SHADING COILS

FOR

ALTERNATING CURRENT ELECTROMAGNETS

by

tafford

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I

TABLE OF CONTENTS

Chapter | Page

Chapter | Page

Chapter Page

XI GRAPHS

## II

## INTRODUCTION

**History.** Electromagnets as the operating force for electrical relays were first conceived and operated by[3] Joseph Henry in the year 1835. These relays were operated by direct current and only after the year 1886 when the first alternating current distribution system was installed was severe difficulty experienced in their use. In attempting to apply alternating current to the relays which had been so successful on direct current, these early pioneers discovered that severe chattering occurred. Attempts were made to reduce this chattering as early as 1895 when a patent was allowed for the use of a shading coil to delay part of the flux of the pole of the electromagnet. These attempts were partially successful in that the relay chattering was reduced sufficiently to allow the relay contacts to remain closed. As years progressed little was accomplished toward providing data for the design of shading coils for relays. At the present time the literature available is not very extensive. It is conventional for modern designers to use purely experimental techniques in determining the best size or shape shading coil for a particular relay application in order to reduce its chattering to a tolerable value. It is for this reason that this investigation was undertaken. It is an attempt to provide experimental data for use in conjunction with present theory toward the end of supplying design relationships to relay designers thus enabling them to attain optimum relay performance.

Investigation Technique. In order to perform this investigation it was felt that the use of several magnetic cores would be desireable. Each of these was as nearly identical as possible to the others except that different sized slots were made in the pole faces of each so as to allow changes to be made in the shading coils. Shading coils were constructed of three different materials and in two basic shapes. Varying thicknesses of each material and of each shape allowed data to be taken for several curves. Readings of input power, noise, and phase angle versus force and shading coil thickness were taken. The curves plotted from these data show definite minimum noise points which represent the best shading coil design for that particular condition of operation.

Acknowledgements. The investigator is indebted to Mr. Rudolph Hensley for his aid in preparing the apparatus for test and to Prof. W. A. Murray for his valuable suggestions and his cooperation in obtaining the equipment needed.

## III

## REVIEW OF LITERATURE

The American Standard definition of a relay states it is "a[1] device that is operative by a variation in the conditions of one electric circuit to effect the operation of other devices in the same or another electric circuit." The[7] irregular pull due to the variation and reversals of flux in a single phase solenoid give rise to excessive noise and chattering unless a shading coil is used. This coil takes the form of one or more loops of wire of relatively large section embedded in a slot in the face of the pole end or the end of the armature so as to embrace about ½ or 2/3 of the pole area. This loop behaves like the short circuited secondary of a transformer, and the flux within the shaded portion of the pole, $\phi_s$, lags in phase $\theta$ degrees behind the flux in the unshaded portion, $\phi_{us}$. It may be seen from figure one that the resultant pull does not at any time pass through zero. Figure two shows the shading coil placed on the pole of the electromagnet with the resultant flux distribution as indicated.

"Relay Engineering" [8] by Charles A. Packard discussed shading coils and states that in addition to reducing hum or chattering the shading coil also introduces considerable heat loss. Unless the shading coil is very carefully designed it is possible that a considerable portion of the input power will be absorbed by it.

In his book [6]"Relays and Electromagnets" B. W. Jones states that "the shaded flux area should be approximately three or four times

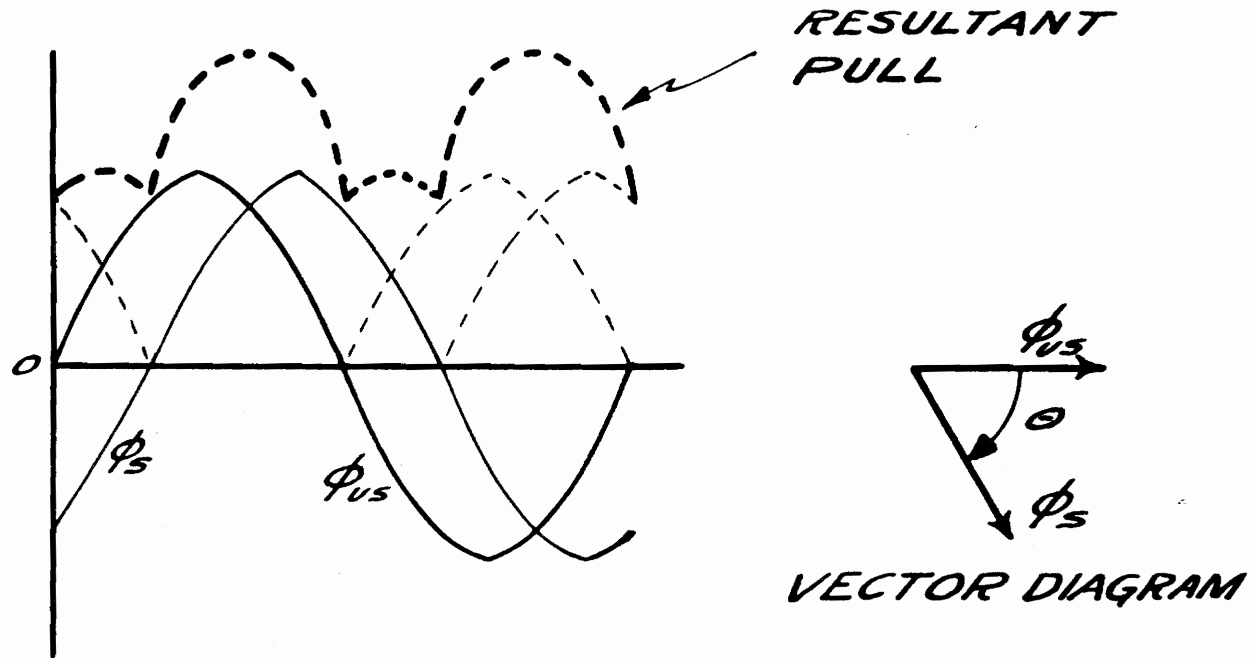



FIGURE 1

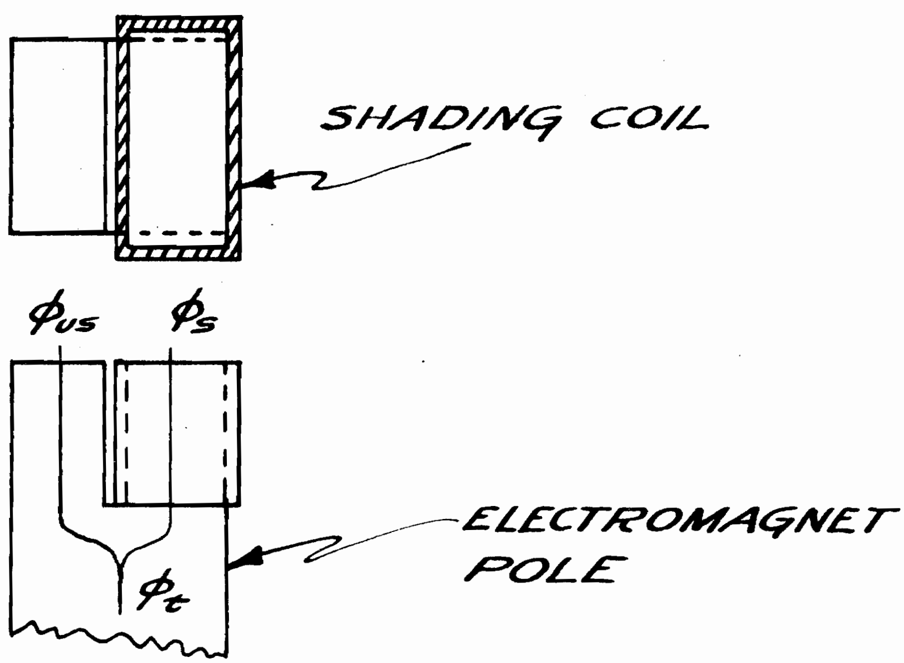



FIGURE 2

that of the unshaded flux area." In the light of work done on shading coils since the writing of this book including that of the investigator it is apparent that this statement must be qualified to include many variables. This makes it possible to use the figure of three or four to one for ratio of shaded coil area to unshaded pole area only where certain specified conditions of electromagnet operation exist and nullifies its use as a general rule.

Previous investigations have been made on methods of predicting optimum shading coil design. One of these was performed in the year 1938 by [2]Leonard A. Doggett and Franz S. Veith. Pennsylvania State College published a bulletin entitled "Design of Shading Coils for Alternating Current Electromagnets " on their work. In this investigation tests were performed on two electromagnets which were removed from two three phase, 10 horse power, induction motor starting compensators of 1910 to 1915 vintage. Thus two electromagnets of identical manufacture were available. In the one the plunger had no shading coil and in the other the plunger was equipped with a copper shading coil. It was found that the shading coil used by the manufacturer had a resistance of 0.0003 ohms. By replacing this shading coil with a coil of four times the resistance of the first, or 0.0012 ohms, it was found that far better performance of the electromagnet was obtained. The designers of 1915, however, did not know this. The extent of their knowledge was that some decrease in noise might be had by using a shading coil.

In designing a relay for use on alternating current the usual technique of choosing proper values from the standpoint of the force required, the size iron core to be used, and the heat dissipating ability required must be used. In addition two questions must be answered as follows:

1. What is the optimum ratio of shading coil flux to unshaded area flux?

2. What is the optimum value of shading coil resistance?

The authors state that they have verified the statement made by [5]P. B. Harwood in his book "Control of Electric Motors" that a ratio of shaded to unshaded area of two to one has been found best. This ratio is closer to that determined by the investigator than that proposed by B. W. Jones[6] but the ratio is still too high and should lie somewhere between two to one and one to one.

The authors also state that results of one test performed show the added pull on the magnet armature due to the shading coil and that this added pull available under closed gap conditions has no commercial value. The investigator found that there is value in having this additional pull in that it is this pull that is utilized to hold the switch or valve in the position desired and that the noise is greater if this closed gap pull is not as large as possible. Thus over design of electromagnets should produce quieter performance. This difference in conclusion is due to the investigator performing tests on noise versus pull whereas the authors of this paper did not perform such tests using different forces on the armature of the magnet.

From tables in this paper the value of shading coil resistance for best operation is given for different total pole areas and for different air gaps. The machining of the relay used by the investigator was such that an air gap of five thousandths of an inch may be assumed. This is based on figures obtained by the authors of this paper. Data appearing in this paper applicable to the electromagnet tested by the investigator is given as follows:

s = length of air gap = 0.005"

$A_1 + A_2$ (total area of the pole face) = 1.125 square inches

$R_{sc}$ (shading coil resistance) = 1200 micro-ohms (from table)

From graph #5 by the investigator the best size shading coil for noise reduction is 1/16" x 1/16" copper crossection and total length equal to $3\frac{1}{2}$ inches.

This represents a resistance of:

$$R = \frac{\rho l}{A} = \frac{(10.37)\left(\frac{7}{2}\right)\left(\frac{1}{12}\right)}{\left(\frac{1}{16}\right)\left(\frac{1}{16}\right)\left(\frac{1}{0.7854}\right)(10)^6}$$

$$= 1210 \times 10^{-6} \text{ ohms}$$

The comparison of this 1210 micro-ohms with the 1200 micro-ohms of the table shows the agreement between the best shading coil resistance as obtained by the investigator and that proposed by the authors of this paper. This can only be considered to be approximate agreement, however, since the constants utilized in the equations could vary considerably from those chosen. The air gap is a very uncertain figure as is the resistance of the shading coil since its temperature at times is much higher than room temperature.

Another investigation has been performed by C. T. Evans on [4]Shading Coil Calculations for Single Phase Magnets. This paper was published in A.I.E.E. Transactions in 1947. The chief value of the work done by C. T. Evans was the establishment of an electrical analogue which could be used to represent the magnetic circuit of an electromagnet. Thus the laborious process of machining magnetic materials to obtain desired changes in the electromagnet for experimental purposes could be avoided. Simply by changing the relative values of resistance in the analogue variations in the original electromagnet and its shading coil could be synthesized. No extensive data was developed by this means since the main purpose of the author was to present this analogue method as a tool for further investigation by those interested in shading coil design.

# IV

# THE INVESTIGATION

**Method of Procedure.** In investigating the effect of changes of shading coils on electromagnets four identical transformer cores were used. These are shown in figure three. Each core was cut by a milling machine across the top so as to allow the "U" shaped section to serve as the electromagnet base and the small straight section to serve as the electromagnet armature. A removable coil was constructed on a satisfactory non-magnetic coil form so that it could be slipped onto each electromagnet core as desired. When assembled each electromagnet appeared as shown in figure four. The hinge was constructed of a discarded copper knife switch and was fitted on each electromagnet as it was tested. A frame was constructed of wood as shown in figure five. As each electromagnet was tested it was bolted to this frame which in turn was clamped to a table. The hook on the armature of the electromagnet was used to attach the scale which was suspended from the ceiling to allow a force to be applied to the armature tending to open the magnet.

In order to investigate the phase relations of the fluxes occurring in the shaded and unshaded portions of the pole two search coils were constructed as shown in figure six. These were inserted between the core and armature of the electromagnet in such a manner that one of the search coils covered the unshaded portion of the core and the other search coil covered the shaded portion. Since the two coils were identical the relative magnitudes of voltages produced by

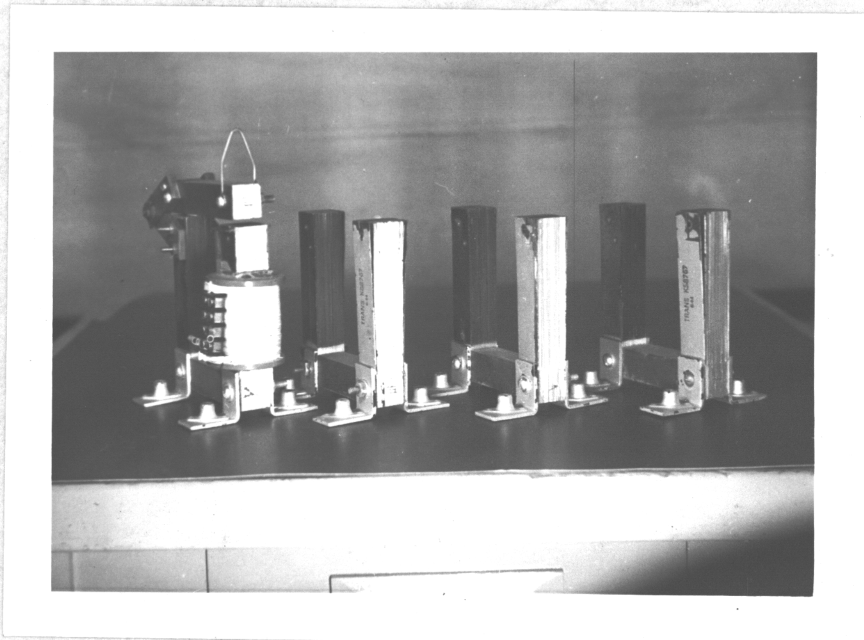


Figure 3. Electromagnet Cores

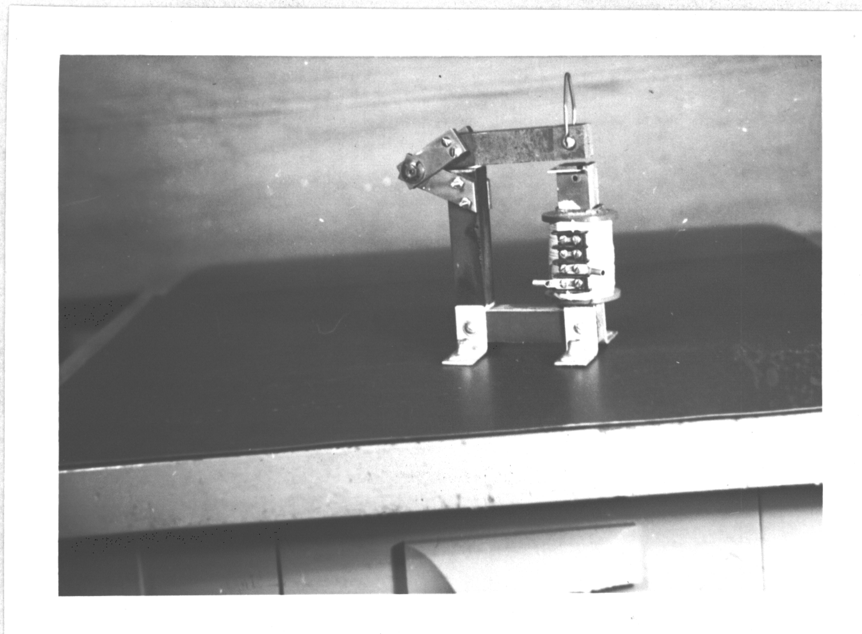


Figure 4. Total Electromagnet Assembly

Figure 5. Electromagnet in Wooden Rack

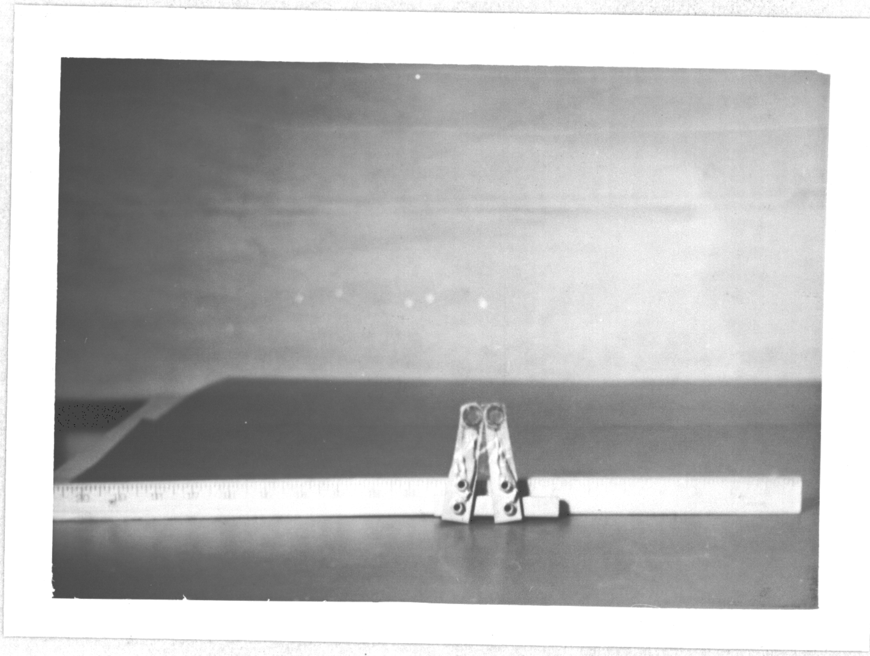


Figure 6. Pole Flux Search Coils

them was a measure of the relationship between the flux existent in the unshaded portion of the pole and the flux in the portion of the pole surrounded by the shading coil. Figure seven shows the search coils inserted between the armature and pole of the electromagnet in such a way that the voltage output of one coil represents the flux in the unshaded portion of the pole and the voltage output of the other coil represents the flux in the shaded portion of the pole.

