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DEPARTMENT OF TRANSPORT
METEOROLOGICAL BRANCH

CEILOMETER PHOTOCELL TEST UNIT

INSTRUMENT RESEARCH AND DEVELOPMENT

REPORT NO. 1

BY

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ABSTRACT

The paper describes a unit designed and constructed at Meteorological Branch Headquarters for the purpose of testing bad sulphide photoconductive cells used in the rotating beam ceilometer. Test conditions are discussed, and related to industrial practice, means of realizing these conditions are described, and a test procedure is outlined.

Circuit descriptions and wiring diagrams of the final units are included.

APPAREIL DE CONTRÔLE DES CELLULES PHOTOÉLECTRIQUES DE CÉLOMÈTRE

par

RÉSUMÉ

L'auteur décrit un appareil conçu et construit au Bureau central de la Direction de la météorologie pour l'essai des cellules photoconductrices au sulfure de plomb utilisées dans le célomètre à faisceau tournant. L'auteur traite des conditions d'essai et en établit la relation avec la pratique industrielle, décrit les moyens de réaliser ces conditions d'essai et expose une méthode d'essai.

Cette étude comprend également des descriptions du circuit et des plans de câblage de l'appareil définitif.

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1. Introduction

Soon after the first installations of rotating beam ceilometers in the field it became apparent that there was a requirement for some means of testing the detector photocells. These are Eastman Kodak type N-2 photoconductive lead sulphide cells, but very little technical information was available on them. It was necessary to know, for example, to what production tests Kodak subjected the photocells and what were the minimum acceptable values of the several important parameters. Then, too, if any of these test conditions were in conflict with field operating conditions a decision was necessary as to which should prevail in the test unit, or what compromise should be made. The requirement was for something more than duplication of a manufacturer's test procedure; but the test system finally developed must be compatible with that used by the manufacturer. Some common ground was necessary in case of disagreement with the supplier about the performance of any one photocell unit.

Essentially, Kodak required that the photocells (at a temperature of 76°F) be exposed to radiation, at a level of 10 microwatts per square centimetre, from a black body source at 500°K. The radiation must be chopped at 90 cycles per second, the photocell loaded with its own resistance, and the output measured with a tuned voltmeter having a bandwidth of 5 cycles per second. With the photocell polarized at 90 volts, the alternating-current output must be at least 850 microvolts root-mean-square.

The problem immediately came to mind that the power level and wavelength distribution of the radiation from the black body source were incompatible with the requirements of the photocell. The total density of energy radiated from a source at 500°K into an ambient of 76°F is, from Stefan's Law, 310 milliwatts per square centimetre. This must be attenuated, by a factor of 31000, to a value of 10 microwatts per square centimetre at the photocell. The wavelength response of the photocell, its filter, and the combination, are shown in Figure 1. It is evident, then, that the photocell system responds only to radiation of wavelength between 1 and 2.75 microns. Planck's equation and Wien's displacement law give the wavelength distribution of energy density from the black body source. This is shown as Figure 2 where it is seen that, at the wavelengths of interest, the energy density is very low indeed. The curve does not reach its peak until quite far out into the infra-red, at a wavelength of 5.768 microns. Thus, the two characteristic curves do not coincide, nor can they be made to do so. However, it should be possible to take advantage of this discrepancy when it comes to attenuating the radiation from the black body source.

It will be seen, too, that some of the test conditions specified are different from those encountered in actual operation. For instance, the modulation frequency in field use is 120 cycles per second rather than 90; the photocell is exposed to the entire meteorological range of temperatures, and its efficiency generally increases at lower temperatures; receiver bandwidth is 20 to 25 cycles per second, whereas, test specifications call for a detector passband of 5 cycles per second; the photocell is connected to a one megohm load, without any attempt to match load and photocell resistance, as test conditions require; in the field the photocell is operated behind an optical filter which eliminates nearly all the radiation at visible wavelengths; test specifications call for the "total radiation" which, presumably, rules out the optical filter.

The test conditions cited here, are, incidentally, fairly uniform throughout the industry. But it seemed desirable, in designing the test unit, to effect a reasonable compromise between operating and idealized test conditions, since the main interest here was how the photocell would perform in a field installation. For the reasons given below, the compromises were worked out essentially as follows:

(i) The modulation frequency was left at 90 cycles per second, since both frequencies are low enough that the cell can respond in a time much less than one period of the modulation. Response time of a lead sulphide photocell is typically of the order of microseconds.

(ii) The testing would be done at room temperature (or a little higher, since there was a slight warming of the test chamber in operation). Here again, the test condition was conveniently attained and was not unduly unrealistic.

