Navy Department - Office of Research and Inventions Lab Memo 117-46

NAVAL RESEARCH LABORATORY
Washington, D.C.

FR-2577

PHYSICAL OPTICS DIVISION - SPECTROSCOPY SECTION

9 July 1945

METAL BOLOMETERS OF SHORT TIME OF RESPONSE AND HIGH SENSITIVITY

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Report H-2577

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NRL Problem No. H-89

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CHAPTER I

INTRODUCTION

Authorization.

The research to be described in this report was carried on under Bureau of Ordnance Project Order 50221 of 21 September 1944, known as Project Spruce. The purpose of the Project was to develop a far-infra-red gunsight for air to air use.

The Problem

The requirements of Project Spruce are that a gunsight, senitive to infra-red radiations from the target, be developed to indicate the presence of an airplane anywhere in an area of sky 30 degrees in diameter (or 30 degrees square) with such speed and resolving power that a fast approaching target can be located to 0.25 degree. Further, the requirement on range of the sight in use is that it detect a fighter airplane at night at distances greater than 1000 yards.

Possible Solutions

Three possible solutions have been considered.

Solution A. A scanning system has been drawn up which would give the gunner an indication of the direction of the target away from the line of sight of the system and an indication of the angular distance of the target away from the line of sight. This solution has not been pursued because the operator of such a device would not be able to distinguish the target signal from those received from clouds and the horizon, and because it would be very difficult to obtain the required resolution with such a system.

Solution B. The possibility of using a mosaic of radiation sensitive elements in the focal plane of an image forming system has been considered. The response of each element would control the brightness of a spot so located on a screen that the response of all the elements together would form a picture. For Project Spruce the mosaic would contain about 15,000 elements. While this is the ideal method of solving the problem, the development of such a mosaic has not been attempted at this Laboratory.

Solution C. The whole field of view may be scanned at frequent intervals, say one a second, by a single bolometer, the size of the bolometer, the scanning rate, and the pattern of scan being such that the required resolution and size of field will be realized. The amplified output of the bolometer can be presented on a screen so that a picture of the infrared "brightness" of objects in the field of view will be formed. This solution has been chosen. The requirements which it sets on the sensitivity and the speed of response are outlined below.

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An infra-red gunsight with a field of view 30 degrees square and with resolution of 0.25 degree can be build and it may detect aircraft at night at ranges greater than 1000 yards if a bolometer and an amplifier can be built such that the combination of bolometer and amplifier will detect a signal difference incident on the bolometer of about 10^{-6} watts and if the time constant of the combination is about 3×10^{-5} seconds. Bolometers and amplifiers meeting these requirements have been built at this Laboratory and they are described in this report.

<u>The Materials Available at the Initiation of this Project.</u>

At the time constant at which they operate, thermistors are the most sensitive of the available bolometers. Under laboratory conditions of operation the combination of a thermistor of area about one square millimeter and a properly designed amplifier, this combination having a time constant of about 3×10^{-3} seconds, can detect a difference in the radiation incident on the thermistor of about 10^{-7} watts. Using such a thermistor with an amplifier designed to give the combination of amplifier and thermistor a time constant of 3×10^{-5} seconds, the resultant combination will just detect a difference in the radiation incident on the thermistor of about 5×10^{-5} watts.

Thermistors have not been made with time constants much less than 3×10^{-3} seconds. They have not been used in this project because, it was thought that any attempts to decrease the time constant of a system using thermistors by changes of the amplifier characteristics alone would result in an unacceptable sacrifice of sensitivity, as indicated in the paragraph above.

The Golay Cell can be made so that in combination with its amplifier a time constant of 3×10^{-4} seconds is realized, and a difference in radiation incident on the cell of about 5×10^{-8} watts can just be detected. It seems possible that cells of this type might be made with the necessary time constants and sensitivities for Project Spruce. Golay Cells have been ordered by this Laboratory, but, to date, they have not been received.

<u>Techniques and Theories of Fast Bolometers Available at the Initiation of this Project.</u>

A method for making fast bolometers had been advanced by Dr. R. D. Havens, Bureau of Ships, Section 660d, who discussed the principles involved in authorized circles and conducted many experiments at this Laboratory, but who has not published his results. Havens proposed a simplified theory of the behavior of bolometers and showed, both theoretically and experimentally, that, by separating a metal bolometer strip from a massive metal base by a film of insulating material of chosen heat conductivity, the time constant and the sensitivity of the bolometer are related in a simple way to the specific heat of the bolometer strip and to the conductivity of the insulating film. He further showed that time constants of the order of 10^{-5} seconds are experimentally possible.

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Havens constructed bolometers by coating massive aluminum plates, say 1 cm x 2 cm x 0.5 cm, with a thermal setting Nylon cement or a plastic and laying ordinary gilder's foil, or evaporating silver or bismuth, on that.

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CHAPTER II

BOLOMETER CONSTRUCTION

An Outline of the Present Method of Bolometer Construction

The separate steps in the construction of a bolometer are described in the following paragraphs. A bolometer strip of silver or gold, usually about one millimeter wide and about 0.03 micron thick is deposited by evaporation through a mask onto a 0.03 micron thick quartz film which is stretched across a hole, larger than the bolometer, in a mica plate of thickness dependent on the time constant desired (usually the thickness is between 15 microns and 50 microns). The length of the bolometer (usually about one millimeter) is controlled by the form of the mask used when metal contacts are deposited, by evaporation, over the ends of the bolometer strip. The mica plate is attached to a massive brass plate so that the bolometer is separated from the brass plate by the thickness of the mica. Absorption of the radiation incident on the bolometer strip is assured by evaporating a gold black on the strip. The absorption of of the blacks used is between 75% and 90% at wavelength 10 microns, and the heat capacity of the black is small compared to that of the rest of the bolometer. Important results of this type of construction are:

a. The heat capacity of the bolometer strip, its support, and the black is as near a minimum as experimental techniques will allow.

b. The time constant of the bolometer may be controlled by varying the thickness of the gap between the bolometer and the massive brass plate and by selection of the gas used in this gap. Effectively all of the heat lost from the bolometer strip is by conduction through the gas in the gap. The heat capacity of the gas in the gap is negligible compared to that of the bolometer strip and its support.

c. More than seventy percent of the radiation incident on the bolometer is absorbed.

d. The specific temperature coefficients of resistance of the metals used in the bolometer strips are about one quarter of those of the bulk metals. This loss of sensitivity may be regained, in part as the techniques for the formation of the metal bolometer strips are improved.

Construction of the Base

The dimensions and the general appearance of the base for the bolometer are shown in Plate I. The base is a cylinder made of two pieces of brass insulated from each other by, and bonded together

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by a glass cloth spacer impregnated with Nylon cement. Metlbond Cement No. N2 is used. It is supplied by National Research and Manufacturing Company, 2330 Cleveland Avenue, National City, California. The plane dividing the two pieces of brass is parallel to the axis of the cylinder and offset from the axis by 1/32 inch. Contacts are provided at one end of the cylinder. The other end of the cylinder is curved so that its surface is a section of a cylinder of about two inch radius, the axis of which is parallel to the plane dividing the two pieces of brass and passes through the axis of the base. This curvature prevents the mica plates from bowing up away from the brass base and it puts the quartz film under a very slight tension.

