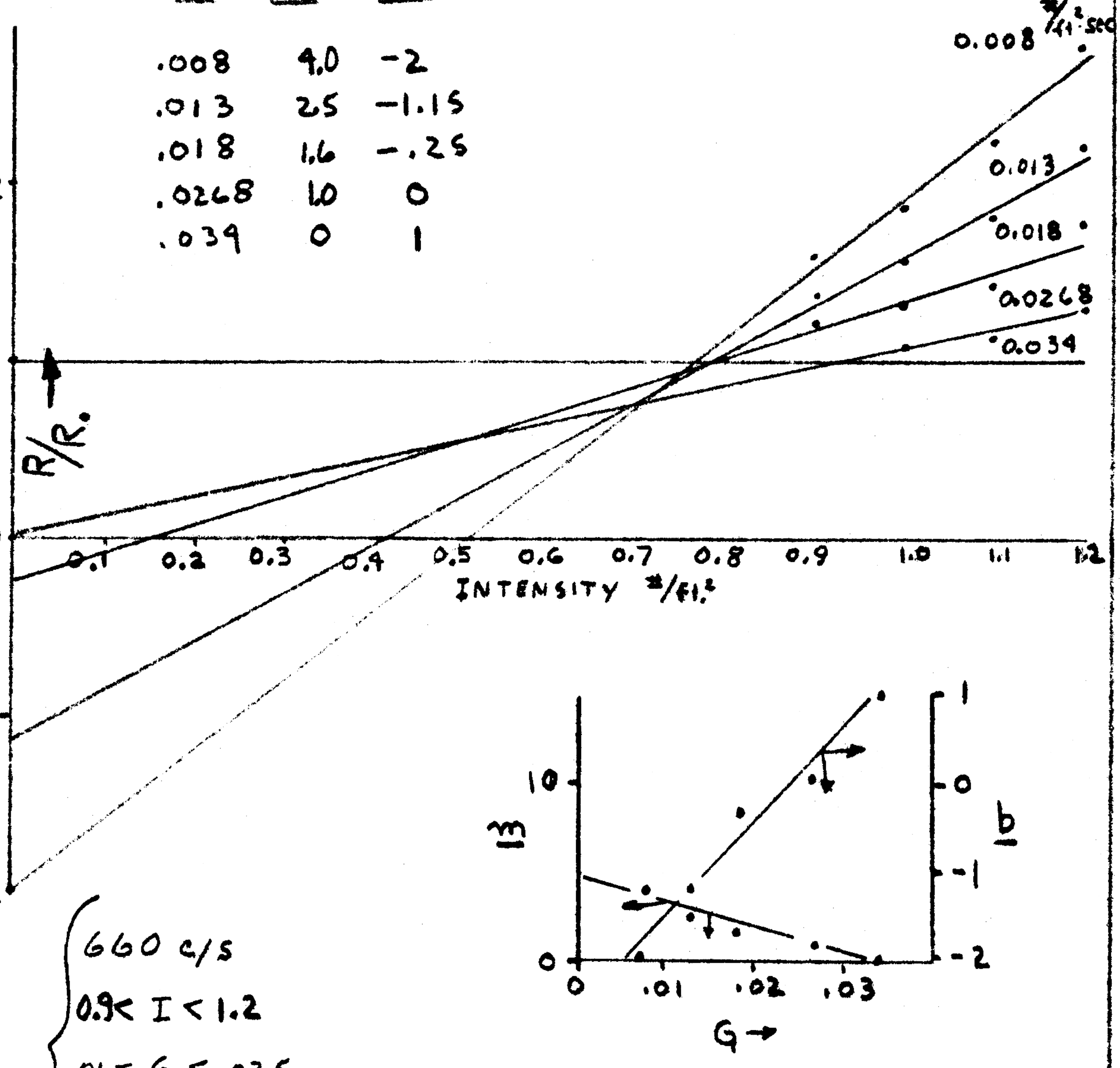
$0.9 < I < 1.2$

$0.01 < G < 0.035$

PLATE XXI

660 CYCLES/SECOND $R/R_0 = mI + b$

G	m	b
.008	4.0	-2
.013	2.5	-1.15
.018	1.6	-.25
.0268	1.0	0
.039	0	1



660 c/s

$0.9 < I < 1.2$

$.01 < G < .035$

$R/R_0 = 5I - 165IG + 55G - 2.75$

EXPLANATION OF PLATE XXII

Arrangement of balsa wood and evaporative head.

