A RELATIVELY SIMPLE DEVICE FOR RECORDING RADIATION INTENSITIES IN THE ULTRAVIOLET PORTION OF THE SPECTRUM

by

HENRY WALLACE HENDRICKS

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APPROVED:

[redacted]

Professor of Physics In Charge of Major

[redacted]

Head of Department of Physics

[redacted]

Chairman of School Graduate Committee

[redacted]

Dean of Graduate School

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INTRODUCTION

Statement of Problem

The purpose of this thesis is to develop a more or less portable apparatus that will measure ultraviolet energy in or near the erythemal region. It is hoped that this piece of apparatus will be useful in a problem on the relation of dental caries to ultraviolet radiation that is being studied by the Department of Foods and Nutrition.

Some Basic Information About Ultraviolet, Sun and Sky Radiation, Its Biological Effectiveness, Etc.

Although H. J. Gerstenberger has shown that dosages of ultraviolet energy insufficient to produce a minimum perceptible erythema, prevent and cure rickets (5), the erythemal effectiveness curve has been used extensively to indicate biologically effective radiation. Though the relationships between erythemal and antirachitic effectiveness is not well established radiant energy which produces erythema of the skin also cures and prevents rickets; this is at least true for the spectral range from 2500 A to 3200 A (10, p.273). Also, erythema is easily produced under known conditions.

Ultraviolet radiation of wavelengths less than about 2900 A and some radiation of longer wavelengths does not reach the earth's surface because of absorption by the upper atmosphere. The atmosphere scatters ultraviolet radiation more than longer wavelengths. This accounts for the fact that the intensities of the region from 2900 A to 3300 A (10, p.48) in skylight and in direct sunlight are nearly equal.

INSTRUMENTS FOR RECORDING ULTRAVIOLET INTENSITIES

The first integrating ultraviolet meter (18) using a photoelectric cell was devised by Rentschler of Westinghouse in 1930. Prior to this time data had been taken by chemical methods (1), by spectral dispersion, and by thermopiles combined with selective filters (17). Rentschler described his "integrator circuit" in a lecture before the American Institute of Electrical Engineers. The radiation incident on the photocell was caused to charge a condenser for a definite period of time, thus integrating the effect of the radiation during this period of time. Luckiesh, Taylor and Kerr of General Electric followed Rentschler's idea and built variations including a portable type and a type using a thermionic tube (10, p.400-421). Coblentz of the National Bureau of Standards made an extensive study of photocell responses and a series of measurements using the same integrating principle (3). Rentschler had used a gas-filled trigger tube containing a radioactive cathode to discharge the condenser and activate a relay. In 1935 Müller and Shriver published an article in the Review of Scientific Instruments (13) describing a precision radiation integrator using an FP 54 electrometer tube and two type 58 thermionic tubes in parallel to measure the incident radiation down to currents of 10^{-14} amps. In 1947, Pal (16) used an illuminated cathode, grid-glow discharge tube in place of the radioactive cathode type of firing tube.

DESIGN CONSIDERATIONS

The apparatus should be simple in construction so that if necessary it may be duplicated at moderate cost. Commercially available parts are therefore to be used whenever possible. It is of course also desirable to have an apparatus that requires a minimum amount of servicing and maintenance.

Four parts of the apparatus to be considered are the receiver, the receiving circuit, the recorder and the power supply.

The Receiver

The modern method of receiving ultraviolet radiation employs a photoelectric cell, either of a metal cathode (pure or purposely contaminated with gas) (22, p.121) having the desired long wavelength cut-off, or a composite surface cathode used with some device to limit the wavelengths of light incident on the cathode surface. The latter may employ a transmission filter, a prism, a grating or a combination of these parts.

Data regarding some metal cathode phototubes that have been used are listed in Table 1.

Metal Cathode	Used by	Cut-off at
Uranium (18,22)	Rentschler and co-workers	3200 A
Cadmium-magnesium alloys (9,20)	Luckiesh, Taylor and Kerr	3200-3400 A
Titanium (2,4)	Coblentz and Stair	3400-3500 A
Cadmium (2,4)	Coblentz and Stair	3200-3300 A

Table 1. Metal Cathode Phototubes
Used in the Ultraviolet

Without the use of filters, a double monochromator has been used by Herrmann to obtain a spectrum free from stray radiation (6). Rentschler used a glass filter in conjunction with his uranium photocell (18) while Kerr (8) used a nonselective photocell in combination with phosphorescent magnesium tungstate as a selective filter-indicator to approximate the erythemal effectiveness curve.

One sub-consideration of the receiver is that the phototube have a high resistance leakage path to permit the measurement of small currents. Another is that the photocell receive nonselectively with respect to the sun's altitude. Herrmann used an Ulbricht sphere open to the sun and sky (6). A simple quartz plate ground rough one one side will diffuse the light incident upon it and correct within the important altitude range for the angle of incidence. For optimum design the cathode should be filled by radiation passing through the window.

A zirconium cathode photocell with a cut-off at 3150 A could have been obtained upon special order and a delay of two months. It was decided to attempt the construction of a much cheaper instrument using a silver-film filter and an RCA 935, S5 composite cathode vacuum phototube (Fig. 1). The transmission region of the silver film was known only approximately from a statement in Jenkins and White, revealing a wide band near 3200 A (7, p.309-310). Unfortunately the transmission band was found to lie entirely to the long wavelength side of the maximum of erythemal effectiveness.

According to Herrmann the distribution of solar energy of wavelengths longer than 3150 A is constant except as modified by clouds directly between the sun and the receiver (6). However no such relation holds for wavelengths less than 3150 A (6). The transmission limits of the silver film, as determined by Pettit, are 3050 and 3350 A (17). (The erythemal region lies between 2900 and 3200 A).