The Mica Plate and the Guncotton Support

Mica sheets are split to the thickness desired for the mica plates and the sheets are then cut with scissors or a razor to the dimensions shown in Plate II Figure 1. The hole is drilled in a stack of plates clamped between thick plastic blocks. A drop of guncotton (viscosity: 29 seconds) dissolved in amyl acetate, in the proportions eight grams and eighty cubic centimeters respectively, is allowed to fall on a clean water surface, and after the amyl acetate has vaporized the film of guncotton is picked up on a wire ring. By stroking the edges of the wire ring with the finger the film is stretched as tight as possible and then it is baked for an hour or so in an oven at about 120 degrees centigrade. The thickness of the film is estimated from the interference colors observed when two or three pieces of the film are stacked together.

The mica plates after careful cleaning are moistened with clean water and laid on the guncotton film. After baking the system for twenty minutes or so at 120 degrees centigrade, the plates with the film attached are cut out and the excess film is carefully removed. Figure 2 of Plate 11 shows the mica plate with the guncotton stretched over it.

Evaporation of the Bolometer Strips

The technique for the evaporation of the bolometer strips is shown roughly in Plate 111 Figure 1 and Figuire 2.

For each evaporation of silver a new tantalum boat is used. After the pressure in the vacuum system has reached 2 or 3×10^{-5} mm of mercury the boat is heated, with the shutter over it, until the silver melts. After thirty seconds or so the power to the boat is turned off and the system is allowed to pump for a few minutes. The shutter is then opened and the boat heated so that evaporation procedes very slowly for about thirty seconds and then the power is turned off for a few minutes. This process is continued until the glass plate with silver foil contacts on its ends, shown in Plate 111 Figure 1, has a resistance between the contacts of two to four ohms.

[redacted]

out in an evacuated bell jar by laying the mica plate on a slightly concave metal ribbon connected to a source of electrical power; the ribbon is heated until the guncotton film disappears from around the bolometer strip. Either process removes the guncotton without destroying the quartz film. Silver is heated in a vacuum because heating silver films to 200 degrees centigrade in air causes the film to deteriorate.

The bismuth and bismuth-tin bolometers are strong enough to support themselves. Thus, the guncotton can be burned off with no quartz film present.

The function of the quartz film is two fold: it serves as a support for the bolometer strip, and it separates the bolometer metal from the black, thereby eliminating the danger of electrical noise being caused in the bolometer by the black.

Mounting the Bolometer on the Base

The method of mounting the bolometer on the base is shown roughly in Plate Vl. Referring to the drawing, the mica plate is attached to the scotch tape strips and lowered onto the base. All the exposed edges of the mica plate are glued to the base with Duco household cement. Holes shown in Plate Vll are punched with a needle in the quartz film so that it will not explode when the bolometer is placed in a vacuum system for blacking. The scotch tape is then trimmed off with a razor and contact is made between the base and the contacts on the mica plate by wetting contacts and base with saliva, on a fine artists brush, and then laying silver foil on, as shown in Plate Vll. Several thicknesses of silver foil are usually used.

Blackening the Bolometer

The bolometer to be blackened is placed on edge under a bell jar about two inches away from and with the quartz film facing a 30 or 40 mil tungsten wire helix which is at the same level as the bolometer and which is connected to an external power supply. Previous to the blackening operation, gold is fused to the tungsten helix in vacuo. Halfway between the helix and the bolometer two large brass rods are placed with their axes vertical and separated so that there is about a three quarter of an inch gap between them through which the line from the bolometer to the center of the helix passes. The rods are included because the man who makes the blacks insists that they are necessary. They could probably be eliminated by the use of other pressures and distances. The black is formed by evaporating the gold in a hydrogen atmosphere at a pressure of from 15 to 50 millimeters of mercury. Evaporation is stopped when the bolometer surface appears to reflect about ten percent of the incident light.

[redacted]

There is some evidence that these blacks are not stable at the temperature at which the bolometers are operated. Other metals and techniques for making blacks are being investigated at this Laboratory.

Sealing the Bolometer in Hydrogen or Air

So far only a few bolometers have been sealed. The method used is shown in Plate VIII.

Variations on the Process for Making Bolometers

Until recently, no quartz was used. The bolometers were made exactly as described above except that no quartz was evaporated on them and the guncotton was not baked off. In this case the black was evaporated directly onto the metal of the bolometer strip.

Sometimes it is convenient to evaporate the contacts before evaporating the bolometer strips. This is not a good practice with silver or gold because the bolometer strip is slightly thinner near the contacts when this sequence of evaporations is used. There is less chance of noise with metals which tend to oxidize if the contacts are put on first. This is expecially true of aluminum.

Double bolometers can be made by attacking a thread to the mica plate before any evaporating is done. The thread is so placed that it splits the bolometer strip lengthwise and also splits the contacts. The thread is removed after the evaporation of the contacts.

Safe Current for the Bolometers

The maximum safe temperature of operation of a bolometer supported by quartz seems to be, at present, about 200 degrees centigrade, and when guncotton supports are used the maximum temperature is about 100 degrees centigrade. The temperature of the bolometer, T, in degrees Kelvin is given as a function of the current through the bolometer, I, in amperes by

$$T = T_o + \frac{I^2 R}{\lambda} ,$$

where T_o is the temperature in degrees Kelvin of the surface of the brass support directly behind the bolometer, R is the resistance of the bolometer, in ohms, and λ is the total conductivity of the gas in the gap between the bolometer and the brass base in watts per degree. For the bolometers described in this report, T_o may be shown to be only a few degrees different from room temperature. The total conductivity, λ, may be calculated, quite accurately, by determining the conductivity of a tube of gas of cross section equal to the area of the bolometer and length to the thickness of the gap.

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CHAPTER III

BOLOMETER CALIBRATION

Measurement of the Dimensions and the Coefficients of a Bolometer

The thickness of the gap between the bolometer and the mount is determined by the choice of thickness of the mica plate. Now and then a bolometer is assembled in which the mica plate does not lie in contact with the mount in the region around the holde in the plate. In these cases the thickness of the gap must be estimated.

The length and width of the bolometer strip is measured with a convenient magnified scale.

The resistance and the temperature coefficient of resistance of the bolometer are measured by connecting the bolometer to a Wheatstone bridge and measuring its resistance at various temperatures.

The total specific heat of the metal in the bolometer strip is calculated from data obtained by determining the increase in weight of a thin glass plate resulting from placing it near the bolometers during their evaporation.

The thickness of the quartz films has been estimated by members of the Electron Optics Section of this Laboratory who have had considerable experience in the use of thin quartz films.

The heat capacity of the blacks used is apparently small compared to that of the bolometer strip and its support because the time constant of a bolometer is about the same before blackening as after.

Measurement of the Time Constant and Sensitivity of a Bolometer

The general set up for testing the sensitivity of bolometers at various frequencies of square wave irradiation of the bolometer is shown in Plate IX.

The amplifier is carefully shielded, and so constructed that the noise from it, when the input is shorted, is equal to the Johnson noise it would amplify from a four ohm resistor. The band pass of the amplifier centers on about 500 cycles and it is roughly 1000 cycles wide. The amplifier was designed at a time when it appeared that the best bolometers would have a resistance of about 10 ohms and time constants of the order of 2×10^{-4} seconds. An amplifier is at present being designed for use with one to two ohm bolometers with time constants of the order of 3×10^{-5} seconds. There is provision for adjusting the bolometer current, and the bolometers are tested at what is believed to be maximum safe current.

