THESIS

on

STANDARDIZATION OF PHOTOTUBE TESTS AND RATINGS

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STANDARDIZATION OF PHOTOTUBE TESTS AND RATINGS

1.0 Introduction

1.1 Purpose of Investigation.- It has been only a few years since the phototube was sufficiently perfected to warrant its use in commercial and industrial devices. However, during the past three or four years many applications have been made, a partial list of which would include talking pictures, television, smoke recorders, signaling systems, color analyzers, photometers, and numerous others.

Due to this rapid extension from the research laboratory to the industries, manufacturers have been chiefly concerned with the problem of making more uniform and more sensitive phototubes, and consequently have been interested in developing simple methods of comparing the relative merits of their own and competitive phototubes rather than standardizing upon circuits and conditions for making tests. Since there is no certainty that all have adopted the same methods and practices, there is a possibility for some confusion in judging the relative merits of phototubes offered by the various manufacturers. It will be shown that curves and test data are sometimes given with little or no information as to certain factors which would cause considerable variation in the results obtained.

It is the purpose of this investigation to obtain and present information regarding the tests made on phototubes; to show that differences in test conditions and equipment sometimes produces great differences in the output characteristics of phototubes; and to point where, in the opinion of the author, the adoption of standardization of certain equipment or practices would be of benefit to the industry.

1.2 Method of Investigation.- The general method followed in conducting the investigation has involved the obtaining of data from manufacturers' experience as well as from personally conducted experiments. This has necessitated the collecting of a large amount of information from manufacturers of phototubes, and a survey of articles and books published on photoelectricity and light. Wherever possible, laboratory data are given in support of conclusions arrived at as a result of the study of this information.

1.3 Acknowledgments.- Acknowledgment is made of the assistance and cooperation received from the several manufacturers of phototubes who contributed data for this investigation.[1] Full recognition is here given as sources of information are not specifically referred to in the report except where permission was given or the material obtained from bulletins, books, or technical journals.

The author wishes to express his appreciation to Mr. A. L. Albert, Assistant Professor of Electrical Engineering, for his advice and direction; Dr. W. Weniger, Professor of Physics; and Mr. L. F. Wooster, Professor of Applied Electricity, of the Electrical Engineering Department, for assistance and information given by them on the theory of light; and to Dr. Weniger for the use of the Physics Laboratory, where considerable experimental work was done.

Part One: Introductory Theory

2.0 Radiation

2.1 Photoelectric Effect and Radiation.- The phenomenon known as the photoelectric effect is the emission of electrons from a body when it is exposed to certain electromagnetic radiations.

2.3 Nature of Radiation.- The exact nature of radiation is not known, but it may be thought of as the energy associated with electromagnetic oscillations propagated through space. The known spectrum of radiant energy extends through a wave-length range of from about 10^{18} to 10^{-4} Ångstrom units (10^{-8} cm.). That part of the spectrum which begins in the infra-red and extends through the visible into the ultra-violet is that which is emitted by common light sources and, therefore, is most important in the consideration of commercial photoelectric devices. Relative to the whole spectrum this band is extremely narrow, extending only from 3×10^3 to 2.6×10^4 Ångstrom units.

2.3 Measurement of Radiation.- Total energy, as well as the energy of various parts of the spectrum, is ordinarily measured by bolometers or thermopiles, instruments which depend upon the conversion of radiant energy into heat to produce measurable changes in electrical circuits. The bolometer is a sensitive electric thermometer incorporated in a Wheatstone bridge circuit; and the thermopile is a small thermocouple or multiple thermocouple constructed of alloys which develop a relatively high e.m.f. with small differences in temperature between junctions.

2.4 Radiation and Temperature.- Measurements of radiant energy from heated bodies are given in terms of radiation from a perfect emitter known as a "black body." This is necessary because no object is a perfect absorber or emitter of radiant energy. This fact was the basis for Kirchhoff's law, which is the foundation of all theoretical deductions regarding incandescence, and which states that a body which is a good absorber is also a good radiator, and in the same proportion. This may be stated mathematically as

$$E_n = a_t E_b$$

where E_n is the radiation for a unit area of a non-black body, a_t is the total absorptivity of the non-black body, and E_b is the radiation for a unit area of a black body. The ratio between the relative intensities of radiations from non-black and black bodies is the total emissivity or total emissive power of the non-black body; thus if this ratio be designated as e_t, then

$$e_t = a_t$$

Likewise, for radiations of a given wave-length

$$E_\lambda = a_\lambda E_\lambda$$

$$a_\lambda = e_\lambda$$

This relation is important because some radiating bodies are selective; that is, their spectral emissivity is not constant for all wave lengths.

Four fundamental laws of black body radiation will now be given:[3]

The Stefan -Boltzman law,

$$E = \delta T^4$$

where E is the rate of emission of total energy, T is the absolute temperature in degrees Kelvin, and δ is a constant numerically equal to a value approximating 5.70×10^{-12} watts per sq. cm. deg.^{4}.

Planck's law,

$$E_\lambda = \frac{C_1}{\lambda^5} \frac{1}{\epsilon^{C_2/\lambda T} - 1}$$

in which λ is the wave-length in microns (1×10^4 Ångstrom units), E_λ any ordinate of the spectral energy curve in watts per square centimeter per centimeter interval of wave length, and C_1 and C_2 are constants whose respective values are approximately 3.72×10^{-12} watts per sq. cm. and 1.433 cm. degrees. This equation tells how the wave length changes with a change in temperature; and the form of the curve expressing the distribution of energy. Curves drawn according to this equation are shown in Fig. 1.

Wien's distribution law,

$$E_\lambda = \frac{C_1}{\lambda^5} \epsilon^{-C_2/\lambda T}$$

is an approximation of Planck's law which may be used for visible radiation.

Wien's displacement law,

$$\lambda m\ T = C_2 / 4.9651$$

which shows that an increase is accompanied by a shift in wave length for which the ordinate of the spectral energy curve is a maximum, λm, from the infra-red toward the ultra-violet end of the spectrum.

2.5 Visible radiation.- For most applications of the photoelectric effect, that part of the radiation spectrum which manifests itself as light is the most important. For this reason it has become the custom to evaluate the output of photoelectric devices in terms of the light flux falling upon it.

Unfortunately, the measurement of intensities of light sources is based upon principles that allow a certain amount of uncertainty to appear in the results. This is due to the fact that the measurements are concerned with the ability or capacity of light to affect the eye, which introduces confusion for two reasons: first, the response of the eye to light is not proportional to the intensity,

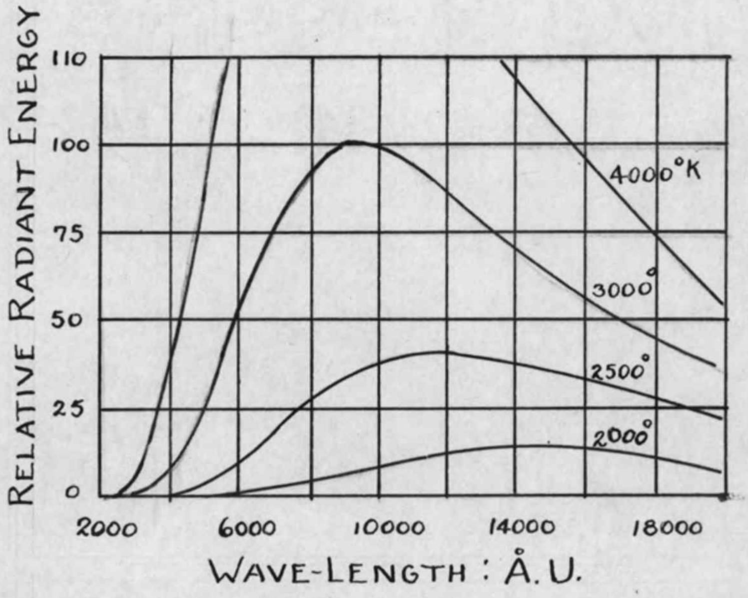


FIG. 1a. SPECTRAL DISTRIBUTION OF BLACK BODY RADIATION[2]

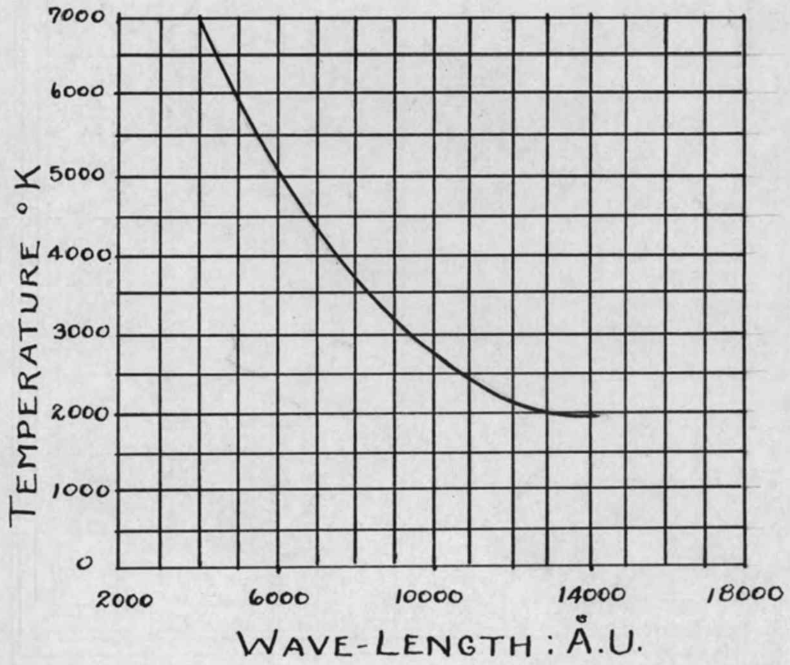


FIG. 1b. SHIFT OF WAVE-LENGTH OF MAXIMUM ENERGY

for as the source becomes increasingly bright the less sensitive the eye becomes to a given increment of increase; second, the eye is not equally affected by the different colors of the spectrum, being most sensitive to yellow-green, which occurs at a wave length of about 5500 Ångstrom units (see Fig. 2). To complicate the situation still more, eyes of different individuals may vary in ability to judge between the light-giving power of two sources. It is therefore extremely important in photoelectric work to distinguish between the actual radiant energy and the luminous radiation as judged by the eye.

In the comparison of light sources there are five fundamental concepts that must be taken into account: flux, intensity, illumination, brightness, and color. Of these luminous intensity is the original and the fundamental quantity although it is defined in terms of the luminous flux which is now considered the basic concept.

Light flux is the amount of light emitted through a solid angle of any size. Its unit is the lumen when the flux is equal to that emitted in a unit solid angle by a source of one candle.

The intensity of a source of light is defined as the amount of light emitted through a cone whose solid angle is unity. Its numerical value is given in terms of candles.

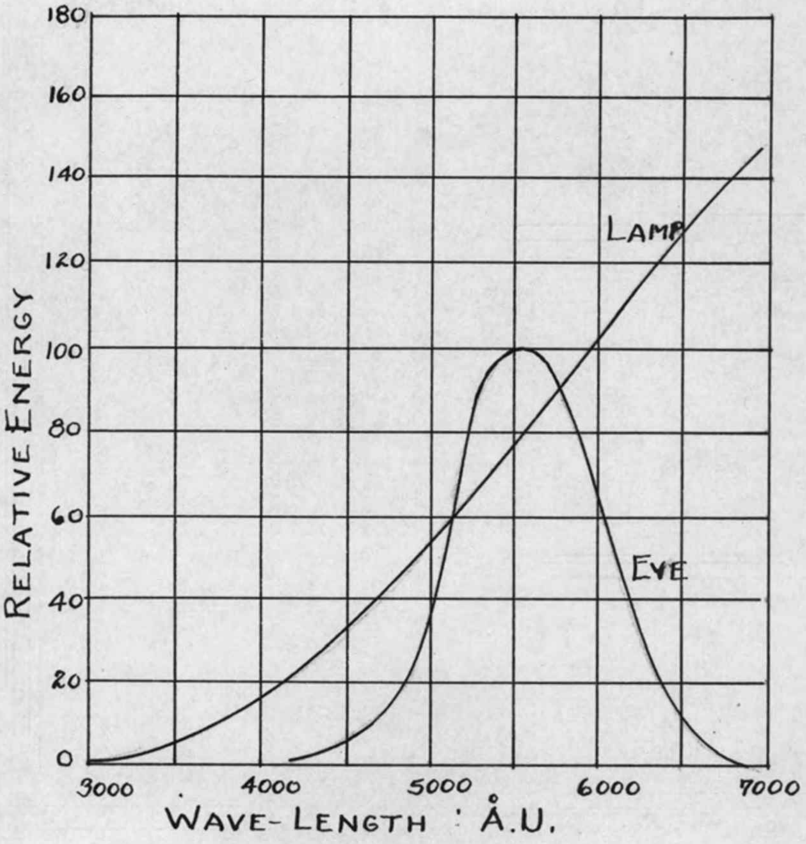


FIG. 2. ENERGY DISTRIBUTION OF GAS FILLED TUNGSTEN LAMP AND THE RELATIVE VISIBILITY OF THE EYE[3].

The illumination of any illuminated surface is the luminous flux falling upon it divided by the area of the surface projected upon a plane perpendicular to the direction of the source. It is dependent upon two fundamental laws: the inverse square law, and the cosine law. The first of these states that the illumination is inversely proportional to the square of the distance to the source; and the other, that the illumination is proportional to the intensity times the cosine of the angle of incidence. Of the several units proposed, the most popular is the foot candle, which is the illumination of a plane surface one foot from a standard candle when the light falls perpendicularly upon the surface. The value may be determined from the equation,

$$E = (I \cos \theta)/ d^2$$

where I is the illumination, θ the angle of incidence, and d the distance from the source.

Brightness is the luminous intensity per unit of projected area. It sesults from the ability of materials to absorb, transmit, and reflect light. differences of brightness result in contrast. As no material obeys Lambert's cosine law exactly, the brightness must be understood to mean that it has the appearance of a perfectly diffusing surface which would have the same brightness.

<u>Color</u> is due to certain stimuli on the retina of the eye produced by radiation frequencies within the visible range of from 4000 to 8000 Ångstrom units. The lowest frequencies produce the sensation of red, and the highest that of violet, while in between these two extremes is the full spectrum as produced by the refraction of white light by a prism. The eye is not equally sensitive to all colors of the spectrum, but favors blue-green, which is at a frequency of about 5550 Ångstrom units. Furthermore, the color sensitivity of eyes of different individuals varies, hence the comparison of sources varying in color is not a definite art, but a matter of personal judgment. No standards for colored sources have been agreed upon, so there is but one standard source, the pentane lamp.

