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MEASUREMENT OF ABSOLUTE PHOTON FLUX USING A SUPERCONDUCTING BOLOMETER

Submitted by

D. L. Judge

Principal Investigator

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Department of Physics
University of Southern California
Los Angeles, California 90007

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CHAPTER I

INTRODUCTION

A bolometer is a device in which the rise of temperature caused by absorption of radiant energy is detected by the change of electrical resistance. Providing the detector surface is perfectly black and absorbs all wavelengths equally, the bolometer will measure absolute radiation intensities and thus give the same response for the same quantity of energy irrespective of wavelength. Such a detector can then be calibrated with radiation from the visible region for subsequent use in any region from the extreme vacuum ultraviolet to the far infrared. This characteristic is in contrast to that of a photomultiplier which has a high sensitivity but is strongly wavelength dependent.

The science of bolometry had been perfected to a point where, by 1939, the factor limiting sensitivity was the magnitude of the thermal indeterminacy of the system.[1] The most sensitive of these room temperature devices was the Golay radiometer which had a noise level equivalent to a 1.4×10^{-3} μwatt signal.[2] Less sensitive flux measuring devices were the thermistor bolometer[3] and the thermopile, both having a signal of about 10^{-2} μwatt equal to the noise of the detecting device.

In order that thermal fluctuations be reduced and the sensitivity of a detector thereby be proportionally increased, Goetz[4] and Andrews[5] independently suggested a reduction in the temperature level of the radiation receiver. In general, it would be difficult to take advantage of low operating temperatures because of the fact that any gain in response

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1 Alexander Goetz, Phys. Rev. 55, 1270 (1939)

2 E. E. Bell, R. F. Buhl, A. H. Nielson, and H. H. Nielson, J. Opt. Soc. Am. 36, 355 (1946)

3 W. H. Brattain and J. A. Becker, J. Opt. Soc. Am. 36, 354 (1946)

4 Goetz, *op. cit.*, p 1271

5 D. H. Andrews, American Philosophical Yearbook, (1938), p 132

due to a reduction in thermal noise is offset by a decrease in the themal emf, the temperature coefficient of conductivity, and the temperature coefficient of resistance of pure metals in the normal state as their temperatures approach absolute zero.

Two notable exceptions to this rule exist in the low temperature behavior of semiconductors and in the super conducting phase of metals at temperatures near absolute zero. The low temperature semiconductor or supercooled bolometer, as described by Low,[6] employs a detector such as germanium and utilizes its low thermal capacity and high thermal conductivity characteristics at 2^{o}K.

A superconducting bolometer not only utilizes the reduction in statistical fluctuations with absolute temperature, and the fact that thermal capacities of metals near absolute zero are decreased from room temperature values by three orders of magnitude, but also benefits from the extremely large temperature coefficient of resistance which superconductors exhibit in the transition between their normal and superconducting phases. Thus, by using a superconducting radiation detecting element, it would appear feasible to operate a receiver at a very low temperature and thereby obtain a sizeable increase in sensitivity and response over detectors operated at ambient temperatures.

Superconducting bolometers have thus been developed to the point where the thermal and electrical noise levels are again of importance. The ratio of the voltage response ΔV, to a given input power ΔP, is defined as the responsivity of the bolometer, and is determined by the physical makeup of the detector. The ultimate sensitivity of a bolometer, which is a function of this responsivity, is determined by calculating the input power that would produce an output equal to that of the noise output of the detector. This calculated input power is called the noise equivalent power (NEP) of the bolometer for a 1 cps band width.

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6 F. J. Low, J. Opt. Soc. Am. 51, 1300 (1961)

There are three primary sources of noise in the bolometer output voltage related to any device at a temperature T. Johnson or electrical noise is due to the random motion of electric charge in the resistive element which is in thermal equilibrium at temperature T, and is present even in the absence of an applied current. Thermal or phonon noise areises from spontaneous variations in temperature of the receiver determined by the statistical interchange being either due to radiation or conduction. In either case, the noise power is a function of the absolute temperature and the conductance between the receiver and the temperature reservoir. Photon noise involves the uncorrelated emission of incoherent radiation and the random variation from the mean in the power emitted from a radiator of area A, emissivity ϵ, and absolute temperature T.[7] There is also a similar noise contribution related to the absorption of the detector of these same power fluctuations from its surrounding environment.

Low[8] gives the NEP of a detector limited by Johnson and thermal noise as

$$\mathrm{NEP} \cong 4 T_o (k G)^{1/2} \tag{1}$$

for a 1 cps band width where T_o is the bath temperature, k is Boltzman's constant, and G the thermal conductance of the system. While the noise limit in principle can be reduced at will by reducing the temperature or the conductance of the sensing element to the temperature reservoir, a practical limit occurs at about 10^{-14} watt based on a temperature of 3.7^oK. A similar expression for photon noise gives a NEP $\cong 10^{-16}$ watt at $T_o = 3.7^oK$.[9] Thus, in practive, the minimum NEP of a cryogenic bolometer is determined by the Johnson and thermal noise.

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7 Vernon L. Newhouse, Applied Superconductivity (New York, John Wiley and Sons, Inc., 1964), p 258

8 Low, op. cit., p 1303

9 Newhouse, op. cit., p 260

The design and instrumentation of the apparatus containing the superconducting receiver must contend with many factors of environmental control at low temperatures. First, temperatures a few degrees above absolute zero must be maintained for several hours in a practical system. Second, isolation of the detector from unwanted power sources due to radiation and conduction is imperative. A series of low temperature radiation shields, optical filters, and highly polished surfaces help eliminate radiation problems whilst high vacuum jackets and long lengths of low-conductive metal walls reduce the conduction problem.

The research apparatus must also maintain a stable reservoir temperature which can be varied as desired according to the characteristics of the particular superconducting element. This temperature control becomes especially important due to the extremely narrow width of the superconducting phase transition (usually of the order of a few millidegrees Kelvin) exhibited by most thin film superconductors. Structural flexibility, ease in assembly and dismantling, and room for implementation of mechanical and electrical components should also be given consideration while designing the apparatus.

The following report delineates the research undertaken in the design and instrumentation of an apparatus capable of efficiently producing and maintaining the environment necessary for the proper function of a thin film superconducting bolometer and in the development of the sensitive detecting element itself.

CHAPTER II

THEORETICAL ASPECTS OF BOLOMETRY

All detectors of radiant energy consist, functionally, of a receiver which absorbs the radiation and is thereby warmed, and a sensitive thermometer which measures the temperature change. In the case of the superconducting bolometer described here, the receiver and thermometer are one and the same. Knowledge of the detector's physical makeup for this system will then establish the requirements for subsequent components.

A typical bolometer element consists of a thin evaporated film of a metallic element exhibiting the superconducting phenomenon at a few degrees above absolute zero. The variance of its resistance with temperature between the normal and superconducting phases is not a step function but rather is determined by a mixture of the two phases which is generally, for thin metallic films, of the order of a few millidegrees wide. In the middle of this phase configuration, the change in resistance with temperature is usually constant within a certain temperature range. It is in this region of maximum change in resistance with temperature $(dR/dT)_{max}$, that the detector will operate. From here on, the term dR/dT will be used to signify the maximum dR/dT of the transition.

The detecting element, for analytical purposes, will be considered to be in a closed system. Energy absorbed by the detector will raise the internal energy of the system and visa versa. The element is considered to have a thermal heat capacity, C, which for an isolated body is its mass times its specific heat at a given temperature. If a small quantity of energy ΔQ is absorbed by the detector, then the detector will come to a temperature ΔT above its surroundings as given by the expression

$$\Delta Q = C\Delta T. \qquad (2)$$

The surrounding environment is assumed to have an infinite thermal capacity and to be at a uniform temperature T. If ΔT is small, then the rate of flow of heat from the detector which is thermally connected to its surrounding will be proportional to ΔT, and can be written

$$\Delta P = G\Delta T, \tag{3}$$

where ΔP is the power flowing from the element, and G is the thermal conductance of the body to its surroundings, by means of both conduction and radiation.

In the simplest case, consider a body which is not connected to any external source of power, but which is allowed to come to a temperature ΔT above that of its surroundings. From Eq. (2), the rate of flow of energy from the body will be given by

$$C\frac{d(\Delta T)}{dt} + G\Delta T = 0, \tag{4}$$

whose solution is

$$\Delta T = \Delta T_o e^{-t/\tau} \tag{5}$$

where $\tau = C/G$. This shows that the temperature difference $\Delta T = \Delta T_o$ at $t = 0$ and decays exponentially to zero with a time constant equal to τ.

For a given detector thermal capacity, the effect of the conductance of the detector can be seen. When the conductance is very large, τ will be very small, and the temperature change ΔT will decay from $\Delta T = \Delta T_o$ at $t = 0$ to $\Delta T \cong 0$ in an extremely short time. Conversely, as the conductance approaches zero, τ will become large, and the resultant temperature change ΔT will decay to zero in a much longer time. There exists, then, an exchange between detector sensitivity and response time, and one must usually be sacrificed for the improvement of the other.

In order that the resistance of the detector be measured, a current must be passed through it, and the resultant voltage recorded. In the absence of incident radiation, the bolometer element will come to thermal equilibrium at a temperature above that of its surroundings. This temperature is determined by joule heating generated by the current and the heat flow to its surroundings as given by the expression

$$G\,(T' - T) = i_o^2\,R, \tag{6}$$

where T' is the equilibrium temperature of the bolometer element, and T the temperature of its surroundings.

Having established the equilibrium temperature T' of the bolometer element with respect to its environment in the absence of radiation, an expression for the time dependent variation in temperature as a function of incident radiation is obtained. A conservation of energy expression is obtained in terms of power flow in and out of the closed system

$$C \frac{d\Delta T}{dt} + G\Delta T = i_o^2 \frac{dR}{dT}\bigg|_T \Delta T + \Delta P \tag{7}$$

where ΔP is the radiation power absorbed by the detector and ΔT is now the resulting change in temperature above the equilibrium temperature T' defined by Eq. (6). The first term on the right represents the joule power dissipation in terms of the temperature dependent phase transition resistance.

In solving Eq. (7), the incident power is assumed to be a periodic function of time given by $\Delta P = \Delta P_o(1 - \cos \omega t)$, where $\omega = 2\pi f$ and f is the frequency at which the radiation is modulated. The solution consists of three terms, one being a transient which rapidly decays to zero with time. The second term is a constant which establishes the temperature about which the fluctuating temperature ΔT of the detector oscillates. The final term is periodic and describes the manner in which the temperature of the bolometer element oscillates as a function of time and radiation frequency. This peak amplitude of the temperature variations in the detector is thus given by[10]

$$\Delta T_{max} = \frac{\varepsilon \Delta P_o}{\left[\omega^2 C^2 + G'^2\right]^{1/2}} \tag{8}$$

where

$$G' = G - i_o^2(dR/dT) \tag{9}$$

10 Newhouse, op. cit., p 254.

and ϵ is the emissivity constant of the detecting surface. The time constant of the system is now given by $\tau = C/G'$. It should be noted that if the power incident upon the detector is not time dependent but constant, then the detector temperature will rise to a maximum temperature given by

$$\Delta T_{max} = \epsilon \Delta P_o / G' \tag{10}$$

and will remain there until the power ceases at which time the temperature will decay back to T' with the time constant $\tau = C/G'$. If G' becomes negative, then the power due to joule heating in the detector becomes greater than the power conducted out. Thus the transient term of the solution will grow with time pushing the temperature of the detector out of the superconducting transition. When G' equals zero, the power due to joule heating exactly equals the power conducted out, and it is in this metastable state that the critical current of the detector is defined. From Eq. (9), then, the current above which the detector experiences this thermal runaway is given by

$$i_c^2 = \frac{G}{(dR/dT)} \; . \tag{11}$$

In operation, the bolometer will exhibit peak voltage fluctuations corresponding to peak temperature fluctuations in the detector given by either Eq. (8) or (10) depending upon whether the incident power is constant or sinusoidal. The voltage change across the detector as a result of incident radiation is given by

$$\Delta V = i_o \; (dR/dT) \Delta T_{max} \; . \tag{12}$$

The responsivity of such a detector, defined as the ratio of this voltage of the amplitude ΔP of the incident radiant power falling on the receiver, is thus given by the expression

$$r = \frac{\Delta V}{\Delta P_o} = \frac{i_o \epsilon (dR/dT)}{\left\{\omega^2 C^2 + \left[G - i_o^2 (dR/dT)\right]^2\right\}^{1/2}} \qquad (13)$$

for a sinusoidal incident radiation power.

