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CHANGES IN SPECTRAL SENSITIVITY OF MULTIPLIER PHOTOTUBES RESULTING FROM CHANGES IN TEMPERATURE

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Abstract

The change in cathode spectral sensitivity of Westinghouse WX 4582 (S-11) and RCA 1P21 (S-4) multiplier phototubes was measured across the visible spectrum, i.e. from 400 nm to 700 nm, for various temperature changes, both increases and decreases. Two methods were used for these measurements, viz., an adaptation of the Hardy spectrophotometer, and the use of an environmental chamber. A decrease in temperature usually caused an increase in sensitivity in the short wavelength part of the spectrum and a decrease (as much as 90 percent at 700 nm) in the long wavelength part of the spectrum, with the crossover point (no appreciable change of sensitivity with change of temperature) at about 590 nm. An *increase* in temperature was accompanied with a reversal of spectral sensitivity changes, i.e., a decrease in the short wavelength part of spectrum and an increase in the long wavelength part of the spectrum. The change in cathode sensitivity varied with different types of phototubes and with phototubes of the same type.

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INTRODUCTION

A number of authors have reported the effects of temperature on the response of multiplier phototubes. Murray and Manning[1], in their report of their low temperature experiments, show that there are great differences in the effect of temperatures between different types of phototubes and between phototubes of the same type. Their data are spectral data, from 400 nm to 700 nm, and for temperatures ranging from ambient of about 22°C down to -190°C. Their data are presented for each phototube as a family of curves of relative anode current vs temperature for six different wave lengths. The curves are normalized to unity at the ambient temperature point and, accordingly, show *relative* changes in spectral sensitivity for each of the six wavelengths. The curves do not show *absolute* changes in spectral sensitivity although, in the last section of their paper, the authors cite the works of others which show that, for the cesium – antimony cathode, a lowering of the temperature of the phototube is accompanied by *increased* sensitivity in the short wavelength part of the spectrum and *decreased* sensitivity in the long wavelength part of the spectrum.

Young[2] points out that while reducing the temperature of a phototube is effective in reducing the thermionic dark current there is also a large effect on the spectral sensitivity due to the temperature change, and to achieve 1 percent stability of gain and color response, temperature regulation of 1°C or better is generally required.

Austin[3] mentions briefly work done by the senior author which showed the effect of temperature on the spectral sensitivity of S-4 and S-11 cathodes. He states that this effect is much greater than is generally realized and suggests that one solution for the problem is temperature control.

This paper reports the authors' work on S-4 and S-11 cathodes much more completely and presents the following conclusions: (1) there is a major change in spectral sensitivity due to temperature change, (2) a lowering of the temperature usually *increases* the short wavelength sensitivity but *decreases* the long wavelength sensitivity, (3) the effect varies between types of phototubes and between phototubes of the same type, and (4) in the authors' opinion, the only solution to this problem is temperature control.*

PROCEDURE

Two work programs, in which the spectral responses of the S-4 and S-11 cathode photubes were measured, were conducted independently at the Visibility Laboratory. Boileau measured the

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*G. C. Barnett of the Visibility Laboratory has developed successful thermoelectric junction temperature controls for stabilizing the temperature of multiplier phototubes used in airborne and ground-based equipment.

change of spectral sensitivity in the phototubes by an adaptation, originally suggested by S. Q. Duntley, of the Hardy spectrophotometer; Miller performed his work by using fairly broad band optical filters in a carefully controlled environment. Boileau worked with one Westinghouse WX4582, Serial No. 61-09-026, and two RCA 1P21 phototubes; Miller worked with several of the Westinghouse phototubes, including the one used by Boileau. Boileau's work produced continuous data from 400 nm to 700 nm, but did not take into consideration the frequency response of the phototube; Miller's procedure eliminated the effect of phototube frequency response but lacked the spectral resolution of the method used by Boileau. The data obtained by both workers were in close agreement in the case of the one Westinghouse phototube tested by both.

METHOD 1.

