BEC 3775

Final Progress Report

for

NASA Photometer

(10 March 1966 - 10 July 1966)

Contract No.: NAS5-10164

Prepared by

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Stamford, Connecticut

for

Goddard Space Flight Center

Greenbelt, Maryland

SUMMARY

The object of this report is to summarize the work accomplished for the Goddard Space Flight Center under NASA Contract NAS5-10164 for procurement of a Laboratory Photometer and Accessory Calibration Source. The instrument is a modification of the Barnes Engineering EP-1 Photoelectric Pyrometer. The required modifications are discussed together with test results of the completed instrument.

The completed instrument achieved the essential requirements offering required sensitivity and S/N ratio. Recommendations for additional testing and design improvements are offered.

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I INTRODUCTION

The work described herein was performed under NAS Contract NAS5-10164 from the Goddard Space Flight Center for a Laboratory Photometer described in GSFC Specification 732-84704/239. The work consisted of modifying the basic design of a BEC EP-1 Photoelectric Pyrometer to accept interchangeable photomultipliers and related changes in electronics and display units. In addition, a spectrally calibrated source of irradiance was furnished.

This report summarizes the design features of the Laboratory Photometer and discusses the test results. Recommendations for possible improvement are included.

II REQUIREMENTS

The requirements for the photometer are contained in NASA/GSFC Specification 732-84764/239 for a Laboratory Photometer. The essential characteristics are listed below for reference:

1. Detector Response - Nominal S-4, S-11 and S-20 response
2. Field of View - Nominal, one degree maximum
3. Relative Optical Transmittance - ±5% 3200A $\leq \lambda \leq$ 10,000
4. Focus - four feet to infinity
5. Image shall be defocussed on the detector

6. Supply Power - 115 ±10% line voltage, 60 ±2 cps line frequency

7. Relative Spectral Sensitivity of Detectors and Transmittance of Optics - to be furnished

8. Sensitivity - must resolve specified target at distances between 5.25 and 87.2 feet (at 87.2 feet the integrated radiant flux is approximately 10^{-10} watts/ft^2)

9. Signal-to-Noise Ratio - minimum 5:1

10. Repeatibility - 1% for 1 hour

11. Alignment - requires sighting scope

The specification further requires a standard of spectral irradiance and a proper handbook on the principle of operation and maintenance of the instruments.

The instrument is intended for use as a transfer standard for measurements of irradiance on various star simulators. Three photomultipliers having nominal S-4, S-11 and S-20 spectral responses are used to evaluate the irradiance as experienced by star tracking equipments utilizing any of these detector responses.

III INSTRUMENT DESIGN

The BEC Laboratory Photometer has been designed as a standard instrument embodying many of the design principles and components of the BEC EP-1 Photoelectric Pyrometer. The instrument is comprised of an electronics unit containing the display, controls and power supplies; and the optical head containing the photomultiplier, objective and sighting optics.

A. Basic Approach

The proposed approach to the Laboratory Photometer incorporates the photomultiplier detector operated in a constant current mode wherein the multiplier dynode voltage impressed upon the detector and, hence, the gain is controlled to achieve a constant anode current. This method is opposed to the somewhat more conventional technique of operating a photomultiplier at a constant dynode voltage and gain wherein the anode current is proportional to the measured illumination.

The benefits of the constant current approach for the intended applicated are:

1. Greater dynamic range of one scale

2. Inherent protection of the detector if accidentally exposed to high brightness levels

3. Improved stability achieved through a closed loop operation

The anode current in this mode by be expressed:

$$I_a \approx V^n \cdot P_{eff} \qquad (1)$$

Where:

I_a = anode current

V = supply voltage

n = number of photomultiplier stages

$P_{eff} = \int H_\lambda S_\lambda d\lambda$ = effective input radiation

H_λ = spectral irradiance

S_λ = spectral responsivity of the photomultiplier cathode

Holding the anode current constant by controlling the applied dynode voltages, then:

$$\log P_{eff} = n \log V + C \quad (2)$$

$$P_{eff} = \frac{C}{V^n} \quad (3)$$

As the instrument will be utilized primarily for the measurement of stellar magnitudes where:

$$\Delta m = 2.5 \log P_2/P_1,$$

the readout is proportional to Δm once calibrated at a particular known irradiance.

The range of stellar irradiances specified is approximately 275:1, implying a stellar magnitude range of six. This dynamic range may be easily handled on one scale with adequate resolution.

B. Design Modifications Encountered

As noted above the Laboratory Photometer was designed mainly as a modification to the BEC EP-1 Photoelectric Pyrometer. As such many of the detailed components, castings and mechanical assemblies are the same. There were certain areas, however, wherein design modifications were undertaken to improve performance and ease operation for use as a stellar photometer.

First, the pyrometer makes use of a pellicle beam splitter in the optical path between the objective lens and the field aperture to provide a simultaneous viewfinder. This allows an operator to view the target while measuring temperature. In the photometer, however, a sixth magnitude star was considered too dim to allow observation from the pellicle. Accordingly, a 45 degree mirror normally used to deflect the optical axis down to the aperture was made movable. A switch was added to the top of the optical head to facilitate control of the mirror. The operation is wholly mechanical, no solenoids or electrical devices being required. The sighting telescope was then moved to the top of the head, coincident with the optical axis of the objective lens. In accomplishing this, numerous small improvements were added to the optical and mechanical components. This change, though not initially proposed, thus allows direct through sighting without the loss of image brightness which would have resulted had the pellicle beam splitter been used. In this modification, optical filters used to limit the spectral response of the instrument were removed. A split field lens assembly, however, intended to uniformly illuminate the photo cathodes, was retained satisfying the requirement for a "blurred" or defocussed image at the detector.

As the basic pyrometer makes use of a 1P28 photomultiplier operating to 1250 volts, design changes in the control electronics were required to raise the voltage for the S-11 and S-20 response tubes. Initial selection of the RCA 7264 and 7265 photomultipliers for the S-11 and S-20 responses were subsequently determined to be inadequate for two reasons. First, these tubes are larger than desired; and, second, the ten stage multipliers offered inadequate gains. This was similarly true for the one inch equivalents of the tube for which an adequate signal to noise ratio was predicted, operating at anode currents of 10^{-8} amperes. It is desirable, however, to operate in the constant current closed loop mode at an anode current of 10^{-7} amperes or greater. Accordingly, EMR tubes type 541A (S-11) and 541E (S-20) were selected. These tubes are compatible with the basic mechanical and electronic components of the EP-1 and necessitated only a change in the photomultiplier housing of the optical head to provide interchangeability with the RCA 1P21. The power supply was therefore modified to provide a maximum 3600 volts for the S-11 and S-20 tubes and 1250 volts for the 1P21 (S-1).

The readout display consists of an indicating instrument meter. Scales are usually drawn specially for each instrument and in this case could have been drawn to P_{eff} or even Δm. In discussion with the cognizant technical representative, however, it was resolved that the simple 100 division linear scale was required.

C. Description of the Final Instrument

The photometer is made up of two major assemblies, the optical head which includes the photomultiplier assemblies and the electronics unit containing the readout. A fifteen foot interconnecting cable is furnished.

Figure 1 shows the optical head assembly. The objective lens is contained in a focussing mount. The clear aperture is 57 mm and the focal length is 146 mm. The objective may be focussed from approximately 3 feet to infinity. Behind the objective is mounted a first surface flat mirror which may be alternately removed from the optical path or swing into the path at 45°. In the first position, the mirror has no effect, and the total target image is viewed through the eyepiece. In the second position, energy from the target is reflected downward to the field defining aperture. The mirror position is selected using the slide switch on the top of the optical barrel. The mirror is out of the path with the forward position of the switch and in the path when in the rear position.

The field defining aperture is .064 inches in diameter. Installed beneath the aperture is a two-element field lens which focusses the objective lens on the photomultiplier. This field lens is used to distribute energy uniformly across the face of the photomultiplier tube, accomplishing the same purpose as defocussing or blurring the image of a point source on the photo cathode.

Three photomultiplier tubes are provided for installation in the otpics head. Each tube is located by an index pin and is secured with four captive screws in the flange. The photomultipliers supplied are the RCA 1P21 (S-4), EMR 541A (S-11) and the EMR 541E (S-20). Front face tubes are mounted with an auxiliary mirror. All electrical interconnections are complete in each interchangeable photomultiplier assembly.

To the rear of the switched mirror is the sighting reticle at the focus of objective. This reticle shows two concentric circles, the outer circle defining the field of view of 0.7° while the inner circle defines a field of approximately 0.3° for reference. Two erector elements and the eyepiece complete the sighting scope. The over-all field of view through the sighting optics is 2.6°.

The optical head mounts on a tripod or other fixture using a 1/4-20 threaded insert in the bottom of the head.

Figure 2 shows the electronics and display unit. In this unit is mounted the control amplifier, the high voltage d-c to d-c converter, the display and the power supply. The control electronics consist of a zener regulated reference current source, a two-stage amplifier, a power regulator and a dc-dc converter using a voltage trippler as the output. To provide for ease in interchanging detectors, the S-11 and S-20 photomultipliers utilize dynode voltage dividers of high resistance while the 1P21 (S-4) tube utilizes a low resistance string making it feasible to limit the current with a simple series resistance in the electronics unit. The utilization of high resistance divider chains for the high voltage tubes is possible because the constant anode current has been set for 0.2 and 0.5 microamperes on the "lo" and "hi" range scales. Loading of the output high voltage is, of course, a problem. Therefore, the display voltage has been taken from the input to the converter. Measurements indicate that the converter is linear within 1/2% over the usable range of the instrument.

D. Calibrated Source

A calibrated source of irradiance is provided. The calibration data and instructions for its use and handling are contained in Appendix 1. The physical source is as described in the application instructions.

IV TEST RESULTS

A. Spectral Response of Photomultipliers

Figure 3 shows the measured spectral response of the RCA 1P21 (S-4) photomultiplier. Response of the S-11 and S-20 photomultipliers is shown in Appendices 2 and 3 to this report, containing certificates for the EMR 541-A-01-14-03900 and EMR 541-E-01-03900, respectively. Each of these latter tubes, end-on types, has incorporated with the tube a first surface mirror adapting it to the optical path of the head. These mirrors show 94% ±2% over the measured range shown for the tube.

B. Spectral Transmittance of the Optical Head

Figure 4 shows the measured spectral transmittance of the optical head. This measurement was made using the RCA 1P21 detector and an NBS calibrated source of spectral irradiance.

C. Sensitivity

Figure 5 shows plots of the relative indicated output as a function of relative source brightness. This plot was prepared based upon the use of the NASA Standard Star Source described in the basic specification. Unity brightness level has been taken as that irradiance achieved at the greatest distance, and other points were measured and plotted using the "inverse square law". It will be noted that the plots are substantially linear on semi log graph paper indicating agreement with equation (2). Reference to the certified data for the EMR phototubes will, however, explain the curvature when it is taken into account that the applied voltage varies considerably and the gain is not truly a logarithmic function. Over a somewhat greater than 10:1 range, each tube does, however, exhibit, a closely logarithmic function. Hence, with two ranges, it is possible to calibrate the instrument conveniently.

The departure of both the S-4 and S-20 tubes is representative of the near maximum gain which is required of these tubes at the minimum light level.

D. <u>Evaluation of the Signal-to-Noise Ratio</u>

Because of the characteristics of the Laboratory Photometer, operation of the photomultiplier at a constant anode current results in the highest signal output (dynode voltage) when the instrument is capped or when observing low intensity targets. Accordingly, the signal-to-noise ratio results cannot be evaluated in terms of the measured signal output when observing the star versus the output signal when capped, as with the more conventional linear current measurement photometer. The inherent compression necessitates an alternate approach to this evaluation.