Inspection of Eq. (13) shows how the physical constants involved are related to the responsivity of a superconducting detector. As one would imagine, a decrease in conductance G yields an increase in the theoretical responsivity. Conversely, an increase in both current and dR/dT yields a greater voltage response and thus the responsivity as well, as seen by Eq. (12). However, these changes, being seemingly favorable, also serve to decrease G' given by Eq. (9) and thus encourage thermal instability. Inspection will also show that the input radiation should be modulated at as low a frequency as possible and that the heat capacity of the detector, should be as small as possible.

By differentiating Eq. (13) with respect to G, the responsivity can be maximized by solving for the optimum value for G at a given modulating frequency $f = \omega/2\pi$.[11] By setting the differential equal to zero,

$$\omega C = G - i_o^2 (dR/dT) = G', \qquad (14)$$

and by expressing the conductance in terms of the time constant, $\tau = C/G'$, maximum responsivity is found when

$$f = \frac{1}{2\pi} \frac{G'}{C} = \frac{1}{2\pi\tau} . \qquad (15)$$

This is an expression for the chopping rate which will produce a maximum response when the detector has the time constant τ.

If the chopping frequency of a synchronous amplification system is fixed, then Eq. (15) sets the value of the ratio of the conductance of the detector to the heat capacity. Equations (14) and (15) again display

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11 Ibid.

the reciprocal relation existing in a bolometer between the magnitude and speed of detector response. As the conductance is increased, effecting a smaller temperature change, as seen in Eqs. (2) and (8), so is the frequency with which the radiation may be chopped and still satisfy the optimum conditions for response. Conversely, a decrease in conductance, while producing a larger temperature change and thus voltage response, yields a lower response frequency capable of satisfying optimum responsivity conditions.

The minimum detectable power (MDP) of a particular bolometer element is a function of responsivity of that detector and the actual noise voltage recorded while in operation. This MDP is the power signal that would produce an output equal to the noise output and is defined as the ratio between the inherent noise voltage of the system to the responsivity of the detector, which is thus given by the expression

$$\mathrm{MDP} = \frac{\Delta P}{\Delta V / V_{noise}} = \frac{V_{noise}}{r} . \qquad (18)$$

To this point, the conductance G between the detector and its surroundings has been considered to be any combination of radiation and thermal conduction. Thermal conduction, ideally, can be decreased almost to zero. As a consequence of Stefan's law for blackbody radiation, pure radiation conductance to a surface of area A, with an emissivity ϵ, and at a very small temperature above the surrounding temperature T, is given by

$$G_r = 4\sigma\epsilon A\, T^3 \qquad (17)$$

where σ is Stefan's constant. As compared to the usual thermal conductance values for the bolometers described here, radiation conductance is of the order of four orders of magnitude less and is therefore considered to be negligible. On the other hand, it should be noted that an ideal detector, thermally linked to its surroundings only through radiative exchange, will have a noise equivalent power as low as 10^{-16} watt.[12]

The type of superconducting bolometer discussed here is capable of obtaining its optimal sensitivity only under the several assumptions made. The value of dR/dT, defined earlier as the maximum rate of change of resistance with temperature in the superconducting transition, must be constant over a finite temperature range. There are considered to be no appreciable temperature gradients in the detector, along the thermal conductance paths, or between the detector and its environment. The sine-wave modulated radiation is considered to fall uniformly on the detector, which must absorb the radiation of all wavelengths equally.

In general, the bolometer system presented here will produce the maximal signal to noise ratio and responsivity when dR/dT is large and constant, the heat capacity of the detector is small, and the optimal relationship between total conductance and current through the detector is obtained for a given modulating rate. While sinusoidal modulation of the radiation signal will produce a temperature change in the detector a factor of $1/\sqrt{2}$ less than were the signal independent of time, the MDP will in general be less because of the fact that with synchronous detection techniques, the resultant out of balance current is received by an amplifier tuned exactly to the modulating frequency, which serves to reduce the relative importance of noise in the detector output.

Nearly all factors concerned in developing the ideal bolometer are at the command of the designer. The development of a total system commensurate with the proceeding considerations follows.

12 D. Martin and D. Bloor, Cryogenics 1, 165 (1961)

CHAPTER III

RESEARCH DEWAR AND DETECTOR DEVELOPMENT

Research Dewar System

The principle experimental problem associated with a superconducting bolometer of the type developed here, concerns the ability to maintain constant temperatures near absolute zero and to isolate the superconducting detector from all unwanted energy transfer. As absolute zero is approached, the heat capacity of all materials rapidly decreases toward zero, thus increasing the sensitivity of the detector to both the signal of interest as well as to extraneous sources.

Within the temperature range of liquid helium are several pure elements which exhibit the superconducting phenomenon. As previously discussed, one characteristic of an ideal detector is that of a low thermal heat capacity, or, the ability to undergo a large temperature change as the result of a correspondingly small amount of energy absorbed. This desirability of an extremely small heat capacity necessitates the evaporation of the superconducting element in the form of a very thin film of the order of a few thousand Angstrom units thick. The element most suited to these requirements and having the lowest thermal heat capacity per unit volume at its transition temperature is tin (Sn), which becomes superconducting at about $T_c(Sn) = 3.7^{\circ}K$. This temperature is easily reached by pumping the vapor of liquid helium to around 475 torr.

Since the change in resistance of the superconducting film is effected by an extremely small change in temperature, it is desirable that the detector be appropriately isolated from all energy transfer which would be of the order of the measured energy. The possible mechanisms by which energy would disturb the detector include convection, thermal conduction, and radiation. Convection of energy is eliminated by designing a research system capable of maintaining a high vacuum, of the order of $p = 10^{-7}$ torr. The vacuum also eliminates any thermal conduction of gases.

Energy transfer by radiation can be described by a consequence of Stefan's Law. The net power transfer between two adjacent surfaces of area A, each having a low emissivity ϵ, and being at two different temperatures T_1 and T_2 is given by the expression[13]

$$P = \sigma\, A(T_1^{\,4} - T_2^{\,4})\frac{\epsilon}{2}\,. \qquad (19)$$

If the power transfer is calculated between two adjacent reflective surfaces with an area of the order of that of a standard research dewar wall (1000 cm^2), the result is that a few watts of power are absorbed by the colder surface when $T_1 = 300^{o}K$ (room temperature) and $T_2 = 4.2^{o}K$. The fact that liquid helium has a low latent heat of vaporization dictates that the liquid helium container should itself be shielded from the surrounding room temperature surfaces. The few watts of power that would be absorbed according to Eq. (18) would cause a boiloff rate of approximately 1/5 liter/min where the latent heat of vaporization of liquid helium at $3.7^{o}K$ is $\ell \cong 3 \times 10^3$ joule/liter. Thus, it is seen that an intermediate low temperature build is highly desirable.

Stefan's Law also gives the power emitted from an area A, of emissivity ϵ, and at the absolute temperature T, by the expression

$$P = \sigma\epsilon A\, T^4. \qquad (19)$$

For a small blackbody detector of area A near absolute zero, adjacent to a surface at temperature T, Eq. (19) gives the power absorbed by the area exactly opposite the detector. A sample calculation from this simple configuration shows that a 1 cm^2 detector will absorb of the order of several milliwatts of power when $T = 300^{o}K$ and $\epsilon \simeq 0.1$. Thus,

13 Guy Kendall White, Experimental Techniques in Low-Temperature Physics. Oxford University Press, 1959, p. 191.

where detection of power levels of 10^{-12} watt or less can only occur with a highly isolated detector, radiation not associated with that to be measured must be shielded from the detector. This shield must be incorporated into the dewar system so that it is at the temperature of the helium bath.

An appropriate intermediate shield between the outer room temperature surface of the dewar and the liquid helium reservoir is a shield at liquid nitrogen temperatures. Liquid nitrogen, existing at $T(N_2) = 77^{\circ}K$, is inexpensive, easy to store, and has a much greater latent heat of vaporization than liquid helium. Also, an extension of this liquid nitrogen container in the form of a shield is necessary to protect the helium temperature radiation shield from the room temperature radiation. Thus, a series of high vacuum chambers along with the liquid nitrogen and liquid helium temperature surfaces can effectively block unwanted radiation power from entering the detector region. In the present system, the radiation whose power is to be measured enters the system through small apertures in the nitrogen and helium shields which are aligned on the optical axis. Optical filters may be added to these apertures to exclude unwanted portions of the electromagnetic spectrum.

The magnitude of thermal energy conducted through a solid is proportional to the temperature gradient ΔT across the solid, the cross sectional area of the material A, the temperature dependent coefficient of conductivity for the material k(T), and inversely proportional to the pathlength ℓ as given by the expression

$$\Delta P = \frac{A}{\ell} k(T) \Delta T \tag{20}$$

where ΔP is the power conducted and where A is uniform over ℓ. By comparing this equation with Eq. (3), we see the conductance of a material at a temperature T is given by the expression

$$G = \frac{A\, k(T)}{\ell} . \tag{21}$$

Isolation of the detector and its radiation shield from the conduction of thermal energy is therefore accomplished by making all possible pathways of a poorly conductive material, thin in cross section and with a long conduction path. All electrical leads should come in contact with both liquid nitrogen and helium temperature surfaces before entering the detection region in order that joule heating and conducted thermal energy be eliminated.

Mark I bolometer system. The first low temperature research apparatus developed in the present work is seen in Fig. 1. Here the liquid helium container sits upon a nylon ring and is suspended within the walls of the liquid nitrogen container. This helium container is made of stainless steel, the least conductive of the common metals at helium temperatures (Appendix I). Nylon, which has an even lower thermal conductivity (Appendex I), is used to isolate the helium container as much as possible from the nitrogen temperature surface. The nitrogen container is in turn suspended by nylon screws from a room temperature flange of the vacuum system.

The superconducting detector is in close contact with a copper bar which extends through the top of the stainless steel container. The bar is made of oxygen free high conductivity (OFHC) copper, one of the best thermal conductors at these temperatures (Appendix I). The helium vapor is pumped through a thin wall nylon vent which is vacuum sealed to the top of the bar. This vacuum seal is obtained by fitting two concentric O-rings made of pure indium wire in a groove at the end of the nylon (Fig. 2). This groove is 40% of the total cross section of the two indium wires and is packed with Apiezon "M" grease before pressure is applied. The nylon is pulled very tightly to the smooth end of the copper bar by a brass nut. The pressure causes the indium to fill the entire groove and to spread evenly over the smooth copper surface. The seal may be broken and retightened as long as the indium is not disturbed. This type of seal has withstood repeated reductions in temperature and consistently held