Theory

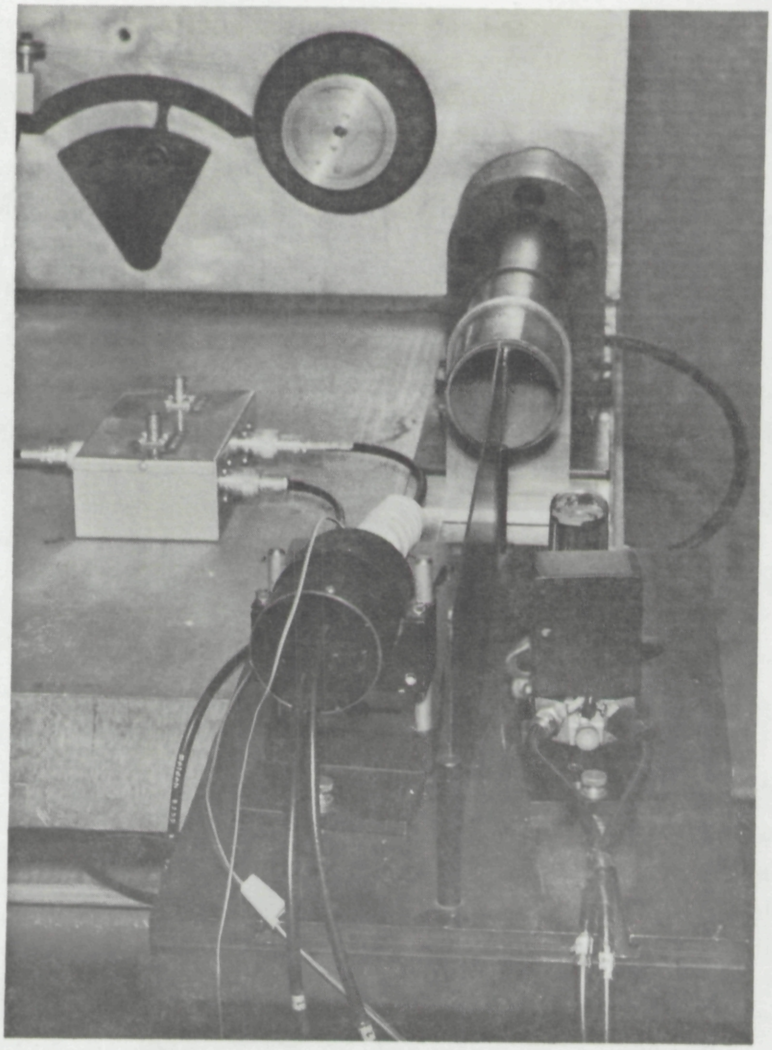
The normal operation of the Hardy spectrophotometer depends on the integration of two modulated flux beams in the integration sphere with a continuous adjustment of the intensities of the two beams so that the sum of the intensities is a steady state.[4] If the sum of the intensities is not a steady state, a sixty cycle per second modulation results, and this modulation, as sensed by a multiplier phototube, is converted to an electrical signal which, after being amplified, operates the photometer balance motor to eliminate the modulation and bring the sum of the intensities to the steady state.

The modification of the spectrophotometer for measuring the spectral sensitivity of a multiplier phototube consists of substituting two phototubes, the phototube under test and the reference phototube, in the photometer servo loop in place of the integrating sphere and its single phototube. The two signals from the phototubes due to the modulated flux beams being incident on the phototubes are added electrically into a single signal. If a sixty cycle per second modulated signal results, the balance motor of the spectrometer operates to change the intensities of the two flux beams until the sum of the phototube signals is unmodulated.

In the operation of the spectrophotometer for measuring reflectances, the spectrophotometer readout is the ratio $R(\lambda)s/R(\lambda)r$ where s and r refer to sample and reference, respectively. The reference is usually magnesium carbonate, the reflectance of which is known. When the spectrophotometer is used for measuring the spectral sensitivity of a phototube cathode the readout is the ratio $S(\lambda)t/S(\lambda)r$, where t and r refer to the phototube under test and the reference phototube, respectively, and *in this case* the relative spectral sensitivity of the *reference* phototube *must* be known.