(iii) The signal-to-noise ratio is proportional to the square root of the photocell area. Noise is defined as the detector output when the photocell is not exposed to radiation from the black body source. Obviously, this output would be a function of detector bandwidth, among other things. Eastman gives the acceptable S/N as $50\,(A)^{1/2}$ which, for the ceilometer photocell, works out to a value in the neighbourhood of 375. It is apparent, too, that if the detector bandwidth were changed, this would necessitate a different proportionality constant in the expression for the signal-to-noise ratio. Accordingly, the 5 cycles per second bandwidth was retained, although it made the circuit design a little more difficult.

(iv) In the later stages of the performance checks on the equipment, a rheostat was connected in the photocell circuit so that its load could be adjusted. It was found that variation of this resistance over a wide range made very little difference in the photocell output. There was a very slight increase with a load resistance of the order of one-half to one-quarter megohm, and a value of 410000 ohms was used in the completed circuit. This, of course, was of the low noise type.

(v) As previously stated, the filter normally used with the photocell passes essentially the wavelength band from 1 to 2.75 microns, and absorbs radiation of wavelengths outside this band. For this reason, the optical filter introduces a high degree of attenuation and advantage of this fact has been taken to reduce the energy level from the black body source to that required at the photocell. These considerations outline the general requirements. The detailed system design fell naturally into three sections which are discussed in turn.

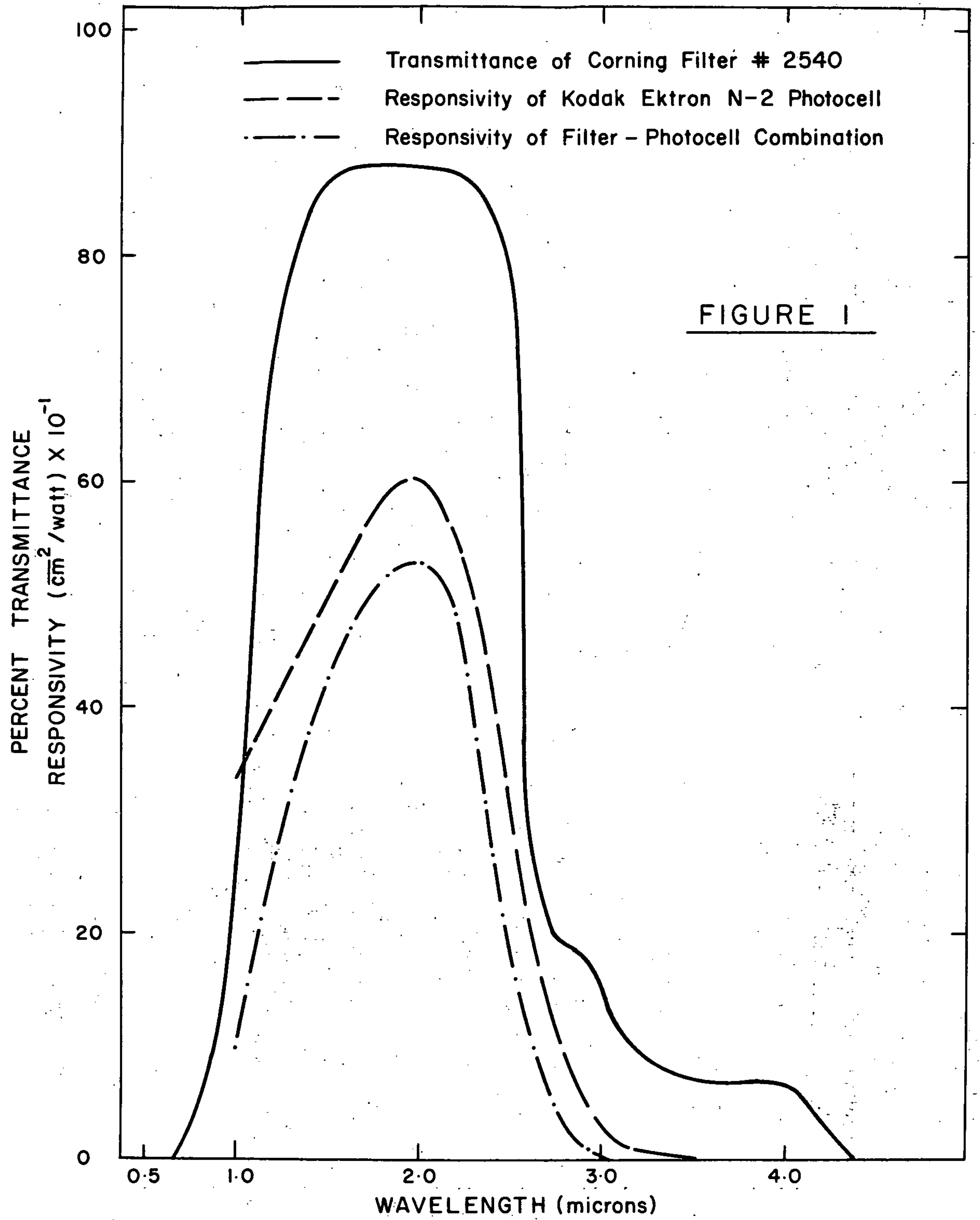
Physical and Geometrical Considerations

The practical approximation to a true black body source has always been a cavity in a block of material heated to the desired temperature.