2.6 <u>Photometry</u>.- The art of photometry or the measurement of light intensities is based upon the inverse square law and the fact that the eye is sensitive to differences in brightness. The most common instrument used in the comparison of light sources is the bar photometer with the Lummer and Brodhun photometer-head. This consists of a track at one end of which is the standard source, and at the other the unknown. In between is the movable photometer-head by means of which diffusing surfaces illuminated by each of the sources may be viewed simultaneously. The distance between the photometer-head and either or both lamps is varied until the two surfaces appear to be equally bright; the square of the distance from the photometer-head to the test lamp is then related to the square of the distance to the standard lamp as the candlepower of the test lamp is to that of the standard lamp.

Measurements are difficult when there is a difference in the colors of the sources, as there is then the problem of comparing both color difference and brightness. Several methods have been used to take care of differences in color; the cascade method, compensating filters, the flicker photometer, and the spectrophotometer.

The cascade method consists of dividing the color difference into small steps by the interposition of sources giving intermediate colors. This method has the disadvantage that an operator who favors the whiter light will do it consistently with the result that errors will accumulate.

By placing the proper filter between one of the light sources and the photometer-head, the colors can be made to match. The difficulty encountered in this method is that each new source needs a new filter to obtain the proper match, and each change in filter means that the transmission factor must be determined for that color of light.

The flicker photometer-head consists of a rotating mechanism which causes the field of view to be illuminated alternately by the lights differing in color. At the proper flicker speed the flicker disappears when the fields are of equal brightness. It is thought that this method agrees with results obtained by the cascade method or by direct comparison only under certain critical conditions of field area and brightness.

Spectrophotometry is the art of comparing relative radiant flux intensities of various wave lengths in the visible spectrum. This gives purely relative results as there are no standards of candlepower for other than white light. This is the most analytical method of determining the quality of light, as it provides a means of comparing the sources wave length by wave length.

3.0 Photoelectric Effect

3.1 Photoelectricity.- There are three photoelectric phenomena which may be produced by light energy: (1) change in ohmic resistance of matter, as in the selenium cell, (2) chemical or physical reaction to produce an e.m.f., as in the copper- copper-oxide electrolytic cell, and (3) the actual liberation of electrons from an electrically conducting body, as in the phototube. The most useful of these at present is the third, which is the true photo-emissive effect.

3.2 Einstein's Equations.- The theory of the photo-emissive effect is best explained by the Planck quantum theory of radiation which states that the energy of light radiation is not distributed continuously in space, but as the radiation spreads out from the source it remains localized in small bundles or quanta which become farther apart as they recede from the source. On the basis of this theory, Dr. Albert Einstein suggested that the simplest explanation would be that the light quantum gave up all its energy hv to the electron, h being Planck's universal constant, and v the frequency of the radiation. It follows that the kinetic energy possessed by the electron would then be hv - P, where P represents the energy lost by the electron in freeing itself from the influence of surrounding atoms while leaving the parent body.

The electrons in an atom may be considered to occupy levels which are characterized by certain definite amounts of energy; hence, light of frequency v incident upon a number of atoms would liberate electrons from a number of energy levels, but none from the levels characterized by amounts of energy more than the energy hv of the quantum. It must then be concluded that if for an electron, P just equals hv, the energy of the quantum is used in extracting the electron. The kinetic energy imparted is, therefore, zero; and there is a minimum frequency below which no electrons will be liberated. It is then possible to say that P is hv_0, where v_0 is the minimum frequency, and that the energy of the electron emitted is $h\ (v - v_0)$. By expressing this as the potential fall in volts it is found that the total kinetic energy imparted as expressed by Einstein's equation is

$$Mc^2\left(\frac{1}{\sqrt{1-\beta^2}} - 1\right) = h(v - v_0) = Ve$$

where m is the mass of the electron, c the velocity of light in a vacuum, β the velocity of the electron, V the potential fall in volts an electron β must pass through to acquire this energy, and e is the charge on the electron in electrostatic units.

3.3 Laws of Electron Emission.- As a result of Einstein's theory of photoelectricity are the following conclusions or laws: (1) the number of electrons released per unit time at a surface is exactly proportional to the intensity of a given quality of incident radiation; (2) for a given surface, there always exists a minimum frequency of radiation, below which absolutely no photoelectric emission is produced; (3) for any surface, the maximum energy of emission of an electron is exactly proportional to the highest frequency present in the incident radiation and is independent of the intensity of the radiation.

Part Two: Analysis of Technical Data

4.0 Sources of Information

The data used in the following discussion is based upon bulletins, descriptive matter, instruction sheets, articles in technical journals, correspondence with manufacturers, and upon personal experiences in a vacuum tube department of an electrical manufacturing concern. No claim is made that further information could not have been obtained from any one company, but only that the data used are authentic and were sent in response to information regarding the tests made on phototubes.

5.0 Types of Phototubes Considered

Phototubes are of two types, the vacuum and the gas filled. The former operates as a true photo-emissive device wherein the current consists only of the flow of electrons emitted from the sensitive surface by the incident light flux. In the latter, the true electron current is amplified by the production of secondary electrons by collision of the primary electrons with the atoms of an inert gas in the tube, and by secondary emission from the cathode by the bombardment of positive ions drawn to it by the electric field. This increases the sensitivity with a sacrifice of constancy, linearity, and equal response at all frequencies; hence tests and rating recommended for one type of tube should not necessarily apply to the other.

Since the Arcturus Photolytic Cell, a photo-voltaic cell, is being advertised and sold as a competitor of the phototube, some of the tests which are applied to it and which are applicable to the phototube will be discussed.

6.0 Leakage Currents

6.1 Leakage.- For satisfactory operation of phototubes the leakage between the cathode and anode should be small; particularly is this true for the vacuum type tube which is relatively insensitive. The most common source of leakage is in the socket, or from anode to cathode connections. With an excess of active material, particularly caesium[2], the vapor pressure at ordinary temperatures may be low enough to cause appreciable distillation and subsequent condensation between internal connections, this increasing the internal leakage.

6.2 Precautions against leakage.- Manufacturers have admitted the importance of leakage in the following ways: (1) incorporation of a guard ring as a part of the phototube which may be negatively charged or connected to the ground,[4,5] as shown in Fig. 3.; (2) Statements in literature cautioning users that high temperatures will vaporize the active materials and deposit it elsewhere, thus increasing the leakage.[6]

6.3 Leakage Tests.- In their technical bulletins, no company stated within what limits leakage was kept for their product. Inquiry revealed that phototubes are commonly given production tests for leakage, the "dark current" being read at normal voltage. The maximum leakage allowed was 0.03 micro-amperes. This test was given both vacuum and gas filled phototubes.

7.0 Fatigue

7.1 Importance of Fatigue.- Fatigue in gas filled phototubes is admitted by all authorities. It is due to photo-chemical action of the bright light on the sensitive surface. Since gas filled phototubes are not recommended in calibrated circuits, fatigue is not important, as any dropping off of the current may be corrected by increasing the anode voltage, thus increasing the sensitivity.

In vacuum phototubes, however, fatigue is important, as the only reason for using this type of tube is that it may be used as a calibrated instrument for purposes of measuring light intensity or quality.

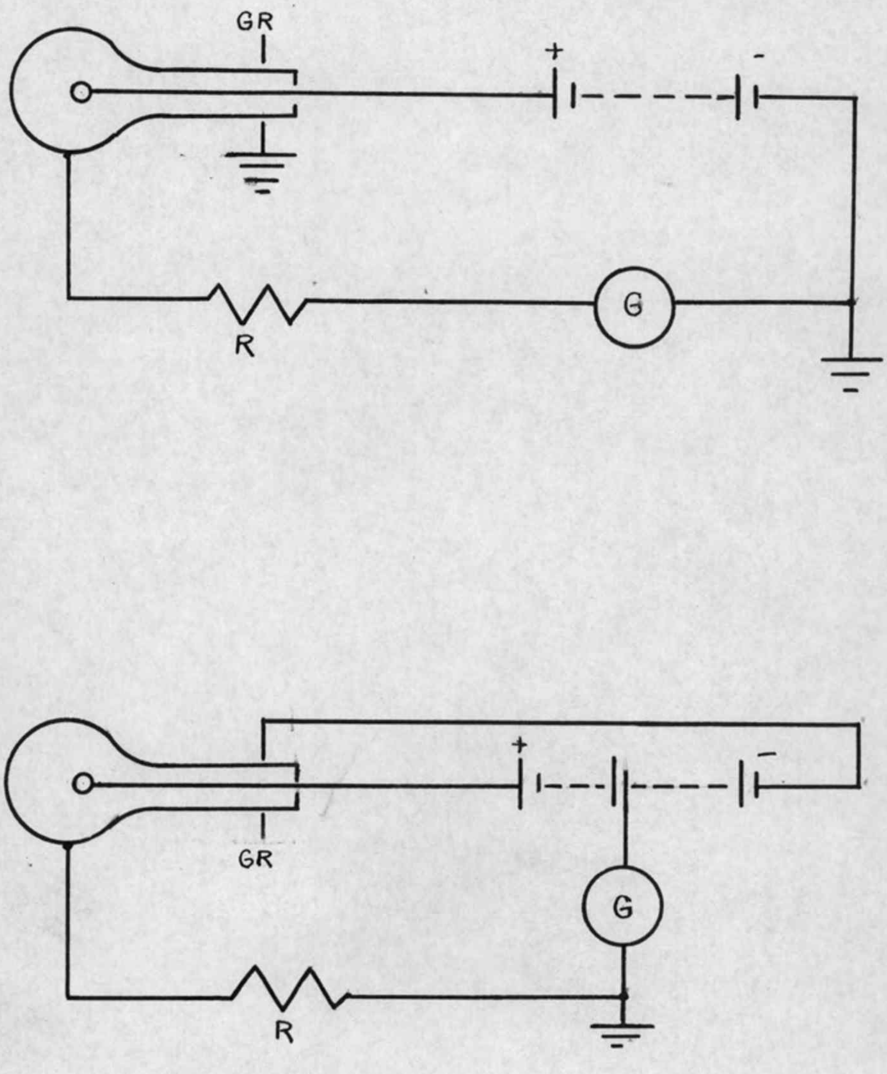


FIG. 3. GUARD RING (GR) PREVENTS LEAKAGE CURRENT[5]

7.2 Tests for Fatigue.- Certain manufacturers are known to make fatigue tests on their products. Apparently, however, only one company cared to give results of such tests. The R. C. Burt Scientific Corporation[4] described a very thorough and exacting test made on their sodium type vacuum phototube. It was stated that a voltage-current curve was taken with a flashlight bulb, after which the phototube was exposed to direct sunlight for two days; a second curve taken immediately afterward gave a result in complete agreement with the first.

Due to the importance of fatigue, more recognition should be given it in technical information regarding phototubes, and if it is absent it should be so stated.

8.0 Spectral Sensitivity

8.1 Variation with Atomic Number.- The color sensitivities of the various phototubes depend upon the alkali metals of which they are made. Miss E. Seiler[7] has shown that the wave length of maximum sensitivity increases in the same order as the atomic number of the alkali elements, and that the relative magnitude of the number of electrons released decreased in the reverse order.

8.2 Spectral Energy Curves.- The common practice among manufacturers is to give spectral energy curves showing relative response to light of various wave lengths. Only two variations were found to this practice: The Arcturus Radio tube did not give a spectral energy curve for their Photolytic Cell;[8] and The R. C. Burt Scientific Laboratories gave the current output of their phototube through Wratten stained gelatin light filters.[4] This gives definite indications of the color characteristics of the tube to one familiar with these filters, but the spectral sensitivity curve seems to be preferable from the engineering standpoint although it might be supplemented by the filter data for the benefit of those familiar with photographic practices. Fig. 4 shows examples of such curves.

9.0 Frequency Characteristics

9.1 Dynamic Response of Phototubes.- The output of the vacuum type of phototube follows fluctuations of light with great fidelity because the electrons emitted from the sensitive film reach the anode almost instantly. When gas is present in the tube, positive ions are created by the collision of the electrons with the gas atoms. These are relatively immobile, and require a finite time to reach the anode where they may strike with sufficient speed to cause new electrons to be emitted. This causes the current to lag slightly behind the rapidly fluctuating light flux

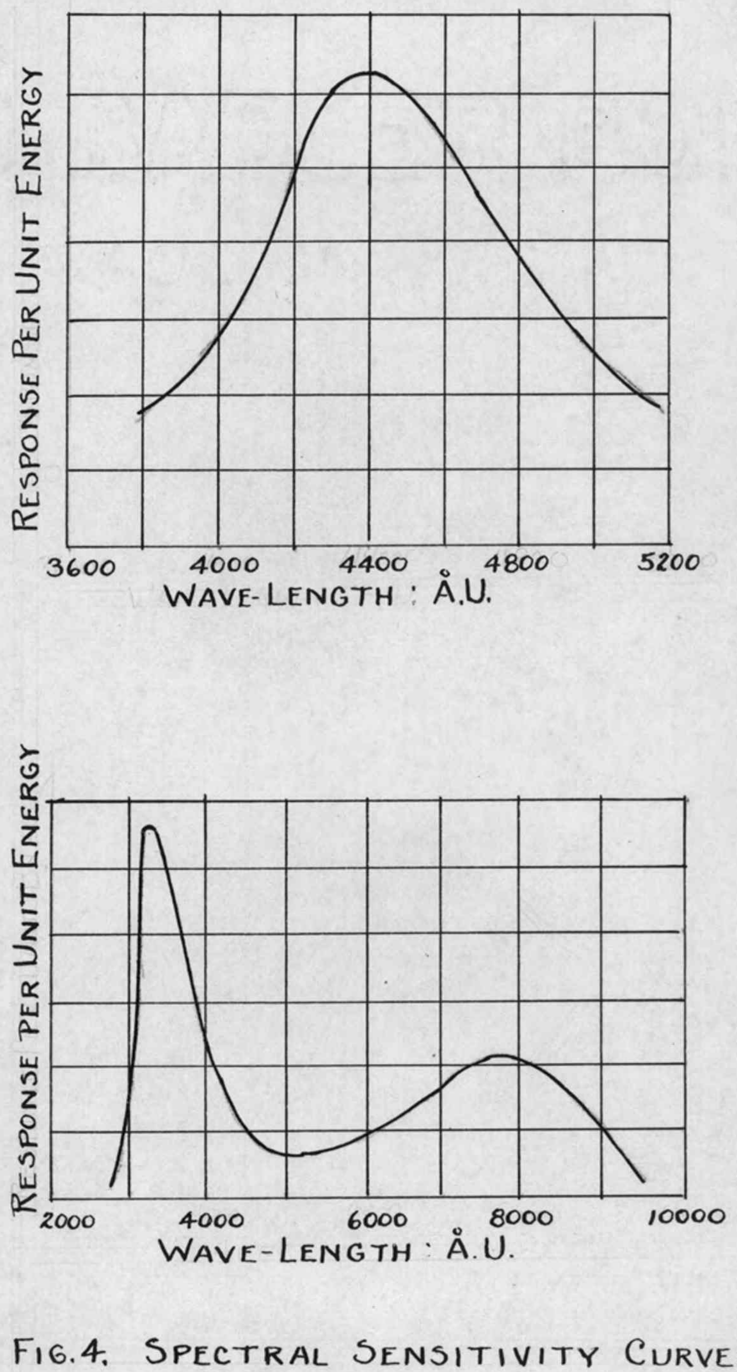


Fig. 4. Spectral Sensitivity Curves[6]

which produces it. The dynamic response of a phototube for a given frequency of light modulation is defined as the alternating current component of the current produced by the light.