Balsa wood was placed in tunnel and around evaporative head.

PLATE XXII

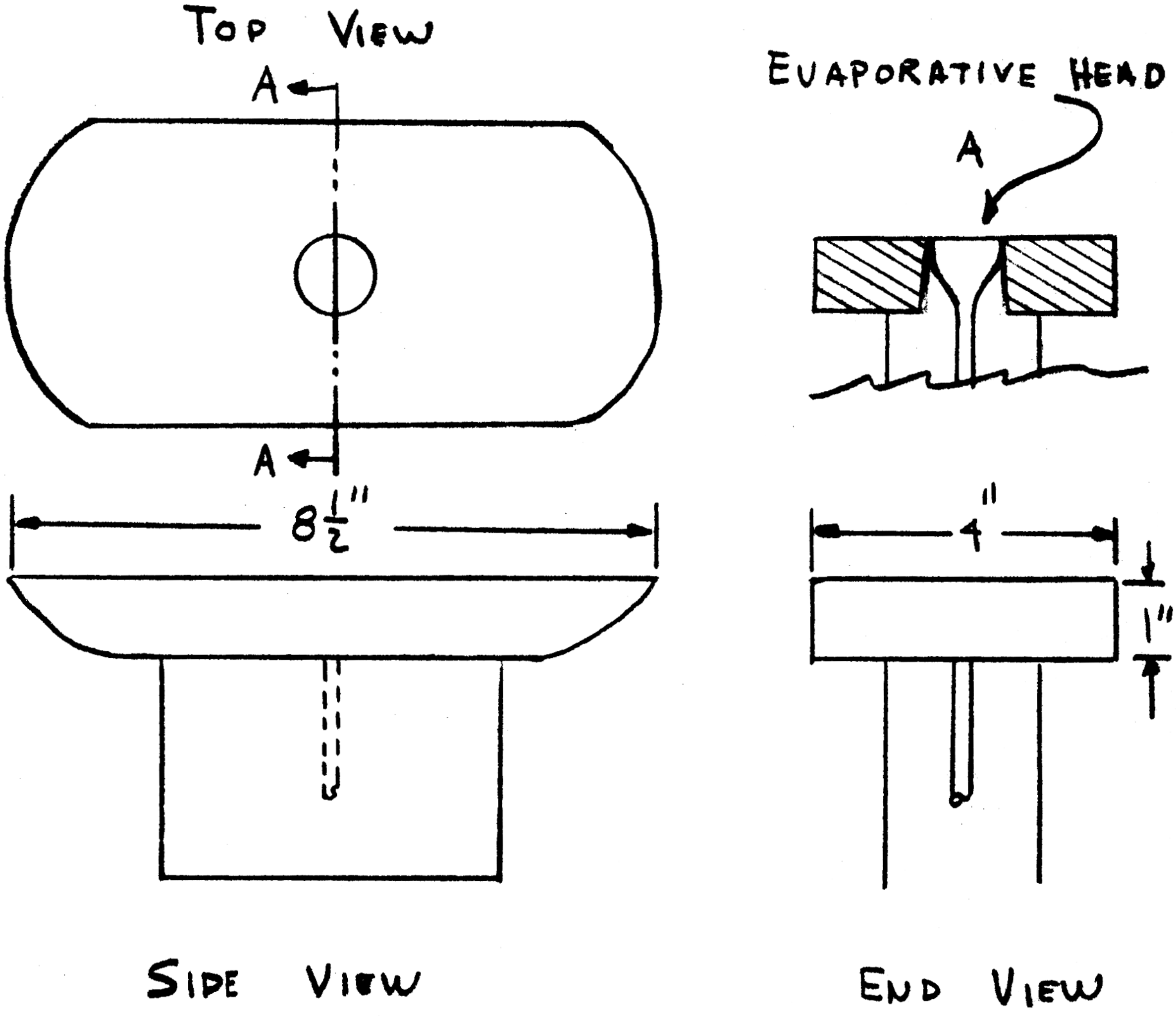


Table 1. Intensity as a function of voltage to transducer.
Intensities in decibels.

