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CHANGES IN COLOR TEMPERATURE OF TUNGSTEN-FILAMENT LAMPS AT CONSTANT VOLTAGE

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ABSTRACT

Seasoned lamps, operated at constant voltage, gradually decrease in color temperature because of evaporation of the filament. Since the current does not decrease enough to correspond to an appreciable change in filament temperature, this decrease in color temperature is ascribed in large part to the accumulation of the familiar brown film on the inside surface of the bulb. The size and shape of the bulb are, therefore, important; each type must be separately investigated. Results are given for five types. The effect of operating seasoned lamps is a gradual decrease in color temperature, linear with time, which, like the rate of evaporation of tungsten, was found for 400-watt projection lamps to be nearly proportional to the thirtieth power of the temperature. The effect of seasoning new lamps for one hour at about rated voltage was a rise in color temperature from 3,050 to about 3,140° K, approximately half of which occurred in the first 3 minutes.

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I. INTRODUCTION

When a seasoned incandescent lamp is burned at constant voltage, its chromaticity is not quite constant but changes slowly toward yellow. This chromaticity is conveniently and customarily specified by color temperature, defined as the temperature which an inclosure would need have in order to yield the same chromaticity by thermal radiation. The light output of the lamp also gradually decreases.

The present investigation was begun in 1930 with the primary purpose of discovering which of a number of types of tungsten-filament incandescent lamps was best suited for standards of color temperature. It was also expected that the study would show how much a working standard could be used before a check against a primary standard was advisable. Furthermore, the suggestion was made that measurements of luminous efficiency might serve as a check on the color-temperature constancy of lamps, and therefore an attempt has been made to correlate the decline in luminous efficiency with the decline in color temperature.

The types of lamp investigated are those which were thought of as possible best choices for color-temperature standards; table 1 gives a description of these types, the number tested, the type of current used, the initial color temperature, and the date and duration of the test.

The general plan of the investigation has been to burn the lamps at constant voltage and to measure at intervals, (1) current, (2) light output, and (3) color temperature.

It is the purpose of this paper to describe the apparatus and method and to give the essential results with some discussion of their significance.

TABLE 1.—*Types of lamp investigated, their number, duration of test, and color temperature*

Rated watts	Type of bulb	Type of filament	Number tested	Duration of test	Type of current	Initial color temperature	Test started (date)
				hr		°K	
400	Tubular, gas-filled	Monoplane	5	64	a-c	3, 100	6/18/32.
			5	64	d-c	3, 100	6/18/32.
			5	700	a-c	2, 850	8/3/32.
			5	700	a-c	2, 360	8/3/32.
500	Pear-shaped, gas-filled	Crown (C7)	5	128	d-c	2, 850	5/4/31.
500	Pear-shaped, gas-filled	Circular-coil (C7A)	5	128	d-c	2, 840	10/19/31.
60	Pear-shaped, vacuum	Squirrel-cage	5	128	d-c	2, 360	5/4/31.
60	Pear-shaped, vacuum	Circular-coil (C9)	5	128	d-c	2, 360	10/19/31.

II. THEORETICAL CONSIDERATIONS

The change in color temperature of a tungsten-filament lamp at constant voltage is ascribable to evaporation of tungsten from the filament. Such evaporation may change the color temperature of the lamp in two ways. It may cause a change in the true temperature of the filament itself, and it may change the color temperature of the lamp by a deposit on the inside of the bulb acting as a selective filter.

The properties of tungsten and tungsten filaments have been thoroughly investigated and summarized by Forsythe and Worthing [1] and by Jones and Langmuir.[2] From these investigations the change in color temperature of the filament itself, from the loss of tungsten, may be closely estimated regardless of whether or not the diameter remains uniform.

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[1] W. E. Forsythe and A. G. Worthing, *The properties of tungsten and the characteristics of tungsten lamps*, Astrophys. J. **61**, 146 (1925).

[2] H. A. Jones and Irving Langmuir, *The characteristics of tungsten filaments as functions of temperature*, Gen. Elec. Rev. **30**, 310-319; 354-361; 408-412 (1927).

1. FILAMENTS OF UNIFORM DIAMETER

Consider, as is usually done, an ideal straight tungsten filament of circular cross section having a smooth, polished surface. Let there be no cooling at the leads nor any cooling by conduction to gases in contact with the filament. For such a filament of constant length, L, with a constant voltage, V, applied over this length, it has been shown by Jones and Langmuir that temperature of the filament, T, and current, I, in it are proportional to certain powers of the diameter, d, so that we may write:

$$T/T_0=(d/d_0)^n, \tag{1}$$

where n varies from 0.168 to 0.176 within the temperature range 2,300 to 3,000 °K, and

$$I/I_0=(d/d_0)^m, \tag{2}$$

where m varies from 1.80 to 1.79 within the same range. The subscript, 0, denotes the values at the beginning of the burning test.

The color temperature, θ, differs from the true temperature of the filament by only 50 to 100 degrees throughout this range of temperatures,[3] so without appreciable error for our purpose eq 1 may be written:

$$\theta/\theta_0=(d/d_0)^{0.17}. \tag{3}$$

Assume that the diameter of the filament is uniform and decreases uniformly because of evaporation from the surface and linearly with time, t, in service, thus:

$$d/d_0=1-t/t', \tag{4}$$

where t' is the time required for the complete evaporation of the filament.