The shading coils shown in figure eight were carefully constructed on a milling machine within close tolerances. The materials used were bronze and copper. The bronze was made up in two forms, one of waveguide having a 1/16" wall thickness, and the other of flat bronze. The copper was made up in two forms but the flat copper used was only one size whereas the waveguide sections of copper were of identical dimensions to those of the bronze waveguide. By varying the length of bronze and then copper waveguide in 1/32" steps data was obtained to show the effect of changing shading coil resistance and material. The flat bronze was varied in thickness and data was taken to allow comparison of values for different shaped shading coils made of bronze. The flat copper shading coil, which consisted of only the one piece 1/16" thick, allowed comparison between flat shading coils of different materials for just one value of thickness. No more flat copper shading coils were cut however, since the curves produced by the flat copper coils in comparison to the flat bronze would bear the same relation as the copper waveguide curves to the bronze waveguide curves.

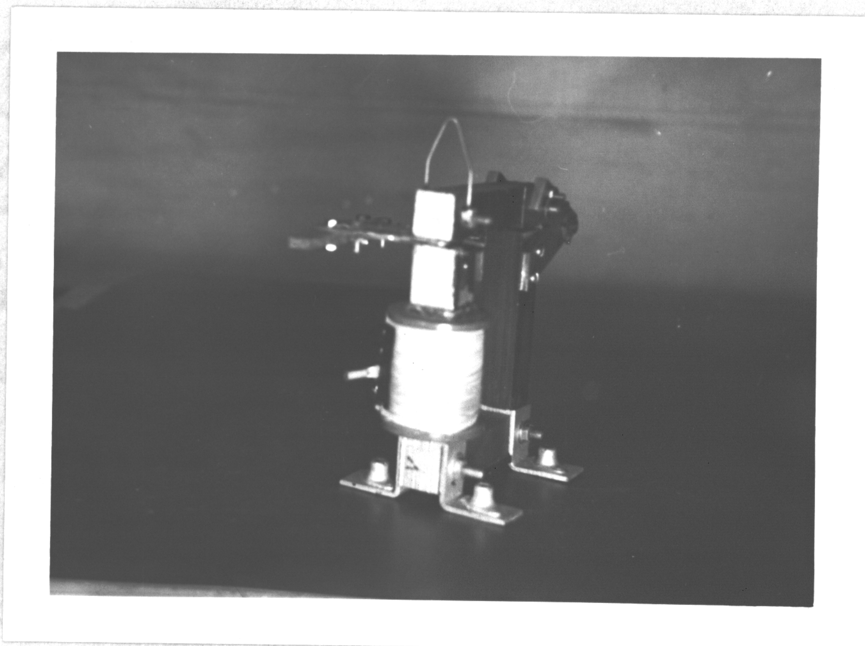


Figure 7. Search Coils in Place on Electromagnet

Figure 8. Shading Coils

In addition to varying the thickness of the shading coil and material of which it was made the relative area of pole included by the shading coil was varied by using four different electromagnet cores each having the shading coil slot cut at different points on the pole face.

Finally, variations were made in the force applied to the magnet armature tending to force the electromagnet open.

Thus by varying shading coil thickness, shading coil material, ratio of shaded to unshaded pole area, and the force tending to open the electromagnet, all of the conditions which would normally affect the design of an alternating current electromagnet had been selectively changed and corresponding data taken. Curves plotted from these data show very well the effects of changes of these parameters.

As a result of changes made in these parameters data were taken on power input, phase angle between shaded and unshaded portions of the pole, and noise produced by the electromagnet for each condition of operation. The power input was read on a Weston model 310 wattmeter. Noise was determined by using a Western Electric Sound Level Meter, Type RA 331 as illustrated in figure nine. It was decided by the investigator that reduction of noise produced by an alternating current electromagnet would be the ultimate aim of its designer since this noise would be objectionable for two reasons.

The first of these is where the electromagnet is to be used at a relatively quiet location and any noise produced by it would have adverse effects on surrounding equipment or personnel. An example of this would be in a magnetic motor starting box. If such a box were located near a machine operator or in an otherwise quiet room a considerable amount of operator fatigue might be attributed to the electromagnet of the motor starting box.

The second reason that noise would be objectionable is based on the fact that where there is noise there must also be vibration. The vibration has been known to hammer the magnetic faces of the pole and armature out of shape to such an extent as to make the magnet inoperative.

Both of these objections were evaluated very well by obtaining the noise produced by the electromagnets by means of the noise meter. Care was taken to use a room in which the background noise was minimum by taking readings at night when the usual activity of the Electrical Engineering Laboratory did not interfere with these results. Other shading coil design investigators have used vibration pickups to determine the vibration of the electromagnet. It was felt by the investigator that the noise meter would serve more satisfactorily since coupling difficulties which occurred on the vibration pickup were not experienced on the noise meter due to the lack of a physical connection between the electromagnet and the noise meter.

The phase angle relation between the flux of the unshaded portion of the electromagnet pole and the shaded portion was determined by photographing the Lissajous patterns obtained on an oscilloscope. The room was placed in total darkness during the time photographs were taken. An inexpensive camera with an f7:7 lens was used by attaching to it an auxiliary lens removed from a war surplus bomb sight. The

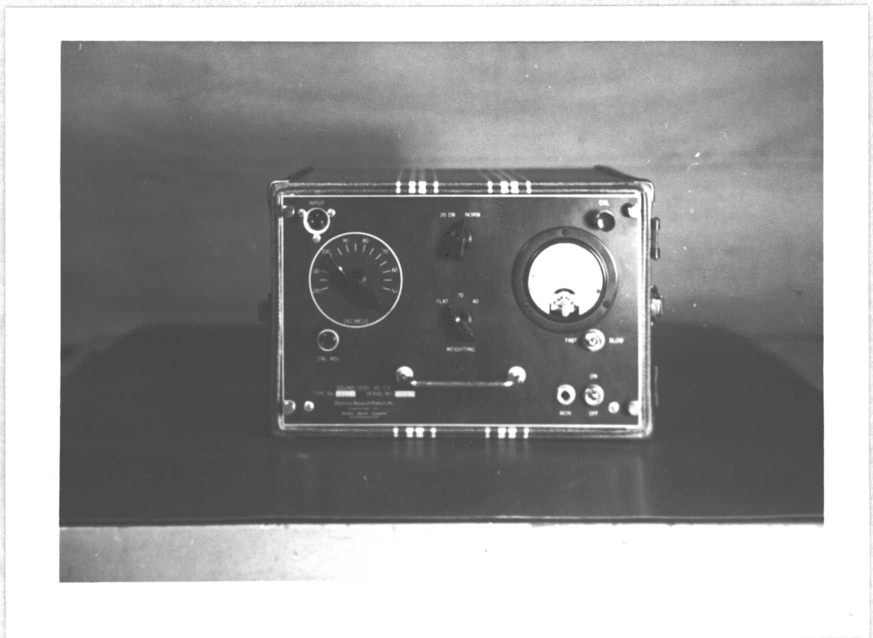


Figure 9. Noise Level Meter

camera was mounted on a wooden frame attached to the oscilloscope in order to assure proper focusing for all pictures. A blue filter was used on the camera to reduce the haze surrounding the waveform being observed. The camera with its mounting bracket attached to the oscilloscope is shown in figure 10.

Lissajous patterns serve well for investigation of the phase angle of one voltage compared to another. The reference voltage may be applied to the horizontal deflection plates of the oscilloscope and the voltage whose phase relation is to be determined is applied to the vertical deflection plates.

Figure 11 shows typical Lissajous pattern and the manner in which the phase angle between the two applied voltages was obtained. Data was taken for graph number one as shown in table one. It was noted that changing the force tending to pull the electromagnet open did not change the phase relation between the flux produced by the unshaded portion of the pole and that produced by the shaded portion of the pole.

<u>Discussion of Curves</u>. Graph one shows the phase relation between the flux produced by the unshaded portion of the pole and that produced by the shaded portion for the flat section bronze shading coil. The shading coil was first placed in the top of the slot and then in the bottom and very little difference was noted in the phase angle determined. From this it may be concluded that the difference in phase angle between placing the shading coil in the top of the slot and in the bottom of the slot is sufficiently insignificant to be ignored from an engineering standpoint.

Figure 10. Oscilloscope with Camera Attached for Taking Photographs of Oscilloscope Patterns.

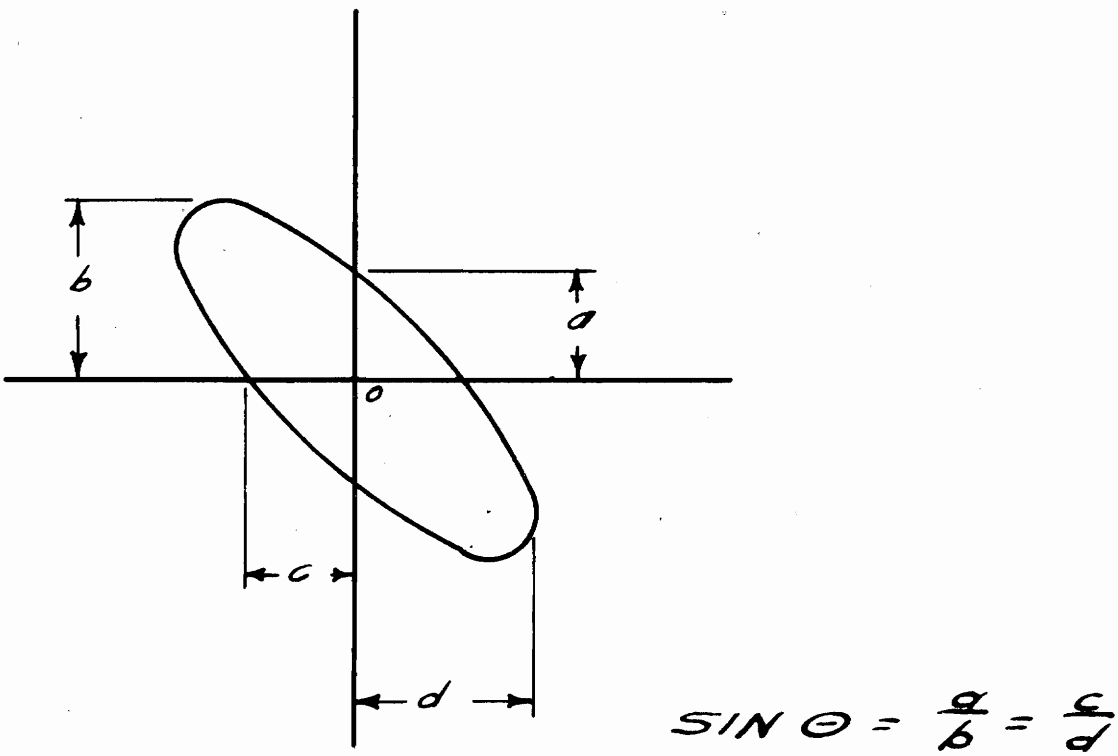



FIGURE 11
LISSAJOUS OSCILLOGRAPH PATTERN FOR DETERMINING PHASE SHIFT

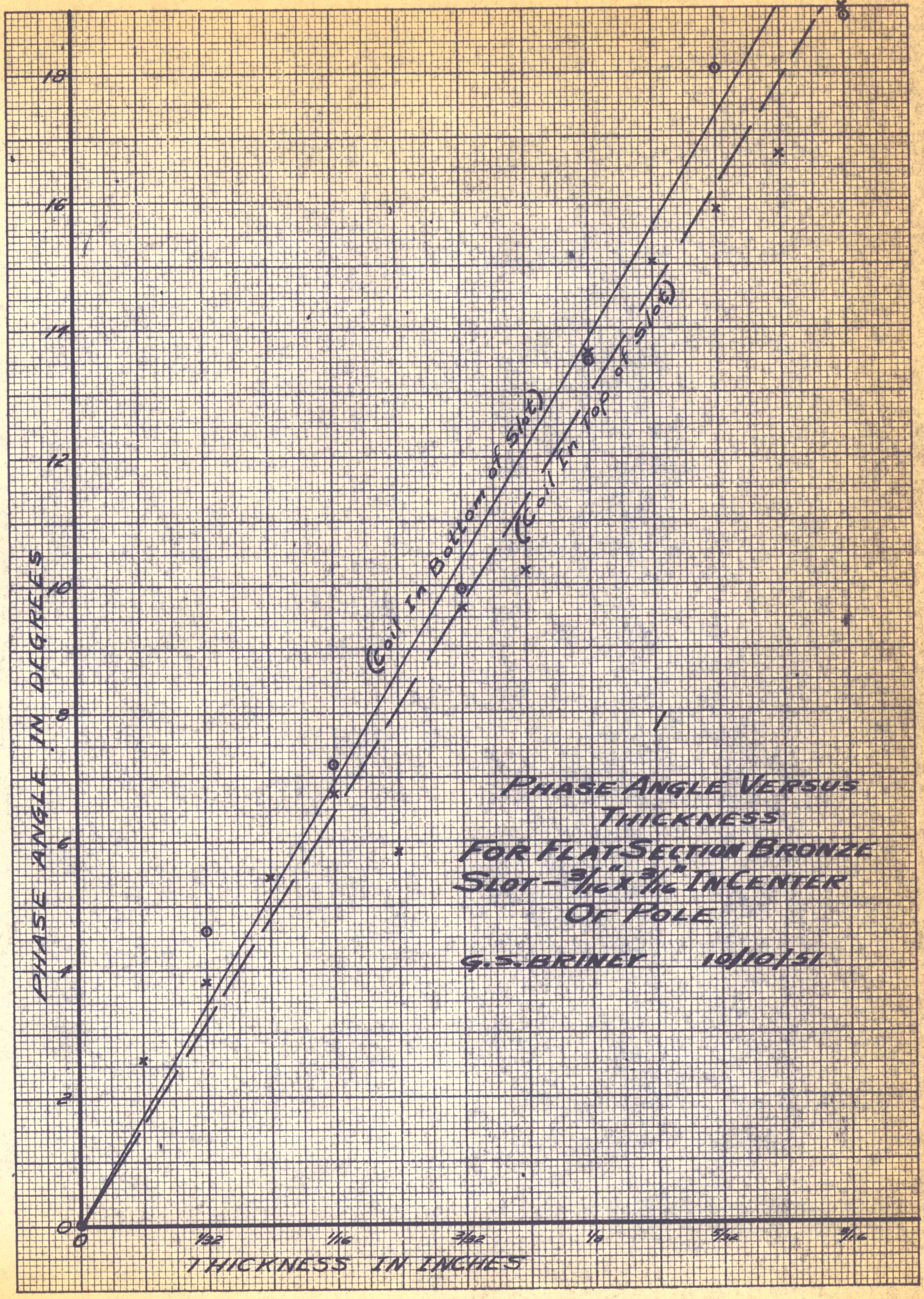

PHASE ANGLE IN DEGREES
18
16
14
12
10
8
6
4
2
0
0
1/32
1/16
3/32
1/8
5/32
3/16
THICKNESS IN INCHES
(Coil In Bottom of Slot)
(Coil In Top of Slot)
PHASE ANGLE VERSUS
THICKNESS
FOR FLAT SECTION BRONZE
SLOT – 3/16" X 3/16" IN CENTER
OF POLE
G.S. BRINEY 10/10/51.