When the desired measurement is the *change* of spectral sensitivity due to a change of temperature of the phototube cathode, two measurements are made, one for the initial temperature of the cathode and one for the final temperature, *all other conditions remaining the same.* The readouts then are $S(\lambda)(T1)t/S(\lambda)(T1)r$ and $S(\lambda)(T2)t/S(\lambda)(T1)r$, and the inverse ratio of these two readouts, $S(\lambda)(T2)t/S(\lambda)(T1)t$, is the desired measurement, i.e., the change of spectral sensitivity of the cathode of the phototube under test as the temperature is changed from T1 to T2. Note that in this case the spectral sensitivity of the reference phototube has been eliminated from the expression, hence, it need not be known.

Fig. 1. Adaptation of Hardy spectrophotometer for the measurement of cathode spectral sensitivity of phototube. The phototube under test, a Westinghouse WX 4582, is on the left, with a white plastic coated sleeve heater surrounding it. Wires from thermocouple junction on phototube cathode are shown above the phototube socket. Heater wires are shown to the left of the phototube socket supporting structure. The phototube on the right is the reference phototube. Both phototubes are positioned so that their cathodes are in the image plane of the photometer. The signal cables from the phototubes are connected to the junction box resting on the spectrophotometer table. The two connections on the top of the junction box are for monitoring the phototube outputs. When measurements are being made a cover is placed over phototubes and base plate. The separator (shown between phototubes) and the cover prevent flux from being reflected between phototubes.



Apparatus

Figure 1 shows the adaptation used for converting the Hardy spectrophotometer into a cathode sensitivity measuring device. It consists of a base plate and a cover, phototube sockets supported on adjustable brackets which in turn are secured to the base plate by T-bolts in milled T-slots, and an electrical signal junction box for combining and monitoring the two phototube outputs. The T-slots in the base plate are parallel to the flux beams so that the phototubes can be shifted longitudinally for locating their cathodes in the image plane of the photometer. The cover has a circular opening in its front end-plate to mate with the optical tube at that point. Two notches in the lower edge of the rear end-plate of the cover permit the two phototube coaxial cables and other wires to be brought out from the rear of the enclosure.

The two pair of coaxial cables from the phototubes are separated, the two high voltage cables connecting to two independent high voltage power supplies, and the two signal cables connecting to the signal junction box. The signal cable normally connected to the spectrophotometer integrating sphere phototube is connected to the output side of the junction box.

Operation

The operation of the spectrophotometer as a cathode sensitivity measuring device is quite straightforward. A suitable dynode voltage from each of the two power supplies is impressed on the two phototubes and the equipment is put in operation. Great care must be exercised at this point to prevent the balance motor from driving the measuring prism and recording pen beyond the 100 percent point, but a reduction of dynode voltage impressed on the dynode of the *sample* phototube will prevent this. After it has been ascertained that the prism and pen stay below the 100 percent position as the wavelength device is operated throughout the spectral range, the dynode voltages are adjusted to optimum values and, *with no more adjustment of the dynode voltages*, the wavelength drive is returned to its normal starting position and, from this position, the instrument is operated across the spectrum thereby making a continuous relative spectral sensitivity measurement from 400 nm to 700 nm.

Tests

The first test consisted of measuring the change of spectral sensitivity of the cathode of a Westinghouse multiplier phototube type WX 4582, Serial No. 61-09-026, when the temperature of the cathode was lowered from room temperature of 17.2°C to 3.3°C, a drop of 13.9°C. The lowering of the temperature was accomplished by surrounding the phototube under test with dry ice. The temperature of the cathode was continuously measured by a thermocouple junction in contact with the cathode surface and a reference junction immersed in ice water.