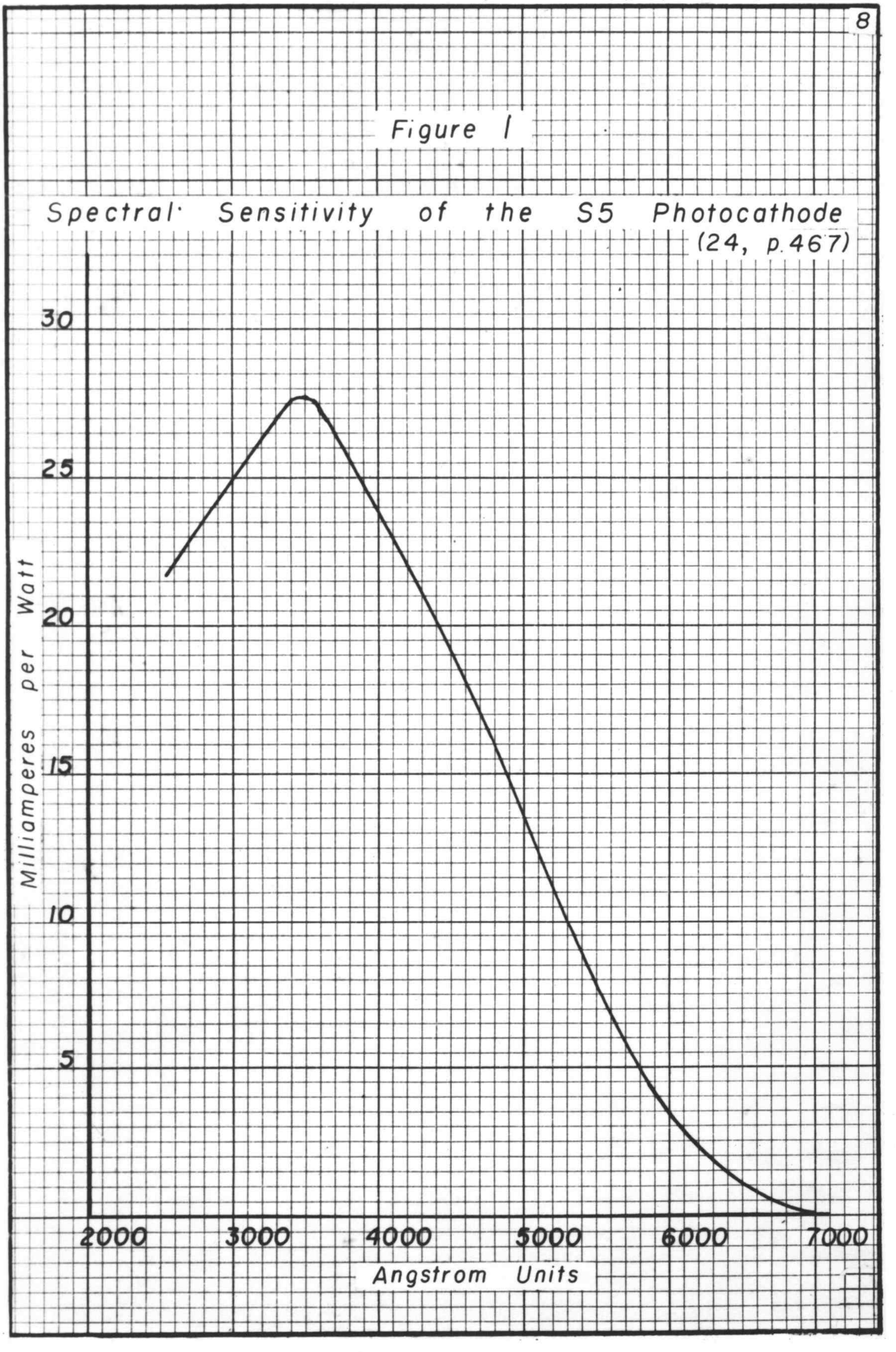


Figure 1
Spectral Sensitivity of the S5 Photocathode
(24, p.467)
30
25
20
15
10
5
Milliamperes per Watt
2000
3000
4000
5000
6000
7000
Angstrom Units

The Receiving Circuit

The indications of a properly selective receiver may be either read or recorded. Adaptations of Rentschler's integrating circuit have been used with considerable success (2,11,12). The current flowing through the photocell charges a condenser to a limiting voltage; when discharged it sets into action some sort of counting or recording mechanism.

The particular adaptation of the integrator circuit to be used is determined by the availability of circuit elements with specific, desired characteristics followed of course by experimental testing. Rentschler ultraviolet meters have taken on several forms, but common to all is an especially constructed cold cathode trigger tube. As already mentioned an attempt was made to use a circuit employing only tubes readily obtainable on the market.

The Recorder

Two problems developed in the selection of a recorder. A printed record of the number of counts (or whatever represents the incident energy) in a given time interval is very convenient, and should ultimately be used (Streeter-Amet Company recorder, model SCI 4, Form B is suitable). For experimental purposes a counter was employed and read at definite time intervals. The counter used was a rewound telephone message register.

The Power Supply

The power supply may be designed for either batteries or 110 volts a.c. Even though very small currents would be drawn from batteries so that they would last their shelf lives, a.c. operation was selected.

EXPERIMENTAL DEVELOPMENT

In the operation of the circuit in Fig. 2, the condenser of capacitance C is charged by the current from the photocell and battery in series with it until the firing voltage E_f of the $\frac{1}{4}$-watt neon tube is reached. At this time the condenser discharges across the gas-filled tube and causes an audible sound in the headset h. Assuming proper operation, the intensity of radiation will be proportional to the number of clicks per selected time interval.

The operating characteristics as shown in Table 2 indicated erratic operation. This was remedied by using the vacuum tube circuit shown in Fig. 3. The

Firing Voltage E_f	Extinguishing Voltage E_x	$E_f - E_x$
65	50	15
69	52	17

Table 2. Operating Characteristics of Original Circuit

photocell draws electrons from the condenser and the control grid of the vacuum tube until enough current