TABLE 1. PHASE ANGLE CHANGE FOR FLAT SECTION BRONZE SHADING COILS IN 3/16" x 3/16" SLOT IN CENTER OF POLE

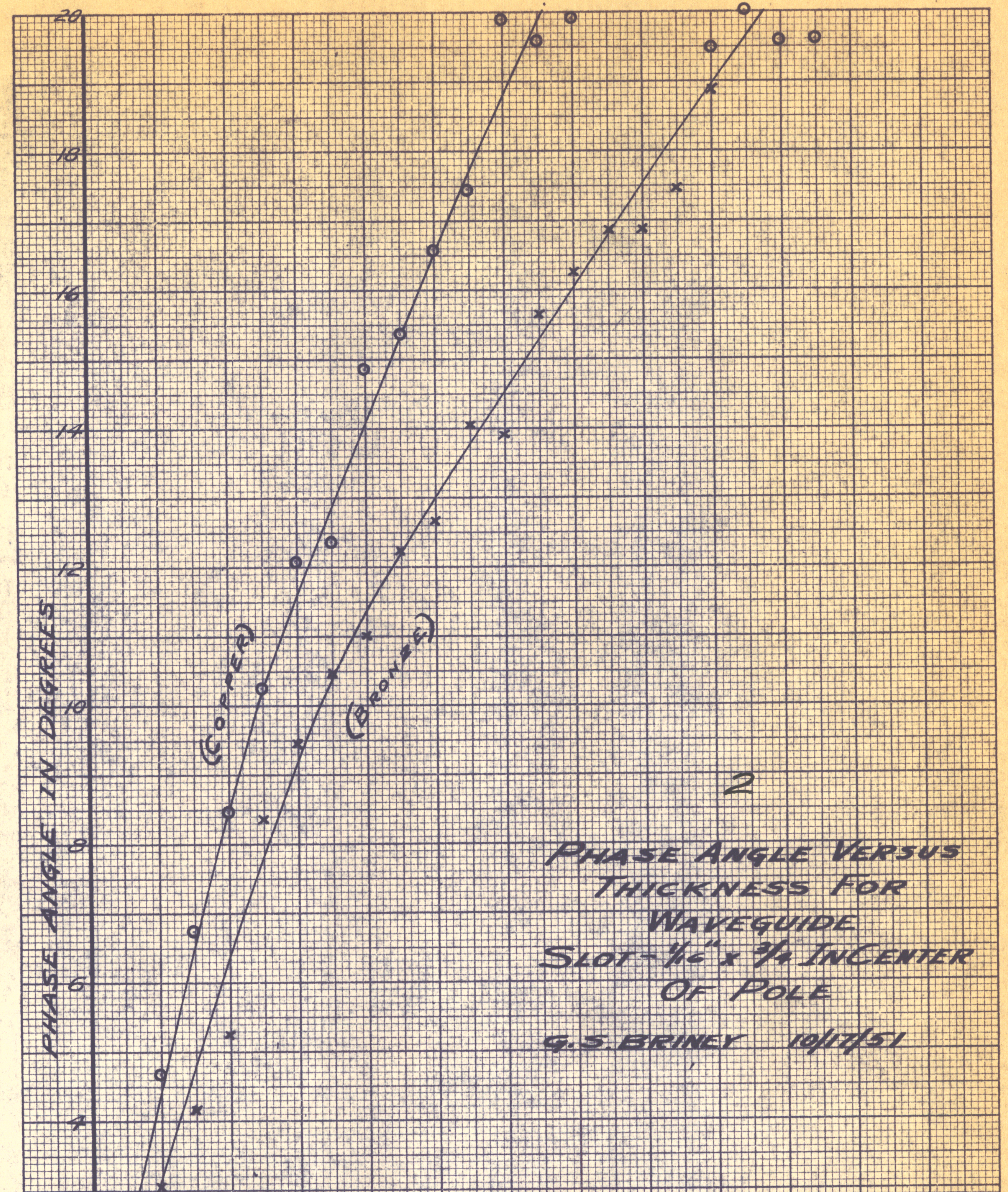
APPLIED VOLTAGE 120 VOLTS, 60 CYCLES

| Coil Thickness in inches | Input Current in amperes | Phase Angle in degrees |
|---|---|---|
| Group a, Coil in bottom of slot | | |
| 0 | 1.61 | 0. |
| 1/32 | 1.61 | 4.62 |
| 1/16 | 1.62 | 6.76 |
| 3/32 | 1.62 | 9.96 |
| 1/8 | 1.62 | 13.50 |
| 5/32 | 1.63 | 18.05 |
| 3/16 | 1.63 | 18.85 |
| Group b, Coil in top of slot | | |
| 0 | 1.59 | 0. |
| 1/64 | 1.59 | 2.60 |
| 1/32 | 1.59 | 3.82 |
| 3/64 | 1.58 | 5.47 |
| 1/16 | 1.58 | 6.78 |
| 5/64 | 1.58 | 5.86 |
| 3/32 | 1.58 | 9.69 |
| 7/64 | 1.58 | 10.26 |
| 1/8 | 1.58 | 13.57 |
| 9/64 | 1.58 | 15.05 |
| 5/32 | 1.58 | 15.88 |
| 11/64 | 1.59 | 16.73 |
| 3/16 | 1.60 | 19.10 |

Curve two shows the relation between the thickness of the waveguide shading coil and the phase angle between the flux produced by the shaded and unshaded portions of the pole for two different materials. From these curves it is seen that the copper produced a greater phase shift than the bronze for equivalent thicknesses of shading coil. In order to obtain as much phase shift with the bronze coil it must be approximately 1.3 times the area of the copper coil. This should be in the same relationship as the resistivity of the bronze to that of copper and is approximately so.

The phase angle data were taken by measuring the intercepts of the Lissajous patterns with the horizontal and vertical axes. In addition to these data photographs were taken for each 1/16" variation in length and are shown in figures 12 through 24. The diagonal straight line represented the zero degree phase angle condition and as the phase angle increased due to the use of thicker shading coils it may be seen from the figures that the ellipse minor diameter increased. This indicates an increasing value of phase shift.

Figure 25 shows the sine waves of voltage in each search coil for a 3/4" long copper shading coil and figure 26 shows the sine waves of voltage for a zero length of shading coil. Thus the phase shift for the 3/4" copper coil may be observed by noting the angular difference between the horizontal axis intercept of the one sine wave with reference to the other in each photograph. This angle is approximately twenty seven degrees for the 3/4" copper coil. From data for graph number two the phase angle was $23.8^{\circ}$ for the 3/4" thick copper waveguide.



PHASE ANGLE IN DEGREES
THICKNESS IN INCHES
0
2
4
6
8
10
12
14
16
18
20
1/16
1/8
3/16
1/4
5/16
3/8
7/16
1/2
9/16
5/8
11/16
3/4
(COPPER)
(BRONZE)
2
PHASE ANGLE VERSUS
THICKNESS FOR
WAVEGUIDE
SLOT-1/16" x 3/4 IN CENTER
OF POLE
G.S. BRINEY 10/17/51

TABLE 2. PHASE ANGLE CHANGE FOR RECTANGULAR WAVEGUIDE SHADING COILS

IN 1/16" x 3/4" SLOT IN MIDDLE OF POLE

APPLIED VOLTAGE 120 VOLTS, 60 CYCLES

| Coil Thickness in inches | Input Current in amperes | Power Input in watts | Phase Angle in degrees |
|---|---|---|---|
| Group a, Copper Waveguide | | | |
| 0 | 0.53 | 15.5 | 0. |
| 1/32 | 0.54 | 20.0 | 1.64 |
| 1/16 | 0.54 | 23.0 | 4.69 |
| 3/32 | 0.55 | 25.0 | 6.72 |
| 1/8 | 0.58 | 26.5 | 8.45 |
| 5/32 | 0.60 | 27.5 | 10.24 |
| 3/16 | 0.60 | 31.0 | 12.05 |
| 7/32 | 0.63 | 31.5 | 12.33 |
| 1/4 | 0.64 | 29.5 | 14.83 |
| 9/32 | 0.66 | 30.0 | 15.35 |
| 5/16 | 0.69 | 29.5 | 16.55 |
| 11/32 | 0.70 | 29.5 | 17.45 |
| 3/8 | 0.76 | 29.5 | 19.90 |
| 13/32 | 0.74 | 30.5 | 19.57 |
| 7/16 | 0.76 | 29.5 | 19.90 |
| 15/32 | 0.76 | 29.0 | 20.30 |
| 1/2 | 0.78 | 29.0 | 21.68 |
| 17/32 | 0.78 | 28.5 | 22.10 |
| 9/16 | 0.80 | 28.5 | 19.47 |
| 19/32 | 0.80 | 28.0 | 20.00 |
| 5/8 | 0.80 | 27.5 | 19.57 |
| 21/32 | 0.80 | 27.5 | 19.60 |
| 11/16 | 0.805 | 27.5 | 21.50 |
| 23/32 | 0.805 | 27.0 | 22.70 |
| 3/4 | 0.81 | 27.0 | 23.80 |
| Group b, Bronze Waveguide | | | |
| 0 | 0.40 | 15.5 | 0. |
| 1/32 | 0.40 | 19.0 | 1.08 |
| 1/16 | 0.40 | 20.0 | 3.02 |
| 3/32 | 0.40 | 22.0 | 4.17 |
| 1/8 | 0.50 | 23.5 | 5.22 |

TABLE 2 (Continued)

| Coil Thickness in inches | Input Current in amperes | Power Input in watts | Phase Angle in degrees |
|---|---|---|---|
| 5/32 | 0.50 | 25.0 | 8.36 |
| 3/16 | 0.50 | 26.0 | 9.42 |
| 7/32 | 0.60 | 27.0 | 10.47 |
| 1/4 | 0.60 | 28.0 | 11.00 |
| 9/32 | 0.60 | 29.0 | 12.26 |
| 5/16 | 0.64 | 31.0 | 12.65 |
| 11/32 | 0.64 | 29.5 | 14.05 |
| 3/8 | 0.65 | 29.5 | 13.90 |
| 13/32 | 0.70 | 30.5 | 15.65 |
| 7/16 | 0.70 | 30.5 | 16.25 |
| 15/32 | 0.70 | 30.5 | 16.85 |
| 1/2 | 0.70 | 30.0 | 16.85 |
| 17/32 | 0.70 | 30.5 | 17.45 |
| 9/16 | 0.70 | 30.5 | 18.88 |
| 19/32 | 0.70 | 30.5 | 20.30 |
| 5/8 | 0.75 | 30.5 | 21.10 |
| 21/32 | 0.75 | 30.5 | 20.90 |
| 11/16 | 0.78 | 30.5 | 21.15 |
| 23/32 | 0.80 | 30.5 | 21.75 |
| 3/4 | 0.80 | 30.5 | 23.60 |

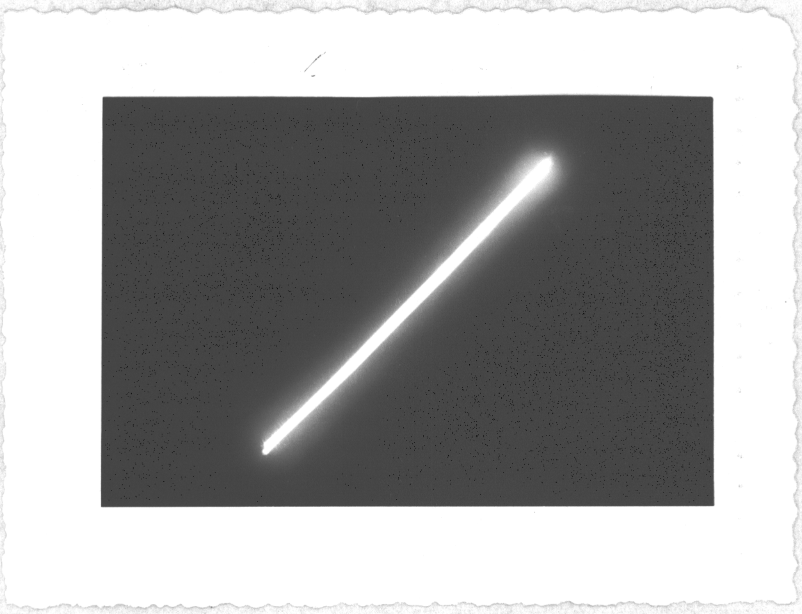


Figure 12. Lissajous Pattern for No Shading Coil

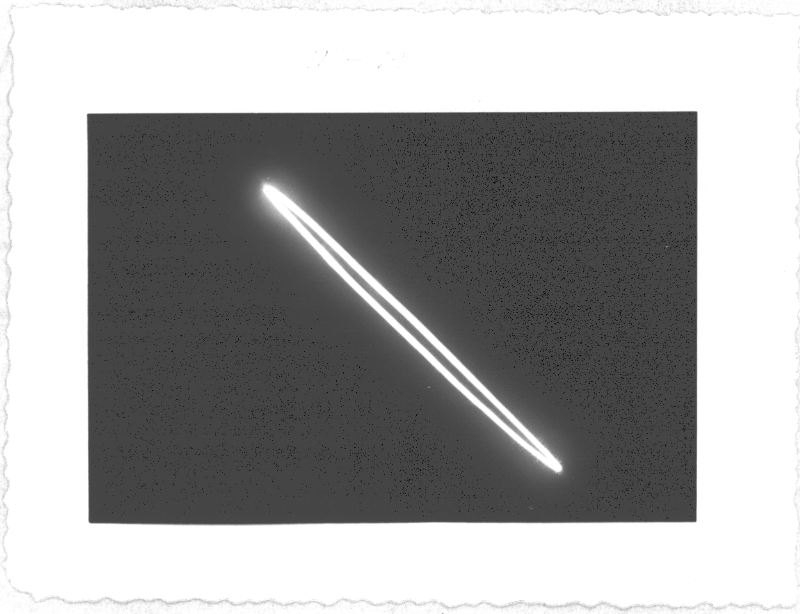


Figure 13. Lissajous Pattern for 1/16" Copper
Waveguide Shading Coil

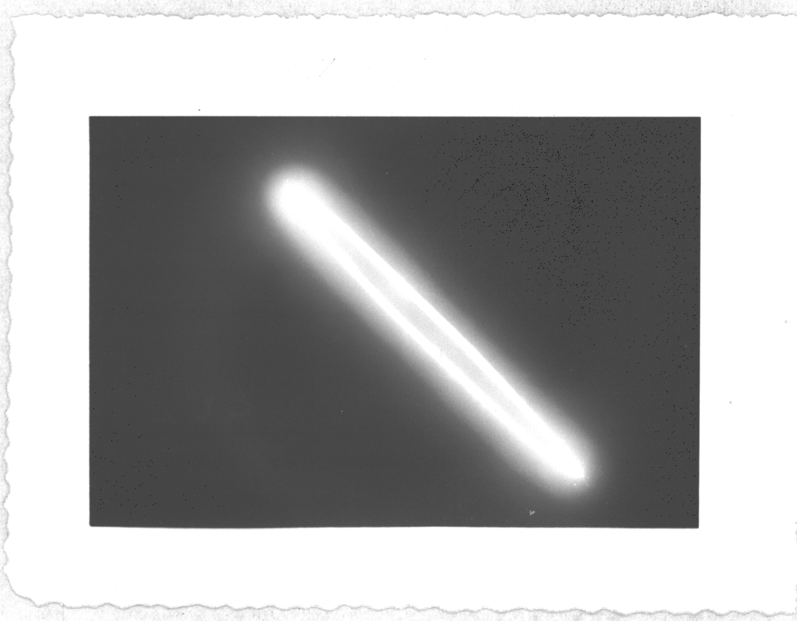


Figure 14. Lissajous Pattern for 1/8" Copper Waveguide Shading Coil.

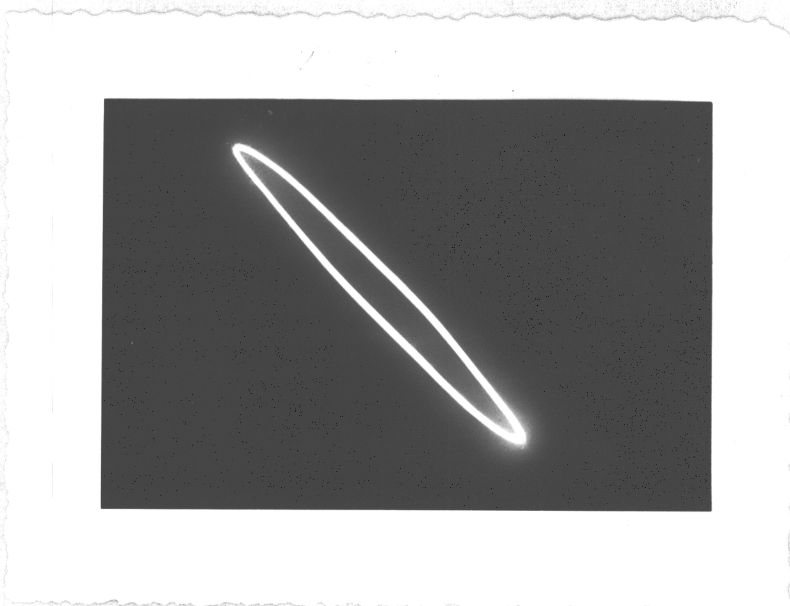


Figure 15. Lissajous Pattern for 3/16" Copper Shading Coil

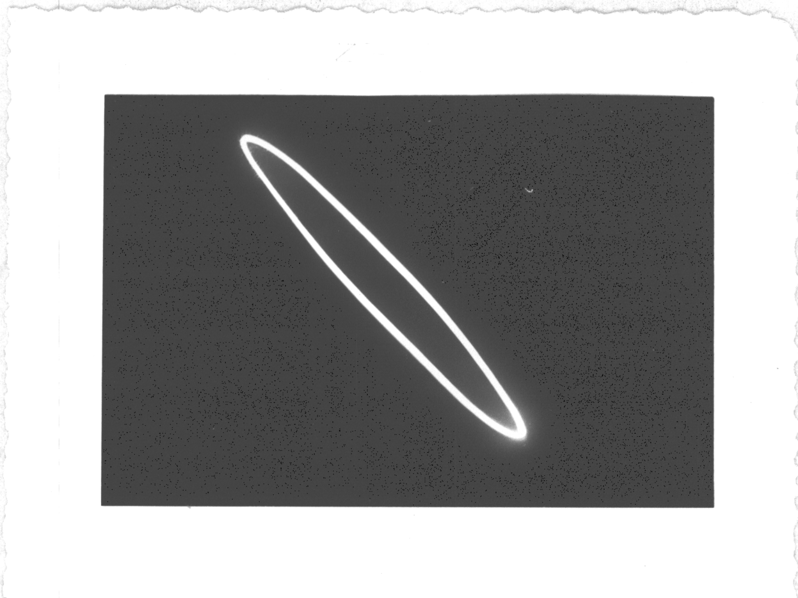


Figure 16. Lissajous Pattern for $\frac{1}{2}$" Copper Waveguide Shading Coil.