9.2 Commercial Importance of Frequency Characteristics.- No curves were given by any of the companies except the Arcturus Radio Tube Company[8], who included a curve giving decibels output against frequency although most manufacturers stated that there was a decrease in current output at high frequencies. The importance of this characteristic is limited almost entirely to the talking picture and television field, where the design engineers are familiar with phototube characteristics. The current output of the gas filled tube is not constant enough to allow calibration; and for most applications outside the fields just mentioned, the decreased output at the higher frequencies may be corrected by increasing the light intensity or by raising the anode voltage. Another factor which decreases the importance of frequency characteristics is the fact that they depend to a great extent on the type of gas used, since the mass of the atom determines the mobility of the positive ion if other factors are constant. Zworykin and Wilson of the Westinghouse Research Laboratories state that the gas almost universely used is argon on account of its abundance and low cost.[2]

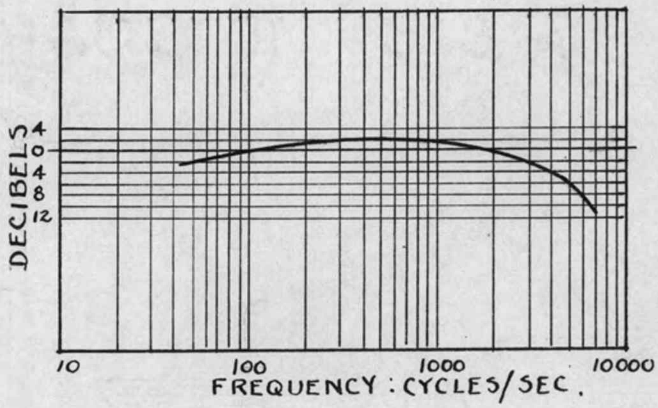
9.3 Methods of Test.- However, if frequency characteristics curves are to be given they should be a type such as to allow comparison with those given by others. The Arcturus Radio Tube Company[8] gives the curve shown in Fig. 5, with the following statement: "The Arcturus Photolytic Cell responds to all frequencies within the audio band with a higher degree of fidelity than has ever been obtained with other cells." Presumably, this curve was made by means of a chopper wheel and calibrated output meter.

Opposed to this was found a statement in the literature of the Jenkins Television Corporation[5], who included no curve, to the effect that, "A study of the characteristics of other types of photoelectric devices, such as the photoconductive cell, best represented by the well known selenium cell, and the photovoltaic cell, in which the photoelectric action takes place upon a liquid electrolyte and metal electrodes, has shown that for linear response and speed of response characteristics, there is no near approach in the art of photoelectric devices to the vacuum and gas filled cells, and it is for this reason that the Jenkins Laboratory work has been confined to this type of cell only."

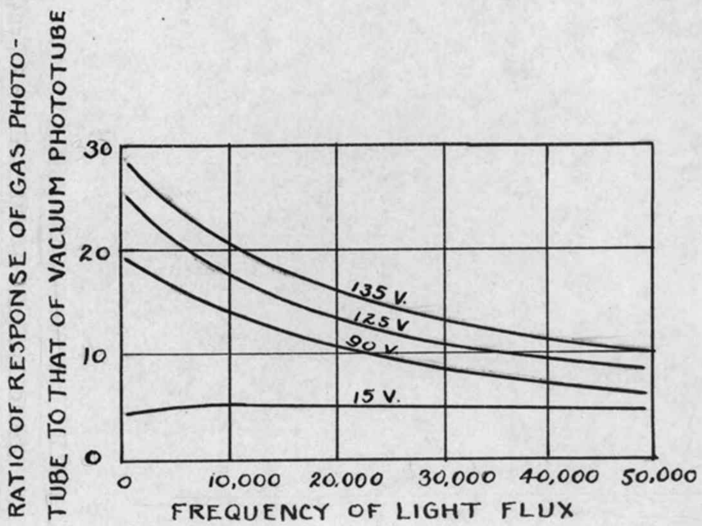
Zworykin and Wilson[2] use a method which they state eliminates characteristic distortions due to the mechanism producing the fluctuations or to the amplifiers. A neon glow tube was used as a light source. Their description of this method is as follows: "The output of an audio oscillator generating sine wave voltage at calibrated frequencies was fed into an amplifier which in turn supplied the potential for the glow tube. The circuits were so devised that a definite direct current could be sent through the tube and, super-imposed, also a definite alternating current of a known frequency. The fluctuating glow was caused to shine into a photocell which was coupled to an amplifier and meter. Only changes in photocell current could pass through the amplifier; the steady current in the cell had no effect on the meter reading. Thus a response curve was first taken with a high vacuum cell and then with a gas cell under exactly the same conditions of operation of the glow tube. Dividing the reading for the gas cell by corresponding reading for the vacuum cell eliminated any characteristic distortions due to the glow tube or to amplifiers." The curve obtained is shown in Fig. 5. Due to the advantages stated, this method is probably preferable to the simpler method used by the Arcturus Company.

10.0 Ionization Voltage

10.1 Cause and Importance of Cumulative Ionization.- The current-voltage relation for vacuum and gas phototubes



a. CURVES TAKEN BY MEANS OF CHOPPER DISK[8]



b. CURVES TAKEN BY MEANS OF NEON TUBE[2]

FIG. 5. DYNAMIC RESPONSE CURVES

are shown in Fig. 7. The initial rise is due to there being, at first, more electrons emitted than can be captured by the anode at low voltages. At a certain voltage all the electrons given off are drawn to the anode, and the curve flattens out. If the tube is of the vacuum type further increase in voltage will not cause an appreciable increase in current; but if the tube contains gas, at some higher voltage ionization by collision will begin with resulting secondary emission from the cathode. As the voltage is further increased the sensitivity of the tube increases until the curve rises almost vertically, and a point is reached where cumulative ionization and glowing begins and continues even if the light source is withdrawn. When operating in this condition current will rise to values which would damage sensitive instruments in the circuit unless protected by resistances, and the tube is subject to serious damage.

10.2 Methods of Determining the Ionization Voltage.- The simplest and most accurate method for determining the ionization voltage is that used by the National Carbon Company[6] for their Eveready Ratheon Fotocells: a resistance of 100,000 ohms is placed in series with the tube and the voltage raised until a sudden increase in current is indicated by a microammeter in series with the tube. The circuit used was that shown in Fig. 6. This would be

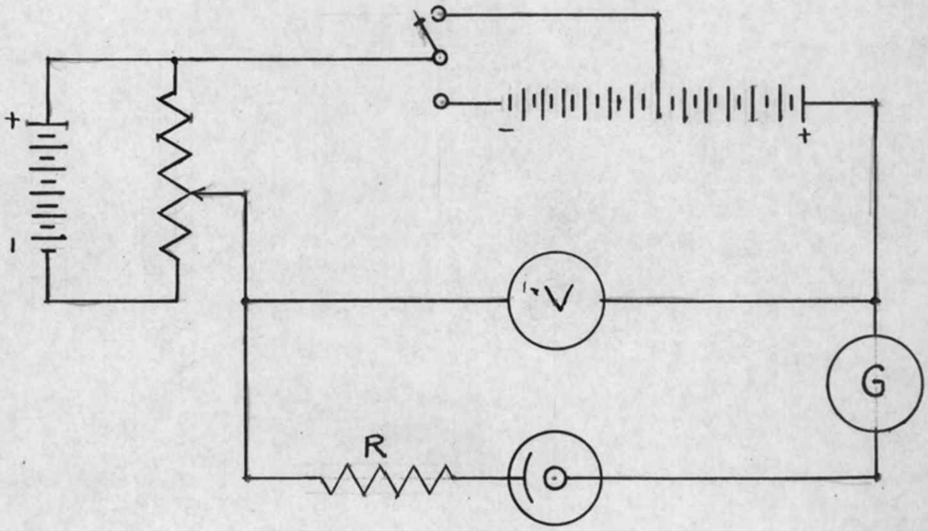


FIG. 6. CIRCUIT FOR PHOTOTUBE TESTS

damaging to some types of tubes, however, and other methods have been developed. The G-M Laboratories[9] determine the approximate ionizing potential by allowing a flux of 0.05 lumens to fall on the phototube, and judging from the voltage which produces a current of 25 micro-amperes what the true cumulative ionization of the tube will be.

Regardless of the manner of securing the data, the ionization voltage at some value of light flux should be given for the phototube, and it would be well to follow the practice of the G-M Laboratories in providing a curve showing the relation of the maximum operating voltage permissible under any given condition of illumination. Fig. 8 shows such a curve.

11.0 Sensitivity

11.1 Factors Influencing Sensitivity.- From the previous discussions it has been evident that as far as operating conditions are concerned that there are four things which influence the output of the phototube: (1) the color of the light source, (2) the total incident light flux, (3) the operating voltage, and (4) the modulation frequency of the light source. It is further apparent that the slope of the current-light flux curve (Fig. 9) is a measure of the response of the phototube to the light flux

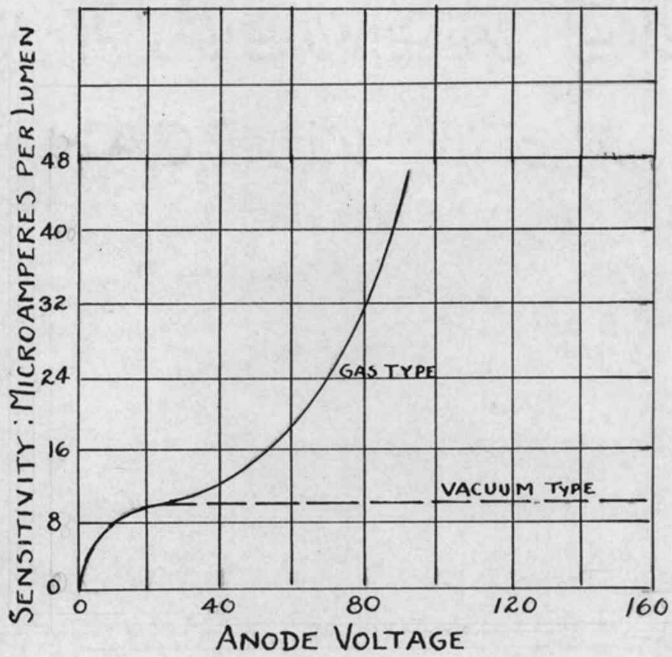


Fig. 7. Sensitivity- Voltage Characteristics[9]

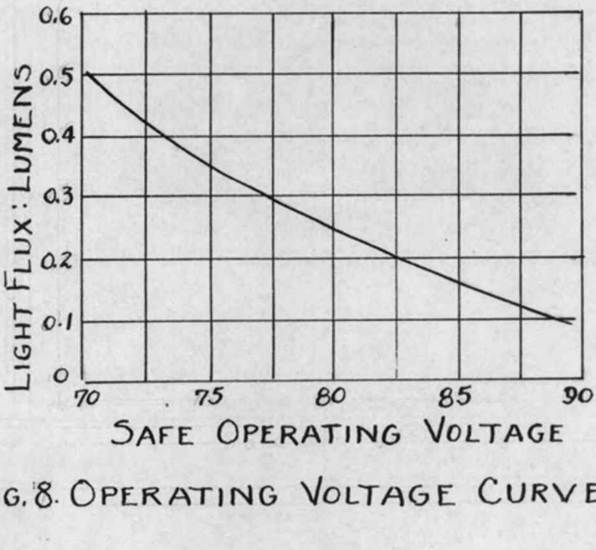
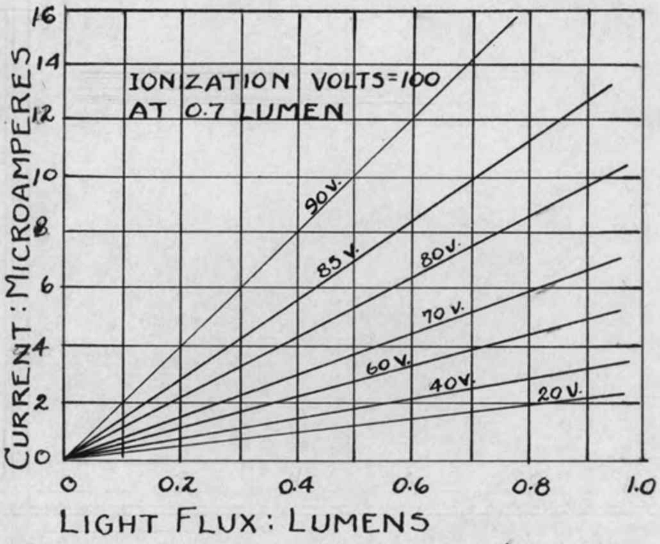
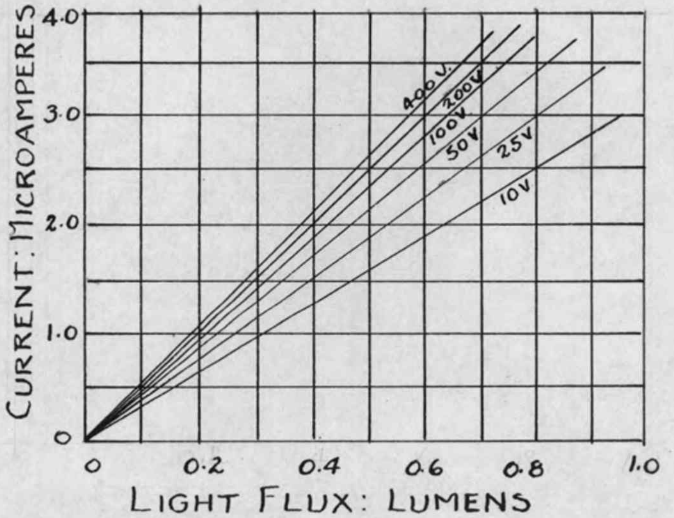


Fig. 8. Operating Voltage Curve[9]



a. GAS TYPE PHOTOTUBE[6]



b. VACUUM PHOTOTUBE

FIG. 9. CURRENT-ILLUMINATION CURVES[6]

under the conditions at which the curve was taken. It has been the custom among all manufacturers of phototubes to give the sensitivity in micro-amperes of current output per lumen of light flux at some specified voltage and quality of incident light.