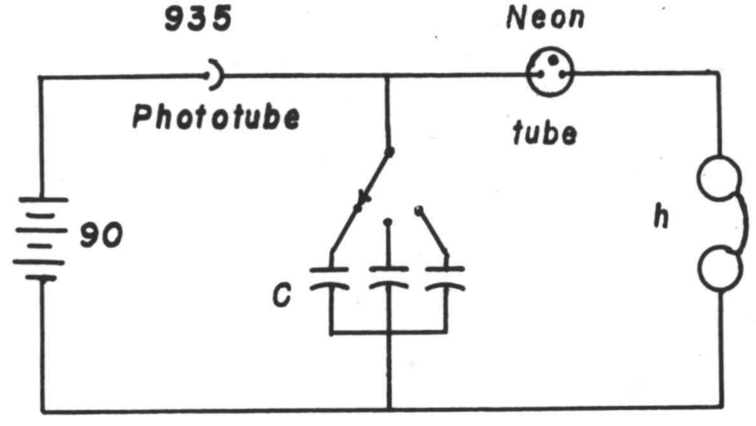


Fig.2 Original Circuit

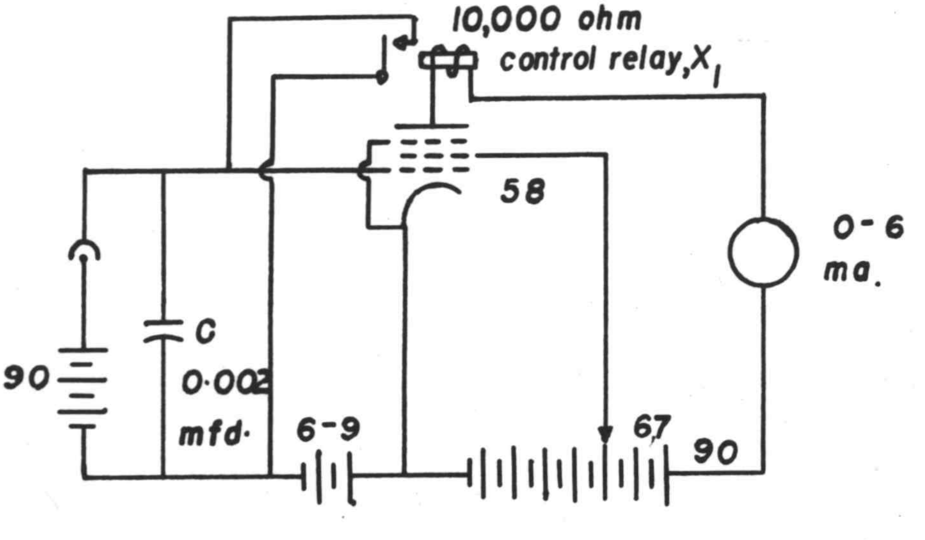


Fig.3 First Vacuum Tube Circuit

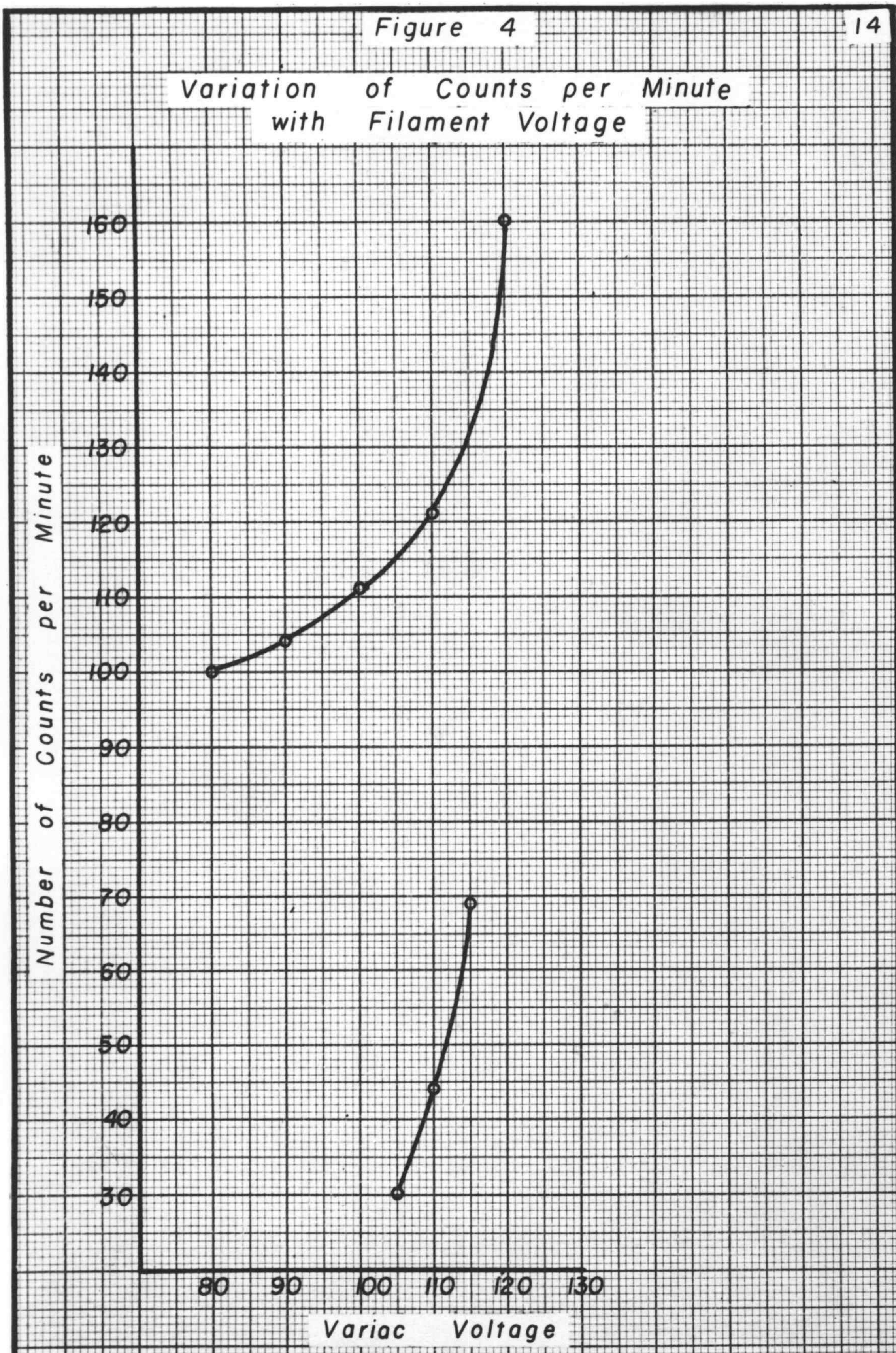
is flowing in the vacuum tube plate circuit to operate the relay. The relay closes a switch shorting out the condenser and applying a 6-volt bias to the control grid which cuts the plate current down below the value required to operate the relay. Thus the switch opens and the order of events is repeated.

By watching the milliammeter placed in the plate circuit, the effect of an internal leakage path in the condenser was noted. The needle of the milliammeter would momentarily fall back when a certain grid voltage was developed. Then the meter reading would again increase indicating that not all the charge had leaked off. Substitutions of a well-insulated air condenser of a capacity of 1500 microfarads eliminated this behavior.

Using a 0.002 microfarad mica condenser, a variation of the number of relay closures with a variation of line voltage on the filament transformer was observed as shown in Fig. 4. Since the intensity used was small and the size of the condenser used in the final apparatus was larger, the expected variation would not be as large. The possibility of a cumulative error from fluctuating line voltage may be avoided by using a storage battery.

A preliminary outdoor test of the apparatus

Figure 4


Variation of Counts per Minute with Filament Voltage
Number of Counts per Minute
160
150
140
130
120
110
100
90
80
70
60
50
40
30
80
90
100
110
120
130
Variac Voltage

indicated an appreciable photoelectric effect in the vacuum tube. This was detected when a stray shadow on the thermionic tube reduced the rate of operation. Hence shielding this tube from light is necessary.