The noise may be defined as the variation or ripple which limits the resolution of the photometer. Accordingly, the signal-to-noise ratio may be defined at the minimum brightness level as:

$$S/N = \frac{1.0 \text{ (minimum brightness level)}}{\underset{\text{calibration constant}}{(\text{slope } \Delta B/\Delta I)} \times \underset{\text{recorder constant}}{(\text{slope } \Delta I/\Delta V)} \times \underset{\text{recorder output}}{(\text{RMS noise } \sigma)}}$$

where:

$\Delta B/\Delta I$ = slope of relative brightness units to indicated output

$\Delta I/\Delta V$ = ratio between the relative output scale and the recorder output voltage

The measurements of noise are most conveniently made by recording the output of the photometer while observing the star. Attached as Figures 6, 7 and 8 are three representative traces of such recordings with the scale factor set at 5 volts full scale, one for each photomultiplier tube. A regulated low noise power supply was used to offset the zero output of the recorder to obtain the traces.

The attached calibration curve, Figure 5, shows the measured output of the photometer for a number of different star brightness levels. The lowest brightness has been defined as unity level for convenience. In measuring the brightness levels at distances greater than 50 feet, it was necessary to reflect the image using an optical flat. The optical reflectance has been calculated as 94% in the spectral band of interest.

For the S-20 (See Figure 6).

1. The calibration of brightness units/volt at the lowest brightness measurement is:

$$\frac{1.08 - 0.93}{3\mu a} = B/U = \frac{0.15}{3} = 0.05\ BU/\mu a$$

2. Recorder output constant (Figure 9)

$$\frac{20}{15.8 - 9.6} = \frac{20\mu a}{6.2\ volts} = 3.22\ \mu a/volt$$

$$S/N = \frac{1}{(\text{slope } \Delta I/\Delta V)(\text{slope } \Delta B/\Delta I)(\text{RMS Noise v})}$$

$$= \frac{1}{3.22\Delta a/v \times 0.05 \text{ BU}/\Delta a \times \frac{.15v}{5} \text{ rms}}$$

$$S/N = \frac{1}{3.22 \times 0.05 \times 0.03} = 206$$

It is readily apparent from Figures 7 and 8, traces of the signal and noise output using the S-4 and S-11 tubes respectively, that the S/N ratio for these tubes is correspondingly high.

V CONCLUSIONS

On the basis of the data taken, it is concluded that the Laboratory Photometer meets the essential requirements of the procurement specification. Only one requirement, the spectral transmittance below 5000A, failed to comply.

The measurement of spectral transmittance of the optics was accomplished twice. The first measurement involved a number of conversions of the basic data and the resulting data showed inconsistencies. The test was repeated, this time measuring the spectral response of the 1P21 and then of the 1P21 and the optics. The measured response of the RCA 1P21 agrees with the published data and data previously taken on other tubes in the same manufacturing lot. The optical transmittance measurement, therefore, appears correct. Pressure for delivery of the photometer and a general feeling that this condition would be acceptable prevented further investigation of this problem. A general approach would require the disassembly of the optical head and the measurement of spectral transmittance of each element to determine the source of the lower transmittance between 4000 and 5000A. A general departure from the 5% maximum deviation in transmittance below 4000A would be expected for the glass elements.

Should it be desirable, other scale configurations are possible and may be desirable.

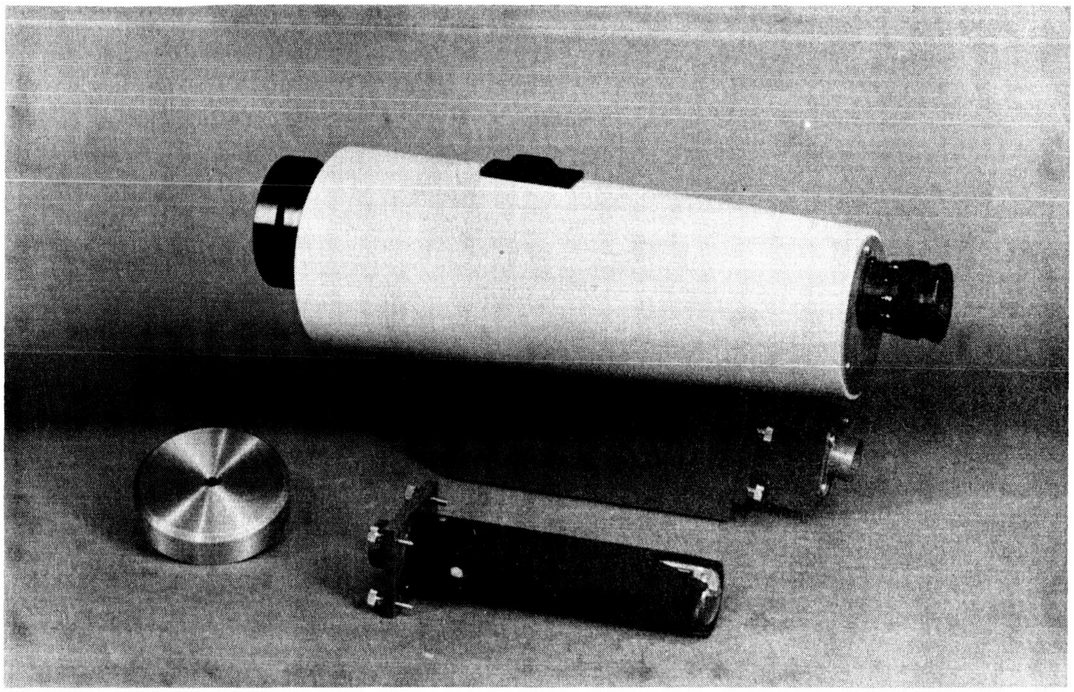


Figure 1 MODEL 12-813 OPTICAL UNIT

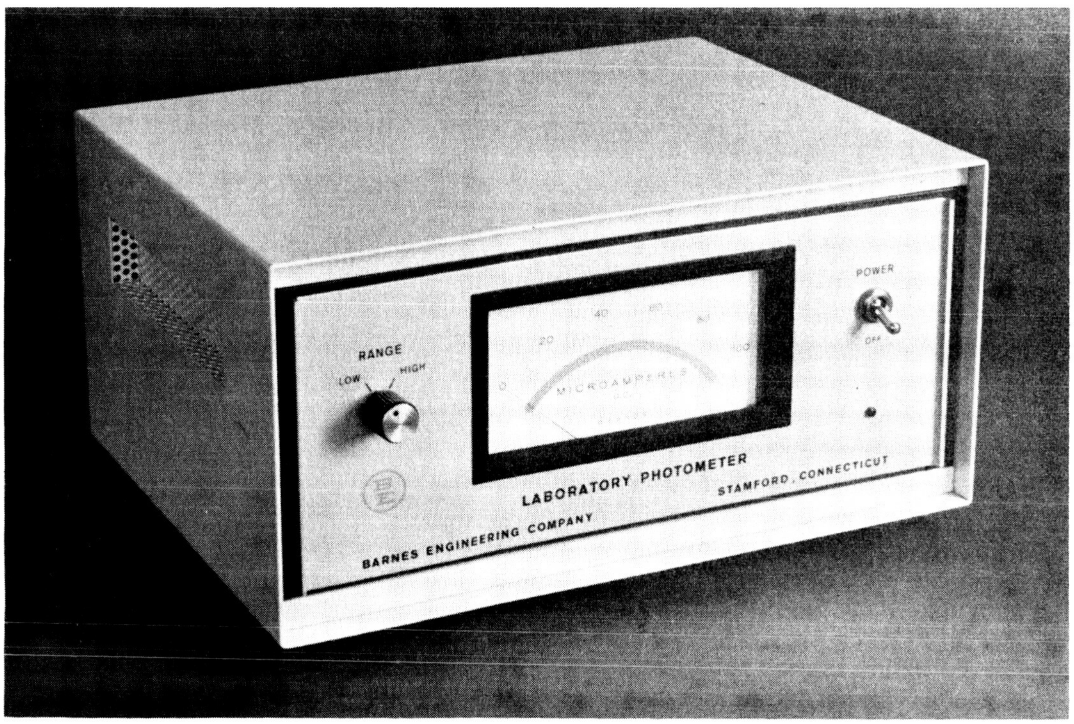


Figure 2 MODEL 12-813 ELECTRONICS UNIT

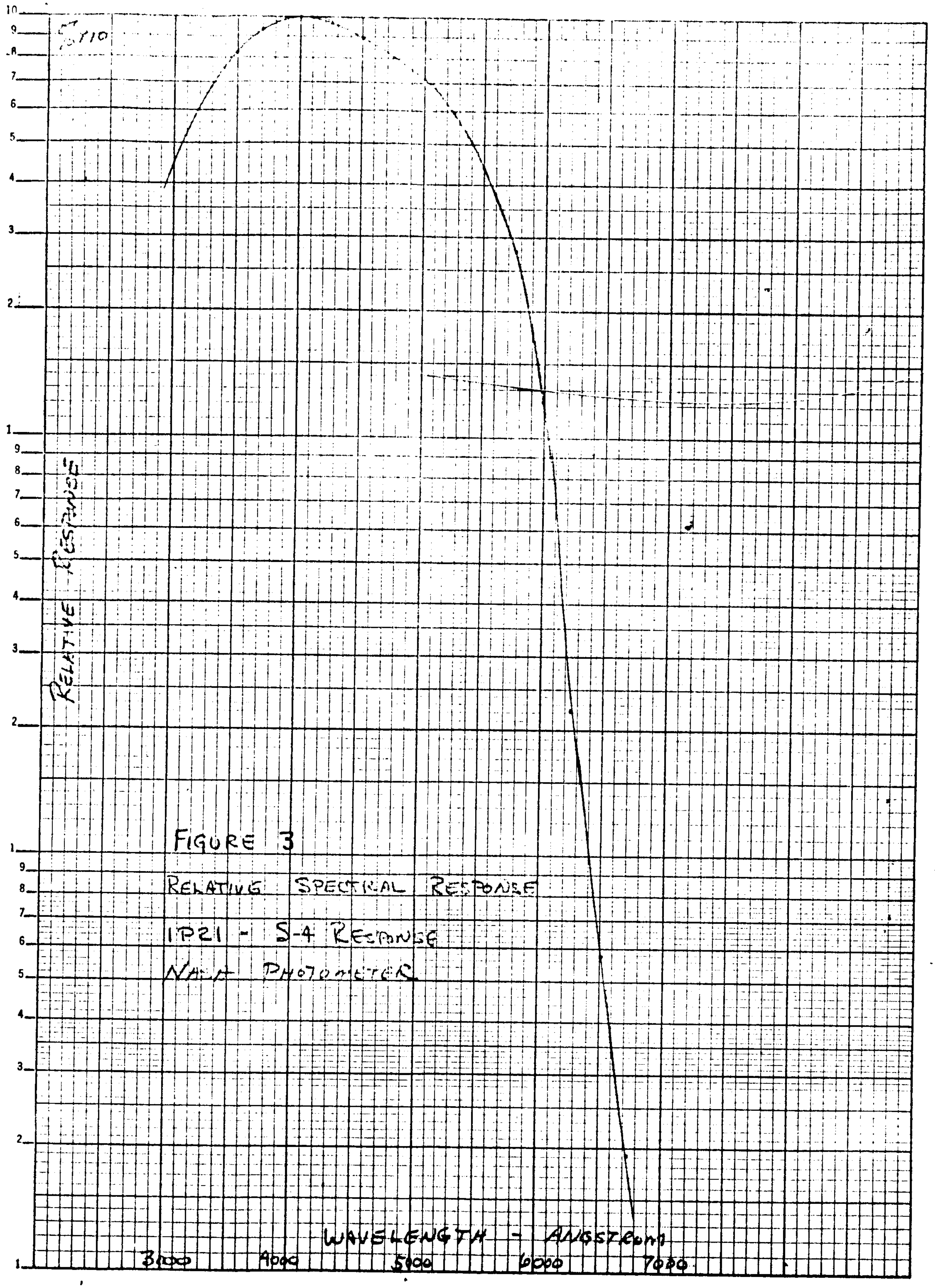


FIGURE 3
RELATIVE SPECTRAL RESPONSE
1P21 - S-4 RESPONSE
RELATIVE RESPONSE
WAVELENGTH - ANGSTROM
3000
4000
5000
6000
7000
10
9
8
7
6
5
4
3
2
1

