NATIONAL BUREAU OF STANDARDS REPORT

4421

Design and Calibration
of a
Remote-Indicating, Photoelectric Brightness Meter

NBS

U. S. DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS

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NATIONAL BUREAU OF STANDARDS REPORT

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NBS REPORT 4421

Design and Calibration
of a
Remote-Indicating, Photoelectric Brightness Meter

By
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Prepared for
Instrument Division
Weather Bureau
Department of Commerce
Washington 25, D. C.

NBS

U. S. DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS

REPORT

on the
Design and Calibration
of a
Remote-Indicating, Photoelectric
Brightness Meter

1. SCOPE

This report describes the design of a remote-indicating, photoelectric brightness meter and gives the results of the calibration and test of the instrument. The instrument was designed for use in making horizon-sky brightness measurements during the visibility tests being conducted at Newark Airport.

2. APPARATUS

The instrument was designed to use, in so far as possible, available experimental transmissometer equipment. Figure 1 is a system block diagram of the instrument.

2.1 Optical Design of the Receiver

The optical portion of the instrument is shown in figure 2. This portion consists of a PJ-14B photocell, an optical filter, a field stop, a lens, and stray-light shield.

2.1.1 Phototube. A type PJ-14B was selected because the spectral response of this type tube is relatively uniform throughout the visible portion of the spectrum, has a low dark current, and is stable.

2.1.2 Filter Design. The purpose of the optical filter is to provide a phototube-filter combination with a spectral response which is essentially the CIE standard observer luminosity function, $\bar{y}$.

Thus $$\bar{y}_\lambda = K\, T_\lambda\, S_\lambda \qquad (1)$$

where T_λ is the spectral transmittance of the filter and S_λ is the spectral response of the phototube at wavelength λ.

Figure 3 shows the relative spectral response of the phototube and the standard luminosity function.

The spectral transmittance of a desired filter was determined by solving equation 1 for KT_λ. Having determined the desired function of KT_λ a suitable combination of glasses was chosen. The spectral transmittance of samples of each glass was determined. From these data the desired thickness of each component was computed. The components were then ground and polished to the desired thicknesses and the spectral transmittances were measured. In those instances in which the measured spectral transmittance did not agree sufficiently well with the desired spectral transmittance, the components were reground to a thickness which gave the desired spectral response. (It is, of course, necessary to be certain that the components are never ground thinner than is required.) The component filters are given in table I.

Table 1

Component Filters

Corning Designation of Glass	Required Thickness
	mm
4784	3
3780	2
3307	1
9788	1

Figure 4 shows the spectral transmittance of the desired and the designed filter, indicating a reasonably good approximation.

2.2 Electronic Design

The electronic circuitry is basically that of the GMQ-10 transmissometer as is indicated in figure 1. Hence a detailed explanation of the circuits will not be given. Only the significant differences in the circuitry will be discussed.

Figure 5 is a detailed block diagram and figure 6 an interconnection diagram of the transmissometer system from which the units were taken. They are directly applicable to the brightness meter except that the projector shown is not used. Note that in these and the figures following the numbering of the components is not the same as that used in the GMQ-10 manual.

2.2.1 Receiver and Amplifier-Power Supply. Figure 7 is a circuit diagram of the receiver and the amplifier-power supply. The circuitry of these units differs significantly from that of the GMQ-10 in the following respects:

V1201. A type PJ-14B phototube is used instead of the type 919 phototube.

Pulse-Rate Meter. The pulse-rate meter has two ranges designed for 12000 pulses per minute and 4000 pulses per minute full scale instead of a single 4000 pulse-per-minute range. This is accomplished by the addition of C209 and R206 and the modification of S205.

2.2.2 Indicator. Figure 8 is a circuit diagram of the indicator. The circuitry of this unit differs from that of the GMQ-10 indicator in the following respects:

Counter Stage. A counter stage is included in the indicator. The purpose of this stage is to provide sufficient power to pulse a relay or operate a counter when the input pulse rate is too slow to produce a satisfactory indication on the meter and the recorder so that the time between individual pulses can be determined. In this instrument the relay K405 is located in the sensitivity-control unit. The plate of tube V311 is connected to B+ through S304 of the indicator and through the contacts of K404 and the coil of K405 of the sensitivity control. When the B+ circuit is complete, tube V311 is triggered once by each signal pulse coming into the receiver and momentarily energizes keying relay K405. Because of the energy required to operate the relay, the capacitance of C316 is much larger than that of the corresponding capacitor C306 of the pulse-rate integrator stage V303. Hence the counter stage cannot respond to pulse rates as high as can the pulse-integrator stage. It will, however, respond satisfactorily to pulse rates higher than 2 pulses per second. Since counting of pulses is not required until the pulse rate falls below 0.5 pulse per second, this response is satisfactory.

Pulse-rate Integrator Stage. The pulse-rate integrator stage is designed to have sensitivity ranges of 20,000 (LOW), 400 (MEDIUM), and 800 (HIGH) pulses per minute instead of only 4000 and 800 pulses per minute. This requires that the resistor chain in the cathode circuit of tube V303 be divided into three sections instead of two. Switch S303 is a four-pole four-position

switch. The first three positions, LOW, MEDIUM, and HIGH, place the indicator on the corresponding sensitivity range. In the fourth position, AUTO, the sensitivity resistors are connected to J302 so that the sensitivity may be controlled by a control outside the indicator. Note that the sensitivity switch does not actuate the recorder marker pens. Thus when the sensitivity is controlled manually, the sensitivity range should be noted on the chart of the recorder.

The capacitance of C306 has been temporarily increased from 2200 μμf to 7200 μμf by the addition of a 5000 μμf capacitor, C306A, in parallel with C306 so that full-scale meter readings can be obtained with pulse rates of the order of 6000, 1200, and 240 pulses per minute.

2.2.3 Sensitivity Control. A sensitivity-control unit which automatically places the indicator on the optimum sensitivity range is included in the system. In addition, the sensitivity-control unit contains a keying relay which, when operated from the counter stage of the indicator, will record individual pulses. Figure 9 is a circuit diagram of the sensitivity control.

The sensitivity control is actuated by galvanometer relay K401 whose coil is in series with the indicator meter, M301, and the recorder. This relay is adjusted so that it closes to L when the indicator output falls to 0.4 ma (a reading of 8 on M301) and to H when the indicator output rises to 4.8 ma (a reading of 96 on M301). As the contacts of this relay are rated at only 200 ma at 6 volts, auxiliary relays K402 and K406 are used to operate the selector relays K403 and K407. Relays K402 and K406 also provide a time delay of about 45 seconds so that momentary changes in the indicator output will not operate the sensitivity-selector relays.

With the contacts of selector relays K403 and K407 as shown, the indicator is on the Medium sensitivity range. When the indicator current increases to 4.8 ma, the galvanometer relay, K401, closes the contact at H thereby energizing the H heater of time-delay relay K402. After about 45 seconds the contact at H_2 is closed, energizing the release coil of the Low-Medium selector relay, K403 (a latching relay), putting its contacts in the position opposite to that shown. This (1) opens the Medium range marker-pen contact (see figure 5 as well as figure 9), thus de-energizing the solenoid of the left-hand marker pen in the recorder, (2) closes the sensitivity contacts shorting resistors R314 and

R315 in the indicator, thus putting the indicator on the Low sensitivity range, (3) opens the limit contact so that further contact at contact H of the galvanometer relay will have no effect, and (4) places the transfer contacts in the position so that if contact is made at the L contact of the galvanometer relay it will energize the L section of relay K402.

Assume the sensitivity control is in the Low position as described above. Then, when the indicator current decreases to 0.4 ma, the galvanometer relay closes the contact at L energizing the L heater of time-delay relay K402. After about 45 seconds the contact at L_2 is closed, operating the latch coil of selector relay K402 returning this relay to the position shown and the indicator to the Medium range.

Again assume that relays K403 and K407 are in the position shown. When the indicator current decreases to 0.4 ma, the galvanometer relay closes the contact at L thereby energizing the L heater of the time-delay relay K406. After about 45 seconds the contact at L_2 is closed, energizing the latch coil of the Medium-High selector relay K407, putting its contacts in the position opposite to that shown. This (1) closes the High range marker-pen contact, thus energizing the solenoid of the right-hand marker pen in the recorder, (2) opens the sensitivity contact that shorts R313 in the indicator, thus putting the indicator on the High sensitivity range, (3) places the limit contact in the position so that further contact of the galvanometer relay at L will energize keyer delay relay K404, and (4) places the transfer contacts in the position so that contact of the galvanometer relay at H will energize the H section of relay K406.

Assume the sensitivity control is in the High position as described above. Then when the indicator current increases to 4.8 ma, the galvanometer relay closes the contact at H energizing the H heater of time-delay relay K406. After about 45 seconds the contact at H_2 is closed, operating the release coil of relay K407 returning this relay to the position shown in figure 9 and the indicator to the Medium-range position.

If, when the sensitivity control is in the High position, the indicator current decreases to 0.4 ma, the heater of time-delay relay K404 is energized. This relay upon closing completes the plate circuit of V311 in the counter stage of the indicator. Then the keying relay is momentarily energized by each pulse on the signal line. This momentarily de-energizes the solenoid of the right-hand marker pen of the recorder producing a pip on the record chart.

2.2.4 Recorder. The recorder is a 5-milliampere Esterline-Angus recorder with a synchronous motor-driven chart drive and spring-driven rewind drive. It has both a left-hand and a right-hand marker pen. These pens are energized through the automatic sensitivity control and indicate the sensitivity range on which the indicator is operating as follows:

Sensitivity	LH Pen	RH Pen
Low	In	In
Medium	Out	In
High	Out	Out

In order to obtain time pips on the record chart by means of the marker pens, a DPDT relay with a 115-volt, 60-cycle coil has been mounted on the back of the recorder. The contacts of the relay are so connected that when the relay is energized by a timing pulse the circuit through the solenoid of the left-hand marker pen is opened, and the solenoid of the right-hand marker pen is energized. Thus, the position of one or both marker pens will be changed regardless of the position in which the sensitivity control has placed them.