The emergent radiation appeared through a hole in the cavity. Indeed, all the research done on infra-red during the last War has not markedly changed this basic approach. The modern black body source is a conical or cylindrical cavity in a block of metal. The inside surface of the cavity is painted black to increase its emissivity, and the radiation emerges from the base of the cone or cylinder. It is possible by this means to achieve an effective emissivity very little short of unity, so that the source is very nearly a perfect emitter (and absorber) of radiation. Hackforth (1) describes various infra-red sources; he also mentions a paper by André Gouffée (2) wherein it is shown that "a material of emissivity 0.75, in the form of a conical 15° cavity, will have a total hemispherical emissivity factor of 0.99".

The first idea as to method of attenuating the radiation by a factor of 31000 was to use two stops in cascade. Then it was realized that use of the filter would be a better duplication of field conditions, and at the same time introduce a large measure of attenuation. The amount could be readily computed from the curves of Figures 1 and 2. The black body energy density curve and the filter transmission curve were multiplied together to give the resultant shown as Figure 3. The area under this curve is 4.06 milliwatts per square centimetre. Thus, the effective energy density from the black body reaching the photocell is this value rather than 310 milliwatts per square centimetre. The filter, then, has introduced an attenuation factor of 76.4 and the additional attenuation factor of 406 can be obtained by use of a single stop.

Calculations were made for hole diameter of stop and distance of photocell from black body source required to achieve the desired attenuation. The results were checked by measurements with a Kipp solarimeter which had a sensitivity of 0.159 millivolt per milliwatt per square centimetre. An energy density of 10 microwatts per square centimetre multiplied by 76.4 (the attenuation of the filter) should give a solarimeter output, then, of 0.121 millivolt. Final adjustment of the photocell holder position was made by locating it at the distance from the aperture which gave this output from the solarimeter. Measurements were made with the modulator removed. The geometry of the system, as finally developed, is illustrated in Figure 4. For modulation of the emergent radiation at 90 cycles per second the simplest system appeared to be a sectored disc driven by a synchronous motor. As constructed, the modulator contained six open and six opaque sectors, and was driven at 900 rpm. The disc was made of sheet brass of such


Transmittance of Corning Filter # 2540
Responsivity of Kodak Ektron N-2 Photocell
Responsivity of Filter - Photocell Combination
FIGURE I
PERCENT TRANSMITTANCE
RESPONSIVITY (cm² /watt) X 10⁻¹
100
80
60
40
20
0
0·5
1·0
2·0
3·0
4·0
WAVELENGTH (microns)