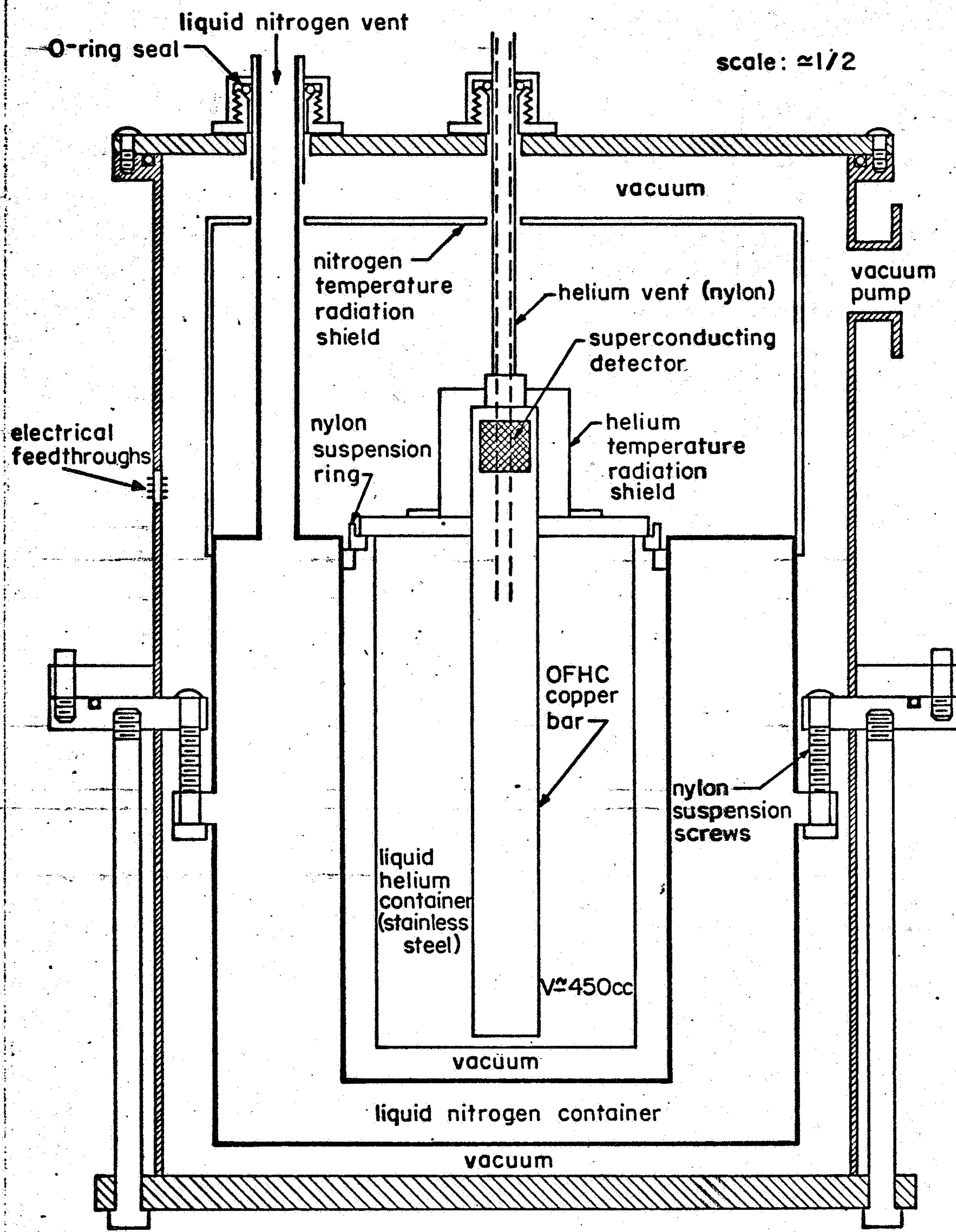


FIGURE 1

SCHEMATIC OF MARK I BOLOMETER SYSTEM

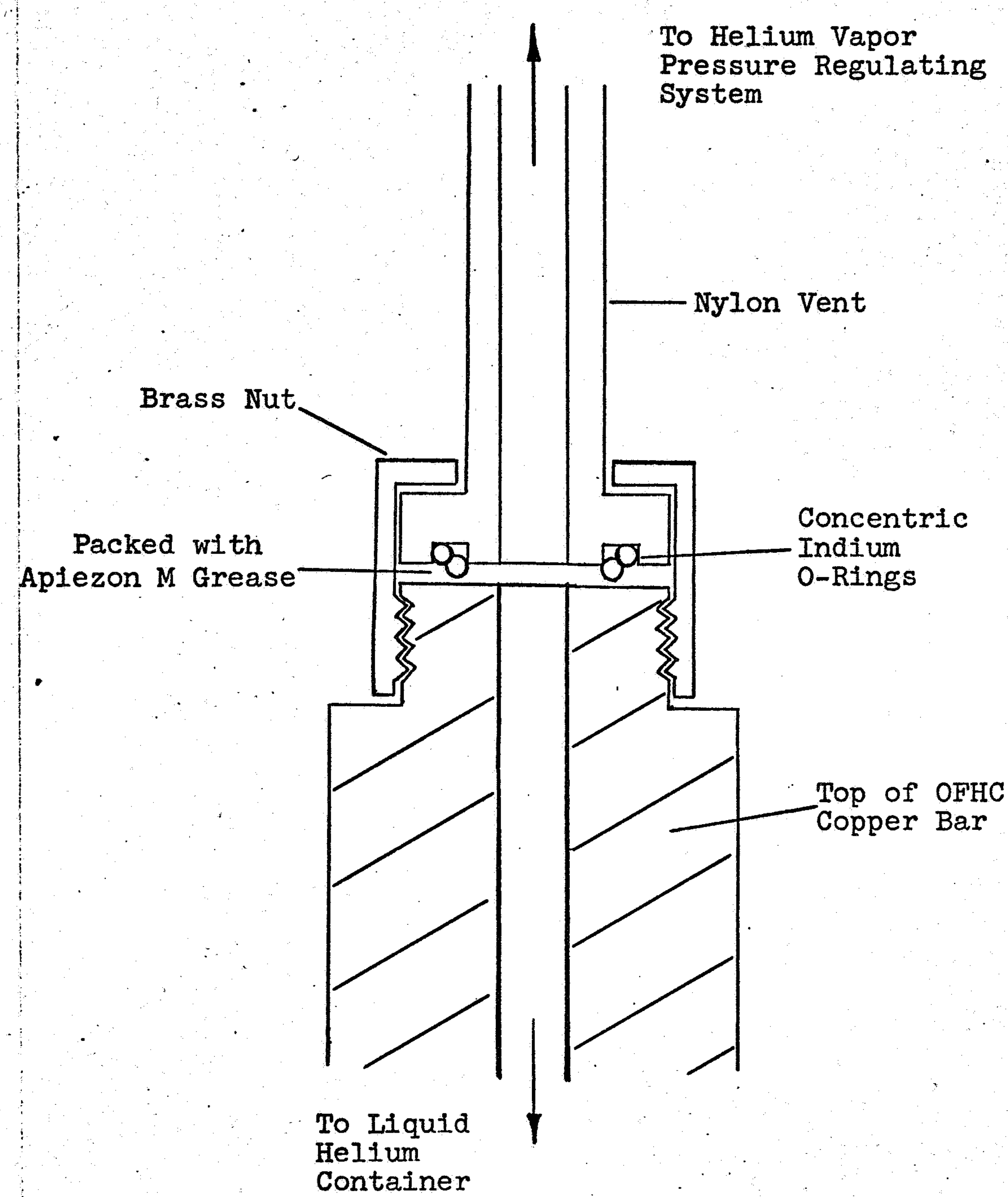


FIGURE 2

NYLON-COPPER LOW TEMPERATURE VACUUM SEAL vacuums greater than 10^{-6} torr. Rubber O-rings are used to obtain vacuum seals at the surfaces of removable flanges and where the nitrogen and helium vents pass through the top of the chamber.

A vacuum is obtained by first roughing out the chamber with a standard fore pump to around 30 microns pressure, and then pumping with a PMC 115 diffusion pump. With the addition of liquid nitrogen and helium, the pressure drops to the 10^{-7} torr range. The liquid helium container holds about 400cc of helium which generally lasts about one hour. This system has provided a valuable test ground enabling the design of a second generation bolometer system. Results of data taken with the Mark I bolometer system are presented in Chapter V.

Mark II bolometer system. The second generation low temperature research dewar is a product of Janis Research Company. It is made primarily of highly polished stainless steel and is basically an inverted model of the Mark I system. The dewar is a completely self-contained vacuum and low temperature system, designed to operate at temperatures down to 1^{o}K and at a vacuum of 10^{-7} torr (Fig. 3).

Liquid helium fills the helium tail as well as the reservoir. At the end of the tail is a permanent OFHC copper heat sink, the bottom of which is very flat. To this flat surface is attached the copper heat sink which holds the superconducting detector. Fastened to the edge of the permanent copper heat sink is the copper, helium temperature, radiation shield. The primary advantage of this design over the Mark I system lies in the inversion of the tail assembly, thus keeping liquid helium in contact with the OFHC sink until all helium is gone. All electrical leads are conveniently wrapped first around the liquid nitrogen wall and then around the liquid helium tail before entering the vicinity of the detector within the helium radiation shield.

The nitrogen tail assembly and radiation shield are made of aluminum which is an extremely good thermal conductor (Appendix I). Attached to each radiation shield is an aluminum optical filter holder

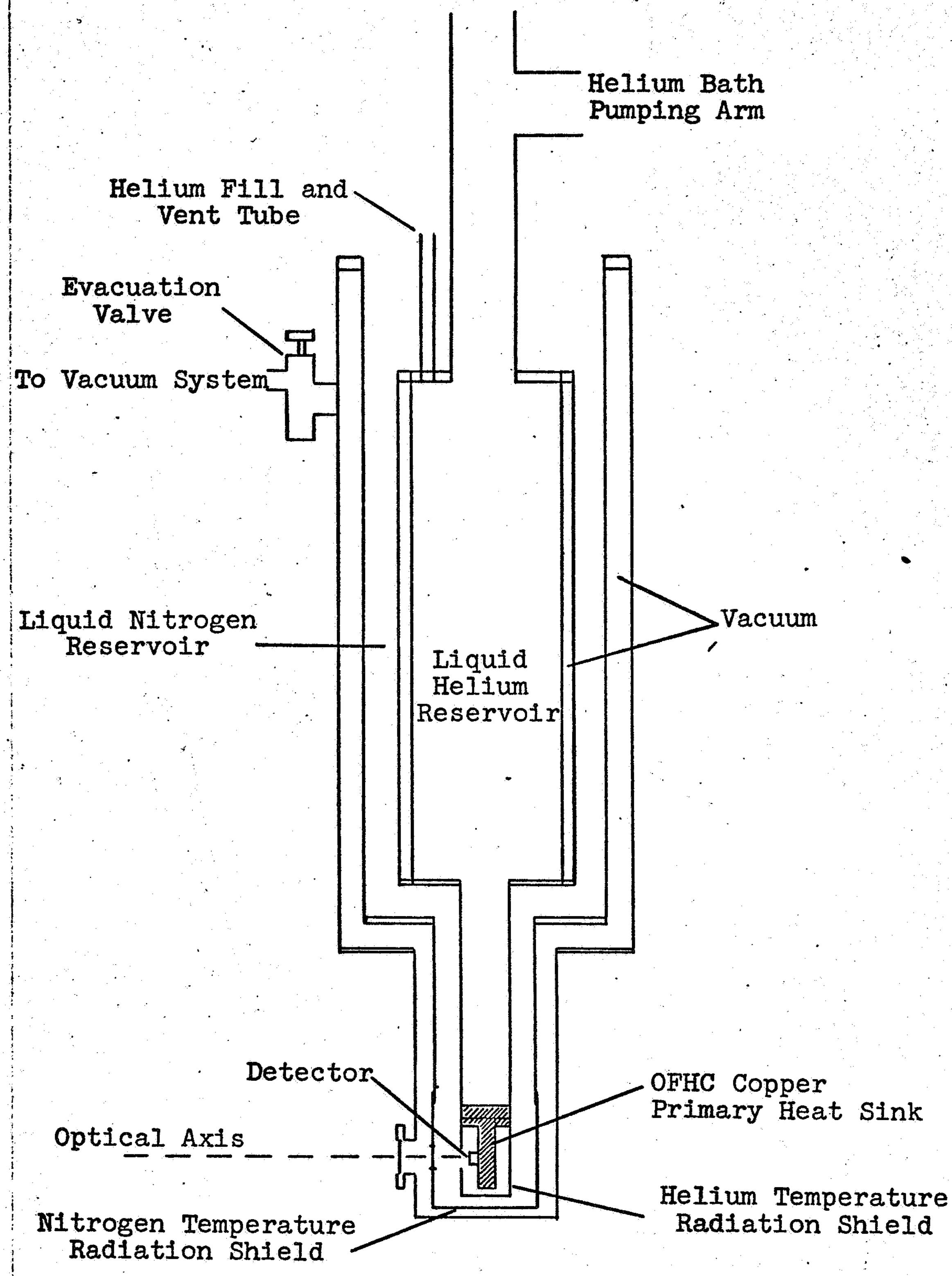


FIGURE 3

SCHEMATIC OF MARK II BOLOMETER SYSTEM

designed to maintain each filter at the temperature of the shield. These filters serve to isolate the spectral region of interest.