3. CALIBRATION

Prior to the calibration of the instrument as a unit, the ratio of the Low to Medium and Medium to High sensitivities was made to be 5.00 in the following manner. With C306A disconnected, a pulse signal of line frequency (60 pulses per second) was applied to the input of the indicator and the voltage applied to V303 adjusted by means of R321 so that a meter reading of 0.90_0 was obtained. Then pulse signals of exactly one-fifth and five times line frequency (12 and 300 pulses per second) were applied with the indicator on the High and Low ranges respectively and adjustments of R315 and R313 were made so that meter readings of 0.90_0 were obtained on these ranges also. The pulse signals were obtained by capacitatively coupling one of the horizontal deflection plates of an oscilloscope to the indicator input and using the patterns generated by a line-frequency test signal applied to the Y-input of the oscilloscope to determine the frequency.

Capacitor C306 was then connected. The value of this capacitor was chosen so that the indicator would produce a full-scale meter reading with pulse rates in the region of 20 pulses per second.

The instrument, using the receiver identified as No. 2, was then connected as shown in figure 1 with the receiver placed before a luminance standard of sufficient size to fill the field of the receiver. The luminance standard was adjusted to have a brightness of 1000 footlamberts. The capacitance of C1201 (in the receiver) was chosen so that a pulse rate of about 20 pulses per second was obtained. (This required the use of a 10 μμf capacitor, which is about the minimum capacitance with which satisfactory operation can be obtained.) This pulse signal was fed into the indicator. The calibration of the indicator was adjusted so that this signal produced a meter reading of 1.00_0 with the indicator on the Medium sensitivity, thus calibrating the brightness meter for the full-scale readings given in table II.

Table II

Sensitivity Range	Brightness for Full-Scale Reading footlamberts
Low	5000
Medium	1000
High	200

The calibrator signal, 60 pulses per second, was then applied to the indicator. A reading of 0.59 was obtained with the indicator on the Low sensitivity. The indicator calibration point is therefore a reading of 0.59 on the Low range, not 0.90 on the Medium Range. By keeping the indicator adjusted to this point by using the CALIBRATION ADJUSTMENT, the effects of possible drifts in the indicator are eliminated from the calibration of the brightness meter. The calibration of the instrument is, therefore, dependent only upon the stability of the phototube V1201, the trigger tube V1202, the charging capacitor C1201, and the color-correcting filter. The calibration data is summarized in Appendix 1.

4. PERFORMANCE CHECKS

4.1 Linearity

The linearity of the brightness meter was checked by adjusting the standard to 200 and to 5000 footlamberts and operating the indicator on High and Low ranges respectively. These checks showed the instrument to be linear within the accuracy of the photometry, the deviations being within 1%.

The spectral response of the receiver was given a rather rigorous test by measuring the luminous transmittance of highly selective filters. The spectral transmittance of these filters is shown in figure 10. The results of this test are given in table III.

Table III

Filter		Transmittance, percent		
NBS Designation	Color	Measured w/Brightness Meter	Computed from Spectrophotometric Data	Difference
3151	Red	16	13	+3
3857	Orange	49	51	-2
5462	Yellow	74	76	-2
5787	Green-Yellow	86	89	-3
6380	Green	39	41	-2
6702	Blue-Green	24	24	0

5. DISCUSSION

The brightness meter was found to perform satisfactorily. The range of selectivity of the filters used in the spectral check far exceeds the range of colors for which the brightness meter was designed.

Appendix 1

Calibration Data of Photoelectric Sky-Brightness Receiver No. 2

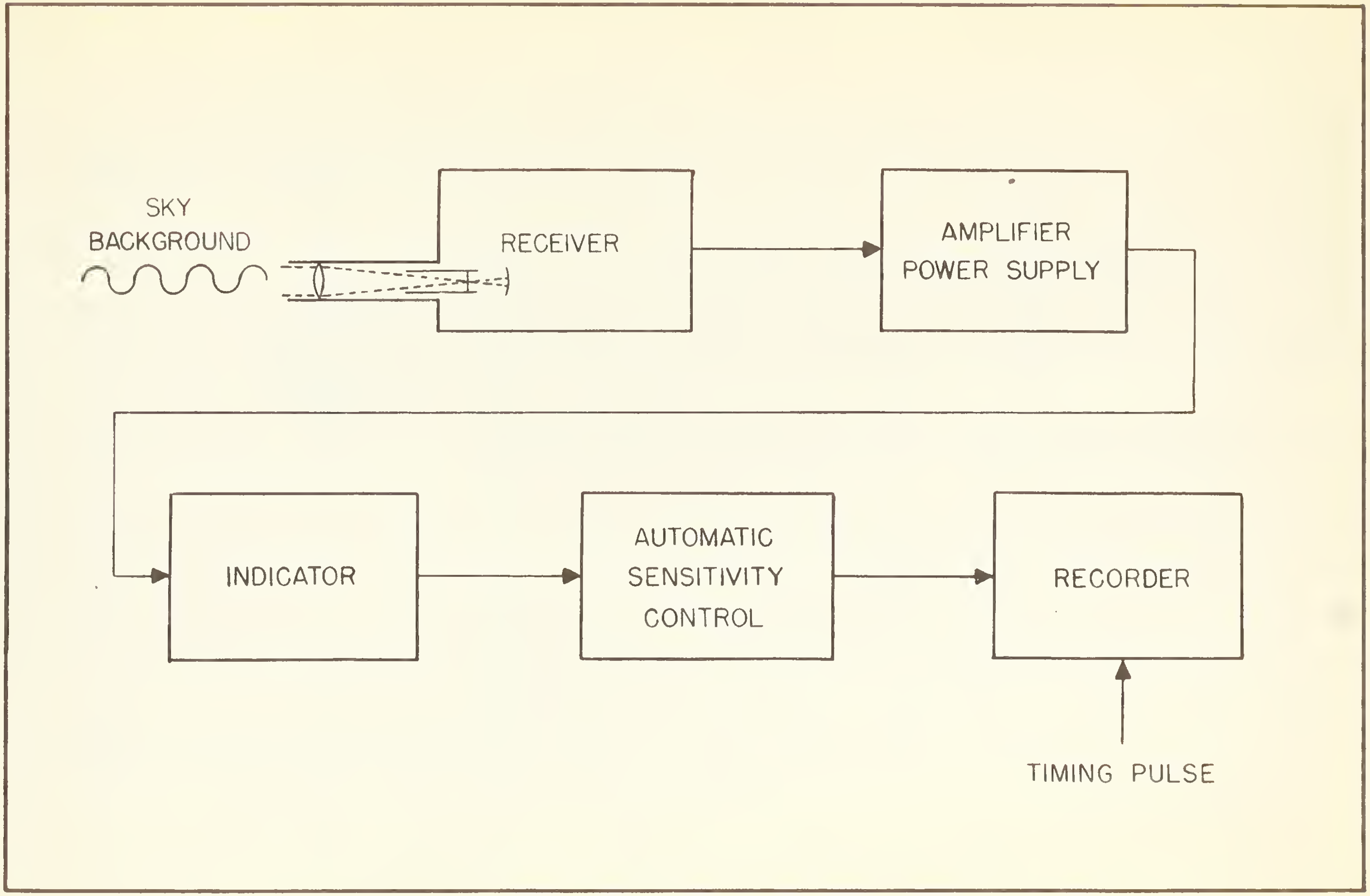
Component	Identifying Marks
Phototube (Type PJ-14B)	2128
Trigger Tube (Type WL-759)	120
Filter	3A
Charging Capacitance (C1201)	10 μμf

Calibration: 0.0204 pulses per second per footlambert

Therefore, adjust indicator calibration by means of the CALIBRATION ADJUSTMENT so that a pulse rate of 60 pulses per second produces a reading of 59 when the indicator is on Low range.

