FLAME STANDARDS IN PHOTOMETRY[1]

By E. B. Rosa and E. C. Crittenden

CONTENTS

I. INTRODUCTION

1. PRESENT PRIMARY STANDARDS OF LIGHT

The need of a reliable standard to serve as a basis for the measurement of light has long been recognized, and in attempts to meet this need much ingenuity has been applied and a tremendous amount of labor has been expended. No standard yet produced has, however, shown such evident superiority as to obtain general acceptance. In France, Germany, and England different forms of flame standards have been recognized as primary standards, but no one of them has been considered entirely satisfactory.

[1] This paper is a revision of one published in the Transactions of the Illuminating Engineering Society (Vol. 5, pp. 753–778; 1910), under the title "Report of progress on flame standards." More recent developments have not materially changed the conclusions then stated, and the present paper differs from the original in form more than in substance. Many additional measurements have been made, covering in all about 80 pentane lamps, but so far as the purposes of this paper are concerned the older data show the performance of the lamps as well as the newer results would, and with a few exceptions the original tables have been retained.

In France the Carcel lamp, invented about 1800, was raised to the dignity of a standard largely as a result of its use as a convenient comparison lamp by Fresnel, although definite directions for its use were not published until 1862, and even those directions have had to be radically modified in recent years.[2] The later prestige of the lamp arose from the fact that Violle practically defined his unit in terms of the Carcel, and in default of a reproduction of the Violle platinum standard, the French unit (the bougie décimale) adopted by the International Electrical Congress of 1889, was in practice maintained by the Carcel lamp, the candlepower of which was taken as 9.62 bougies décimales.

The Hefner lamp was proposed by von Hefner-Alteneck in 1884 and rapidly displaced the candles previously used in Germany. In 1893 the Physikalisch-Technische Reichsanstalt began to certify lamps of this type, and in 1895 the present German unit, called at first the Hefnerlicht and later the Hefnerkerze, was defined as the intensity of a Hefner lamp under certain atmospheric conditions.

The Harcourt 10-cp pentane lamp, the final product of a series of pentane lamps devised by Vernon Harcourt and others, was adopted in 1898 for all tests made under the direction of the Metropolitan Gas Referees of London. Since some doubt existed regarding the reproducibility of the lamps, the Engineering Standards Committee defined its unit of candlepower as one-tenth of the candlepower under standard conditions of a particular lamp kept at the National Physical Laboratory.

The defects of such standards are illustrated by the fact that for years after the three types were adopted in the respective countries there remained a considerable margin of uncertainty as to the relative numerical values of the three units. Several direct intercomparisons of the flame standards gave more or less discordant results, and no definite agreement was reached until a comparison of the units actually used in each of the national standardizing laboratories was obtained through measurements of groups of seasoned electric incandescent lamps carried from one laboratory to another. These measurements showed that within the limits of experimental error the units in use in France and in

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[2] J. Gas Lighting, 99, p. 234; 1907.

England were equal, while the Hefnerkerze was 0.9 as large as the others; and this simplicity of ratios made possible the agreement which has reduced the units of light to two, namely, the Hefnerkerze and the international candle of England, France, and America.[3]

The light unit of the Bureau of Standards has always been maintained by groups of electric lamps, because it has been believed that the unit once agreed upon could be so maintained with an accuracy considerably above that with which it could be reproduced by reference to any of the so-called reproducible standards at present in use. In other words, the incandescent lamps have really been employed as primary standards, and the flame standards, which logically should play the part of primary standards, have been relegated to a subordinate position. For example, a given pentane lamp is not assumed to give 10 candles, but is compared with the electric standards and is assigned a value as a result of the comparison.

2. NEED OF A BETTER STANDARD

Although the electric lamps are very satisfactory as secondary standards, and although as empirical primary standards they may serve to maintain the unit of light constant for many years, yet there is a possibility of an appreciable drift in the value of the unit occurring sooner or later, if there is no photometric standard accurately reproducible from its specifications which is capable of serving as a reliable check upon the electric standards. Consequently, while the present unit may be considered as definitely and permanently adopted, there is need of a reproducible standard to preserve the value of that unit unchanged. There have been proposed several possible methods of constructing such standards which would be more rational than the essentially crude flame standards, but not one of them has yet been developed to a sufficient extent to be of any use as a permanent custodian of the unit, and none gives much promise of being able to supplant the flame lamps in the immediate future. It has therefore appeared worth while to make a study of the best types of flame lamps to see how closely they would reproduce in our laboratory the values adopted

[3] Circular of the Bureau of Standards, No. 15, on the "International unit of light."

by international agreement and also to find whether their reliability as primary standards could be increased by any changes in construction or in operation.

Another reason for improving flame standards is their extensive use in gas photometry, to which they are in some respects better adapted than electric standards. At the suggestion of representatives of the gas industry, the Bureau of Standards some years ago took up the study of some of the more important flame standards with the hope of improving current practice in gas testing in American cities. We may anticipate our conclusion by saying that for such use the pentane lamp has appeared far superior to any of the others, and the results of the Bureau's experience have been incorporated in a special paper [4] for the guidance of those who may have occasion to use that form of lamp.

The present paper is intended to give some of the details of the experimental work done on lamps of various types which have found a more or less extensive use. The most important are the three primary flame standards mentioned above, and the modified form of the pentane lamp which is widely used in the United States, and only these four forms will be considered.

In any flame standard the lamp itself is not the standard but, along with the fuel and the air, it constitutes a means for producing the actual standard, the flame. In considering the property of reproducibility we have therefore to interpret the word in a double sense; we must consider the possibility of producing different lamps and different lots of fuel which are sufficiently like each other to give sensibly the same candlepower, and we must also take into account the exactness with which a given lamp can be made to reproduce the intensity of its flame at different times. In a secondary standard the second consideration is the one of chief importance. In a primary standard a high degree of reproducibility of this second kind is desirable but is not really indispensable, provided the departures from normal value are not systematic; the property of first importance is the reproducibility of the lamp and the fuel.

The excellent performance of the electric lamps makes it possible to test very accurately the qualities of various lamps, for we

[4] The Pentane Lamp as a Working Standard, this Bulletin, 10, pp. 391–415; 1913.

can not only measure the lamps from day to day and compare various lamps with each other with the certainty that the basis of comparison remains constant, but we can also determine whether lamps of each type give the same intensity as is found in other laboratories, and hence can form an opinion as to the possibility of an independent reproduction of the unit.

II. EFFECTS OF ATMOSPHERIC CONDITIONS

1. VARIATIONS IN THE ATMOSPHERE

Besides the lamp and the fuel the third factor, the air, must be considered, for it affects the intensity of the flame very markedly. Oxygen is supplied by the atmospheric air drawn into the flame. With the oxygen go nitrogen, carbon dioxide, and water vapor, which are not needed for combustion and which cool the flame and reduce its intensity. If the air supplied to the flame varies in its composition, the rate of combustion is altered and the cooling effect of the inert gases varies. Fortunately the proportions of oxygen, nitrogen, and carbon dioxide in the open air are remarkably constant and are sensibly the same in different places, so that it is not difficult to obtain standard conditions in this respect if the photometer room has provision for a liberal continuous supply of fresh air. In the present work therefore no attempt has been made to determine the effects of abnormal quantities of carbon dioxide or of a deficiency of oxygen, but care has been taken to secure such good ventilation that no correction would be necessary for such variations in the composition of the air.

The barometric pressure and the proportion of water vapor in the air are, however, variable, and it is not easy to control the variations so as to obtain normal conditions. Consequently, in order to determine the normal value of a flame standard, it is usually necessary to apply corrections for the departure of these two conditions from normal.

The necessary correction factors, the rates of change of candlepower with variation in barometric pressure and in atmospheric moisture, have been previously determined for both the Hefner and the pentane lamp, but the determinations have not agreed as well as they should. The discrepancy between the results obtained at the Physikalisch-Technische Reichsanstalt and those of the English National Physical Laboratory is great enough to cause a difference of over 1.5 per cent in the average corrected value of lamps measured at Washington in the summer. The data of the present investigation are sufficient to give a new determination of those factors, and with respect to the effects of water vapor the results have been so definite and consistent that the new value has been adopted for use both in reducing the data presented in this paper and in calculating the normal values of lamps tested at the Bureau.

2. EFFECT OF BAROMETRIC PRESSURE

The range of barometric pressure included in these measurements has not been sufficient to give a thoroughly reliable value for the corresponding correction factor, and the results have been considered only as an approximate check on previous values. In Table 1 are given the results obtained by various investigators:

TABLE 1

Percentage Decrease in Candlepower Caused by a Fall of 1 cm in Barometric Pressure

Authority	Hefner lamp	10-cp pentane lamp
Liebenthal [5]	0.11	0.6
Paterson [6]	.2	.8
Butterfield, Haldane & Trotter [7]	.4	.8
Bureau of Standards	.14	0.6–0.8

[5] Zs. f. Instrument., 15, p. 163, 1895; J. f. Gas. u. Wasser., 49, p. 561, 1906.