Long, thin, polished stainless steel walls afford low thermal conduction between nitrogen and helium surfaces. Once the apparatus is precooled to liquid nitrogen temperatures, the nitrogen reservoir must be filled only every 18 hours. Four liters of helium are sufficient for 12 hours work at $3.7^{\circ}K$ with the evaporation rate being about 1/3 liter/hour. The system is leak tight, so that closing the evacuation valve before adding liquid helium, allows the system to cryopump with the addition of the helium. The seal between the helium tail and reservoir is of crushed indium and is removable and replaceable, thus demonstrating the flexibility of the system. A photograph of the Mark II research dewar is shown in Fig. 4 mounted alongside instrumentation for helium vapor pressure control.

Superconducting Detector

In general, the radiation detecting element consists of a thin metalic film which has been evaporated upon a solid substrate material. There are different types of detectors which have been used in both bolometer systems which differ by the degree to which the detecting element is isolated from the heat sink. The conductance between the film and the heat sink depends both upon the conductive nature of the substrate material and upon how the substrate is attached to the heat sink. The total effective heat capacity of the detector element, is a combination of the heat capacity of the metallic film and that of the substrate, and can be determined experimentally by measuring the thermal time constant τ for a given conductance G. The conductance of a substrate is calculated by use of Eq. (21) where the temperature dependent coefficient of conductivity of glass is known. In practice, however, the experimental conductance is a function of how the substrate is attached to the heat sink as well. This interface conductance then accounts for the difference between the

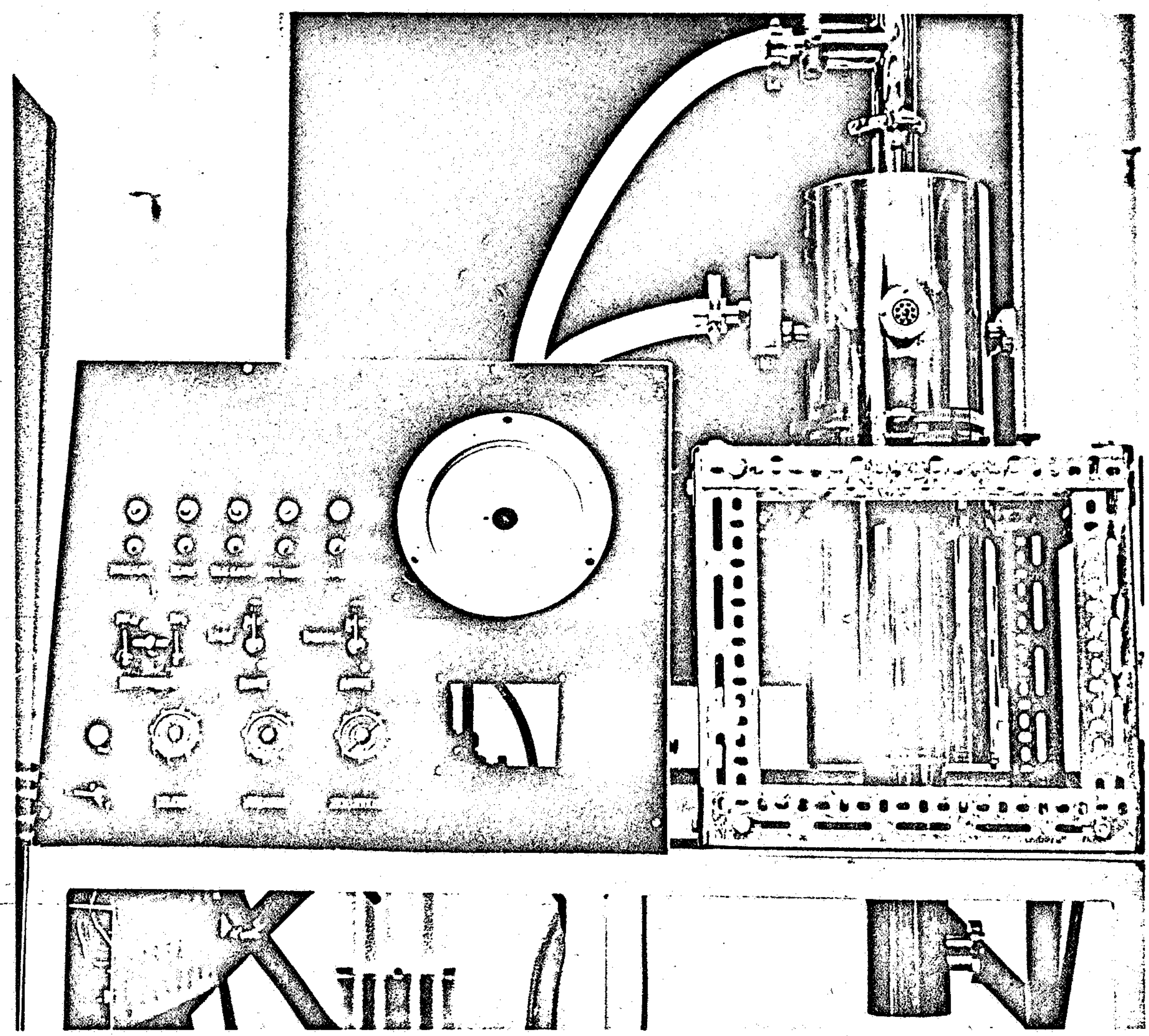


FIGURE 4

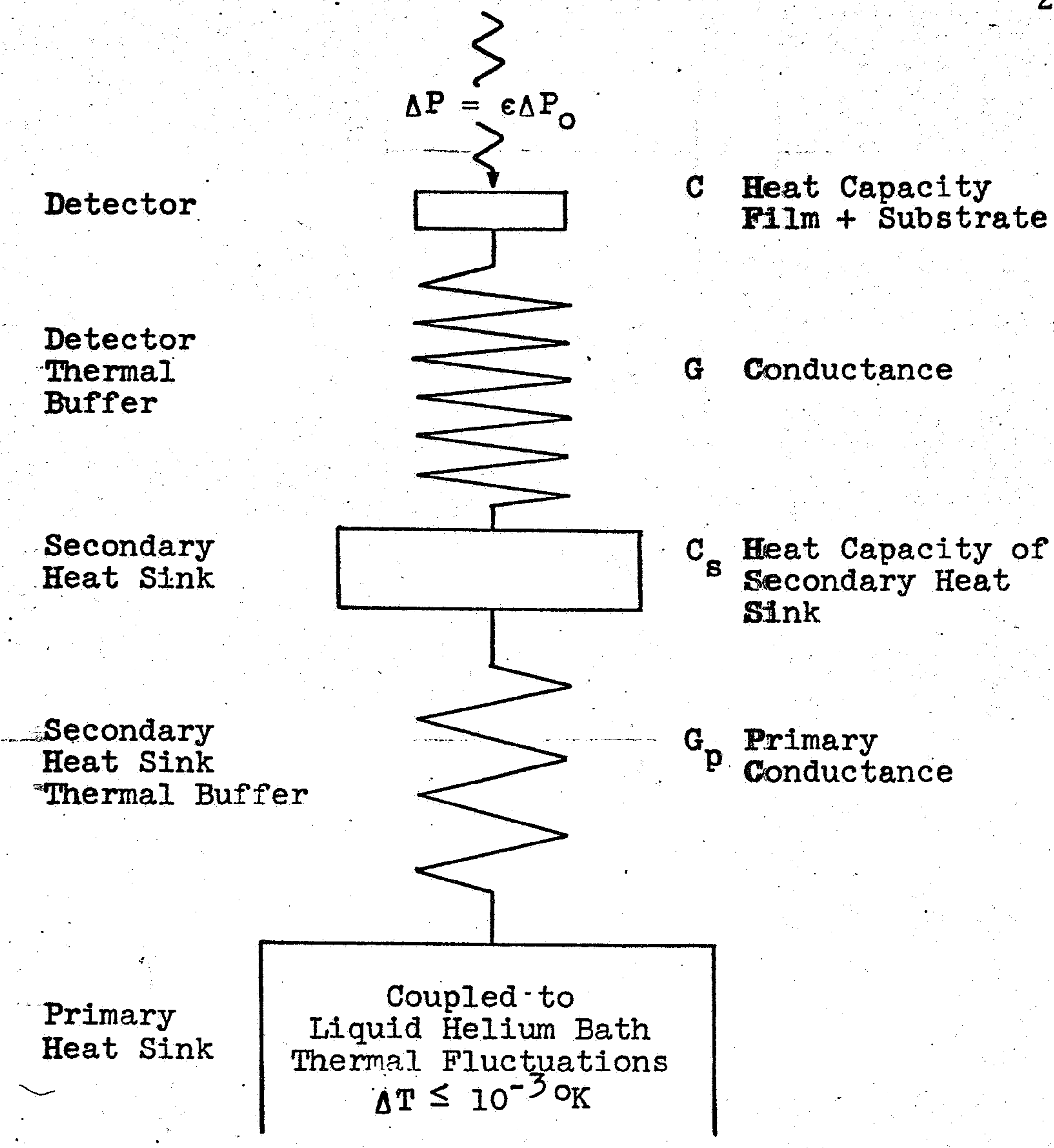
MARK II BOLOMETER SYSTEM

calculated value and the experimental conductance, which is usually smaller than the calculated conductance, and can be determined accurately by varying the number of interface surfaces between the substrate and the heat sink and measuring the resulting change in conductance for a 1 cm^2 interface has been found to be approximately 1×10^{-3} (watt/^oK).

The detectors, whose substrates have been simply pressed directly upon the primary heat sink, are generally square with areas of from 1 cm^2 to 4 cm^2 and with substrates made of glass of a thickness of either 1 mm or 0.2 mm. The films are generally from 500 Å to 3000 Å thick. Electrical contact is made with the thin film by soldering small electrical leads to it with pure indium, which has a low melting point of 157°C. To insure a strong contact, an 85% silver-15% manganese film is first evaporated along the edges of the film where the contact is to be made. The electrical leads are then soldered to this surface being careful not to overheat the solder and destroy the thin film. Also, a unique feature of these detectors is a maze which is mechanically scribed on the substrate after the film has been deposited. The maze lengthens and narrows the electrical pathway, thereby increasing the resistance and the maximum dR/dT of the superconducting transition.

The primary factor determining the maximum allowable conductance between a detector and a heat sink is the fluctuation in temperature of the helium bath. The vapor pressure of helium can usually be controlled accurately to within 1/2 torr or to within 1 m°K at 3.7°K according to published vapor pressure versus vapor temperature tables.[14] With Eq. (3), one can thus determine the amount of power flow to the detector through a conductance G caused by a heat sink fluctuation of $\Delta T_b = 1 \times 10^{-3}$ °K. If 10^{-12} watt is the radiant power level to be detected, then a conductance as low as $G = 10^{-9}$ watt/°K is necessary in order that this temperature fluctuation ΔT_b not produce a thermal power flow

14 White, _op. cit._, p 104



Primary Time Constant $\tau = C/G$

Total Time Constant $\tau_t = C/G_t$ where $G_t = \frac{G_p G}{G_p + G}$

FIGURE 5

IDEALIZED THERMAL DIAGRAM OF A
SECONDARY HEAT SINK DETECTOR

greater than the level being detected. The power flow will decrease, however, as the frequency of the thermal fluctuations becomes high, thus, relaxing the requirements for the conductance G. From the relation $C = \tau G$, it can be seen that the values $G = 1 \times 10^{-9}$ watt/^{o}K and $\tau = 14$ msec [the optimal time constant for an 11 cps modulation given by Eq. (15)] require $C \cong 10^{-11}$ joule/^{o}K, which is physically impractical to accomplish.

The problem of thermal bath noise is solved by adding a secondary heat sink having the necessary thermal inertia to reduce the effect of the fluctuations of the primary heat sink. Figure 5 presents an idealized thermal diagram of a secondary heat sink detector showing the damping effect that the primary conductance G_p and the secondary heat sink of thermal capacity C_s have on detector temperature fluctuations. The primary conductance attenuates the power flow whose value at a given instant is $\Delta P_b = G_p \Delta T_b$. Knowing the conductance of the detector G, Eq. (3) allows one to calculate the maximum temperature change produced by a desired minimum detectable power. This variation then represents the maximal temperature fluctuation which can be tolerated in the secondary heat sink giving a signal to noise ratio equal to unity. Thus by analyzing the frequency of the power fluctuations in the helium bath, the heat capacity of the secondary heat sink, needed to buffer the power fluctuations ΔP_b, can be determined within an order of magnitude.