Then full-scale readings will be

Range	Footlamberts
Low	5000
Medium	1000
High	200



SYSTEM BLOCK DIAGRAM OF SKY BRIGHTNESS METER

FIGURE 1

NBS

SCHEMATIC OF OPTICAL SYSTEM OF THE ILLUMINOMETER

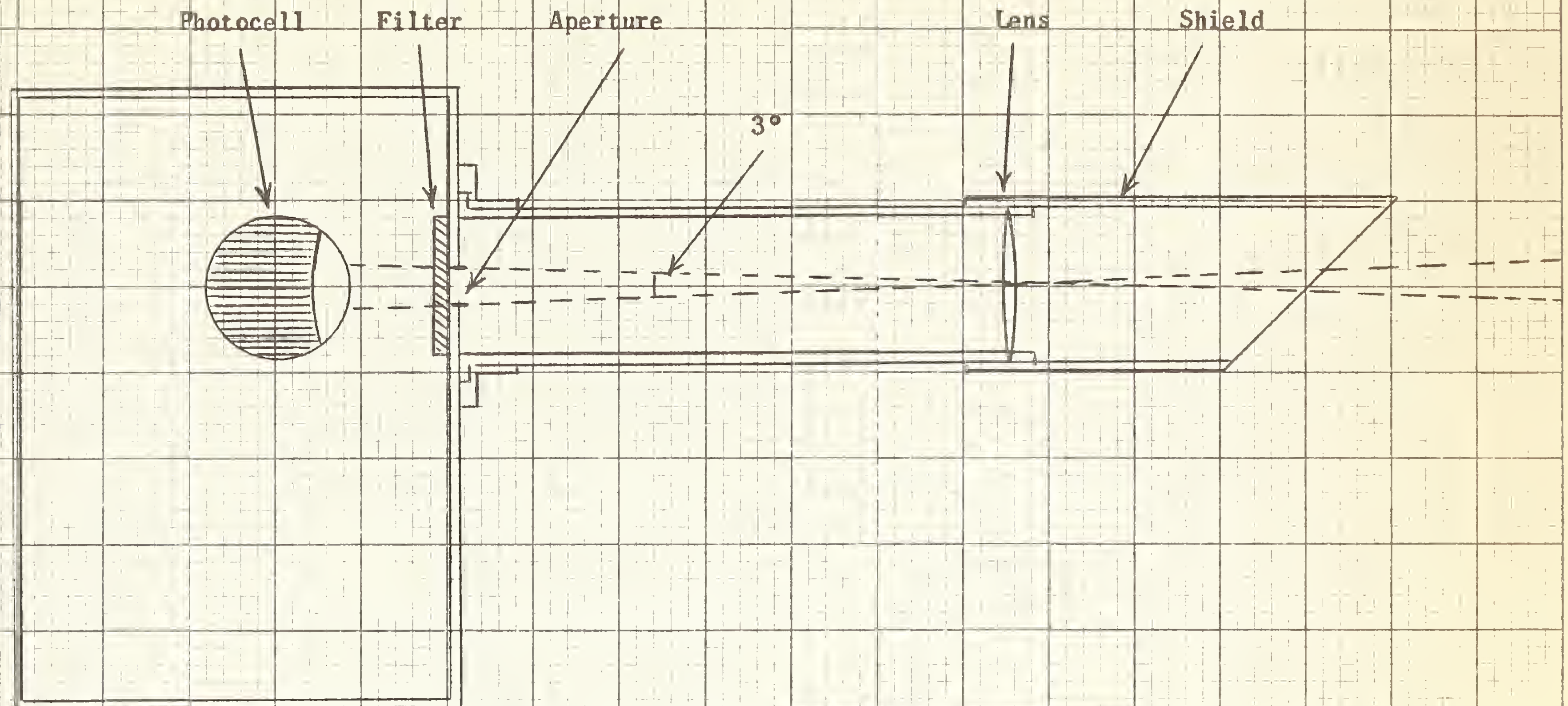


Figure 2

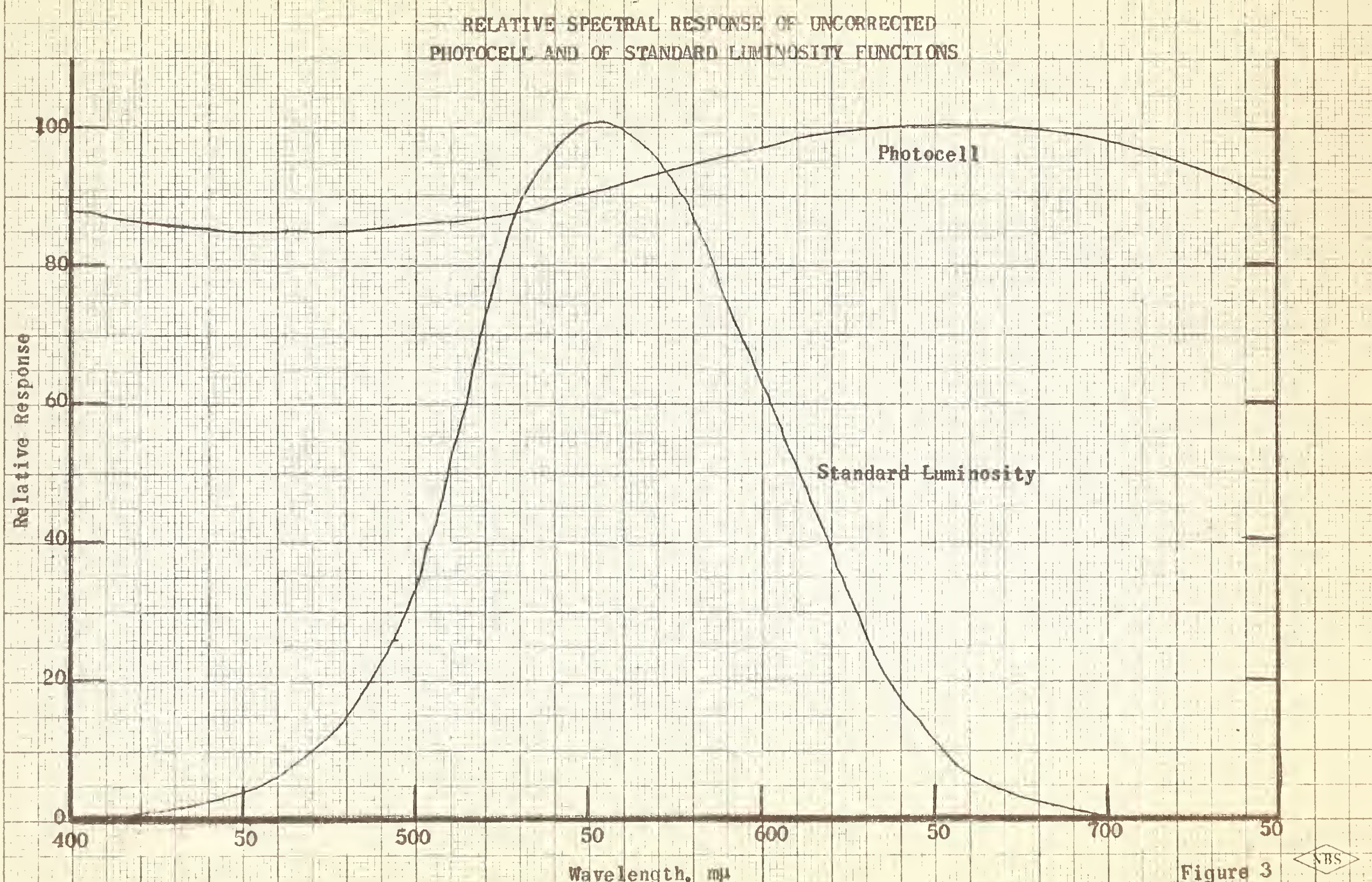
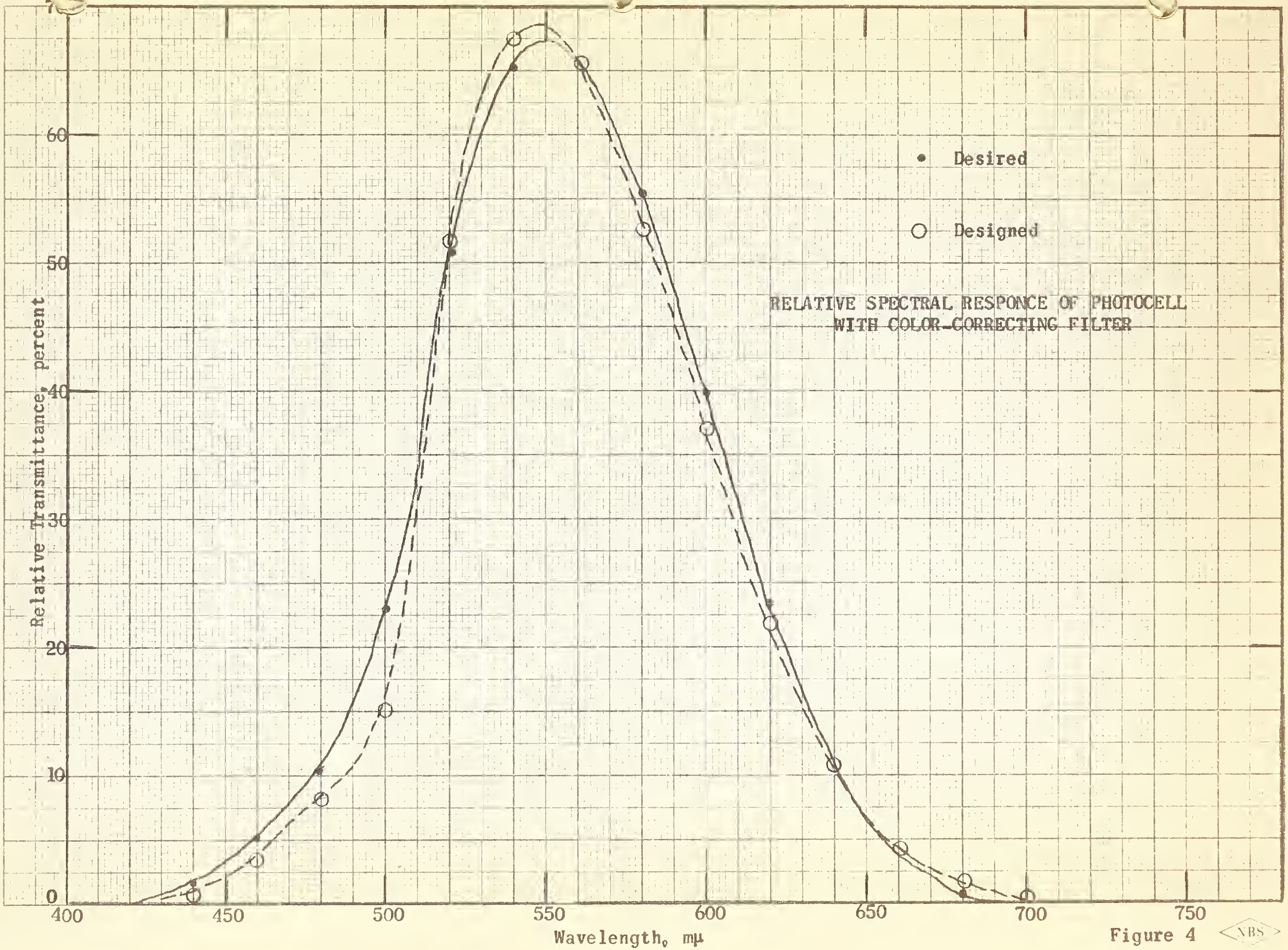
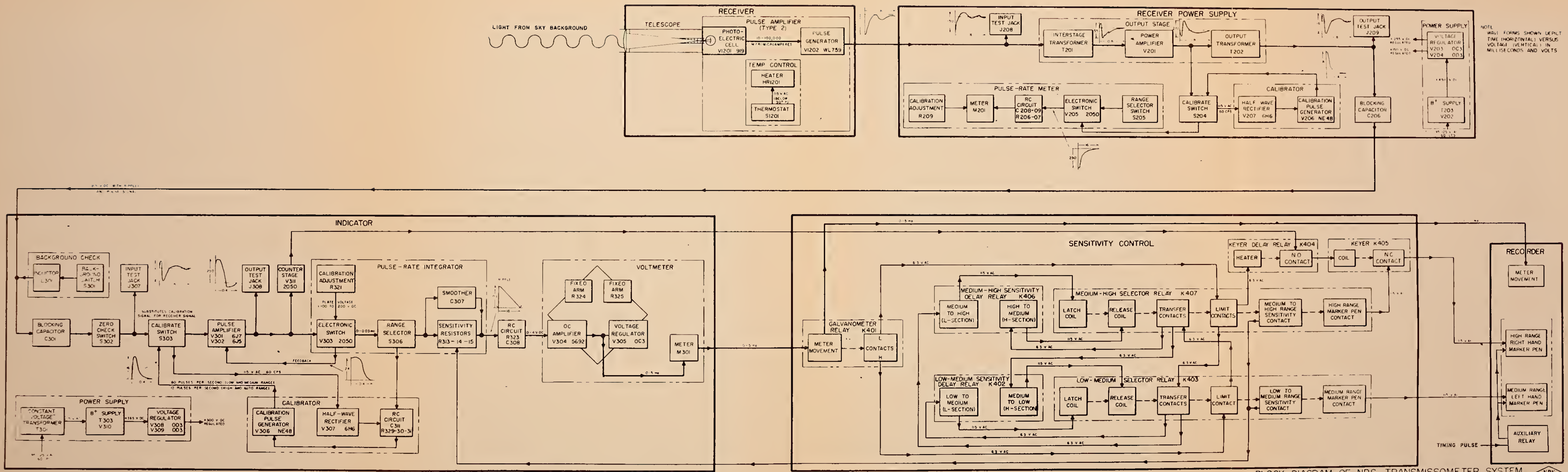