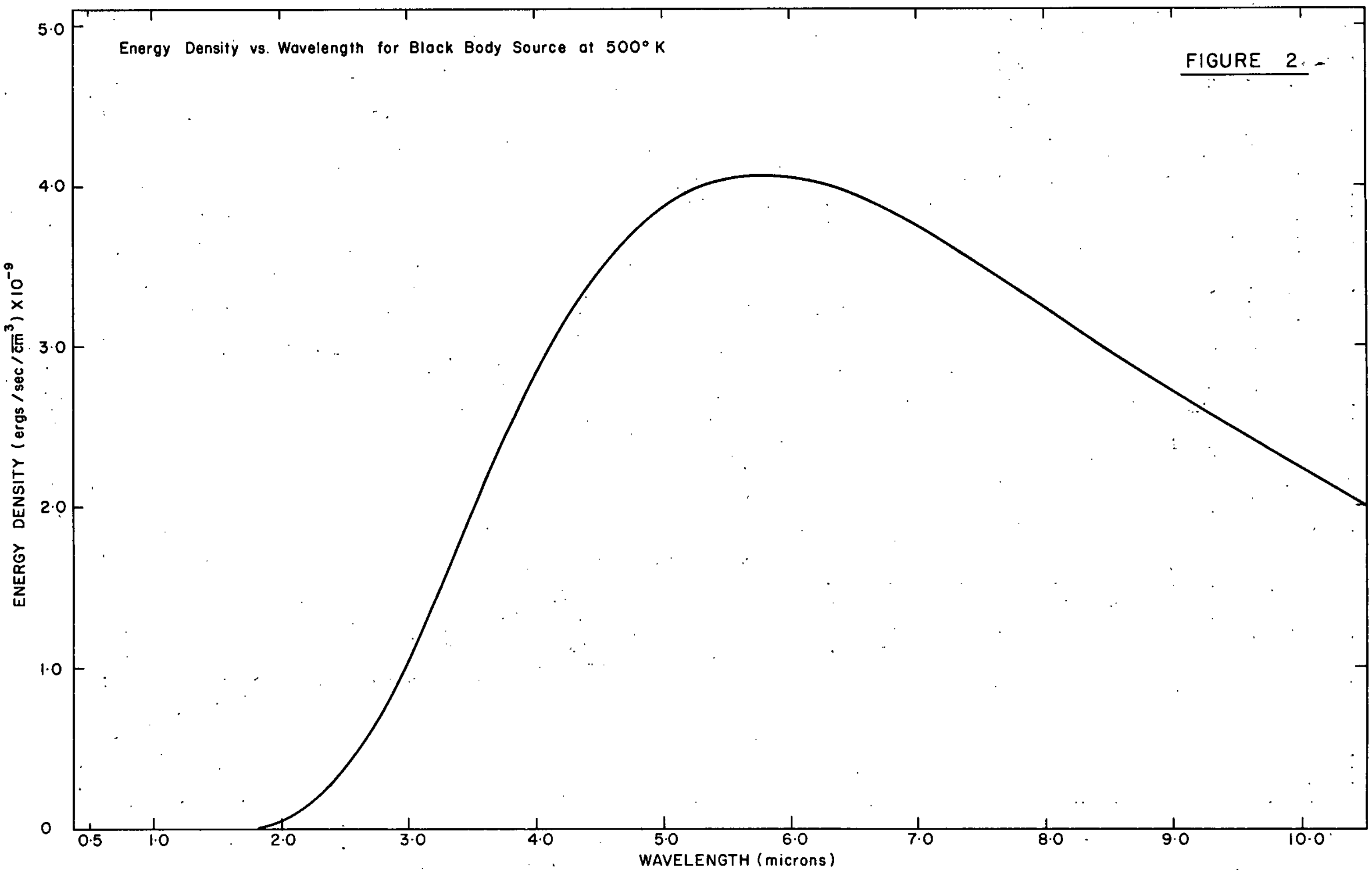