For a lamp whose change in color temperature is ascribable wholly to change in true temperature of a uniform filament it could be expected from eq 3, 2, and 4 that the color temperature and current would vary with time as follows:

$$\theta/\theta_0=(1-t/t')^{0.17} \tag{5}$$

$$I/I_0=(1-t/t')^{1.8}, \tag{6}$$

that is, the color temperature should decrease approximately as the sixth root of time and the current should decrease approximately as the square.

Actual filaments, however, are not uniform to start with, and it may be readily seen that a narrow, constricted region of the filament will cause development of a "hot spot" which will be always at a higher temperature than other parts of the filament and which, barring other accidents, will ultimately cause its failure.[4] Irregularities in the filament also appear because of formation of large crystals.[5] The filaments of the lamps burned for 700 hours show considerable evidence of such crystallization.

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[3] See footnote 1.

[4] R. Becker, *Lebensdauer und Wolframverdampfung,* Z. techn. Physik **6**, 309 (1925).

[5] G. R. Fonda, *Burn-out of incandescent lamps,* Gen. Elec. Rev. **32**, 206 (1929).

2. FILAMENTS OF NONUNIFORM DIAMETER

Consider changes in the original filament such that a certain fraction, f, of the length is reduced in diameter to a certain fraction, c, of the original diameter. To trace the effect of these changes in dimensions requires three separate sets of symbols as follows:

(1) Voltage, V, applied to the original filament, diameter, d_0, produces current, I_0, color temperature, θ_0, and resistivity, ρ_0.

(2) Voltage, V, applied to the diminished filament produces in the unreduced part, diameter, $d'=d_0$, a lower current, I', a lower color temperature, θ', and a lower resistivity, ρ'.

(3) And it produces in the reduced part, diameter $d=cd_0$, the same current, $I''=I'$, and, as will appear presently, a higher color temperature, θ'', and a higher resistivity, ρ''.

The resistance, R, of the partially reduced filament may be expressed in terms of the resistivities of the two component parts, thus:

$$R=\frac{L}{d_0^2}[\rho'(1-f)+\rho''(f/c^2)]. \tag{7}$$

The current flowing through the partially reduced filament is: $I''=I'=V/R$; that flowing through the original filament is: $I_0=Vd_0^2/L\rho_0$; and the ratio from eq 7 may be written

$$I''/I_0=I'/I_0=\frac{\rho_0}{\rho'(1-f)+\rho''f/c^2}. \tag{8}$$

Assuming that no heat is transferred from the narrow part of the filament to the unreduced part by conduction, we may write from the Jones and Langmuir table of relations between the variables of ideal tungsten filaments [6] for constant current, since $I''=I'$:

$$\theta''/\theta'=(d_0/d)^{0.9}=1/c^{0.9} \tag{9}$$

also:

$$\rho''/\rho'=1/c^{1.1} \tag{10}$$

The effect of introducing a narrow place in the filament is, of course, to decrease the current, but as shown below, even with this decreased current (except for f nearly unity) there is a rise in the color temperature of the narrow part of the filament.

The color temperature of the filament as a whole is a mean of the color temperatures of the two component parts. Use has been made of the red-blue ratio,[7] taking wave lengths 660 and 470 mμ for estimating the mean. The total amount of radiant energy at 660 mμ from both the narrow and unchanged parts of the filament was computed by Wien's law from the respective color temperatures, a similar total at 470 mμ found, and the ratio computed. The color temperature of the filament as a whole was taken as the temperature of the Wien radiator having this same red-blue ratio.

As an illustration of the dependence of color temperature on the degree of irregularity with which the filament decreases in diameter, there have been computed the color temperatures of five filaments each differing from the original filament by losing enough tungsten

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[6] Gen. Elec. Rev. **30**, 357-358 (1927).

[7] W. E. Forsythe, *Color match and spectral distribution*, J. Opt. Soc. Am. & Rev. Sci. Instr. **7**, 1115 (1923).

to reduce the current with constant voltage, V, by 1 percent. The first of these five filaments has its diameter reduced uniformly over the entire length ($f=1$), the second is unchanged over nine-tenths of its length, but has its diameter uniformly decreased over the remaining one-tenth ($f=0.1$), and so on for $f=0.05$, 0.02, and 0.01. The details of the computation and the results are shown in table 2.

The reduction in diameter, c, required to reduce the current from I_0 to 0.99 I_0 was found from eq 8 and 10:

$$c^{3.1}=\frac{\rho' f}{\rho_0/0.99-\rho'(1-f)} \tag{11}$$

The resistivities ρ' and ρ_0 refer to filaments of the same diameter ($d'=d_0$) but the filament of resistivity, ρ', carries 1 percent less current. From relations given by Jones and Langmuir, the temperatures, and hence the color temperatures, of the filaments, are closely proportional to the 0.6 power of the current for diameter constant:

$$\theta'/\theta_0=(I'/I_0)^{0.60} \tag{12}$$

TABLE 2.—*Change in color temperature according to distribution of tungsten removed from filament*

[These computations refer to a 1 percent decrease in current, $I'/I_0=0.99$]