112. Types of Light Sources.- Since the sensitivity of phototubes depends to a great extent upon the color of the light to which they are exposed, it is obvious that the light source used for sensitivity measurements should be representative of that to which the great majority of phototubes are to be exposed in practice. It is probable that this light source would be a low-voltage, concentrated-filament type lamp since it is small and the concentrated filament is of importance where the lamp is to be used with an optical system.

Although a special inquiry was made regarding the type of light source used in the various laboratories, only the following referred to it in any way: The National Carbon Company stated that their curves were taken with a gas filled tungsten lamp operated at an efficiency of one watt per candle, which is below rated voltage; the G-M Laboratories stated that their tests were made with "a Bureau of Standards calibrated lamp;" and the Jenkins Television Corporation gave curves taken with a "hot filament lamp run at rated voltage."

The Westinghouse Research Laboratories[2] measure the temperature to obtain data as to the spectral distribution of the energy, and the Bell Telephone Laboratories give phototube sensitivities at certain color temperatures. The color temperature is defined as the temperature of a black body which has the same spectral distribution of radiation through the visible range as the source in question.

It is evident that there is a wide variation in the voltage at which lamps are operated while making tests, that the lamps used may have entirely different color characteristics at the same voltage, and that even the efficiency is not a true indication of color characteristics except for a given type and size of lamp. As previously mentioned, there is a definite relation between color and temperature for a given material, hence the true temperature or the color temperature should be used for accurate measurements of sensitivity.

11.3 <u>Optimum Anode Voltage</u>.- As has been shown, the slope of the current-illumination curve changes with the applied voltage. With the vacuum type tube it is only necessary that the voltage be above the saturation point and at a convenient operating value.

With the gas type phototube no saturation point is reached, and some other method must be used. Mr. A. J.

McMaster of the G-M Laboratories suggests: "To make possible comparisons between phototubes having different voltage ratings, the specific cell sensitivity is expressed in micro-amperes per lumen at 10 per cent below the light flow voltage (for a definite amount of light flux such as 0.2 lumens)." A definite light flux is necessary because an increase in the light flux decreased the ionization voltage. There is no evidence that this method has been adopted by any company other than the G-M Laboratories.

12.0 Conclusions

(1) All testing laboratories do not give the same characteristics, and the methods of measuring important characteristics of phototubes have not been standardized.

(2) The calibration of phototubes at the factory is the exception rather than the rule, the R. C. Burt Scientific Laboratories being the only manufacturer who ships each tube with a "standardized calibration."

(3) The standardization of one light source for all phototubes is not desirable because of special purpose tubes which operate best with ultra-violet or infra-red radiations.

(4) No standardized operating temperature for tungsten filament lamps has been accepted by the testing laboratories of the manufacturers cooperating with this investigation. As a result the characteristic curves for phototubes published by one company cannot be compared with those of a competitor with any assurance that they were taken under identical conditions. The photophone exciter lamp is easily obtainable and is used as a light source for a great number of phototubes. It is, therefore, recommended that this lamp, operated at a specified temperature, be used as a standard light source. The temperature should be the average value for normal

voltage.

(5) To make possible comparisons between different gas phototubes having different voltage ratings, the sensitivity in micro-amperes per lumen at 10 per cent below the glow voltage should be given. Some companies give values and characteristic curves for gas tubes without this information concerning the glow voltage.

(6) Spectral sensitivity curves are standardized as to form, but are not always furnished. It is recommended that such curves be taken for all phototubes and published in the descriptive data.

(7) Frequency characteristics of gas phototubes are often referred to in technical bulletins but seldom given. It is recommended that a frequency characteristic curve be given showing the relative outputs from zero to at least 10,000 cycles per second.

(8) Leakage currents at normal voltage and no illumination should be given. This has not been the practice for all laboratories heretofore.

PART THREE: EXPERIMENTAL DATA

13.0 Investigation of Light Sources

13.1 The Problem.- The problems associated with the test of phototubes are obviously too numerous to permit of a thorough investigation of each of them for a paper of this type. After a consideration of the time available, and a survey of the apparatus at hand, it was decided to determine what differences might be expected in the characteristic curves of common types of phototubes using tungsten filament light sources operated at different temperatures. In this way the importance of standardization of such sources for test purposes would be shown.

13.2 Types of Lamps.- For most work a small, concentrated filament lamp is preferable to a large size lamp, hence it was decided to calibrate several of these. Three gas filled and one vacuum Mazda lamps was selected. They were of the 6 to 8 volt type designed for automobile use. For convenience, these lamps were designated by number in order of their current ratings at normal voltage:

Lamp No. 1	3 Cp.	Gas filled Mazda
Lamp No. 2	21 Cp.	Vacuum Mazda
Lamp No. 3	21 Cp.	Gas filled Mazda
Lamp No. 4	50 Cp.	Gas filled Mazda

This includes a wide range of candlepower ratings and should be fairly representative of the low voltage lamps. The bulbs were of the smooth glass type which is necessary for uniform light distribution.

13.3 <u>Calibration of Lamps</u>.- The lamps were aged artificially by passing a momentary current through them approximately three times normal voltage. They were then allowed to burn several hours at 7.5 volts to determine if the current changed appreciably over this period.

After four satisfactory lamps had been found, the candlepower of each was determined at several voltages near the rated value. The exact voltage range over which readings were taken was determined entirely by the color match obtainable, as it was thought necessary to keep the colors of the lights as nearly the same as possible so as not to cause inconvenience or uncertainty in making settings on the photometer.

The calibration was done by means of a two meter bar photometer equipped with an equality type Lummer and Brodhun photometer-head, and a Bureau of Standards 120 volt calibrated lamp of the tungsten filament type. The substitution method[3] was used in comparing the test lamp with the standard to avoid errors due to lack of symmetry, since such errors as appear in the comparison of the intermediary lamp with the standard also appear when the unknown is substituted for the standard and compared with the intermediary lamp.

Voltage and current measurements were made with long-scale precision instruments. Since a one per cent error in voltage means an error of about three and one-half per cent in candlepower, the voltage readings were always taken at such voltages that the pointer would be on a division mark to avoid approximations, and several readings of candlepower were taken at this voltage so that an average value might be obtained. To further reduce error the data were plotted on logarithmic paper and the equations of the curves found by the Steinmetz "Sigma Delta" method. Fig. 10 to Fig. 15 inclusive show the curves for the four test lamps. Experimental data and derivation of the equations are included in Appendix C, page 66.

13.4 <u>The Phototube Circuit</u>.- All measurements were made with a sensitive galvanometer incorporated in a circuit similar to that shown in Fig. 6. The galvanometer used was a Leeds and Northrup Type R instrument used with a four meter scale at a distance of nine meters. The sensitivity of the instrument with this scale was 1.55×10^{-10}