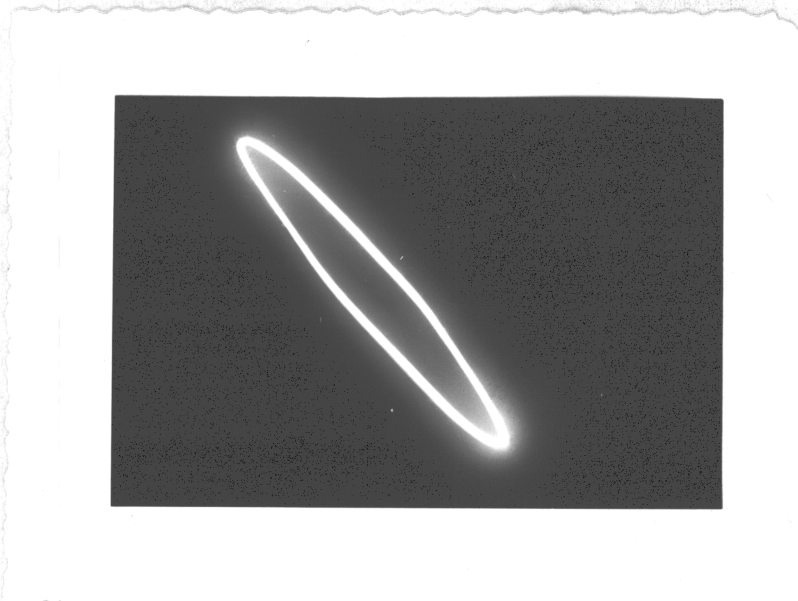


Figure 17. Lissajous Pattern for 5/16" Copper Waveguide Shading Coil

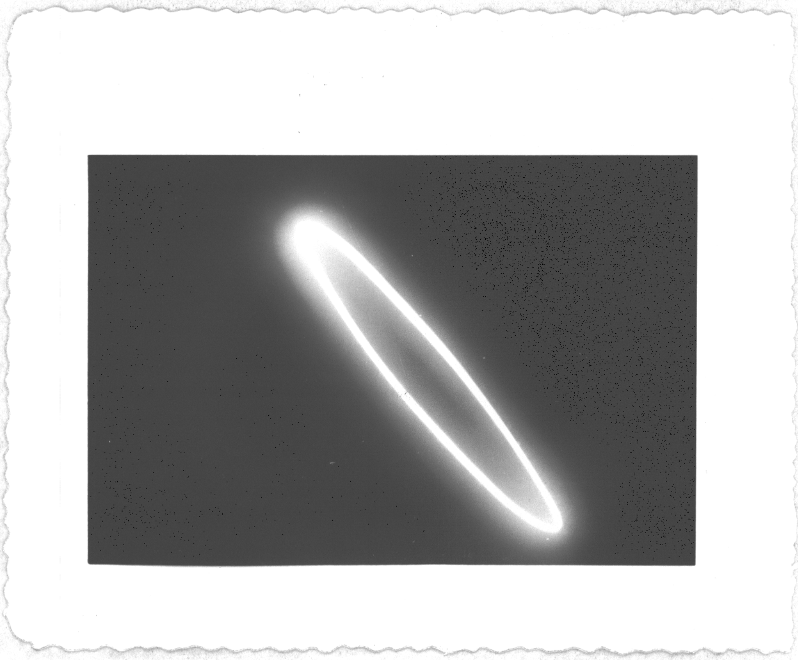


Figure 18. Lissajous Pattern for 3/8" Copper Waveguide Shading Coil

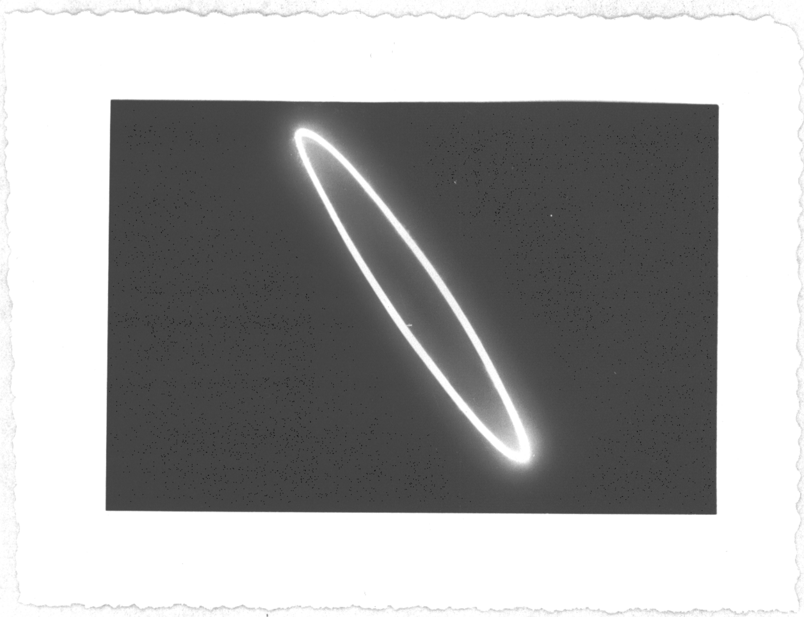


Figure 19. Lissajous Pattern for 7/16" Copper Waveguide Shading Coil

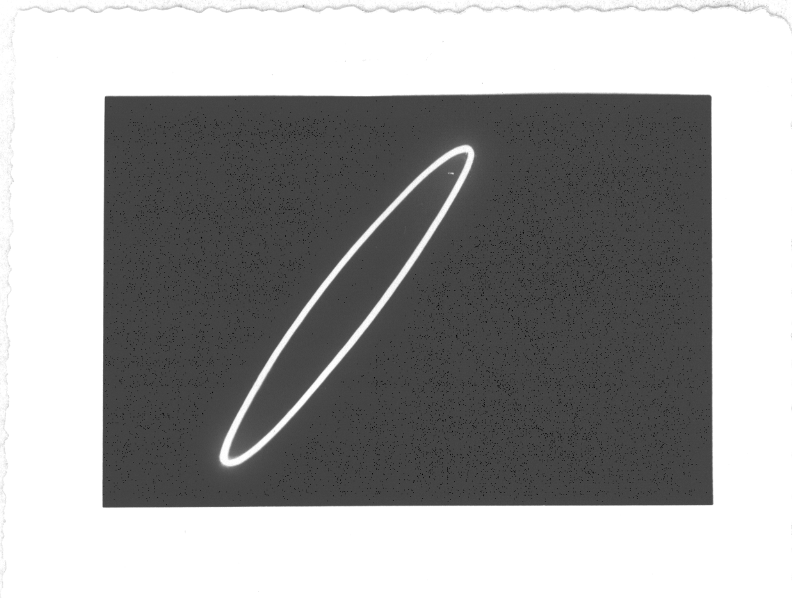


Figure 20. Lissajous Pattern for ½" Copper Waveguide Shading Coil

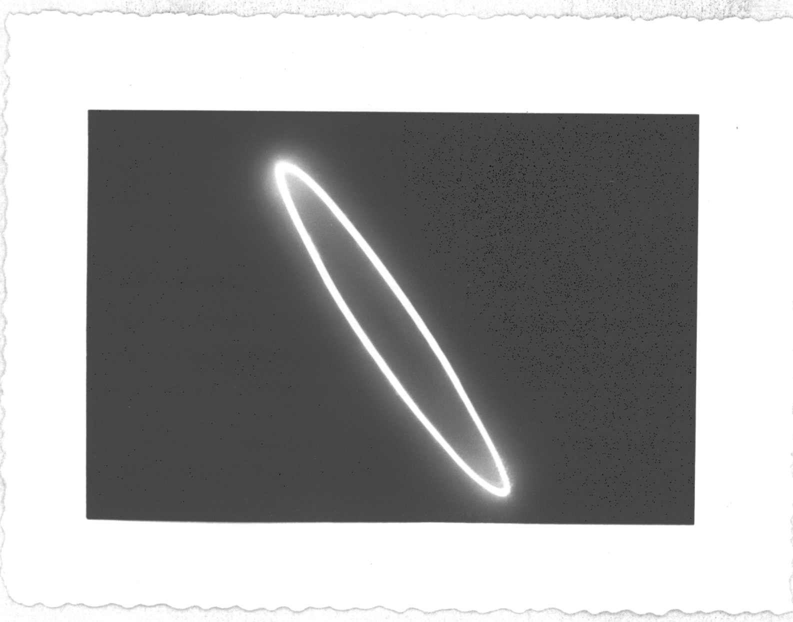


Figure 21. Lissajous Pattern for 9/16" Copper Waveguide Shading Coil

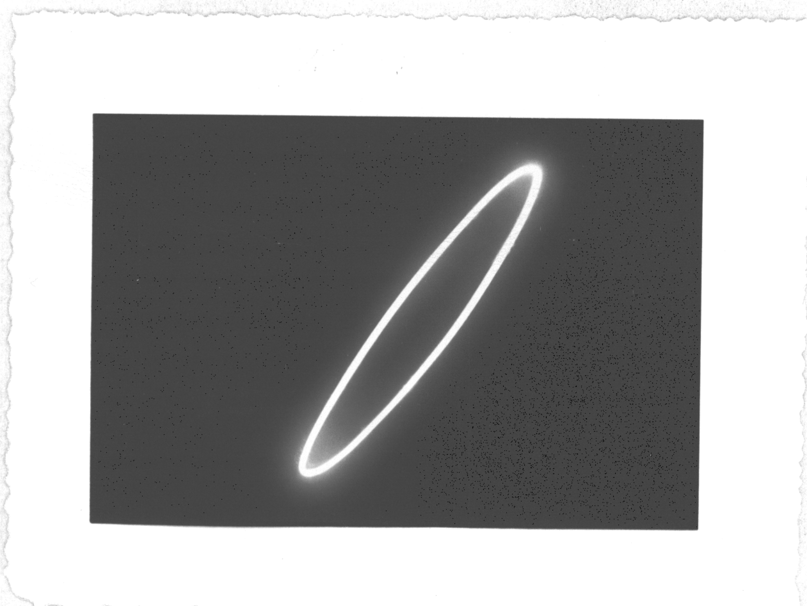


Figure 22. Lissajous Pattern for 5/8" Copper Waveguide Shading Coil

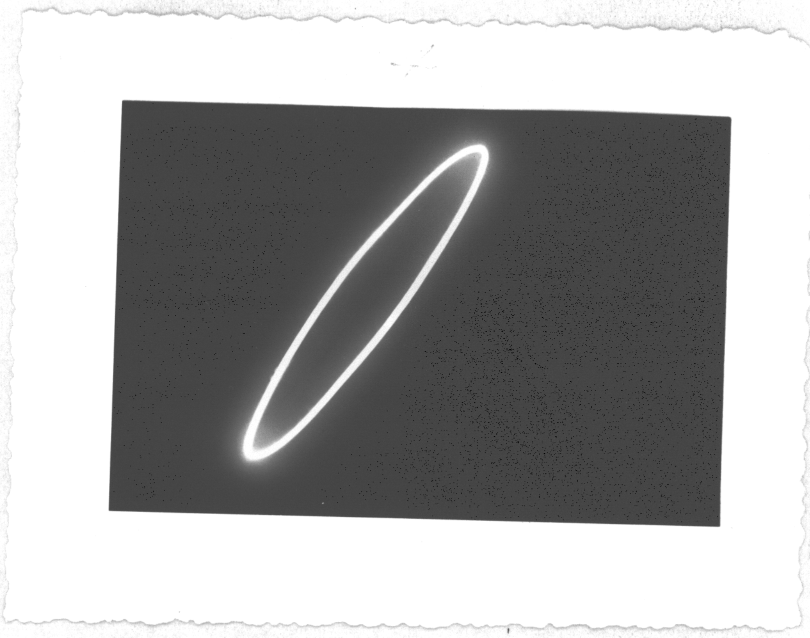


Figure 23. Lissajous Pattern for 11/16" Copper Waveguide Shading Coil

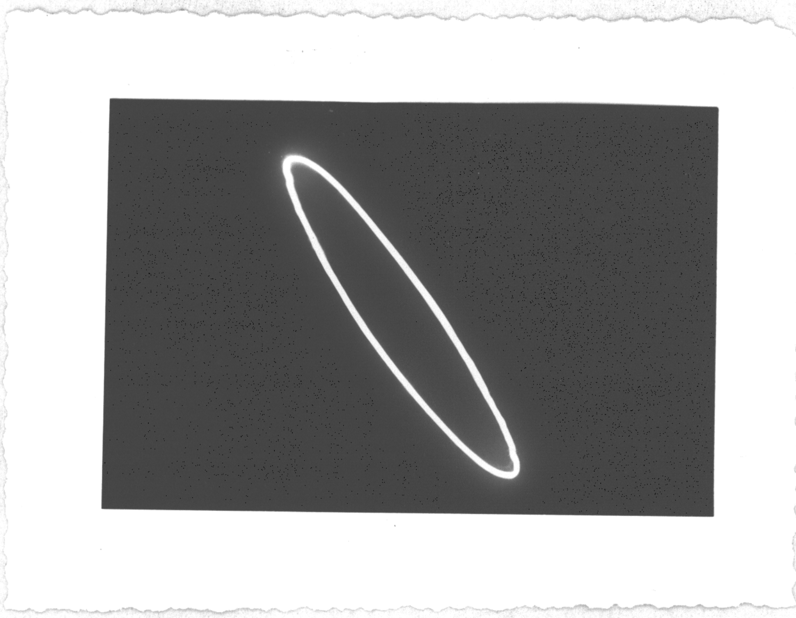


Figure 24. Lissajous Pattern for $\frac{3}{4}$" Copper
Waveguide Shading Coil

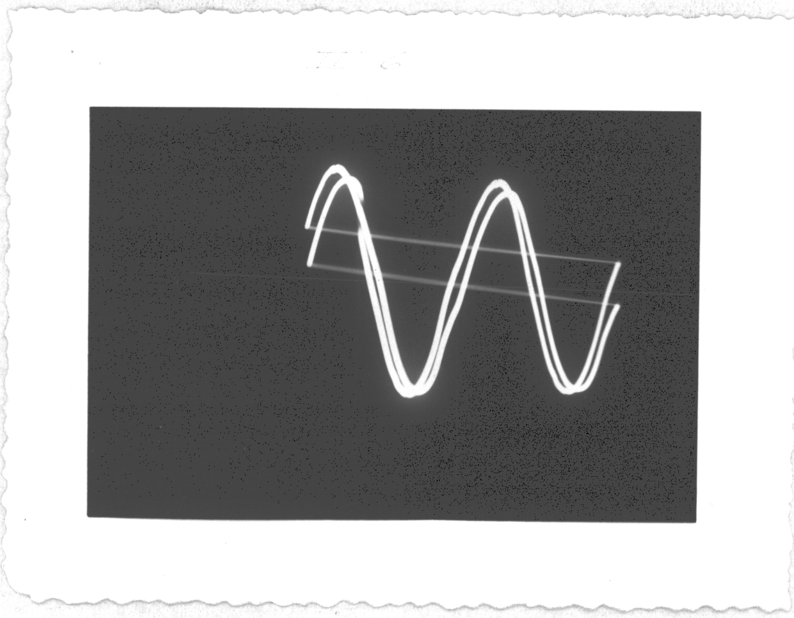


Figure 25. Flux Sine Waves Applied to Electronic Switch for $\frac{3}{4}$" Copper Waveguide Shading Coil

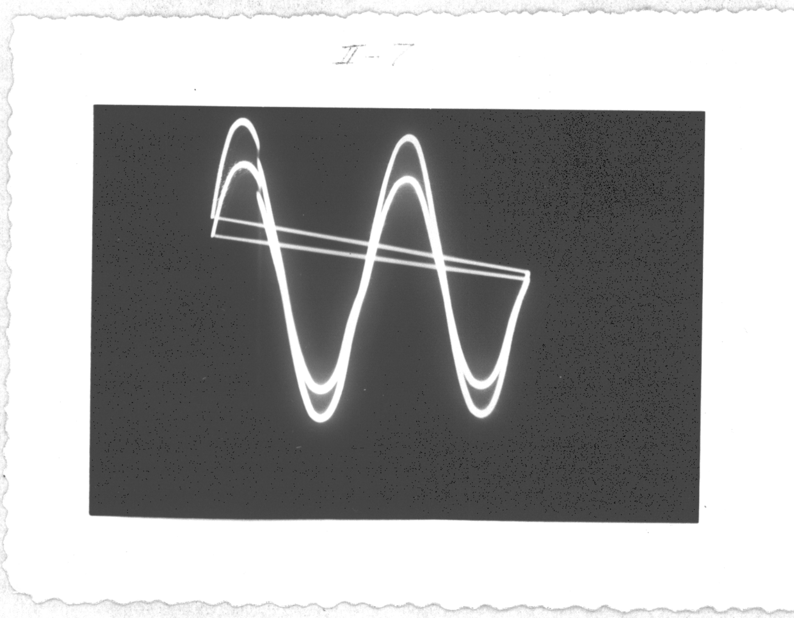



Figure 26. Flux Sine Waves Applied to Electronic Switch for No Shading Coil

It may be seen that due to difficulty of measurement of phase angle for the two sine waves considerable error existed in that measurement compared to the more accurate Lissajous pattern method.

Figure 27 is the Lissajous pattern for the 3/4" bronze waveguide shading coil. Comparison of figure 27 with figure 24 shows the phase shifting effect of bronze compared to copper for equivalent size shading coils. Very little difference is observable partially due to the small scale of the photgraph. From the data for graph two it may be observed that the 3/4" bronze coil produced a phase shift of $23.6^{\circ}$ whereas the 3/4" copper coil produced a phase shift of $23.8^{\circ}$. This verifies the photographic results obtained.