At low radiation intensities an occasional relay chatter was observed. This was eventually attributed to the fact that the type 58 tube was a remote cut-off tube. Though a 6J7G tube could be used it would supply only 2 milliamperes plate current whereas the miniature tube (the 6AK5) would furnish well over 5 milliamperes. Another advantage of this type of tube is the lower filament drain on the battery. One possible disadvantage could be the possibility of leakage of very small currents between the cathode pin (No. 2) and the control grid pin (No. 1) on the base of the tube, or leakage between elements inside the tube (19, p.413-414). For example, positive ions from the filament might travel to the grid causing the condenser charge to be dissipated.

THE FINAL CIRCUIT AND POWER SUPPLY

The final circuit (Fig. 5) consists of a regulated power supply, a 6AK5 sharp cut-off pentode, a pilot relay to operate the counter through a half-wave rectifier, and a control relay shunted by a variable resistance. This rheostat divides the plate current between the control relay and itself, thus regulating the total plate current. To count impulses, this value must be greater than the current required to operate the pilot relay.

Since the cathode must be at a positive potential with respect to the control grid for cut-off and must, at the same time, be at a negative potential with respect to the plate, a voltage doubling circuit is convenient.

When terminal No. 1 is positive, the conventional current will pass through rectifier No. 1 and charge the condenser C_1. During the other half-cycle when terminal No. 1 is negative, rectifier No. 2 will conduct and the corresponding condenser will be charged. Thus the output terminals will be at approximately double the maximum value of the applied alternating voltage. On a 110 volt circuit

$$2E_{max} = 2\sqrt{2} \cdot 110 = 310 \text{ volts.}$$

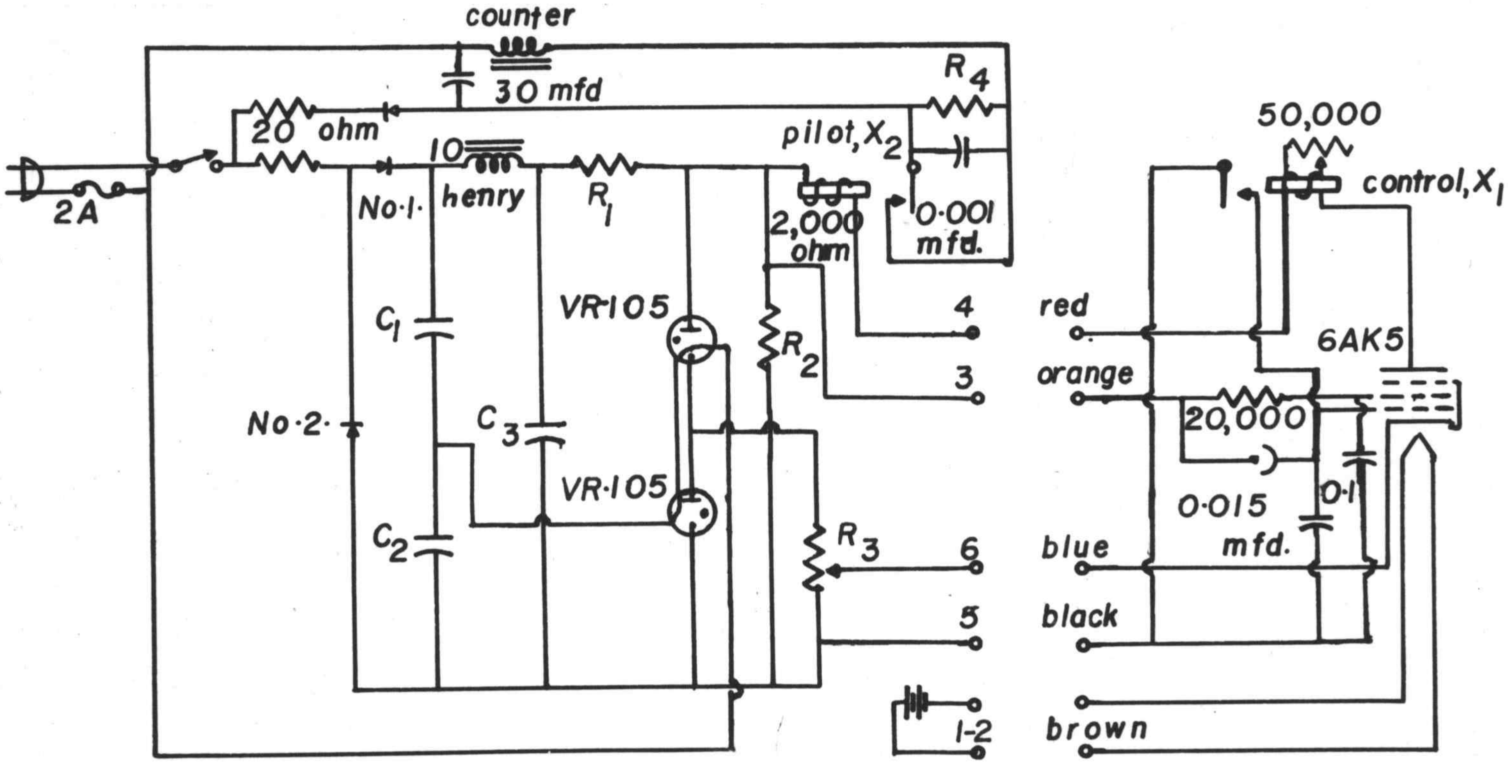


Fig. 5 The Final Circuit

A voltage regulator was necessary because variations of the line voltage affect the operating characteristics of the thermionic tube.

The capacitance in the filter forms the low-impedance path while the choke assists in diverting the 120 cycle-per-second signal through the condenser by offering a high impedance as shown by the computations below.

$$X_C = \frac{1}{2\pi fC} = \frac{1}{(377)2 \times 20 \times 10^{-6}} \text{ ohms}$$

$$X_C = \frac{1}{.015} = 66 \text{ ohms at } 120 \frac{\text{cycles}}{\text{second}}$$

$$X_L = 2\pi fL = 2(377) \frac{\text{cycles}}{\text{second}} 10 \text{ henry}$$

$$X_L = 7{,}540 \text{ ohms}$$

Also the 16 microfarad condenser C_3 offers much less resistance to those signals that do get through than does the 100,000 ohm bleeder resistor R_2.

The two voltage regulators are connected in series with a resistor R_1, the value of which was determined experimentally so as to draw about 20 milli-amperes and cause a voltage drop of 210 volts at the regulator. This resistor also absorbs fluctuations in supply voltage (21, p.617). This causes maximum regulation since the tubes can conduct 35 to 5 milliamperes current without appreciable variation of the voltage across them.

$$\Delta I_{max} = \frac{35 - 5}{2} = 15 \text{ ma.}$$

$$I_{max} = 5 + \frac{35 - 5}{2} = 20 \text{ ma.}$$

A wire-wound 150,000 ohm variable rheostat R_3 was found to be useful to adjust the cut-off voltage and therefore the rate of operation of the relay for a constant intensity of radiation.