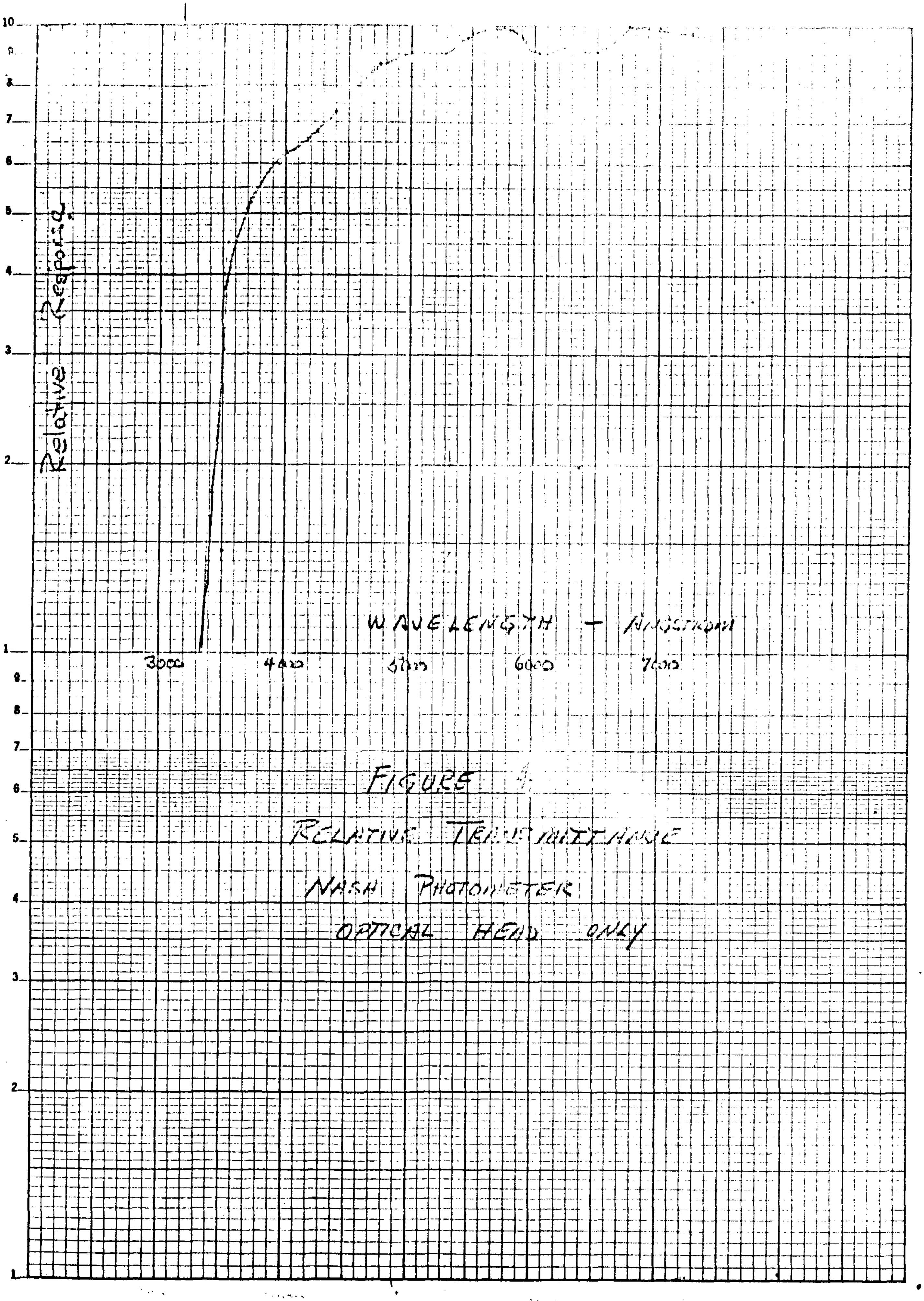


FIGURE 4

RELATIVE TRANSMITTANCE

NASH PHOTOMETER

OPTICAL HEAD ONLY

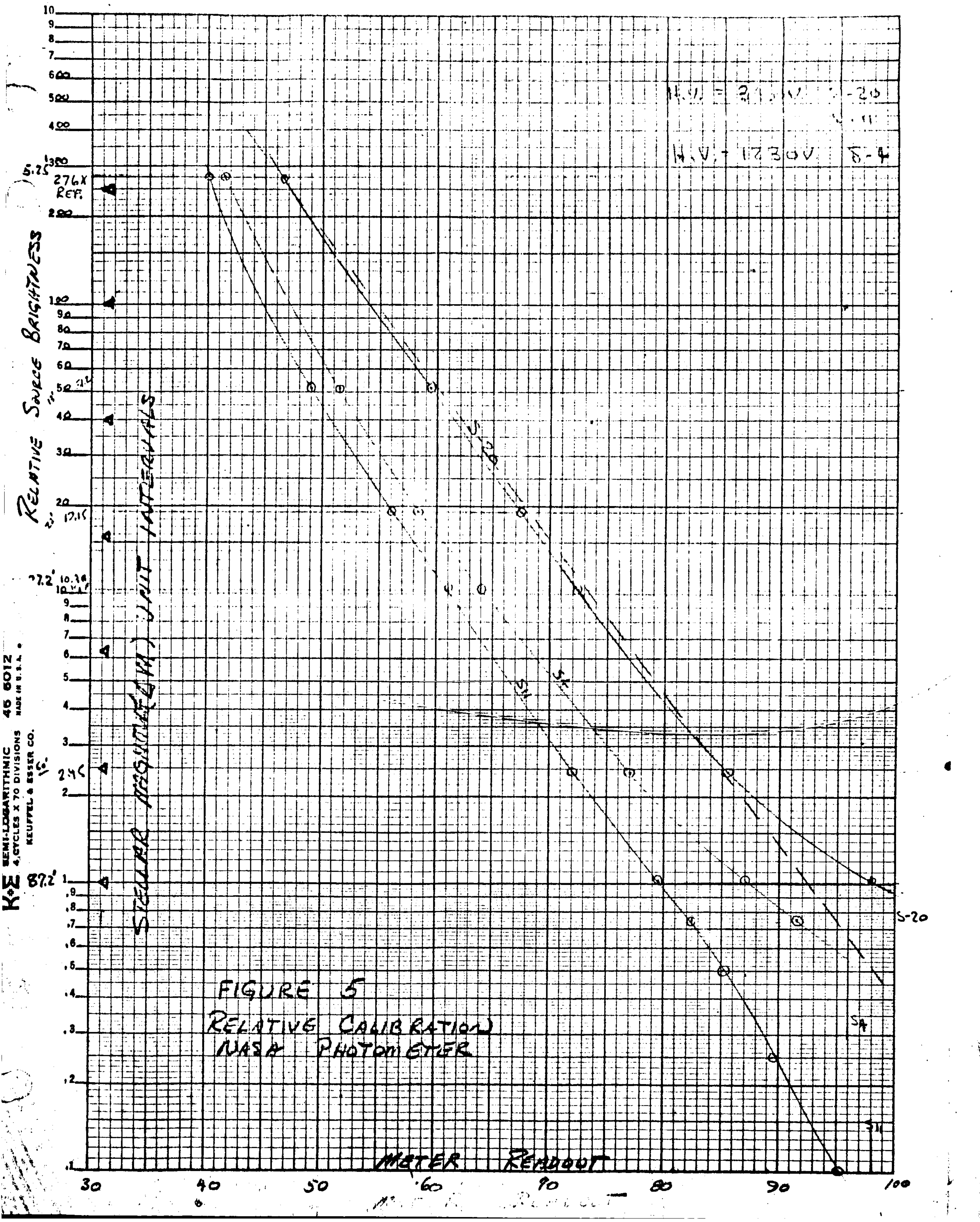
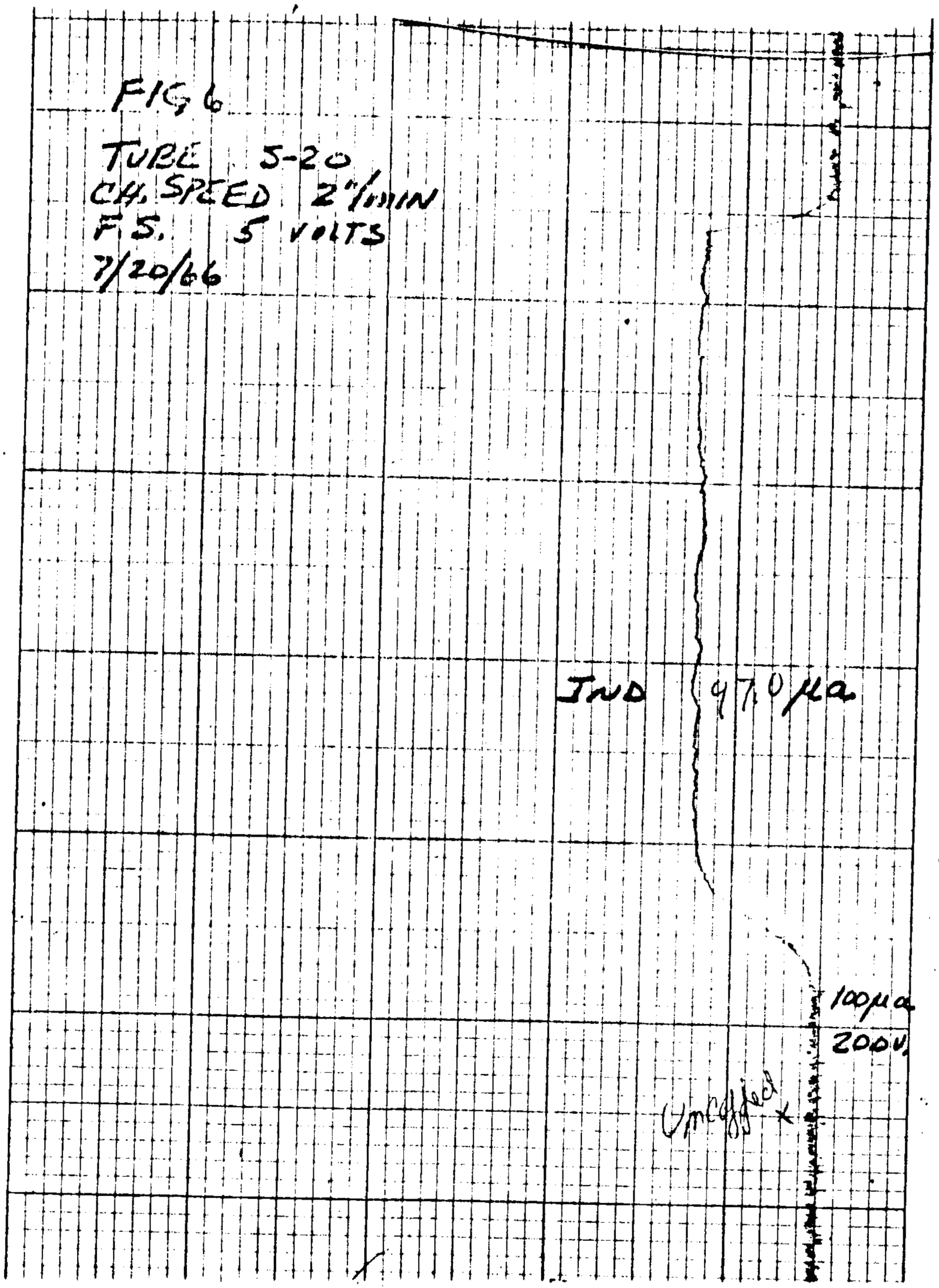
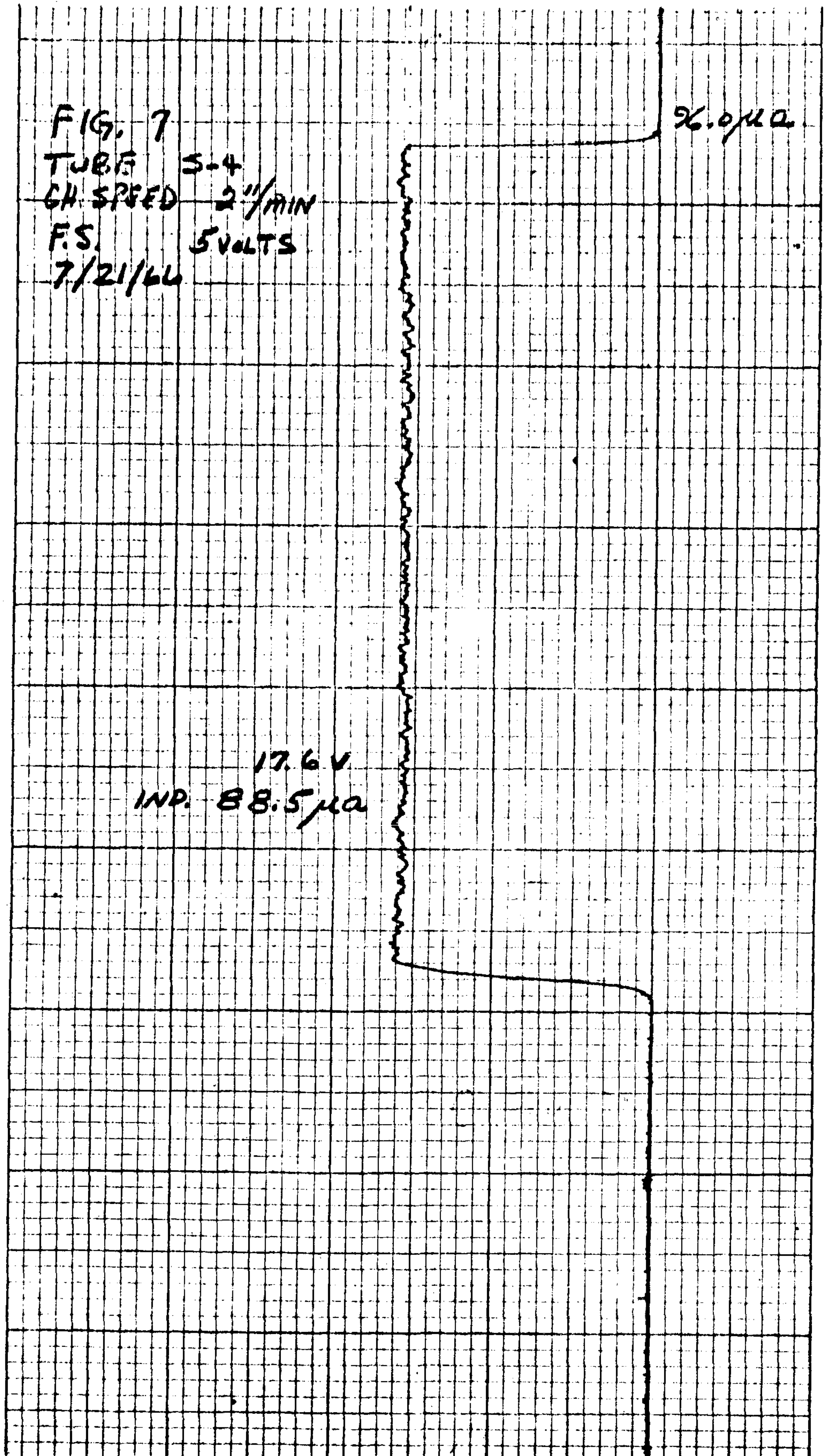