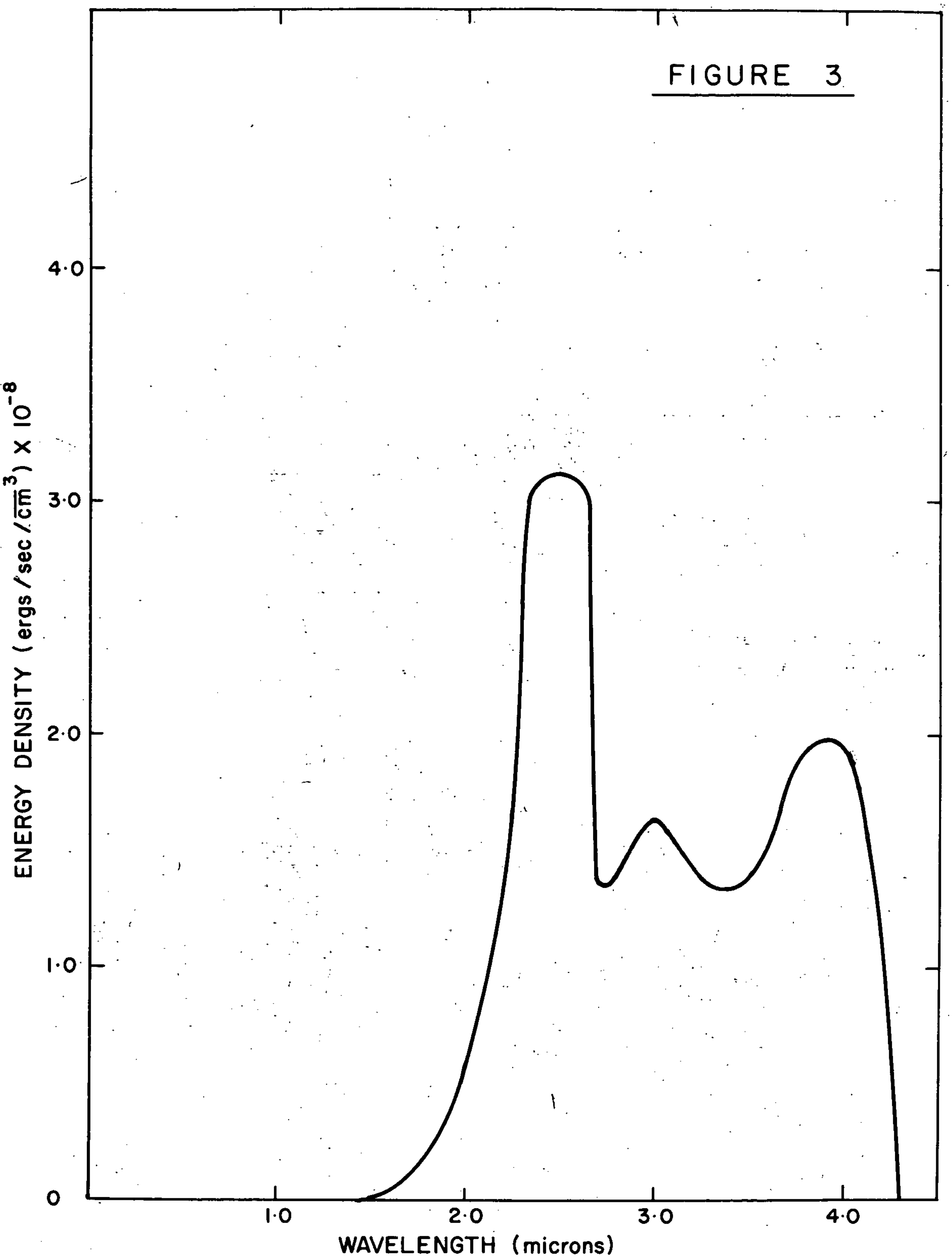