PREPARATION AND SILVERING OF THE QUARTZ PLATES

Delayed delivery of the polished quartz plates made it necessary to grind, polish, and silver some scrap quartz in order to determine the transmission limits of silver films. The grinding was accomplished by placing the quartz in a grooved piece of wood and inverting it on top of a grinding wheel. A piece of paper was used to hold the quartz in place while inverting it. Everything was washed thoroughly between changes of size of the carborundum which ranged from size F down to 500.

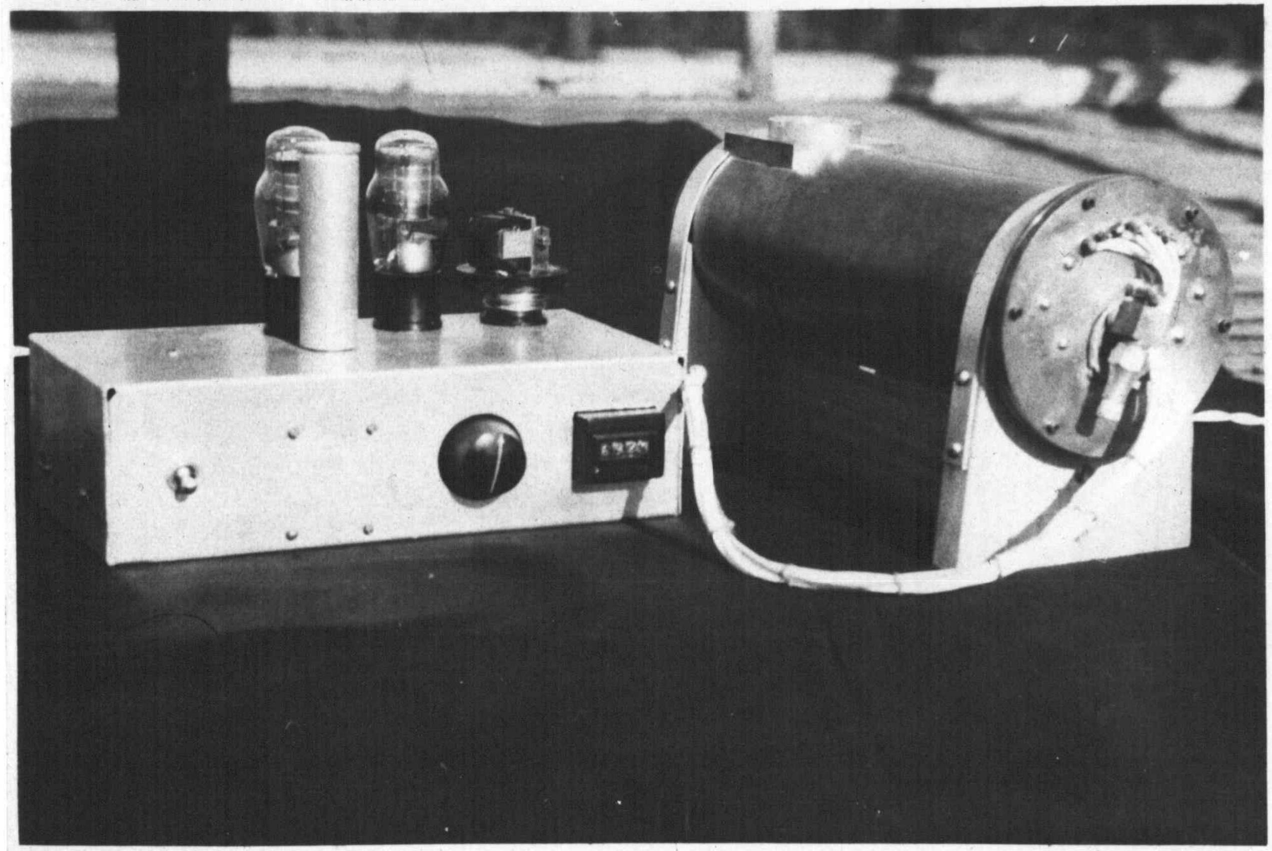
The quartz plates were mounted in hot pitch poured on a wooden block. They were made flat by pressing them down with a wet glass plate. Tin oxide was used for fine-grinding the quartz on glass. Some scratches seemed to have come from glass chips working out of the plate. These scratches were so fine as to be mistaken for burnishes that might have been caused by fine-grinding with the material too dry. The block and plates were very thoroughly washed under fast running water. Final polish was given by rouge on a pitch surface.

Silvering was done by the Brashear process. After trial four coats of ordinary thickness were deposited, the surfaces being kept under distilled water until completed.

Using a quartz-prism monochromator it was determined that polished plates with two films of silver transmitted some yellow and green as well as the 3132 A line. Through three films of silver no yellow or green could be detected, while in a well darkened room the 3132 A line could be seen to "hop" across the zinc sulphide screen as the monochromator screen passed the spectrum. Four layers of silver did not diminish the 3132 A line greatly. The sun was not visible through this thickness.

Six and ten silver films were tried. The sun could not be seen through them, nor could the 3132 A mercury line be detected although it is possible that not a sufficient amount of time was allowed for dark adaptation of the eyes to detect a very faint line. One side of each plate was carefully cleaned with nitric acid. The sun was visible as a blue disk through 3 silver layers, but could not be detected through 5.

Conclusions from these observations were that 4 or 5 layers of silver on a single quartz plate would be sufficient to keep out the visible radiation and yet thin enough to transmit the region 3050 A to 3350 A as described by Pettit (17).