The second test was a measurement of the change of spectral sensitivity of the cathode of the same phototube when the temperature of the cathode was raised above room temperature. Three measurements were made when the temperature was increased from room temperature of 25.6°C to 41.7°C, 52.2°C, and 58.8°C, and one measurement when the temperature was increased from 22.3°C to 68.8°C. The increase in temperature was accomplished by a bifilar wound sleeve heater surrounding the phototube, with the power to the heater controlled by a Variac. Again the temperature was measured by the thermocouple junction. Results of the first two tests are shown in Fig. 2. The data for the temperature change from 25.6°C to 41.7°C showed a similar, but smaller effect, as that shown by the temperature change from 25.6°C to 52.2°C, but in the interest of clarity of the illustration, were omitted from Fig. 2.

A third test was made which consisted of measuring the change in spectral sensitivity of the cathode of an RCA 1P21 phototube when the temperature was raised from 23.2°C to 52.2°C, and maintained at that temperature. Measurements were made after the phototube had been subjected to this elevated temperature for twelve minutes and at subsequent ten minute intervals. Three sets of data obtained from this test are presented in Fig. 3. The fourth set of data was virtually the same as the third set which is interpreted as indicating that the phototube had reached thermal equilibrium.

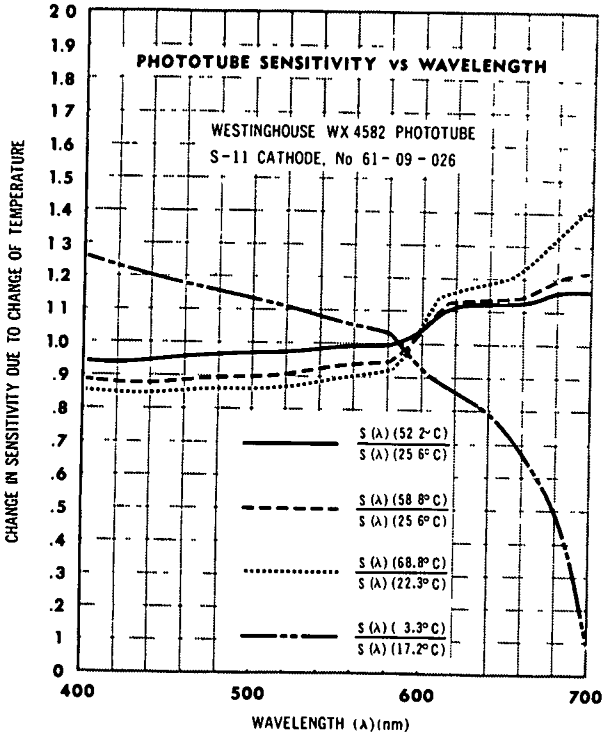


Fig. 2. Change of cathode spectral sensitivity of Westinghouse WX 4582 phototube Serial No. 61-09-026 for both increase and decrease in temperature. Crossover point where sensitivity is virtually independent of temperature is approximately 590 nm. Note the increasing effect of temperature change at longer wavelengths above crossover point.

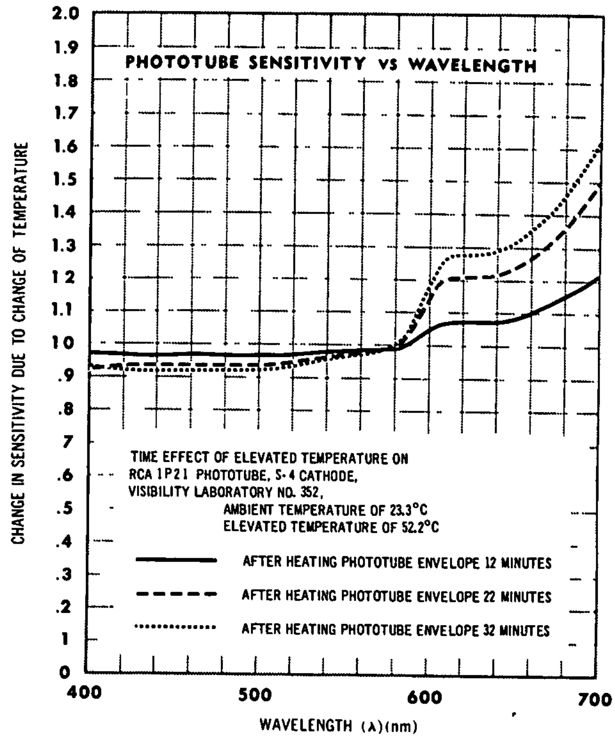


Fig. 3. Changes of spectral sensitivity following prolonged temperature change for RCA 1P21 phototube having internally supported cathode. Crossover point at approximately 580 nm. Note the much greater effect at the longer wavelength compared to the short wavelength.