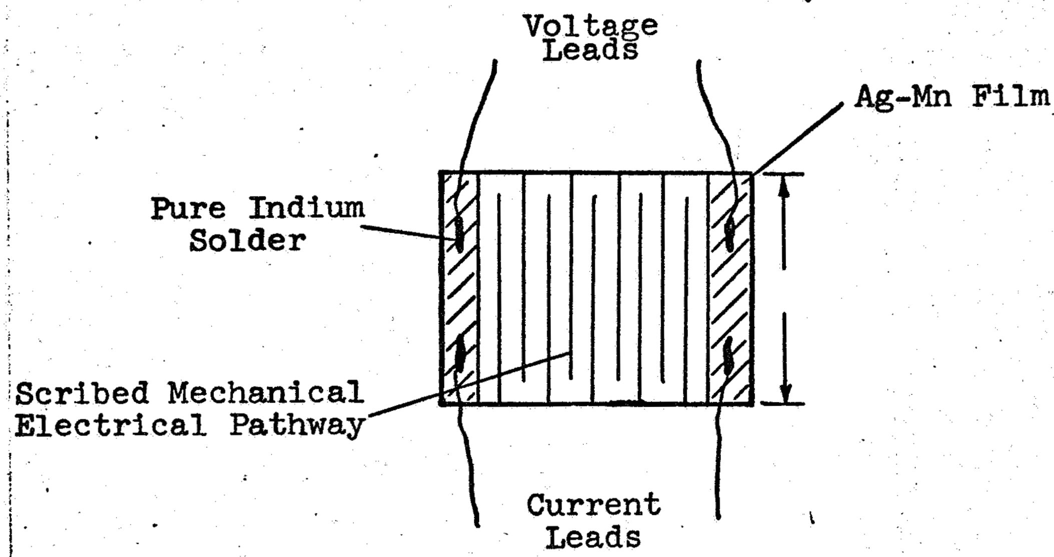
There are two thermal time constants associated with the isolation of the detector. The primary thermal time constant $\tau = C/G$ involves the exchange of thermal energy between the detector and the secondary heat sink only. Referring to the thermal diagram, the total thermal time constant is defined as $\tau_t = C/G_t$ where $G_t = GG_p/(G + G_p)$ is the total conductance between the detector and the primary heat sink. In the case where $G << G_p$, and the total time constant approaches the same value as the primary time constant.

Two types of secondary heat sink detectors have been developed. The more simple of the two is shown in Fig. 6. Here, both secondary heat sinks are separated from the primary heat sink, each by three nylon pegs. The pegs have a diameter of d = 0.067 in. and are pressed tightly onto both heat sinks with the separation being ℓ = 0.040 in. or about 1 mm. The total conductance of all six pegs is calculated to be $G_p = 5.2 \times 10^{-4}$ watt/^{o}K. The two electrically isolated secondary heat sinks are made of OFHC copper and have a mass of 10 g each.

A glass substrate 1 mm thick, on which a thin tin film has been evaporated, brings the gap between the two secondary heat sinks. As described above, the film has been mechanically scribed, and electrical leads have been soldered to each side of the film (Fig. 6A). A moderate film of vacuum grease is put between the sink and the substrate which is held in place by small strips of masking tape, known to hold well at low temperatures. The surfaces upon which the substrate rests and the bottom of the primary heat sink which attaches to the helium reservoir of the dewar system, are "lapped" to insure good thermal contact.

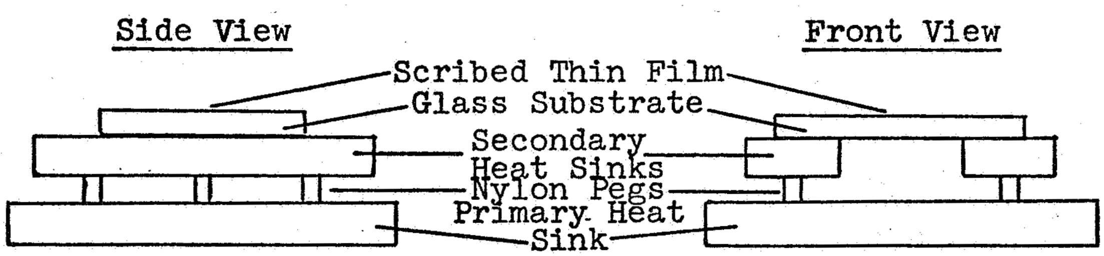
Thermal bath noise present in measurements by detectors without secondary heat sinks is greatly reduced, although not totally, by this simple configuration, thus displaying the effect of the secondary heat sink system. Theoretical and experimental values for the constants and response of this simple detector configuration described above are tabulated in Chapter V.

The results obtained with the superconducting detectors thus far discussed have lead to the development of a nylon net suspended detector which is illustrated in Fig. 7A. The three nylon pegs to each of the secondary heat sinks have a diameter of d = 0.040 in. and a calculated conductance of $G_p = 8 \times 10^{-5}$ watt/^{o}K. The substrate material is cleaved mica of about a .0018 in. thickness, and generally has an area of less than 1 cm^2. This substrate, covered with a scribed tin film, is suspended between the secondary heat sinks by four nylon strands having a diameter of 0.0005 in. or about 12 μ. Electrical contact with the thin



Scribed Thin Film Detector (on Glass Substrate)

(A)



Detector on Secondary Heat Sink

(B)

FIGURE 6

SECONDARY HEAT SINK BRIDGE DETECTOR

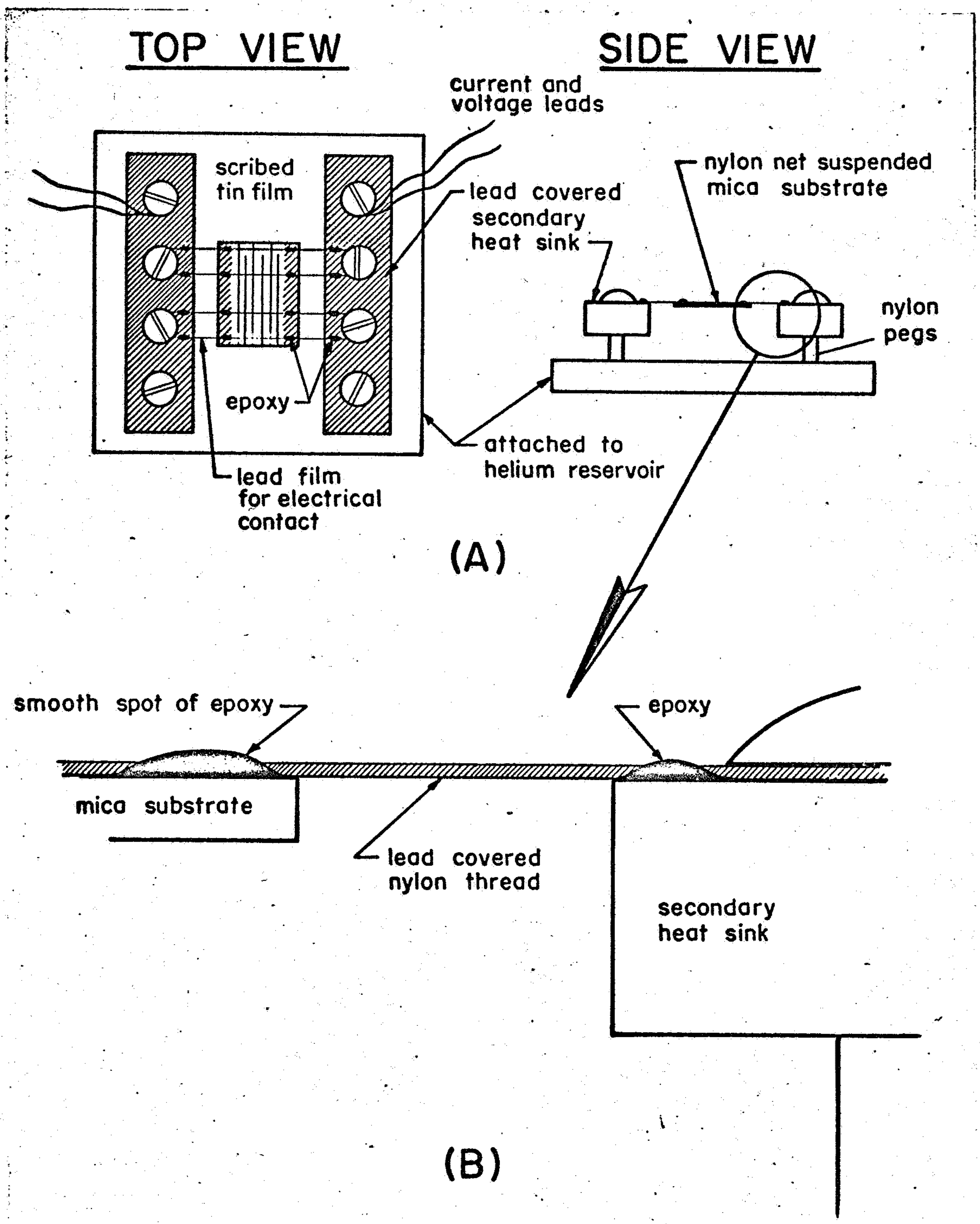


FIGURE 7

NYLON NET SUSPENDED RADIATION DETECTOR

film detector is achieved by evaporating a continuous film of lead (superconducting at operating temperatures) on the edges of the detector the nylon net and the secondary heat sinks to which current and voltage leads are attached. It is the thickness of this lead film across the nylon netting which controls the conductance between the detector and the secondary heat sink. The conductance can therefore be easily varied without altering the dimensions of the rest of the detector.

Electrical continuity is difficult to maintain when the mica substrate is placed on top of the netting, due to the discontinuous contact between the nylon and the edge of the substrate. Epoxy is an adhesive onto which metallic films may be evaporated and maintain electrical continuity across its surface. It is therefore used in affixing the mica substrate to the nylon netting, and the nylon netting to the secondary heat sink thus creating a smooth, solid electrical contact. Figure 7B shows how a small bead of epoxy helps create a continuous surface. When the epoxy is thoroughly dry, the center of the tin film is masked and lead is then deposited to provide electrical contact with the detecting element.

A discussion of the experimental and theoretical values for the constants and response of this net suspended detector are listed in Chapter V. Figure 8 shows the nylon net suspended detector mounted upon its OFHC copper holder which fastens to the reservoir heat sink of a research dewar.