The values of phase shift obtained by the investigator were considerablY lower than those obtained by others as representing the best shading coil design. The best angle suggested by several authors is approximately 60 degrees. The maximum shift obtained by the investigator was approximately 23 degrees and this represented a far larger shading coil than was considered the best design from data taken later in the investigation. The search coils were placed in an insulating material one eighth inch thick so that the assembly would be rigid as shown in figure eight. When this assembly was placed between the pole and armature of the electromagnet, as shown in figure seven, the pole and armature were prevented from coming together by the thickness of the search coil assembly. Apparently this influenced the phase relation of the flux produced by the shaded portion of the pole and that produced by the unshaded portion by allowing some mixing of these fluxes

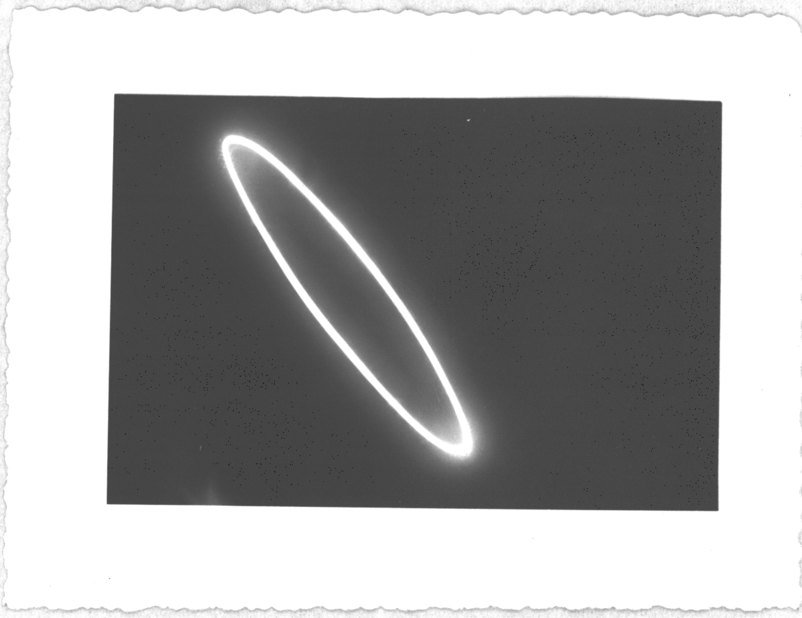


Figure 27. Lissajous Pattern for $\frac{3}{4}$" Bronze Waveguide Shading Coil

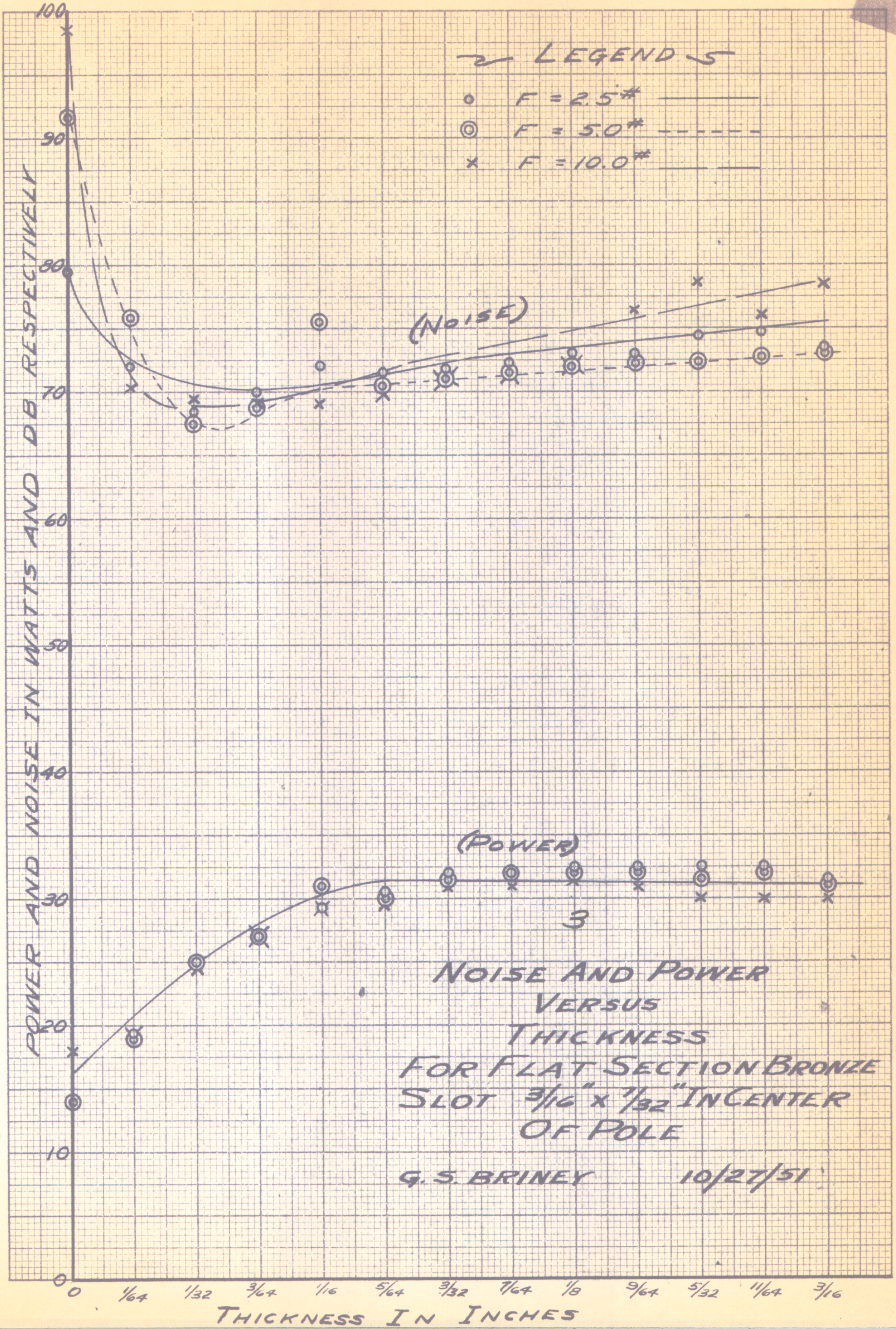
in the air gap. This caused the voltages induced in the search coils to show an apparent phase angle considerably less than that actually occurring. Using search coils which surrounded the portion of the pole being investigated but in the shading coil slot instead of in the air gap would more precisely measure the phase angle.

Although the phase angles shown are in error in their absolute values the value of one angle compared to that produced by a change in the electromagnet is still satisfactory in showing the relation between phase angle and the change made. The investigator was only attempting to find relative values so the data do serve well to show these relationships.

Corrections would have been made for this apparent error but the error was not discovered until the investigator had made a library search at the Franklin Institute in Philadelphia, Pennsylvania. This was a considerable time after the original data were taken by the investigator and the facilities of the Virginia Polytechnic Institute Electrical Engineering laboratory were no longer conveniently available to the investigator.

Graphs three and four show the effect on power input and noise output of varying the thickness of the shading coils made of flat bronze and bronze waveguide respectively and varying the force tending to open the electromagnet. In general the statement may be made that as the force tending to open the magnet increases the noise produced by the magnet increases. Another way of saying the same thing is that as a particular magnet is required to exert more force to operate an electrical contact or a valve the chattering of the electromagnet will increase

3



LEGEND
F = 2.5#
F = 5.0#
F = 10.0#
(NOISE)
(POWER)
3
NOISE AND POWER
VERSUS
THICKNESS
FOR FLAT SECTION BRONZE
SLOT 3/16" x 7/32" IN CENTER
OF POLE
G. S. BRINEY
10/27/51
POWER AND NOISE IN WATTS AND DB RESPECTIVELY
THICKNESS IN INCHES
0
1/64
1/32
3/64
1/16
5/64
3/32
7/64
1/8
9/64
5/32
11/64
3/16
100
90
80
70
60
50
40
30
20
10
0

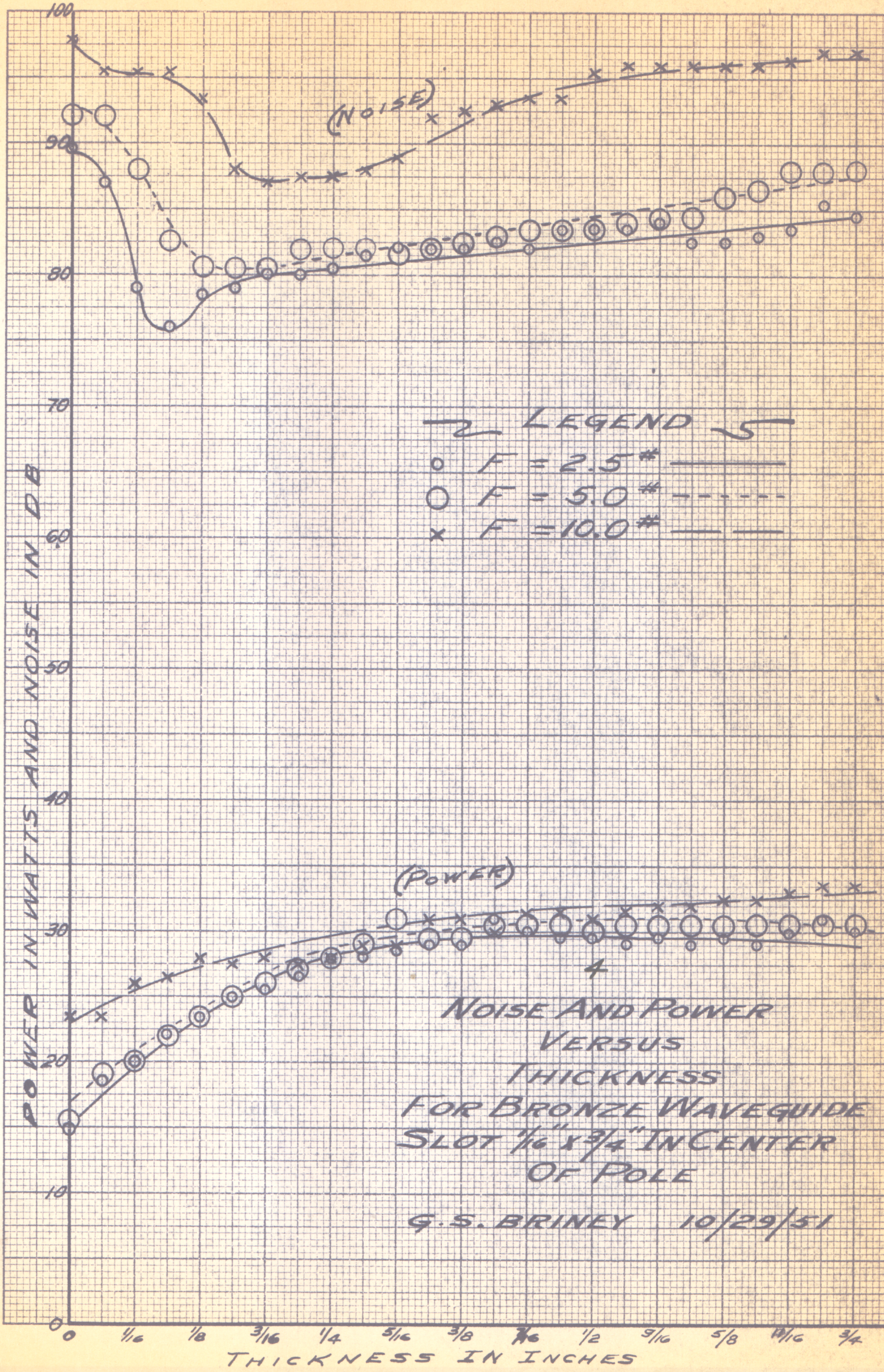
TABLE 3. POWER AND NOISE CHANGE FOR VARIATION IN THICKNESS OF FLAT BRONZE SHADING COIL IN 3/16" x 7/32" SLOT IN CENTER OF POLE

APPLIED VOLTAGE 110 VOLTS, 60 CYCLES

| Coil Thickness in inches | Input Current in amperes | Power Input in watts | Noise Output in decibels |
|---|---|---|---|
| Group a, Opening Force 2.5 Pounds | | | |
| 0 | 0.40 | 14.0 | 79.5 |
| 1/64 | 0.43 | 19.3 | 72.0 |
| 1/32 | 0.46 | 25.0 | 68.5 |
| 3/64 | 0.50 | 27.0 | 70.0 |
| 1/16 | 0.53 | 29.3 | 72.0 |
| 5/64 | 0.58 | 30.5 | 71.5 |
| 3/32 | 0.60 | 32.0 | 71.7 |
| 7/64 | 0.62 | 32.0 | 72.2 |
| 1/8 | 0.64 | 32.5 | 73.0 |
| 9/64 | 0.66 | 32.5 | 73.0 |
| 5/32 | 0.69 | 32.5 | 74.3 |
| 11/64 | 0.70 | 32.5 | 74.7 |
| 3/16 | 0.70 | 31.5 | 73.5 |
| Group b, Opening Force 5 Pounds | | | |
| 0 | 0.40 | 14.0 | 91.7 |
| 1/64 | 0.42 | 19.0 | 73.3 |
| 1/32 | 0.45 | 25.0 | 67.5 |
| 3/64 | 0.50 | 27.0 | 68.7 |
| 1/16 | 0.53 | 31.0 | 75.5 |
| 5/64 | 0.55 | 30.0 | 70.5 |
| 3/32 | 0.60 | 31.5 | 71.0 |
| 7/64 | 0.63 | 32.0 | 71.5 |
| 1/8 | 0.63 | 32.0 | 72.0 |
| 9/64 | 0.65 | 32.0 | 72.2 |
| 5/32 | 0.67 | 31.5 | 72.4 |
| 11/64 | 0.68 | 32.0 | 72.7 |
| 3/16 | 0.70 | 31.0 | 73.0 |

TABLE 3 (Continued)

| Coil Thickness in inches | Input Current in amperes | Power Input in watts | Noise Output in decibels |
|---|---|---|---|
| Group c, Opening Force 10 Pounds | | | |
| 0 | 0.43 | 16.0 | 98.5 |
| 1/64 | 0.43 | 19.5 | 70.3 |
| 1/32 | 0.45 | 24.5 | 69.5 |
| 3/64 | 0.50 | 27.0 | 69.0 |
| 1/16 | 0.53 | 29.0 | 69.0 |
| 5/64 | 0.58 | 29.5 | 70.0 |
| 3/32 | 0.60 | 31.0 | 72.7 |
| 7/64 | 0.61 | 31.0 | 71.2 |
| 1/8 | 0.63 | 31.5 | 72.0 |
| 9/64 | 0.63 | 31.0 | 76.5 |
| 5/32 | 0.63 | 30.0 | 78.8 |
| 11/64 | 0.67 | 30.0 | 76.0 |
| 3/16 | 0.67 | 30.0 | 78.5 |




4

NOISE AND POWER
VERSUS
THICKNESS
FOR BRONZE WAVEGUIDE
SLOT 1/16" x 3/4" IN CENTER
OF POLE

G.S. BRINEY 10/29/51

TABLE 4. NOISE AND POWER INPUT DATA FOR CHANGES IN THE THICKNESS OF BRONZE WAVEGUIDE SHADING COILS IN A 1/16" x 3/4" SLOT IN THE CENTER OF THE POLE. APPLIED VOLTAGE 120 VOLTS, 60 CYCLES

| Coil Thickness in inches | Current in amperes | Power in watts | Noise in decibels |
|---|---|---|---|
| Group a, Force of 2.5 pounds tending to separate armature from pole. | | | |
| 0 | 0.43 | 15.0 | 89.5 |
| 1/32 | 0.45 | 18.5 | 87.0 |
| 1/16 | 0.47 | 20.0 | 79.0 |
| 3/32 | 0.50 | 22.0 | 76.0 |
| 1/8 | 0.50 | 23.5 | 78.5 |
| 5/32 | 0.50 | 25.0 | 79.0 |
| 3/16 | 0.55 | 25.5 | 80.0 |
| 7/32 | 0.57 | 26.5 | 80.0 |
| 1/4 | 0.60 | 28.0 | 80.5 |
| 9/32 | 0.60 | 28.0 | 81.5 |
| 5/16 | 0.62 | 28.5 | 82.0 |
| 11/32 | 0.63 | 29.0 | 82.0 |
| 3/8 | 0.65 | 29.0 | 82.0 |
| 13/32 | 0.65 | 31.0 | 82.5 |
| 7/16 | 0.68 | 30.0 | 82.0 |
| 15/32 | 0.69 | 29.5 | 83.5 |
| 1/2 | 0.70 | 29.5 | 83.5 |
| 17/32 | 0.70 | 29.0 | 33.5 |
| 9/16 | 0.70 | 29.5 | 84.0 |
| 19/32 | 0.70 | 29.0 | 82.5 |
| 5/8 | 0.73 | 29.5 | 82.5 |
| 21/32 | 0.73 | 29.0 | 83.0 |
| 11/16 | 0.75 | 30.0 | 83.5 |
| 23/32 | 0.75 | 31.0 | 85.5 |
| 3/4 | 0.75 | 30.0 | 84.5 |
| Group b, Force of 5 pounds tending to separate armature from pole. | | | |
| 0 | 0.40 | 15.5 | 92.0 |
| 1/32 | 0.40 | 19.0 | 92.0 |
| 1/16 | 0.40 | 20.0 | 88.0 |
| 3/32 | 0.40 | 22.0 | 82.5 |
| 1/8 | 0.50 | 23.5 | 80.5 |

TABLE 4 (Continued)

| Coil Thickness in inches | Current in amperes | Power in watts | Noise in decibels |
|---|---|---|---|
| 5/32 | 0.50 | 25.0 | 80.5 |
| 3/16 | 0.50 | 26.0 | 80.5 |
| 7/32 | 0.60 | 27.0 | 82.0 |
| 1/4 | 0.60 | 28.0 | 82.0 |
| 9/32 | 0.60 | 29.0 | 82.0 |
| 5/16 | 0.64 | 31.0 | 81.5 |
| 11/32 | 0.64 | 29.5 | 82.0 |
| 3/8 | 0.65 | 29.5 | 82.5 |
| 13/32 | 0.70 | 30.5 | 83.0 |
| 7/16 | 0.70 | 30.5 | 83.5 |
| 15/32 | 0.70 | 30.5 | 83.5 |
| 1/2 | 0.70 | 30.0 | 83.5 |
| 17/32 | 0.70 | 30.5 | 84.0 |
| 9/16 | 0.70 | 30.5 | 84.3 |
| 19/32 | 0.70 | 30.5 | 84.5 |
| 5/8 | 0.75 | 30.5 | 86.0 |
| 21/32 | 0.75 | 30.5 | 86.5 |
| 11/16 | 0.78 | 30.5 | 86.0 |
| 23/32 | 0.80 | 30.5 | 88.0 |
| 3/4 | 0.80 | 30.5 | 88.0 |