METHOD 2

Procedure

This method consisted of measuring the output of the phototube when it was maintained in a carefully controlled environment with the flux incident on the cathode being limited by optical filters either to a band in the 400-500 nm part of the spectrum, or to a band in the 600-700 nm part of the spectrum, or to the broad band photopic or human eye sensitivity. The S(λ) T(λ) curves for these filters and the nominal spectral sensitivities of the phototubes are shown in Fig. 4.

The multiplier phototube under test, installed in a remotely controlled optical filter changer, was placed in an environmental test chamber. Flux from an external source was brought into the test chamber and allowed to fall on the cathode of the phototube through the intervening filter by means of a plastic "light pipe". The flux from the external source was monitored externally by a multiplier phototube selected for its stability. The voltage and current of the source were monitored with sensitive meters, and during the tests the output voltage of the monitoring phototube varied less than 1 percent.

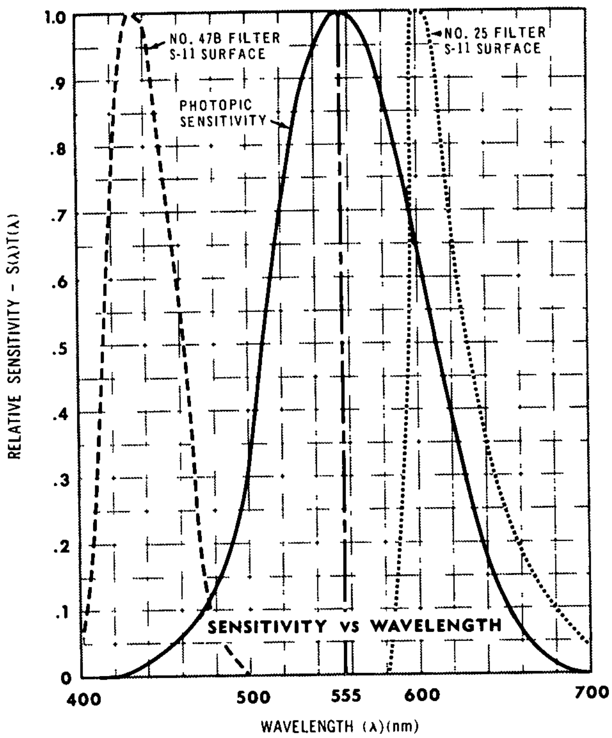


Fig. 4. Band passes for the three filter-phototube combinations used for Method 2 tests. The curve marked "Photopic Sensitivity" approximates the visual efficiency curve, i.e., the sensitivity of the daylight-adapted human eye. All of these curves are only approximations inasmuch as each phototube tested had its own spectral sensitivity.

The initial temperature of the test chamber was approximately 30°C. This temperature was maintained for a period of thirty minutes after which three measurements of the output of the phototube were made, one measurement with each of the three optical filters in position. Then the temperature was reduced. A thermistor in contact with the cathode of the phototube under test showed that thermal equilibrium had been reached before the measurements were recorded.