FIG. 10

LOG VOLTAGE - LOG CURRENT CURVES

6-8 VOLT TUNGSTEN LAMPS

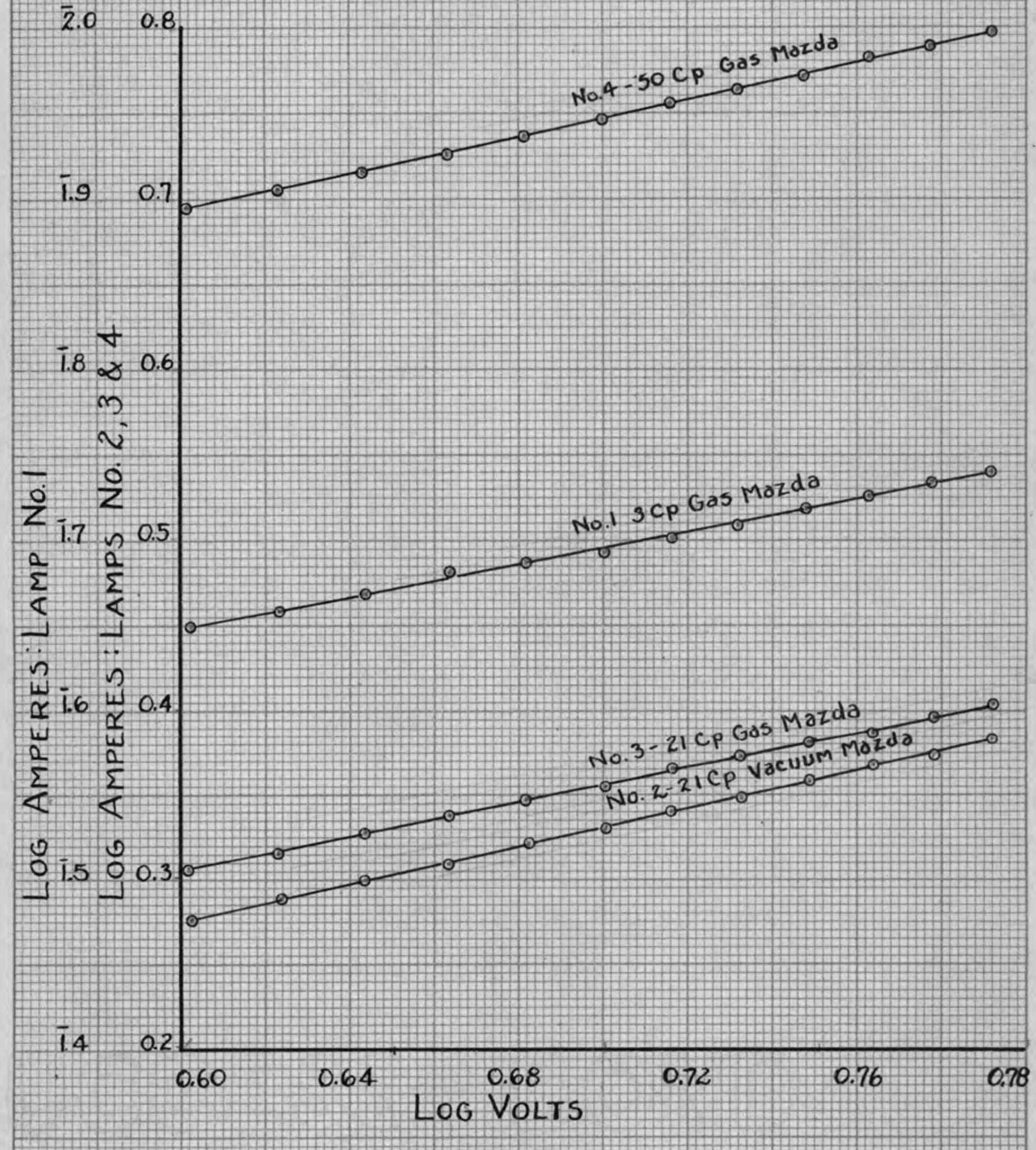


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FIG. 11

LOG CANDLEPOWER–LOG VOLTAGE CURVES

6-8 VOLT MAZDA TUNGSTEN LAMPS

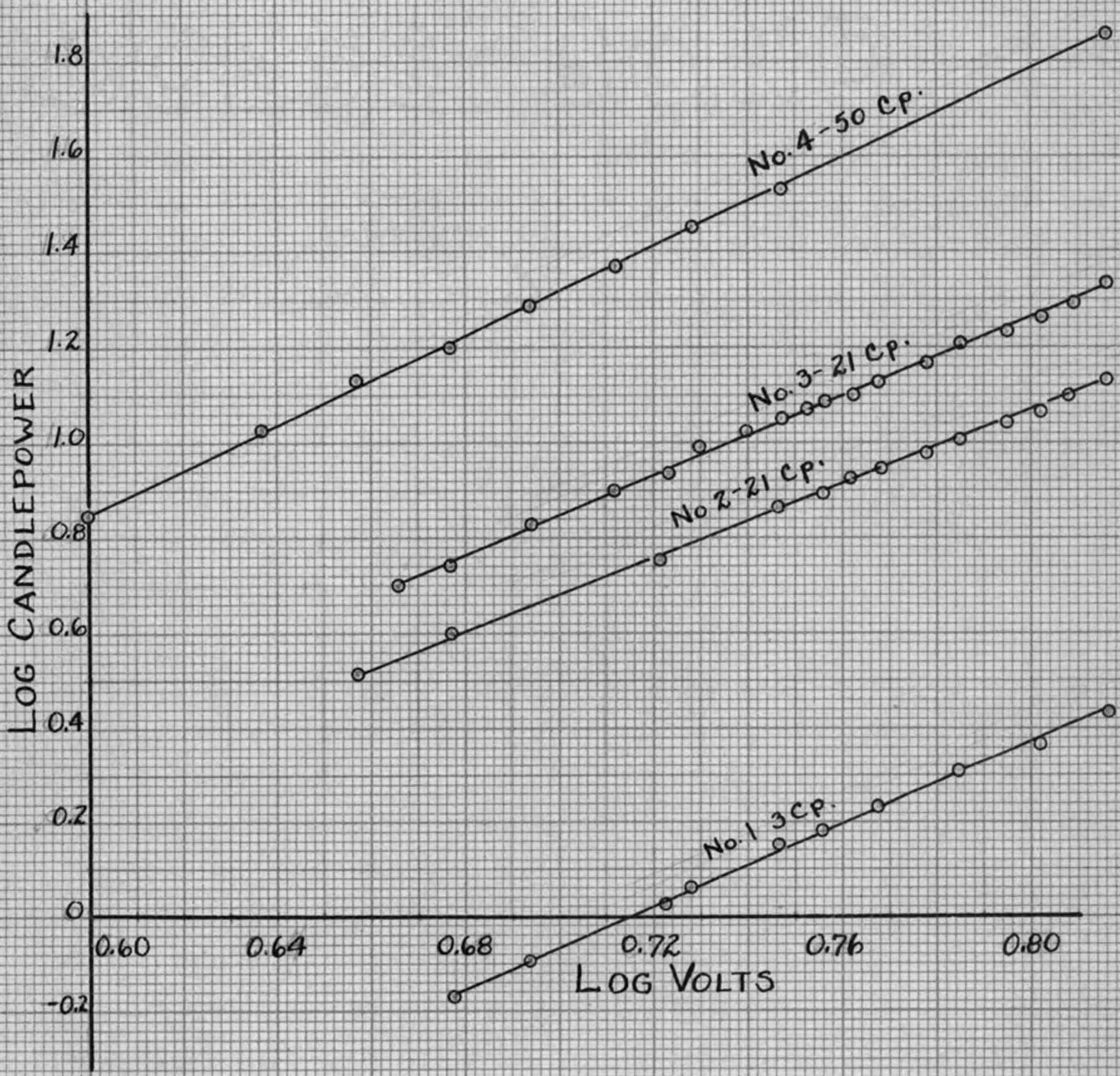

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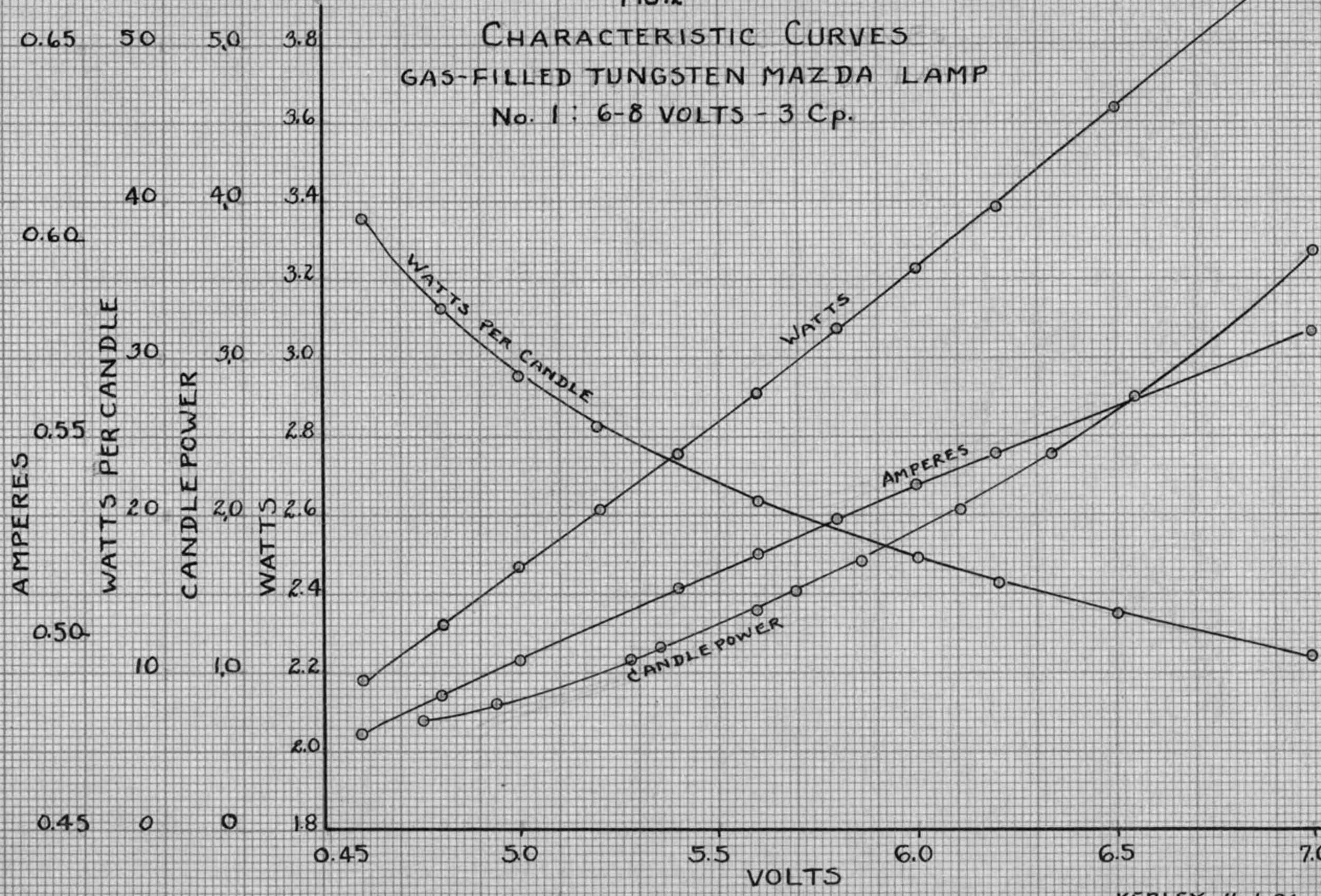
FIG 12

CHARACTERISTIC CURVES

GAS-FILLED TUNGSTEN MAZDA LAMP

No. 1 : 6-8 VOLTS - 3 Cp.



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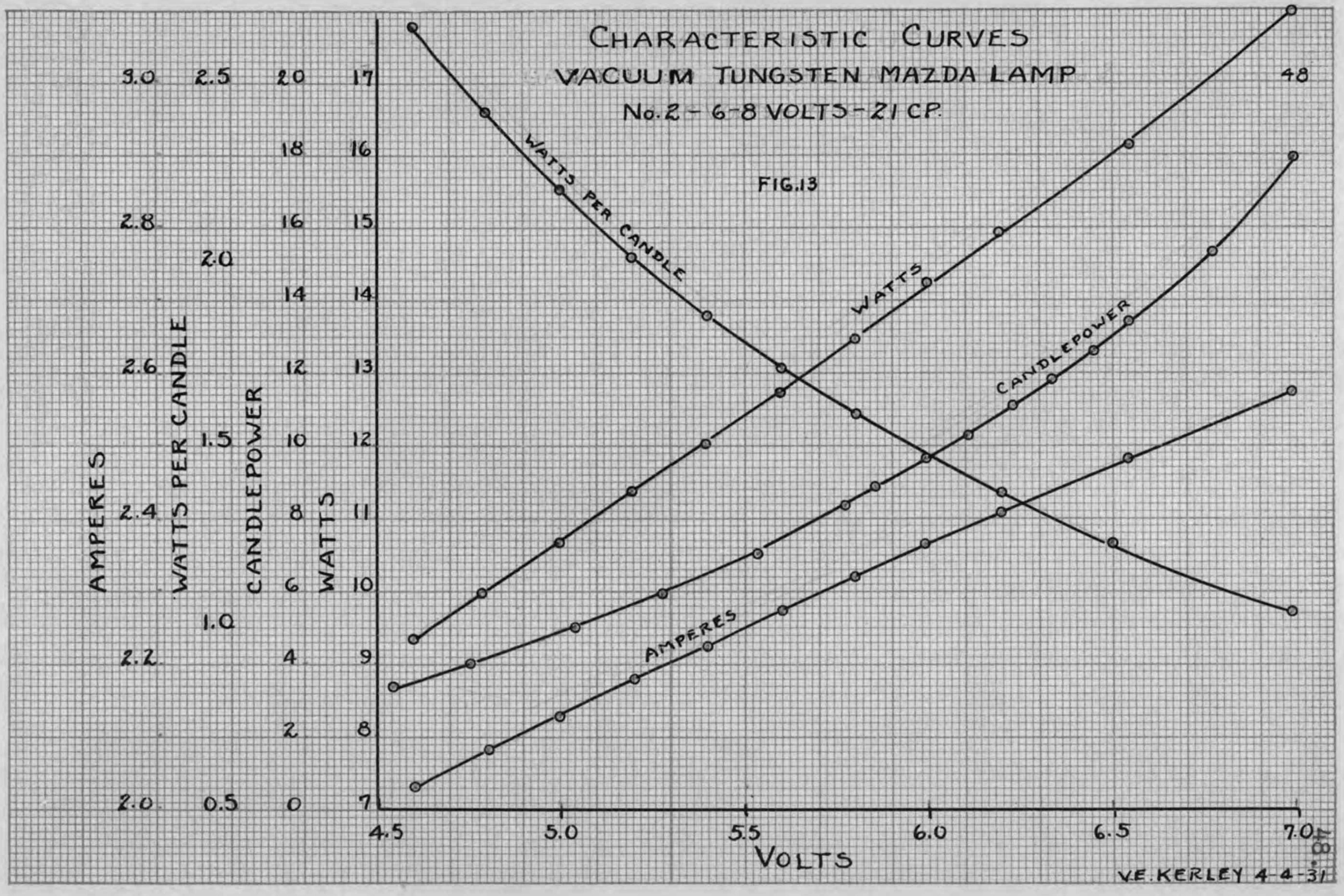
CHARACTERISTIC CURVES
VACUUM TUNGSTEN MAZDA LAMP
No. 2 - 6-8 VOLTS - 21 CP.
FIG.13
WATTS PER CANDLE
WATTS
CANDLEPOWER
AMPERES
AMPERES
WATTS PER CANDLE
CANDLEPOWER
WATTS
3.0
2.8
2.6
2.4
2.2
2.0
2.5
2.0
1.5
1.0
0.5
20
18
16
14
12
10
8
6
4
2
0
17
16
15
14
13
12
11
10
9
8
7
4.5
5.0
5.5
6.0
6.5
7.0
VOLTS
48
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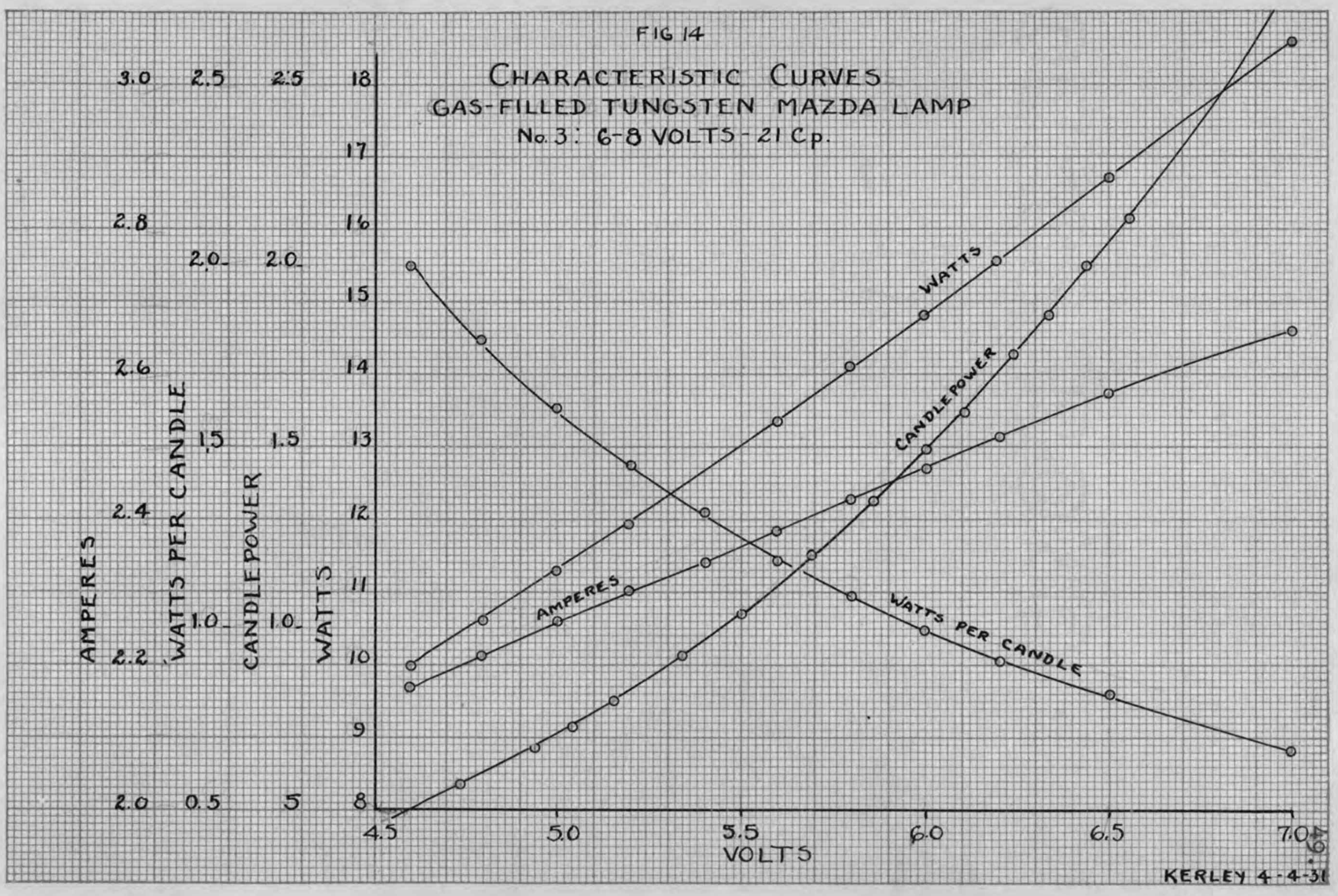


FIG 14
CHARACTERISTIC CURVES
GAS-FILLED TUNGSTEN MAZDA LAMP
No. 3: 6-8 VOLTS - 21 Cp.
AMPERES
WATTS PER CANDLE
CANDLEPOWER
WATTS
VOLTS
3.0
2.8
2.6
2.4
2.2
2.0
2.5
2.0
1.5
1.0
0.5
2.5
2.0
1.5
1.0
5
18
17
16
15
14
13
12
11
10
9
8
4.5
5.0
5.5
6.0
6.5
7.0
WATTS
CANDLEPOWER
AMPERES
WATTS PER CANDLE
KERLEY 4-4-31