[6] Electrician (London), 53, p. 751, 1904; J. Institution of Elect. Eng., 38, p. 271, 1906–7; J. Gas Light., 99, p. 232, 1907; N. P. L., Collected Researches, 3, p. 49, 1908.

[7] J. Gas Light., 115, p. 290, 1911; Amer. Gas Light J., 95, p. 145, 1911.

The Bureau's earlier measurements, of which the results were published in 1910, gave an average value of 0.6 per cent for the factor for the pentane lamp, but since the range of pressures was very small the value 0.8 per cent, which seemed better established, has been used in correcting observations on test lamps. Later measurements with slightly greater range continued to give somewhat discordant results, until our most recent experiments which tend to confirm the value 0.6 at normal atmospheric pressure. It may be noted from the table that the pentane lamp is affected decidedly more than the Hefner by variation in pressure, and there is evidence that on some flames the effect is still greater. Since for some purposes this effect and the relative change in various types of flame are important, there has recently been undertaken at this Bureau a special investigation of this subject, in which the determination of the effect on the flame standards over considerable ranges of pressure is being made. Within the range of pressure which occurs at Washington the present uncertainty in the correction factor is not of great importance, since the possible errors introduced by it are within the errors of measurement.

3. EFFECT OF WATER VAPOR

The discrepancies between the different values previously given for the water-vapor correction factor are much more serious, and it is therefore a source of gratification that the determinations at the Bureau have been remarkably consistent over the period of four years during which this work has been carried on.

The first thorough investigation of the effect of atmospheric moisture on flames was made by Liebenthal at the Physikalisch-Technische Reichsanstalt, and the method of expressing the variation used by him has been generally followed by others. The humidity (h) is stated in liters of water vapor per cubic meter of (dry) air, and it is found that the variation in intensity of flames is proportional to the humidity. Consequently, if the candlepower of a lamp is defined as normal (I_n) when there are n liters of water vapor per cubic meter of air, the candlepower (I) corresponding to any proportion of water vapor is given by the equation

$$I = I_n[1 + a(n - h)]$$

The method of determining the humidity is to ascertain, by means of a hygrometer, the pressure of the water vapor in the atmosphere at the time of the measurements. This divided by the barometric pressure minus the vapor pressure gives the ratio of the water vapor to the dry air with which it is mixed; this ratio multiplied by 1000 gives the number of liters of water vapor in 1000 of dry air; that is, in a cubic meter of dry air. For other purposes it is more common to state the number of liters of water vapor in a cubic meter of the damp atmosphere. The difference between the two methods of calculation is negligible except at extremely high humidities, but in order to make the results exactly comparable with those of other investigators, the calculations in this paper are based on dry air.

It is evident that the adoption of a flame lamp as a primary standard does not fix the value of the unit unless a standard humidity is specified. The normal humidity for the Hefner lamp has been fixed as 8.8, this being the condition under which Liebenthal found the lamp to give the intensity which had already been adopted as the unit of the Reichsanstalt. For the pentane lamp the normal humidity was originally given as 10 liters per cubic meter of air, which was the average humidity shown by the observations of three years at the Meteorological Office in London and the National Physical Laboratory Observatory at Kew. It later developed that in the calculation of the results of observations on the lamp an error had been made, and that the condition which had been taken as normal was not actually a humidity of 10 liters per cubic meter. Atmospheric humidities were formerly measured at the National Laboratory (as generally in England) by the ordinary wet and dry bulb thermometers, without any artificial ventilation, while in the other countries the instrument used was the more accurate hygrometer (psychrometer) of Assmann, which is ventilated by a rapid current of air and which, therefore, gives a greater depression of the wet bulb. The unventilated hygrometer gives fairly correct results if one uses the tables or formula appropriate to that instrument, although it is less reliable, owing to the fact that the air in the room is not always equally still. It appears, however, that the formula used at the National Physical Laboratory was the formula for the ventilated hygrometer, and hence the values of the humidity obtained were too high.

When this error was discovered, there were two ways of correcting it. The number 10 might have been retained as giving the normal humidity, but since the actual humidity which had been called normal was less than 10 liters per cubic meter of air, raising the normal to an actual 10 liters would be equivalent to decreasing the normal intensity of the lamp. Retaining the 10 would therefore make it necessary either to reduce the unit of candlepower slightly or to assign for the normal intensity of the standard pentane lamp a value somewhat below 10 candles. The other method of adjustment was to leave unchanged all the actual quantities (humidity, unit of candlepower, and candlepower of the standard lamp), and to put into the formula instead of 10 the number which correctly represented the humidity previously given as 10 liters per cubic meter of air. This appeared to be the most reasonable method of effecting the correction. Moreover, it would retain the extremely simple ratios which had been found to exist between the French, English, and German units as maintained at the respective national laboratories.[8] This method was therefore adopted and Dr. Glazebrook announced in a paper read before the British association[9] that the humidity previously determined as 10 liters by the unventilated instrument was found to be actually 8, so that the correction formula was

$$\text{Candlepower} = 10 + 0.066\,(8 - h)$$

where h is the number of liters of water vapor in a cubic meter of dry air. The Gas Referees of London concurred in this proposal, and the official value of the pentane lamp has since been expressed by the above equation.

In effect, then, it is true of both the Hefner and the pentane lamps that a value approximating the yearly average was found by comparing the flame with electric lamps, and this average

[8] The statement has been repeatedly made (see, for example, H. Krüss, J. f. Gasbeleuchtung, **52**, p. 705, 1909; J. Gas Lighting, **107**, p. 439, 1909; Amer. Gas Light J., **91**, p. 676, 1909; and the report of the German committee of the International Electrotechnical Commission, Elektrotech. Zeitschrift, **30**, p. 593, 1909) that the British candle was changed to secure this agreement, whereas in fact the course chosen was that which avoided a change in the unit of the National Physical Laboratory, which had been adopted by the Engineering Standards Committee as the British unit. Even in England there seems to have been an impression that the standard conditions were changed (see Electrician, **63**, p. 203, 1909), and this impression has found its way into various American publications. Unfortunately, in the numerous direct comparisons between flame standards which were made in 1906 and 1907 confusion arose from the different methods of measuring humidity, and the results obtained were not the real ratios between the units in use in the different countries. For instance, on the Continent measurements on the pentane lamp were reduced to a basis of 10 (actual) liters of water vapor per cubic meter of air, and consequently a low value was found for the pentane candle. In England, on the other hand, the value assigned to the Hefner was that obtained with a real humidity in the neighborhood of 7 instead of 8.8, and consequently Paterson found the large value 0.914 for the Hefnerkerze in terms of the unit of the National Physical Laboratory. Later, when proper corrections were made so that each standard was reduced to the normal condition obtaining in the laboratory where it constituted the primary standard, it was found that the direct comparisons gave results in close agreement with those obtained by interchanging electric standards. (See Paterson on "The Proposed International Unit of Candlepower," Phil. Mag. (6), **18**, p. 263, 1909; Proc. Phys. Soc. of London, **21**, p. 867, 1910; N. P. L. Coll. Researches, **6**, p. 117, 1910; J. Gas Lighting, **107**, p. 383, 1909.)

[9] B. A. Report, 1908, p. 623, and Electrician, **61**, pp. 922–923, 1908.

value, maintained by means of the electric standards, constituted the real unit of candlepower. Later the conditions under which the flame lamps themselves gave the standard values were determined, giving a more exact definition of the unit in terms of the flames.

4. THE WATER-VAPOR COEFFICIENT

The choice of a normal humidity must of necessity be more or less arbitrary, but the value of the coefficient which gives the change in candlepower caused by a variation of one unit in the amount of water vapor is a matter for experimental determination. In Table 2 are given the values which have been published for this coefficient.

TABLE 2

Water-Vapor Correction Factors

[The numbers given are the percentage of decrease in candlepower caused by an increase of 1 liter of water vapor per cubic meter of air.]

Authority	Hefner lamp	10-cp pentane lamp
Liebenthal[10]	0.55	0.55
Paterson[11]	.66	.66
J. S. Dow[12]	....	.71
Butterfield, Haldane & Trotter[13]	.625	.625
Bureau of Standards	.56	.57

[10] See note 5, p. 562.
[11] See note 6, p. 562.
[12] Electrical Review (London), 59, p. 496; 1906.
[13] See note 7, p. 562.

The large value obtained by Mr. Dow is not entitled to much weight, because the measurements of humidity were made with an unventilated hygrometer and because the value given is apparently derived from 50 measurements of candlepower remaining after a half dozen others had been rejected on the ground that they differed by 2 per cent or more from the value to be expected.