Group c, Force of 10 pounds tending to separate armature from pole.

| | | | |
|---|---|---|---|
| 0 | 0.5 | 23.5 | 98.0 |
| 1/32 | 0.5 | 23.5 | 95.5 |
| 1/16 | 0.5 | 26.0 | 95.5 |
| 3/32 | 0.5 | 26.5 | 95.5 |
| 1/8 | 0.5 | 28.0 | 93.5 |
| 5/32 | 0.5 | 27.5 | 86.0 |
| 3/16 | 0.55 | 28.0 | 87.0 |
| 7/32 | 0.58 | 27.5 | 87.5 |
| 1/4 | 0.59 | 28.0 | 87.5 |
| 9/32 | 0.60 | 29.0 | 88.0 |
| 5/16 | 0.60 | 29.0 | 89.0 |
| 11/32 | 0.62 | 31.0 | 92.0 |
| 3/8 | 0.63 | 31.0 | 92.5 |
| 13/32 | 0.63 | 30.0 | 93.0 |
| 7/16 | 0.64 | 31.5 | 93.5 |

TABLE 4 (Continued)

| Coil Thickness in inches | Current in amperes | Power in watts | Noise in decibels |
|---|---|---|---|
| 15/32 | 0.65 | 31.5 | 93.5 |
| 1/2 | 0.68 | 31.0 | 95.5 |
| 17/32 | 0.68 | 31.6 | 96.0 |
| 9/16 | 0.70 | 32.0 | 96.0 |
| 19/32 | 0.70 | 32.0 | 96.0 |
| 5/8 | 0.70 | 32.5 | 96.0 |
| 21/32 | 0.70 | 32.5 | 96.0 |
| 11/16 | 0.73 | 33.0 | 96.5 |
| 23/32 | 0.75 | 33.5 | 97.0 |
| 3/4 | 0.75 | 33.5 | 97.0 |

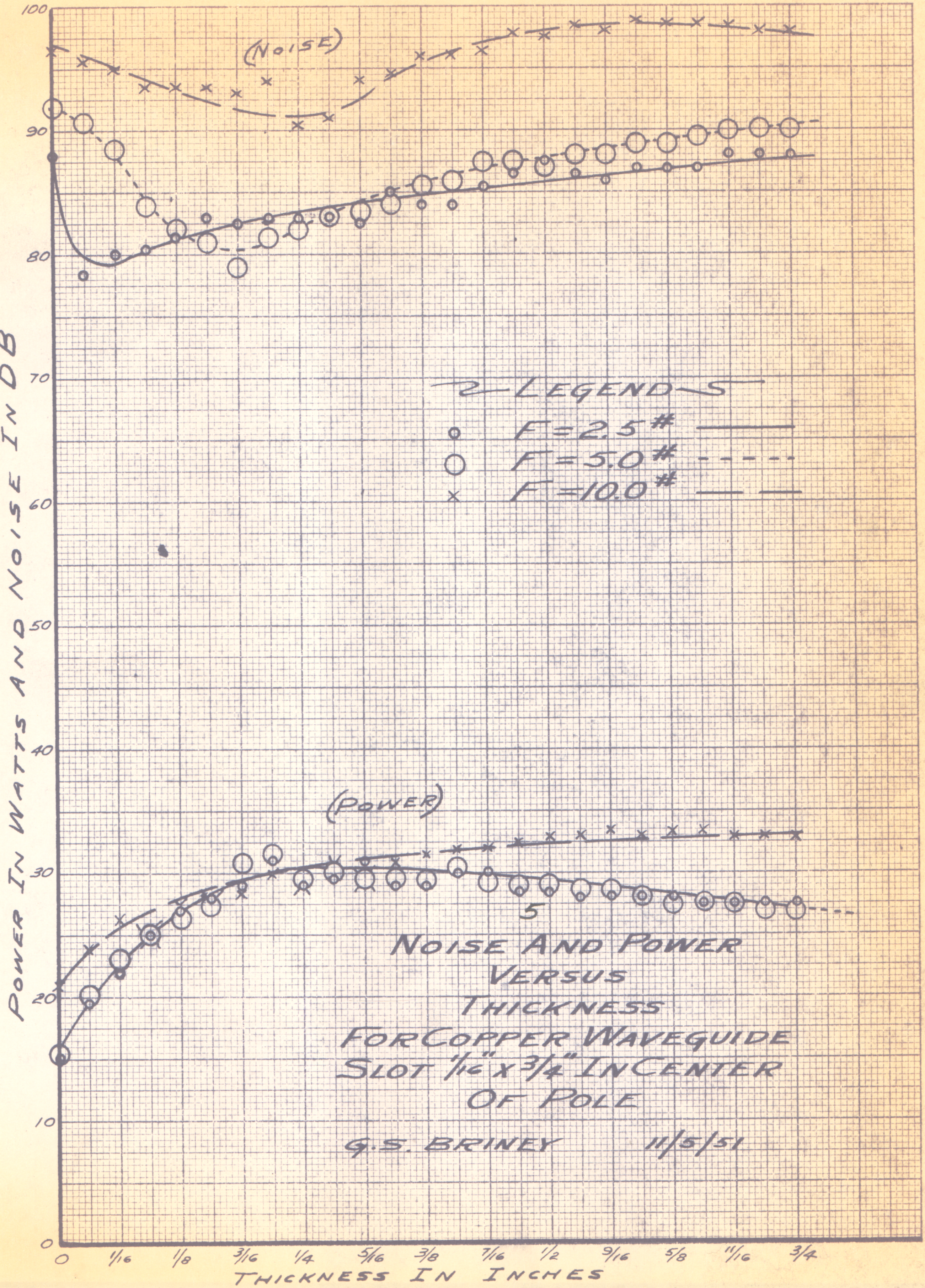
thus producing an increasing amount of noise.

In addition to this it may be observed from these curves that a definite minimum noise point exists. It happens that this also represents a relatively small power input compared to that occurring when the maximum thickness shading coil was used. As the force on the electromagnet is increased a different sized shading coil is called for in order to obtain minimum noise. This means that any electromagnet which is used where the force required of it is not always constant cannot have a universal shading coil designed for minimum noise since the size coil needed for minimum noise varies depending on the force tending to open the magnet. For such an application the shading coil can only be a compromise between absolutely minimum noise for the force likely to be encountered most and the minimum noise for the range of forces required by the electromagnet. The shading coil will then be too large for the small forces exerted by the electromagnet and too small for the large forces exerted by the electromagnet. This is a situation which must be accepted, however, where the range of forces required by the electromagnet is large.

Most applications of electromagnets are such that the force requirement of the magnet is relatively constant. Only one correct size shading coil exists for such a magnet as indicated by the curves. In these applications a decided improvement in electromagnet operation can be realized by using a shading coil which produces this minimum noise condition.

By observing graphs three and four it may be seen that the flat bronze was more effective than the bronze waveguide in reducing the noise produced. This was logical in view of the fact that the waveguide was long and had a thin crossection whereas the flat bronze was short or thin with a crossection such that more conducting material appeared near the air gap than was true with the waveguide. Burying the shading coil deep in the pole decreases its effectiveness in reducing noise and causes the range of coil change over which a fair reduction in noise is achieved to be narrower. This also means that a shading coil having a high "Q" or a high ratio of inductive reactance to resistance is to be avoided since the minimum noise condition will then tend to be sharper as exhibited in curves three and four.

Graph five shows the effect of using copper waveguide as the shading coil and varying its thickness for three different forces acting on the armature. As was observed for the bronze shading coil, increasing the force tending to open the electromagnet caused the noise to increase. The two and one-half pound force did not produce a minimum noise point less than that of the five pound force as would be expected. Closer examination of the points, however, indicates that if more data had been taken for thicknesses of shading coils less than one thirty second of an inch the minimum noise point would probably have occurred at seventy six decibels as was the case on curve four. The curve representing the noise produced when five pounds was applied to the electromagnet armature gave the same minimum noise point as was obtained on the bronze waveguide shown on graph four. As was previously observed on graph three the use of a flat shading coil and a shallow slot was more




5

NOISE AND POWER
VERSUS
THICKNESS
FOR COPPER WAVEGUIDE
SLOT 1/16" x 3/4" IN CENTER
OF POLE

G.S. BRINEY 11/5/51

TABLE 5. NOISE AND POWER INPUT DATA FOR CHANGES IN COPPER SHADING COIL THICKNESS IN A 1/16" x 3/4" SLOT IN THE CENTER OF THE POLE

APPLIED VOLTAGE 120 VOLTS, 60 CYCLES

| Coil Thickness in inches | Current in amperes | Power in watts | Noise in decibels |
|---|---|---|---|
| Group a, Force of 2.5 pounds tending to separate armature from pole. | | | |
| 0 | 0.45 | 15.0 | 88.0 |
| 1/32 | 0.45 | 19.5 | 78.5 |
| 1/16 | 0.50 | 22.0 | 80.0 |
| 3/32 | 0.50 | 25.0 | 80.5 |
| 1/8 | 0.57 | 27.0 | 81.5 |
| 5/32 | 0.60 | 28.0 | 83.0 |
| 3/16 | 0.60 | 29.0 | 82.5 |
| 7/32 | 0.63 | 31.0 | 83.0 |
| 1/4 | 0.65 | 29.0 | 83.0 |
| 9/32 | 0.69 | 29.5 | 83.0 |
| 5/16 | 0.70 | 31.0 | 82.5 |
| 11/32 | 0.70 | 29.0 | 85.0 |
| 3/8 | 0.73 | 29.0 | 84.0 |
| 13/32 | 0.73 | 30.0 | 84.0 |
| 7/16 | 0.75 | 30.0 | 85.5 |
| 15/32 | 0.75 | 28.5 | 86.5 |
| 1/2 | 0.78 | 28.5 | 87.5 |
| 17/32 | 0.79 | 28.0 | 86.5 |
| 9/16 | 0.80 | 28.0 | 86.0 |
| 19/32 | 0.80 | 28.0 | 87.0 |
| 5/8 | 0.80 | 28.0 | 87.0 |
| 21/32 | 0.80 | 27.5 | 87.0 |
| 11/16 | 0.81 | 27.5 | 88.0 |
| 23/32 | 0.81 | 27.5 | 88.0 |
| 3/4 | 0.81 | 27.5 | 88.0 |
| Group b, Force of 5 pounds tending to separate armature from pole. | | | |
| 0 | 0.53 | 15.5 | 92.0 |
| 1/32 | 0.54 | 20.0 | 90.75 |
| 1/16 | 0.54 | 23.0 | 88.5 |
| 3/32 | 0.55 | 25.0 | 84.0 |
| 1/8 | 0.58 | 26.5 | 82.0 |

TABLE 5. (Continued)

| Coil Thickness in inches | Current in amperes | Power in watts | Noise in decibels |
|---|---|---|---|
| 5/32 | 0.60 | 27.5 | 81.0 |
| 3/16 | 0.60 | 31.0 | 79.0 |
| 7/32 | 0.63 | 31.5 | 81.0 |
| 1/4 | 0.64 | 29.5 | 82.0 |
| 9/32 | 0.66 | 30.0 | 83.0 |
| 5/16 | 0.69 | 29.5 | 83.5 |
| 11/32 | 0.70 | 29.5 | 84.0 |
| 3/8 | 0.76 | 29.5 | 85.5 |
| 13/32 | 0.74 | 30.5 | 86.0 |
| 7/16 | 0.76 | 29.5 | 87.5 |
| 15/32 | 0.76 | 29.0 | 87.5 |
| 1/2 | 0.78 | 29.0 | 87.0 |
| 17/32 | 0.78 | 28.5 | 88.0 |
| 9/16 | 0.80 | 28.5 | 88.0 |
| 19/32 | 0.80 | 28.0 | 89.0 |
| 5/8 | 0.80 | 27.5 | 89.0 |
| 21/32 | 0.80 | 27.5 | 89.5 |
| 11/16 | 0.805 | 27.5 | 90.0 |
| 23/32 | 0.805 | 27.0 | 90.0 |
| 3/4 | 0.81 | 27.0 | 90.0 |

Group c, Force of 10 pounds tending to separate armature from pole.

| | | | |
|---|---|---|---|
| 0 | 0.55 | 21.0 | 96.5 |
| 1/32 | 0.55 | 24.0 | 95.5 |
| 1/16 | 0.55 | 26.5 | 95.0 |
| 3/32 | 0.55 | 25.5 | 93.5 |
| 1/8 | 0.55 | 27.5 | 93.5 |
| 5/32 | 0.56 | 28.0 | 93.5 |
| 3/16 | 0.58 | 28.5 | 93.0 |
| 7/32 | 0.60 | 30.0 | 94.0 |
| 1/4 | 0.62 | 29.0 | 90.5 |
| 9/32 | 0.63 | 31.0 | 91.0 |
| 5/16 | 0.63 | 30.0 | 94.0 |
| 11/32 | 0.63 | 31.0 | 94.5 |
| 3/8 | 0.65 | 31.5 | 96.0 |
| 13/32 | 0.70 | 32.0 | 96.0 |
| 7/16 | 0.70 | 32.0 | 96.5 |

TABLE 5. (Continued)

| Coil Thickness in inches | Current in amperes | Power in watts | Noise in decibels |
|---|---|---|---|
| 15/32 | 0.74 | 32.5 | 98.0 |
| 1/2 | 0.75 | 33.0 | 97.5 |
| 17/32 | 0.78 | 33.0 | 98.5 |
| 9/16 | 0.78 | 33.5 | 98.0 |
| 19/32 | 0.80 | 33.0 | 98.5 |
| 5/8 | 0.80 | 33.5 | 98.5 |
| 21/32 | 0.80 | 33.5 | 98.5 |
| 11/16 | 0.80 | 33.0 | 98.5 |
| 23/32 | 0.81 | 33.0 | 98.0 |
| 3/4 | 0.81 | 33.0 | 98.0 |

effective in reducing noise than the deep narrow slot and the waveguide shading coil.

The plot of data on graph six shows the comparison of the effect of changing the type of material of which the shading coils were made. It is significant that very little difference is noted between the minimum noise points for the different materials used. There is, of course, a difference between the thicknesses of coils needed to produce the minimum noise point depending on the material used and its physical dimensions.

Graph seven shows the comparison of noise produced versus force applied to the electromagnet armature for two different shading coils. It is apparent from observation of the curves that the bronze waveguide was most effective in reducing noise. This indicates that the resistance of the copper shading coil was too low for best reduction of noise. The force applied to the electromagnet caused it to open beyond the last point on the right for each curve shown. This shows that the electromagnet would be suitable for service where it is required to exert a force of approximately ten pounds on the contacts of a relay or on a valve.

The reduction in noise observed in graph eight as compared to the noise shown in graph seven is further evidence that a flat shading coil in a shallow, wide slot is superior to a long thin wall shading coil in a deep slot as represented by the waveguide coils. There is no logical explanation as to why the noise curves crossed as shown on graph eight other than to attribute this discrepancy to erroneous data for the twenty pound point.