Fraction of original length, L, reduced in diameter	Fraction of original diameter required over fractional length, f, to produce a 1% decrease in current (see eq 14)	Fractional increase in color temperature at narrow part of filament $\frac{\theta''}{\theta_0}=\frac{0.994}{c^{0.9}}$*	Color temperature of unchanged part of filament, θ', of narrow part, θ'', and of whole filament, $\theta_{R/B}$, for two initial color temperatures, θ_0, in °K.					
			For $\theta_0=2{,}400°$ K			For $\theta_0=2{,}800°$ K		
			θ''	θ' See note**	$\theta_{R/B}$	θ''	θ' See note**	$\theta_{R/B}$
f	c	θ''/θ_0						
1.00	0.995	0.999	2,398	---------	2,398	2,797	---------	2,797
.10	.950	1.042	2,501	2,386	2,403	2,918	2,783	2,801
.05	.909	1.084	2,602	2,386	2,407	3,035	2,783	2,804
.02	.818	1.191	2,858	2,386	2,422	3,335	2,783	2,814
.01	.724	1.330	3,192	2,386	2,460	3,724	2,783	2,840

* The factor, 0.994, is introduced because eq 3 requires θ''/θ_0 to equal 0.999 for $c=0.995$; this is a drop in color temperature with voltage and length constant due to decreased current; it does not follow from eq 9 which refers to constant current.

** The length of filament, (1–f) L, unchanged in diameter has a color temperature lower than θ_0 because of the 1 percent decrease in current, thus: from eq 12: $\theta'/\theta_0=(I'/I_0)^{0.60}=0.99^{0.60}=0.994$.

and resistivity is closely proportional to the 1.2 power of the color temperature regardless of filament dimensions:

$$\rho'/\rho_0=(\theta'/\theta_0)^{1.2} \tag{13}$$

These exponents vary slowly with color temperature much as those of eq 1 and 2; but, as before, values representative of 2,800° K are used for simplicity, the errors resulting from neglect of the more accurate relations being of no consequence for the present purpose.

From eq 12 and 13 may be written:

$$\rho'/\rho_0=(I'/I_0)^{0.72}$$

which for I'/I_0 equal to 0.99 is approximately 0.993. Substitution of this value in eq 11 gives the relation from which the values of c in the second column of table 2 were found:

$$c^{3.1}=0.983f/(0.017+0.983f) \tag{14}$$

It may be noted that the numerical results computed from eq 14 differ only slightly from those obtained from the simpler relation:

$$c^2=f/(0.01+f) \tag{14a}$$

found from eq 8 by neglecting the differences between ρ_0, ρ', and ρ''.

The third column gives the ratio of color temperature of the "hot spot" to the original color temperature, $\theta''/\theta°$, according to a relation found from eq 3 and 9. There are also given for two initial color temperatures, 2,400 and 2,800° K, the color temperature of the "hot spot", f, the color temperature of the remainder, $1-f$, of the filament, and the color temperature of the whole filament, $\theta_R/_B$, estimated by the red-blue-ratio method.

It may be seen for $f=1$ that a reduction in diameter of the whole filament by 0.5 percent is required to produce a 1-percent reduction in current. This reduction may be expected to lower the color temperature by but 0.1 of 1 percent (2 or 3 degrees); this is in accord with eq 3. The remainder of the entries in the table show that the color temperature of the whole filament is relatively independent of how the reduction in diameter required to reduce the current by 1 percent is distributed, the effect of deviating from uniform reduction in diameter ($f=1$) being to raise the color temperature slightly. Only when the whole decrease is limited to one-twentieth or less of the filament length does the increase amount to more than 9° K. Such an irregularity produces a rather severe "hot spot", a locality in which the color temperature rises about 200° K above that of the remainder of the filament. The extreme restriction, $f=0.01$, was included as representative of a lamp burning out from development of a "hot spot."

These results apply to ideal straight filaments in a vacuum; most of the lamps actually tested had coiled filaments in gas-filled bulbs. It is believed, however, that the considerations apply essentially to such lamps also. We may expect therefore that the color temperature of the filament will, in general, rise slowly with continued operation, and even in the unlikely case of a very uniform filament the fractional decrease in color temperature is expected not to be any more rapid than the tenth root of the fractional decrease in current (see eq 5 and 6). This permits a considerably simplified discussion of the results which may conveniently be mentioned now. As will appear later, decreases have been found in color temperature of as much as 35° K accompanied by decreases in current up to 1 percent. From table 2 it may be seen that the maximum decrease ascribable to change in color temperature of the filament is 3° at 2,800° K. It may be concluded, therefore, that by far the largest part of the decrease in color temperature is ascribable to the accumulation of the brown film on the inside of the bulb. No further attention will be paid to possible changes in color temperature of the filament because there is no evidence that such changes have significantly influenced the experimental results.

This conclusion emphasizes, however, that size, shape, and gaseous content of the bulb determine the permanence of the lamp as a color-temperature standard. A large bulb provides a larger glass surface on which the film may be deposited with a consequent reduction in its thickness. By variation in shape of the bulb convection currents within may be controlled so that most of the film is deposited on parts of the bulb off the line of sight. Each type of lamp must therefore be separately investigated.

III. APPARATUS

The apparatus consisted of devices for operating lamps at constant voltage, and devices for measuring luminous flux and color temperature at known voltages.