Volts	6	8	10	12	14	16	18
CPS							
200	87	89	90	91	93	94	95
300	91	94	95	96	98	99	100
400	104	106	107	108	110	111	111
450	109	111	112	113	115	116	116
500	105	107	109	110	112	113	114
550	109	111	112	113	115	116	116
600	113	115	117	118	119	120	121
650	115	117	118	119	121	121	121
700	112	114	116	117	118	119	119
750	107	109	110	111	113	113	113
800	107	109	110	111	113	113	113
900	111	112	114	115	116	117	---
1000	114	116	117	118	119	120	---
1050	120	122	123	124	126	---	---
	1v	2v	3v	4v			
1100	115	119	123	124			
1200	109	112	115	117			

Sonic Transducer SA-HF#5

Table 2. Intensity as a function of frequency. Volts = 10 v.

CPS	Decibels	CPS	Decibels
240	94	500	108
290	115	501	110
300	104	540	109
350	94.5	550	121
359	117	600	115.5
360	113	625	104.5
379	120	660	119
390	101	704	116
419	121	720	109
420	111	780	114
422	102	840	110.5
470	119	860	116
475	106	900	115
480	115	960	117
482	109	1020	118

Sonic Transducer SA-HF-#S

Table 3. R/R_o as a function of I and G.

	G	600 Cycles Per Second I				660 Cycles Per Second I			
In.H_2O	$\#/ft^2$-sec	0.6	0.7	0.8	0.9	0.9	1.0	1.1	1.2
		R/R_o	R/R_o	R/R_o	R/R_o	R/R_o	R/R_o	R/R_o	R/R_o
0.3	0.008	3.0	3.55	4.15	4.48	1.58	1.85	2.22	2.75
0.6	0.013	2.3	2.94	3.34	3.58	1.35	1.54	1.77	2.18
1.0	0.018	1.8	2.50	2.79	3.04	1.18	1.3	1.43	1.77
2.0	0.0268	1.3	1.88	2.16	2.40	1.0	1.07	1.13	1.26
3.0	0.34	1.2	1.65	1.98	2.18	-	-	-	-
4.0	0.0392	1.16	1.49	1.87	2.02	-	-	-	-
5.0	0.0444	1.11	1.39	1.75	1.89	-	-	-	-
6.0	0.0490	1.07	1.25	1.50	1.65	-	-	-	-
7.0	0.0572	1.06	1.15	1.32	1.46	-	-	-	-
8.0	0.064	1.02	1.08	1.20	1.32	-	-	-	-
9.0	0.078	1.01	1.04	1.11	1.18	-	-	-	-
10.0	0.092	1.00	1.00	1.03	1.06	1.0	1.0	1.0	1.0

Values of R and R_o were taken from the curves on Plate X and XIII, where

R = Rate of vaporization with sound
R_o = Rate of vaporization without sound
I - Intensity of sound $\#/ft^2$
G = Mean flow rate of air $\#/H^2$-sec

Table 4. Original Data. Head No. 10. Transducer No. 5.

Run No.	G #/ /ft.^{2} sec.	Mano-meter Inclined	Temp. mv.	$^{\circ}$F	F c/sec	V volts	db deci-bels	Intens. Press. #/ft^2	Time min.	vx10^5 ml.	Rate x10^5 ml/min	Rate x10^5 #/ /ft^2 sec.
A-14-01	0.008	0.11	1.160	73	--*	--*	--*	--*	5.56	1148	206	1.39
-02	"	"	1.219	75	--*	--*	--*	--*	5.75	1181	206	1.39
-03	"	"	1.230		--*	--*	--*	--*	5.29	1091	206	1.39
-04	"	"			600	9	124.9	0.72	1.55	1160	748	5.04
-05	"	"			"	6	122.0	0.52	2.31	1120	485	3.26
-06	"	"			"	11	126.7	0.84	1.36	1141	838	6.64
-07	"	"	1.240	76	--*	--*	--*	--*	5.91	1148	195	1.31
-08	"	"			600	12	126.8	0.88	1.33	1181	888	5.90
-09	"	"			"	4	119.2	0.38	3.85	1091	301	2.03
-10	"	"			"	10	125.6	0.76	1.43	1120	782	5.27
-11	"	"			"	13	127.3	0.94	1.30	1141	880	5.93
-12	"	"	1.248	76	--*	--*	--*	--*	6.12	1124	184	1.24
-13	"	"			600	8	124.0	0.66	1.76	1148	653	4.40
-14	"	"			660	10	129.0	11.4	2.26	1091	483	3.25
-15	"	"			"	6	125.4	0.76	4.31	1120	260	1.75
-16	"	"			"	12	130.3	1.32	1.79	1142	638	4.30
-17	"	"			"	9	128.3	1.05	2.83	1124	397	2.68
-18	"	"	1.262	76	--*	--*	--*	--*	5.76	1148	200	1.35
-19	"	"			660	2	117.8	0.32	6.06	1181	195	1.31
-20	"	"			--*	4	122.3	0.56	5.06	1160	230	1.55
-21	"	"			--*	11	129.6	12.3	1.83	1120	610	4.10
-22	"	"			--*	11	129.6	12.3	1.61	1120	695	4.68
-23	"	"			--*	8	127.4	0.96	3.42	1141	334	2.24
-24	"	"			--*	12	130.3	1.32	1.65	1124	682	4.59
-25	"	"	1.271	77	--*	--*	--*	--*	5.69	1120	197	1.32
A-15-01	0.0168	0.3	1.007	68	--*	--*	--*	--*	3.90	1148	295	1.98
-02	"	"			--*	--*	--*	--*	4.00	1181	295	1.98
-03	"	"			--*	--*	--*	--*	3.68	1091	296	1.99
-04	"	"			600	8	124.0	0.66	1.79	1160	640	4.36
-05	"	"			"	13	127.3	0.94	1.27	1120	881	5.93