49

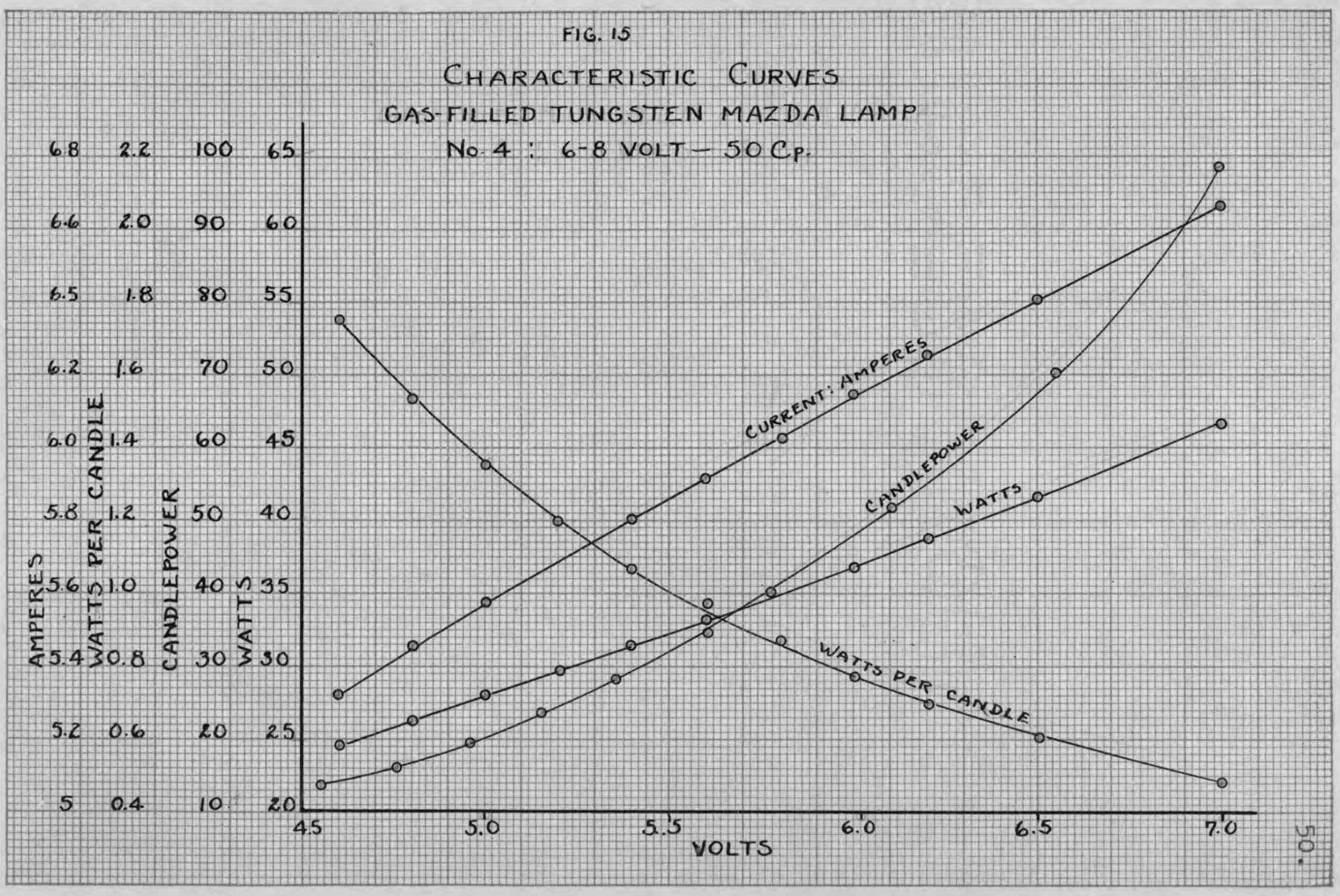


FIG. 15
CHARACTERISTIC CURVES
GAS-FILLED TUNGSTEN MAZDA LAMP
No. 4 : 6-8 VOLT — 50 Cp.
AMPERES
WATTS PER CANDLE
CANDLEPOWER
WATTS
VOLTS
CURRENT: AMPERES
CANDLEPOWER
WATTS
WATTS PER CANDLE
6.8 2.2 100 65
6.6 2.0 90 60
6.5 1.8 80 55
6.2 1.6 70 50
6.0 1.4 60 45
5.8 1.2 50 40
5.6 1.0 40 35
5.4 0.8 30 30
5.2 0.6 20 25
5 0.4 10 20
4.5 5.0 5.5 6.0 6.5 7.0

amperes per millimeter.

One alternative would have been to use a vacuum tube voltmeter to measure the change in voltage across a resistor. Several factors of uncertainty are introduced by this method which were undesirable. These include doubtful constancy of amplifier tubes available, temperature coefficient of resistors, and the voltage coefficient of resistors.

13.5 Voltage-current Curves.- Voltage-current characteristics were taken for two types of phototubes at normal voltage and voltages above and below normal. The light flux incident upon an aperture at the front of the phototubes was kept constant. The phototubes used were an Eveready Ratheon Phototube, Type VS 3, which has a spectral sensitivity curve with a peak at 4300 Ångstrom units; and a Westinghouse Type VB phototube with a spectral energy curve having a double maximum, one at 3500 Ångstrom units, and another at 7500 Ångstrom units. These spectral energy curves are similar to those shown in Fig. 4 . The tabulated data are shown in Tables 12 and 13 , and in curve form in Fig. 16 and Fig. 17. It will be noted that due to the different color sensitivities of the phototubes that the current output of the blue sensitive phototube is greater at the higher lamp voltages, while for the red sensitive phototube the reverse is true.

FIG 16

CURRENT-VOLTAGE CURVES SHOWING THE EFFECT OF CHANGING THE LAMP FILAMENT TEMPERATURE ON THE PHOTOTUBE ANODE CURRENT WITH NO CHANGE IN LIGHT FLUX

EVEREADY RATHEON 3VS PHOTOTUBE
LIGHT FLUX HELD CONSTANT AT 0.15 LUMENS - LAMP No 2; 21 CP.; 6-8 VOLTS

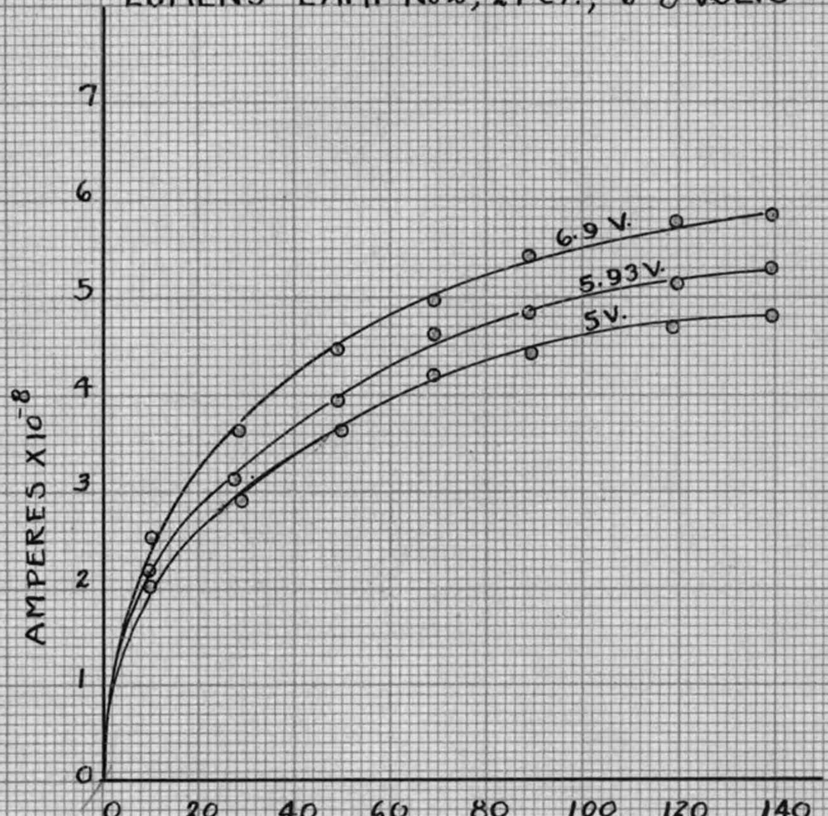
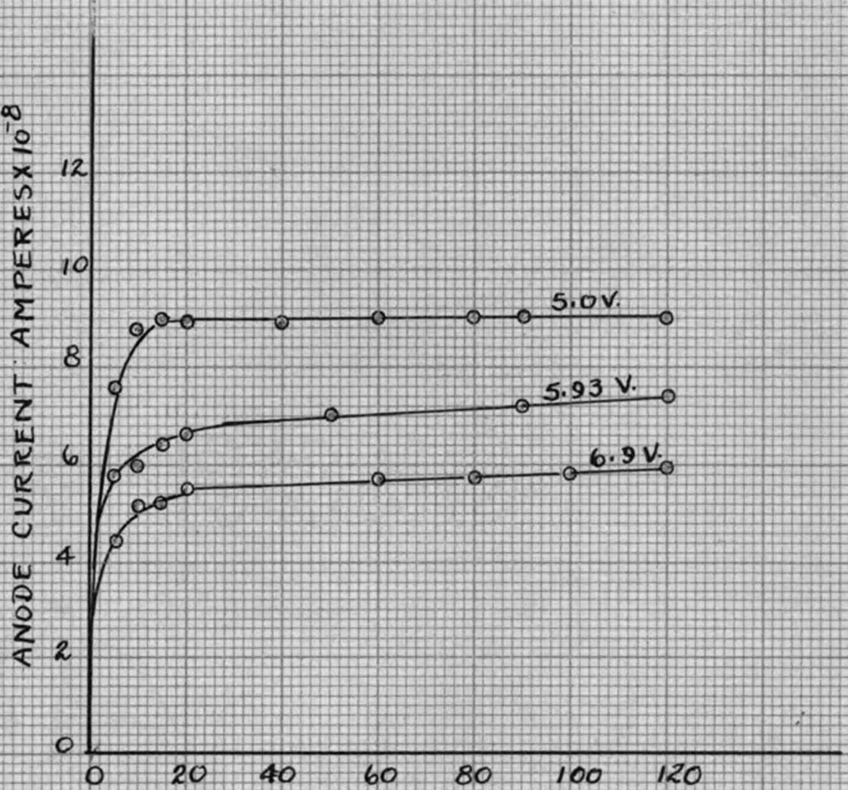


FIG 17

CURRENT-VOLTAGE CURVES SHOWING THE EFFECT OF CHANGING THE LAMP FILAMENT TEMPERATURE ON THE PHOTOTUBE ANODE CURRENT WITH NO CHANGE IN LIGHT FLUX

WESTINGHOUSE VB VACUUM PHOTOTUBE
LIGHT FLUX HELD CONSTANT AT 0.011 LUMENS — LAMP No. 2; 21 CP.; 6-8 VOLTS



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After a study of the curves, it was decided that error might have been introduced by placing the lamps too close to the phototube aperture for the lower illuminations. The light rays could not have then been considered parallel, and more light would have entered when the lamp was close to the phototube than when it was farther away, since the lamp filament is not a true point source. This is illustrated by the diagram in Fig. 18. Current illumination characteristics were taken to verify the foregoing results.

13.6 Current-illumination curves.- Data were taken for current illumination curves by holding the anode voltage constant at each of three lamp filament voltages and varying the illumination. As a further check a new lamp was used, and no aperture was placed in front of the phototubes to decrease the light flux. In this way the distance between the light source and the phototube was increased, and the distance from the limiting aperture to the sensitive surface eliminated in the case of the type VB phototube and greatly reduced for the VS 3 phototube.

These curves which are shown in Fig. 19 and Fig. 20 indicate the same things as the previous curves, but due to the precautions previously mentioned, and the fact that more values of illumination were used, there was less opportunity for error.