The amplifier can be calibrated for its amplification of either sine waves or square waves. The output of a bolometer is roughly a square wave when it is exposed to square wave irradiation of period large compared to 2π times the time constant of the bolometer; hence

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the square wave calibration of the bolometer is important. The output of the bolometer is approximately a sine wave when the bolometer is exposed to square wave irradiation of period equal to or greater than 2π times the time constant.

A calibrated tungsten lamp is used as a source in testing because it is more convenient than a warm body source. To the accuracy of the calibration tests, which is about $\pm$ 25 percent, the bolometers show the same sensitivity to warm sources as they do to the tungsten source; this means that the black is approximately neutral.

The radiation incident on the bolometer is chopped by a sector wheel. Wheels representing various frequencies may be used, or, more conveniently, a wheel may be used such as that shown in Plate IX, which has been cut with sectors which chop the radiation at 300, 600, 1200, 2400 and 3600 cycles. To determine the response of a bolometer and its amplifier to a pulse of radiation, the light incident on the bolometer may be chopped by using a rotating disk cut to have in it a single aperature of size appropriate to the duration of the desired pulse.

The time constant of a bolometer may be found either by determining its response as a function of the duration of single pulses of radiatin incident upon it or by determining its response as a function of the frequency of square wave chopped light incident upon it. If V is the total change in potential across the bolometer resulting from exposure to a given source of radiation, then the change in potential, $V_{\Delta t}$, resulting from a pulse of radiation from the source, of duration Δt, falling on the bolometer is given by

$$V_{\Delta t} = V\left(1 - e^{-\frac{\Delta t}{\tau}}\right),$$

where τ is the time constant of the bolometer. The peak to peak fluctuations in the potential across the bolometer, V_f due to exposing it to chopped radiation from the source of frequency f is given approximately by

$$V_f = V\left(1 - e^{-\frac{1}{2\pi f \tau}}\right).$$

The exact expression for V_f is a little awkward, being

$$V_f = 0.9V\left(\sum_{n=0}^{\infty} \frac{1}{(2n+1)^2\left\{1 + (2n+1)^2\, 4\pi^2 f^2 \tau^2\right\}}\right)^{\frac{1}{2}}$$

<u>A Summary of the Results of Tests.</u>

A great many data have been taken on the several hundred bolometers which have been built during the development of the techniques which are described above. These data justify the following statements:

[redacted]

(a) Silver, gold, nickel, and possibly bismuth bolometers can be built in which the current noise is not greater than Johnson noise.

(b) The theory, summarized later in this report, predicts numerical values for the time constants and sensitivities of the bolometers, which values are correct to the accuracy with which the dimensions and coefficients of the bolometers are known.

(c) Bolometers have been built with time constants between 10^{-3} and 2×10^{-5} seconds such that, if used with properly designed amplifiers, the minimum detectable pulse of radiation U, in watts, of duration equal to the time constant of the bolometer τ in seconds, is given by

$$U = (2 \pm 1) \times 10^{-11} \tau^{-1} A^{\frac{1}{2}},$$

where A is the area of the bolometer in square millimeters.

The minimum detectable pulse of radiation for the combination of a bolometer and an amplifier is considered here to be that which causes a signal in the output of the amplifier equal to the noise in the output of the amplifier when the bolometer is connected to it.

CHAPTER IV

BOLOMETER EQUATIONS

Basis for the Equations

To make a fast bolometer it is not only necessary to have the specific heat of the bolometer strip, its black and its support reduced to a minimum, but it is also necessary to have the conductivity of heat from the bolometer large. To make the bolometer sensitive, all of the material involved in the conduction of the heat from the bolometer to places of approximately room temperature must have a total specific heat as small as possible. In the case of the bolometers described above the conductivity of heat away from the bolometer to the brass base, which may be shown to be nearly at room temperature, is through the gas in the gap. The specific heat of the gas in the gap is small compared to that of the bolometer strip.

In vacuum bolometers the heat lost from the bolometer is by radiation and by conduction down the leads. When a bolometer is operated in a gas filled chamber heat is conducted away from the bolometer by the gas. Some of the heat warms up the gas and some of it is conducted to the side walls of the chamber.

In the bolometers described here the conductivity from the bolometer through the gas in the gap to the base is so large that the other losses may be neglected.

Since the bolometer strips are in a plane parallel to the plane of the metal base the conductivity from each element of the bolometer is approximately the same as that from every other element. To a good approximation each element of the bolometer and its associated support and black is the same as every other element. These conditions allow the use of a single value for the conductivity away from the bolometer, a single value for the heat capacity of the bolometer and its support and black, and all of the bolometer may be considered to be at one temperature, while all of the base is considered to be at another temperature.

These conditions have been used in developing the equations for the behavior of the bolometers.

Noise Due to Statistical Fluctuations

The statistical fluctuations in the potential across a bolometer which is connected in series with a resistance and through which a current is flowing is different from that which Johnson noise would predict, and the mathamatical expression for it is rather complicated. This difference is small enough to be neglected in the bolometers built at present at this Laboratory. When two identical bolometers are connected in series and a source of E.M.F. is applied across them, the statistical fluctuations in the potential at the connection between the bolometers is equal to that which Johnson noise would predict. In the following paragraphs the approximate expressions for the behavior of single bolometers assume the noise to be Johnson noise.

[redacted]

This assumption is safe as long as

$$\alpha(T - T_0) \leq 0.25,$$

where α is the specific temperature coefficient of resistance of the bolometer strip $\left(\frac{1}{R}\ \frac{dR}{dT}\right)$, and where $(T - T_0)$ is the difference in temperature between the bolometer strip and the metal base. The exact expressions given below are all for double bolometers (i.e., two identical bolometers in series) in which the noise is exactly Johnson noise.

An evaluation of the ability of a bolometer to detect radiation can only be made when the band pass of the amplifier to be used with the bolometer is taken into consideration. This is true because the magnitude of the amplified Johnson noise is a function of the band pass of the amplifier. In this report a pulse of radiation incident on a bolometer is said to be just detectable of the magnitude of the amplified pulse is equal to the root-mean-square magnitude of the amplified noise.

<u>The Equation for the Time Constant of a Bolometer</u>

The time constant of either a single bolometer or a double bolometer is given approximately, by

$$\tau = \frac{\sigma}{\lambda}$$

where τ is the time constant, in seconds, σ is the total heat capacity of the bolometer strip, its support and its black, in joules per degree centigrade, and λ is the total thermal conductivity from the bolometer to the base, in watts per degree centigrade.

The exact expression for the time constant of a single bolometer in a bridge circuit is given by

$$\tau = \frac{\sigma}{\lambda\left[1 - \alpha\,(T - T_0)\left(\frac{S-R}{S+R}\right)\right]},$$

where α is the specific temperature coefficient of resistance of the bolometer strip, $(T - T_0)$ is the difference in temperature in degrees centigrade between the bolometer strip and the base, R is resistance of the bolometer in ohms, and S is the resistance in series with the bolometer.

The exact expression for the time constant of a double bolometer, i.e., S is now an identical bolometer to R, is given by

$$\tau = \frac{\sigma}{\lambda\left[1 - \alpha\,(T - T_0)\right]}$$

[redacted]

The minimum detectable pulse of radiation of duration Υ for the combination of a properly designed double bolometer and amplifier is given by

$$U = \frac{6.7 \times 10^{-12}}{|\alpha_T \Upsilon|} \sqrt{\frac{\sigma T}{T - T_0}} ,$$

where it is assumed that the radiation falls on only one of the two identical single bolometers making up the double bolometer.