It will be seen from the table that all investigators agree in the conclusion that the two kinds of lamps are affected equally by humidity; but observers disagree as to the magnitude of the effect. It appears therefore that the cause of the difference is probably to be found elsewhere than in the methods of operating the lamps. It is probable either that the methods of measuring the humidity are different or that some condition more or less systematically connected with the humidity, such as temperature or vitiation of the air, has affected measurements in some laboratories more than in others.

The accidental variation in the results obtained is not great even when relatively few measurements are made. For example, in Table 3, which shows the factors calculated separately from measurements made at the Bureau on six Hefner lamps, it will be seen that the "probable error" of the mean is small compared with the differences exhibited in Table 2.

TABLE 3

Water-Vapor Correction for Hefner Lamp

The factor given is the percentage of decrease in candlepower caused by an increase of 1 liter of water vapor per cubic meter of air.]

Lamp number	Number of measurements	Correction factor
786	19	0.525
887	20	0.564
1343	21	0.578
804	15	0.575
879	13	0.562
1342	13	0.532
Total	101	.....
Weighted mean	...	0.557

Figs. 1 and 2 show the distribution of the observations on two typical lamps. The larger part of the measurements are grouped at low humidities, and consequently the slope of the curves depends very largely on a small number of observations at higher humidities. These observations were made under the conditions least favorable for accurate measurements, and the data of Table 3 might well be expected to show the extreme variations likely to arise from accidental errors of measurement. However, the values given for separate lamps in the table can hardly be considered as entirely independent determinations since the whole group of lamps were usually measured one after another in each set of measurements, and the agreement is therefore less significant than it would be if the measurements on the several lamps had been made at different times.

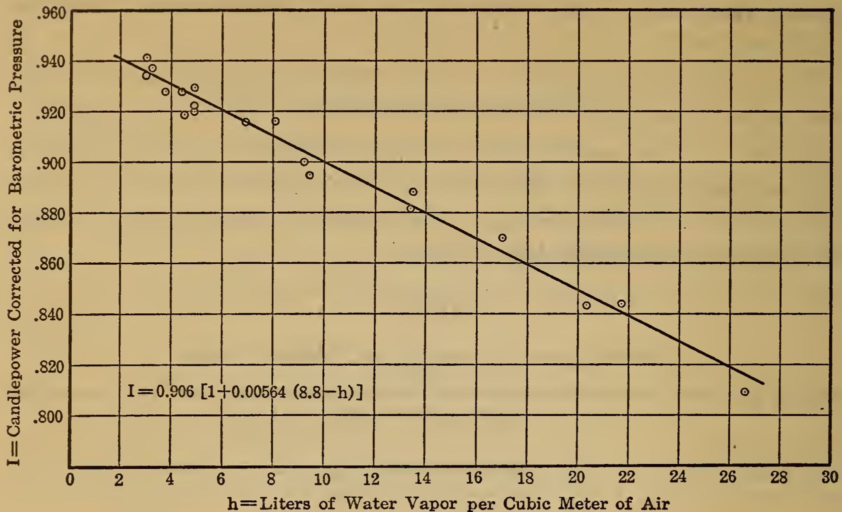

Fig. 1.—*Variation of candlepower with humidity, Hefner lamp No. 887.*

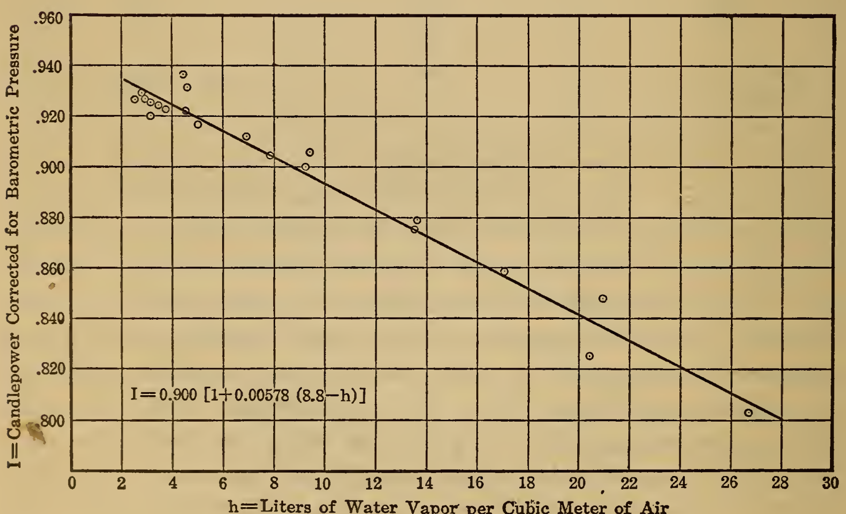

Fig. 2.—*Variation of candlepower with humidity, Hefner lamp No. 1343.*

On the pentane lamps many more measurements have been made, and the data obtained are sufficient for many entirely independent determinations of the correction factor. Table 4 gives the results published in 1910, and the observations on which these results were based are shown graphically in Figs. 3 and 4.

TABLE 4

Water-Vapor Correction for Pentane Lamps

[The factor given is the percentage of decrease in candlepower caused by an increase of 1 liter of water vapor per cubic meter of air.]

Lamp	Number of measurements	Factor derived	Range of water vapor (l per cu m of air)
Chance, No. 116	220	0.569	4.0–27.0
Chance, No. 118	81	0.572	14.1–26.8
Sugg, No. 171	165	0.561	4.0–27.0
Mean		0.567	
American, No. 25	42	0.577	5.0–14.3
American, No. 74	43	0.558	5.0–27.0
American, No. 157	46	0.570	18.2–26.8
American, No. 162	31	0.562	13.7–26.0
Total	628		
Mean		0.567	
Mean of all		0.567	

The same coefficient is found for the low range of humidities (4 to 14 liters per cubic meter) as for the higher range (14 to 27 liters per cubic meter); in other words, the relation between candlepower and humidity is linear from the lowest to the highest humidities encountered. The same coefficient is obtained for lamps of the American type as for those of the original form, and measurements made on the various lamps at different times as well as with different humidities agree very closely. The mean value, 0.567 per cent change in candlepower for a change of 1 liter per cubic meter in the water vapor, found from 628 observations on seven different lamps, would seem to be subject to very little uncertainty.

Since there seemed to be so little room for doubt that the smaller coefficient was correct, at least for the conditions encountered at the Bureau, an attempt was made to ascertain why the value found in England was so much higher. Mr. Paterson's work on the pentane lamp is of a high order and great confidence was placed in the precision of his measurements. It was recalled, however, as has been mentioned above, that in his experiments humidities had been measured with the ordinary unventilated hygrometer, whereas at the Bureau the Assmann instrument had always been used. In the paper announcing the change in the

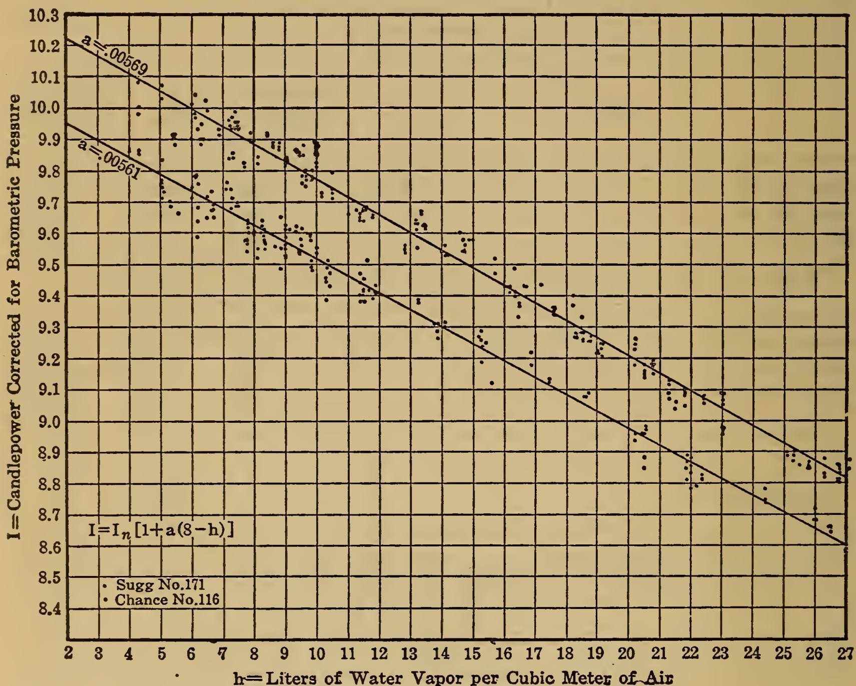

Fig. 3.—*Variation of candlepower of pentane lamps with humidity.*

normal humidity, Dr. Glazebrook stated also that "a complete series of experiments has shown that the constant 0.066 in the formula holds both for the ventilated and unventilated instruments." This means, of course, that the constant is the same when the humidity is computed from observations made on unventilated hygrometers using the formula or tables intended for ventilated hygrometers, the only change in the correction formula being from 10 to 8 in the parenthesis. In other words, the straight line of which the correction formula is the equation has been displaced parallel to itself, its slope remaining unchanged. A little consideration shows that this can only be true under special conditions.