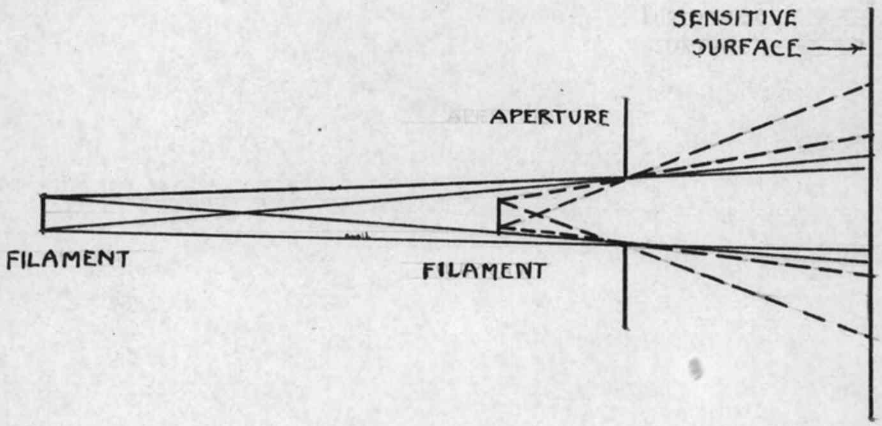

FIG. 18. DIAGRAM SHOWING ERROR WHEN SOURCE IS CLOSE TO APERTURE DUE TO NON-PARALLEL LIGHT RAYS

FIG 19

CURRENT-ILLUMINATION CURVES SHOWING THE EFFECT OF CHANGING THE LAMP FILAMENT TEMPERATURE ON THE PHOTO-TUBE CURRENT

EVEREADY RATHEON 3VS PHOTOTUBE
ANODE VOLTAGE CONSTANT AT 130 V.
LAMP No. 3 ; 21 CP ; 6-8 VOLTS

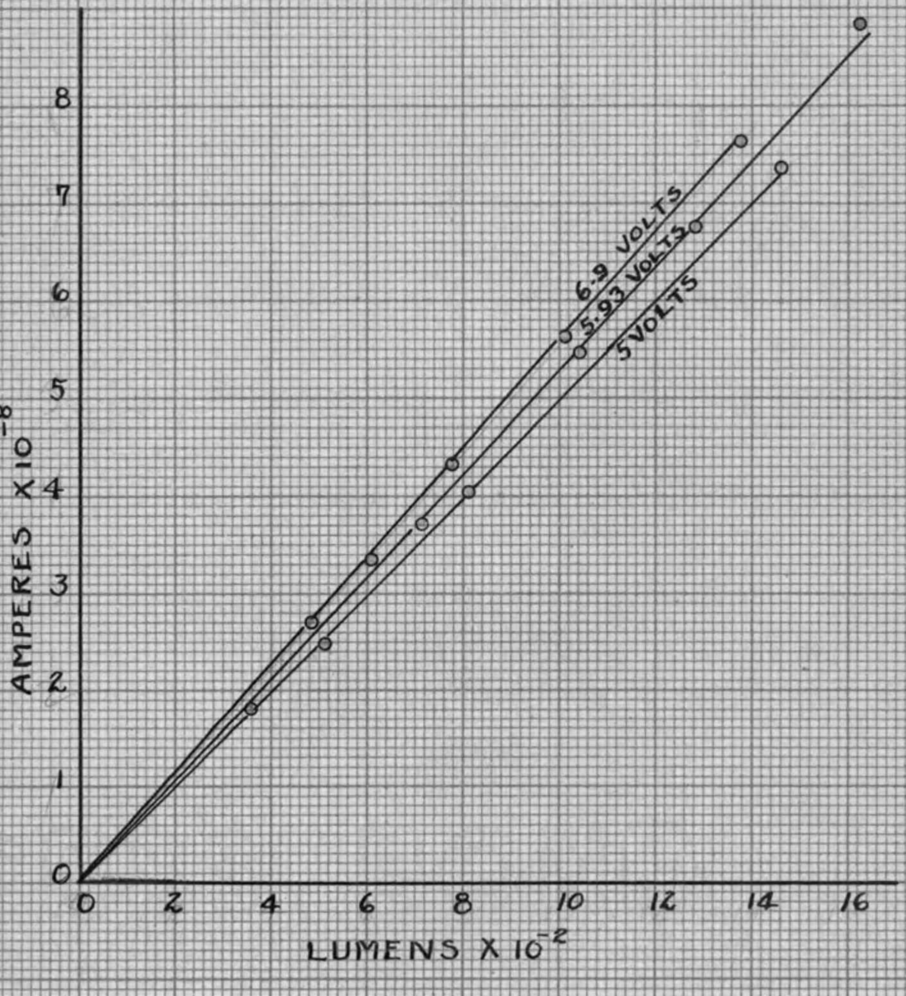

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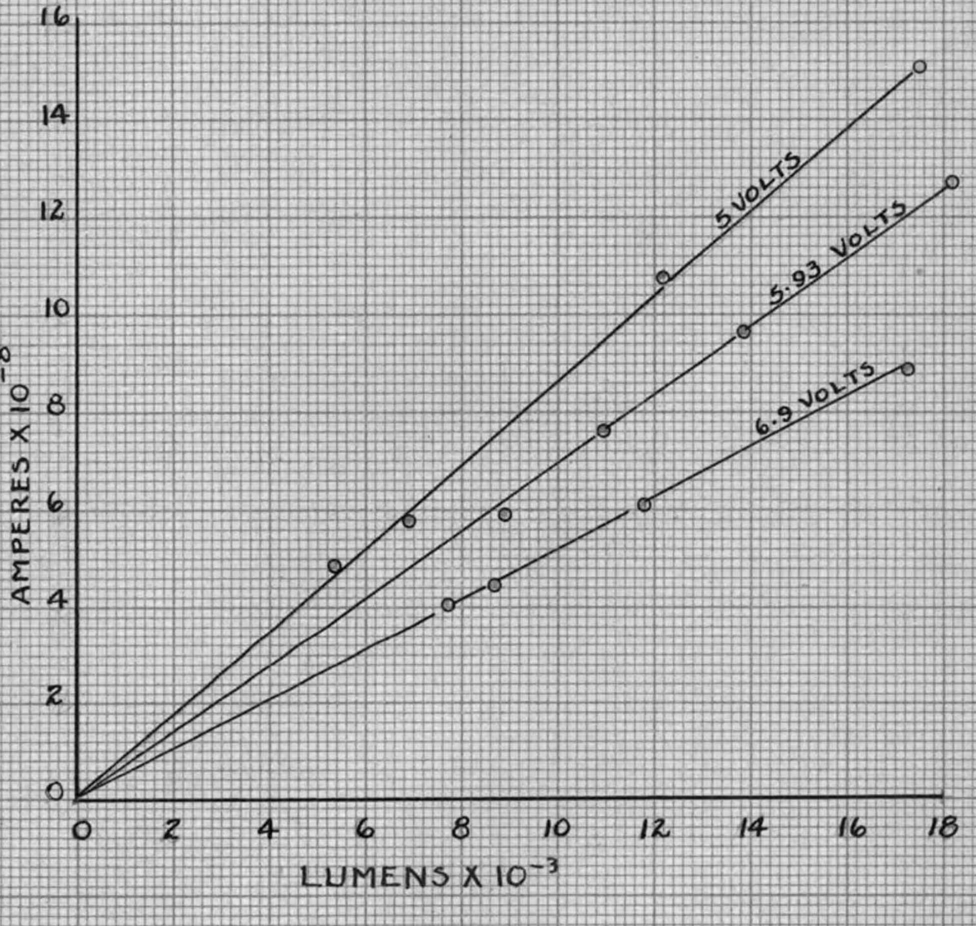
FIG.20

CURRENT-ILLUMINATION CURVES SHOWING THE EFFECT OF CHANGING THE LAMP FILAMENT TEMPERATURE ON THE PHOTO-TUBE CURRENT

WESTINGHOUSE VB PHOTOTUBE - VACUUM TYPE
ANODE VOLTAGE CONSTANT AT 130 VOLTS
LAMP No. 3; 21 C.P.; 6-8 VOLTS



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13.7 Discussion of Results.- The characteristic curves of the four sources show that there is considerable variation among lamps of the same voltage rating. Work on the photometer bar showed a considerable shift in color toward the violet end of the spectrum as the candlepower ratings of the lamps increased. This was due to the increase in operating temperature possible with lamps using the larger filaments which it is possible to incorporate in lamps with larger ratings, and is similar to the shift in the black body radiations toward the shorter wavelengths as was shown in Fig. 1. Since the shift of the maximum wave-length is from the infra-red into the visible, the efficiency of the lamps increase with the increase in rated candlepower.

The variation in the characteristic curves obtained by use of the two types of phototubes and lamps burning at different efficiencies is due to several things. There is some difficulty in obtaining true photometric readings where colors are not exactly matched, and for this reason voltages were used where the resulting color differences were not great enough to cause inconsistant readings. It was at all times possible to form a judgment as to when the fields illuminated appeared equally bright. Nevertheless, there was some color difference, and this may have given rise to a phenomenon known as the "Purkinje effect", which is the name given to the tendency for the eye to favor blue light in preference to red at weak illuminations. This would have the effect of making the candle-power readings of the test lamp lower than they should have been when the color was more red than the comparison lamp, and higher when it was whiter.

The spectral energy of the eye, as shown in Fig. 2, is such that only a small part of the total radiation from a lamp is visible as light. This the eye evaluates in proportion to the luminous sensation produced by it. Analogous to this is the response of the phototube to radiant energy as is evidenced by its current output, which changes with frequency with a constant radiant energy falling upon it.

Referring to the black body curves of Fig. 1 (curves for tungsten are similar in shape), it is seen that between $2000^{\circ}K$ and $3000^{\circ}K$, which includes ordinary tungsten temperatures, that an increase in temperature increases the energy under the curve and shifts the wave-length of maximum energy toward the violet. The eye is sensitive to a comparatively narrow band, and for ordinarily attainable temperatures the shift of the maximum with increasing temperature is toward this band. This results in more energy being evaluated as light by the eye so that a proportionately smaller amount of radiation is necessary to produce the same visual effect of intensity as before. This enters into photometric measurements and helps to explain the curves obtained for the phototubes.

It must be remembered that the phototubes were exposed to equal illuminations and not to equal total energies.

The output of the VS 3 phototube increased with increasing lamp filament temperatures, but with equal illumination, because there was more light energy in the shorter wave-lengths, and the phototube was sensitive to these wave-lengths. Because of its broad peak in the red and infra-red, the VB phototube was more sensitive to the long waves and hence did not respond to increased energy in the short waves. Furthermore, although the light flux remained constant, the total energy required to produce it decreased, and this with the relative insensitivity of the phototube to the more abundant short wave-lengths caused the current to decrease.

13.8 Conclusions.-

(1) The variation of sensitivity with increasing temperature depends upon the spectral sensitivity of the tube and upon how near the spectral sensitivity curve of the tube resembles that of the eye.

(2) These data show conclusively that characteristic curves taken by the various manufacturers with their

present light sources are useless except as means of comparing the phototubes tested in the same laboratory.

(3) Since a 16 per cent change in voltage may cause as much as a 16 per cent change in the anode current of phototubes similar to the VB tube tested, and a 10 per cent change in those similar to the VS 3, the practice of operating the test light source at voltages lower than normal should not be permitted, unless it is necessary to lower the voltage to obtain a standardized color temperature. As previously stated, one manufacturer has standardized (for its own laboratory purposes) on a lamp operated at 1.1 watts per candle, which is below normal voltage.

(4) All phototubes which are intended primarily for use with tungsten filament lamps should be tested with a standardized tungsten filament lamp operating at a specified color temperature. The fact that the tests were made with such a lamp should be so stated with sensitivity ratings, and on all characteristic curves.

It is suggested that a photophone exciter lamp, operated at a definite color temperature corresponding to that near normal voltage be used as a standard source for ordinary phototubes manufactured for use with common light sources.

PART FOUR: CONCLUSIONS AND RECOMMENDATIONS

14.0 Summary of Conclusions

(1) Testing laboratories are not entirely in agreement as to what characteristics curves or data should be given as evidence of a phototube's worth. Neither have they standardized on the methods of measuring important characteristics.

(2) The standardization of one light source for all phototube tests is not desirable because of special purpose tubes which operate best with ultra-violet or infra-red radiations.

(3) No standardized operating temperature for tungsten lamps has been adopted for testing phototubes sensitive to radiations in the visible band. As a result the characteristic curves of one company cannot be compared with those of a competitor with any assurance that they were taken under identical conditions. Tests show that a change of 16 per cent in voltage of the source causes as much as 16 per cent variation of current with phototubes sensitive in the red end of the spectrum, and as much as 10 per cent with those sensitive at the blue end. Standardization of light sources is therefore needed for the common types of phototubes. The photophone exciter

lamp at a specified color temperature is recommended.

(4) This investigation shows that data for gas phototubes is given without information as to the glow voltage of the tube. To make possible comparisons between different gas phototubes having different voltage ratings the sensitivity in micro-amperes per lumen at 10 per cent below the glow voltage should be given.

(5) Spectral sensitivity curves are standardized in form, but are not always given. It is recommended that such curves be taken for each type of phototube and published in the descriptive data.

(6) Frequency characteristics of gas phototubes are not standardized, and although often referred to in technical bulletins, they are seldom given. It is recommended that a frequency characteristic curve of a standardized type be given for each type of phototube showing the relative outputs from zero to at least 10,000 cycles per second.

(7) Leakage currents at normal voltage and with no illumination should be given. This has not been the practice heretofore.

APPENDIX A

References

1. The data for Part Two of this paper came from the following:

   Arcturus Radio Tube Company; Newark, New Jersey

   R. C. Burt Scientific Laboratories; Pasadena, Calif.

   National Carbon Company; New York, N. Y.

   General Electric Company; Schenectady, N. Y.

   Gaertner Scientific Corporation; Chicago, Ill.

   G-M Laboratories; Chicago, Ill.

   Bell Telephone Laboratories; New York, N. Y.

   Jenkins Television Corporation; Jersey City, N. J.

   Westinghouse Elect. and Mfg. Co.; East Pgh., Pa.

2. Zworykin and Wilson: "Photocells and Their Application"
3. Cady and Dates: "Illuminating Engineering"
4. Burt Scientific Laboratories Bulletin No. 271
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6. National Carbon Company: "Eveready Ratheon Photocells"
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10. A. J. McMaster: "Photoelectric Cells in Chemical Technology," Industrial and Engineering Chemistry, October, 1930
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APPENDIX B

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"Projection Engineering," Bryan Davis Publishing Co.

"Electric Journal," Westinghouse.

"General Electric Review," General Electric Company.

APPENDIX C

Laboratory Data and Calculations on Tungsten Filament Lamps

v	Lamp voltage
i	Lamp current
I	Candlepower of Lamp
Δ	Difference between numbers

TABLE 1

LIGHT SOURCE No. 1

VARIATION OF CURRENT WITH VOLTAGE

Mazda Lamp: Gas Filled; 3 Cp.; 6-8 Volts

v	i	Log v	Log i	Calc. Log i	Δ	Calc. i
7.0	--	--	--	$\bar{1}.7613$	--	0.577
6.5	0.557	0.1829	$\bar{1}.7459$	$\bar{1}.7463$	+ 0.0004	.557
6.2	.545	.7924	$\bar{1}.7364$	$\bar{1}.7360$	−.0002	.545
6.0	.538	.7782	$\bar{1}.7308$	$\bar{1}.7299$	−.0009	.537
5.8	.529	.7634	$\bar{1}.7235$	$\bar{1}.7231$	−.0004	.529
5.6	.520	.7482	$\bar{1}.7160$	$\bar{1}.7159$	−.0001	.520
5.4	.510	.7324	$\bar{1}.7076$	$\bar{1}.7085$	+.0011	.511
5.2	.501	.7160	$\bar{1}.6998$	$\bar{1}.7008$	+.0010	.502
5.0	.492	.6990	$\bar{1}.6920$	$\bar{1}.6928$	+.0008	.493
4.8	.483	.6812	$\bar{1}.6840$	$\bar{1}.6845$	+.0005	.484
4.6	.475	.6628	$\bar{1}.6767$	$\bar{1}.6760$	−.0007	.474
4.4	.465	.6435	$\bar{1}.6675$	$\bar{1}.6655$	−.0020	.463
4.2	.455	.6233	$\bar{1}.6580$	$\bar{1}.6573$	−.0015	.454

TABLE 2

LIGHT SOURCE No. 1

VARIATION OF LUMINOUS INTENSITY WITH VOLTAGE

Mazda Lamp: Gas Filled; 3 Cp.; 6-8 Volts

v	I	Log v	Log I	Calc. Log I	Δ	Calc. I
7.00	--	--	--	0.565	--	3.67
6.55	2.73	0.8162	0.436	.439	+ 0.003	2.75
6.34	2.32	.8021	.366	.378	+ .012	2.39
6.11	2.03	.7854	.308	.306	- .002	2.02
5.86	1.73	.7679	.238	.230	- .008	1.70
5.70	1.52	.7559	.182	.179	- .003	1.51
5.59	1.43	.7474	.156	.142	+ .014	1.39
5.35	1.15	.7284	.061	.060	- .001	1.15
5.28	1.06	.7226	.026	.034	+ .008	1.08
4.94	0.798	.6937	-0.098	-0.091	- .007	0.811
4.75	0.698	.6767	- .169	- .165	- .004	0.684

TABLE 3

LIGHT SOURCE No. 1

CHARACTERISTIC EQUATIONS BY THE $\Sigma\Delta$ METHOD

6 log v	4.2670	4.0258
6 log i	2.3602	2.0780
12 log v	8.653	
12 log i	4.438	

n = (2.3602 - 2.0780)/(4.2670 - 4.0258)

= 0.4653

(4.438 - 0.4695 x 8.653)/12 = - 0.6354

Log i = - 0.6354 0.4695 log v

$$i = 2.315\ v^{0.4695}$$

5 log v	3.928	3.569
5 log I	1.530	0.024
10 log v	7.497	
10 log I	1.506	

n = (1.530 - 0.024)/(3.928 - 3.569)