Energy Density vs. Wavelength for Black Body Source at 500° K
ENERGY DENSITY (ergs / sec / cm³) X 10⁻⁹
5·0
4·0
3·0
2·0
1·0
0
0·5
1·0
2·0
3·0
4·0
5·0
6·0
7·0
8·0
9·0
10·0
WAVELENGTH (microns)

FIGURE 2


ENERGY DENSITY (ergs / sec / cm³) X 10⁻⁸
0
1·0
2·0
3·0
4·0
WAVELENGTH (microns)
FIGURE 3

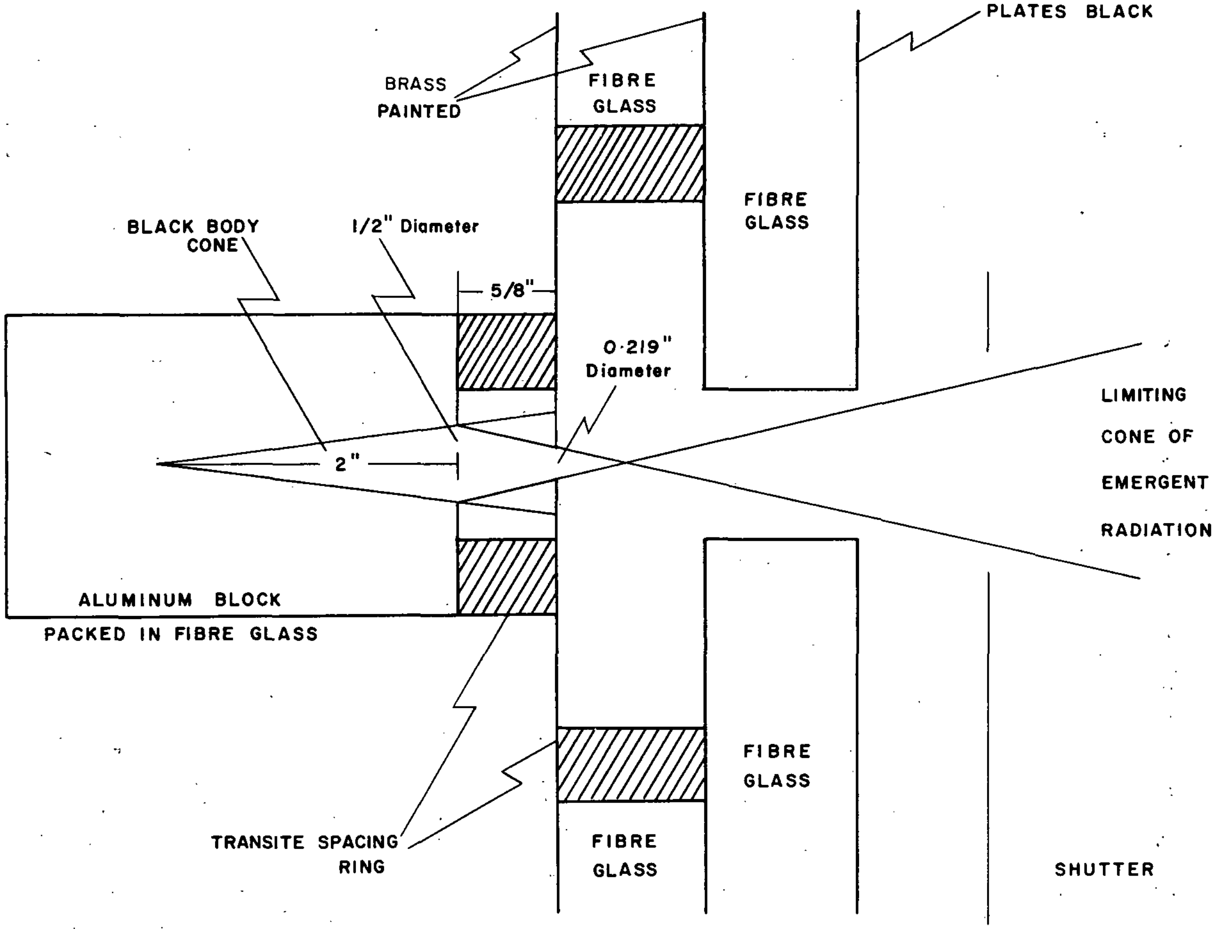

PLATES BLACK
BRASS
PAINTED
FIBRE
GLASS
FIBRE
GLASS
BLACK BODY
CONE
1/2" Diameter
5/8"
0·219"
Diameter
LIMITING
CONE OF
EMERGENT
RADIATION
2"
ALUMINUM BLOCK
PACKED IN FIBRE GLASS
FIBRE
GLASS
TRANSITE SPACING
RING
FIBRE
GLASS
SHUTTER

FIGURE 4

diameter as to provide openings which would yield 100% modulation of the radiation emergent from the aluminum block. It also was painted flat black. At the low rotational speed employed mechanical balance did not appear to be a problem.

Temperature Control

The aluminum block containing the hollow cone black body source must be maintained at a temperature of 500° Kelvin. This corresponds to 227° Celsius or 440° Fahrenheit. The block dimensions were established as 2" in diameter by 3" long, with a conical hole drilled out along the axis to a depth of 2" and on a base of 1/2" diameter. The included angle of the cone was thus 14 1/2°.

In the other end of the block, holes were drilled, again parallel to the cylinder axis, to contain: the heater (50 watts, 115 volts); a platinum temperature sensing element of 100 ohms ice-point resistance, for control and a copper-constantan junction for monitoring purposes.

The Platinum control element was incorporated into a Wheatstone bridge fed from 6.3 volt supply at power line frequency. The bridge output was amplified and used to drive a full-wave grid-controlled rectifier. The heater was connected in the rectifier output circuit.

The theory of operation of the control unit may be briefly described as follows, with reference to Figure 5:

> At 227°C platinum has a resistance approximately 190% of its ice point value. Since the most sensitive Wheatstone Bridge is one which has all arms of equal value and the load impedance equal to this, all fixed arms are set at 200 ohms. The output of the bridge circuit is transformer-coupled to the amplifier input through a large step-up ratio in order to match the low bridge output impedance to the high input impedance of a Class A amplifier. Precautions were taken in the design of the control system to keep the phase shift in the amplifier quite low.

The grid-controlled rectifiers are two rare gas filled thyratrons whose plates are supplied through a transformer from the power line. If the grids are driven with a wave of sufficient magnitude at the power line frequency and in phase with the plate potential, the thyratrons