The exact expression for the double bolometer is

$$U = \frac{6.7 \times 10^{-12}}{|\alpha \Upsilon|} \sqrt{\frac{\sigma T}{T - T_0} \left\{ 1 - \alpha (T - T_0) \right\}}$$

For the combination of a bolometer and an amplifier designed to have a time constant of Υ, the minimum detectable pulse of radiation $U_{\Delta t}$ of duration Δt is given roughly by

$$U_{\Delta t} = 0.63\, U \left(1 - e^{-\frac{\Delta t}{\Upsilon}}\right)^{-1}$$

<u>Discussion of the Equations</u>

The total heat capacity of the bolometer is proportional to the area of the bolometer; thus the minimum detectable signal is proportional to the square root of the area of the bolometer.

If the area remains constant, the minimum detectable signal is independent of the ratio of the length of the bolometer to its width.

For the bolometers reported here the minimum detectable signal is inversely proportional to the specific temperature coefficient of resistance of the bolometer strip, and it is independent of the resistance of the bolometer strip.

The specific temperature coefficient of resistance of the metals used in the bolometer strips is a function of the temperature of operation.

The minimum detectable signal is inversely proportional to the time constant for which the bolometer-amplifier combination is designed. If the bolometer and the amplifier cannot be designed to match the duration of the pulses to be detected the minimum detectable signal will be larger than it would be if the match could be made.

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Calculation of the Minimum Detectable Signal

The minimum detectable signal for a double bolometer will be calculated below, using the data given above in the calculation of the gap to be used in making a bolometer of time constant 4.5×10^{-5} seconds.

For a single bolometer assume that $S >> R$, then

$$U = \frac{4.7 \times 10^{-12}}{\alpha_T \tau} \sqrt{\frac{\sigma T}{T - T_o}}$$

The values of the coefficients are:

$\alpha_T = 0.001$ (degrees centigrade)$^{-1}$

$\tau = 4.5 \times 10^{-5}$ seconds

$\sigma = 1.1 \times 10^{-7}$ Joules per degree centigrade

$T = 450$ degrees absolute

$(T - T_o) = 150$ degrees absolute.

$U = 6 \times 10^{-8}$ watts

for $\tau = 4.5 \times 10^{-5}$ seconds.

For a double bolometer, where it is assumed that the radiation falls on only one of the two identical strips

$$U = \frac{6.7 \times 10^{-12}}{\alpha_T \tau} \sqrt{\frac{\sigma T}{T - T_o}}$$

or $U = 8.5 \times 10^{-8}$ watts

for $\tau = 4.5 \times 10^{-5}$ seconds

Using the exact expression for U gives the answer; $U = 1.1 \times 10^{-7}$ watts for $\tau = 4.5 \times 10^{-5}$ seconds.

The Figure of Merit

For the method of construction of bolometers discussed in this report the equation

$U \tau A^{-\frac{1}{2}} =$ constant

[redacted]

may be shown to be true theoretically; experimentally it has been found to be true over the range of time constant, $10^{-3} \geq \tau \geq 2 \times 10^{-5}$ seconds. Here again, U is the minimum pulse of radiation, of duration τ, which the combination of the bolometer and a properly designed amplifier can detect, τ is the time constant of the bolometer and A is its area. This relation, combined with the range of τ for which it holds, may be considered to be a figure of merit for the method of construction of bolometers.

Using the equations given in this report and the measured dimensions and coefficients of the bolometers, the calculated figure of merit for the method of bolometer construction described here is

$$U \tau A^{-\frac{1}{2}} = 2.7 \times 10^{-12} \text{ watts, seconds, mm}^{-1}.$$

This value assumes a perfect amplifier.

The experimental value of the figure of merit for these bolometers is

$$U \tau A^{-\frac{1}{2}} = (2 \pm 1) \times 10^{-11} \text{ watts, seconds, mm}^{-1}.$$

The difference between these two values will probably be reduced as the amplifiers used with the bolometers are improved.

[redacted]

CHAPTER V

FUTURE WORK ON PROJECT SPRUCE

The development of bolometers has reached the point where it is now reasonable to start plans of scanning systems, amplifiers, and presentation methods for a laboratory model of a gunsight with which studies of sky backgrounds and targets may be made. This work is now underway.

At present it is planned to use a single bolometer at the focus of an optical system for scanning. It is possible that double bolometers may have to be used in the focal plane of the optical systems to reduce the effect of the sky background.

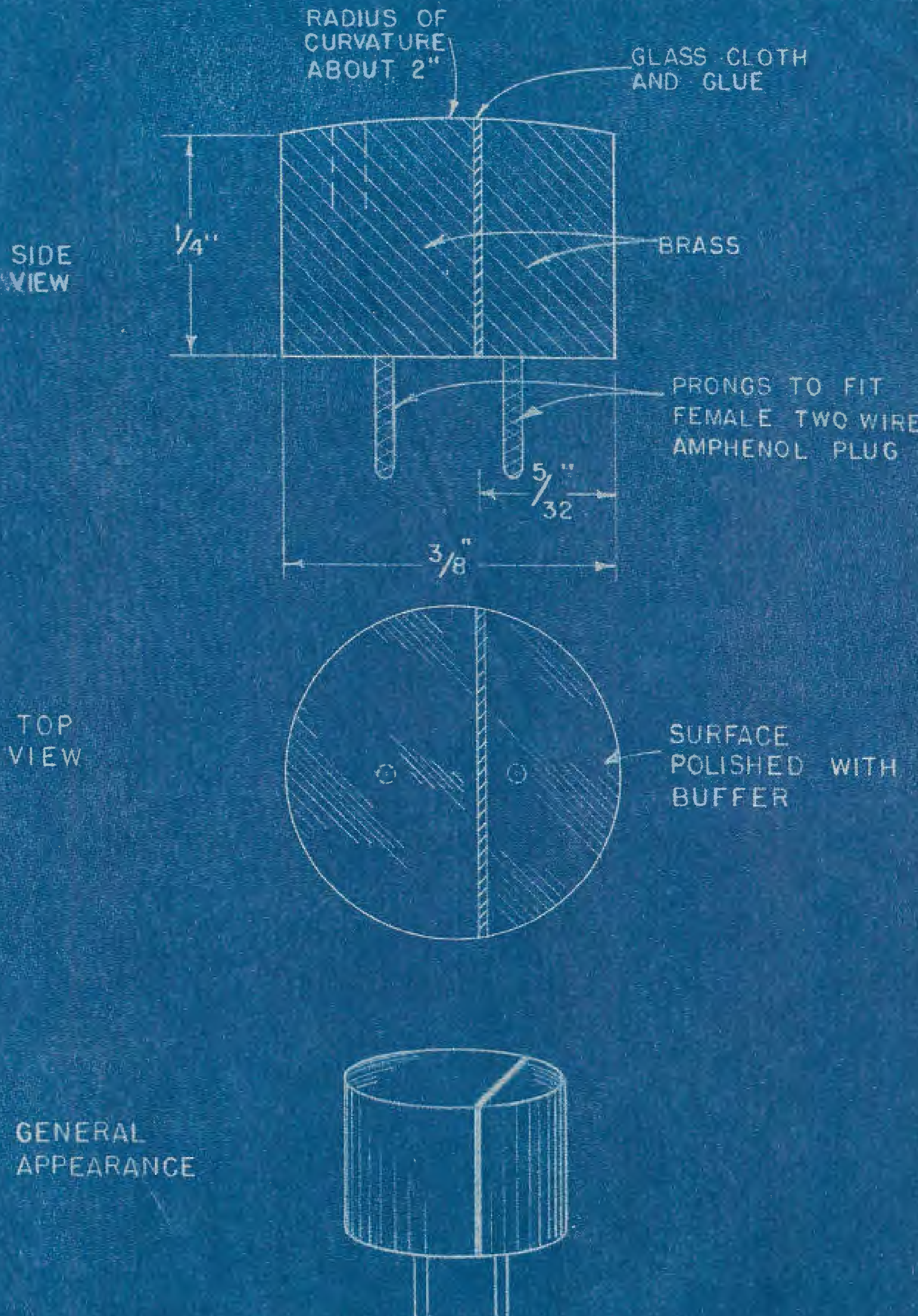
There are a few modifications of the techniques for the construction of bolometers which may improve the figure of merit. There are also several possible ways of using semi-conductors to make fast sensitive bolometers. This work is also being started.