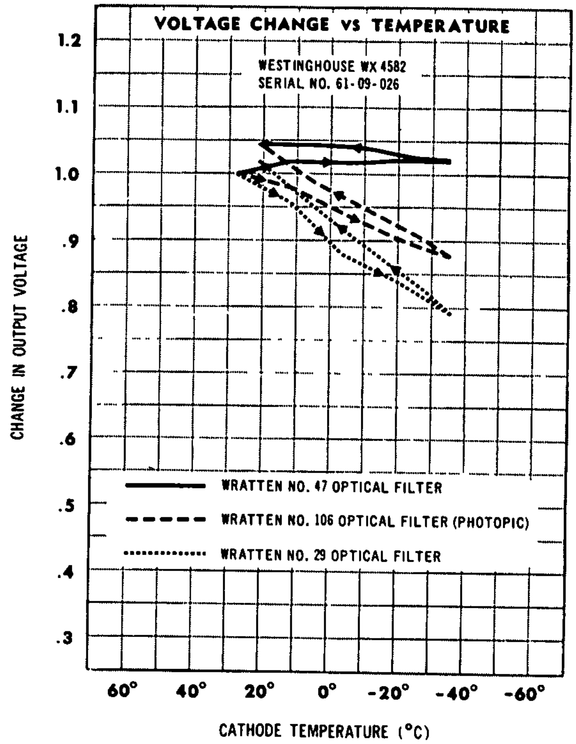
The temperature of the test chamber was reduced from the initial temperature to a low of approximately –35°C in increments of about 15°C. Each temperature in the chamber was maintained for the thirty-minute period prior to measurements being made, and in each case the thermistor on the cathode showed that thermal equilibrium had been reached. After the minimum temperature measurements the temperature was raised in increments of about 15°C until the measurements at the initial temperature had been repeated.

An exception in the procedure as described above was made in the case of Westinghouse phototube Serial No. 62-48-029. When measurements of this phototube sensitivity were plotted as a function of the temperature, it was found that the results were very erratic. Accordingly, this phototube was re-measured but the initial temperature change was a temperature increase to 51°C, and this was followed by incremental decreases until a low of –38°C was reached, after which the temperature was increased until 13°C was reached.

Results

Figure 5 shows the results of measuring the sensitivity of Westinghouse multiplier phototube WX 4582, Serial No. 61-09-026, the same phototube used for the data shown in Fig. 2. In both tests in the short wavelength part of the spectrum the spectral sensitivity increased with

Fig. 5. Sensitivity change with temperature change for Westinghouse WX 4582, Serial No. 61-09-026, multiplier phototube. Note the "hysteresis" effect in *gain* of sensitivity when phototube temperature was decreased and then increased.



decrease in temperature. Fig. 5 shows, additionally, that the sensitivity in that part of the spectrum continued to increase as the temperature was raised to the ambient or room temperature.

Figure 5 also shows a decrease of sensitivity with decrease in temperature for the photopic and the long wavelength filtered flux. When it is considered that the external flux source, an incandescent lamp, radiates strongly in the long wavelength region of the spectrum it becomes apparent that in the case of the photopic filter the greater decrease from 590 nm to 700 nm, as shown in Fig. 2, will dominate the lesser increase sensitivity in the 400 nm to 590 nm region.

Figure 6 shows the result in the case of phototube Serial No. 60-39-060. A comparison with the data in Fig. 5 shows that Serial No. 60-39-060 has a much greater sensitivity change with temperature change than Serial No. 61-09-026, and that, further, the sensitivity of 60-39-060, increases and then *decreases*, with drop in temperature, in the 400-500 nm band.

Figures 7, 8, and 9 show the differences between the effects of temperature changes for Westinghouse phototubes Serial Nos. 60-44-083 and 62-48-029. In the case of Serial No. 60-44-083, the sensitivity changes are nonlinear with temperature change, the rate of sensitivity change increasing with lowered temperature. This is also shown in Fig. 6 in the case of Serial No. 60-39-060. In the case of Serial No. 62-48-029 the sensitivity change with temperature change is probably best described by one word: erratic.