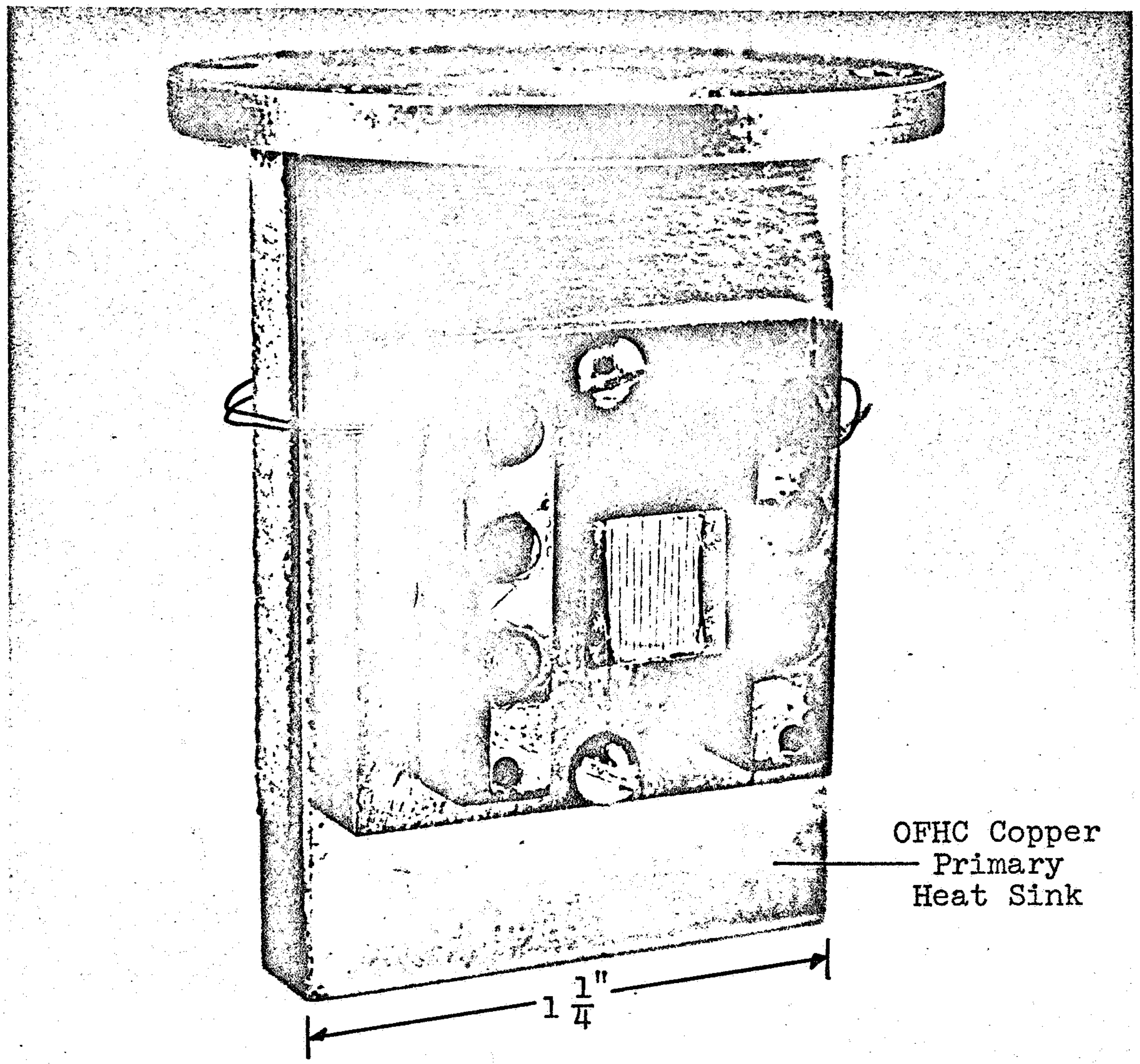


FIGURE 8

NYLON NET SUSPENDED DETECTOR
MOUNTED ON PRIMARY HEAT SINK

CHAPTER IV

SUPPORTING INSTRUMENTATION AND APPARATUS

Electronics

To each detector there are permanently attached two sets of electrical leads. One set provides a constant current through the thin film while the other measures the resultant voltage across the film. The lead film detectors used in the Mark I bolometer system have room temperature resistances of $R \leq 100\ \Omega$ and $dR/dT \approx 10\ \Omega/^{\circ}K$. For instance, detector # 5A has a room temperature resistance of $92\ \Omega$, a transition resistance of $R_t = 6.6\ \Omega$, $dR/dT = 10\ \Omega/^{\circ}K$, and a calculated critical current of $i_c = 22$ ma. For these lead detectors whose critical currents range as high as 50 ma, the current source is simply a constant dc voltage applied across the series combination of a large resistor and the detector, whose total superconducting transition is only a few ohms wide. All data taken with lead detectors are with 27 volts across a 27 kΩ resistor in series with the detector thus supplying a 1 ma current to the detector. The voltage across the detector is recorded by a Varian F-50 X-Y recorder through the second set of electrical leads. Certain of the Mark I data are obtained by chopping the incident radiation at an 11 cps rate, thus modulating the bolometer current. Synchronous detection of this signal is supplied by a Brower Laboratories synchronous amplifier tuned to 11 cps, permitting a voltage sensitivity of the order of 10^{-9} volt.

The tin film detectors used in the Mark II bolometer system have room temperature resistances averaging $R = 600\ \Omega$ and values of dR/dT from $1000\ \Omega/^{\circ}K$ to $6500\ \Omega/^{\circ}K$. For these detectors, the critical current becomes of the order of 1×10^{-5} amp, and a more sensitive current supply is needed. In this case, a Keithly Instruments Model 261 Picoampere Source is used. The voltage is monitored with a Keithly Model 105B Microvolt Ammeter which is sensitive to 10^{-8} volt. The meter amplifies the voltage signal, which is monitored with a Hewlett-Packard Model 7000A X-Y recorder (Fig. 9). All current and voltage cables are shielded. The shielding and negative side of the electrical signal are at ground potential as is the metallic research dewar itself.

Helium Vapor Pressure Regulation

The vapor pressure of the liquid helium bath is monitored, and controlled by the regulating system shown in Fig. 10. A vacuum forepump pumps on the helium vapor through a diaphramed pressure regulator. A bellows type manometer, accurate to 1/2 torr, monitors the pressure of either the reference ballast of the pressure regulator or the helium vapor.

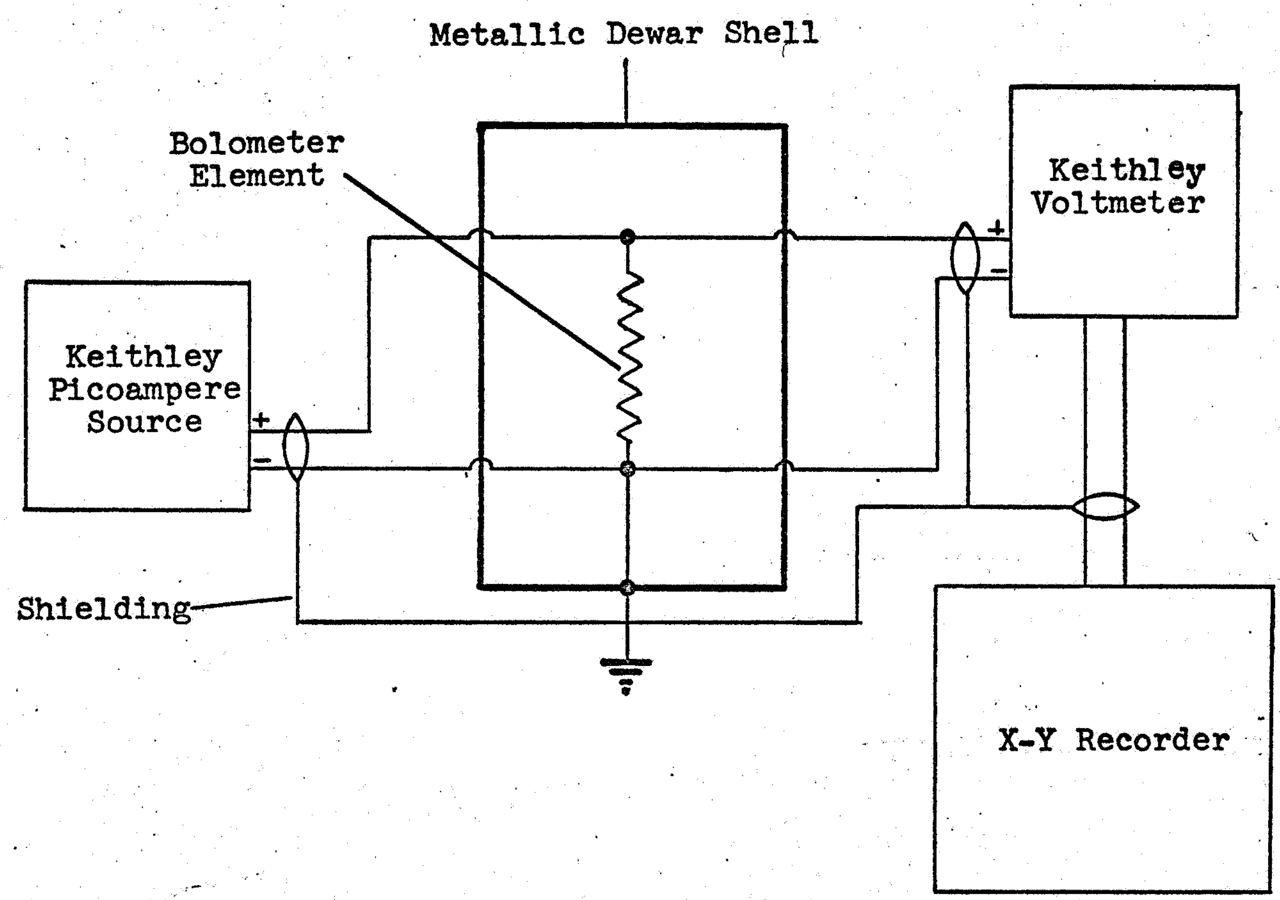


FIGURE 9

MARK II ELECTRONICS SCHEMATIC DIAGRAM

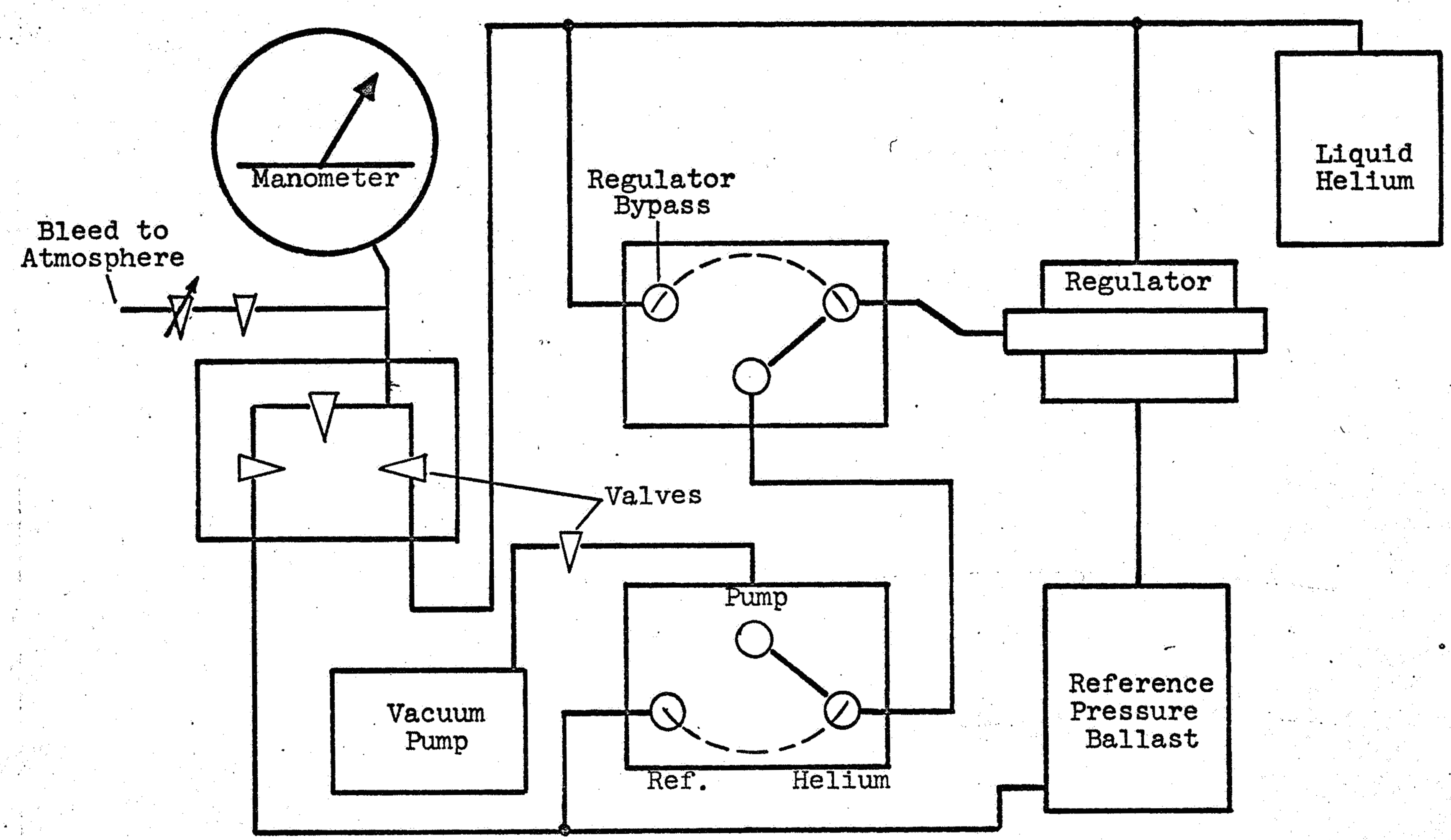


FIGURE 10

LIQUID HELIUM VAPOR PRESSURE REGULATING SYSTEM

Standard Radiation Source and Optical Filters

The radiation source used to calibrate detector response is a single loop filament bulb rated as 16 cp at 120 VAC. A National Bureau of Standards standard lamp is used to calibrate the radiation intensity of this source. Since there are window materials in both of the research dewards through which the radiation passes, the source intensity of the "16 cp" lamp has been determined through these windows.