1. DEVICES FOR OPERATING LAMPS AT CONSTANT VOLTAGE

For most of the work the lamps were operated on alternating current at prescribed voltages in the equipment developed for life testing of incandescent lamps. Since lamps used for standards of color temperature are customarily operated by direct current, the early tests were made with direct current until a comparison of the two methods showed little significant difference. In each case the voltage was controlled to within 0.25 volt.

2. MEASUREMENT OF LUMINOUS FLUX

The light output of each lamp was measured either by means of an 88-inch photometric integrating sphere and visual photometric equipment used in routine tests at the Bureau for many years, or by a 60-inch sphere equipped with a cesium photoelectric cell in a Sharp and Smith circuit.[8] It has been found possible, in routine measurements, to detect variations in luminous flux as small as 0.25 percent with the photoelectric photometer, which is a precision somewhat higher than was obtained with the visual photometer.

3. MEASUREMENT OF COLOR TEMPERATURE

The color temperature of the lamps was measured by comparison with lamp standards on the Nela scale of color temperature [9] according to the substitution method on the color comparator described in 1930[10] either with the flat 16° circular photometric field divided vertically in the center and viewed binocularly, or with the Lummer-Brodhun contrast photometer head with the contrast strips removed giving a 9 × 13° field with a complex double-trapezoid pattern viewed monocularly. The latter more complex field gave no higher precision, but was preferred because it largely eliminated errors due to changes in chromatic sensitivity of one-half of the observer's retina relative to the other half over time intervals of the order of 10 minutes.

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[8] C. H. Sharp and H. A. Smith, *Further developments in photoelectric photometers*, Trans. Illum. Eng. Soc. **23**, 434 (1928).

[9] This work was done in 1930 to 1932 prior to the establishment of the present scale of color temperature (see BS J. Research **12**, 527 (1934) RP677). The Nela scale differs so little from the present scale that no useful purpose would be served in transferring these results.

[10] D. B. Judd, *Precision of color temperature measurements under various observing conditions; A new color comparator for incandescent lamps*, BS J. Research **5**, 1161 (1930) RP252.

IV. METHOD

The method for seasoned lamps was (1) to set them for the desired initial color temperature, θ_0 (see table 1), by adjustment to voltage, V; (2) to check for possible seasoning effects by measurement of current and color temperature at this voltage immediately after this period (about 3 minutes) of adjustment; (3) to operate them at this voltage for the following time intervals, in hours, 1, 2, 4, 8, 16, 32, 64, 50, 50, 50 . . . ., continuing until the durations given in table 1 had been reached; and (4) after each such time interval to measure current, luminous flux, and color temperature.

The method for unseasoned lamps was the same, except that they were seasoned for 1 hour at 3,140° K and the check for seasoning effect was applied once during this hour after about 7 minutes, the initial adjustment requiring longer than 3 minutes because of the rapid rise in color temperature during initial stages of seasoning. For two lamps the seasoning effect was studied continuously for 10 minutes by settings of color temperature every 30 seconds.

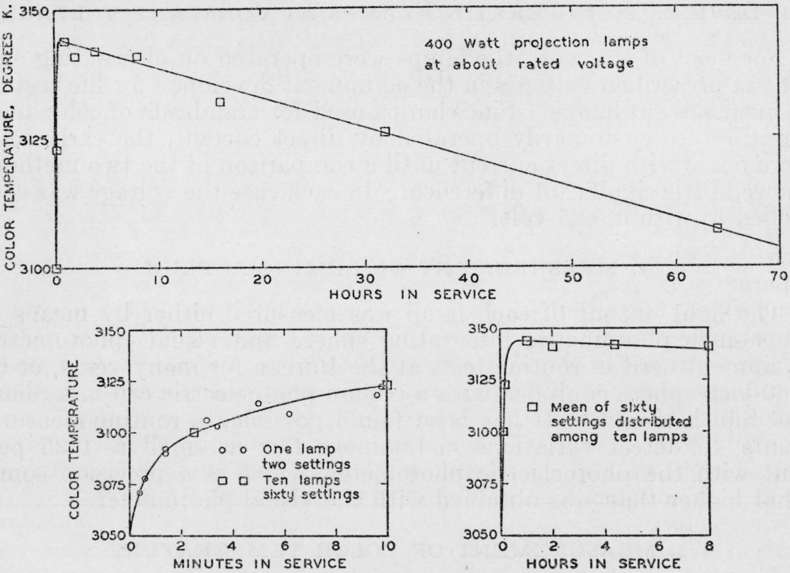

FIGURE 1.—*Color temperature of unseasoned lamps as a function of time in service.*

The color temperature rises rapidly during seasoning, then declines slowly.

V. REDUCTION AND SUMMARY OF DATA

The 400-watt lamps were taken from stock; the 60-watt, squirrel-cage filament lamps were taken from lamp sockets after actual use of unknown amount; the remainder of the lamps (see table 1) were purchased as photometric standards. As might be expected, only the lamps taken from stock showed any evidence of a seasoning effect.