Table I

Characteristics of Evaporated Metals

Metal	Silver	Gold	Copper	Bismuth	Bismuth-Tin
Resistance of Square	3.9 ohms	4	5.9	30	22
Thickness Calculated from Resistance	4.1×10^{-3} microns	6×10^{-3}	2.5×10^{-2}	4×10^{-2}	6×10^{-2}
Thickness Calculated from Weight	2×10^{-2} microns	2.5×10^{-2}	2.2×10^{-2}	4.5×10^{-1}	6×10^{-1}
Specific Temperature Coeficient of Resistance	from 25° C to 100° C in degrees^{-1}	30° C to 100° C	25° C to 100° C	40° C to 150° C	Similar to Bismuth
Measured Value	0.001	0.0009	0.001	- 0.31%	No numerical data taken
Hand book Value	0.0037	0.003	0.0038	+ 0.45%	No numerical data taken
Heat Capacity of one square mm	Joules/degree 4.8×10^{-8}	6.25×10^{-8}	7.5×10^{-8}	4.5×10^{-7}	7.2×10^{-7}

[redacted]



[redacted]

THE BASE

PLATE I

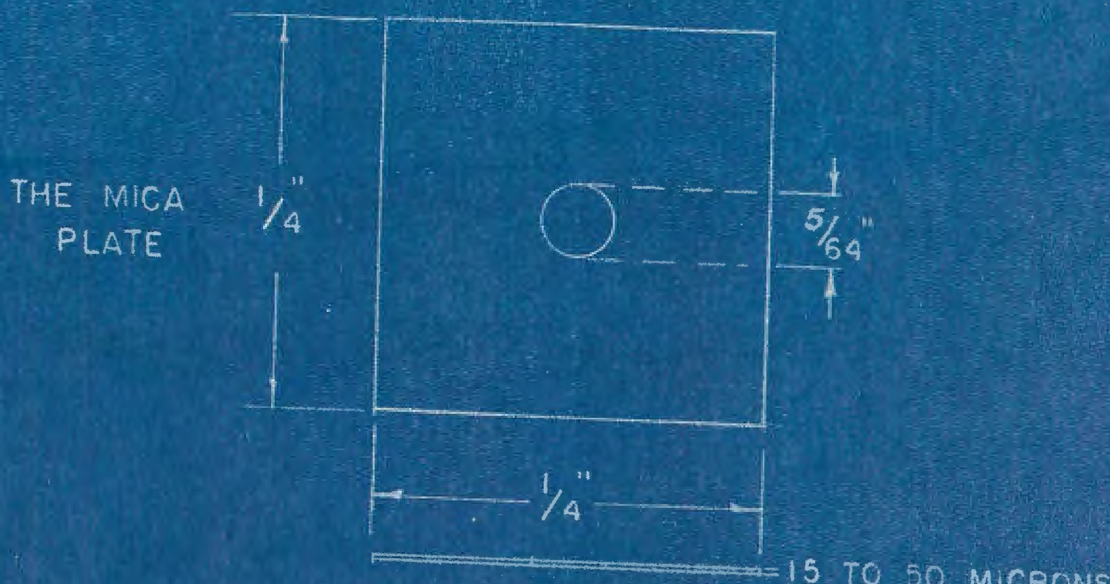


FIG. 1

FIG. 2

THE MICA PLATE

[redacted]