In the Mark I bolometer system, the window materials are plexiglass and SUPRASIL. SUPRASIL windows are on the nitrogen and helium temperature radiation shields, while the plexiglass window is the outer room temperature optical window. As seen in Fig. 11, SUPRASIL transmits wavelengths well from about 1600 Å up to about 5 μ. This, then, excludes a large portion of all room temperature radiation which has its peak monochromatic energy density at a wavelength of 9.6 μ.

The room temperature optical window in the Mark II bolometer system is made of General Electric 101 quartz glass. Figure 11 shows its transmission characteristics. The inner two inner filters on each of the radiation shields are made of Corning Glass # 1-69 and are approximately 2-1/2 mm thick. Virtually all radiation is out off above 1 μ or 10,000 Å. Table I lists the intensity of the "16 cp" lamp at a distance of 2 meters as a function of filament current

FIGURE 11. TRANSMISSION OF WINDOW MATERIALS

the detector, we measure $G = 1.9 \times 10^{-7}$ watt/^{o}K along with a thermal time constant of $\tau = 25$ sec. In the case of this nylon net suspended detector, $G \ll G_p$ so that the total and primary thermal time constants are the same, $\tau = C/G$, as discussed in Chapter III. The heat capacity of the film and substrate is thus calculated to be $C = 5 \times 10^{-6}$ joule/^{o}K which is two orders of magnitude less than the heat capacity of the bridge detector # 1F. The superconducting transition for detector # 2H is shown in Fig. 11.

The emissivity ϵ of the detector surface can be calculated when the basic parameters and the actual experimental response of the detector are measured as follows: with radiation incident upon the detector, the detector is allowed to come to equilibrium at a slightly higher temperature within the range of constant dR/dT. The responsivity r to a known radiation power is given by Eq. (13), without the $\omega^2 C^2$ term because the radiation is not modulated, and may be solved for ϵ giving

$$\epsilon = \frac{r\left[G - i_o^2 (dR/dT)\right]}{i_o (dR/dT)} . \qquad (22)$$

By measuring r experimentally, and having already determined the basic parameters G and dR/dT, ϵ is determined.

Table V lists the experimental results of the nylon net suspended detector # 2H. Data were taken in this experiment with a current of 4 μ amp where the critical current in the region of maximum

TABLE I

INTENSITY AT 2 METERS AND POWER OF STANDARD LAMP THROUGH QUARTZ AND CORNING # 1-69, PLEXIGLASS AND SUPRASIL WINDOWS AS A FUNCTION OF FILAMENT CURRENT

16 cp Standard Lamp			
Current (ma)	Plexiglass	Plexiglass + SUPRASIL	Quartz + Corning # 1-69
	LAMP POWER RATING (watt)		
485 (115 VAC)	28.2	27.5	--
400	16.7	16.7	0.463
350	--	--	0.209
300	7.85	7.85	0.093
250	--	--	0.046
200	--	--	0.023
	RADIATION INTENSITY AT 2 METERS (watt/cm^2)		
485 (115 VAC)	56.0×10^{-6}	54.7×10^{-6}	--
400	33.1 "	33.1 "	9.20×10^{-7}
350	--	--	4.15 "
300	15.6 "	15.6 "	1.84 "
250	--	--	0.92 "
200	--	--	0.23 "

for the different window materials and the lamp power rating for these windows as a function of filament current.

CHAPTER V

EXPERIMENTAL RESULTS AND DISCUSSION

There are four basic parameters associated with every detector. These are the resistance R of the element, the rate of change of resistance with temperature dR/dT, the thermal time constant of the element τ, and the thermal conductance G linking the element to the heat sink. When taking data with a new detector, the first task is to experimentally determine these parameters, before measurements of response to radiation are made. Knowledge of the magnitude of G and dR/dT allows one to calculate the maximum current which may pass through the detector without causing thermal instability as expressed by Eq. (11). An accurate resistance versus temperature curve will display the exact region within which dR/dT is maximum and constant. Also, τ determines the optimal radiation modulation rate producing a maximum detector response as given by Eq. (15).

The measurement of R and dR/dT as a function of temperature is accomplished by reducing the vapor pressure of the liquid helium through the superconducting transition of the detector and recording the resistance of the detector as a function of temperature. In order that accurate values be taken, the current through the detector for these measurements must be low enough such that an increase in temperature due to joule heating in the detector is entirely negligible.

The magnitude of this measuring current may be determined with knowledge of the approximate conductance of the detector. Thus, for a detector with $G = 10^{-6}$ watt/^{o}K, a current of 10^{-7} amp at a resistance of 100 ohm has a power dissipation of 10^{-2} watt which by Eq. (3) causes a temperature increase of 10^{-6} ^{o}K. This is considered to be quite negligible for a detector whose transition is greater than 1 m^{o}K wide.

The conductance of the detector may be determined by utilizing the joule heating phenomenon as the mechanism for a known power input to the detector. An accurate method of conductance measurement involves maintaining the helium bath at a constant temperature in the superconducting transition where dR/dT has been determined to be constant. The current through the detector is then increased and the change in resistance and temperature is recorded. A known increase in power has thus caused a measured increase in temperature and the conductance of the detector is thereby calculated.

The thermal time constant is determined by pulsing a small amount of energy upon the detector in its transition and recording the time for the resulting response to drop a factor of $1/e$ or about 63% of its total response to that energy pulse.

Table II presents the electrical and thermal characteristics for typical detectors used in the Mark I bolometer system. In this bolometer system, thermal energy is conducted to the immediate

TABLE II

PHYSICAL CONSTANTS OF LEAD FILM DETECTORS*

	Detector # 6B 1 mm Glass Subst.	Detector # 5A 0.2 mm Glass Subst.	Detector # 2D 0.2 mm Glass Subst.
Room Temperature Resistance (Ω)	160	92	71.5
Transition Resistance $R_t(\Omega)$	14.2	6.6	3
dR/dT maximum ($\Omega/^oK$)	22	10	2
τ Experimental (sec)	1	0.1	0.2
G Calculated (watt/^oK)	1×10^{-3}	4.8×10^{-3}	5×10^{-3}
i_c Minimum (amp)	6.8×10^{-3}	2.2×10^{-2}	5.0×10^{-2}

*All substrates are pressed directly on the primary heat sink.

vicinity of the superconducting detector through the nylon helium vent tube and the nylon suspension ring as shown in Fig. 1. Because of this thermal energy, there exists a sizeable temperature gradient along the copper bar creating the necessity for a detecting element made of lead, which has a superconducting transition temperature of about $T_c(Pb) = 7.2\ ^\circ K$. The lead films, being between 1000 Å and 3000 Å thick, have relatively low resistances at cryogenic temperatures and low dR/dT values. Lead film detector # 6B is typical of the lead detectors used in the Mark I bolometer system, and Table III shows the experimental response of this detector to radiation. Data were taken with constant radiation power input and also with a sinusoidally modulated power source (11 cps) employing synchronous detection techniques. Equation (13) shows that the response to modulated radiation power is less than if the incident power is constant. Synchronous detection techniques, however, reduce the detection noise level such that the signal to noise ratio for a modulated radiation source is still larger than that for constant radiation. Therefore, the MDP of the detector, given by Eq. (16) is lower with synchronous detection. Table III shows this to be the case for lead detector # 6B. It should be pointed out that the main purpose of the Mark I bolometer system was to provide a diagnostic tool for the design of the Mark II bolometer system. It is for this reason that extensive research and time were not devoted to lead film detector development. Otherwise,

TABLE III

RESPONSE TO RADIATION OF DETECTOR # 6B (Pb)

	Constant Power	Modulated Power (11 cps)
i (ma)	1	1
Power ΔP ($\times 10^{-5}$ w)	3.12	3.12
Response ΔV (μv)	550	42
V_{noise} (μv)	2	0.1
Sig./Noise $\Delta V/V_n$	280	420
Responsivity (v/watt)	17.6	1.35
MDP (watt)	11×10^{-8}	7.5×10^{-8}

a lower MDP could have been obtained.

In the Mark II bolometer system, nylon net suspended detectors, bridge type detectors, and detectors placed directly upon the primary heat sink have been used for experimentation. Nearly all tin film detectors used in this system have a $dR/dT > 1000\ \Omega/^{o}K$ and small temperature fluctuations are therefore noticeable unless the detector is properly isolated from them. For instance, if a simple detector of tin on a glass substrate is placed directly upon the primary heat sink, thermal fluctuations of the primary sink make control of a given resistance in the transition nearly impossible. A temperature fluctuation of 1 $m^{o}K$ can cause a voltage fluctuation in the detector of the order of $\Delta V_t = 10$ mv.

The bridge detector (Fig. 6) has the secondary heat sinks separated from the primary sink by a primary conductance of $G_p = 5.3 \times 10^{-4}$ watt/^{o}K. The glass substrate is placed directly upon the secondary sinks and has a conductance of $G = 4.9 \times 10^{-4}$ watt/^{o}K. Thus the over-all conductance to the tin film is about $G_t = 2.5 \times 10^{-4}$ watt/^{o}K, which is not sufficient to totally suppress the temperature fluctuations below the calculated minimum level as discussed in Chapter III. Data taken with this bridge detector, however, clearly indicates the effect of the secondary heat sinks. The resistance of the detector is easily controlled at any level but shows a small, low frequency fluctuation in temperature calculated to be about $\Delta T_b = 0.2\ m^{o}K$. Table IV lists the

TABLE IV

PHYSICAL CONSTANTS OF SECONDARY HEAT SINK DETECTORS (Sn)

	Detector # 1F Bridge Detector	Detector # 2H Nylon Net Suspended	Detector # 1H Nylon Net Suspended
Room Temperature Resistance R (Ω)	940	630	472
Transition Resistance R_t (Ω)	156	74.5	43.6
80% of Transition Width (m°K)	17	26	39
dR/dT Maximum (Ω/°K)	6500	4430	952
Thermal Time Constant τ (sec)	Primary 0.2 Total 1.5	25	25
Exp. Conductance G (watt/°K)	3.0×10^{-4}	1.9×10^{-7}	2.2×10^{-7}
Effective Heat Capacity C (joule/°K)	4.5×10^{-4}	5×10^{-6}	6×10^{-6}
Critical Current I_c (amp)	2.15×10^{-4}	6.6×10^{-6}	1.5×10^{-5}

basic physical parameters measured for detector # 1F, which is typical of the bridge detectors. It should be pointed out that in the case where the primary conductance G_p and the conductance of the detector G are the same order of magnitude, the primary thermal time constant τ will be different than the total time constant τ_t, which is defined in Chapter III, Fig. 5.

Table V presents the experimental results of the response of detector # 1F to radiation. The minimum detectable power for this detector is expressed in this table with respect to both thermal and electrical noise.

A nylon net suspended detector (Fig. 7) has eliminated measurable the detector temperature fluctuations due to fluctuations in the temperature of the helium bath. In this detector, the primary conductance between the primary and secondary heat sinks is calculated to be $G_p = 8 \times 10^{-5}$ watt/^oK and the conductance between the secondary sink and the thin film is of the order of $G = 2 \times 10^{-7}$ watt/^oK.