Figure 1 shows typical variation of color temperature with time in service for unseasoned lamps. The seasoning effect found is a rapid rise of 50 to 100° K in color temperature accompanied in every case, contrary to expectation, by a 1 percent decrease in current. The color-temperature rise is best shown on figure 1 by the plot with the enlarged time scale. The effect of burning seasoned lamps is a slow decline in color temperature with continued but slow decrease in current. The plot to the intermediate time scale shows that seasoning is completed sometime in the first hour of burning. This result justified the usual seasoning procedure which is to operate such lamps at about this color temperature (3,140° K) for an hour. The color temperature rises during the first minute of seasoning by an amount about equal to the decrease produced by 50 hours of burning after seasoning; hence color temperature during the initial stages of the seasoning process changes several thousand times as fast as it does during operation of a seasoned lamp. This rapid rise in color temperature is customarily ascribed to change in surface condition of the filament so as to increase within the visible spectrum the spectral emissivity of short-wave radiant energy relative to that for long wave.

Lamps other than those taken from stock showed only the gradual decrease in color temperature characteristic of seasoned lamps. It is important to note that the color-temperature–time curve closely approximates a straight line. Analysis of the data shows that the actual deviations from a straight line are not significant. For the mean of these 10 lamps, the deviations from a straight line are in each case less than 3° ; they are ascribable to experimental error, apparently in large part, because of error in control by the lamp standard of color temperature. In addition to this, the individual lamps, whose mean is represented on figure 1, gave a spread of about 20°, but this is due chiefly to uncertainty in the initial determination of voltage for 3,100° K because of the rapidity of the seasoning effect during the first 5 minutes. The curves for the individual lamps showed generally parallel courses; significant deviations could be traced to the fusing of two adjacent coils of the filament accompanied by an increase in current, to development of an unusually heavy region of brown deposit in the line of sight, or similar incidents. Significant erratic variations not accompanied by these incidents, such as reported by Howe [11] and Dziobek, [12] were not found with these lamps. The previously noted erratic variations would seem from the present tests to be ascribable to undetected sources of error; but it is possible that the present results fail to be typical because of insufficient number of lamps tested.

The other types of lamps and the same type at lower initial color temperatures likewise exhibited a decrease in color temperature not significantly nonlinear with time, though, of course, the rapidity of color-temperature change at the lower temperatures was notably less than at 3,140° K. It is concluded, therefore, that the permanence of a lamp for use as a standard of color temperature at a given voltage can be satisfactorily indicated by the average decline in color temperature per unit time.

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[11] H. E. Howe, *The color temperature of the gas-filled tungsten lamp as a function of time in service*, J. Opt. Soc. Am. & Rev. Sci. Instr. **13**, 304 (1926).

[12] W. Dziobek, *Über die Verwendbarkeit der Wolfram-Vakuumlampe zu sensitometrischen Messungen*, Z. wiss. Phot. **31**, 96 (1932).

Luminous efficiency and current of the lamps studied were also found to decrease with time in a nearly linear way; this agrees with results found for gas-filled lamps used as photometric standards.[13]

The method used in reducing the data was accordingly to compute the change per hour by reference to the average current, luminous efficiency, and color temperature for the group of lamps, no further attention being paid to values for individual lamps. In the case of current the method was merely to divide the difference between the initial and final values by the number of hours the lamps had been burned; this gives a result of the right order of magnitude. But, with luminous efficiency and color temperature least-square solutions were found for the constants a and b in the expression, $a+bt$; the values of b thus found expressed as the change per hour are given in table 3, together with uncertainties of these values. The uncertainties are taken as 4.9 times the probable error obtained in the customary way from the departures of the actual data from the linear relation found by least squares. On the assumption that the lamps studied are fair samples of all lamps of the same type, these uncertainties may be interpreted as limits which would be exceeded on the average only once in a thousand such tests as these.

TABLE 3.—*Current, luminous efficiency, and color temperature for the types of lamps studied, and their time rates of change when the lamps are operated at constant voltage, V*

[See table 1, for further description of lamps]

Identification of lamp type	Voltage, V	Current, I_0	dI/dt	Luminous efficiency, ϵ_0	$d\epsilon/dt$	Color temperature, θ_0	$d\theta/dt$
	v	amp	ma/hr	lpw	lpw/hr	°K	°K/hr
Projection	110	3.82	−0.6	24.6	−0.058 ±.006	3,140	−0.6 ±0.1
	85	3.31	−.03	16.0	−.0026 ±.0004	2,850	−.06 ±.01
	52	2.54	−.003	5.7	−.00015 ±.00011	2,360	−.006 ±.005
Old standard type (C7)	110	4.20	+.04	16.5	−.0029 ±.0011	2,850	−.09 ±.05
New standard type (C7A)	100	4.08	+.02	16.1	−.0026 ±.0011	2,840	−.08 ±.06
Commercial vacuum type	105	.475	−.01	7.4	−.0018 ±.0009	2,360	−.01 ±.08
Standard vacuum type	95	.469	.00	7.4	−.0015 ±.0005	2,360	−.05 ±.04

Table 3 is a summary of these results including the uncertainties in rates of change of luminous efficiency and color temperature with duration of the test. The data cannot be correctly interpreted without a consideration of these uncertainties which in some cases are undesirably large. Note, for example, that the projection lamps were found at 2,850° K to decline in color temperature at the rate of from 0.05 to 0.07 degrees per hour, while the new standard type at about the same temperature yielded from 0.02 to 0.14 degrees. The conclusion is therefore that there is no significant difference in permanence between these two types of lamps; this is borne out by a consideration of the corresponding decline in luminous efficiency. In another example, however, the projection lamps at 2,360° K showed an average decline greater than 0.001 and less than 0.011 degree per hour, while the standard-vacuum-type lamps yielded an average between 0.01 and 0.09. The conclusion is that the superior permanence of the

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[13] R. P. Teele, *Gas-filled lamps as photometric standards*, Trans. Illum. Eng. Soc. **25**, 78 (1930).

projection lamps at 2,360° K to vacuum lamps at the same color temperature has been established to a high degree of probability; consideration of the corresponding results for luminous efficiency establishes this superiority beyond reasonable doubt because in this case there is no overlapping whatsoever.