FIGURE 5
RELATIVE CALIBRATION
NASA PHOTOMETER



HEWLETT-PACKARD, MOSELEY DIVISION 9270-1012



HEWLETT-PACKARD/MOSELEY DIVISION 9270-1012

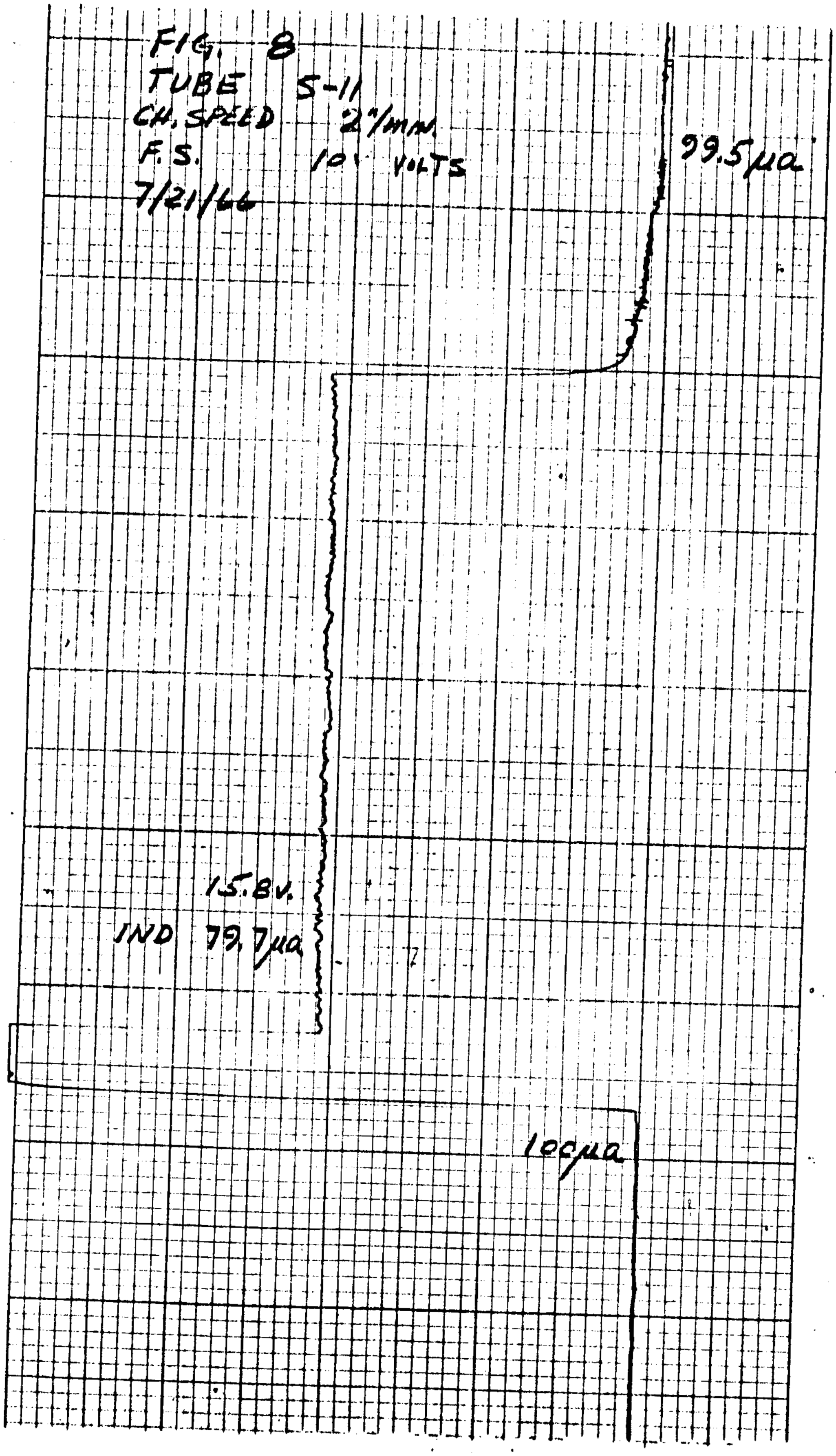


FIG. 8
TUBE S-11
CH. SPEED 2"/MIN.
F.S. 10 VOLTS
7/21/66
99.5µa
15.8V.
IND 79.7µa
100µa

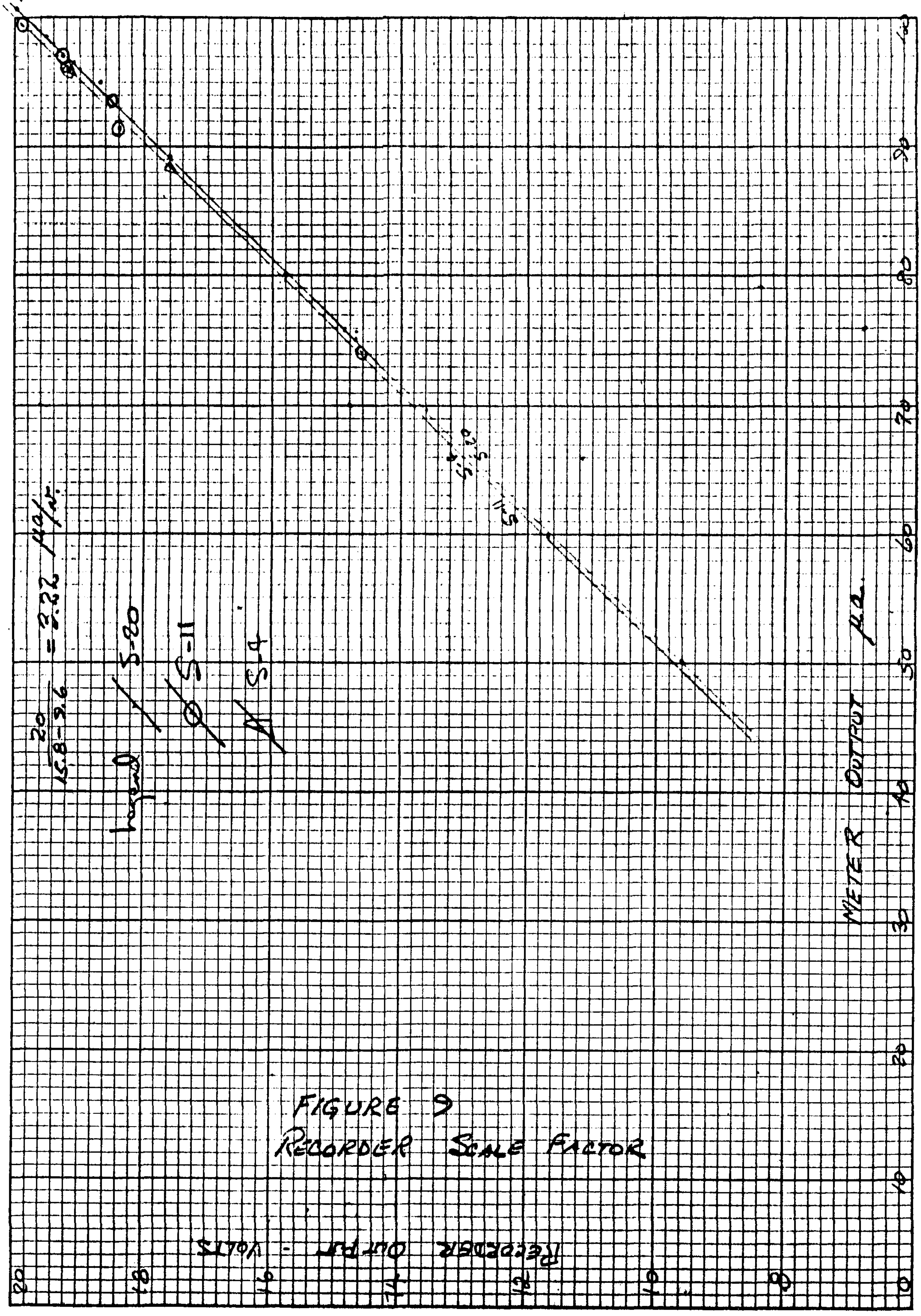


FIGURE 9
RECORDER SCALE FACTOR

APPENDIX 1

EPLAB

THE EPPLEY LABORATORY, INC.

SCIENTIFIC INSTRUMENTS

NEWPORT, R.I.