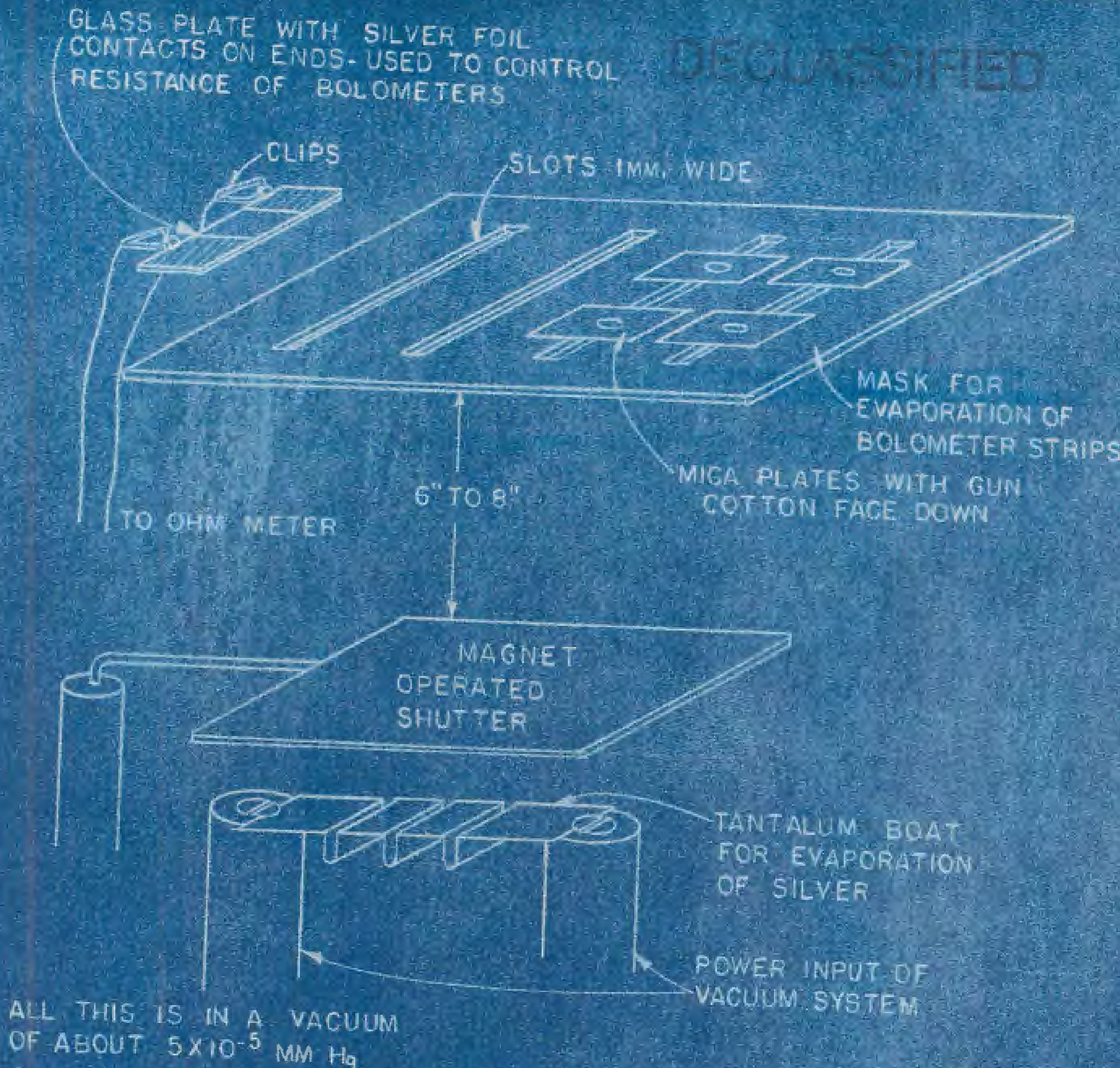


FIG. I
EVAPORATION OF BOLOMETER

FIG. 2

[redacted]