Table 4. (Cont.)

Run No.	G #/ft.²/sec.	Manometer Inclined	Temp. mv.	°F	F c/sec	V volts	db decibels	Intens. Press. #/ft²	Time min.	vx10⁵ min.	Rate x 10⁵ ml/min	Rate x 10⁵ #/ft²sec
A-15-06	0.0168	0.3	1.020	68	600	10	125.6	0.76	1.58	1141	772	
-07	"	"	1.010	675	--*	--*	--*	--*	4.5	1148	255	1.72
-08	"	"			600	4	119.2	0.38	4.11	1181	290	1.95
-09	"	"			--*	12	126.8	0.88	1.32	1160	880	5.93
-10	"	"			--*	11	126.2	0.84	1.36	1120	822	5.54
-11	"	"	1.010	67.5	"	6	122.0	0.52	2.92	1141	391	2.63
-12	"	"			--*	--*	--*	--*	4.27	1124	267	1.80
-13	"	"			600	9	124.9	0.72	1.55	1148	741	4.99
-14	"	"	1.031	68.5	660	11	129.6	12.3	1.85	1091	590	3.97
-15	"	"			--*	4	122.3	0.56	4.32	1120	261	1.76
-16	"	"			--*	2	117.8	0.32	4.36	1142	262	1.77
-17	"	"			--*	9	12813	105	2.69	1124	418	2.82
-18	"	"	1.050	69	--*	--*	--*	--*	4.30	1148	267	1.80
-19	"	"			660	12	130.3	13.2	1.77	1181	668	4.50
-20	"	"			--*	6	125.4	0.76	4.11	1160	282	1.90
-21	"	"			660	10	129.0	11.4	2.42	1120	463	3.12
-22	"	"	1.062	69	"	8	127.4	0.96	3.46	1141	330	2.22
A-16-01	0.0228	0.5			--*	--*	--*	--*	3.49	1148	329	2.22
-02	"	"			--*	--*	--*	--*	3.62	1181	326	2.20
-03	"	"			--*	--*	--*	--*	3.28	1091	332	2.24
-04	"	"			600	11	126.2	0.84	1.47	1160	790	5.32
-05	"	"			"	8	124.0	0.66	1.89	1120	552	3.72
06	"	"			"	4	119.2	0.38	3.56	1141	320	2.16
-07	"	"			--*	--*	--*	--*	3.46	1148	332	2.23
-08	"	"			600	13	127.3	0.94	1.34	1181	881	5.93
-09	"	"	1.268	76	"	10	125.6	0.76	1.56	1160	744	5.00
-10	"	"			--*	6	122.0	0.52	2.87	1120	390	2.62
-11	"	"			--*	12	126.8	0.88	1.32	1141	864	5.81
-12	"	"	1.279	77	--*	--*	--*	--*	3.43	1124	338	2.28
-13	"	"			600	9	124.9	0.72	1.62	1148	709	4.77

Table 4. (Cont.)