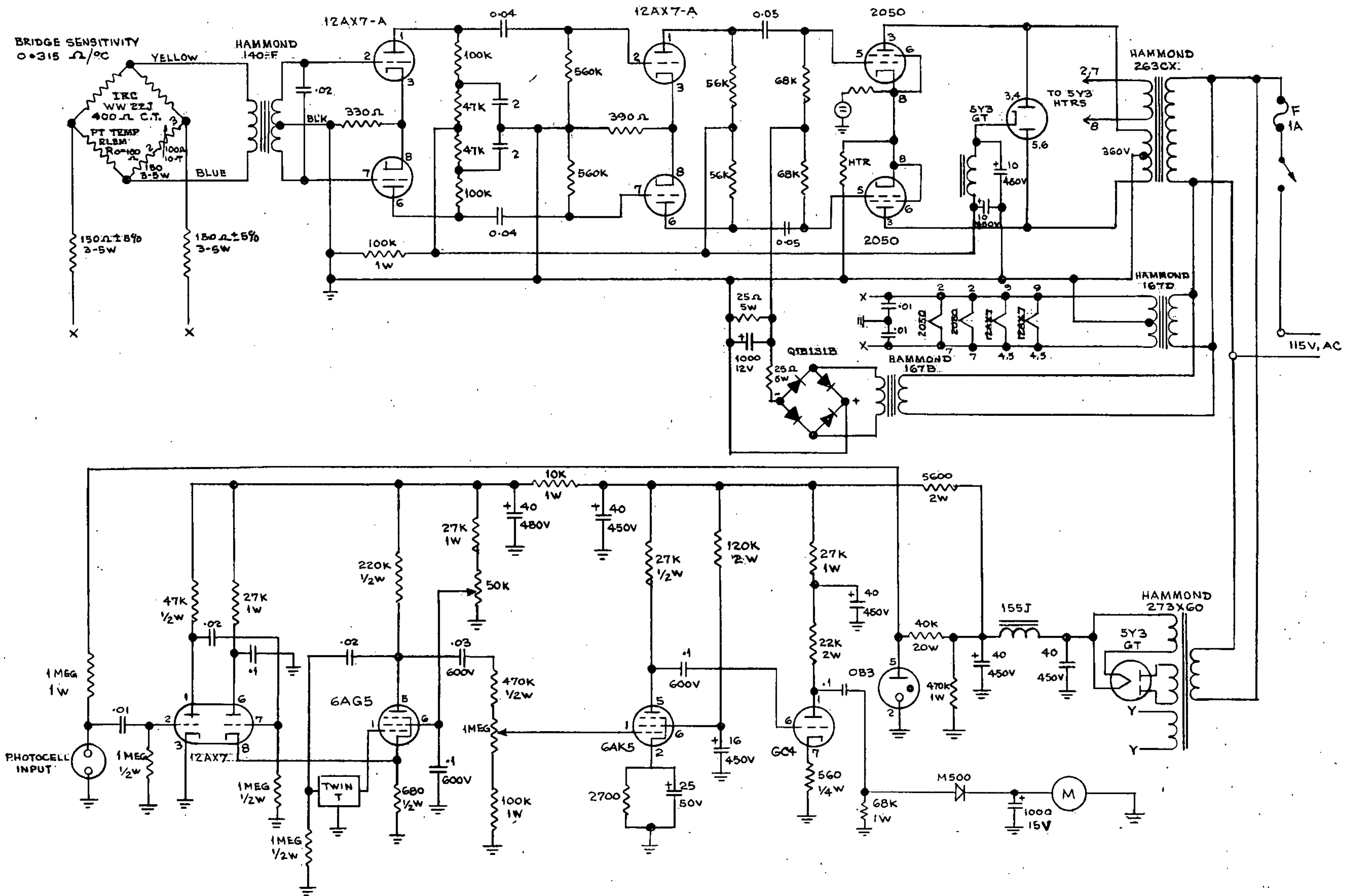
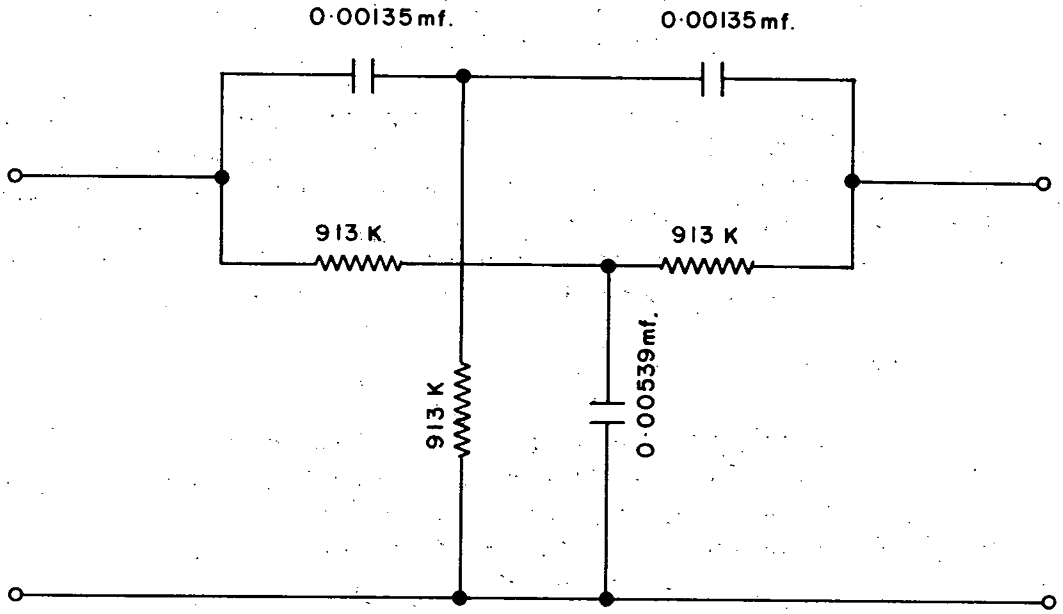


FIGURE 5

CAPACITANCE IN MICROFARADS } UNLESS OTHERWISE SPECIFIED
RESISTANCE IN OHMS



90 — cps Twin — T Network

FIGURE 6

will conduct continuously. On the other hand, if the phase of the grid drive is reversed, so that plate and grid potentials are in opposition, neither thyratron will conduct. Intermediate phase differences will cause plate current to flow for varying percentages of the cycle of the power line voltage. In short, the average power delivered by the tubes will be an approximately linear function of the phase difference between grid and plate supplies (if both are at the same frequency).