RELATIVE SPECTRAL RESPONSE OF UNCORRECTED
PHOTOCELL AND OF STANDARD LUMINOSITY FUNCTIONS
Photocell
Standard Luminosity
Relative Response
100
80
60
40
20
0
400
50
500
50
600
50
700
50
Wavelength, mμ
NBS

Figure 3



Desired
Designed
RELATIVE SPECTRAL RESPONCE OF PHOTOCELL
WITH COLOR-CORRECTING FILTER
Relative Transmittance, percent
0
10
20
30
40
50
60
400
450
500
550
600
650
700
750
Wavelength, mμ

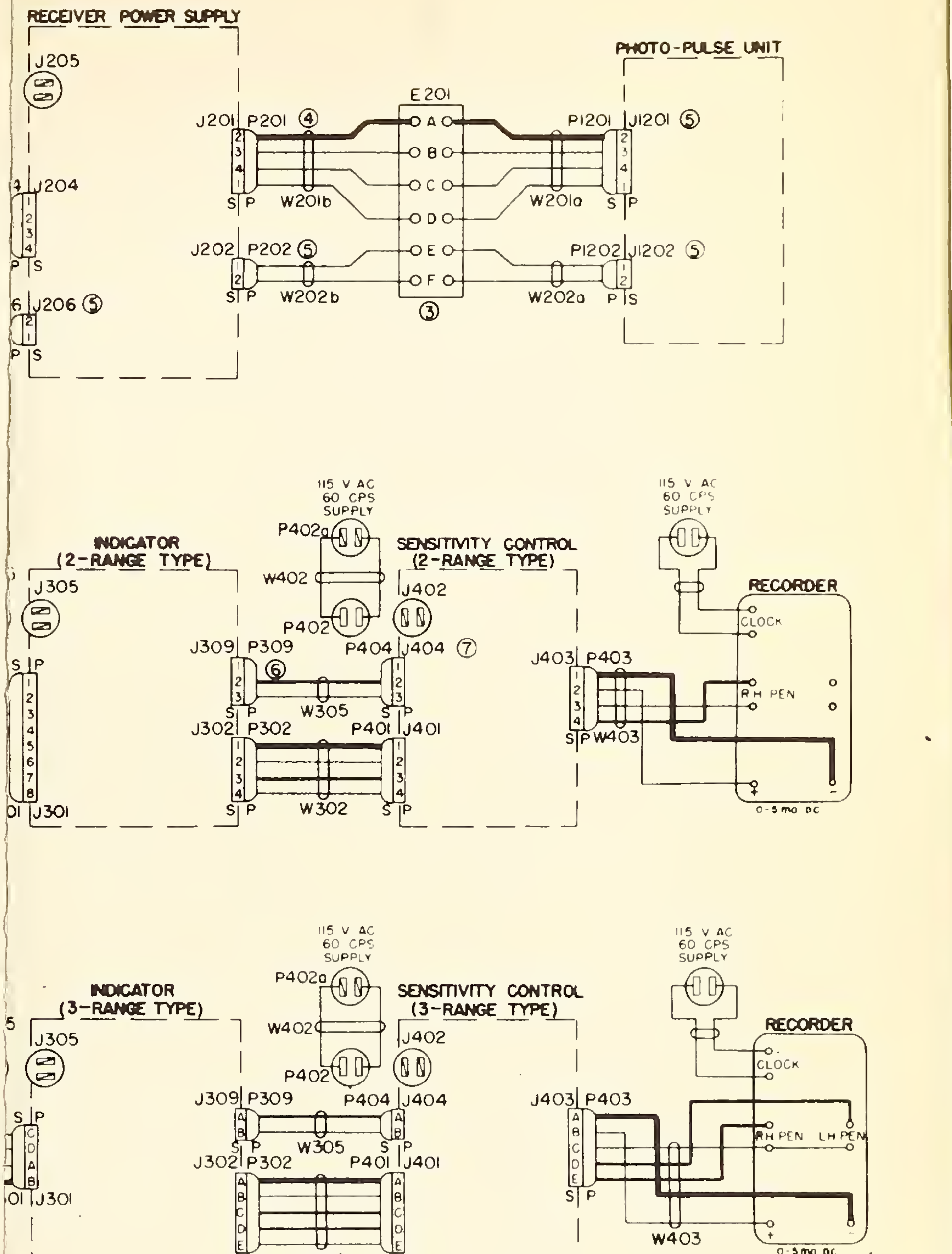
Figure 4



BLOCK DIAGRAM OF NBS TRANSMISSOMETER SYSTEM MODIFIED FOR USE AS A SKY BRIGHTNESS METER

NBS

FIGURE 5



NBS TRANSMISSOMETER INTERCONNECTION DIAGRAM

FIGURE 6

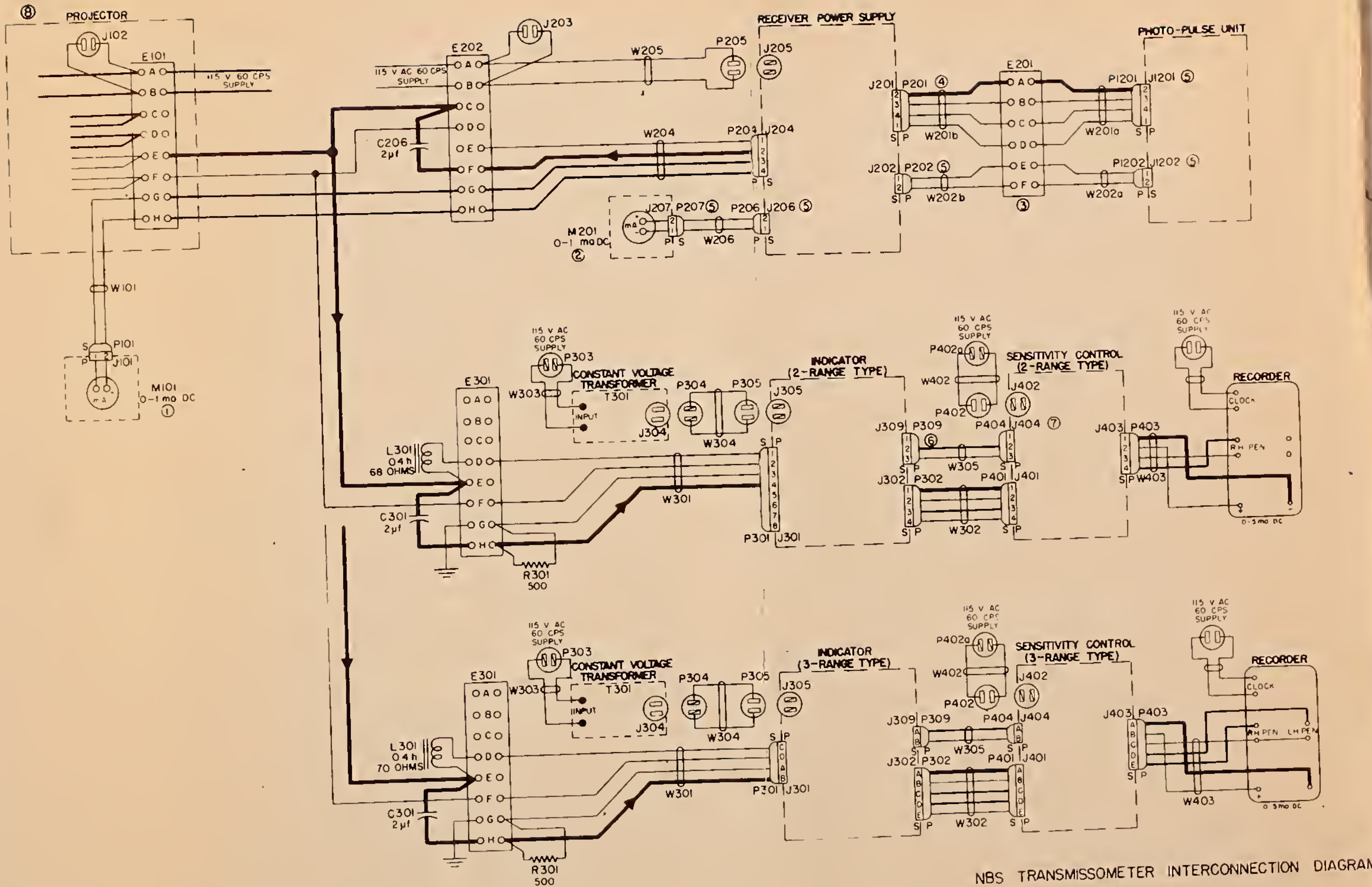
NBS

NOTES

1. OMITTED ON CXFJ-1-L, L-8
2. OMITTED ON P-1, P-2, P-3, CXFJ-1-P
3. USED ONLY ON P-6, P-7, CXFJ-1-P
4. CONNECTIONS ON CXFJ AS FOLLOWS:

J201	P201	CORRESPONDING TERMINALS OF OTHER UNITS
F		P201 (2)
A		P201 (3)
B		P201 (4)
E		P201 (1)
C		P202 (1)
		P202 (2)

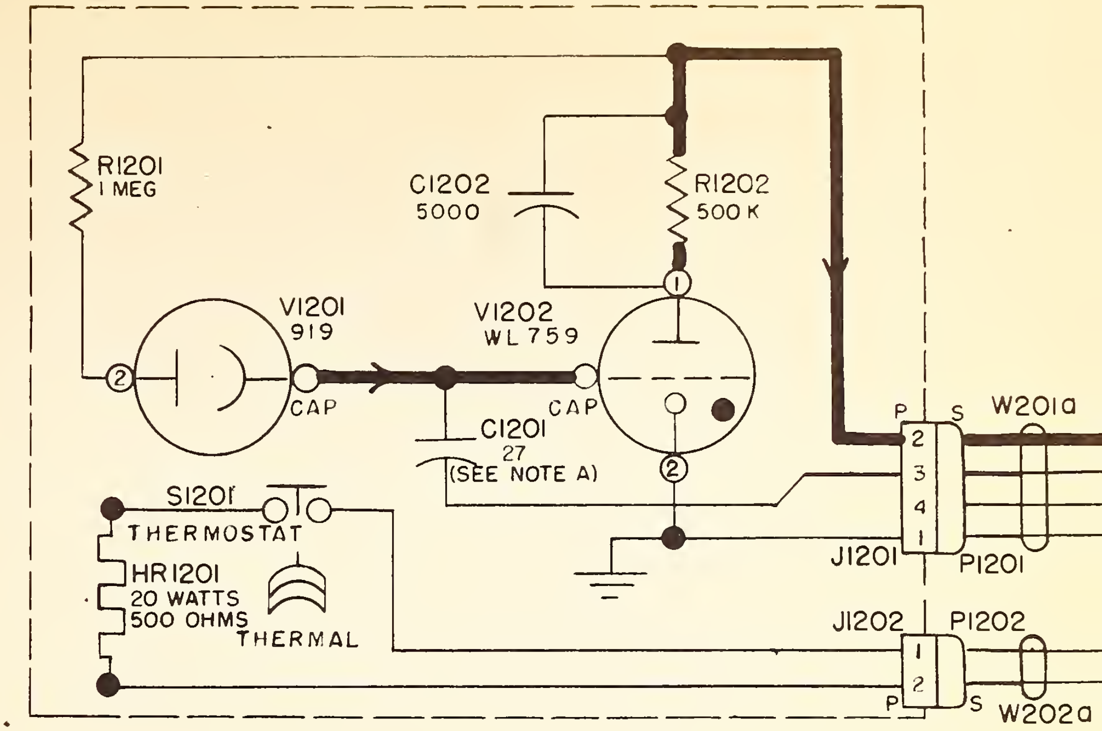
5. OMITTED ON CXFJ
6. OMITTED ON I-1, I-2, I-3
7. OMITTED ON S-2, S-3, S-8
8. PROJECTOR NOT USED ON BRIGHTNESS METER



NBS TRANSMISSOMETER INTERCONNECTION DIAGRAM

FIGURE 6

NBS



NOTES:

CAPACITOR VALUES = MICROMICROFARADS EXCEPT AS NOTED.

RESISTOR VALUES = OHMS K = 1,000 MEG

CPS = CYCLES PER SECOND

SUPPLY VOLTAGE = 95 — 125 VAC, 60 CPS

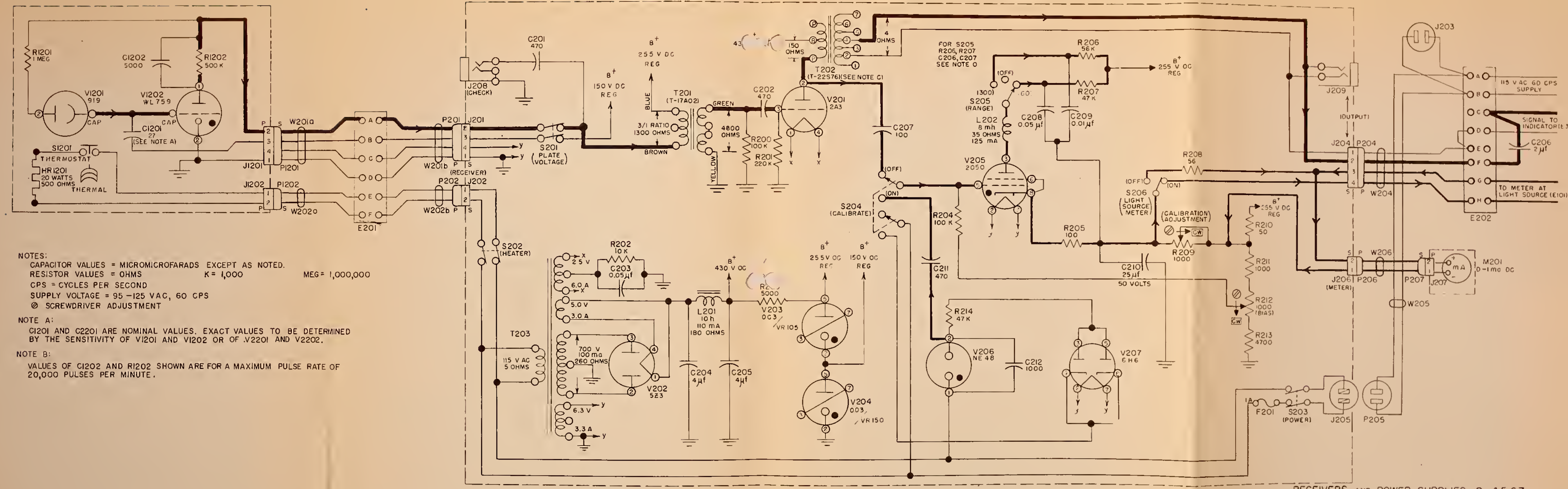
⊘ SCREWDRIVER ADJUSTMENT

NOTE A:

C1201 AND C2201 ARE NOMINAL VALUES. EXACT VALUES TO BE DETE
BY THE SENSITIVITY OF V1201 AND V1202 OR OF V2201 AND V2202

NOTE B:

VALUES OF C1202 AND R1202 SHOWN ARE FOR A MAXIMUM PULSE RAT
20,000 PULSES PER MINUTE.



NOTES:

CAPACITOR VALUES = MICROMICROFARADS EXCEPT AS NOTED.
RESISTOR VALUES = OHMS K = 1,000 MEG = 1,000,000
CPS = CYCLES PER SECOND
SUPPLY VOLTAGE = 95 –125 VAC, 60 CPS
⊘ SCREWDRIVER ADJUSTMENT

NOTE A:

C1201 AND C2201 ARE NOMINAL VALUES. EXACT VALUES TO BE DETERMINED BY THE SENSITIVITY OF V1201 AND V1202 OR OF V2201 AND V2202.

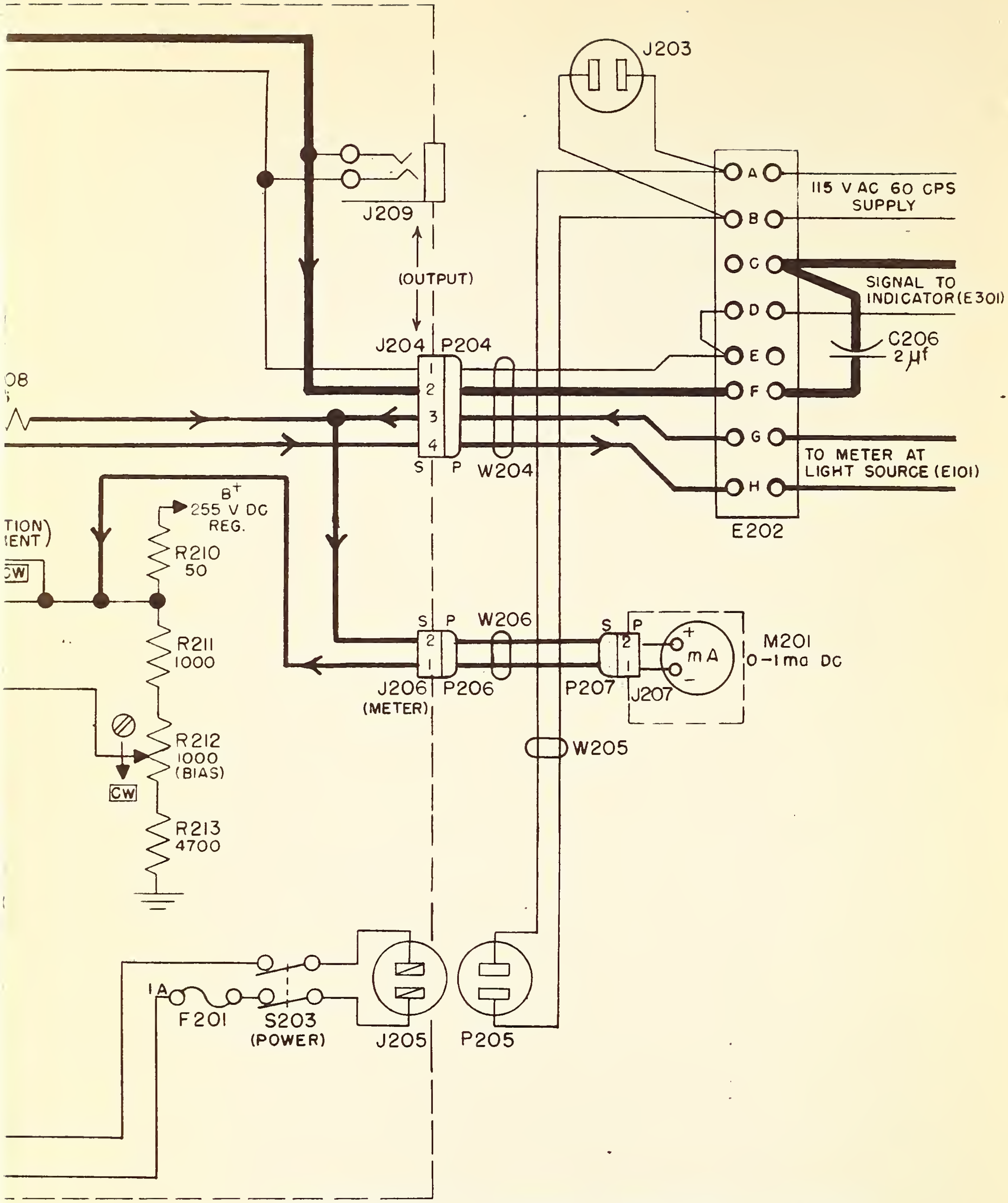
NOTE B:

VALUES OF C1202 AND R1202 SHOWN ARE FOR A MAXIMUM PULSE RATE OF 20,000 PULSES PER MINUTE.

RECEIVERS AND POWER SUPPLIES P-4,5,6,7

FIGURE 7

NBS



RECEIVERS AND POWER SUPPLIES P-4,5,6,7

FIGURE 7

IOW

IOW

0.4

E [illegible]
; [illegible]

25

NN

VA
CI

NOTES.

SUPPLY VOLTAGE = 95-125 V AC, 60 CPS

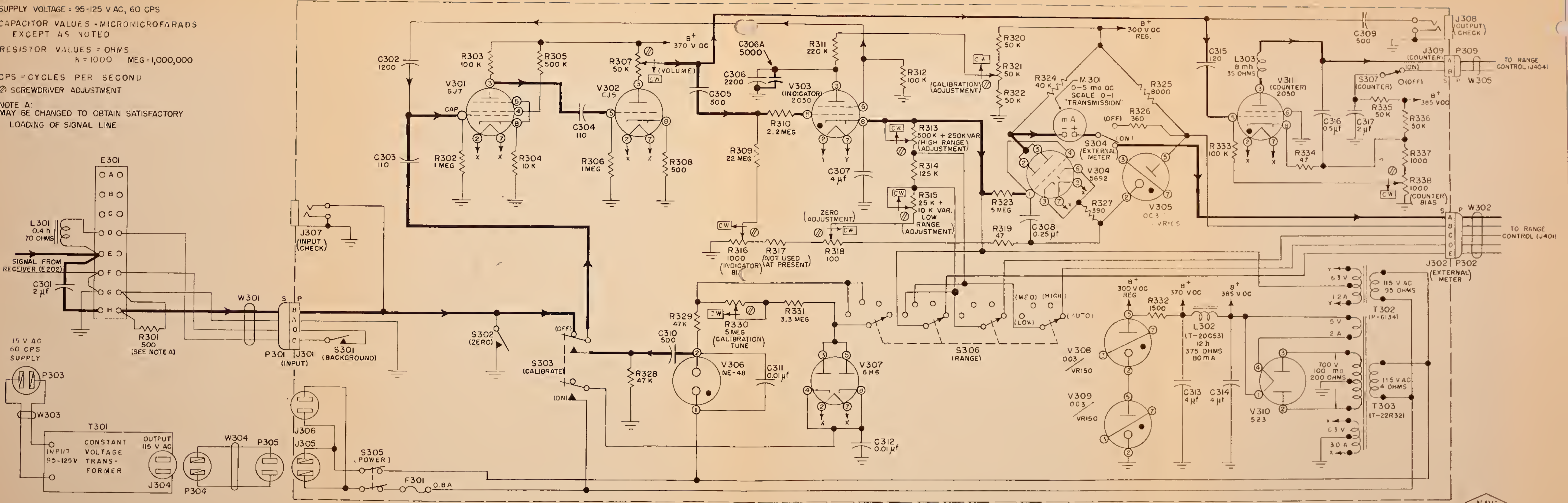
CAPACITOR VALUES - MICROMICROFARADS EXCEPT AS NOTED

RESISTOR VALUES = OHMS
K = 1000 MEG = 1,000,000

CPS = CYCLES PER SECOND

⊘ SCREWDRIVER ADJUSTMENT

NOTE A:
MAY BE CHANGED TO OBTAIN SATISFACTORY LOADING OF SIGNAL LINE



INDICATORS I-6,7

NBS

FIGURE 8

NOTES:

K403 (LOW-MEDIUM) SHOW

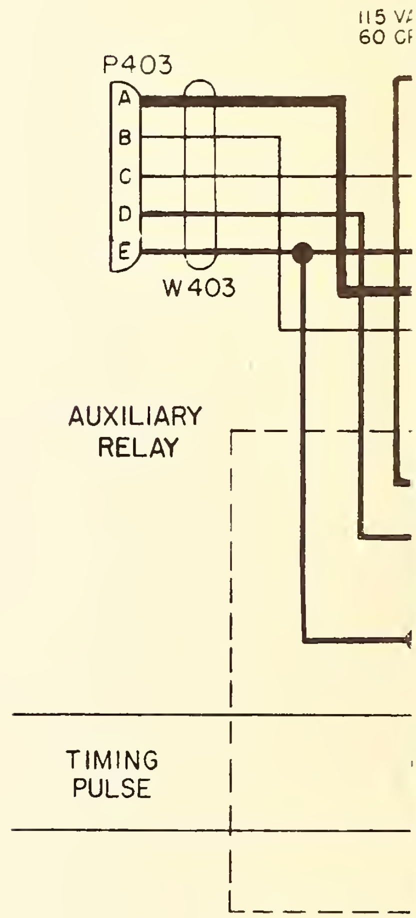
K407 (MEDIUM-HIGH) SHOW

K401 CLOSES TO L AT 0.

K402, K404, K406 (TIME
30 TO 60 SECONDS

SUPPLY VOLTAGE = 95-125

NOTE A. RECORDER CONN



NOTES

K403 (LOW-MEDIUM) SHOWN IN "MEDIUM" POSITION

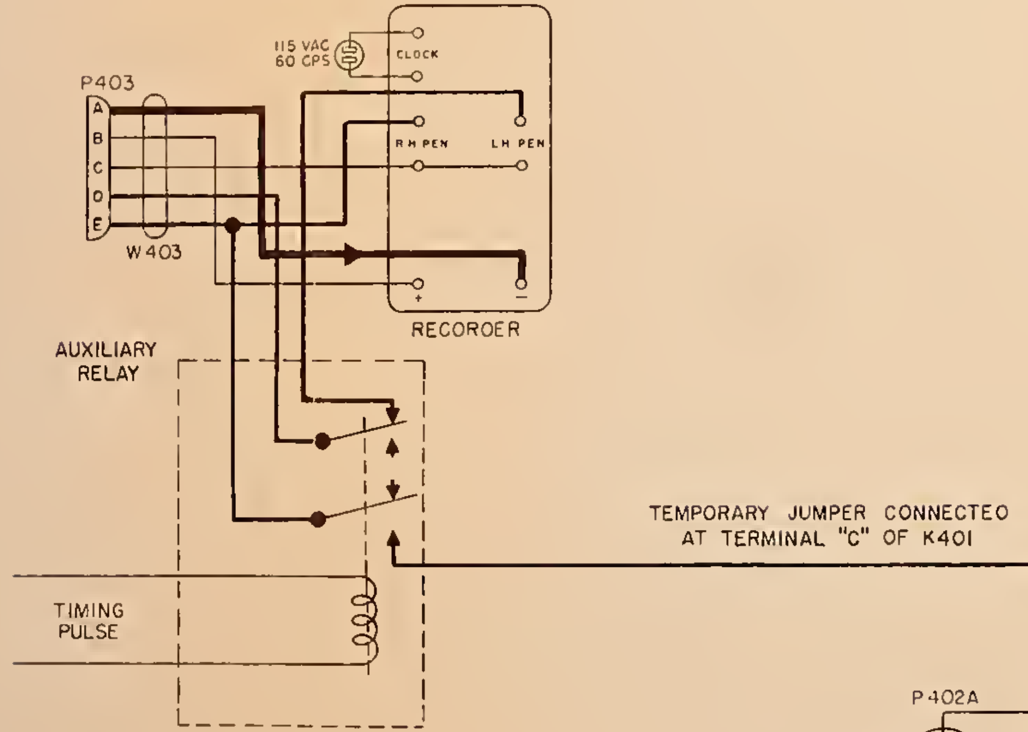
K407 (MEDIUM-HIGH) SHOWN IN "MEDIUM" POSITION