Run No.	G #/ /ft^2 sec.	Manometer Inclined	Temp. mv.	°F	F c/sec	V volts	db decibels	Intens. Press. #/ft^2	Time min.	vx10^5 min.	Rate x 10^5 ml/min	Rate x 10^5 #/ /ft^{2}sec
A-16-14	0.0228	0.5			660	6	125.4	0.76	3.33	1091	328	2.21
-15	"	"			"	10	129.0	1.14	2.60	1120	431	2.90
-16	"	"			"	12	130.3	1.32	2.08	1142	549	3.70
-17	"	"			"	8	127.4	0.96	3.30	1124	341	2.30
-18	"	"			--*	--*	--*	--*	3.41	1148	336	2.26
-19	"	"			660	4	122.3	0.56	3.49	1181	338	2.28
-20	"	"			"	11	129.6	1.23	2.38	1160	488	3.28
-21	"	"	1.299	78	"	9	128.3	1.05	3.00	1120	374	2.52
-22	"	"	1.305	78	"	2	117.8	0.32	3.28	1124	343	2.31
A-17-01	0.0274	0.7	1.342	79	--*	--*	--*	--*	3.14	1148	366	2.46
-2	"				--*	--*	--*	--*	3.27	1181	361	2.43
-03	"				--*	--*	--*	--*	3.00	1091	364	2.45
-04	"				600	11	126.2	0.84	1.41	1160	820	5.52
-05	"				"	6	122.0	0.52	2.82	1120	397	2.67
-06	2				"	4	119.2	0.38	3.21	1141	357	2.40
A-17-07	0.0274	0.7	1.330	79	--*	--*	--*	--*	3.15	1148	364	2.45
-08	"	"			600	10	125.6	0.76	1.56	1181	758	5.10
-09	"	"			"	13	127.3	0.94	1.27	1160	914	6.14
-10	"	"			"	8	124.0	0.66	1.90	1120	589	3.96
-11	"	"			"	9	124.9	0.72	1.65	1141	692	4.66
-12	"	"	1.345	79	--*	--*	--*	--*	3.15	1124	358	2.41
-13	"	"			600	12	126.8	0.88	1.33	1148	863	5.80
-14	"	"			660	4	122.3	0.56	3.07	1091	355	2.39
-15	"	"			"	2	117.8	0.32	3.04	1120	368	2.48
-16	"	"			"	12	130.3	1.32	2.91	1142	495	3.33
-17	"	"			"	6	125.4	0.76	3.08	1124	366	2.46
-18	"	"	1.358	80	--*	--*	--*	--*	3.00	1148	382	2.57
-19	"	"			660	11	129.6	1.23	2.40	1091	454	3.06
-20	"	"			"	9	128.3	1.05	2.95	1120	380	2.56
-21	"	"			"	8	127.4	0.96	3.10	1142	361	2.43

Table 4. (Cont.)

Run No.	G #/ /ft^2 sec.	Mano- meter Inclined	Temp. mv.	^{o}F	F c/sec	V volts	db deci- bels	Intens. Press. #/ft^2	Time min.	vx10^5 min.	Rate x 10^5 ml/min	Rate x 10^5 #/ /ft^{2}sec
A-17-22	0.0274	0.7			660	10	129.0	1.23	2.72	1124	413	2.78
A-18-01	0.0338	1.0			--*	--*	--*	--*	3.14	1148	366	2.46
-02	"	"			--*	--*	--*	--*	3.24	1181	364	2.45
-03	"	"			--*	--*	--*	--*	2.95	1091	370	2.49
-04	"	"			600	12	126.8	0.88	1.44	1160	805	5.42
-05	"	"			"	9	124.9	0.72	1.76	1120	636	4.18
-06	"	"			"	8	124.0	0.66	2.15	1141	531	3.57
-07	"	"			--*	--*	--*	--*	3.18	1148	361	2.42
-08	"	"			600	13	127.3	0.94	1.44	1181	820	5.52
-09	"	"			"	10	125.6	0.76	1.68	1160	690	4.64
-10	"	"			"	4	119.2	0.38	3.13	1120	358	2.41
-11	"	"			"	6	122.0	0.52	2.99	1141	382	2.57
-12	"	"			--*	--*	--*	--*	3.01	1124	374	2.52
-13	"	"			600	11	126.2	0.84	1.51	1148	760	5.11
-14	"	"	1.262	76	660	10	129.0	1.14	2.85	1091	383	2.58
-15	0.0338	1.0			"	8	127.4	0.96	3.15	1120	356	2.40
-16	"	"			"	9	128.3	1.05	3.14	1142	364	2.45
-17	"	"			"	11	129.6	1.23	2.76	1124	407	2.74
-18	"	"			--*	--*	--*	--*	2.97	1148	386	2.60
-19	"	"	1.287	77	660	6	125.4	0.76	3.18	1181	372	2.50
-20	"	"			"	12	130.3	1.32	2.61	1160	445	3.00
-21	"	"			"	2	117.8	0.32	2.89	1120	387	2.50
-22	"	"	1.287	77	"	4	122.3	0.56	3.00	1141	380	2.56
A-18-23	0.0418	1.5			--*	--*	--*	--*	2.85	1148	403	2.72
-24	"	"			--*	--*	--*	--*	2.96	1181	401	2.70
-25	"	"	1.287	77	--*	--*	--*	--*	2.72	1091	402	2.71
-26	"	"			600	8	124.0	0.66	2.29	1160	507	3.41
-27	"	"			"	13	127.3	0.94	1.40	1120	800	5.39
-28	"	"			"	10	125.6	0.76	1.79	1141	638	4.30