The nylon net suspended detector # 2H is typical of this type of detector. It is shown in Figs. 7 and 8 where the thin film is on a mica substrate about 0.85 cm^2 in area, and is suspended from four lead covered nylon strands each about 12 μ in diameter. As shown in Table IV, the transition has a maximum slope of $dR/dT = 4330\ \Omega/^oK$ where the middle 80% of the transition is 26 m^oK wide. By means of the second method discussed above for determining the conductance of

TABLE V

RESPONSE OF SECONDARY HEAT SINK DETECTORS (Sn) TO RADIATION

	Detector # 1F Bridge Detector	Detector # 2H Nylon Net Suspended	Detector # 1H Nylon Net Suspended
Measuring Current I (amp)	1.1×10^{-4}	4×10^{-6}	1×10^{-6}
Incident Power ΔP ($\times 10^{-9}$ watt)	927	2.48	4.57
Experimental Noise V_n (μv)	thermal 200 electrical 0.75	0.05	0.05
Voltage Response ΔV (μv)	1400	48	2.9
Responsivity r (v/watt)	1500	1.93×10^{4}	635
Emissivity ϵ	~ 0.4	0.15	0.15
MDP (watt)	thermal 1.3×10^{-7} elect. 5.0×10^{-10}	2.6×10^{-12}	7.9×10^{-11}
Black Body (MDP)ϵ (watt)	thermal 5.2×10^{-8} elect. 2.0×10^{-10}	3.9×10^{-13}	1.2×10^{-12}

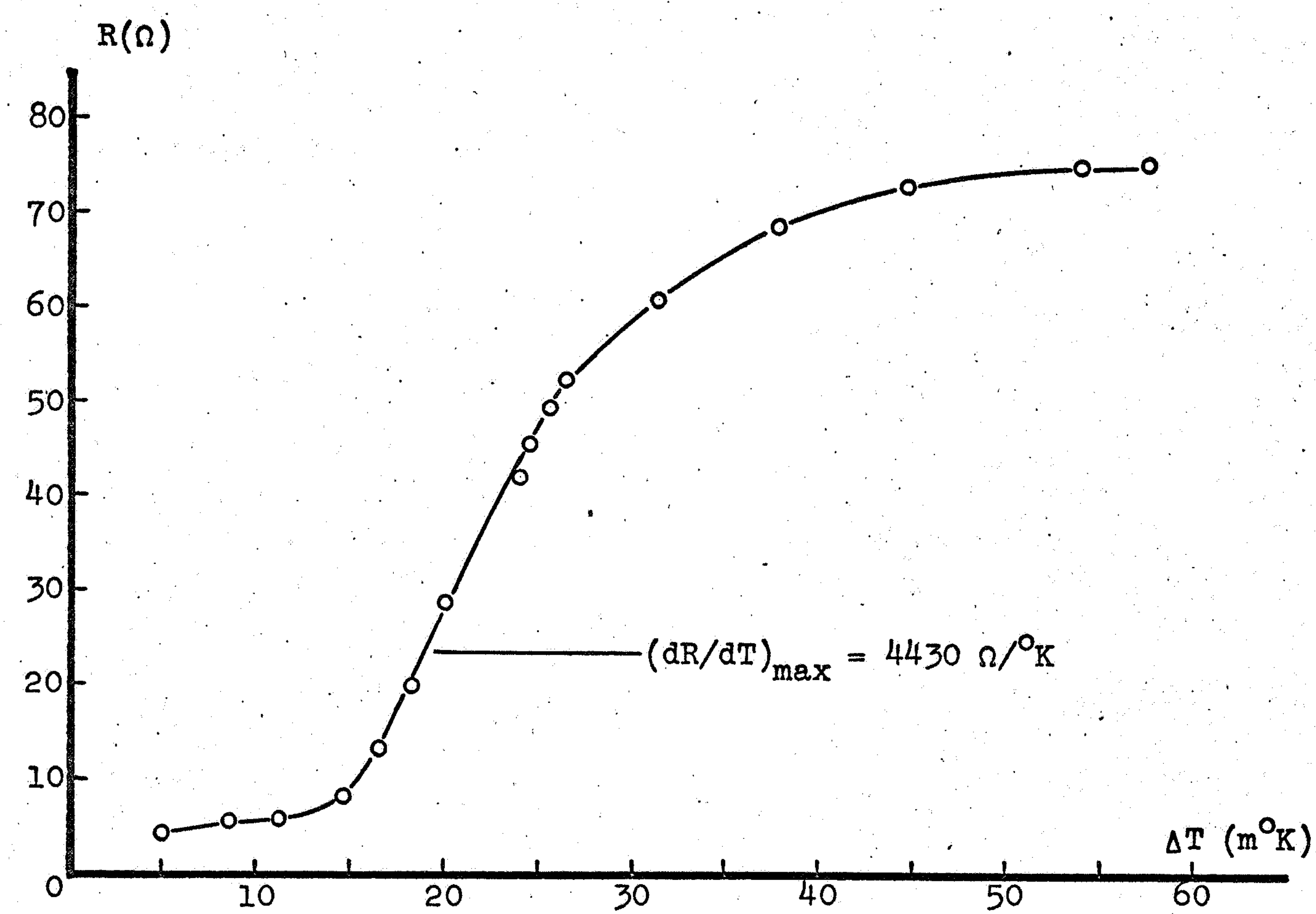


FIGURE 12

SUPERCONDUCTING TRANSITION OF NYLON NET SUSPENDED DETECTOR # 2H (Tin)

dR/dT is 6.6 μ amp. The responsivity to an input power of $\Delta P = 2.48 \times 10^{-9}$ watt was 1.9×10^{4} v/watt giving an emissivity of $\epsilon = 0.15$. The noise level is measured as 0.75 μv and is filtered to 5×10^{-8} v with a thermal time constant short compared to the 25 sec thermal time constant of the detector. The MDP for this detector is thus calculated to be 2.6×10^{-12} watt based on the filtered noise level. If the detector surface had a black body emissivity ($\epsilon = 1$), then theoretically, the MDP would decrease by a factor of this experimental emissivity. Thus, if detector # 2H were a black body receiver, it would have a minimum detectable power of $MDP_B = (MDP)\epsilon = 3.9 \times 10^{-13}$ watt.

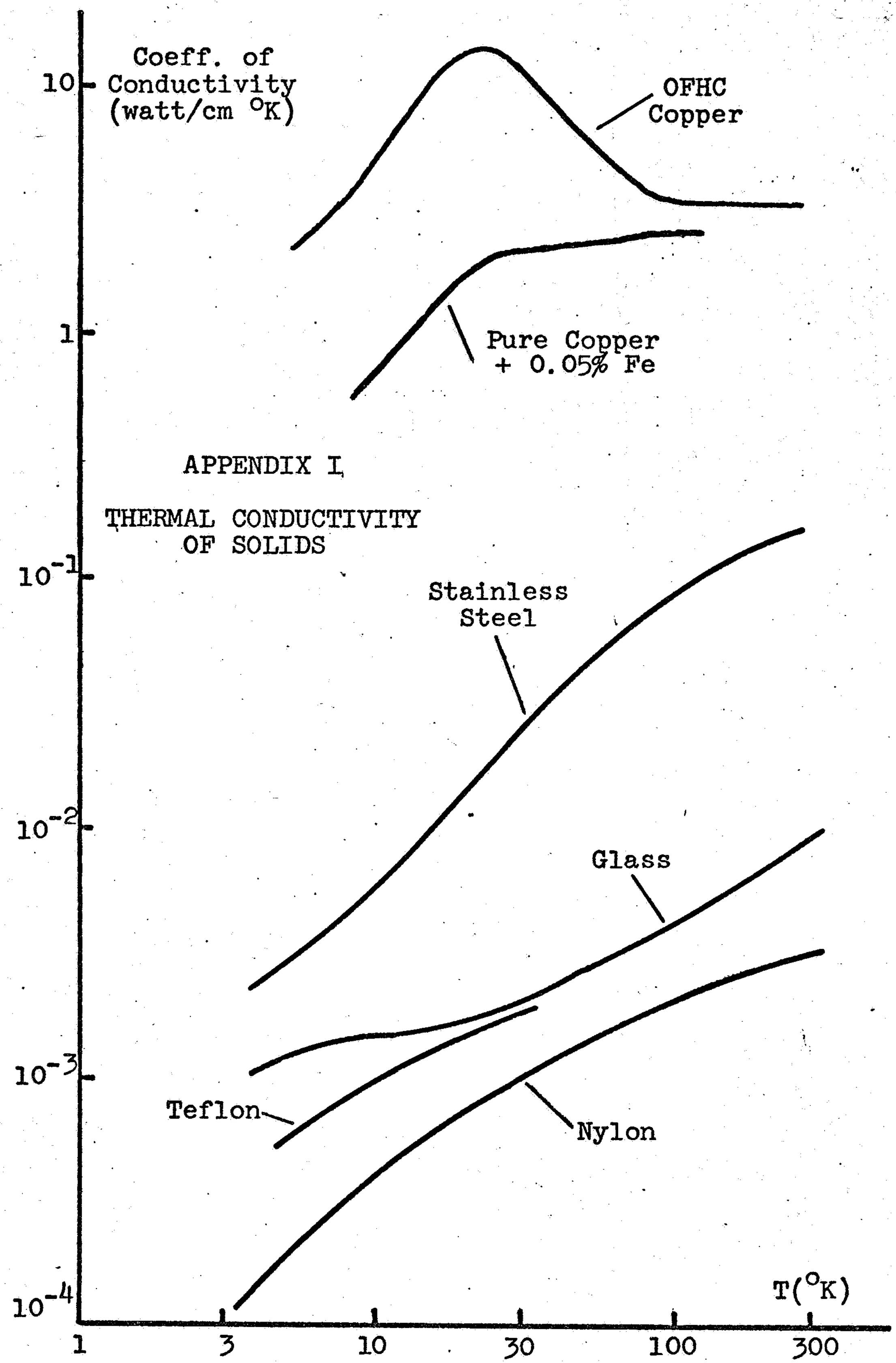
CHAPTER VI

CONCLUDING REMARKS

The primary objective of the research undertaken has been to develop a highly sensitive radiation detector. While the responsivity reported here is high, the speed of response to radiation can well be improved. In order that responsivity remain at a high value and thermal fluctuations be suppressed, it is imperative that a detector be as isolated thermally as are the present net suspended detectors ($G = 2 \times 10^{-7}$ watt/^{o}K). It is then apparent that a smaller heat capacity is the key to a faster response. A simple calculation shows that only about 1/1000th of the effective heat capacity measured in the net suspended detectors is due to the tin film itself. The detector may thus be reduced to the limit of no substrate whatever, resulting in an effective heat capacity of the order of that of the tin film. A tin film 1000 Å thick and 1 cm^2 in area has a calculated heat capacity of $C = 1.5 \times 10^{-9}$ joule/^{o}K at 3.6^{o}K. This heat capacity combined with a conductance of $G = 2 \times 10^{-7}$ watt/^{o}K gives a total thermal time constant less than 10 msec which satisfies time constant requirements for an 11 cps modulating rate.

It is possible that not only can a detector be deposited upon a net without a substrate, but also that the film can be deposited in the same maze configuration used thus far. This could be done, for example, by first evaporating a thin film on a smooth pellet made of a substance which sublimes in a vacuum when heated above room temperature. The electrical pathway is then carefully etched and the pellet is placed upon the nylon net strung between the two secondary heat sinks. The pellet is then sublimed and the thin film electrical maze is left upon the net. Then, as is presently done, the middle of the maze is masked, and a coating of lead is evaporated to electrically and thermally connect the edge of the film to the secondary heat sink. If these techniques are used, a detector will result which has a short time constant and which will still have the high degree of thermal isolation and responsivity as the net suspended detectors discussed in this report.

To further reduce the MDP for the nylon net suspended detector reported here, one need only blacken the detecting element and decrease the bandwidth of the electronics. While the 25 sec thermal time constant determines the frequency response of this system, electronic noise limits the MDP. Thus, if the amount of incident radiation absorbed in the nylon net suspended detector is increased by a factor of five ($\epsilon = 0.75$), and the noise level is decreased by a factor of ten to $V_{noise} = 5 \times 10^{-9}$ v, the resulting MDP will be decreased by a factor of 2×10^{-2} to a value of $MDP_{min} = 5.2 \times 10^{-14}$ watt. This value for the minimum detectable power is substantially lower than that of most bolometers thus far developed and is at least comparable to that of the most sensitive absolute radiation detectors.


Coeff. of
Conductivity
(watt/cm °K)
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
OFHC
Copper
Pure Copper
+ 0.05% Fe
APPENDIX I
THERMAL CONDUCTIVITY
OF SOLIDS
Stainless
Steel
Glass
Teflon
Nylon
T(°K)
1
3
10
30
100
300

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