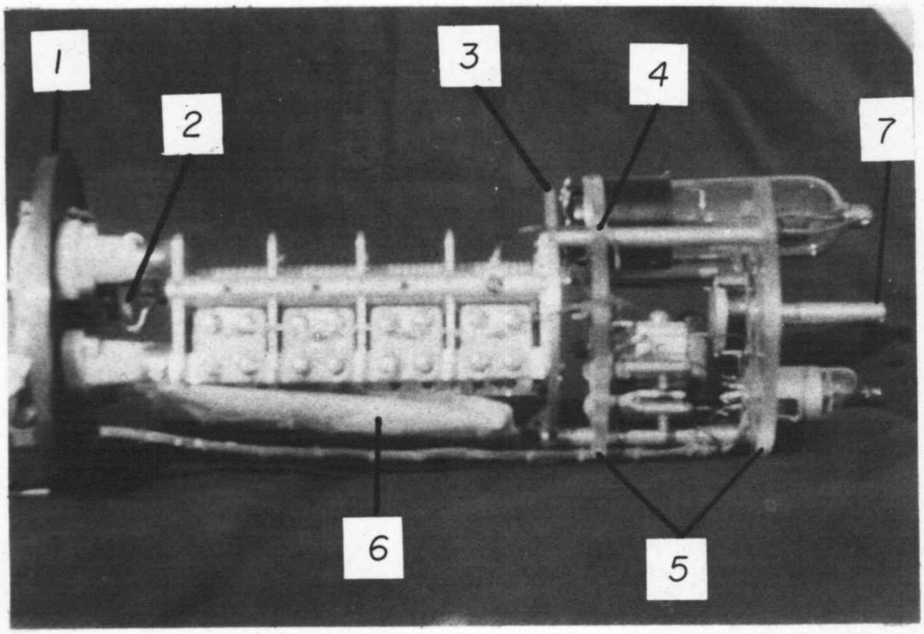
The Power Supply, Counter and Receiver

Figure 6

THE RECEIVER UNIT

The container for the receiving unit is a brass tube 4 inches in diameter and 11 inches long, closed at one end except for a central opening for adjustments which was later closed by a plate. The other end has a machined face with an O-ring rubber seal. The end plate is easily removed and has mounted on it all the parts of the receiving circuit and the receiver, except the window with the silver film filter. This is attached by a ring to a flat piece of brass which is silver-soldered to the end of the tube and admits radiation to the cathode of the phototube, Figs. 6 and 7.

An adjusting screw passing through an O-ring seal is connected by means of an insulated coupling (2, Fig. 7) to a well insulated air condenser. The condenser is mounted on the base plate (1, Fig. 7) using stand-off insulators. Three rods are mounted on a connecting plate (3, Fig. 7) on the other end of the condenser. They are slotted (4, Fig. 7) and hold two polystyrene disks (5, Fig. 7) in place. These disks serve as mounting platforms for the vacuum tube, the relay, the 0.1 microfarad condenser, the phototube, and the 20,000 ohm fixed resistor. Connections are as short as possible in the grid circuit. Screwdriver



The Receiver

Figure 7

adjustment of the 50,000 ohm rheostat (7, Fig. 7) was made through a hole in the sealed end of the tube. The leads to the weld-wire glass seals in the base plate of the container are color coded as shown in Fig. 5.

A brass fitting (Fig. 6) is fastened to the base plate so that nitrogen or dry air can fill the container to prevent leakage of charge due to the presence of moisture. Calcium chloride in a paper envelope (6, Fig. 7) was used as a drying agent during preliminary runs.

TEST OF APPARATUS

Adjustments

When the circuit was first tried a great deal of chatter was heard in the two relays. This continued after adjusting the two rheostats for proper plate current. The base plate was removed and the circuit inspected. A lead of the 0.1 microfarad condenser previously disconnected was now resoldered; one lead from the air condenser was moved farther from the other through a new hole in the polystyrene base. The insulation of the air condenser was washed off with 95% ethyl alcohol and then coated with ceresin. The envelope containing the drying agent was inserted and a waxed cork plugged into the brass fitting. A short iron bolt was screwed into the hole left for adjustment of the 50,000 ohm variable resistor. When put back into operation the pilot relay no longer chattered.

Adjustments were being made on the roof of the physics building. The counter power supply was at first taken from the lower condenser of the voltage doubler. As this was found to interfere with the proper operation of the voltage regulators, a separate half-wave rectifier was introduced as shown in Fig. 5. A 20,000 ohm resistor R_4 was placed in series with the 2,600 ohm counter. A 50,000 ohm wire-wound fixed resistor R_4 and a 0.001 microfarad condenser eliminated sparking across the pilot relay points. The resistor also acted as a bleeder. The points no longer stuck and operation was very good except for some mechanical difficulties encountered with the message register.

Results and Conclusions

Step diagrams are plotted of the average number of counts during time intervals. The resultant curves approximate curves published by Luckiesh (10, p.50) for records of the erythemal energy. Operation shows that the instrument indicates ultraviolet energy passing the transmission band of silver, 3050 A to 3350 A. Automatic recording can be obtained by substituting for the pilot relay and counter, a Streeter-Amet quarter-hour cumulative counter SCI 4. The operating current of the pilot relay in the latter must be such that it will close within the limits of the pentode and the control relay used in the receiver.

If it seems sufficiently important to measure the recognized erythemal interval 2900 to 3200 A, a Westinghouse zirconium cathode phototube, WL 767, may be inserted in place of the RCA 935 tube. Sufficient room for this tube has been allowed in the design.