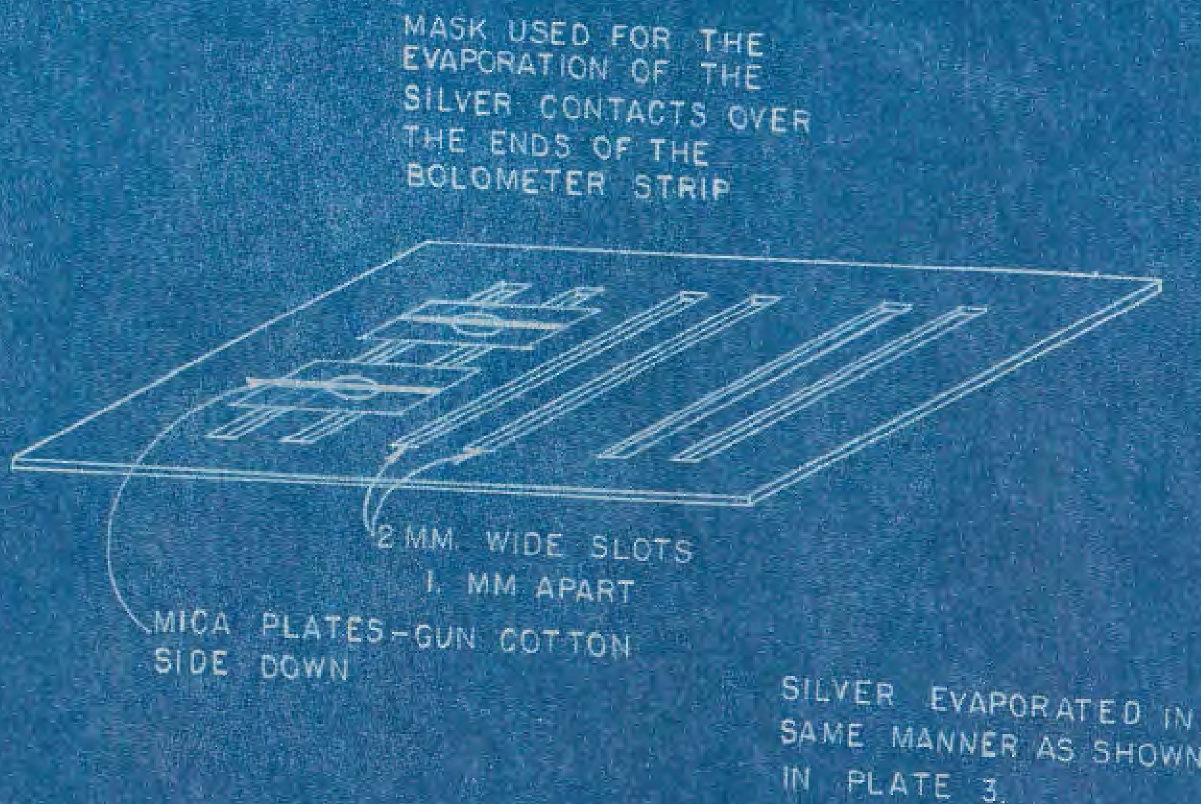


FIG. 1

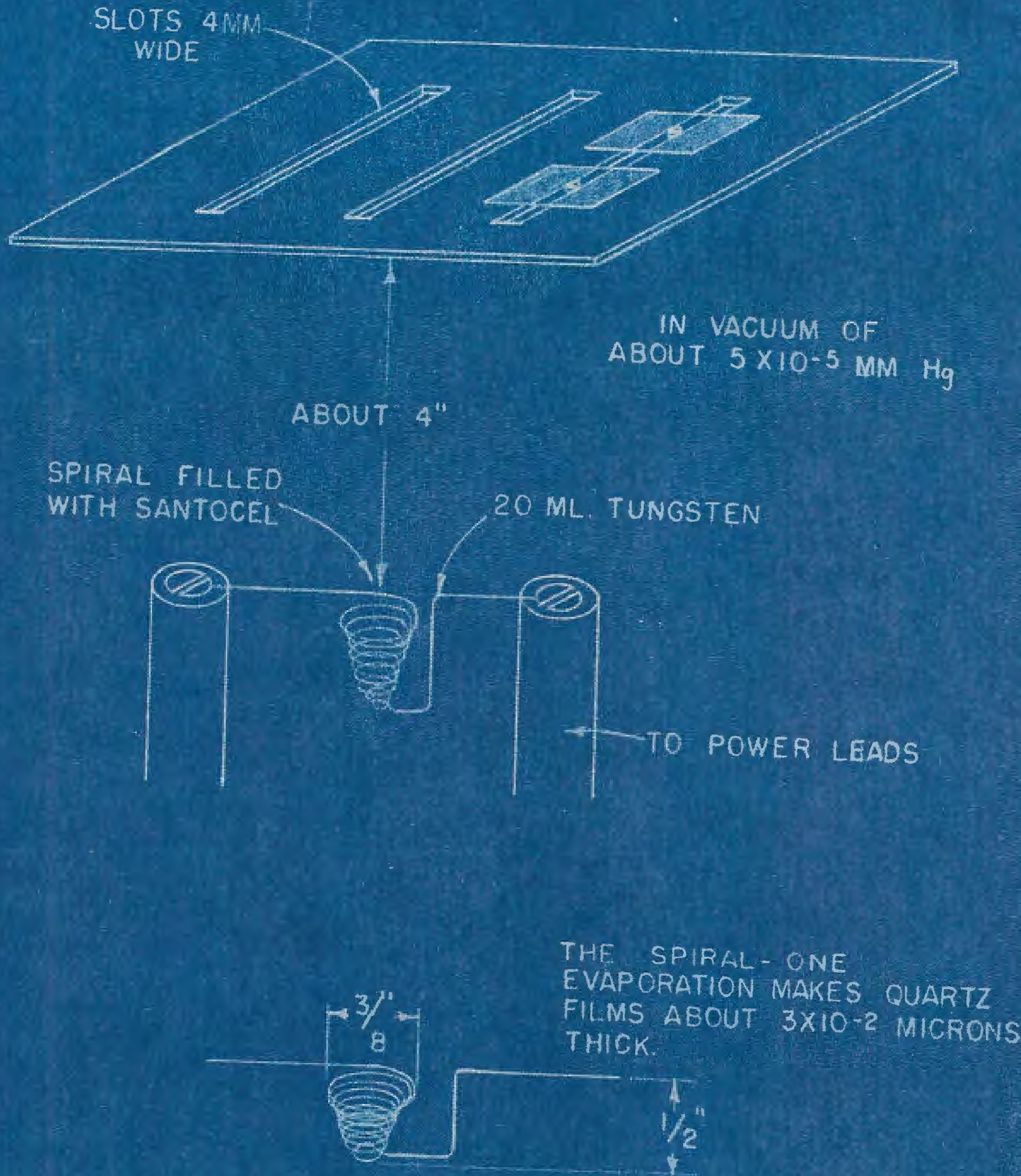
EVAPORATION OF CONTACTS

APPEARANCE OF BOLOMETER AFTER CONTACTS HAVE BEEN EVAPORATED ON IT

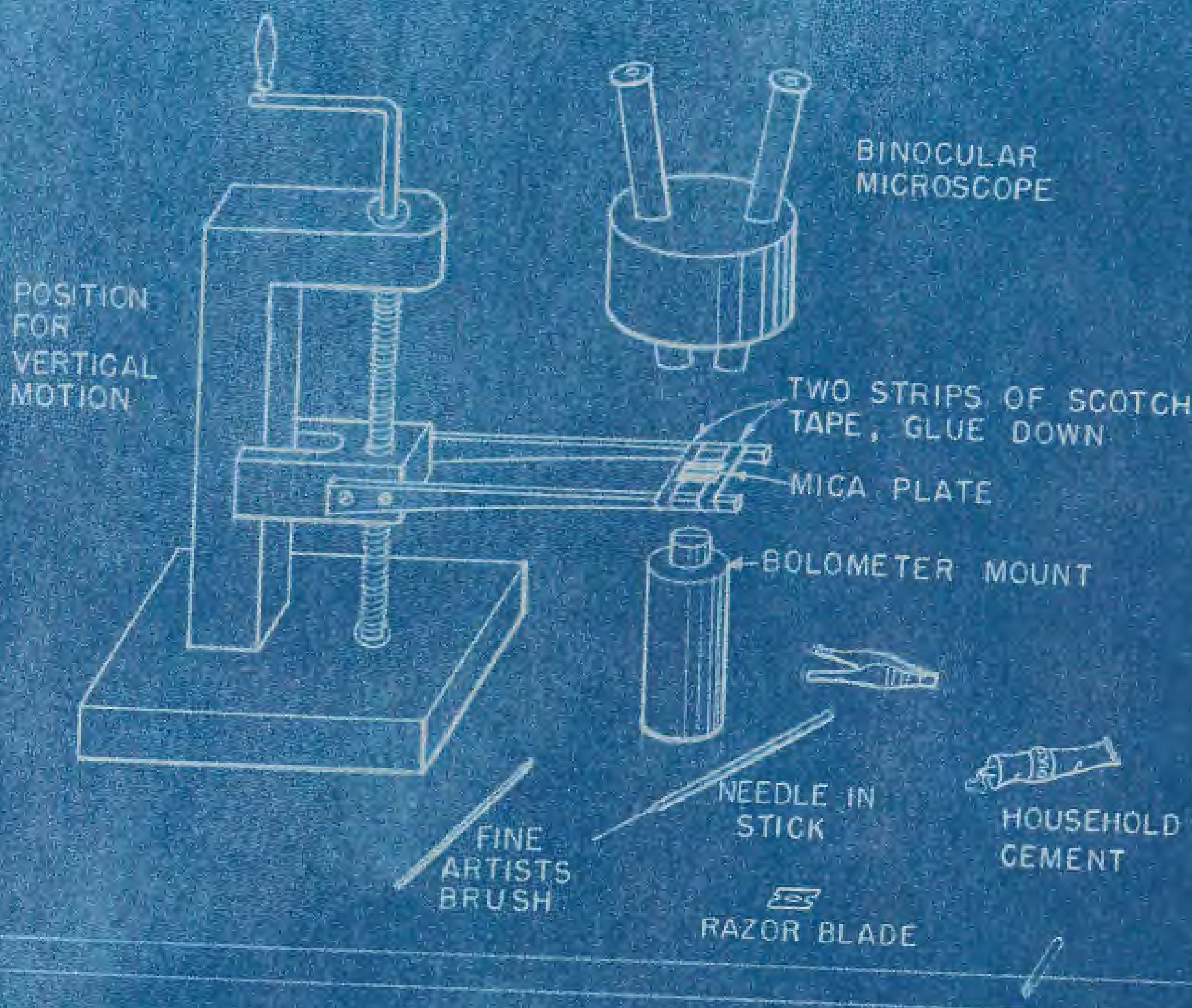
FIG. 2

[redacted]

PLATE IV

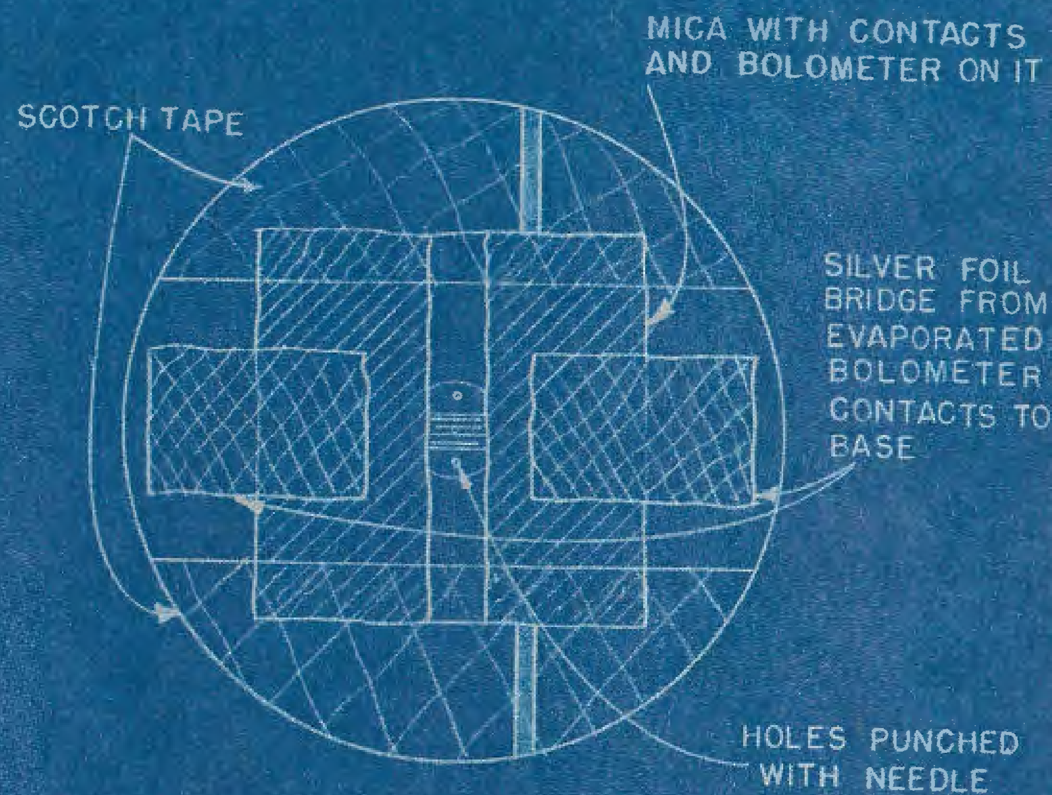


EVAPORATION OF QUARTZ OVER THE BOLOMETER



MOUNTING THE BOLOMETER
ON THE BASE

[redacted]