Table 4. (Cont.)

Run No.	G #/ /ft^2 sec.	Mano- meter Inclined	Temp. mv.	Temp. $^{\circ}$F	F c/sec	V volts	db deci- bels	Intens. Press. #/ft^2	Time min.	vx10^5 min.	Rate x 10^5 ml/min	Rate x 10^5 #/ /ft^{2}sec
A-18-29	0.0418	1.5			--*	--*	--*	--*	2.80	1148	410	2.76
-30	"	"			600	4	119.2	0.38	3.03	1181	390	2.62
-31	"	"			"	12	126.8	0.88	1.52	1160	754	5.08
-32	"	"			"	11	126.2	0.84	1.51	1120	742	5.00
-33	"	"			"	6	122.0	0.52	2.84	1141	402	2.71
-34	"	"	1.278	77	--*	--*	--*	--*	2.78	1148	413	2.78
-35	"	"			600	9	124.9	0.72	2.02	1181	586	3.94
-36	"	"			660	11	129.6	1.23	2.58	1091	423	2.85
-37	"	"			"	4	122.3	0.56	2.71	1120	413	2.78
-38	"	"			"	2	117.8	0.32	2.76	1142	414	2.79
-39	"	"			"	9	128.3	1.05	2.78	1124	405	2.73
-40	"	"			--*	--*	--*	--*	2.76	1148	416	2.80
-41	"	"			660	12	130.3	13.2	2.55	1181	463	3.12
-42	"	"			"	6	125.4	0.76	2.84	1160	409	2.76
-43	"	"	1.254	76	"	10	129.0	1114	2.67	1120	428	2.88
-44	"	"			"	8	127.4	0.96	2.82	1141	405	2.73
A-19-01	0.0488	2.0	1.311	78	--*	--*	--*	--*	2.87	1148	400	2.69
-02	"	"			--*	--*	--*	--*	2.96	1181	400	2.69
-03	"	"			600	9	124.9	0.72	2.10	1160	553	3.72
-04	"	"			"	6	122.0	0.52	2.81	1120	400	2.69
-05	"	"			"	11	126.2	0.84	1.79	1141	638	4.30
-06	"	"	1.331	79	--*	--*	--*	--*	2.86	1148	400	2.69
-07	"	"			600	12	126.8	0.88	1.85	1181	639	4.30
-08	"	"				4	119.2	0.38	2.98	1160	390	2.62
-09	"	"				10	125.6	0.76	1.95	1120	574	3.86
-10	"	"				13	127.3	0.94	1.64	1141	695	4.68
-11	"	"				8	124.0	0.66	2.47	1148	465	3.14
-12	"	"			660	10	129.0	11.4	2.83	1091	386	2.60
-13	"	"			"	6	125.4	0.76	2.87	1120	391	3.63
-14	"	"			"	12	130.3	1.32	2.77	1142	413	2.78

Table 4. (Cont.)