In an unventilated hygrometer the air about the wet bulb retains some of the moisture taken up by the evaporation, and thus evaporation is retarded, whereas in the Assmann hygrometer the air moves over the bulb so rapidly that it is always surrounded with air of practically the same humidity as that of the room. Hence,

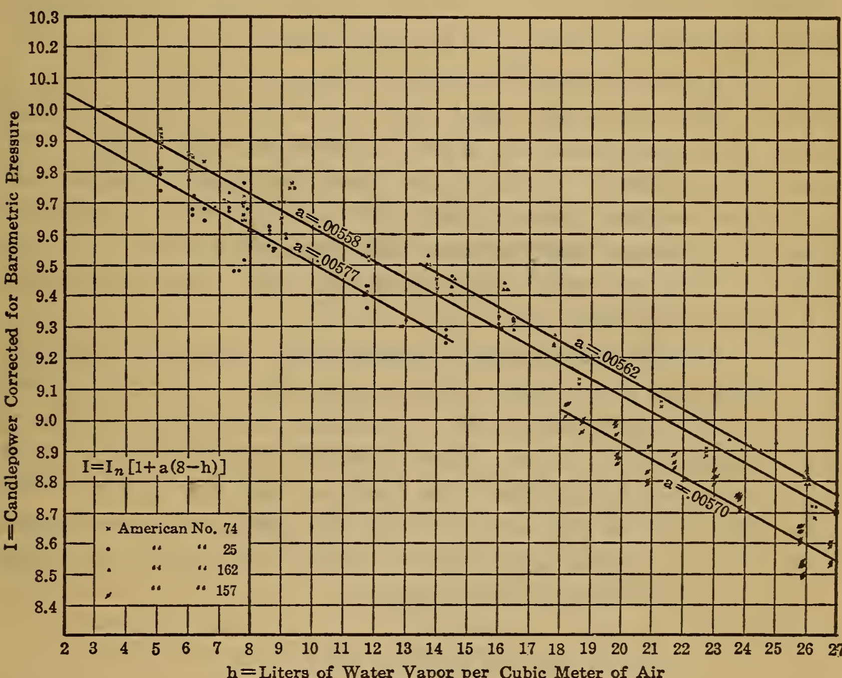

Fig. 4.—*Variation of candlepower of pentane lamps mith humidity.*

the unventilated instrument will show a smaller depression than the other. The difference, which is considerable at low humidities, decreases as the humidity increases and disappears at saturation. That is, the depression of the reading of the wet-bulb thermometer is zero in both instruments in saturated air, and hence they will agree as to its humidity.

Suppose, for example, that a pentane lamp is measured in air that contains 8 liters of water vapor per cubic meter at 18° C, and again in air containing 20 liters of water vapor at the same temperature. Suppose its candlepower be found to be 10 international candles in the first case, and 9.32 candles in the second. The change of 0.68 candles is due to a change of 12 liters of water vapor per cubic meter, and since the change in candlepower is simply proportional to the humidity it is seen that the coefficient is 0.68 divided by 12, or 0.057. If, however, an unventilated hygrometer had been employed and an incorrect formula used, so that the first humidity came out 10 instead of 8, the second humidity would have been correctly shown to be full saturation, which the tables show to be 20 liters per cubic meter at 18° C, then the coefficient found would have been 0.68 divided by 10, or 0.068. This shows that there must be an error in the coefficient found if measurements at different humidities are made at the same temperature. If the higher humidities are at higher temperatures, as they generally are, the error will be less, and it is possible to choose temperatures and humidities so as to get the same error in the water vapor each time, and thus get a correct humidity coefficient.

In the weights and measures division of the Bureau of Standards, Mr. Pienkowsky has observed readings of an unventilated wet-and-dry bulb hygrometer and an Assmann ventilated hygrometer (both instruments in the same room) for several years past, calculating the humidities from both sets of observations. The expression for the difference between the pressure e_1 of saturated aqueous vapor at the temperature t_1 of the wet bulb and the actual vapor pressure e in the atmosphere is

$$e_1 - e = Ab\ (t - t_1),$$

where $t - t_1$ is the depression of the temperature of the wet bulb thermometer, b is the barometric pressure and A is a constant depending on the instrument and on the velocity of motion of the air over the wet bulb.

In Jelinek's tables for a mean barometric pressure of 755 mm the value of the product of Ab is taken as follows:

1. For still air	0. 906
2. For slightly moving air	0. 604
3. For rapidly moving air	0. 495

The coefficient given for the Assmann hygrometer is 0.500. Mr. Pienkowsky has computed the humidity from the unventilated instrument, using the constant 0.906, and from the Assmann using 0.495, and the results have agreed as nearly as could be expected. When, however, the same formula is used for both instruments, the unventilated instrument, which gives smaller depressions of the wet bulb by from 0°.5 to 3° in actual practice, gives humidity values which are too high by from 1 to 4 liters of water vapor per cubic meter of air, the difference depending both on the absolute humidity and the temperature, being less as the humidity is greater, and less as the temperature is lower. It is, however, not the same at the same relative humidity, when both temperature and humidity vary. In order to ascertain what the average difference is between the two methods of obtaining humidity, some of Mr. Pienkowsky's observations have been used to compute the unventilated hygrometer readings by the formula for the other instrument, the differences being plotted against the actual humidities. The mean result is that 10 liters of water vapor per cubic meter of dry air by the unventilated instrument corresponds to 6 liters by the Assmann, under the conditions of temperature under which the observations were taken, namely, a temperature of about 20° C. If the laboratory temperature had been 15° C, the difference would have been about two liters. This conclusion has been checked by theoretical calculations from the formula using the coefficient 0.906 for the unventilated instrument, and 0.495 for the Assmann.

We have not learned what formulas were used by Mr. Paterson in determining his humidity coefficient and in recalculating the value on the basis of the ventilated hygrometer, but the data which he has kindly communicated to us seem to indicate that in his measurements the average relation between humidity and temperature was such as to make the error in the determination of the humidity practically constant and in the neighborhood of 2 liters.

Since the original publication of the Bureau's results, as given above, the work of Messrs. Butterfield, Haldane and Trotter has appeared, and correspondence with the National Physical Laboratory has failed to disclose any reason for the difference between our value and theirs. Consequently, our original data has been thoroughly examined for possible errors, and the results have been recalculated. In part of the original observations barometric pressures were taken from a barograph, checked at intervals. It was found that some small errors were introduced by this instrument, and in the recalculation correct pressure data furnished by W. C. Bishop have been used. The effect of these corrections, however, has been to leave the mean result absolutely unchanged, while the three lamps which were measured over the larger range of humidity are brought still closer to this mean. The coefficients derived for these three lamps become 0.568, 0.565, and 0.564, respectively. In terms of candlepower measurements, this agreement of results means that the curves derived give the same relative values for the three lamps at the lowest humidity as at the highest within less than one-tenth per cent.

Further determinations including some 2300 measurements on 27 different lamps in 1911 and 1912 have given identically the same result as the data of Table 4, and so far as accidental errors are concerned the value of the coefficient seems to be settled for the conditions under which measurements are made at the Bureau.

A possible explanation of the large differences between results obtained in different laboratories may be found in a direct effect of temperature on the candlepower. Changes of temperature and of humidity are closely related; the so-called humidity correction might really represent the combined effects of moisture and temperature changes. The relative variation of the two elements is probably not the same in different laboratories; for example, measurements made at the Bureau include a larger range of humidity than do those made at the National Physical Laboratory, while the range of indoor temperatures is probably about the same in the two laboratories, the average temperature at the Bureau being higher. We have not, however, been able to obtain any definite indication that changes of temperature within the usual laboratory range affect the candlepower of either the Hefner or the pentane lamp, and both Paterson and Butterfield, Haldane and Trotter have concluded that they do not affect the pentane lamp. It therefore appears unlikely that temperature effects will afford a solution of the difficulty.