In general, the uncertainty in rate of decline is greater for color temperature than for luminous efficiency. This is ascribable partly to the relatively less dependence of total luminous flux on distribution of the brown deposit on the bulb, but it is chiefly ascribable to the generally higher precision of the measurements of luminous flux. In the first part of the work, changes in the lamps could be detected much better (perhaps five times as well) by following the luminous flux than by following the color temperature. After two years of practice in technique of setting for color-temperature match and after several refinements in method and equipment, including installation of the Lummer-Brodhun contrast photometer head, it was found possible to do about equally well with either method. At the end of the work measurements of luminous flux were again found somewhat superior for tracing small changes in the lamps, the increased precision being ascribable chiefly to the substitution of the photoelectric cell for the visual photometer.

VI. DISCUSSION AND SUPPLEMENTARY RESULTS

1. DEPENDENCE OF LAMP PERMANENCE ON FILAMENT TEMPERATURE

It should first be pointed out that the rate of decline in both color temperature and luminous efficiency indicated in table 3 varies approximately according to the thirtieth power of the temperature of the filament. The rate of vaporization of tungsten[14] has a similar dependence. The results are therefore in approximate accord with the view that the decline of both color temperature and luminous efficiency of these lamps is ascribable to formation of a brown film of tungsten or some tungsten compound on the inside of the bulb. Table 4 shows a comparison of the observed values of these rates with powers of the true temperature of the filament; it indicates that within the uncertainty of the results color temperature of the lamp declines according to the twenty-third power of the temperature of the filament, and that luminous efficiency declines closely according to the thirty-first power of the temperature; but the agreement is not perfect. The indication is that even the small changes observed at color temperature 2,360° K are somewhat larger than would be expected from the rate of vaporization of tungsten. It is evident that other factors not taken into account have a significant influence on the results. Evaporation of material from the leads and filament supports may produce this effect; also the higher pressure of the gas may interfere with evaporation of tungsten from the filament at the higher temperatures.

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[14] Gen. Elec. Rev. **30**, 355 (1927).

TABLE 4.—*Dependence on temperature of filament of rate of decline of luminous efficiency, ϵ, and color temperature, θ, of the lamp*

Color temperature, θ	True temperature, [a]T	$\frac{-0.59\ T^{31}}{10^{109}}$	$\frac{d\epsilon}{dt}$	$\frac{-0.44\ T^{23}}{10^{80}}$	$\frac{d\theta}{dt}$
°K	°K		lpw/hr		°K/hr
3,140	3,046	−0.058	−0.058 ±.006	−0.59	−0.6 ±.1
2,850	2,768	−.0030	−.0026 ±.0004	−.065	−.06 ±.01
2,360	2,310	−.00003	−.00015 ±.00011	−.0010	−.006±.005

[a] Taken from data by Forsythe and Worthing (see Astrophys. J. **61**, 146 (1925)) connecting true temperature with color temperature on the Nela scale.

The fact that the color-temperature change varies more slowly with temperature (twenty-third power) than rate of vaporization (thirtieth power and higher) suggests that at the high temperatures the convection currents of gas within the bulb are such as to favor, relative to low temperatures, the deposition of tungsten off the line of sight. This explanation does not apply to luminous efficiency because the light output refers to all directions from the filament rather than only one, nor is this explanation needed because luminous efficiency declines much more closely (thirty-first power) according to rate of vaporization of tungsten.

2. TYPE OF LAMP FOR COLOR-TEMPERATURE STANDARDS

From table 3 it may be noted that the gas-filled lamps specially constructed for photometric standards were not found to be any more permanent in color temperature near 2,850° K than the 400-watt projection lamps. Indeed, the projection lamps seem to be slightly more permanent although the difference is not certain. The reverse had been expected because the projection lamps had considerably smaller bulbs which should cause a thicker brown deposit in the line of sight if the distribution of deposit were uniform. The greater permanence of the projection lamps is now ascribed to the tubular shape of the bulbs which seems to cause a greater proportion of the deposit to occur out of the line of sight.

It may also be noted from table 3 that, as is to be expected, the projection lamps are definitely more permanent at 2,360° K than the vacuum lamps tested at the same temperature.

The projection-type of lamp was therefore chosen for new standards of color temperature over the whole scale.[15] Advantages gained by this choice apart from the gain in permanence just noted are: (1) a single lamp can be used over the whole scale; (2) the projection lamps are more convenient because they are smaller and burn base down; and (3) they are cheap because they are produced in large quantities for another purpose.