Run No.	G #/ /ft^2 sec.	Mano- meter Inclined	Temp. mv.	°F	F c/sec	V volts	db deci- bels	Intens. Press. #/ft^2	Time min.	vx10^5 min.	Rate x10^5 ml/min	Rate x 10^5 #/ /ft^{2}sec
A-19-15	0.0488	2.0			660	9	128.3	1.05	2.89	1124	390	2.62
-16	"	"	1.331	79	--*	--*	--*	--*	2.77	1148	413	2.78
-17	"	"			660	2	117.8	0.32	2.90	1181	407	2.74
-18	"	"			" 4	4	122.3	0.56	2.85	1160	406	2.74
-19	"	"			"	11	129.6	1.23	2.72	1120	412	2.78
-20	"	"			"	8	127.4	0.96	2.90	1141	393	2.65
		U-tube										
A-20-01	0.0611	1.05 3.05			--*	--*	--*	--*	2.93	1181	403	2.71
-2	"	"	1.210	75	--*	--*	--*	--*	2.68	1091	407	2.74
-03	"	"			600	11	126.3	0.84	2.11	1160	551	3.70
-04	"	"			"	8	124.0	0.66	2.59	1120	433	2.91
-05	"	"			"	4	119.2	0.38	2.86	1141	399	2.68
-06	"	"	1.210	75	--*	--*	--*	--*	2.81	1148	408	2.75
-07	"	"			600	13	127.3	0.94	1.99	1181	593	3.99
-08	"	"			"	10	125.6	0.76	2.36	1160	492	3.31
-09	"	"			"	6	122.0	0.52	2.79	1120	402	2.70
-10	"	"			"	12	126.8	0.88	2.02	1141	566	3.81
-11	"	"			--*	--*	--*	--*	2.74	1124	412	2.77
-12	"	"	1.218	75	600	9	124.9	0.72	2.50	1148	458	3.08
-13	"	"			660	6	125.4	0.76	2.71	1091	403	2.71
-14	"	"			"	10	129.0	1.14	2.79	1120	402	2.71
-15	"	"			"	12	130.3	1.32	2.77	1142	412	2.77
-16	"	"			"	8	127.4	0.96	2.78	1124	405	2.72
-17	"	"	1.218	75	--*	--*	--*	--*	2.72	1148	413	2.78
-18	"	"			660	4	122.3	0.56	2.85	1181	414	2.78
-19	"	"			"	11	129.6	1.23	2.78	1160	418	2.81
-20	"	"			"	9	128.3	1.05	2.72	1120	412	2.77
-21	"	"			"	2	117.8	0.32	2.74	1141	416	2.80
A-21-01	0.0785	0.1 5.1			--*	--*	--*	--*	2.60	1148	442	2.97
-02	"	"			--*	--*	--*	--*	2.70	1181	438	2.95

Table 4. (Cont.)

Run No.	G #/ /ft^2 sec.	Manometer		Temp. mv.	°F	F c/sec	V volts	db decibels	Intens. Press. #/ft^2	Time min.	vx10^5 ml.	Rate x10^5 ml/min	Rate x10^5 #/ /ft^{2}sec
A-21-03	0.0785	0.1	5.1			--*	--*	--*	--*	2.46	1091	444	2.98
-04	"	"	"			600	11	126.2	0.84	2.29	1160	507	3.41
-05	"	"	"			"	6	122.0	0.52	2.53	1120	442	2.98
-06	"	"	"			"	4	119.2	0.38	2.60	1141	439	2.96
-07	"	"	"	1.402	81	--*	--*	--*	--*	2.54	1148	451	3.04
-08	"	"	"			600	10	125.6	0.76	2.45	1181	482	3.22
-09	"	"	"			"	13	127.3	0.94	2.13	1160	545	3.66
-10	"	"	"			"	8	124.0	0.66	2.40	1120	467	3.14
-11	"	"	"			"	9	124.9	0.72	2.43	1141	469	3.16
-12	"	"	"			--*	--*	--*	--*	2.45	1124	459	3.09
-13	"	"	"			600	12	126.8	0.88	2.12	1148	542	3.65
-14	"	"	"			660	4	122.3	0.56	2.37	1091	461	3.10
-15	"	"	"			"	2	117.8	0.32	2.43	1120	461	3.10
-16	"	"	"			"	12	130.3	1.32	2.52	1142	453	3.05
-17	"	"				"	10	129.0	1.14	2.47	1124	455	3.06
-18	"	"	"	1.405	81	--*	--*	--*	--*	2.42	1148	475	3.20
-19	"	"	"			660	11	129.6	1.23	2.59	1181	456	3.07
-20	"	"	"			"	8	127.4	0.96	2.51	1160	462	3.11
-21	"	"	"			--*	--*	--*	--*	2.37	1120	473	3.18
-22	"	"	"	1.405	81	--*	--*	--*	--*	2.34	1120	478	3.22
-23	"	"	"			--*	--*	--*	--*	2.43	1142	470	3.16
-24	"	"	"			--*	--*	--*	--*	2.41	1181	473	3.18
-25	"	"	"			--*	--*	--*	--*	2.34	1124	477	3.21
-26	0.112	2.4	7.6	1.452	83	--*	--*	--*	--*	2.18	1148	527	3.54
-27	"	"	"	1.452	83	--*	--*	--*	--*	2.25	1181	525	3.53
-28	"	"	"			600	12	126.8	0.88	2.01	1091	543	3.67
-29	"	"	"			"	8	124.0	0.66	2.14	1120	523	3.52
-30	"	"	"			"	13	127.3	0.94	2.11	1142	542	3.65
-31	"	"	"			"	10	125.6	0.76	2.09	1124	538	3.62