The resistance of the platinum sensing element determines the state of the Wheatstone Bridge and its output. As the platinum resistance increases, the bridge approaches balance and the output potential decreases suddenly almost to zero, then starts to increase again. There is also a sudden phase reversal of output potential as the bridge system goes through the balance conditions. Amplifier connections must be made, then, so that if the Wheatstone Bridge is unbalanced on the low temperature side, the thyratrons will be conducting and heat will be applied to the aluminum block. By the same token, when the bridge is unbalanced on the high temperature side, heat will be cut off. Amplifier gain will play a large part in determining how much the temperature of the block will vary above and below its set point.

Amplifier Circuit

For the photocell output an amplifier of different characteristics is required. Whereas, the control amplifier must have minimum phase shift at the power line frequency and deliver only potential, the output amplifier must be sharply tuned to a higher frequency and supply power to operate a meter. Previous experience with a redesign of the ceilometer detector amplifier made the problem here less formidable. A conventional inductance-capacitance circuit with the required low resonance frequency and narrow pass band is extremely difficult to realize. Accordingly, the method adopted in the design of the new ceilometer amplifier was again used for the tuned voltmeter. The theory of operation of the amplifier can be briefly summarized as follows:

> The Twin-T is a resistance-capacitance filter with the capability, when properly adjusted, of complete rejection at one frequency. In practice, the network is made part of a negative-feedback loop in a high-gain amplifier. Thus, the overall amplification will be reduced by the feedback except at the rejection frequency of the Twin-T, where the (gain-reducing) feedback vanishes and the full

amplifier gain is realized. It is readily apparent, then, that such an amplifier will behave as if it were tuned, and the sharpness of resonance will depend upon the gain of the amplifier in the absence of negative feedback (open-loop gain). The fractional bandwidth of a tuned circuit is given, in terms of its "quality" factor Q, by the quantity 1/Q. Valley and Wallman (3) show that the effective Q of a Twin-T amplifier is given approximately by:

$$Q = \frac{A + 1}{4}$$

where A is the amplification with the feedback loop open. To achieve a bandwidth of 5 cycles per second at a centre frequency of 90 then requires an effective Q of 18; the Twin-T must, therefore, be used in connection with an amplifier whose amplification factor is 73. This was achieved by the use of a voltage pentode in the "tuned" first stage. The remainder of the amplifier was left "broadband", that is, no special precautions were taken to widen or narrow the passband of the later stages. A rectifier, filter, and meter complete the amplifier circuit. The schematic is shown in Figure 5, network details in Figure 6.

The 50,000 ohm potentiometer in the screen circuit of the 6AG5, by adjusting the amplification of the stage, serves as a bandwidth control. It is possible to achieve a half-power bandwidth of 2 to 3 cycles per second. The 1 megohm potentiometer in the grid circuit of the 6AK5 stage is the gain control, which adjusts amplifier sensitivity. Calibration of the amplifier was done by injecting measured signals at 90cps, attenuated a known amount through a precision voltage divider, and noting the reading of the output meter. The overall transfer characteristic (output current versus input potential) so obtained is non-linear because of a tendency toward saturation in successive stages by amplified signal. However, this non-linearity is not of great consequence, and the input (photocell) potential can be measured with more than sufficient accuracy.

Before use, the equipment requires approximately one-half hour for the aluminum block to reach temperature equilibrium. This state will be shown by cycling of the heater, as indicated by the neon lamp which is connected from the thyratron cathodes to ground. The photocell under test is connected into the amplifier, and the noise check made by placing the cell in its holder face down on the bench or table. The amplifier output should be essentially zero during this test. The photocell is then screwed into its holder in the cabinet, and the meter in the amplifier output will indicate a signal. The meter reading at this test must be at least 62% corresponding to 850 microvolts.

Several photocells have already been salvaged by use of this test unit, and returned to the field. Perhaps the most spectacular was the cell which indeed proved noisy and insensitive - due to a break in the cable. When the break was located and repaired, the photocell showed excellent sensitivity and signal-to-noise ratio. Reinstallation in the field confirmed this result.

Thanks are due Mr. J. R. Latimer of Research and Training Division, for the extended loan of the Kipp solarimeter used in final adjustment of the test unit.

APPROVED,

J. R. H. Noble,
Director,
Meteorological Branch.

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8 pps. 6 figs. 4 refs.

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2. Instrument Test Units.

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