It is perhaps worth noting that in case of insufficient ventilation there is a connection also between the humidity and the vitiation of the air, since the processes which exhaust the oxygen of the air usually produce considerable quantities of water vapor. If the arrangements are such that the thoroughness of the ventilation varies, there will be some tendency for the coincidence of high humidities with poor ventilation, for whenever the ventilation becomes insufficient the water vapor produced by the lamps and observers will increase the humidity. In a room where the flow of air depends on difference of temperature between indoor and outdoor air, still more serious effects might be produced by a systematic difference in the flow, which would probably be less in summer, and, if so, would tend to give fictitiously large values for the humidity effect. The room in which the present work has been done is supplied with air by a system of forced ventilation, assuring a flow independent of weather conditions. It was considered desirable to remove immediately from the room the air which rises about the lamp, carrying with it products of combustion, and this was accomplished by placing a hood above the lamp with a pipe leading to a ventilating outlet. That the ventilation was sufficiently good is shown by the fact that lamps burned continuously for several hours showed no decrease in intensity, and that a complete change of the air (obtained by placing a fan in an open window and blowing outdoor air through the room) caused no perceptible increase of candlepower. In the work of Butterfield, Haldane and Trotter, however, where the ventilation was insufficient, measurements of the carbon dioxide were regularly made as a test for the condition of the air, and corrections for vitiation were made; their value for the humidity coefficient is larger than that obtained either at the Bureau of Standards or at the Reichsanstalt, where such correction was unnecessary.

5. COMPLETE EQUATIONS FOR HEFNER AND PENTANE LAMPS

In reducing to normal conditions the data discussed in the following pages, the coefficients given by Liebenthal have been used for the Hefner lamps, while for the pentane the officially adopted formula has been modified by the substitution of our own value (0.0057) for the water-vapor coefficient. The equation for the Hefner lamp is then

$$I = I_n [1 + 0.0055 \, (8.8 - h) - 0.00011 \, (760 - b)]$$

and that for the pentane lamp is

$$I = I_n [1 + 0.0057 \, (8.0 - h) - 0.0008 \, (760 - b)]$$

where I is the observed candlepower of the lamp under the given atmospheric conditions; I_n is the normal value of the lamp, that is, its candlepower at an atmospheric humidity of 8.8, or of 8, liters of water vapor per cubic meter of air, and a barometric pressure of 760 mm of mercury; h is the number of liters of water vapor per cubic meter of air, as found by the Assmann psychrometer; and b is the barometric pressure in millimeters of mercury.[10]

I_n is not assumed for either Hefner or pentane lamps, but is the quantity to be determined by each measurement. Putting A and B for the two correction terms,

$$I = I_n \, (I + A - B),$$

or

$$I_n = \frac{I}{I + A - B}$$

In accordance with this equation a value for I_n is calculated from each observed value for I, and in judging the performance of a lamp it is important to find how closely these different values for I_n for a given lamp agree with other, whether the average values of I_n found for different lamps of the same type are the same, and whether the value found for lamps of a given type is the nominal one, namely, 10 candles for the pentane lamp and nine-tenths of a candle for the Hefner.

[10] The coefficients 0.00011 and 0.0008 apply only to pressures near the normal; for higher pressures the variation is less and for lower pressures greater. When the investigations now in progress at the Bureau are completed we shall probably change the coefficient for the pentane lamp to 0.0006 at normal pressure.

III. OBSERVATIONS ON THE SEVERAL TYPES OF LAMPS

1. WORKING STANDARDS USED

The measurement of the flame standards in terms of the fundamental electric standards of the Bureau, which are 16 candlepower carbon lamps burned at 4 watts per candle, involves a comparison between lights of marked difference in color, except in the case of the Carcel. For both pentane and Hefner lamps this difficulty is very serious, the case of the Hefner being worst of all, not only because it is reddest but also because it requires a larger step down in intensity, which of itself is difficult to make with accuracy. For this investigation sets of electric working standards were calibrated at voltages below the normal, chosen to make the lamps match the flames in color. The heterochromatic measurements were thus confined to the calibration of these standards, and in the measurements of the flames variations due to color difference were avoided. Any uncertainty in the calibration of the electric working standards is, of course, carried over into all the values obtained for the flames. The questions of heterochromatic photometry involved need not be discussed here, but it is not probable that the results obtained by other groups of observers would differ by more than one-half per cent from that used in the case of the standards calibrated to match the pentane flame. For those which match the Hefner flame the uncertainty is greater, and differences of 1 per cent might occur between independent calibrations.

2. THE CARCEL LAMP

In the discussion of correction coefficients no mention has been made of the Carcel lamp, because its performance is so erratic that no one has been able to determine any of its coefficients. Very few measurements on the lamp have been made at the Bureau, but those made have confirmed the conclusions reached by other observers in that the lamp never does reach a steady state, the intensity in different directions and with different chimneys varies considerably, shifting the chimney up or down a small distance often changes the candlepower by several per per cent, and the departure of any one measurement from the mean value of the lamp is likely to exceed 2 per cent when the utmost care is taken to reproduce the conditions of burning. While the mean candlepower obtained happened to fall very near the normal value (9.62 international candles), no confidence could be felt in any value so determined, and it appeared useless to spend more time on the lamp.

3. THE HEFNER LAMP

The Hefner lamp has had a long and honorable career. Although it has some serious defects and requires much patience and skill and many observations to obtain accurate results, it nevertheless has some important merits. If it had not, it would not now be contesting for first place among primary flame standards, after the world has had more than a quarter of a century in which to replace it by a better one.

Its principal merits as a primary standard are its simplicity of construction and operation, ease of manipulation, portability, durability, and the excellent agreement of one lamp with another. Its defects are its small intensity, unstable flame, reddish color, and the difficulty of setting the flame at exactly the right height. For either a primary or a secondary standard these, it must be admitted, are serious objections.

The Reichsanstalt certifies Hefner lamps as correct if within 2 per cent of their standard. At the Bureau of Standards we have eight Hefner lamps—four made by one company and four by another—and all fall within this limit. Indeed, the maximum departure of any lamp from the mean of all is scarcely more than 1 per cent. However, a primary photometric standard is not entirely satisfactory so long as appreciable differences exist among a lot of lamps made to the same specifications. Accidental errors will, of course, occur in the measurements, but of these eight Hefner lamps, certain ones are regularly high and others regularly low, showing that the lamps are not as nearly identical in construction as they should be. This result is due to two things. In the first place, the specifications are not as precise as they should be, and in the second place there are in some lamps slight departures from the specifications. That the intensity of the flame may always be the same—under the same atmospheric conditions—it is necessary (1) that the fuel be uniform, (2) that the wick tube shall always be of the same material and dimensions, and (3) that the height of flame be constant. In comparing lamps, the same fuel and the same kind of wick are used in the different lamps, and comparisons are made with the same apparatus and practically in the same atmosphere, as they are used in succession by the method of substitution. Hence the differences observed are due (1) to differences in flame height or (2) to differences in the effect of the wick tubes on the size or temperature of the flame.

There are two styles of sight used on Hefner lamps. The earlier form has a horizontal plate, 0.2 mm thick in the center of the sight tube, and the height of the flame is adjusted until sighting along this plate one sees the tip of the flame in the correct position with respect to the plate. In the other form, due to Krüss, the flame is projected by a lens upon a ground-glass screen, and the tip of the flame is made to fall on a line across the center of this screen. This is the more convenient and preferable form. The eye is fatigued by the naked flame viewed through the first form of sight, and the adjustment can not be made as accurately to the plate as to the line on the screen in the second form. A slightly higher average candlepower is obtained for the lamps having the Krüss sight than for those having the Hefner sight. The authors recommend the use of the Krüss sight only, and for these three separate reasons: (1) It is less fatiguing to the eye, (2) it permits more consistent settings, (3) it makes possible a higher degree of reproducibility by avoiding whatever difference there may be due to using two forms of sight. When it is remembered that 1 mm change in flame height represents 2 per cent change in flame intensity, and hence the allowable error is only a few tenths of a millimeter in the position of the nearly nonluminous tip of the flame, it is seen that this adjustment is one which requires great care and experience, and an optical device for a sight that is accurately reproducible. Unfortunately, this setting at best is not wholly free from personal equation.

The flame gauge is satisfactory and permits a very close reproducibility in setting the wick tube with respect to the sight. The gauges could, however, be made somewhat more accurately than they are, since several of those examined were in error by two tenths per cent.

The wick tube affects the flame in several ways. The bore should be 8 millimeters exactly, and this determines to some extent the size of the flame. This dimension is very accurately met in all the lamps. The thickness of the tube is specified to be from 0.14 to 0.17 mm. The tube conducts heat down to the liquid amyl acetate which saturates the wick, the top of which is from 1 to 3 mm below the top of the tube, but it also conducts heat on down to the body of the lamp and dissipates more from its surface. The thicker the tube the more readily is the heat conducted, and hence with the thicker tube the top of the wick must be higher in the tube to give the correct flame height. Also, the thicker-walled tube cools the flame more, and therefore reduces its candlepower. Hence, the wick tube should be very accurately specified to insure reproducibility. A departure of one or two hundredths of a millimeter from the mean in the thickness of the wall of the wick tube might seem negligible, but its effect is not negligible. To insure strict reproducibility, the weight of the tube should be specified in addition to its bore and its length; the composition of the German silver of which the tube is made ought also to be specified, to insure uniform results. There is reason to believe that if the specifications were drawn closer and the construction were as exact as it might be, a considerable improvement in the reproducibility would result.