Table 4. (Concl.)

Run No.	G #//ft² sec.	Manometer U-tube		Temp. mv.	°F	F c/sec	V volts	db decibels	Intens. Press. #/ft²	Time min.	vx10⁵ ml.	Rate x10⁵ ml/min	Ratex10⁵ #//ft²sec
A-21-32	0.112	2.4	7.6	1.452	83	--*	--*	--*	--*	2.14	1148	537	3.61
-33	"	"	"			600	4	119.2	0.38	2.26	1181	523	3152
-34	"	"	"			"	11	126.2	0.88	2.13	1160	544	3.66
-35	"	"	"			660	9	128.3	1.05	2.12	1120	528	3.56
-36	"	"	"			"	11	129.6	1.23	2.17	1141	526	3.54
-37	"	"	"	1.470	84	--*	--*	--*	--*	2.11	1124	532	3.58
-38	"	"	"			--*	--*	--*	--*	2.13	1148	538	3.62
-39	"	"	"			660	6	125.4	0.76	2.24	1181	528	3.55
-40	"	"	"			"	12	130.3	1.32	2.20	1160	527	3.55
-41	"	"	"			"	2	117.8	0.32	2.08	1120	538	3.62
-42	"	"	"	1.470	84	--*	--*	--*	--*	2.15	1142	532	3.58
-43	"	"	"			--*	--*	--*	--*	2.13	1141	536	3.60

--* = No sound applied

THE EFFECT OF SONIC VIBRATIONS ON THE RATES OF MASS TRANSFER

by

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There were three objectives of this investigation. The first objective was to correlate the effects of sonic vibrations on the rate of mass transfer. The second was to investigate the relationship between frequency and intensity of the sonic energy. The third objective was to explain why the rate of mass transfer was so sensitive to the frequency and the intensity of the sonic vibrations. This work was limited to the range of frequencies 240 to 1,200 cycles per second.

Pure water and dry air were chosen for study in this investigation of mass transfer between liquid and gaseous phase. Liquid water was evaporated into an air stream. The effect of sonic vibrations on the rates of evaporation was studied. The rate of evaporation at given conditions without application of sound was compared with the rate of evaporation under the same conditions but with the application of sound. The differences in the rates of mass transfer were assumed to be due to the effect of sonic energy or pulsations.

Two restricted equations which correlated the effect of sonic vibrations on the rate of mass transfer were:

1. $R/R_o = 5I - 50IG + 15.5G - 0.65$

with the restrictions:

frequency $=$ 600 cycles per second

$0.6 < I < 0.9$ pounds per square foot

$0.01 < G < 0.09$ pounds per square foot per second and 2. $R/R_o = 5I - 165IG + 55G - 2.75$

with the restrictions:

frequency = 660 cycles per second

$0.9 < I < 1.2$ pounds per square foot

$0.01 < G < 0.035$ pounds per square foot per second

where I = intensity in pounds per square foot

G = mass flow rate of air in pounds per square foot per second

R = rate of evaporation with sound applied to the system

R_o = rate of evaporation without sound applied to the system.

It was noted that the coefficient of the intensity term was the same in both equations, eg., 5. This seemed to indicate that the term, 5I, was independent of the frequency of the sonic vibrations.

The relationship between frequency and intensity was found to be quite complex. There will be disagreement among investigators of sonic energies as to the optimum frequencies to be employed because of this "complex relationship" between frequency and intensity and because of the difficulty in reproducing identical frequencies.