3. ALTERNATING-CURRENT VERSUS DIRECT-CURRENT OPERATION

Five of the ten lamps burned at about 3,100° K were operated on direct current, the other five on alternating current. When the results on these two groups of lamps were plotted it appeared from visual inspection of the graphs that there was no significant difference

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[15] H. T. Wensel, D. B. Judd, and Wm. F. Roeser, *Establishment of a scale of color temperature*, BS J. Research **12**, 527 (1934)RP677.

between the two kinds of operation. Alternating current did not, it is true, produce quite as much lowering of color temperature as direct current. For three reasons, however, this result at the time seemed incredible: (1) it had been suspected that a small effect in the reverse sense might show up because of possible fluctuations (60 per second) in temperature from alternating-current operation, the vaporizing action of which might therefore exceed that of direct-current operation at the same color temperature; (2) no difference in the decline of luminous efficiency was noted between the two groups; and (3) the difference observed seemed ascribable to chance. Hence in subsequent burning the less convenient method using direct current was given up and alternating-current burning used.

Later on, however, when the least-square analysis was applied to the data, it was found that the rather uncertain difference previously noted might be significant. Table 5 shows the result of the analysis carried out as previously described for the results presented in table 3. Note that the difference in decline of luminous efficiency is quite insignificant, but that apparently direct-current produces a significantly more rapid decline in color temperature than alternating current. No satisfactory explanation of this result has been found. From the computed uncertainties it is to be expected to occur because of pure chance only about once in ten thousand such tests as were carried out.

TABLE 5.—*Alternating-current operation compared to direct-current operation for 400-watt projection lamps at rated voltages (110* v, *3,140°* K) *burned base down*

Type of current	$\frac{d\epsilon}{dt}$	$\frac{d\theta}{dt}$
	lpw/hr	°K/hr
a-c	−0.058±.006	−0.33±.18
d-c	−.059±.006	−.69±.12

4. CORRELATION BETWEEN LUMINOUS EFFICIENCY AND COLOR TEMPERATURE OF INDIVIDUAL LAMPS IN THE LIFE TEST

It has been proposed that measurements of luminous efficiency might be made on lamp standards of color temperature as a check on their permanence. This proposal was based on two assumptions—first, that the precision with which luminous flux may be measured is considerably superior to that with which color temperature may be measured; and second, that there is a close correlation between the two quantities. The first assumption is not very well borne out by present practice because the superiority is slight. However, the second assumption has some justification, if referred to average values for groups of lamps as may be seen from table 3, though table 5 illustrates a case of poor correlation.

Accordingly, an attempt was made for a number of the individual lamps tested to correlate luminous efficiency with color temperature. The correlation found was poor, too poor to be of any use; there was little tendency for the lamps having rapidly decreasing luminous efficiency to have rapidly decreasing color temperature as well. This lack of correlation accords with the conclusion reached from theoretical considerations (see section II) that both luminous efficiency and color temperature decline chiefly because of the brown deposit on the inside of the bulb, and that the former decrease corresponds to the average deposit all over the bulb, the latter to the deposit which forms on that part of the bulb in the line of sight. This view suggests that an improved correlation might be obtained by measuring apparent candle power in this one direction instead of mean spherical candle power, but the permanence of lamp standards of color temperature may now be so conveniently and reliably checked by color-temperature comparison with other similar standards set aside for that purpose that further work seems not to be justified.

5. EFFECTS OF SEASONING THE LAMPS

The changes which occur during seasoning are thought to be (1) expulsion of gases from the filament and a sintering of the filament accompanied by a decrease in resistance, and (2) a surface change of the filament causing a rise in color temperature. This surface change might be merely a decrease in area causing a rise in filament temperature, or it might be a change in surface character causing an increase of emissivity in the blue relative to that for red. The result with the projection lamps at 3,100° K was unexpected because the current fell sharply, indicating a sharp increase in filament resistance. The rise in color temperature was as expected. All lamps of the twenty seasoned at 3,100° K agreed in these respects.

For the lamps constructed especially for photometric standards no rise in color temperature was found. The current, however, increased gradually throughout the 128-hour period of burning. This held true for each of the 10 lamps tested. This increase suggested that the lamps had not been thoroughly seasoned and that sintering of the filament was continuing throughout the entire period of burning at 2,850° K. Details of construction and seasoning which might account for this result are not known.

6. SUPPLEMENTARY MEASUREMENTS OF THE BROWN DEPOSIT

The results of the tests thus far discussed suggest that the color-temperature impermanence of seasoned incandescent lamps is to be ascribed to brown deposit on the inside of the bulb. The amount of deposit in the line of sight even for the lamps burned for 700 hours is too small to be certainly detected by direct visual inspection although a dark deposit usually appears near the top of the lamps even before any certain decline in color temperature is noted. The question arises, therefore, whether there is really enough brown deposit in the line of sight to account for the decline in color temperature.

Accordingly, the bulb of a lamp which had declined in color temperature about 20° K from 64 hours burning near 3,140° K was removed and the spectral transmittance[16] of the deposit determined on the König-Martens spectrophotometer[17] both for the part of the bulb in the line of sight during the color-temperature measurements and for a part of the bulb near the top which seemed to bear the heaviest deposit. The spectrophotometer provided for unidirectional illumination and viewing, the direction of both being normal to the surface of the specimen.

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[16] For definition of this term, see J. Opt. Soc. Am. **10**, 177 (1925).