= 4.329

(1.506 - 4.329 x 7.497)/10 = - 3.094

log I = - 3.094 4.329 log v

$$I = 0.00805\ v^{4.329}$$

TABLE 4

LIGHT SOURCE No. 2

VARIATION OF CURRENT WITH VOLTAGE

Mazda Lamp, Vacuum Type; 3 Cp.; 6-8 Volts

v	i	Log v	Log i	Calc. Log i	Δ	Calc. i
7.00	--	0.8451	--	0.4104	--	2.57
6.55	--	.8162	--	.3942	--	2.48
6.20	2.40	.7924	0.3802	.3808	+ 0.0006	2.40
6.00	2.36	.7782	.3729	.3729	.0000	2.36
5.80	2.32	.7634	.3655	.3647	− .0008	2.32
5.60	2.27	.7482	.3560	.3561	+ .0001	2.27
5.40	2.22	.7324	.3464	.3472	+ .0008	2.22
5.20	2.18	.7160	.3385	.3380	− .0005	2.18
5.00	2.13	.6990	.3284	.3285	+ .0001	2.13
4.80	2.08	.6812	.3181	.3186	+.0006	2.08
4.60	2.03	.6628	.3075	.3082	+.0007	2.03
4.40	1.98	.6435	.2967	.2979	+.0012	1.98
4.20	1.94	.6233	.2878	.2861	− .0019	1.93
4.00	1.88	.6021	.2742	.2741	− .0001	1.88

TABLE 5

LIGHT SOURCE No. 2

VARIATION OF LUMINOUS INTENSITY WITH VOLTAGE

Mazda Lamp: Vacuum Type; 21 Cp.; 6-8 Volts

v	I	Log v	Log I	Calc. Log I	Δ	Calc. I
7.00	--	0.8451	--	1.252	--	17.9
6.78	--	.8312	--	1.184	--	15.3
6.55	13.6	.8162	1.1335	1.127	− 0.006	13.4
6.45	12.7	.8096	1.1038	1.102	− .002	12.6
6.34	11.8	.8021	1.0718	1.074	+ .001	11.8
6.24	11.0	.7952	1.0414	1.048	+ .007	11.1
6.11	10.4	.7854	1.0170	1.011	− .006	10.3
6.00	9.54	.7782	0.9795	0.984	+ .004	9.96
5.86	8.77	.7679	.9430	.945	+ .002	8.81
5.78	8.26	.7619	.9170	.922	+ .005	8.36
5.70	7.92	.7559	.8987	.900	+ .001	7.95
5.66	7.71	.7528	.8871	.881	− .006	7.60
5.59	7.48	.7474	.8739	.868	− .006	7.39
5.04	5.10	.7024	.7076	.698	− .009	5.00
4.75	4.01	.6767	.6031	.601	− .002	3.99
4.54	3.28	.6571	.5159	.527	+ .011	3.37

TABLE 6

LIGHT SOURCE No. 2

CHARACTERISTIC EQUATIONS BY THE $\Sigma\Delta$ METHOD

6 log v	4.5306	3.9119
6 log i	2.1595	1.8127
12 log v		
12 log i		

n = (2.1595 - 1.8127)/(4.5306 - 3.9119)

= 0.5605

(3.9722 - 0.5605 x 8.443)/12 = -0.06334

log i = -0.633 0.5605 log v

$$i = 8.644\ v^{0.5605}$$

7 log v	5.5546	5.0542
7 log I	7.2900	5.4033
12 log v	10.61	
12 log I	12.69	

n = (7.2900 - 5.4033)/(95.5546 - 5.0542)

= 3.771

(12.69 - 3.771 x 10.61)/14 = -1.951

log I = -1.951 3.771 log v

$$I = 0.894\ v^{3.771}$$

TABLE 7

LIGHT SOURCE No. 3

VARIATION OF CURRENT WITH VOLTAGE

Mazda Lamp: Gas Filled; 21 Cp.; 6-8 Volts

v	i	Log v	Log i	Calc. Log i	Δ	Calc. i
7.0	--	0.8451	--	0.4249	--	2.66
6.5	--	.8129	--	.4099	--	2.57
6.2	2.51	.7924	0.3997	.3988	- 0.0009	2.51
6.0	2.47	.7782	.3927	.3919	- .0008	2.47
5.8	2.43	.7634	.3838	.3847	+ .0009	2.43
5.6	2.38	.7482	.3766	.3772	+ .0006	2.38
5.4	2.34	.7324	.3692	.3695	+ .0003	2.34
5.2	2.30	.7160	.3617	.3614	- .0003	2.30
5.0	2.26	.6990	.3541	.3531	- .001	2.26
4.8	2.21	.6812	.3444	.3444	+ .0000	2.21
4.6	2.16	.6628	.3345	.3354	+ .0009	2.17
4.4	2.12	.6435	.3263	.3260	- .0003	2.12
4.2	2.06	.6233	.3161	.3159	- .0002	2.07
4.0	2.02	.6021	.3054	.3057	+ .0003	2.02

TABLE 8 LIGHT SOURCE No. 3

VARIATION OF LUMINOUS INTENSITY WITH VOLTAGE

Mazda Lamp: Gas Filled; 21 Cp.; 6-8 Volts

v	I	Log v	Log I	Calc. Log I	Δ	Calc. I
7.00	--	0.8451	--	1.448	--	28.0
6.78	--	.8312	--	1.390	--	24.6
6.55	21.6	.8162	1.335	1.329	− 0.006	21.6
6.45	17.7	.8096	1.295	1.302	+ .007	19.7
6.34	18.4	.8021	1.265	1.270	+ .005	18.4
6.24	17.1	.7952	1.233	1.242	+ .009	17.1
6.11	16.3	.7854	1.212	1.202	− .010	16.3
6.00	14.7	.7782	1.167	1.172	+ .005	14.7
5.86	13.6	.7679	1.134	1.130	− .004	13.6
5.78	12.6	.7619	1.100	1.105	+ .005	12.6
5.70	12.3	.7559	1.090	1.081	− .009	12.3
5.59	11.3	.7474	1.053	1.051	− .002	11.2
5.50	10.4	.7404	1.017	1.017	− .000	10.4
5.35	9.72	.7284	0.988	0.967	− .021	9.27
5.28	8.64	.7226	.937	.943	+ .006	8.77
5.15	7.45	.7118	.900	.899	− .001	7.93
5.04	7.40	.7024	.869	.860	− .006	7.25
4.94	6.69	.6937	.826	.824	− .002	6.67
4.75	5.56	.6767	.745	.754	+ .009	5.68
4.64	5.07	.6665	.705	.712	+ .007	5.15
4.54	4.61	.6571	.664	.674	+ .010	4.73

TABLE 9

LIGHT SOURCE No. 3

CHARACTERISTIC EQUATIONS BY THE $\Sigma\Delta$ METHOD

6 log v	4.5306	3.9119
6 log i	2.2837	1.9808
12 log v	8.4425	
12 log i	4.2645	

n = (2.2837 - 1.9808)/(5.5306 - 3.9119)

= 0.4896

(4.2645 - 0.4896 x 8.4425)/12 = 0.0109

log i = 0.0109 0.4896 log v

$i = 1.025\ v^{0.4896}$

10 log v	7.8252	7.0470
10 log I	11.9070	8.7040
20 log v	14.8722	
20 log I	20.6110	

n = (11.907 - 8.704)/(7.8252 - 7.047)

= 4.116

(20.611 - 4.116 x 14.872)/20 = 2.031

log I = -2.031 4.116 log v

$I = 0.09311\ v^{4.116}$

TABLE 10

LIGHT SOURCE No. 4

VARIATION OF CURRENT WITH VOLTAGE

Mazda Lamp: Gas Filled; 50 Cp.; 6-8 Volts

v	i	Log v	Log i	Calc. Log i	Δ	Calc. i
7.0	--	0.8451	--	0.8237	--	6.66
6.5	--	.8129	--	.8064	--	6.40
6.2	6.25	.7924	0.7959	.7955	− 0.0004	6.25
6.0	6.14	.7782	.7882	.7881	− .0001	6.14
5.8	6.03	.7634	.7803	.7803	.0000	6.03
5.6	5.91	.7482	.7716	.7719	+ .0003	5.91
5.4	5.80	.7324	.7634	.7735	+ .0001	5.80
5.2	5.68	.7160	.7544	.7547	+ .0003	5.68
5.0	5.57	.6990	.7459	.7457	− .0002	5.57
4.8	5.45	.6812	.7364	.7362	− .0002	5.45
4.6	5.32	.6628	.7259	.7264	+ .0005	5.32
4.4	5.20	.6435	.7160	.7161	+ .0001	5.20
4.2	5.06	.6233	.7042	.7053	+ .0011	5.06

TABLE 11

LIGHT SOURCE No. 4

VARIATION OF LUMINOUS INTENSITY WITH VOLTAGE

Mazda Lamp: Gas Filled; 50 Cp.; 6-8 Volts

v	I	Log v	Log I	Calc. Log i	△	Calc. I
7.0	--	0.8451	--	1.994	--	98.6
6.55	70.2	.8162	1.8463	1.859	+ 0.013	70.2
5.59	34.3	.7474	1.535	1.540	+ .005	34.7
5.35	28.3	.7284	1.452	1.451	- .001	28.3
5.15	23.8	.7118	1.377	1.374	- .003	23.7
4.95	19.6	.6937	1.290	1.288	- .002	19.4
4.75	16.0	.6767	1.204	1.211	+ .001	16.3
4.54	13.4	.6571	1.127	1.120	- .007	13.2
4.34	10.7	.6375	1.029	1.030	+ .001	10.7
4.15	8.45	.6180	0.927	0.939	+ .012	8.45
4.04	7.02	.5994	.8463	.843	- .003	6.79
3.98	6.08	.5866	.7839	.7930	- .009	6.21

TABLE 12

LIGHT SOURCE No. 4

CHARACTERISTIC EQUATIONS BY THE $\Sigma\Delta$ METHOD

6 log v	4.5306	3.9119
6 log i	4.6538	4.3236
12 log v	8.4425	
12 log i	8.9774	

n = (4.6538 - 4.3236)/(4.5306 - 3.9119)

= 0.5337

(8.9774 - 0.5337 x 8.4425)/12 = 0.3726

log i = 0.3726   0.5337 log v

$$i = 2.358\ v^{0.5337}$$

3 log v	2.1876	1.9713
3 log I	4.364	3.360
6 log v	4.1589	
6 log I	7.724	

n = (4.364 - 3.360)/(2.1876 - 1.9713)

= 4.642

(7.724 - 4.642 x 4.1589)/6 = -1.93

log I = -1.930   4.642 v

$$I = 0.1175\ v^{4.642}$$

APPENDIX D

Laboratory Data on the Effect of Lamp Temperature on Phototube Characteristics

Table 12

EFFECT OF CHANGING LAMP FILAMENT TEMPERATURE
ON PHOTOTUBE ANODE CURRENT

Westinghouse VB Phototube; Light Flux
Held Constant at 0.011 Lumens

	5 Volts		5.93 Volts		7 Volts	
E_a	d	I_a	d	I_a	d	I_a
5	480	7.43	365	5.65	283	4.38
10	565	8.76	422	5.86	335	5.19
15	570	8.83	435	6.38	335	5.19
20	570	8.83	445	6.54	345	5.34
40	565	8.76	---	----	353	5.47
50	---	----	457	7.08	---	----
60	570	8.83	---	----	358	5.54
80	580	8.98	---	----	363	5.62
90	---	----	470	7.28	---	----
100	580	8.98	---	----	373	5.77
120	580	8.98	475	7.36	378	5.86

E_a Anode Voltage

d Galvanometer Deflection in mm.

I_a Anode Current in 10^{-8} Amperes

Lamp No. 2 Used as Source

Galvanometer Constant 1.55×10^{-10}

EFFECT OF CHANGING LAMP VOLTAGE ON PHOTOTUBE ANODE CURRENT

Eveready Ratheon Type 3 VS Phototube; Light Flux Held Constant at 0.15 Lumens

	5 Volts		5.93 Volts		7 Volts	
v	d	I_a	d	I_a	d	I_a
10	134	2.08	141	2.19	165	2.56
30	190	2.94	202	3.13	237	3.67
50	237	3.64	253	3.93	290	4.50
70	275	4.26	300	4.66	320	4.96
90	287	4.44	312	4.84	350	5.42
120	308	4.77	330	5.12	376	5.84
140	311	4.82	342	5.30	380	5.89

v Anode Voltage

d Galvanometer Deflection in mm.

I_a Anode Current in 10^{-8} Amperes

Lamp No. 2 Used as Light Source

Galvanometer Constant 1.55×10^{-10}

Table 14

VARIATION OF PHOTOTUBE CURRENT-ILLUMINATION CHARACTERISTIC WITH LIGHT SOURCE VOLTAGE

(Eveready Ratheon Type 3 VS Phototube with no Limiting Aperture; Anode Voltage 130 Volts; Lamp No. 3)

r	F	d	I_a	v
100	0.0495	175	2.71	7.0
90	.0615	215	3.33	7.0
80	.0778	278	4.31	7.0
70	.102	362	5.61	7.0
60	.138	492	7.62	7.0
60	.0360	117	1.81	5.0
50	.0515	160	2.48	5.0
40	.0808	260	4.03	5.0
30	.146	485	7.52	5.0
60	.0725	238	3.69	6.0
50	.105	352	5.45	6.0
45	.129	435	6.74	6.0
40	.163	572	8.86	6.0

r distance in cm. I_a Amperes x 10^{-8}

F Lumens v Lamp Voltage

d Deflection in mm.

Galvanometer Constant 1.55×10^{-10}

Table 15

VARIATION OF PHOTOTUBE CURRENT-ILLUMINATION

CHARACTERISTIC WITH LIGHT SOURCE VOLTAGE

(Westinghouse VB Vacuum Phototube with No Limiting Aperture; Anode Voltage 90 Volts; Lamp No. 3)

r	F	d	I_a	v
90	0.00542	320	4.96	5.0
80	.00686	370	5.73	5.0
70	.00896	507	7.86	5.0
60	.0122	705	10.9	5.0
50	.0175	985	15.2	5.0
100	.0089	382	5.92	6.0
90	.0110	490	7.60	6.0
80	.0139	618	9.6	6.0
70	.0182	820	12.7	6.0
150	.00754	265	4.1	7.0
140	.00865	290	4.5	7.0
120	.0118	398	6.16	7.0
100	.0170	578	8.95	7.0

r Distance in cm — I_a Amperes x 10^{-8}

F Lumens — v Lamp Voltage

d Deflection in mm.

Galvanometer Constant 1.55×10^{-10}

AUTHOR'S NOTE:

Since the writing of this Report, the Year Book of the Institute of Radio Engineers has appeared with details of standardized tests on phototubes as recommended by the Committee on Standards of the Institute. It is gratifying to note that many of these are in agreement with those recommended in this Paper.

The Year Book appeared as a supplement to the Proceedings of the Institute of Radio Engineers for March, 1931.

V.E.K. May 13, 1931.