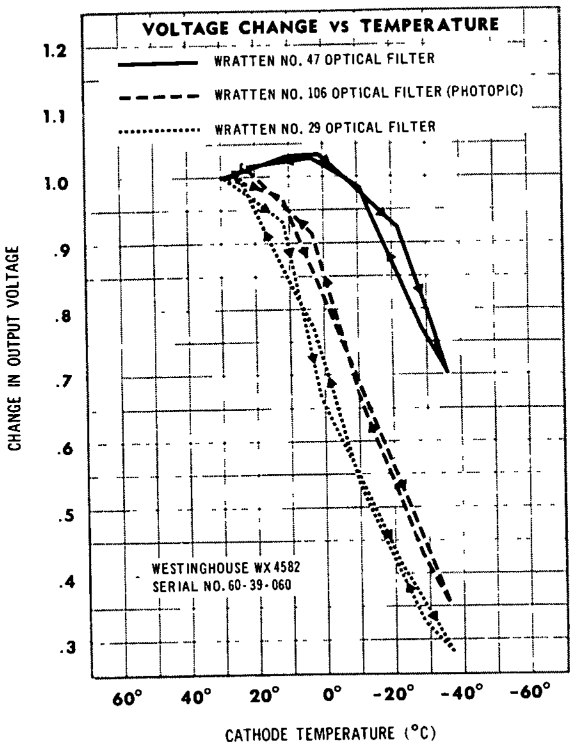


Fig. 6. Sensitivity change with temperature change for Westinghouse WX 4582, Serial No. 60-39-060, multiplier phototube. Note the much greater effect than that shown in Fig. 5. Note, also, the effect in the short wavelength region of the spectrum, i.e., *increase* of sensitivity or temperature was lowered to 0°C followed by *decrease* of sensitivity as temperature was lowered to -36°C. "Hysteresis" effect was considerably less than that shown in Fig. 5.

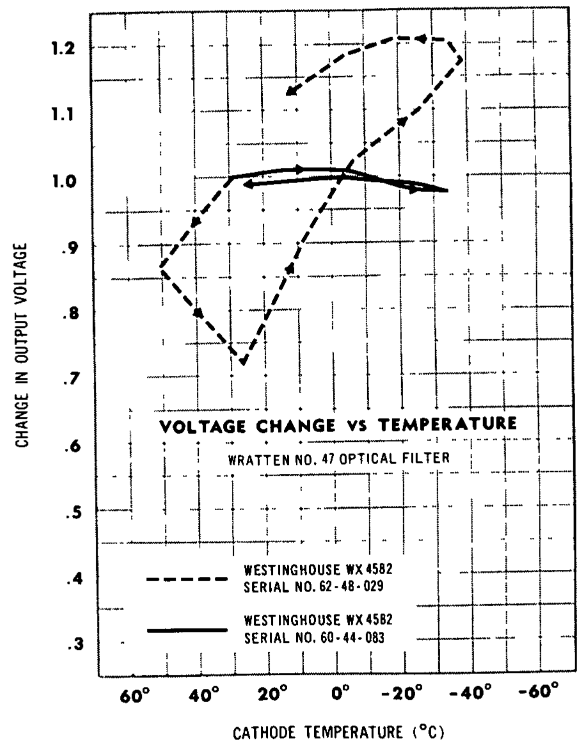


Fig. 7. Sensitivity change with temperature change for two Westinghouse WX 4582 phototubes, Serial Nos. 62-48-029 and 60-44-083, showing great variability between phototubes of the same type. These data are for short wavelength part of spectrum.

ANALYSIS

Others have argued that, as long as the temperature dependency of the cathode sensitivity has been determined and the temperature variations are known, it is possible to correct the raw data recorded by means of a phototube and obtain thereby accurate data. The following analysis shows this to be a false concept.

Let a phototube with a spectral sensitivity of S(λ) fitted with an optical filter having transmittance T(λ) to used, for example, in an irradiometer for measuring irradiance H. Assume further that the instrument is to be calibrated by being irradiated by flux from an incandescent lamp of known radiant emittance. During calibration the instrument measures irradiance

$$H = \Sigma\, S(\lambda)\, T(\lambda)\, H(\lambda)\, \Delta\, \lambda \qquad (1)$$

where the wavelength limits are automatically set by the sensitivity S(λ) and the transmittance T(λ).