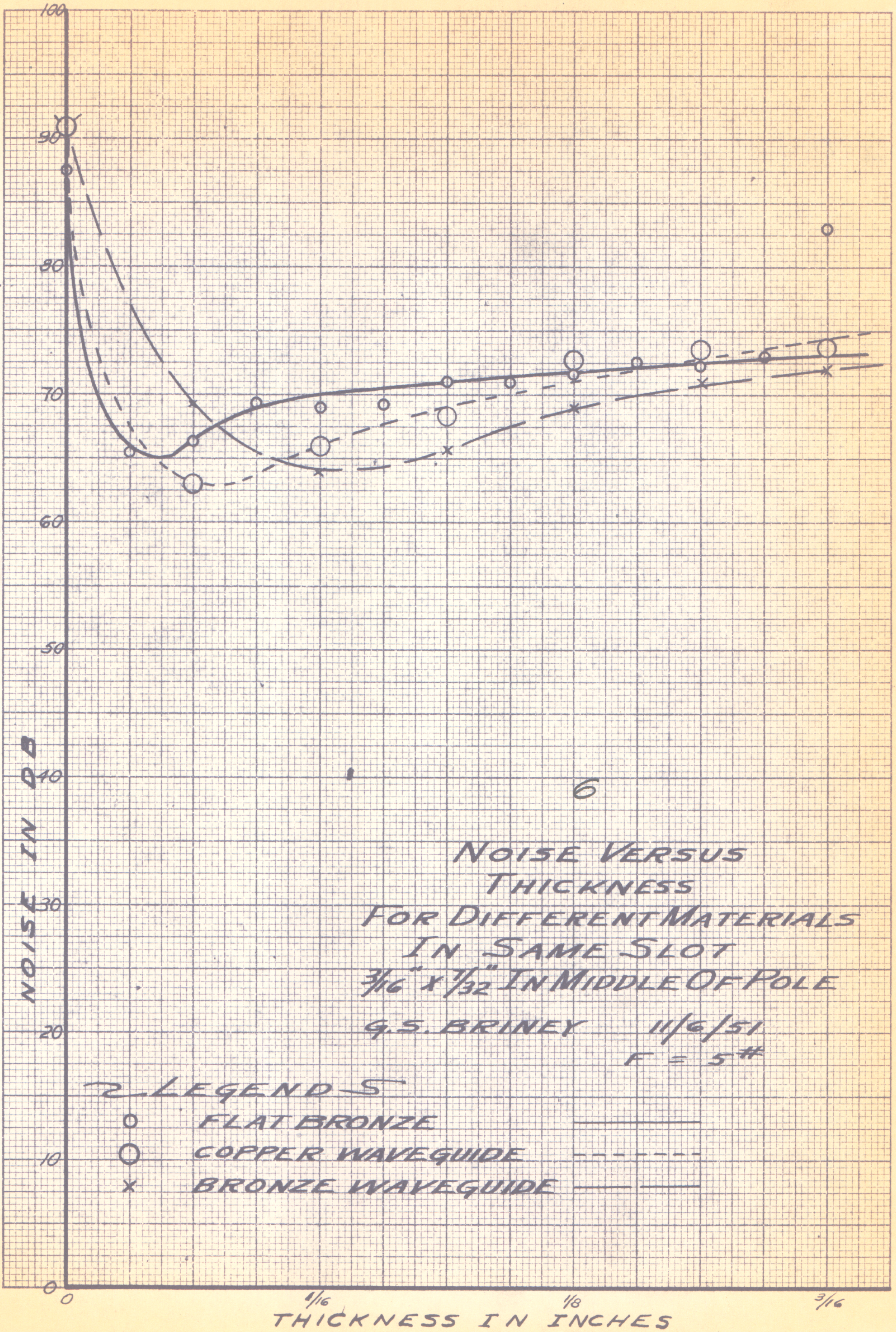
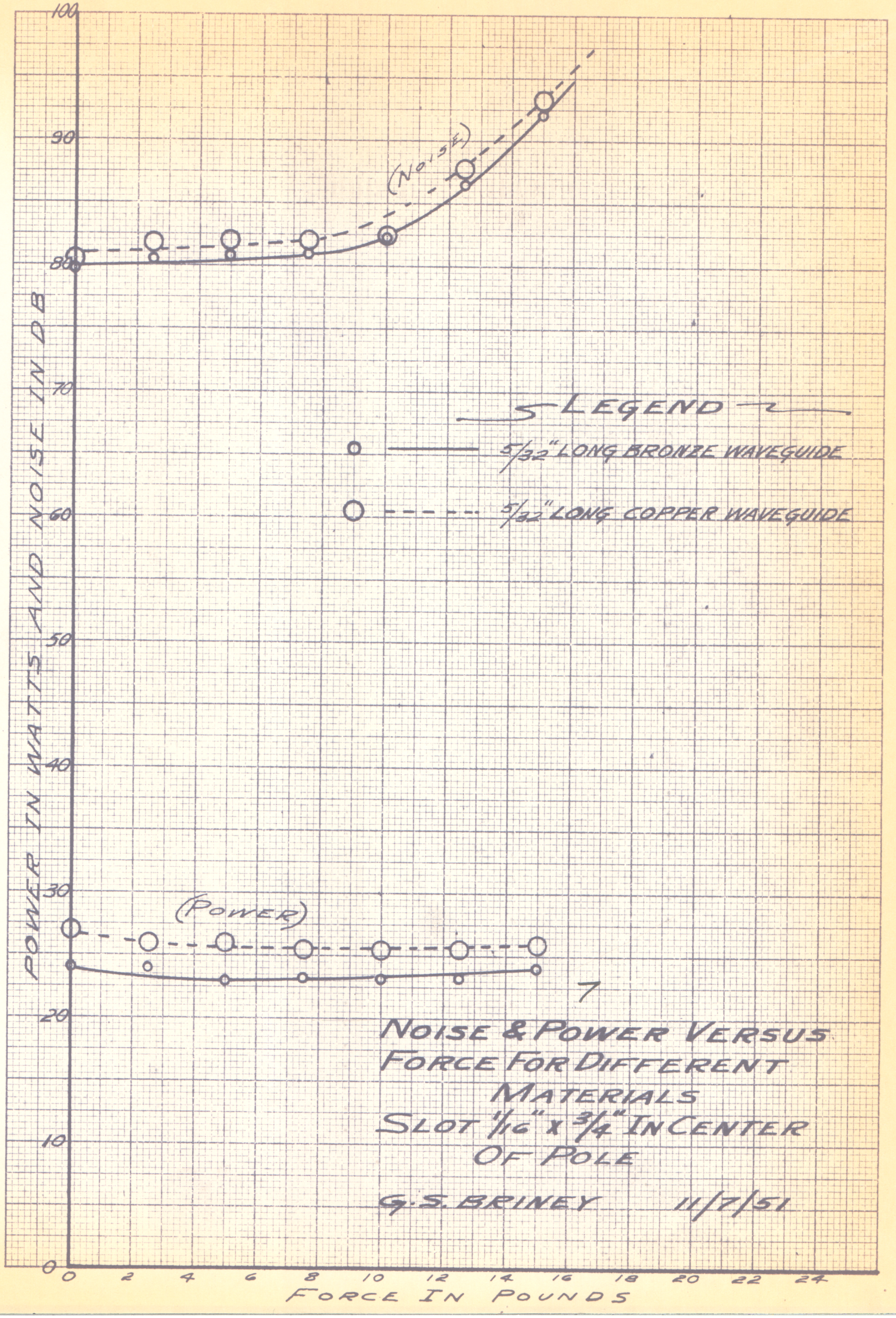

100
90
80
70
60
50
40
30
20
10
0
NOISE IN DB
0
1/16
1/8
3/16
THICKNESS IN INCHES
6
NOISE VERSUS
THICKNESS
FOR DIFFERENT MATERIALS
IN SAME SLOT
3/16" X 7/32" IN MIDDLE OF POLE
G.S. BRINEY 11/6/51
F = 5#
LEGEND
FLAT BRONZE
COPPER WAVEGUIDE
BRONZE WAVEGUIDE

TABLE 6. NOISE AND POWER INPUT DATA FOR CHANGES IN THE THICKNESS OF SHADING COILS OF DIFFERENT MATERIALS IN A 3/16" x 7/32" SLOT IN MIDDLE OF POLE. APPLIED VOLTAGE 120 VOLTS, 60 CYCLES

| Coil Thickness in inches | Current in amperes | Power in watts | Noise in decibels |
|---|---|---|---|
| Group a, Flat bronze coil, force: 5 pounds. | | | |
| 0 | 0.50 | 15.0 | 87.5 |
| 1/64 | 0.50 | 18.5 | 65.5 |
| 1/32 | 0.53 | 24.0 | 66.3 |
| 3/64 | 0.53 | 24.0 | 69.3 |
| 1/16 | 0.53 | 24.0 | 69.0 |
| 5/64 | 0.53 | 24.0 | 69.2 |
| 3/32 | 0.53 | 24.0 | 71.0 |
| 7/64 | 0.53 | 24.0 | 71.0 |
| 1/8 | 0.53 | 24.0 | 71.7 |
| 9/64 | 0.53 | 24.0 | 72.5 |
| 5/32 | 0.53 | 24.0 | 72.2 |
| 11/64 | 0.53 | 24.0 | 73.0 |
| 3/16 | 0.53 | 24.0 | 83.0 |
| Group b, Bronze waveguide, force: 5 pounds | | | |
| 0 | 0.4 | 14.0 | 91.3 |
| 1/32 | 0.43 | 18.5 | 69.2 |
| 1/16 | 0.44 | 21.5 | 64.0 |
| 3/32 | 0.47 | 24.0 | 65.7 |
| 1/8 | 0.50 | 26.5 | 69.0 |
| 5/32 | 0.50 | 28.0 | 71.0 |
| 3/16 | 0.55 | 29.0 | 72.0 |
| Group c, Copper waveguide, force: 5 pounds | | | |
| 0 | 0.40 | 14.0 | 91.7 |
| 1/32 | 0.43 | 20.5 | 63.0 |
| 1/16 | 0.47 | 23.5 | 66.0 |
| 3/32 | 0.50 | 26.0 | 68.3 |
| 1/8 | 0.53 | 28.0 | 72.7 |
| 5/32 | 0.55 | 29.0 | 73.5 |
| 3/16 | 0.55 | 29.5 | 73.7 |



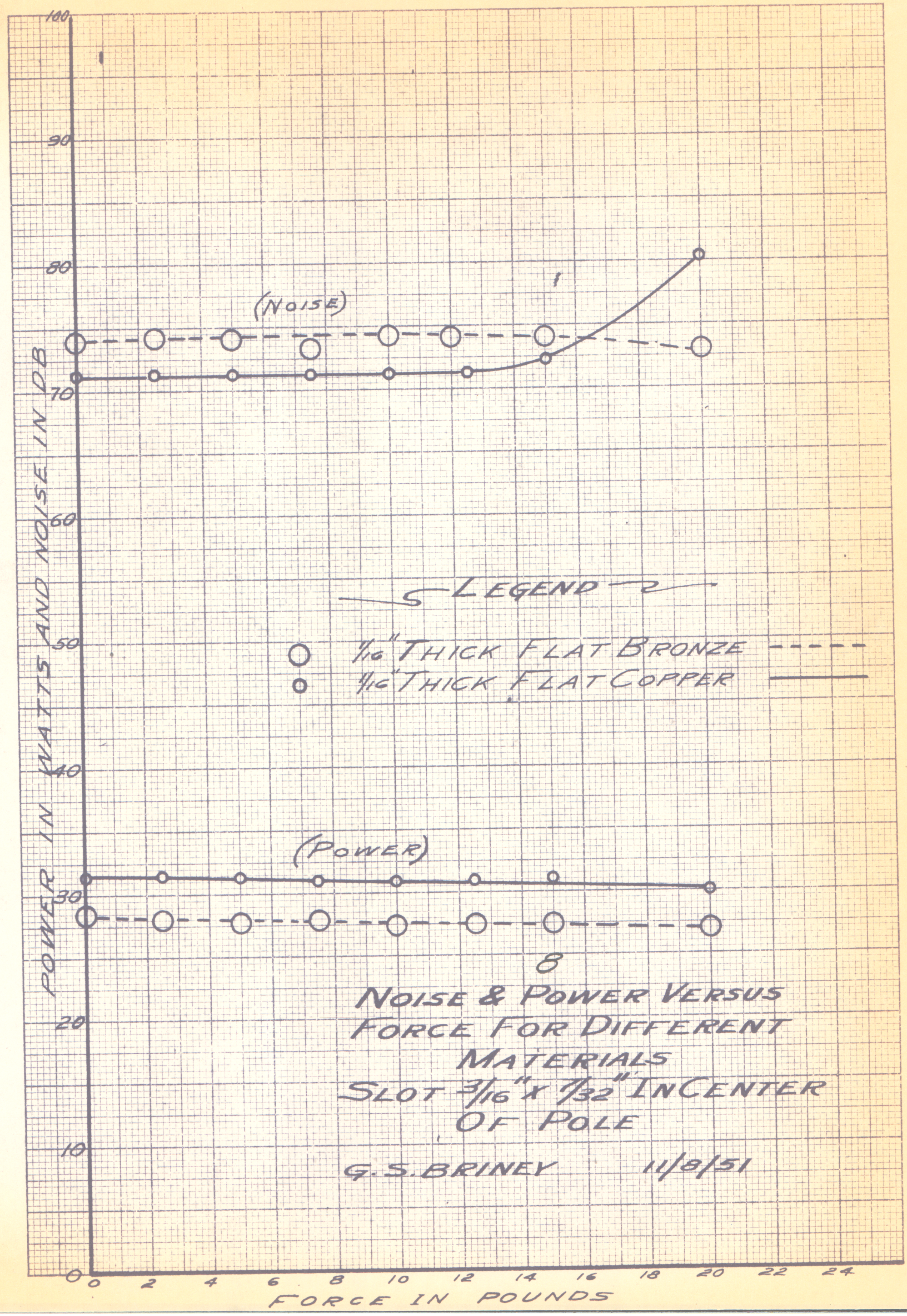

7

NOISE & POWER VERSUS FORCE FOR DIFFERENT MATERIALS
SLOT 1/16" x 3/4" IN CENTER OF POLE

G. S. BRINEY 11/7/51

TABLE 7. NOISE AND POWER INPUT DATA FOR CHANGES IN FORCE TENDING TO SEPARATE POLE AND ARMATURE. APPLIED VOLTAGE 120 VOLTS, 60 CYCLES SLOT 1/16" x 3/4" IN CENTER OF POLE

| Force on Armature in pounds | Current in amperes | Power in watts | Noise in decibels |
|---|---|---|---|
| Group a, 5/32" Long Bronze Waveguide shading coil | | | |
| 0 | 0.5 | 24.0 | 79.75 |
| $2\frac{1}{2}$ | 0.5 | 24.0 | 80.5 |
| 5 | 0.5 | 23.0 | 80.7 |
| $7\frac{1}{2}$ | 0.5 | 23.5 | 81.0 |
| 10 | 0.5 | 23.2 | 82.3 |
| $12\frac{1}{2}$ | 0.5 | 23.2 | 86.5 |
| 15 | 0.5 | 24.0 | 92.0 |
| 16 | | relay opened | |
| Group b, 5/32" Long Copper Waveguide shading coil | | | |
| 0 | 0.55 | 27.0 | 80.5 |
| $2\frac{1}{2}$ | 0.55 | 26.0 | 81.8 |
| 5 | 0.55 | 26.0 | 82.0 |
| $7\frac{1}{2}$ | 0.55 | 25.5 | 82.0 |
| 10 | 0.55 | 25.5 | 82.5 |
| $12\frac{1}{2}$ | 0.55 | 25.5 | 87.7 |
| 15 | 0.55 | 26.0 | 93.2 |
| 16.5 | | relay opened | |



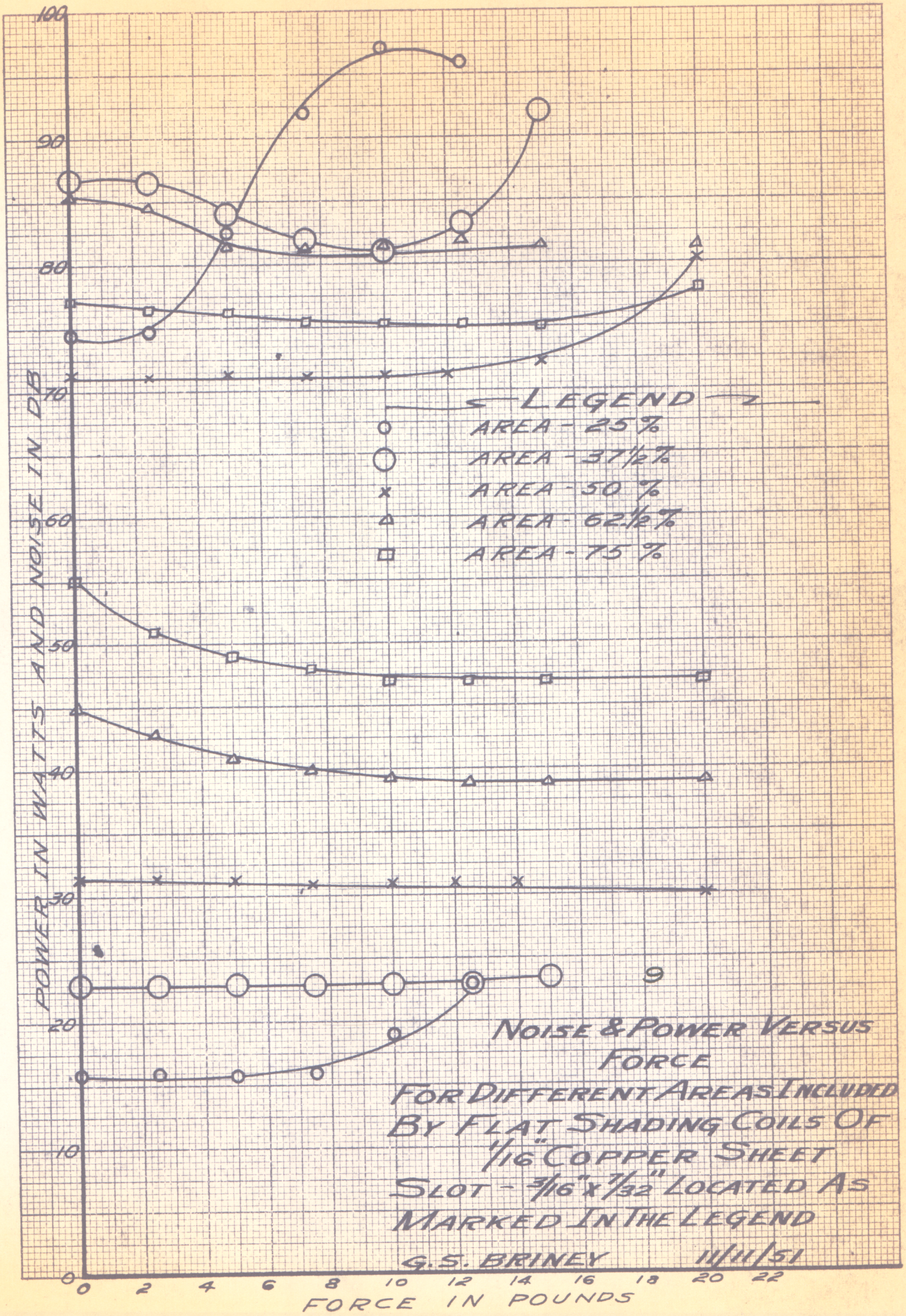

8
NOISE & POWER VERSUS
FORCE FOR DIFFERENT
MATERIALS
SLOT 3/16" X 7/32" IN CENTER
OF POLE

G. S. BRINEY 11/8/51

TABLE 8. NOISE AND POWER INPUT DATA FOR CHANGES IN FORCE TENDING TO SEPARATE POLE AND ARMATURE. APPLIED VOLTAGE 120 VOLTS, 60 CYCLES. SLOT 3/16" x 7/32" IN CENTER OF POLE

| Force on Armature in pounds | Current in amperes | Power in watts | Noise in decibels |
|---|---|---|---|
| Group a, 1/16" Thick Flat Bronze Shading Coil | | | |
| 0 | 0.52 | 28.5 | 74.0 |
| $2\frac{1}{2}$ | 0.52 | 28.0 | 74.2 |
| 5 | 0.52 | 27.7 | 74.0 |
| $7\frac{1}{2}$ | 0.50 | 27.7 | 73.2 |
| 10 | 0.50 | 27.5 | 74.2 |
| $12\frac{1}{2}$ | 0.50 | 27.5 | 74.2 |
| 15 | 0.50 | 27.5 | 74.0 |
| 20 | 0.50 | 27.0 | 73.0 |
| 23 | | relay opened | |
| Group b, 1/16" Thick Flat Copper Shading Coil | | | |
| 0 | 0.65 | 31.5 | 71.3 |
| $2\frac{1}{2}$ | 0.64 | 31.5 | 71.2 |
| 5 | 0.60 | 31.3 | 71.3 |
| $7\frac{1}{2}$ | 0.60 | 31.0 | 71.3 |
| 10 | 0.60 | 31.0 | 71.2 |
| $12\frac{1}{2}$ | 0.60 | 31.0 | 71.2 |
| 15 | 0.60 | 31.0 | 72.2 |
| 20 | 0.58 | 30.0 | 80.3 |
| 23 | | relay opened | |

In observing the noise versus force curves of graphs nine and ten appearing at the top of the pages it may be seen that when the shading coil embraced one-half the pole area minimum noise occurred for both the copper and bronze coils. The bronze shading coil curve of graph ten, however, represents the best coil for reducing noise for all forces applied to the armature and this bronze coil is also superior to the same size copper coil with regard to its smaller power consumption. A compromise must always be made between choosing a coil for minimum power consumption and choosing one for minimum noise. Minimum power consumption occurrs when there is no shading coil present as shown on the graphs. This also represents maximum noise. The shading coil of flat bronze in graph ten thus represents a good compromise between the minimum noise and minimum power qualifications for shading coil design.