U.S.A.

CERTIFICATE OF CALIBRATION OF A STANDARD OF SPECTRAL IRRADIANCE

For: Barnes Engineering Co.
30 Commerce Road
Stamford, Connecticut

S. O. 15918 Lamp Serial No. EPI-1037

1. Spectral Range of Calibration: 250 mμ to 2500 mμ.

2. Method of Calibration

See "Instructions for Using the NBS 1000 Watt Quartz Iodine Lamp Standards of Spectral Irradiance", one copy of which is enclosed. See particularly paragraphs 2, 3 and 4 of the instructions regarding orientation of the standard.

3. Standards of Reference

The serial numbers of the National Bureau of Standards' reference standards employed are: QM-111 EPI-1001 QM-112

4. Results

The results are contained in the appended Table.

Tested by: D. B. Daniels
D. B. Daniels

Checked by: J. R. Hickey
J. R. Hickey

Date: 4 May 1966

TABLE OF RESULTS

Spectral irradiance in microwatts per (cm^2-nanometer) at a distance of 50 cm of lamp No. EPI-1037 operated at 8.3 amperes

λ(nm ≡ mμ)	Spectral Irradiance
250	.0159
260	.0285
270	.0489
280	.0784
290	.118
300	.167
320	.325
350	.765
370	1.15
400	2.05
450	4.18
500	6.96
550	10.3
600	13.7
650	17.0
700	19.8
750	21.5
800	23.1
900	23.7
1000	23.2
1100	21.8
1200	20.1
1300	18.1
1400	16.2
1500	14.2
1600	12.5
1700	10.9
1800	9.59
1900	8.20
2000	7.17
2100	6.23
2200	5.54
2300	4.99
2400	4.51
2500	4.06

Instructions for Using the NBS 1000-Watt Quartz Iodine Lamp
Standards of Spectral Irradiance

November 30, 1964

These instructions cover the use of tungsten-filament quartz-iodine lamps issued as standards of spectral irradiance for the wavelength range of 0.25 to 2.5 microns. The lamps employed are commercial G.E. type DXW-1000-watt lamps having a tungsten coiled-coil filament enclosed in a small (3/8 inch x 3 inches) quartz envelope containing a small amount of iodine.

The spectral radiant intensity of the entire lamp as mounted in the manner prescribed below is measured and reported. The spectral irradiance from these lamps is based upon the spectral radiance of a blackbody as defined by Planck's equation and has been determined through comparison of a group of quartz iodine lamps with (1) the NBS standards of spectral radiance, (2) the NBS standards of luminous intensity, and (3) the NBS standards of total irradiance.

The lamp is mounted vertically with the NBS-numbered end of the lamp down-with number away from the detector. Measurements of distance (from lamp filament) are made along a horizontal axis passing through the center of the lamp filament. The correct vertical position is determined by setting the centers of the upper and lower seals along a plumb line as viewed from one side of the lamp. The plane of the front surface of the upper press seal is set to contain the horizontal perpendicular to the line connecting the lamp filament center and detector.

The lamp is mounted in the supplied holder which is constructed in such a manner as to reflect a negligible amount of radiant flux in the direction of the radiometer or spectrometer slit. A black shield should be placed at a distance of about 4 feet to the rear of the lamp to intercept stray radiant flux along the radiometric axis and adequate shielding should be provided to intercept stray flux, from other directions.

If there is excessive water vapor in the laboratory atmosphere, errors may result at the wavelengths of water-vapor absorption bands. In the original calibrations the comparisons of the lamps with the other NBS standards were made in such a manner that the effect of water-vapor absorption was eliminated.

Values of spectral irradiance for these lamps are tabulated as a function of wavelength in microwatts per (square centimeter-nanometer) at a distance of 50 centimeters from center of lamp to receiver. Values of spectral irradiance for wavelength intervals other than one nanometer, say x nanometers, may be found by multiplying the tabulated values by x.

Use of the Standards of Spectral Irradiance

These standards require no auxiliary optics. If any are employed proper correction must be made for their optical characteristics. The lamp is simply placed at a measured distance from the detector or spectrometer slit. If a distance other than 50 centimeters is used, the inverse-square law may be used to calculate the spectral irradiance (the inverse-square law should not, however, be used for distances shorter than about 45 centimeters).

In measurements wherein two sources (a standard source and a test source) are being compared by the direct substitution method (slit widths kept unchanged, use of the same detector) no knowledge of the spectral transmittance of the spectrometer, nor of the spectral sensitivity of the detector is required. It is necessary, however, to make sure that the entrance slit of the spectrometer is fully and uniformly filled with radiant flux both from the standard and from the test source; and if at any one wavelength the detector response for the standard is significantly different from that for the test source, the deviation from linearity of response of the detector must be evaluated and taken into account. Furthermore, if the standard and test source differ in geometrical shape, it must be ascertained that the instrument transmittance and detector response are not adversely affected thereby. Many detectors are highly variable in sensitivity over their surface area and may require diffusion of radiant flux over their surface to insure accurate radiant energy evaluations.

All calibrations were made by the use of alternating current and it is recommended that they be so used in service. To reduce the line voltage a 20-ampere variable autotransformer may be employed for coarse control. For fine control a second (5-ampere) variable autotransformer may be used to power a radio-filament transformer whose secondary (2.5-5 volt) winding is wired in series with the primary of the 20-ampere transformer. It was found that this method is very effective for accurate control of the 8.30-ampere current.

These standards of spectral irradiance are expensive laboratory equipment and it is suggested that they be operated sparingly and with care in order to prolong their useful life. They should be turned on and off at reduced current, and great care should be taken so that at no time will the current appreciably exceed 8.30 amperes. It is recommended that for general use, working standards be prepared by calibrating them relative to the laboratory standard supplied by NBS.

These lamps operate at high temperature such that the quartz envelope is above the flammable point of organic materials. They may thus cause fires, and also the burning of lint, etc. on the envelope which may result in optical damage to its surface. In no case should the fingers come into contact with the quartz envelope, either hot or cold, as the resulting finger prints will burn into its surface during lamp operation.

USCOMM-NBS-DC

Reprinted from APPLIED OPTICS, Vol. 2, page 1151, November 1963

A New Standard of Spectral Irradiance

Ralph Stair, William E. Schneider, and John K. Jackson

The National Bureau of Standards has made available a new standard of spectral irradiance in the form of a 200-W quartz-iodine lamp with a coiled-coil tungsten filament operating at about 3000°K and calibrated over the spectral range of 0.25 to 2.6 μ. The calibration of this standard is based upon the radiance of a blackbody as defined by the Planck law of radiation, since it was done by comparisons with the NBS standards of spectral radiance, of luminous intensity, and of total irradiance, each of which was established through the use of blackbodies. This standard is used without auxiliary optics. Because of its small physical size and high operating temperature, relatively high spectral irradiances may be obtained through its use.

I. Introduction

The precise measurement of irradiance from a source requires the use of a calibrated detector or a calibrated source which may be employed in a transfer calibration. The need for a calibrated source was originally met by Coblentz[1] in 1914 with the development of a carbon filament standard of total irradiance. Calibration and use of this type of standard have been subsequently reported by Coblentz and other personnel of the NBS Radiometry Laboratory.[2-4] Accurate calibration with this type of standard requires a detector with a nonselective spectral response. A thermopile heavily coated with dull lampblack or carbon black meets this requirement reasonably well from the near ultraviolet through the visible and near infrared portions of the spectrum. However, the relatively low sensitivity of thermopiles and other thermal detectors together with the fact that they are not entirely nonselective spectrally makes their use difficult for the evaluation of the spectral distribution of radiant flux.

Considerable work has been done on the emissivity of tungsten ribbon and wire filament lamps,[5-11] and, coupled with measurements of temperature, an approximate standard of spectral radiance or of spectral irradiance can be set up. A number of laboratories including the National Bureau of Standards have followed this procedure.[12-17] In 1960, the National Bureau of Standards developed a standard of spectral radiance[18] in the form of a tungsten ribbon-filament lamp calibrated by direct comparison with a blackbody, the spectral radiance of which is computed from Planck's radiation equation. These lamp standards have found wide use in the calibration of spectroradiometric and other equipment in which a small area, like a slit, is to be irradiated. However, the use of this standard is limited by the small area which can be irradiated, by the low irradiance which the standard provides in the ultraviolet, and by the auxiliary optics required. For many types of spectroradiometric calibration, a standard of spectral radiance has been found to be very useful and will no doubt continue to be useful. However, in many cases, a standard of spectral irradiance is needed. To fulfill this need and to provide a source of higher irradiance in the ultraviolet, a new standard of spectral irradiance has been developed.

II. Apparatus and Method

Before proceeding with the establishment of a standard of spectral irradiance for the region of 0.25 to 2.6 μ based upon the radiance of a blackbody at a known temperature, we made a study of possible lamp designs. First thought was given to the specially constructed tungsten-in-quartz lamp previously employed in this laboratory[12,13] as a standard of spectral irradiance based upon color temperature and the published spectral emissivity data for tungsten. It was recognized that this lamp had three principal deficiencies: its low operating temperature, poor optical quality and bulkiness of the quartz envelope, and relatively large filament area. Only very low ultraviolet irradiances could be realized at a spectrometer slit. Also, since each tungsten filament differs somewhat in emissivity as a function of its specific shape and surface condition,

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The authors are in the Radiometry Laboratory, National Bureau of Standards, Washington 25, D.C.

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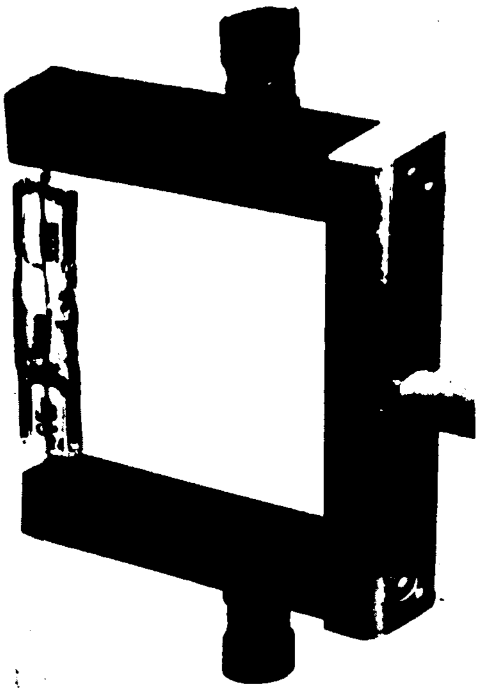

Fig. 1. Quartz-iodine lamp standard of spectral irradiance.

the computed values of spectral irradiance were uncertain by an indefinite amount.

Attention was given next to lamps being made commercially. The General Electric (GE) Model 6.6A/-T4Q/1CL-200-W quartz-iodine lamp (see Fig. 1) was examined and found to have acceptable characteristics for use as a standard. It is of robust construction, in a small quartz envelope of relatively good optical quality so that the intensity usually varies but little over a considerable solid angle centered normal to the axis of the lamp. The filament is a compact coiled coil with over-all dimensions approximating 3 mm × 13 mm. The small size of the lamp envelope (about 13 mm × 5 cm) together with the small area of the filament permits placing the lamp within a few centimeters of the slit of a spectrometer. Since this lamp is being set up as a standard of spectral irradiance to be employed without auxiliary optics, relatively high irradiance at a slit can be realized simply by placing the source close to it.

Because of its high operating temperature, the quartz-iodine lamp emits a relatively large percentage of ultraviolet radiation. The high temperature is made possible through the unique chemical action of the iodine vapor[19,20] which results in the return of evaporated tungsten from the bulb to the lamp filament, thereby keeping the envelope clean and prolonging the useful life of the lamp. The design life of this lamp when operated at 6.6 A is 500 h. For calibration as a standard, the current is set at 6.50 A which usually gives a color temperature between 3000 and 3100°K, corresponding to a filament temperature around 3000°K.