[17] H. J. McNicholas, *Equipment for routine spectral transmission and reflection measurements.* BS J. Research **1**, 793 (1928) RP30.

Although the lamp was chosen because of the relative uniformity of the brown deposit on its bulb, this deposit was found to be sufficiently nonuniform to cause considerable trouble in making photometric settings. The results shown in table 6 are values adopted from a smooth curve drawn among the points representing the actual data. The last column in the table shows the seventh root of the transmittance of the heavy deposit. It is seen that these values agree very well with the transmittance of the deposit in the line of sight. This agreement indicates (1) that the nonuniformity of the deposit has not vitiated the results, (2) that the deposit at the top of the bulb is merely a thicker layer of the same material forming the deposit in the line of sight, and (3) that the deposit at the top of the bulb is seven times as thick as that on the bulb in the line of sight.

TABLE 6.—*Spectral transmittance of brown deposit on the bulb of a lamp whose color temperature had declined about 20° K during a 64-hour period of burning near 3,140 K*

[Illuminating beam and direction of view both nearly normal to surface of deposit]

Wave length	Transmittance		Seventh root of transmittance at top of bulb
	In line of sight	At top of bulb	
mμ			
440	0.848	0.306	0.843
480	.861	.354	.861
520	.874	.400	.876
560	.886	.437	.888
600	.897	.471	.897
640	.907	.502	.906
680	.916	.533	.914

By the red-blue-ratio method it is found that the deposit in the line of sight is sufficiently selective to reduce the color temperature of the lamp by 65° K near 3,140, and that the heavy deposit is enough for a reduction of nearly 400° K. Since the observed decline in color temperature is only 20° K, it may be concluded that the selectivity of the brown deposit is ample to account for observed changes in color temperature.

In a sense, the measurements have proved too much; they indicate that three times the observed change ought to have been found. This might be caused by (1) a rise of 45° K in the color temperature of the filament from development of a severe "hot spot", or (2) to a possible division of the observed selectivity into about two-thirds from selective scattering and one-third from selective absorption. From table 2 it is judged that the lamp would burn out from a "hot spot" severe enough to cause a rise of even half of 45° K; furthermore, no "hot spots" were observed in the burn-out of these lamps; they burned normally with an occasional fusing of adjacent coils of the filament and continued loss of filament strength due to crystallization until an accidental jar broke the filament, which would then crumble into many pieces. This rules out the first possibility.

Whether the deposit owes its measured selectivity to scattering or to absorption deserves further consideration. If the selectivity found by unidirectional illuminating and viewing normal to the surfaces of the deposit were entirely caused by selective scattering, such a deposit would be expected to change the color temperature of the lamp not at all, since the short-wave light which is scattered by the fragment of bulb in the spectrophotometer and lost by not entering the viewing slit is saved in the measurements of color temperature because the test plate is illuminated not only by light penetrating the bulb normally along the line of sight but also by light scattered from the deposit on other parts of the bulb. Accordingly, an attempt was made to determine what part of the selectivity observed was caused by selective scattering and what part by selective absorption. What is required for measurement of the selectivity from selective absorption alone is spectral transmittance from unidirectional illumination counting in the measurement all light transmitted regardless of direction. The equivalent conditions, diffuse illumination and normal viewing, were tried by placing the sample over the sphere of the Priest-Lange reflectometer [18] and some evidence was obtained that a considerable part of the selectivity is ascribable to selective scattering, but the nonuniformity of the sample introduced too much uncertainty in the measurement to permit any quantitative conclusion.

VII. CONCLUSIONS

The results of these tests may be summarized as follows:

1. Decrease of color temperature and luminous efficiency of seasoned incandescent lamps during burning at constant applied voltage is caused by the brown deposit forming on the inside of the bulb.
2. Color temperature of a lamp declines during such burning approximately in proportion to the twenty-third power of the filament temperature.
3. Luminous efficiency declines approximately in proportion to the thirty-first power of the filament temperature.
4. No good correlation between color temperature and luminous efficiency of individual lamps in the life test was found, nor is any to be expected since the two quantities depend differently on the distribution of the brown deposit over the inside surface of the bulb.
5. The spectral transmittance of the brown deposit has been found for two thicknesses, one deposit occurring at the side of a tubular bulb, the other, apparently about seven times as thick, occurring at the top of the bulb. The spectral selectivity of this deposit is probably to be ascribed partly to selective absorption and partly to selective scattering.
6. Lamps with tubular bulbs seem to have a more constant color temperature than those with pear-shaped bulbs, probably because a greater proportion of the brown deposit on the tubular bulb occurs near the top out of the line of sight.
7. These results suggest that the permanence of lamp standards of color temperature would be increased several fold by building into the lamps a device for brushing off the deposit, but 400-watt projection lamps are already very permanent, decreasing in color temperature when burned at about 2,850° K by an average of less than one-tenth of a degree per hour.

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[18] I. G. Priest, *The Priest-Lange reflectometer applied to nearly white porcelain enamels,* J Research NBS **15,** 529 (1935) RP847.

The operation of the lamps at constant voltage was carried out by R. S. Hunter, and the measurements of luminous flux were made by R. P. Teele and L. E. Barbrow. Dr. J. F. Meyer aided with his knowledge of incandescent lamps and his acquaintance with the extensive literature of the subject.

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