The fuel, amyl acetate ($C_7H_{14}O_2$), is readily obtained pure enough to satisfy the specifications. We have, however, received from a reputable chemical firm amyl-acetate which was guaranteed by them to be pure, which did not conform to the specifications, and which gave a flame of slightly different intensity from amyl-acetate fulfilling the specifications. Hence, the only safe way in precise work is to test the fuel before using it, or purchase only amyl acetate that has been tested with reference to its use in the Hefner lamp.

The flame height specified in the Hefner lamp is 40 mm, at which height it gives nine-tenths of an international candle. An extended study has been made of the amyl-acetate lamps when burning at a flame height of 45 mm, at which height they give one international candle; at least those with Krüss sights give, on an average, one international candle. Taking the mean of all, the height should be about 45.25 mm. It is believed, however, that when the wick tube is more accurately specified, and the Krüss sights alone are employed, a flame height of 45.0 mm will give very accurately one international candle.

There is no appreciable temperature-light coefficient to the Hefner lamp between the limits of temperature that are commonly employed. It is, however, steadier at from 15° to 20° C than at higher temperatures. Hence, for work of highest precision a comparatively narrow range of temperature might well be specified.

In Table 5 is given a summary of results obtained on eight Hefner lamps, two of which, however, are new lamps and have been compared only a few times. Of the remaining six, three have the Hefner sights and three the Krüss sights. In the first part of the table the results are given for a flame height of 40 mm and in the second for 45 mm. In the second column is given the number of measurements made on each lamp, a "measurement" being the value found on a given occasion as the mean of 20 or more separate settings on the photometer and two to five new adjustments of the flame. More than half of the measurements were made by Mr. Crittenden and Mr. Taylor, while the others were made by various persons of less experience with flame standards. For comparison, the results obtained by the more experienced observers are given separately.

TABLE 5

Summary of Measurements on Eight Hefner Lamps

Lamp	Weight of wick tube in grams	Flame 40 mm high				Flame 45 mm high				Percentage of mean deviation from mean cp	
		All measurements		E. C. C. & A. H. T.		All measurements		E. C. C. & A. H. T.			
		No. of meas.	Mean cp int. candles	No. of meas.	Mean cp int. candles	No. of meas.	Mean cp int. candles	No. of meas.	Mean cp int. candles	40 mm	45 mm
Hefner sights:											
804 K	1.246	21	0.889_7	15	0.890_7	17	0.990_7	11	0.992_5	0.74	0.66
879 S-H	1.145	19	0.897_3	13	0.898_5	17	0.991_0	11	0.993_7	0.50	0.65
1342 S-H	1.144	19	0.896_1	13	0.897_3	17	0.991_2	11	0.988_7	0.67	0.92
Mean	....	......	0.894_4	......	0.895_5	......	0.991_0	......	0.991_6	0.64	0.74
Krüss sights:											
786 K	1.311	26	0.901_1	19	0.901_1	23	0.997_5	17	0.998_4	0.50	0.65
887 S-H	1.153	32	0.907_5	20	0.906_8	25	1.001_9	18	1.001_3	0.44	0.47
1343 S-H	1.121	33	0.903_2	21	0.901_8	24	1.000_1	17	0.999_7	0.54	0.70
Mean	....	......	0.903_3	......	0.903_2	......	0.999_8	......	0.999_8	0.49	0.61
Mean of all	....	......	0.899_2	......	0.899_4	......	0.995_4	......	0.995_7	0.56	0.68
New lamps:											
1714 K	1.177	5	0.890_8	4	0.887_1	......	....	......	....	....	....
1715 K	1.184	5	0.896_8	4	0.895_1	......	....	......	....	....	....

The numbers given above for the several lamps are the numbers placed upon them at the Physikalisch-Technische Reichsanstalt, where all were tested and certified. The letters following the numbers indicate the maker.

The mean value of the first three lamps at 40 mm flame height (to three decimal places) is 0.896, and of the second three 0.903, the mean of the six being 0.899 international candles. This is very near indeed to the value 0.900 international candles, assigned to the Hefner lamp in the international agreement of 1909; in fact, it is nearer than one can expect to repeat the determination, because of the difficulties of color and intensity mentioned above.

The mean value of the first three lamps at 45 mm flame height is 0.992, and of the second group of three is 1.000, the mean of all being 0.996 international candles. This is very near, indeed, to one international candle. As the different lamps vary in candle-power on account of slight differences in their dimensions, the agreement between lamps can be improved, and when the closer specifications are drawn they should be so fixed as to make the candlepower at 45 mm as near as possible to one international candle.

The average difference of the separate measurements from the mean of all, for each lamp, is given in the last columns of the table, for the measurements of the more experienced observers only. They average 0.64 and 0.49 per cent, respectively, for the two groups of lamps at 40 mm, or 0.56 per cent for all. At 45 mm the average is 0.74 and 0.61 per cent, respectively. That is to say, a single "measurement" is in error on the average a little more than one-half per cent. In the case of lamp No. 1,343 at 40 mm, the 21 measurements were divided into three groups of seven each. Calling the mean of each group of seven measurements a determination, we find—

	International candles.	Difference from mean.
First determination	0.8997	0.0021
Second determination	0.9017	0.0001
Third determination	0.9049	0.0031
Mean	0.9018	
Average		0.0018

Thus, each determination differs from the mean of the three by two parts in a thousand. If the lamp should continue to do as well, and other lamps could be made to agree with it accurately, this would be a very good performance for a primary standard. No reason is known why the lamp should not continue to do as well, nor why different lamps may not be made to agree much better than heretofore. Since the chief differences in the lamps are believed to be due to the wick tubes, it is mainly a matter of careful construction and painstaking inspection, wherein all tubes not conforming to strict specifications are rejected. Then if each lamp has three or more tubes, all of which are used in succession, and the mean of the results taken, the accidental unavoidable errors in the tubes will be largely eliminated. If the Hefner lamp were to be adopted as a primary photometric standard, it would be advisable to specify further that the mean value of at least three lamps, each supplied with three tubes (at least 10 determinations being made with each tube), be taken as the value of the unit.

In the above table, the lamp in each group that has the lowest candlepower has the thickest (and heaviest) wick tube. Both are from the same maker and both have the flame gauge 0.2 per cent too short. The high values of No. 887 are also due in part to an incorrect gauge, in this case 0.2 per cent too high.

The results shown above are better than have been obtained heretofore at the Bureau and illustrate what can be done by experienced observers working under the most favorable conditions, As a working standard under ordinary conditions, much greater errors would, of course, be found.

4. THE PENTANE LAMP

The Harcourt pentane lamp presents a striking contrast to the Hefner. It is bulky, relatively complicated in construction, less portable, and less convenient in manipulation, more expensive in first cost and in fuel, and requires much better ventilation and a larger photometer room. On the other hand, its higher candlepower, steadier flame, and better color are very great advantages. As to reproducibility, it is easier to reproduce results with a given pentane lamp than with a Hefner lamp when both are operated under correct conditions, but there is a greater difference among different pentane lamps than among different Hefners.

No wick is used in the pentane lamp. The fuel (pentane, C_5H_{12}) is contained in an elevated reservoir or saturator. Air enters the inlet and mixes with the vapor of pentane as it passes over the liquid pentane through the maze into which the saturator is divided by vertical vanes, and this mixture flows down the supply pipe to the burner. In hot weather the pentane may evaporate so rapidly as to flow out through the inlet, and thus prevent the air from entering. In this case, only pentane vapor is fed to the flame. Air, heated by passing through the annular space between the inner and outer chimney, flows down through the hollow standard and into the central chamber below the burner. Thus the flame resulting from the combustion of the vapor of pentane as it issues from the ring of 30 holes in the steatite burner is fed with preheated air within the flame. while it takes atmospheric air directly through its outer surface. The length of flame used is determined by the distance between the burner and the chimney, which is adjusted to be 47 mm when cold, and the height of flame is controlled by the rate of supply of the fuel. The latter is regulated by a stopcock. The tip of the flame is viewed through a mica window in the lower end of the inner chimney, and must be watched and frequently regulated in work of the highest precision. When the flame is at the correct height its candlepower is a maximum. As in the case of the Hefner, the intensity of the flame depends upon the dimensions of the lamp, the composition of the fuel, the atmosphere in which it is burned, and the manipulation of the lamp, especially as regards regulating the flame height and screening the flame.