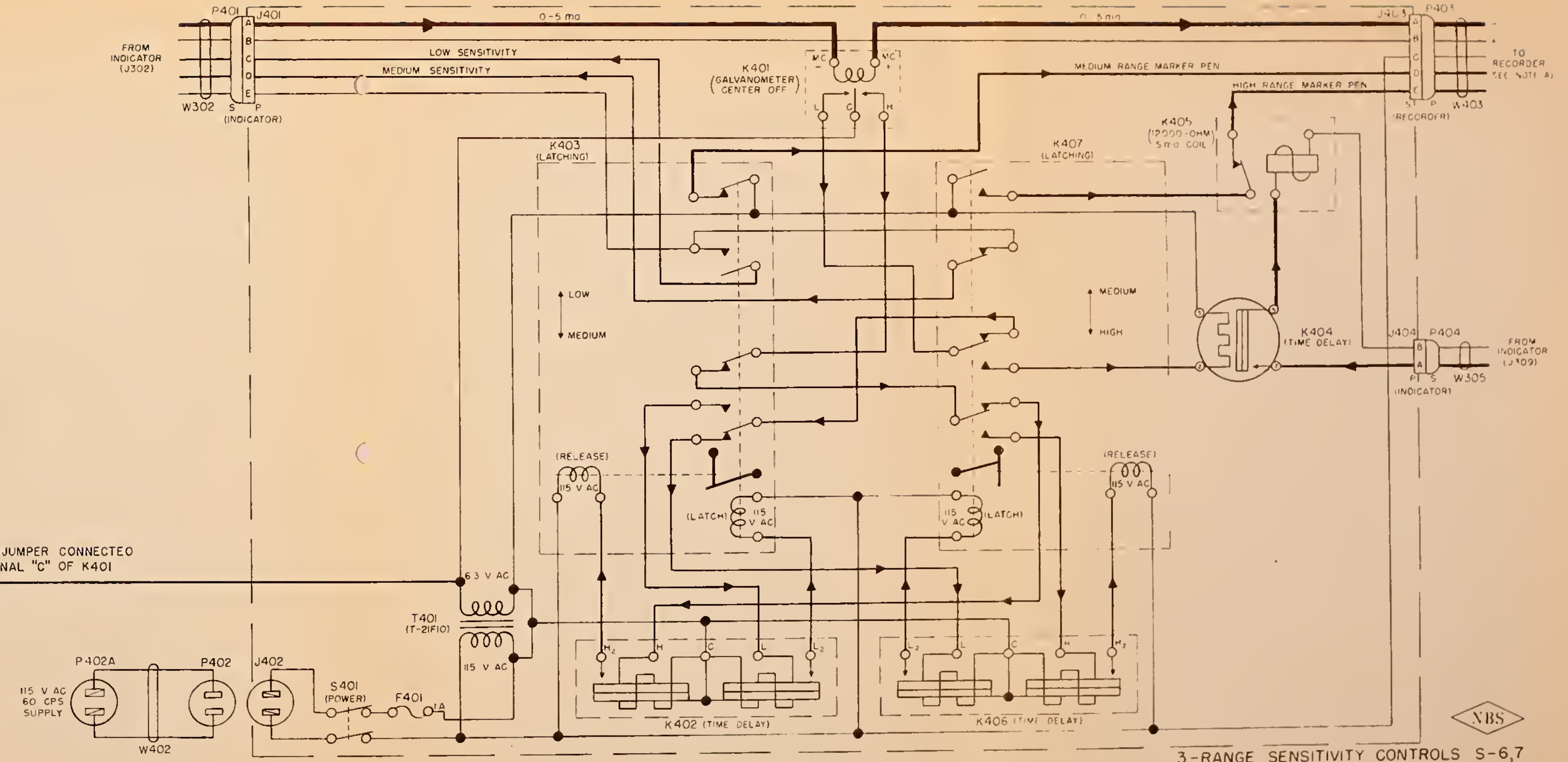
K401 CLOSES TO L AT 0.4 ma; TO H AT 4.8 ma

K402, K404, K406 (TIME DELAY, 6-VOLT HEATERS) HAVE 30 TO 60 SECONDS DELAY.

SUPPLY VOLTAGE = 95-125 V AC, 60 CPS

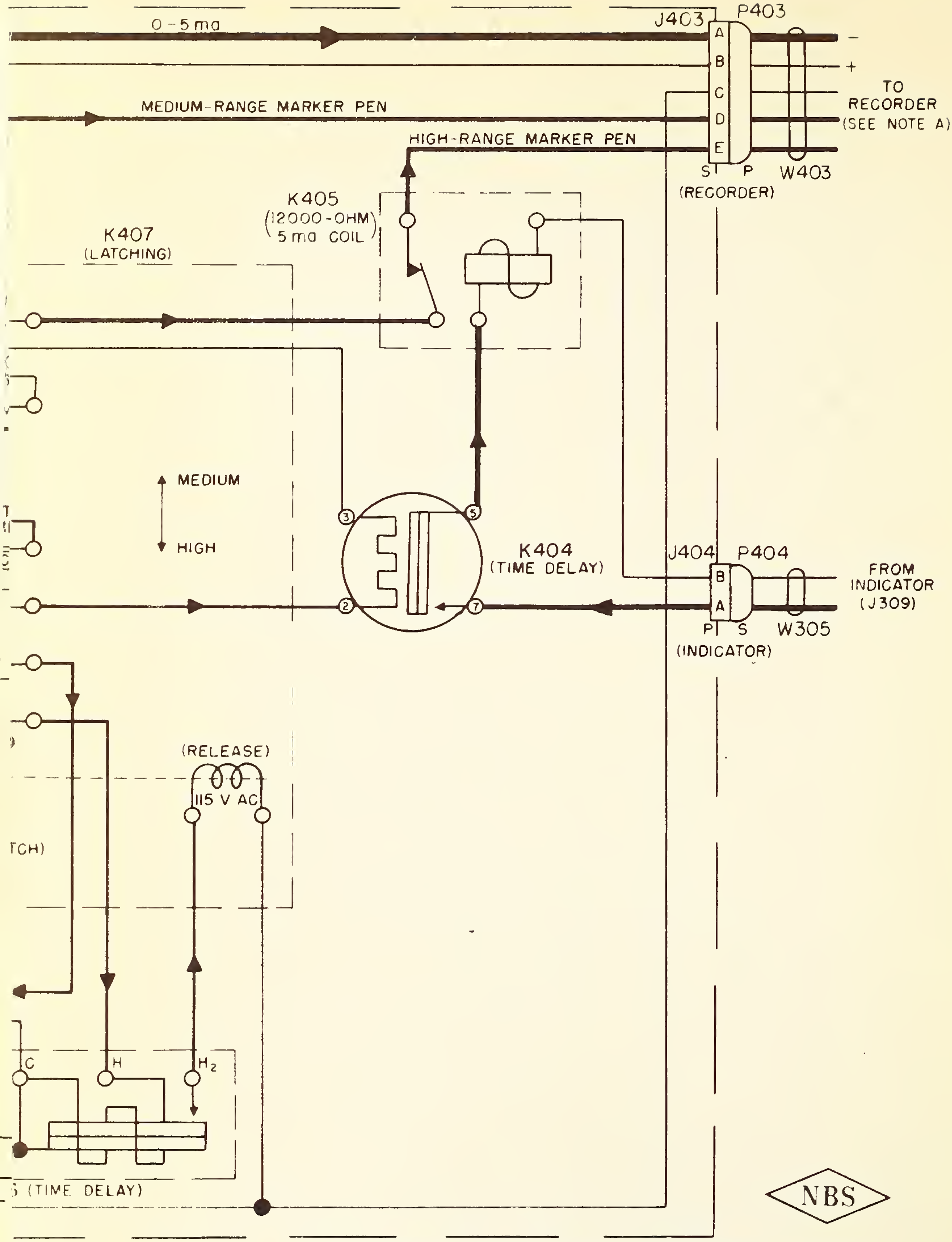
NOTE A RECORDER CONNECTIONS:





3-RANGE SENSITIVITY CONTROLS S-6,7

FIGURE 9



3-RANGE SENSITIVITY CONTROLS S-6,7

FIGURE 9

SPECTRAL TRANSMITTANCE CURVES OF FILTERS USED
IN CHECKING COLOR-CORRECTION OF BRIGHTNESS METER

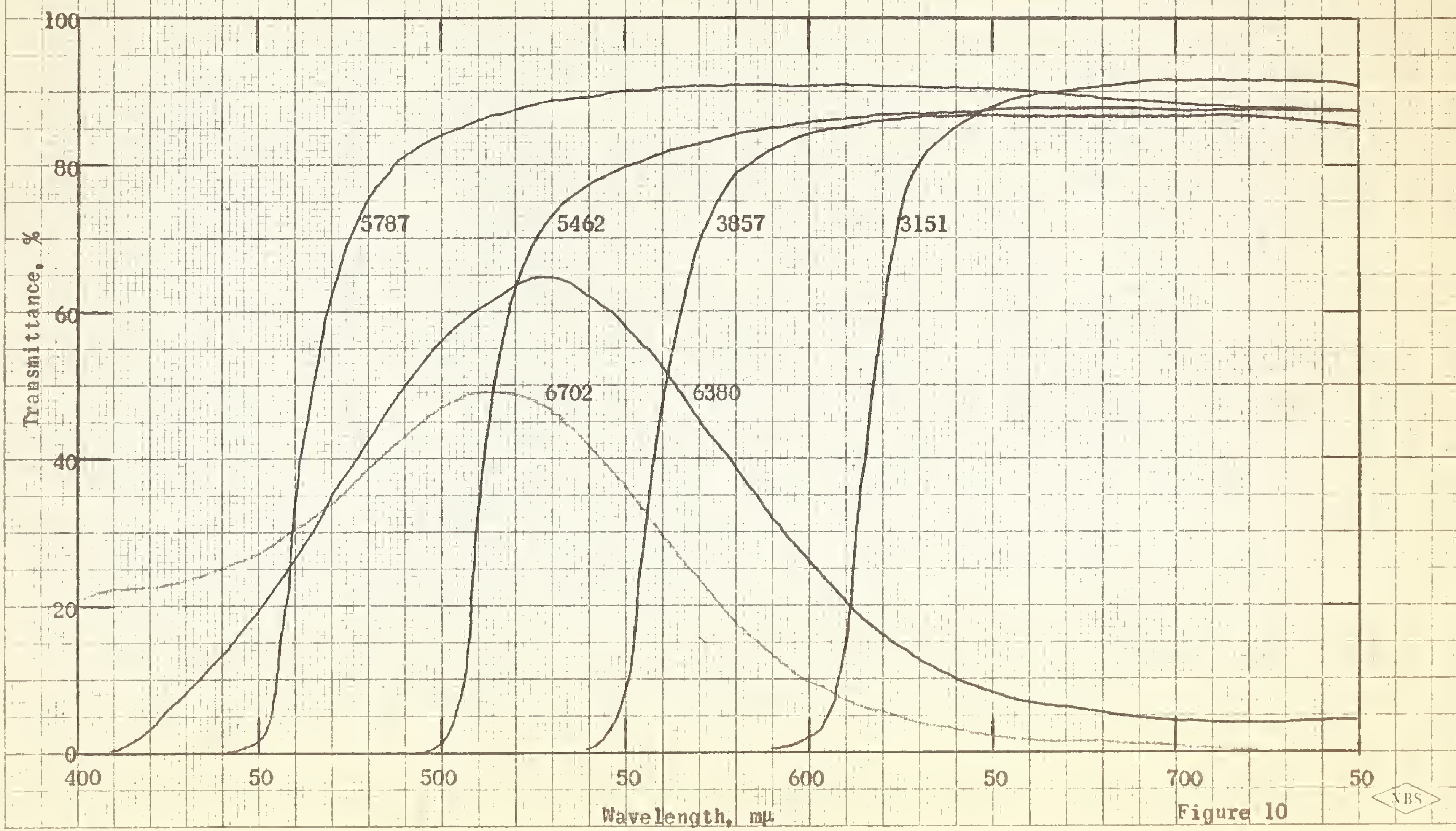


Figure 10

NATIONAL BUREAU OF STANDARDS REPORT

4408

CHROMATICITIES EXHIBITING MAXIMAL CONTRAST

By

Deane B. Judd

To

U. S. Department of the Air Force
Aerial Reconnaissance Laboratory
Wright Air Development Center
Wright-Patterson Air Force Base, Ohio

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Optics and Metrology. Photometry and Colorimetry. Optical Instruments. Photographic Technology. Length. Engineering Metrology.

Heat and Power. Temperature Measurements. Thermodynamics. Cryogenic Physics. Engines and Lubrication. Engine Fuels.

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NATIONAL BUREAU OF STANDARDS REPORT

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CHROMATICITIES EXHIBITING MAXIMAL CONTRAST

By

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To
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Wright Air Development Center
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NATIONAL BUREAU OF STANDARDS

Preface

This is one of a series of reports prepared under National Bureau of Standards Project No. 0201-20-2325, entitled "Color Reconnaissance Studies", financed by the Aerial Reconnaissance Laboratory, Wright Air Development Center, Wright-Patterson Air Force Base, Ohio; Air Force Contract No. AF 33(616) 52-21. It is coordinated with Air Force Contract 33(616)-262 under Dr. Hugh T. O'Neill, O'Neill Associates, Annapolis, Maryland. The present report resulted from one of Dr. O'Neill's work requests.

H. J. Keegan
Project Leader

CHROMATICITIES EXHIBITING

MAXIMAL CONTRAST

By

Deane B. Judd

I. REQUEST:

1. Which two hues will give the greatest contrast visible to the eye?

2. Which will give the least contrast?

3. Is there any table, chart, or graph, published or unpublished, which would give this information in terms of the CIE chromaticity diagram?

4. Could we have a copy of such a diagram showing areas of color contrast?

II. Introduction

Color contrast may be defined as the perceptual size of the difference between two colors. As shown in NBS Report 3773, Determination of Color of Maximum Contrast, [1]* color contrast may be broken down into a lightness component and two chromatic components, and the relative importance of the lightness component depends upon the observing conditions, particularly upon the angular subtense of the elements to which the colors are perceived to belong. For fields of small angular subtense (0.01°) the lightness component determines the color contrast, and, indeed, no chromatic component is perceptible. For fields of large angular subtense (10°), the chromatic component of the color contrast assumes an importance at least as great as that of the lightness component. The question, "Which two hues will give the greatest contrast visible to the eye?", is interpreted as having reference only to the chromatic components of contrast. It might be rephrased: "What two colors of identical luminance are perceived as maximally different?", or "What two chromaticities are perceived as maximally different?"

As in NBS Report 3773, the basic information is to be found in formulas already derived and verified within about a factor of 2 for various specific observing conditions; see formulas 28, 29, 30, 31, 32, 33, 34, and 35, given by Judd (1952) [2]. The determination of the two maximally different chromaticities is especially convenient

*Figures in brackets indicate the index references at the end of this report.

from formula 30, which expresses the difference ΔE, between two colors of equal luminance as:

$$\Delta E = k_2 \Delta S \qquad (1)$$

where ΔS is proportional to the distance between the two chromaticity points plotted on a uniform-chromaticity-scale diagram, such as that by Judd (1935) [3], MacAdam (1937) [4], or Breckenridge and Schaub (1939) [5].

III. Maximally different chromaticities for 2° fields

The method of finding maximally different chromaticities suggested by equation 1 is by inspection of the uniform-chromaticity-scale (UCS) diagram valid for the particular field size in question. The Judd-UCS diagram (see Fig. 74, reference 2) applies to field sizes of about 2°. The area inclosed by the spectrum locus and the straight line joining its extremes is the locus of points representing chromaticities producible by all additive mixtures of spectrum lights, that is, all possible chromaticities. From the shape of this locus it is evident that one of the maximally different chromaticities must be that of the long-wave (red) extreme of the spectrum. The second chromaticity to be paired with this is not sharply defined. What is evident from inspection of this locus is that any spectrum chromaticity from about 510 (bluish green) to 465 mμ (blue) is separated from extreme spectrum red by about the maximum amount. The Breckenridge-Schaub-RUCS diagram (Figure 1 of this report, or Fig. 77, reference 2) gives the same indication, as does, indeed, the MacAdam-UCS diagram (reference 4).

IV. Maximally different chromaticities for 0.1° fields

If one of the two chromaticities whose contrast must be maximized subtends an angle of the order of 0.1° the spacing indicated for 2° fields does not apply. The perceptibility of chromaticity differences from the gray point in the purplish blue to greenish yellow direction becomes vanishingly small. This phenomenon is known as small-field tritanopia (Judd, 1949 [6], Wright, 1949 [7], Middleton and Holmes, 1949 [8]). Under these conditions all chromaticities represented by any straight line passing through the tritanopic co-punctal point ($x = 0.165$, $y = 0.000$ or thereabouts), which is near the short-wave (violet) extreme of the spectrum locus, become indistinguishable from each other. A measure of the chromaticity contrast between two colors viewed with an angular subtense of about 0.1° is the distance between the projections of the corresponding two chromaticity points from the tritanopic co-punctal point to the straight line representing the long-wave branch of the spectrum locus. By this measure the maximum chromaticity contrast would be found between

spectrum red and spectrum blue at about 465 mμ, but nearly as great contrast is indicated between extreme spectrum red and any spectrum chromaticity of wavelength between 450 and 510 mμ. The indication derived from the 2° condition thus holds fairly well for smaller field sizes as well.

V. Answers to the specific questions

1. Maximally contrasting pairs of chromaticities are produced by extreme spectrum red paired with the spectrum bluish green to spectrum blue.

2. Minimally contrasting chromaticities are those yielding a perfect match, or zero contrast. These pairs may be produced by colors of any hue.

3. The UCS diagrams show approximately the perceptibility of the difference between any two chromaticities by the distance between the points representing them when they are presented in fields of about 2° subtense.

4. Fig. 1 is the RUCS diagram developed by Breckenridge and Schaub [5]. It is a projection of the CIE chromaticity diagram such that for viewing in fields of about 2° subtense the distance between the two points is approximately proportional to the contrast between the two chromaticities represented. From this diagram there may be read off immediately a measure (linear distance on diagram) of the chromaticity contrast between any two spectrum colors. Since it is also a mixture diagram, the chromaticities of any mixture of two colors fall on the straight line connecting the points representing them. This diagram thus yields indirectly a measure of the contrast between any two colors viewed in fields of about 2° subtense. It may also be extended to yield estimates of chromaticity contrast between colors viewed in fields of about 0.1° subtense by distance between projections of the two chromaticity points from the tritanopic co-punctal point ($x'' = -0.391$, $y'' = 0.014$) onto the straight line $x'' = 0.075$, as explained above.

VI. References

[1] D. B. Judd, Determination of color of maximum contrast, NBS Report No. 3773 to WADC, November 12, 1954.

[2] D. B. Judd, Color in Business, Science, and Industry, pp. 256-265, New York, John Wiley & Sons, 1952.

[3] D. B. Judd, A Maxwell triangle yielding uniform chromaticity scales, J. Research Natl. Bur. Standards, 14, 41 (1935) RP756.

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[5] F. C. Breckenridge and W. R. Schaub, Rectangular uniform-chromaticity-scale coordinates, J. Optical Soc. Am. 29, 370 (1939).

[6] D. B. Judd, Response functions for types of vision according to the Müller theory, J. Research NBS, 42, 1 (1949) RP1946.

[7] W. D. Wright, Les courbes de mélange des couleurs enregistrées sur la fovéa sous de très petits champs visuels, Rev. optique, 28, 174 (1949).

[8] W. E. K. Middleton and M. C. Holmes, The apparent colors of surfaces of small subtense - A preliminary report, J. Optical Soc. Am. 39, 582 (1949).

Figure 1.

The spectrum locus and Planckian (color temperature) locus plotted in rectangular-uniform-chromaticity-scale (RUCS) coordinates by F. C. Breckenridge and W. R. Schaub [5].

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