The establishment of the new standard of spectral irradiance was accomplished by comparing a group of quartz-iodine lamps with three other types of NBS standards, each of which is based upon the spectral radiance of a blackbody computed from Planck's radiation equation, wherein the radiation constants $c_1 = 1.19088 \times 10^{-12}$ W cm²/ster and $c_2 = 1.4380$ cm °K.

The group of quartz-iodine lamps was first compared spectroradiometrically with the NBS standards of spectral radiance.[18] The optical arrangement is shown in Fig. 2. Additional details may be found in the reference cited. To cover the complete spectrum from 0.25 to 2.6 μ, three detectors were employed. An RCA type 1P-28 multiplier phototube was used to cover the range from 0.25 to 0.75 μ. For the range of 0.35 to 1.2 μ, an RCA type 7102 multiplier phototube was employed, while an Eastman PbS cell was used through the range of 0.5 to 2.6 μ. To eliminate the effect of spectral reflectance of the two aluminized mirrors employed with the ribbon-filament standards of spectral radiance, two plane mirrors having identically prepared surfaces were used with the quartz-iodine lamps. Actually, plane mirror M_1 was common to both optical systems (see Fig. 2). By this procedure, all instrumental characteristics were identical or closely similar for the two types of lamps. Hence, the optical and electronic factors should cancel out in the procedure. However, it was found that the light beam from the quartz-iodine lamp passed through the spectroradiometer somewhat differently and irradiated a slightly different area of the detector from that irradiated by the ribbon-filament standard. The beam of flux from the ribbon filament converged on entering the spectrometer, then diverged filling an appreciable part of the instrumental aperture, and finally at the exit slit emerged as a divergent beam. The flux from the quartz-iodine lamp passed through the spectrometer and emerged as

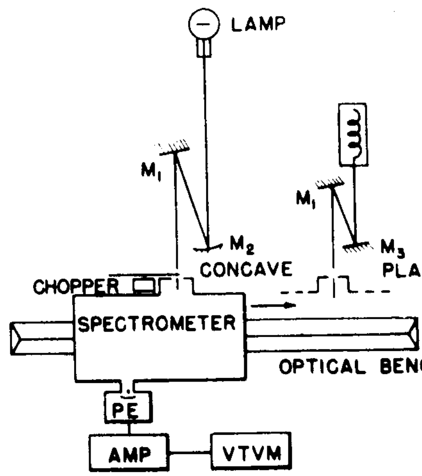

Fig. 2. Optical arrangement of spectrometer, lamp, mirrors, and associated equipment for comparing the quartz-iodine lamp standards of spectral irradiance with the ribbon-filament standards of spectral radiance.

Table I. Spectral Irradiance of Three 200-W Quartz-Iodine Tungsten-Filament Lamps[a]

Wavelength (nm)	Lamp QL-2	Lamp QL-5	Lamp QL-10
250	0.0051	0.0052	0.0051
260	0.0093	0.0093	0.0090
270	0.0158	0.0159	0.0155
280	0.0253	0.0252	0.0244
290	0.0380	0.0380	0.0369
300	0.0545	0.0548	0.0532
320	0.104	0.105	0.102
350	0.237	0.242	0.234
370	0.366	0.374	0.363
400	0.643	0.647	0.630
450	1.26	1.26	1.23
500	2.04	2.04	2.02
550	2.93	2.96	2.91
600	3.88	3.94	3.88
650	4.79	4.91	4.80
700	5.54	5.72	5.58
750	6.11	6.32	6.14
800	6.51	6.69	6.49
900	6.72	6.94	6.71
1000	6.51	6.73	6.53
1100	6.07	6.25	6.11
1200	5.53	5.67	5.55
1300	4.97	5.09	4.98
1400	4.44	4.52	4.44
1500	3.93	4.00	3.93
1600	3.46	3.51	3.45
1700	3.03	3.06	3.01
1800	2.63	2.65	2.61
1900	2.29	2.28	2.26
2000	1.98	1.97	1.95
2100	1.73	1.71	1.70
2200	1.52	1.51	1.50
2300	1.36	1.34	1.33
2400	1.22	1.21	1.21
2500	1.12	1.10	1.11
2600	1.04	1.03	1.04

[a] In μW per cm^2 per nm at a distance of 43 cm (measured from the axis of the lamp filament and normal to the plane of the lamp press) when operated at 6.50 A.

an essentially narrow "pencil" of flux, thereby being confined to a small part of the instrumental aperture and falling upon a small area of the detector. As a result, differential transmission within the spectrometer and variations in the sensitivity of the detector over its surface area* resulted in small errors of unknown magnitude. Hence, the resulting spectral energy curves for the quartz-iodine lamps, obtained by this method, require adjustment.

Three methods for determining the correction for the observed data were pursued. They are:

(a) Direct comparison, without the use of a spectrometer, of the quartz-iodine lamps with the ribbon-filament lamps by a thermopile and filter method, wherein selected spectral regions were compared radiometrically. This comparison was accomplished by focusing an image of the ribbon filament on the receiver of the thermopile by means of the two aluminum mirrors usually employed with the standard of spectral radiance. The quartz-iodine lamp directly irradiated the thermopile receiver. Correction was made for the spectral reflectance of the two aluminum mirrors. The ratio between the two radiometric readings gave a measure of the relative spectral intensities of the two sources for the different spectral regions defined by the filters employed.

(b) Measurement of luminous intensity as compared to calculated luminous intensity based upon the spectroradiometrically determined curve and the spectral luminous efficacy of the CIE standard observer. This method gave an independent evaluation of the spectral irradiance of the quartz-iodine lamps in the visible spectrum based upon NBS standards of luminous intensity, which had been assigned values by measurements relative to a blackbody at the freezing point of platinum.[21]

(c) Measurement of irradiances over selected spectral regions by employing optical filters and a thermopile found by comparison with a cavity detector to have a relatively flat spectral response and calibrated through the use of the NBS carbon-filament standard of total radiation. This method afforded an independent evaluation of the spectral irradiance from the quartz-iodine lamps based upon the NBS standard of total irradiance and the blackbodies used in its establishment.[1,2] Corrections ranging from 4.2 to 5.3% and nonselective with wavelength were indicated by the three methods. The original spectroradiometric data were accordingly corrected by 5.0%.

III. Results

Spectral irradiance data obtained on three quartz-iodine lamps are given in Table I in μW/cm^2 at a distance of 43 cm (measured from the axis of the lamp filament and normal to the plane of the lamp press) for a wavelength interval of 1 nm. It is estimated that the maximum uncertainty in the results ranges from about 8% at the shortest wavelengths in the ultraviolet to about 3% in the visible and infrared. The data have been corrected for the water-vapor absorption occurring at or near 1.1, 1.4, 1.9, and 2.6 μ. No significant radiant-energy absorption occurs at other wavelengths because of other gases normally present in the usual laboratory environment.

The quartz-iodine lamps may be employed at any convenient distance by computing or otherwise determining the irradiance at the new distance. The inverse square law should not be applied to these lamps

* Much of the variation of the detector sensitivity was eliminated by placing in front of it a quartz plate finely ground on both faces.

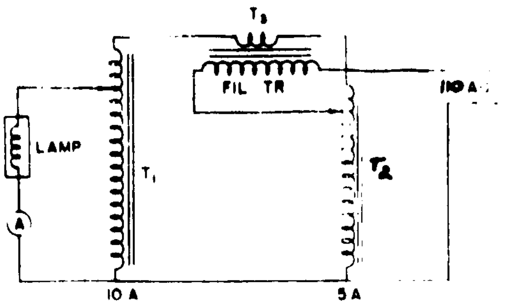

Fig. 3. Electrical circuit for lamp operation to provide smooth current control.

for distances shorter than about 40 cm. In most laboratory atmospheres the correction for water-vapor absorption will be small for distances of less than 50 cm. However, for greater distances and under conditions of high humidity, a correction may be required.[22-26] The relationship between the apparent absorption of water vapor (as indicated in a prism spectrum) and the amount of vapor is not a simple one, since each absorption band really consists of many fine lines of unequal intensity and irregular spacing. Furthermore, the attenuation at any wavelength due to water vapor is a complicated function of the pressure, temperature, and concentration of the vapor per unit volume.

Aging tests conducted on three quartz-iodine lamps indicate after 100 h of operation an increase at 6.50 A of less than 1% in total irradiance, luminous intensity, and ultraviolet irradiance around 360 nm.

IV. Use of the Standard of Spectral Irradiance

Each quartz-iodine standard is marked with an identifying number at one end of the lamp. The lamp is mounted in a metal support and is calibrated with this marked end down and with the plane of the front surface of the lower press seal set to contain the horizontal perpendicular to the line connecting the lamp filament axis and detector or spectrometer slit. The lamp tip seal is positioned away from the detector or slit. Precise setting of the lamp as regards to verticality and to rotation about the filament as an axis are important, since a few degrees displacement may result in an error of 1% or more.

The current is set at 6.50 A ac, and the lamp is allowed to operate for at least 5 min before data are recorded. Any convenient method may be employed to control the current; however, the circuit illustrated in Fig. 3 has been found very useful in this laboratory. It consists of two variable autotransformers (10-A and 5-A capacities) and a radio filament transformer. (One-half of a center-tapped 5- or 6.3-V secondary has been found to be satisfactory for smooth current control.) If a 30-V step-down transformer is available, it may profitably be used between the variable autotransformer, T-1, and the lamp.

V. Conclusions

The quartz-iodine lamp is a useful working standard for use in spectral irradiance measurements within the region of 0.25 to 2.6 μ. The methods of calibration are based upon indirect comparisons with the radiances of blackbodies and thus do not involve evaluation of filament temperature or tungsten emissivity. The principal uncertainties in the results are due to difficulties involved in accurate blackbody high-temperature evaluation and precise current settings for the various lamps. The maximum uncertainty in the results is estimated to range from about 8% at the shortest wavelengths in the ultraviolet to about 3% in the visible and infrared.

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APPENDIX 2

S-11

CERTIFICATE OF COMPLIANCE

Date: June 17, 1966

Vendor: Electro-Mechanical Research, Inc.
PRINCETON DIVISION
P. O. Box 44
Princeton, New Jersey

Shipped To:
Barnes Engineering
30 Commerce Road
Stamford, Connecticut 06902

Customer's Purchase Order No. C 16272

S-11 Tube

E.M.R. Order No. POA 4472

QUANTITY	DESCRIPTION
1	541A-01-14-03900 Multiplier Phototube Serial Number 7252

I hereby certify the above material(s) have been manufactured in accordance with and meet the required specification(s).

Anthony Marciano
Authorized Representative

Princeton Division
ELECTRO-MECHANICAL RESEARCH, INC.
Name of Vendor

Princeton Division

Electro-Mechanical Research, Inc.

Model No. 541A-01-14-03900

Rev.	Date	By	Ck'd	Q.C. App.	Eng. Conc.	Rev.	Date	By	Ck'd	Q.C. App.	Eng. Conc.	Rev.	Date	By	Ck'd	Q.C. App.	Eng. Conc.
–	[illegible]	[illegible]	[illegible]	[illegible]													

Test Technician Ernie Bowers

Date 6/16/66

Account Number 2041-4472

Serial No. 7252

Quality Assurance Approval 6/16/66

EMR-P 1 Q.C. INSP.

P A No. 4472

Reference Spec.