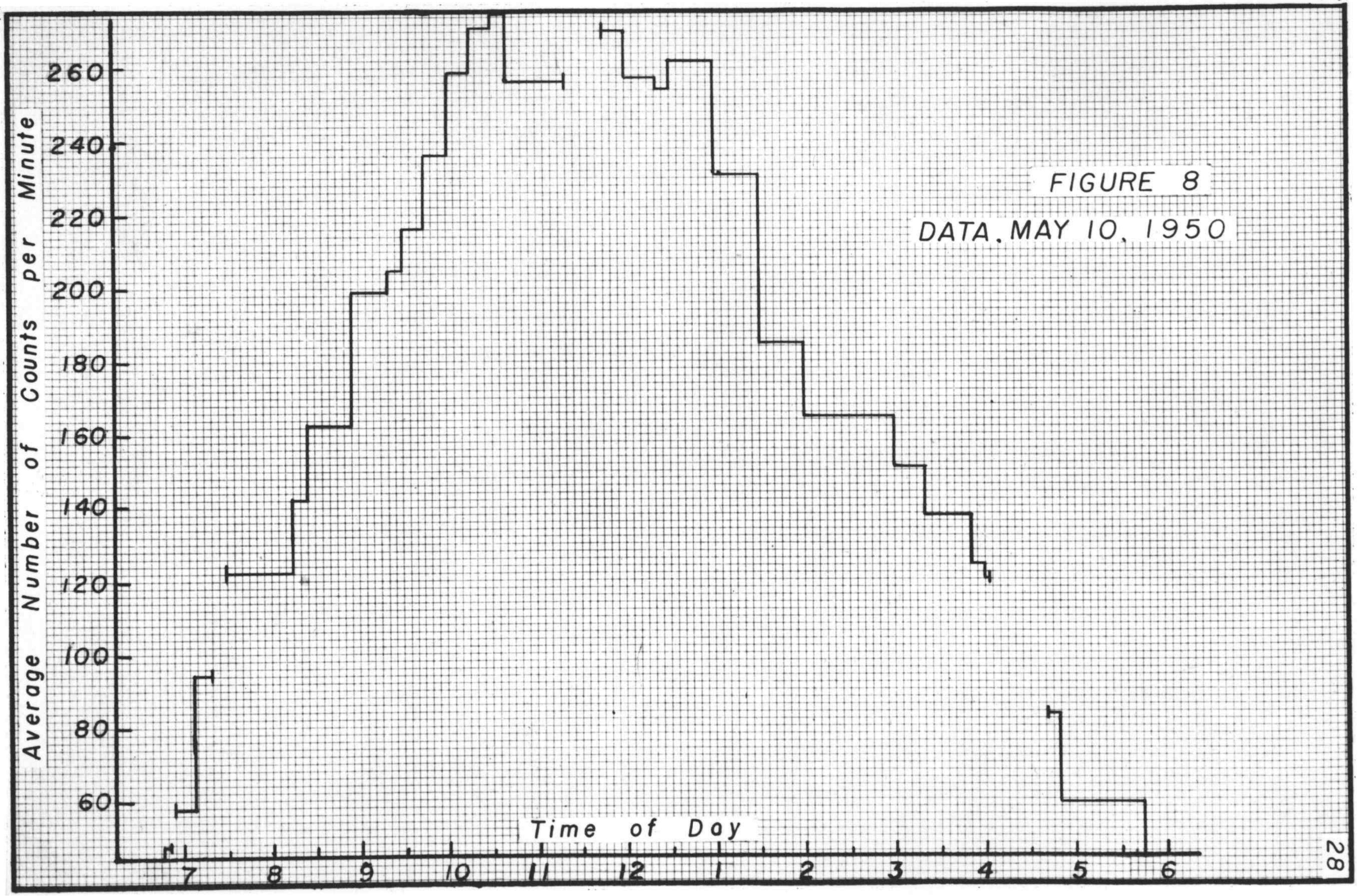


FIGURE 8

DATA, MAY 10, 1950

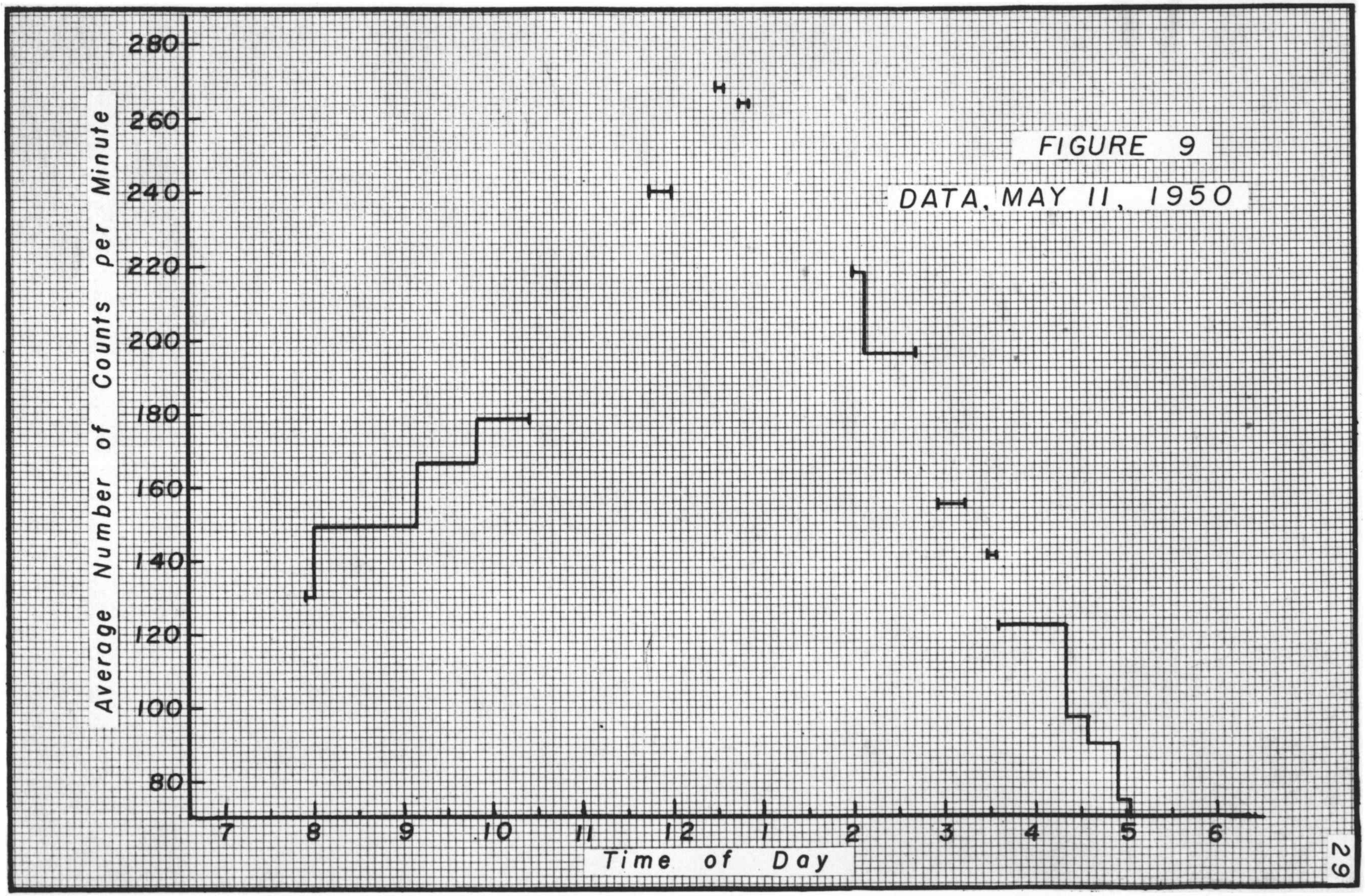


FIGURE 9
DATA, MAY 11, 1950
Average Number of Counts per Minute
280
260
240
220
200
180
160
140
120
100
80
7
8
9
10
11
12
1
2
3
4
5
6
Time of Day