The specifications of the standard pentane lamp were carefully drawn, and have been closely followed by the several makers of the lamps, with, however, some variations in the American lamps. But that the specifications are not sufficiently exact and complete is shown by the fact that different lamps differ in candlepower appreciably. That is, different pentane lamps burning the same fuel, in the same atmosphere and operated by the same people, differ by as much as 2 or 3 per cent, quite independently of the errors of observation. It is not possible, therefore, to take the light of a pentane lamp as 10 international candles under the stated standard conditions. It may in any particular case be only 9.6 or 9.8 candles at standard humidity and barometric pressure, even when the fuel and all external conditions are right.

The total intensity of the light of the flame depends, of course, on its dimensions, and this is affected by the size of the burner. The specifications say that there shall be 30 holes (from 1.25 to 1.5 mm in diameter) drilled in a circle in the steatite burner, the outside and inside diameter of which are 24 mm and 14 mm, respectively. But the precise diameter of the ring of holes is not specified, and this is found to vary in different burners.

Of the three English lamps for which values are given in this paper all fulfill the specifications regarding burners, and all have the individual holes about the same size (1.35 mm in diameter), but in the one which gave the low candlepower the diameter of the circle of holes was 2 per cent smaller than in the others. This was thought to be a possible explanation of the low value, but it has since been found that the effect on the candlepower does not exceed 0.5 per cent. A series of interchangeable burners, in which the variations were made even greater than the specifications permit, have been tested. In these the outer diameter of the circle of holes varies by 4 per cent, and the different burners have holes ranging from 1.1 mm to 1.5 mm in diameter; the combined effect of variation in holes and in size of circle is only about 1 per cent in candlepower. The reason that this effect is so small is probably to be found in the fact that the pressure on the vapor is very small, and the flow from the holes is so gentle that the vapor spreads so as to cover the whole top of the burner. Consequently, the size of the flame is determined more by the size and shape of the top of the burner than by the dimensions and location of the holes in it. Still, a closer specification of the latter would remove a source of small differences between lamps.

It is well known that a pentane lamp increases in candlepower for a time after lighting up, and that one should wait from 15 to 30 minutes before taking measurements. In Fig. 5 are given four curves taken during the heating-up period of the lamp, showing that the light increases to a maximum and then decreases to its steady value. This maximum is from 1.5 to 3 per cent above the final value, which is reached in from 15 to 30 minutes. The first two curves are for English lamps, which reach a steady condition in half the time required by the early American lamps whose performance is shown in the lower curves. These American lamps were of the type first made in this country, which had lower candlepowers than most English lamps, and the study of these heating curves led to the discovery of one cause of the low candlepower. The form of the curves indicates the presence of two opposing influences, one tending to make the candlepower high and the other, which becomes effective a little later, tending to lower the candlepower. In the American lamp this second effect is greater than in the English form. These two opposing influences are simply the temperatures of the two columns which constitute the circulatory air system of the lamp. The chimney becomes hot first and a vigorous circulation is set up, making a strong draft up through the burner and thus broadening the flame. As the lamp standard, through which the air flows down, becomes warmer, the temperature difference of the two columns

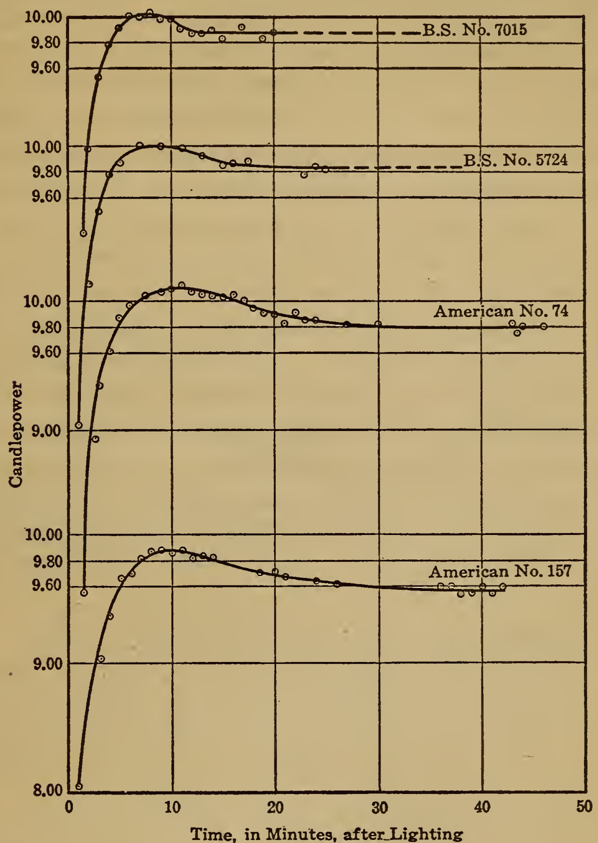

Fig. 5.—*Variation of candlepower of pentane lamps after lighting.*

is less; the circulation is less vigorous, and the flame becomes slightly narrower.

Beneath the saturator is a flat radiating plate, which in the English lamps is brazed to the standard and serves to conduct heat away, thus keeping down the temperature of the down-flowing air. In the early American lamps this plate was considered primarily as a support for the saturator, and it was connected to the standard only by two bands. It therefore failed to function properly as a radiator of heat; the standard became too warm, so that the air flow was decreased and the candlepower lowered. Experimental tests showed that the substitution of a brazed plate for the loose one increased the candlepower by about 1 per cent, while freeing the plate from the standard, even without removing it entirely from the lamp, caused a reduction of the candlepower. In one case, the same American lamp gave 9.63 candles when the plate was not in contact with the standard and 9.75 in the regular condition. This suggests the possibility of an appreciable variation being introduced by accidental change of the contact between the plate and the standard. For this reason, as well as to bring the lamps nearer 10 candles, the brazed plate should be used.

Another detail of construction which makes a measurable difference in the same way is the connection between the bottom of the chimney and the standard. This should be of nonconducting material, but in the first American lamps it was made of metal, which conducted heat across to the standard and thereby reduced the candlepower. When these two faults of construction are remedied, as they have been in more recent lamps, the American form will reach a steady state in about 20 minutes after lighting. The newer lamps also give higher candlepowers than those shown in this paper.

By interchanging parts so far as possible, evidence has been obtained that the discrepancy between the English lamps studied is largely due to some difference in the air system, but, unfortunately for this work, the lamps are not intended to be taken apart and the parts are not interchangeable in general. Consequently the exact cause of the difference has not been found.

The candlepower of a pentane lamp can be appreciably increased by any method of cooling the standard. Even the introduction of a screen to cut off the radiation of heat from the flame to the standard makes a perceptible difference, and drafts of air blowing over the lamp probably produce more effect through the disturbance of temperature conditions than by disturbing the flame directly. Precautions should therefore be taken to obtain a gentle and regular flow of air past the lamp when it is in use.

There is one feature which tends to make the American lamp higher in candlepower than the English form. This is the method of supporting the inner chimney. The chimney is set, when cold, 47 mm above the burner, but the expansion on heating reduces the height. Since the chimney is supported near the bottom in the American lamp and at the top in the English, the reduction in height is less in the former type. The actual height when the lamps are burning has been found to be 46.7 mm in one American lamp and 45.9, 45.8, and 45.7 mm, respectively, in three English lamps. Incidentally these variations suggest that if the lamp is to be a primary standard some better method of fixing the height is necessary.

Although many lamps of English and of American manufacture have been tested, none of them except a few very recent American lamps have shown a candlepower as high as that of the standard pentane lamp of the National Physical Laboratory. The maker of that lamp, from whom the bureau purchased two lamps, was unable to duplicate it exactly as to candlepower.

One of the difficult features of the use of pentane lamps is the fuel. In addition to the inconvenience of pentane being very volatile and explosive, its composition is variable, and as sometimes supplied does not conform to specifications. It is distilled from gasoline, its composition being made nearly uniform by repeated distillation. Besides the great difficulty in separating all the butanes (C_4H_{10}) and all the hexanes (C_6H_{14}), pentane itself (C_5H_{12}) exists in three separate forms, which have different boiling points. Two of these come within the range of temperature used in the final distillation, and in addition the distillation carries over more or less of the substances which have higher boiling points. Hence if pentane which complies strictly with the specifications be distilled it may be separated into three portions of appreciably different boiling points. This fractionation goes on in the saturator, and the photogenic value of the pentane changes to an appreciable extent in a few hours. The official specifications of the London Gas Referees direct that the residual pentane be emptied out of the saturator at least once in each calendar month. For work of the highest precision the authors find that it is desirable to do this every time the lamp is refilled, and that this refilling be done frequently, not waiting until the pentane is nearly exhausted. This requires the rejection of a considerable fraction of the pentane. For less precise work, such as ordinary testing, it is allowable to use a larger portion of the pentane, but even then it is better to make correction when the heavier fractions are used. This correction is discussed in the paper on the use of the pentane lamp to which reference has been made.