TOP VIEW OF BOLOMETER
MOUNTED ON BASE

PLATE VII

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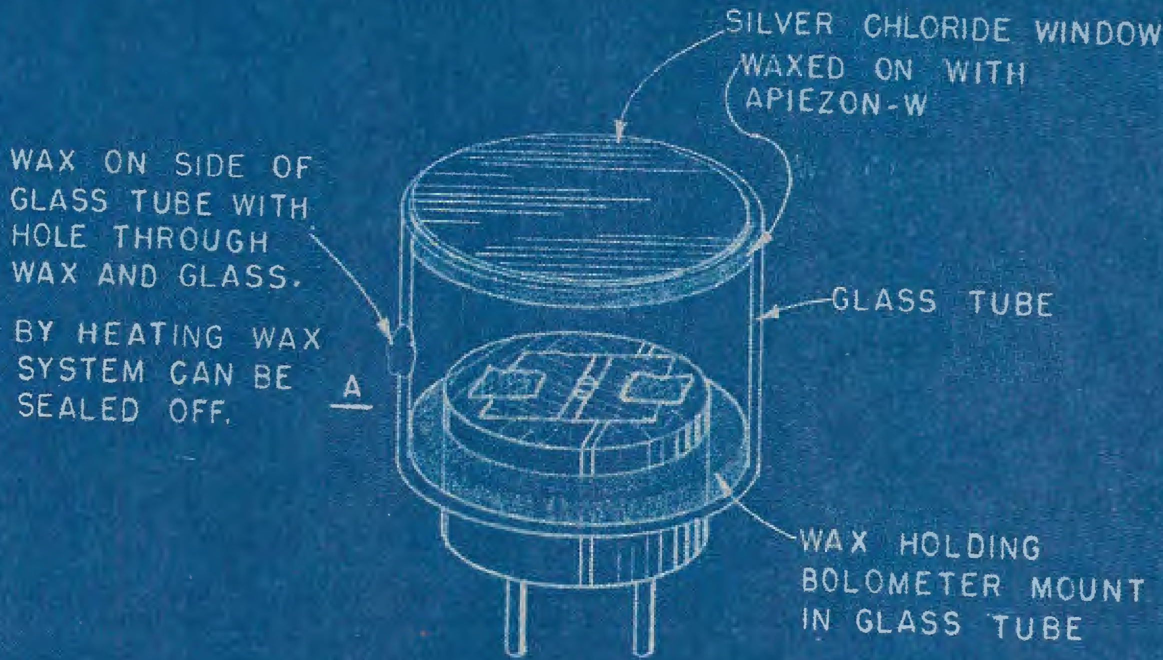

SYSTEM IS PLACED IN A BELL JAR, THE AIR IS PUMPED OUT, HYDROGEN IS FLUSHED IN, AND A FILAMENT WIRE IS HEATED AT POINT A, UNTIL WAX RUNS AND SEALS OFF THE BOLOMETER.

METHOD OF SEALING BOLOMETER IN HYDROGEN

SECRET

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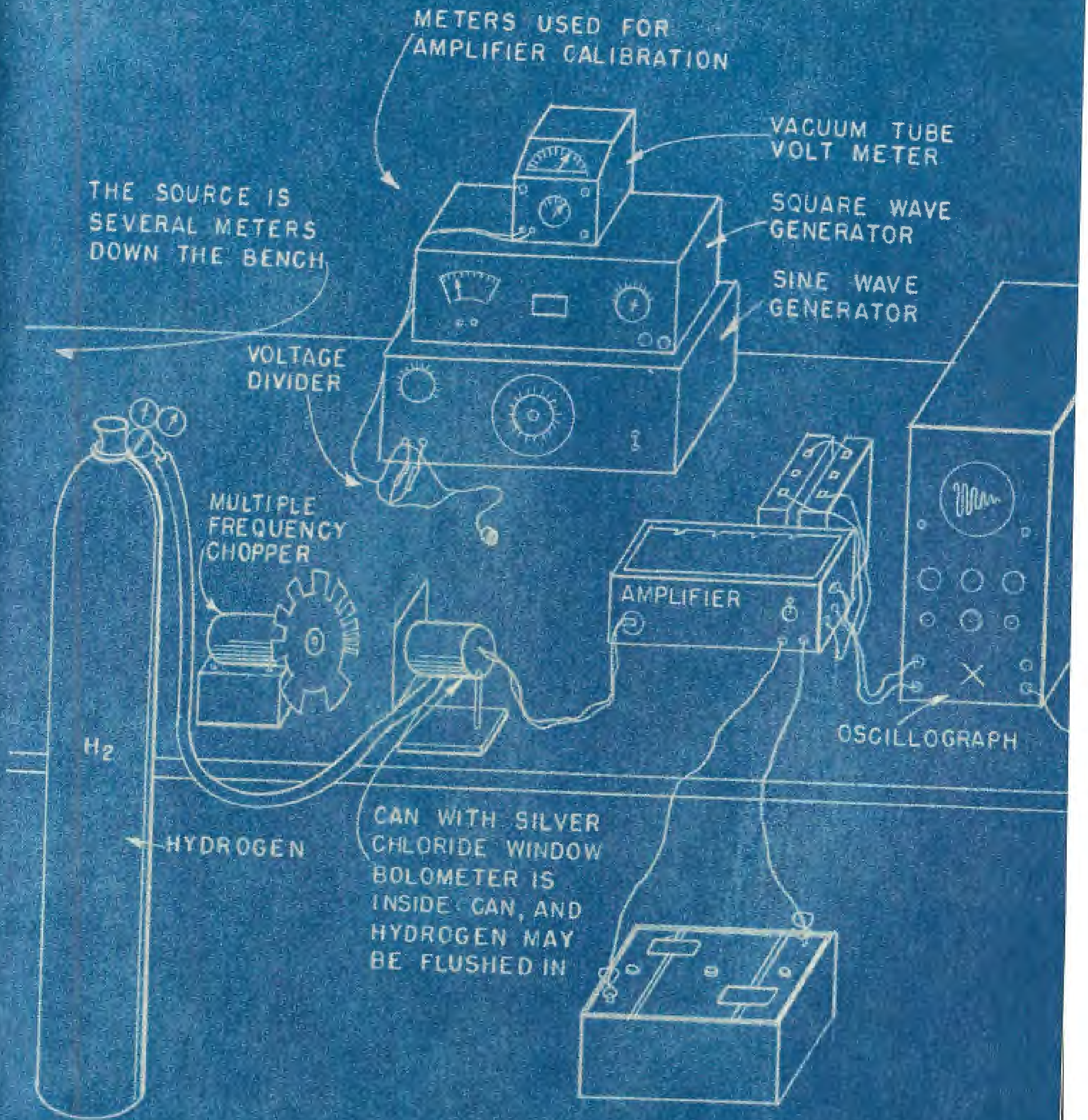
PLATE VIII



APPARATUS FOR FREQUENCY AND SENSITIVITY CALIBRATION OF BOLOMETERS.

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