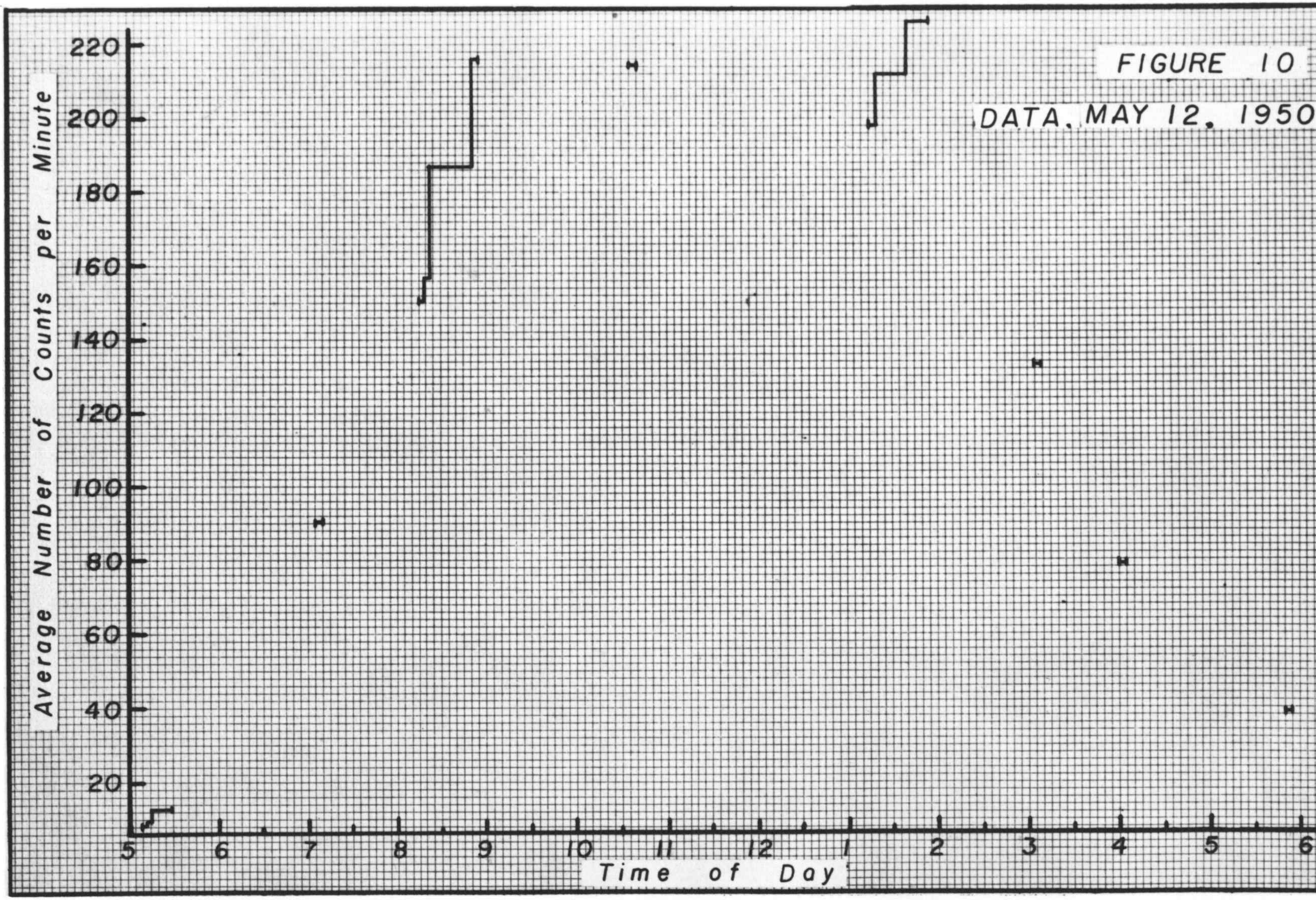


FIGURE 10
DATA, MAY 12, 1950
Average Number of Counts per Minute
220
200
180
160
140
120
100
80
60
40
20
5
6
7
8
9
10
11
12
1
2
3
4
5
6
Time of Day

DATA

May 10, 1950

Hazy throughout the day

Time of Day	Reading on Recorder	Average No. of Counts/Min.	Interval of Time in Minutes
7:47	2703		
7:52	2940	47	5
7:55	3069		
8:00	3334	53	5
8:04	3569	59	4
8:08	3793	56	4
8:20	4925	94	12
8:30	5711		
9:15	1203	122	45
9:25	2623	142	10
9:55	7495	162	30
10:20	2470	199	25
10:30	4520	205	10
10:45	7760	216	15
11:00	1309	237	15
11:15	5195	259	15
11:30	0261	271	15
11:40	2010	275	10

May 10, continued

Time of Day	Reading on Recorder	Average No. of Counts per Minute	Interval of Time in Minutes
12:00	7140	257	20
12:20	2270	257	20
12:45	5330		
1:00	9384	270	15
1:20	4535	258	20
1:30	7080	255	10
2:00	4960	263	30
2:30	1900	231	30
3:00	7455	185	30
4:00	7370	165	60
4:21	0545	151	21
4:53	4952	138	32
5:00	5820	125	7
5:42	9718		
5:50	0384	83	8
5:46	3693	59	56

May 11, 1950

Hazy throughout the day

Time of Day	Reading on Recorder	Average No. of Counts per Minute	Interval of Time in Minutes
7:00	4559		
7:04	4685	32	4
7:10	4893		
7:25	5478	45	4
8:57	6420		
9:00	6810	130	3
10:08	6925	149	68
10:30	0181	167	22
10:50	3527	167	20
11:25	9430	169	35
12:45	5290		
1:00	8888	240	15
1:32	2020		
1:34½	2790	308	2½
1:37	3470		
1:44	5598	304	7
3:02	5854 (counter	132 stuck)	78
3:08	7148	218	6
3:42	3840	197	34

May 11, continued

Time of Day	Reading on Recorder	Average No. of Counts per Minute	Interval of Time in Minutes
4:00	6620		
4:37	2542		
5:23	8170	122	46
5:56	1230	90	21
6:03	1760	76	12
8:03	4098	20	120

May 12, 1950

Time of Day	Reading on Recorder	Average No. of Counts per Minute	Interval of Time in Minutes	Condition of Sky
6:11½	4115			
6:12½	4123	8	1	
6:15	4145	9	2½	
6:30	4330	13	15	heavy clouds
8:04½	8737			
8:07½	9009	91	3	clearing
9:14	7480			
9:15	7630	150	1	"
9:18	8100	157	3	"
9:50	4073	187	32	scattered clouds
9:52	4505	216	2	
11:36	7240			
11:39½	7990	214	3½	"
2:15	1545			
2:17	1942	199	2	heavy clouds
2:41	7018	212	24	windy, clouds shifting
2:51	9275	226	10	
4:05½	2696			
4:07	2898	134	1½	heavy clouds
5:05	9936			
5:06½	0054	79	1½	"

May 12, continued

Time of Day	Reading on Recorder	Average No. of Counts per Minute	Interval of Time in Minutes	Condition of Sky
6:51½	5813			
6:53	5870	38½	1½	heavy clouds
8:15	6914			

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