In Table 6 are given the results of candlepower measurements made upon three English and four American pentane lamps. In the second column is given the number of measurements made on each lamp from which the mean value has been computed. As with the Hefner lamp previously discussed, a "measurement" is the mean of a large number (30 or more) of individual settings on the photometer, the flame being inspected (and adjusted, if necessary) several times during the set. A group of 30 settings (constituting one measurement) on the pentane lamp is made in about 5 minutes, whereas a group of 20 settings on a Hefner lamp requires on an average about 15 minutes. The difference is due to the much greater unsteadiness of the Hefner flame, which often requires waiting for the flame to be steady and at the right height; whereas, with the pentane, settings are made in rapid succession. The method employed of automatically recording the photometer settings makes rapid settings practicable in the most precise work. The average deviation of a single measurement from the mean of all is given for each lamp in the fourth column, and amounts to a little less than 0.4 per cent on the average.

TABLE 6

Measurements of Pentane Lamps, Apr. 8 to Sept. 9, 1910

Lamp	Number of measurements	Mean candlepower international candles	Mean deviation from mean candlepower
Chance, No. 116	220	9.875	0.03_9
Chance, No. 118	81	9.89	0.02_8
Sugg, No. 171	165	9.62	0.03_8
American, No. 25	42	9.61	0.04_5
American, No. 74	43	9.73	0.03_8
American, No. 157	46	9.58	0.04_1
American, No. 162	31	9.80	0.02_6

In Table 7 are given the separate measurements in sets of 10, each group constituting a "determination" of candlepower, for four pentane lamps. This shows the order of magnitude of the deviations of each measurement from the mean of a group. These variations are due to a considerable number of factors, such as variation in the atmosphere, in the fuel, in the effects of drafts and of flame adjustment, as well as errors of the photometric measurements.

TABLE 7

Separate Measurements of Candlepower for Two Pentane Lamps

AMERICAN LAMP, NO. 25

9.64	9.67	9.61	9.56
9.59	9.67	9.61	9.62
9.63	9.75	9.62	9.58
9.65	9.70	9.64	9.64
9.53	9.65	9.63	9.64
9.53	9.64	9.56	9.62
9.53	9.63	9.57	9.64
9.46	9.62	9.60	9.56
9.46	9.60	9.65	9.60
9.50	9.57	9.59	9.64
9.552	9.650	9.608	9.610
Mean of all=9.605			

AMERICAN LAMP, NO. 157

9.60	9.57	9.62	9.53
9.63	9.61	9.64	9.65
9.64	9.61	9.47	9.61
9.61	9.55	9.48	9.60
9.61	9.59	9.51	9.57
9.58	9.58	9.51	9.64
9.60	9.58	9.52	9.62
9.61	9.59	9.51	9.58
9.61	9.62	9.54	9.62
9.57	9.64	9.53	9.54
9.606	9.594	9.533	9.596
Mean of all=9.582			

In Table 8 the results are given of different determinations on four American pentane lamps. In the columns headed △ are the differences from the mean, which average 2 parts in 1000 for all the determinations of candlepower on the four lamps. The error in the mean would, of course, be less than this if the lamps are as consistent with themselves as they appear to be.

TABLE 8

Determination of Candlepower for Four American Pentane Lamps

Determination	Lamp No. 25		Lamp No. 74		Lamp No. 157		Lamp No. 162	
	Int. candles	Δ	Int. candles	Δ	Int. candles	Δ	Int. candles	Δ
1....................	9.552	−0.053	9.675	−0.052	9.606	+0.024	9.796	−0.004
2....................	9.650	+0.045	9.754	+0.027	9.594	+0.012	9.807	+0.007
3....................	9.608	+0.003	9.734	+0.007	9.533	−0.049	9.797	−0.003
4....................	9.610	+0.005	9.744	+0.017	9.596	+0.014	....	....
Mean..........	9.605	0.026	9.727	0.026	9.582	0.025	9.800	0.005

In the above table Δ is the difference between a single determination and the mean of the several determinations given in the table. A "determination" is the mean of 10 "measurements."

In Table 9 are given similar results of a larger number of determinations on three English pentane lamps. The 22 determinations on the first Chance lamp represents 220 measurements, or probably about 10 000 separate photometric settings. The average value of the deviations of the separate determinations from the mean of all is 2 in 1000 for two lamps, and 1.3 for the third. If the determinations on each lamp be divided up into groups of four, the mean of each group differs from the mean of all by only one-tenth of 1 per cent. This is a gratifying degree of reproducibility. Of course, such results would be obtained only as the means of a considerable number of measurements, even if the flame standards were ideal in their performance, for the errors of the photometric measurements are considerable. That the errors belonging to the flame standards themselves could be so small when measured in all kinds of weather, with a wide range of humidity and temperature, and considerable range of barometric pressure, with many resettings of the lamps, and over a period of some months, we would not have thought possible when this work was begun.

But while the value of a given lamp can be determined with so little uncertainty, the differences between lamps are very considerable. The candlepower of the Sugg lamp is 2.6 per cent less than that of the Chance lamps, whereas two American lamps are slightly smaller in candlepower than the Sugg lamp. It is recognized in England that different pentane lamps differ in candlepower, so that the standard of the National Physical Laboratory is not that of any pentane lamp taken at random, nor the mean value of a group of lamps, but a particular pentane lamp. It remains to learn how to make different lamps agree as closely as a particular lamp will agree with itself, as was remarked above.

TABLE 9

Determination of Candlepower for Three English Pentane Lamps

Determination	Chance, No. 116		Chance, No. 118		Sugg No. 171	
	Int. candles	△	Int. candles	△	Int. candles	△
1	9.821	−0.054	9.880	−0.011	9.585	−0.031
2	9.827	−0.048	9.876	−0.015	9.587	−0.029
3	9.846	−0.029	9.933	+0.042	9.612	−0.004
4	9.875	0.0	9.889	−0.002	9.579	−0.037
5	9.910	+0.035	9.884	−0.007	9.590	−0.026
6	9.894	+0.019	9.882	−0.009	9.599	−0.017
7	9.880	+0.005	9.902	+0.011	9.644	+0.028
8	9.911	+0.036	9.884	−0.007	9.616	0.0
9	9.870	−0.005			9.620	+0.004
10	9.903	+0.028			9.646	+0.030
11	9.895	+0.020			9.614	−0.002
12	9.907	+0.032			9.668	+0.052
13	9.872	−0.003			9.618	+0.002
14	9.883	+0.008			9.630	+0.014
15	9.847	−0.028			9.610	−0.006
16	9.854	−0.021			9.633	+0.017
17	9.871	−0.004				
18	9.898	+0.023				
19	9.858	−0.017				
20	9.876	+0.001				
21	9.867	−0.008				
22	9.878	+0.003				
Mean	9.875	0.019	9.891	0.013	9.616	0.019

The determinations of the Chance, No. 116, and of the Sugg lamp recorded above were made between April 8 and September 9, 1910, during which period the amount of water vapor per cubic meter of air varied from 4 liters to 27 liters. The determinations of the Chance, No. 118, were made between July 18 and September 9, the range of water vapor being approximately from 14 to 27 liters per cubic meter of air.

5. CONCLUSION

While much remains to be done on the pentane lamp to make it a thoroughly satisfactory flame standard, the authors believe that a much closer agreement between different lamps, and a little higher degree of reproducibility in the same lamp, is possible. For use as a practical standard in photometric measurements, and for use as a primary standard for fixing the unit of light, the same lamp should not be employed, and the specifications should be appreciably different. One would not think of employing an ordinary meter bar for a primary standard of length, or of using an ordinary precision resistance box for the reference standards of a national standardizing institution. No more should one think of using a pentane lamp that is not too good for a gas works or for ordinary photometric practice as a primary standard for fixing and maintaining the unit of light. There should be as much difference here as in other physical standards. Vernon Harcourt has rendered a great service to photometry and to the industries in developing his various pentane lamps, and the authors can not refrain from expressing their admiration for the thoroughness with which he worked in the pioneer days of precise photometry. His lamp has stood the test of use, and after years of criticism it remains the most practical flame standard we have. Nevertheless, the results of this study indicate that, at least as made at present, the pentane lamp can not be considered as a reproducible primary standard, its value in this respect being decidedly less than that of the Hefner lamp. If the principles of the present lamp are to be applied to the development of a primary standard, further improvement is necessary, not only in the construction of the lamp, but in its use as well. Instead of using the ordinary style of lamp, at any temperature and any humidity, with the pentane that satisfies ordinary requirements, there should be a lamp (or several lamps) built to very exact specifications, operated within very narrow limits of temperature and humidity, with pentane satisfying much more rigorous requirements as to density and boiling point, and an atmosphere maintained constant as to oxygen content with great care. With such painstaking procedure the unit of light can be fixed with either the Hefner or the pentane lamp with very considerable precision, sufficient at least to serve as a valuable check on the admirable electric standards now in use. It is with a view of contributing something to the working out of such precise specifications that the work of investigation at the Bureau will be continued.

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