Photocathode Material: Cs Sb "visible"

Window Material: 7052

CHARACTERISTICS

Spectral response: see attached curve

Cathode radiant sensitivity at 4100 Å	59	x 10^{-3} A/W
Cathode quantum efficiency at 4100 Å	17.9	%
Cathode radiant sensitivity at 2537 Å	NA	x 10^{-3} A/W
Cathode quantum efficiency at 2537 Å	NA	%
Average luminous sensitivity:	74	µA/lumen

Current amplification[1,2]: see attached curve

Amplification 10^5 at	1560	volts	[2]Dark Current	2.6x10-10	A
Amplification 10^6 at	2125	volts	Dark Current	2.4x10-9	A
Amplification 10^7 at	2940	volts	Dark Current	2.2x10-8	A
Amplification 10^8 at		volts	Dark Current		A

MAXIMUM OPERATIONAL RATINGS

Supply Voltage: 3600 volts at 20°C

MAXIMUM RATINGS (ABSOLUTE-MAXIMUM VALUES)

Supply Voltage: 3600 volts
Anode Current: 1 ma
Temperature: 75°C

REMARKS

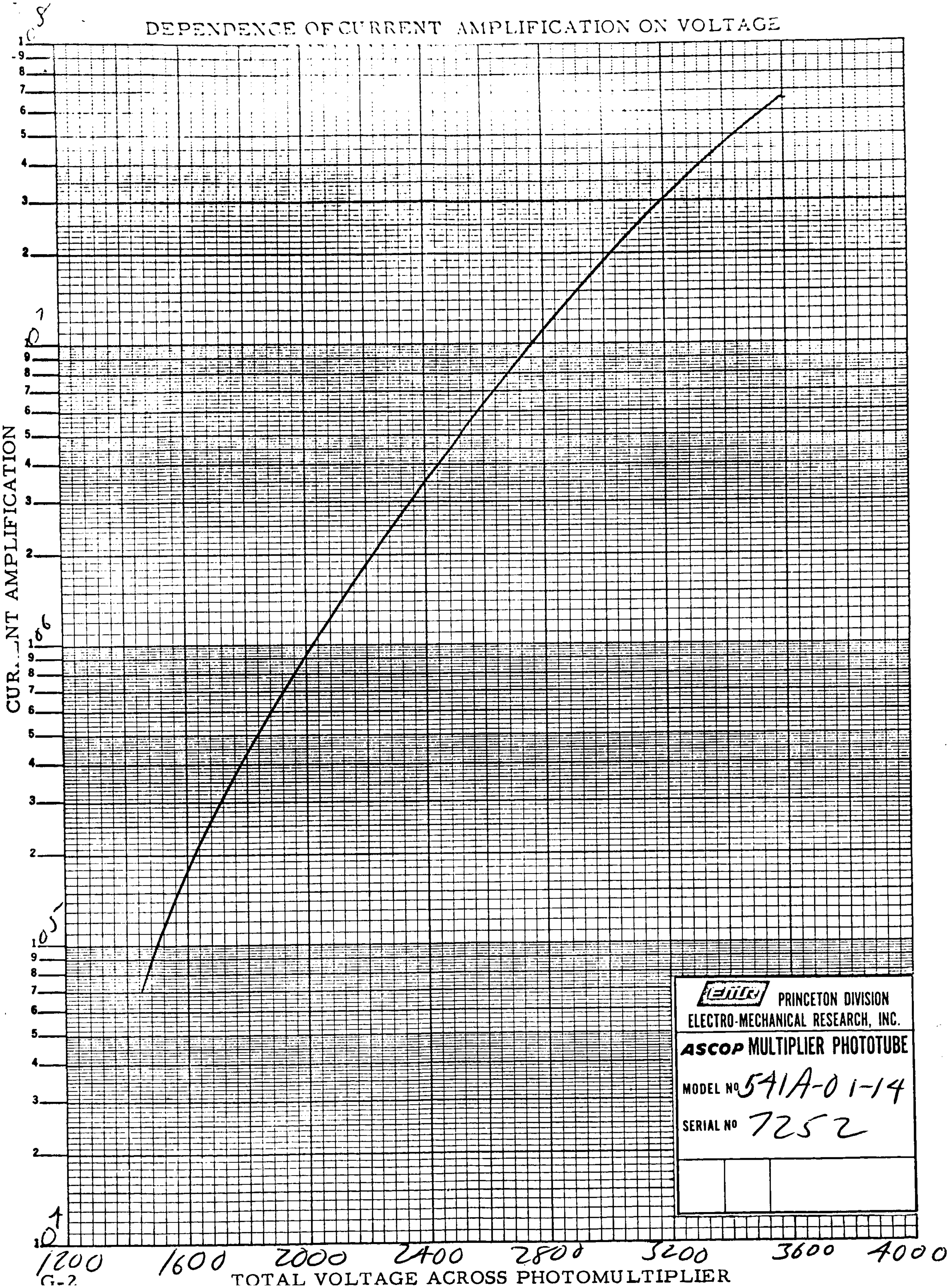
I Hereby Certify The Above Data is True and Correct.

Anthony Marciano
Quality Assurance Group Leader

NOTES:

Enter NA when not applicable
[1]See schematic diagram for voltage distribution
[2]Measured at 20°C

Form: A-1



DEPENDENCE OF CURRENT AMPLIFICATION ON VOLTAGE
CURRENT AMPLIFICATION
TOTAL VOLTAGE ACROSS PHOTOMULTIPLIER
1200
1600
2000
2400
2800
3200
3600
4000
10^8
10^7
10^6
10^5
10^4
EMR PRINCETON DIVISION
ELECTRO-MECHANICAL RESEARCH, INC.
ASCOP MULTIPLIER PHOTOTUBE
MODEL NO 541A-01-14
SERIAL NO 7252

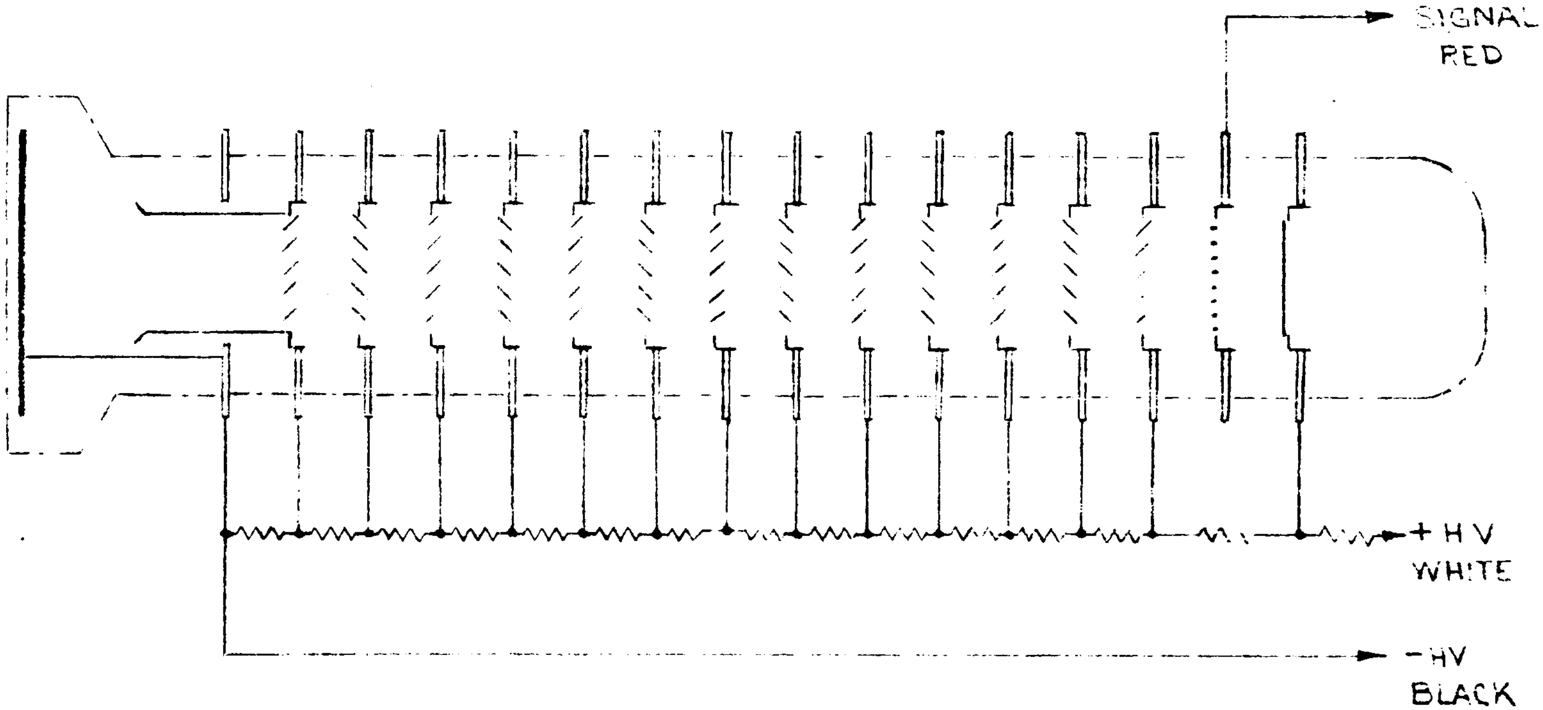
G-2

PHOTOMULTIPLIER SPECTRAL RESPONSE

SR-1

NOTES:

1- RESISTOR VALUES EQUAL THRU OUT UNIT.



SCHEMATIC DIAGRAM

EMR MULTIPLIER PHOTOTUBE

14 STAGES

EMR PRINCETON D
ELECTRO-MECHANICAL
MULTIPLIER PHOT

MODEL NO.	DRAWING NO.
541 & 542	54

APPENDIX 3

S-20

CERTIFICATE OF COMPLIANCE

Date: June 23, 1966

Vendor: Electro-Mechanical Research, Inc.
PRINCETON DIVISION
P. O. Box 44
Princeton, New Jersey

Shipped To:

Barnes Engineering
30 Commerce Road
Stamford, Connecticut 06902

Customer's Purchase Order No. C 16272

E.M.R. Order No. POA 4472

S-20 Tube

QUANTITY	DESCRIPTION
1	541E-01-14-03900 Multiplier Phototube Serial Number 8639

I hereby certify the above material(s) have been manufactured in accordance with and meet the required specification(s).

Anthony Marciano
Authorized Representative

Princeton Division
ELECTRO-MECHANICAL RESEARCH, INC.
Name of Vendor

Princeton Division

Electro-Mechanical Research, Inc.

Test Data Sheet 1 of 1

Model No. 541E-01-14-03900

Rev.	Date	By	Ck'd	Q.C. App.	Eng. Conc.	Rev.	Date	By	Ck'd	Q.C. App.	Eng. Conc.	Rev.	Date	By	Ck'd	Q.C. App.	Eng. Conc.
-	11-23-65	JC	Lk	11l													

Test Technician Gene Worek Date 6/22/66

Account Number 2041-4472 Serial No. 8639

Quality Assurance Approval 6/22/66 POA No. 4472

Reference Spec. ______ (EMR-P 7 INSP)

CHARACTERISTICS

Spectral Response: see attached curve

Cathode radiant sensitivity at 4100Å:	88.4	$\times 10^{-3}$ A/W	084
Cathode quantum efficiency at 4100Å:	26.8	%	25
Cathode radiant sensitivity at 2537Å:	NA	$\times 10^{-3}$ A/W	
Cathode quantum efficiency at 2537Å:	NA	%	
Cathode radiant sensitivity at 6300Å:	30.8	$\times 10^{-3}$ A/W	
Cathode quantum efficiency at 6300Å:	6.07	%	5.6
Average luminous sensitivity	139	ua/lumen	

Current Amplification[1,2]: see attached curve

Amplification 10^5	**at** 1800 **volts,**	[2]**Dark Current:**	2.2×10^{-10}	**Å**	1759/2050
Amplification 10^6	**at** 2430 **volts,**	**Dark Current:**	2.0×10^{-9}	**Å**	2400/2800
Amplification 10^7	**at** 3300 **volts,**	**Dark Current:**	2.0×10^{-8}	**Å**	3300
Amplification ____	**at** ____ **volts,**	**Dark Current:**		**Å**	

MAXIMUM OPERATIONAL RATINGS

Supply voltage: 3600 **volts at 20° Centigrade**

MAXIMUM RATINGS (ABSOLUTE-MAXIMUM VALUES)

Supply voltage: 3600 **volts**
Anode Current: **1 milliampere**
Temperature: **75° Centigrade**

I Hereby Certify The Above Data is True and Correct.