When the instrument is set up for field use it is irradiated by radiant flux having a spectral distribution H′(λ) which is probably *never* the same as H(λ). Then the instrument measures,

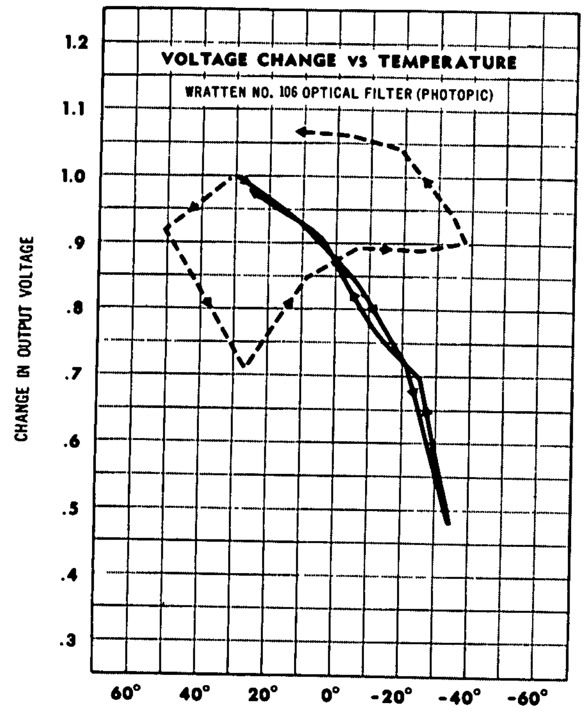


Fig. 8. Sensitivity change with temperature change for same phototubes of Fig. 7 but filtered for photopic response. Again, the great variability between phototube of the same type is shown.

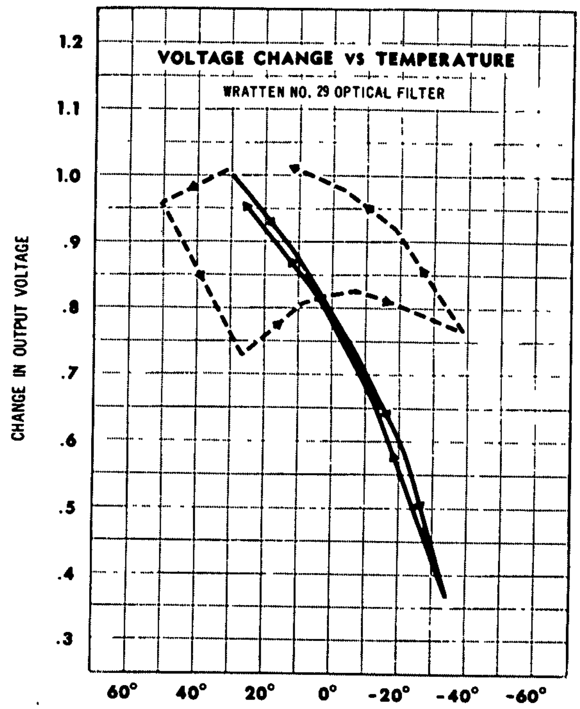


Fig. 9. Sensitivity change with temperature change for same phototubes of Figs. 7 and 8 but filtered for long wavelength part of spectrum.

within the same wavelength limits set by $S(\lambda)$ *and* $T(\lambda)$, the incident irradiance

$$H' = \Sigma S(\lambda) T(\lambda) H'(\lambda) \Delta \lambda \qquad (2)$$

If, in Eq. (2), the $S(\lambda)$ changes, e.g., the short wavelength sensitivity increases due to decrease in temperature, the *apparent* H' from incident short wavelength flux will be greater than the *real value* of H'. It can be argued that, by knowing the change in $S(\lambda)$, the H' can be corrected. If *both* $S(\lambda)$ and $H'(\lambda)$ were known, this *could* be done. But $H'(\lambda)$ is not known. That is the reason for making the measurement.

CONCLUSION

All of the foregoing, then, brings us to the conclusion that, when multiplier phototubes are being used for radiometric or photometric measurements, change in temperature of the cathode, with the resultant change in the spectral sensitivity, cannot be tolerated if any reasonable degree of accuracy or precision is to be achieved.

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