POWER IN WATTS AND NOISE IN DB
100
90
80
70
60
50
40
30
20
10
0
0 2 4 6 8 10 12 14 16 18 20 22
FORCE IN POUNDS
LEGEND
AREA - 25%
AREA - 37½%
AREA - 50%
AREA - 62½%
AREA - 75%
9
NOISE & POWER VERSUS FORCE
FOR DIFFERENT AREAS INCLUDED BY FLAT SHADING COILS OF 1/16" COPPER SHEET
SLOT - 3/16" x 7/32" LOCATED AS MARKED IN THE LEGEND
G. S. BRINEY
11/11/51

TABLE 9. NOISE AND POWER INPUT DATA FOR CHANGES IN AREA INCLUDED BY FLAT 1/16" THICK COPPER SHADING COILS AND CHANGES IN FORCE TENDING TO SEPARATE POLE AND ARMATURE. SLOT 3/16" x 7/32".

APPLIED VOLTAGE 120 VOLTS, 60 CYCLES

| Force on Armature in pounds | Current in amperes | Power in watts | Noise in decibels |
|---|---|---|---|
| Group a, Enclosed Area: | 25 Percent of Pole | | |
| 0 | 0.7 | 16.0 | 74.5 |
| $2\frac{1}{2}$ | 0.7 | 16.0 | 74.7 |
| 5 | 0.7 | 15.8 | 82.5 |
| $7\frac{1}{2}$ | 0.7 | 16.0 | 92.0 |
| 10 | 0.7 | 19.0 | 97.0 |
| $12\frac{1}{2}$ | 0.7 | 23.0 | 96.0 |
| 14 | | relay opened | |
| Group b, Enclosed Area: | $37\frac{1}{2}$ Percent of Pole | | |
| 0 | 0.6 | 23.0 | 86.7 |
| $2\frac{1}{2}$ | 0.6 | 23.0 | 86.5 |
| 5 | 0.6 | 23.0 | 84.0 |
| $7\frac{1}{2}$ | 0.6 | 23.0 | 82.0 |
| 10 | 0.6 | 23.0 | 81.0 |
| $12\frac{1}{2}$ | 0.6 | 23.0 | 83.2 |
| 15 | 0.6 | 23.5 | 92.0 |
| 19 | | relay opened | |
| Group c, Enclosed Area: | 50 Percent of Pole | | |
| 0 | 0.65 | 31.5 | 71.3 |
| $2\frac{1}{2}$ | 0.64 | 31.5 | 71.2 |
| 5 | 0.60 | 31.3 | 71.3 |
| $7\frac{1}{2}$ | 0.60 | 31.0 | 71.3 |
| 10 | 0.60 | 31.0 | 71.2 |
| $12\frac{1}{2}$ | 0.60 | 31.0 | 71.2 |
| 15 | 0.60 | 31.0 | 72.2 |
| 20 | 0.58 | 30.0 | 80.3 |
| 23 | | relay opened | |

TABLE 9. (Continued)

| Force on Armature in pounds | Current in amperes | Power in watts | Noise in decibels |
|---|---|---|---|
| Group d, Enclosed Area: 62½ Percent of Pole | | | |
| 0 | 0.64 | 45.0 | 85.4 |
| 2½ | 0.80 | 43.0 | 84.7 |
| 5 | 0.73 | 41.0 | 81.7 |
| 7½ | 0.72 | 40.0 | 81.7 |
| 10 | 0.72 | 39.5 | 81.5 |
| 12½ | 0.70 | 39.0 | 82.0 |
| 15 | 0.70 | 39.0 | 81.5 |
| 20 | 0.70 | 39.0 | 81.5 |
| 22 | relay opened | | |
| Group e, Enclosed Area: 75 Percent of Pole | | | |
| 0 | 1.00 | 55.0 | 77.3 |
| 2½ | 0.94 | 51.0 | 76.5 |
| 5 | 0.90 | 49.0 | 76.2 |
| 7½ | 0.89 | 48.0 | 75.5 |
| 10 | 0.88 | 47.0 | 75.3 |
| 12½ | 0.88 | 47.0 | 75.2 |
| 15 | 0.88 | 47.0 | 75.0 |
| 20 | 0.88 | 47.0 | 78.0 |
| 22 | relay opened | | |

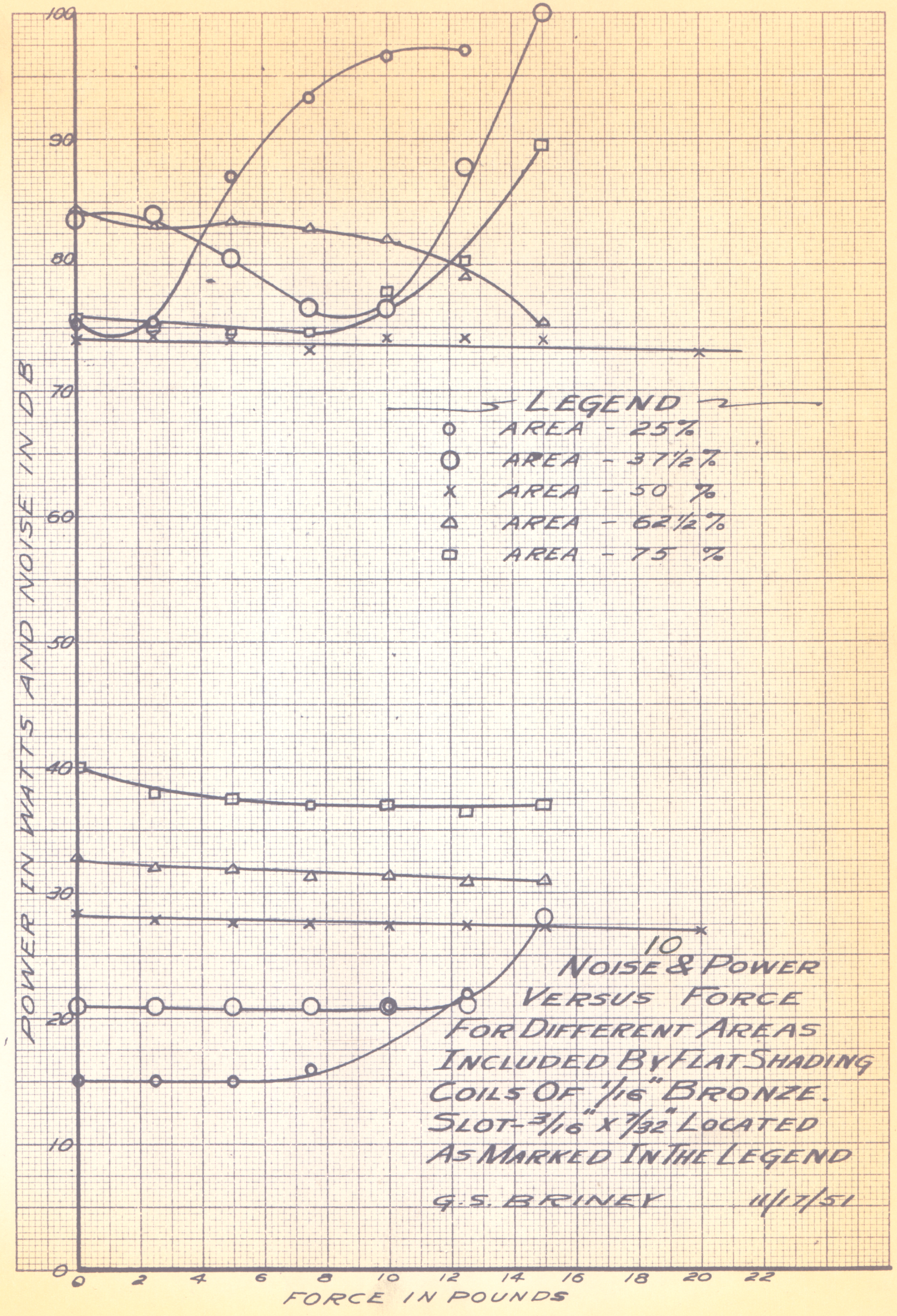

LEGEND
AREA - 25%
AREA - 37½%
AREA - 50 %
AREA - 62½%
AREA - 75 %
POWER IN WATTS AND NOISE IN DB
FORCE IN POUNDS
10
NOISE & POWER
VERSUS FORCE
FOR DIFFERENT AREAS
INCLUDED BY FLAT SHADING
COILS OF 1/16" BRONZE.
SLOT-3/16" X 7/32" LOCATED
AS MARKED IN THE LEGEND
G.S. BRINEY
11/17/51

TABLE 10. NOISE AND POWER INPUT DATA FOR CHANGES IN AREA INCLUDED BY FLAT 1/16" THICK BRONZE SHADING COILS AND CHANGES IN FORCE TENDING TO SEPARATE POLE AND ARMATURE. SLOT 3/16" x 7/32"

APPLIED VOLTAGE 120 VOLTS, 60 CYCLES

| Force on Armature in pounds | Current in amperes | Power in watts | Noise in decibels |
|---|---|---|---|
| Group a, Enclosed Area: 25 Percent of Pole | | | |
| 0 | 0.63 | 15.0 | 75.2 |
| 2½ | 0.63 | 15.0 | 75.5 |
| 5 | 0.63 | 15.0 | 87.0 |
| 7½ | 0.63 | 16.0 | 93.3 |
| 10 | 0.65 | 21.0 | 96.5 |
| 12½ | 0.70 | 22.0 | 97.0 |
| 14 | relay opened | | |
| Group b, Enclosed Area: 37½ Percent of Pole | | | |
| 0 | 0.55 | 21.0 | 83.6 |
| 2½ | 0.55 | 21.0 | 83.6 |
| 5 | 0.55 | 21.0 | 80.5 |
| 7½ | 0.55 | 21.0 | 76.6 |
| 10 | 0.55 | 21.0 | 76.5 |
| 12½ | 0.55 | 21.0 | 87.3 |
| 15 | 0.60 | 28.0 | 100.0 |
| 18 | relay opened | | |
| Group c, Enclosed Area: 50 Percent of Pole | | | |
| 0 | 0.52 | 28.5 | 74.0 |
| 2½ | 0.52 | 28.0 | 74.2 |
| 5 | 0.52 | 27.7 | 74.0 |
| 7½ | 0.50 | 27.7 | 73.2 |
| 10 | 0.50 | 27.5 | 74.2 |
| 12½ | 0.50 | 27.5 | 74.2 |
| 15 | 0.50 | 27.5 | 74.0 |
| 20 | 0.50 | 27.0 | 73.0 |
| 23 | relay opened | | |

TABLE 10. (Continued)

| Force on Armature in pounds | Current in amperes | Power in watts | Noise in decibels |
|---|---|---|---|
| Group d, Enclosed Area: 62½ Percent of Pole | | | |
| 0 | 0.62 | 33.0 | 84.0 |
| 2½ | 0.62 | 32.3 | 83.0 |
| 5 | 0.62 | 32.0 | 83.5 |
| 7½ | 0.61 | 31.5 | 83.0 |
| 10 | 0.61 | 31.5 | 82.0 |
| 12½ | 0.62 | 31.0 | 79.0 |
| 15 | 0.62 | 31.2 | 75.5 |
| 19 | relay opened | | |
| Group e, Enclosed Area: 75 Percent of Pole | | | |
| 0 | 0.84 | 40.0 | 75.5 |
| 2½ | 0.82 | 38.0 | 75.0 |
| 5 | 0.82 | 37.5 | 74.7 |
| 7½ | 0.82 | 37.0 | 74.8 |
| 10 | 0.80 | 37.0 | 77.8 |
| 12½ | 0.80 | 35.5 | 80.3 |
| 15 | 0.80 | 37.0 | 89.5 |
| 18 | relay opened | | |

# V.

## CONCLUSIONS

As a result of this work several conclusions may be drawn as follows:

1. In general, contrary to popular opinion, heavy shading coils are not as effective in reducing noise in an alternating current electromagnet as those which are smaller and thus have a greater value of resistance. This occurrs because in addition to obtaining the greatest shift possible between flux produced by the unshaded and shaded portions of the pole the magnitudes of these fluxes should be equal. If the shading coil is too large its effect is to increase the flux produced by that portion of the pole to such a great extent that it becomes much greater in magnitude than the flux due to the unshaded portion of the pole. In order to prevent the magnetomotive force of the shading coil from being so large that its resultant flux does not become much larger than the flux of the unshaded portion of the pole it is necessary to increase the resistance of the shading coil. One way of achieving this is to decrease the size of shading coil used. This automatically decreases the phase angle between the shaded and unshaded pole fluxes, but less noise is produced due to the two fluxes being more nearly equal. Thus it is evident that a shading coil represents a compromise between what appear to be the ideals of maximum or ninety degree phase shift of fluxes and equal magnitudes of fluxes. By virtue of work done by others the shading coil must be designed so that

the phase angle between shaded and unshaded pole flux becomes approximately sixty degrees. The investigator found this to be approximately correct by comparing the minimum noise shading coil of his investigation with the coil of best design from the paper by [5]Leonard A. Doggett and Franz S. Veith entitled "Design of Shading Coils for Alternating Current Electromagnets".

2. Electromagnet shading coils should be such as to fit into a wide shallow slot in preference to a deep narrow slot in the pole.

3. Contrary to results of work by others the investigator found that for minimum noise a shading coil should embrace fifty percent of the pole area of an electromagnet.

4. Increasing the force required of an alternating current electromagnet causes the noise produced by it to increase. A particular shading coil can produce minimum noise for primarily one particular force tending to open the electromagnet. Here again a compromise must usually be made between a shading coil which produces a sufficiently small noise over the range of forces for which it is to be used to be considered satisfactory.

# VI

## RECOMMENDATIONS

As a result of this study certain recommendations regarding work by future investigators appear pertinent. These are given as follows:

1. Since it was beyond the scope of this investigation to produce mathematical relationships for design of shading coils, some work should be done to correlate the work done by others as discussed in the review of literature section, with the results of this investigation so as to arrive at more precise design data for electromagnet shading coils.

2. This investigation was concerned with shading coils for alternating current electromagnets. Some effort should be made to determine how conclusions drawn as a result of this investigation could be applied to shading coils as used on small shaded pole motors, and how these techniques could be applied to motor shading coil investigations.

# VII

## SUMMARY

This investigation has utilized changes in all physical parameters affecting shading coil design to allow appropriate conclusions to be drawn. These conclusions supplement those drawn by previous writers and represent in part phases of investigation not undertaken before. The availability of several identical magnetic cores allowed more changes to be made in this investigation than was done by others. The results obtained were good and were partially verified by comparison with work done by previous investigators.

Great care was taken to insure accuracy both in the preparation of equipment and in the taking of data. With the exception of three relatively minor discrepancies all data taken were consistant and the discrepancies can be attributed to experimental error without seriously affecting the other results.

Since this investigation was performed additional references which were not available at Virginia Polytechnic Institute have been examined through the facilities of the Franklin Institute Library in Philadelphia, Pennsylvania. The methods used in approaching the problem of proper shading coil design as given in these references combined with those of the investigator would serve as an excellent beginning for any future research in this field.

# VIII

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The authors have constructed a nomogram by means of which optimum design data for any given requirements can be determined.

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A discussion of the use of shading coils on single phase alternating current motors is presented.

# IX

## VITA

Gerald S. Briney was born in Akron, Ohio March 30, 1921. He attended the University of Akron three and one-half years, majoring in Electrical Engineering, and participated in the University of Akron Engineering Cooperative program working as a mechanic and later as an electrical draftsman. Due to family financial difficulty brought on by injury to his father he took a position with Goodyear Aircraft Corporation as a Junior Electrical Engineer in 1942. It was while working there that he was married. In October, 1943 he was drafted into the United States Naval Reserve and spent fourteen months in radio and radar technician training after which he became an instructor in the same school. He was separated from the service in 1946 and at that time re-enrolled at the University of Akron to finish the requirements for a Bachelor of Electrical Engineering degree in September, 1947. He then joined the staff of the Electrical Engineering Department of Virginia Polytechnic Institute where he attained the rank of Assistant Professor. He left the field of teaching in order to gain industrial experience and has been employed by the Brown Instruments Division of the Minneapolis-Honeywell Regulator Company as an Application Engineer since June, 1951. He now has two sons and resides in Philadelphia, Pennsylvania.

Gerald S. Briney