REMARKS

Anthony Marciano

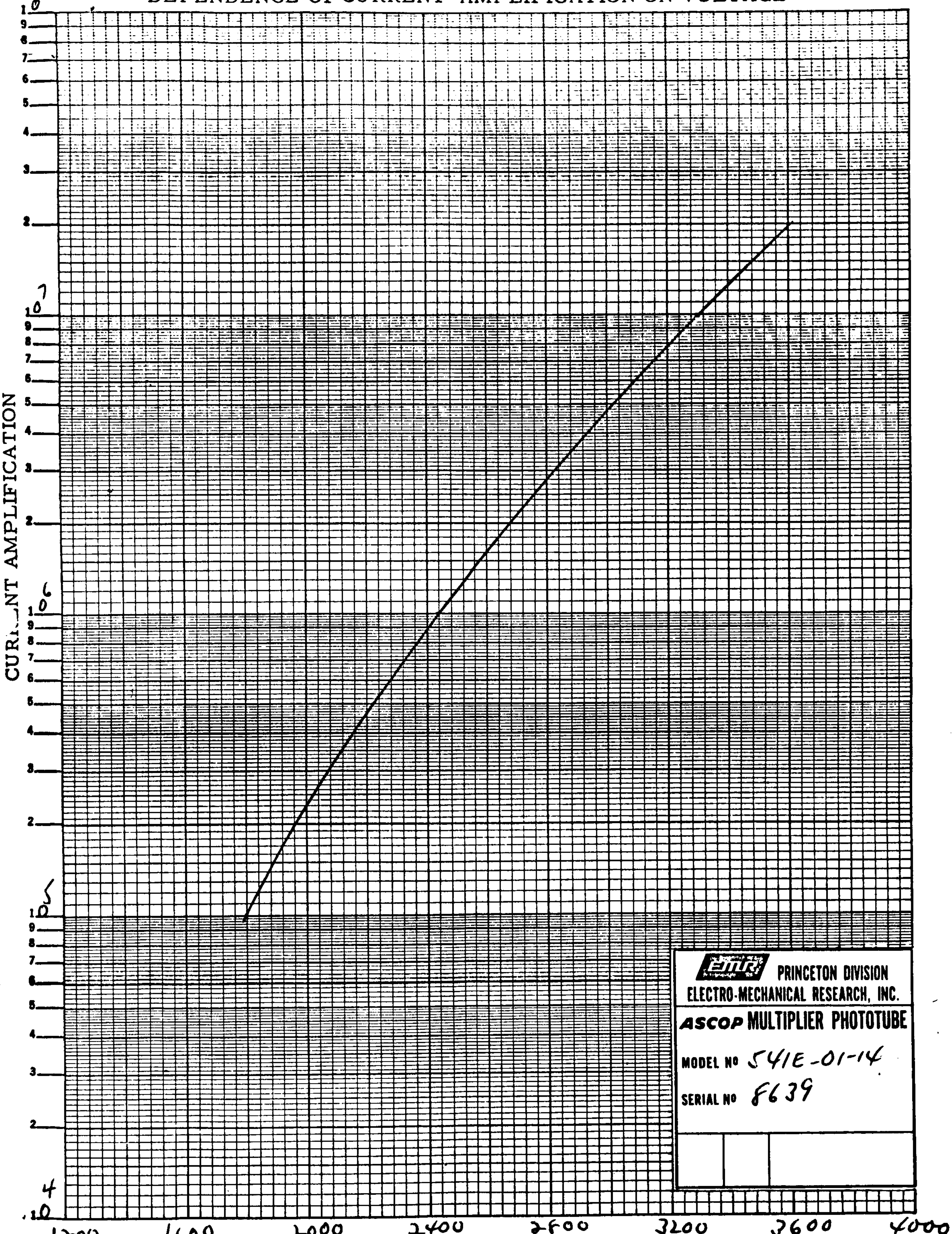
Quality Assurance Group Leader

NOTES:

NA: Not Applicable
[1]**See schematic diagram for voltage distribution**
[2]**Measured at** 20° **Centigrade**

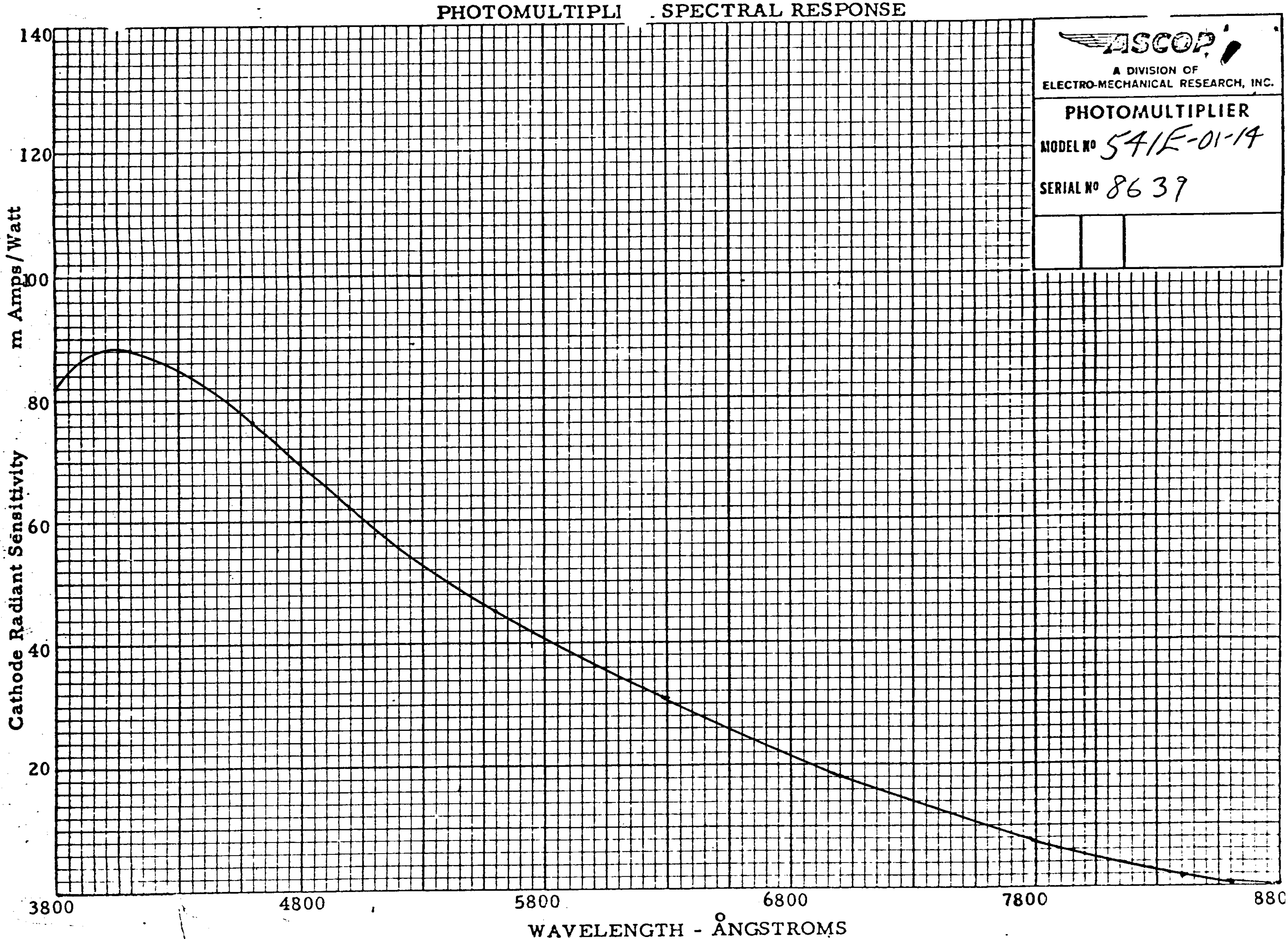
Form E-1

DEPENDENCE OF CURRENT AMPLIFICATION ON VOLTAGE



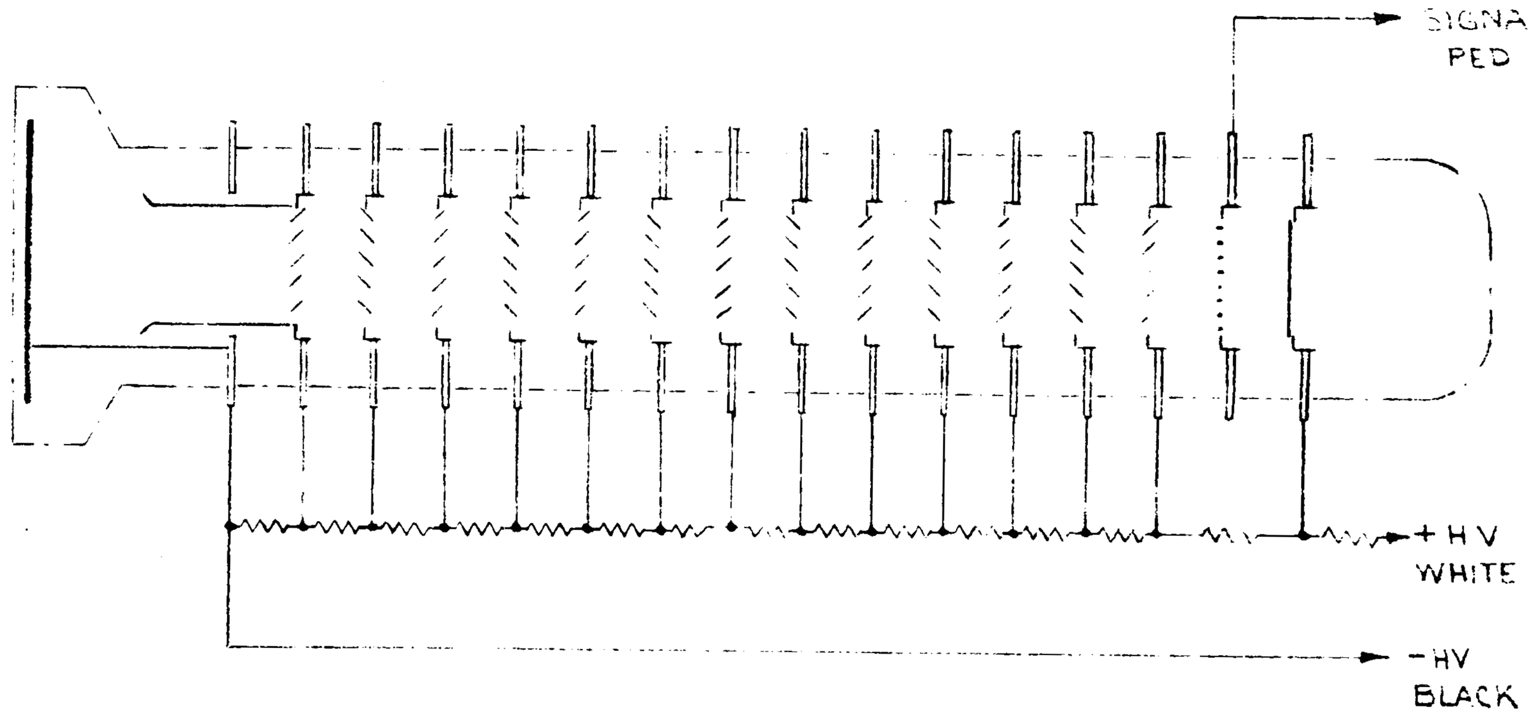
TOTAL VOLTAGE ACROSS PHOTOMULTIPLIER

PHOTOMULTIPLI . SPECTRAL RESPONSE



SR-2

NOTES:
1- RESISTOR VALUES EQUAL THRU OUT UNIT.



SCHEMATIC DIAGRAM

EMR MULTIPLIER PHOTOTUBE

14 STAGES

EMR PRINCETON D
ELECTRO-MECHANICAL
MULTIPLIER PHOTO

MODEL NO. 541 & 542

DRAWING