

DISCUSSION ON "METAL FILAMENT LAMPS", NEW YORK,
MAY 17, 1910.

Clayton H. Sharp: I would refer for a moment to the importance of the tungsten lamp in street lighting. At the present time it would seem that our older illuminants for street lighting are on the decline. The arc lamp, as we have it, is being superseded by the more powerful arc lamps which have more recently been produced. The series incandescent lamp with the carbon filament, a lamp which never was very satisfactory for its purpose, has been most certainly pushed aside by the tungsten lamp. Not only this, but the advent of the tungsten lamp with its high efficiency and long life and favorable color has enabled the electrical engineer to go into fields of street lighting which previously have been practically closed to him, and which

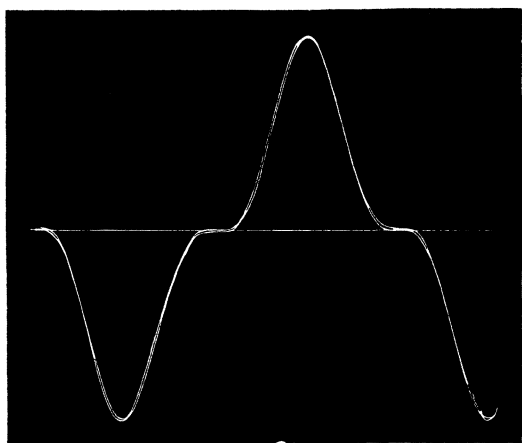


FIG. 1

have been the exclusive domain of other less convenient and less satisfactory illuminants. I wish to point out further that there remains now the next stage, which is to provide means for utilizing more efficiently and satisfactorily the flux of light which the tungsten lamp produces in order to extend its usefulness in the range of street lighting still further. Such plans have been under consideration, and I recently had the pleasure of presenting to the Illuminating Engineering Society the details of a form of reflector by which the light which under ordinary circumstances is wasted by being thrown to the heavens, or thrown to the sides of the streets where it is not wanted, is directed into the dark portions of the street, midway between lamps, where such additional illumination is most desired. Along these lines I think the next step in progress is to be made.

I wish to refer also to another feature of the tungsten lamp

which is intimately connected with the over-shooting of current at the moment the circuit is closed, due to the large positive temperature coefficient. Another thing results from this, which is perhaps of academic interest only and that is that the change in resistance of the filament during a cycle of alternating current necessarily lags somewhat behind the change in electromotive force, on account of the thermal capacity of the filament. Since the resistance of the filament lags behind the e.m.f., the current in it must lead the e.m.f. by a certain small amount and the lamp is not strictly non-inductive, but behaves as if it possessed a certain electrostatic capacity. In an attempt to demonstrate this effect, an e.m.f. having an extremely peaked wave was built up using the harmonic synthesis set of the Electrical Testing Laboratories. This wave form was selected

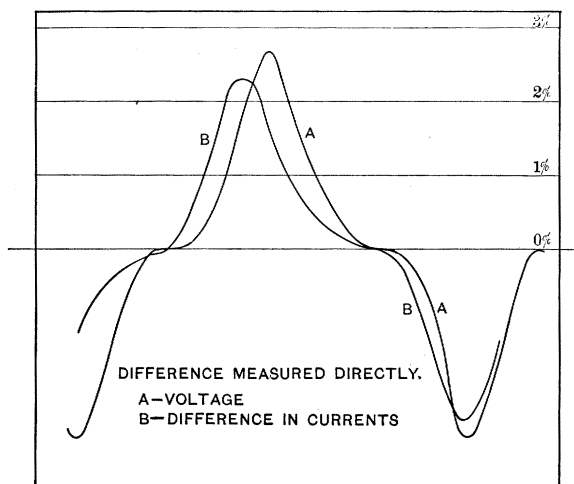


FIG. 2

so that the effect might be exaggerated as much as possible. Wavemeter curves were taken of the e.m.f. and of the current in a 25-watt 110-volt tungsten lamp with a frequency of 25 cycles per second. This frequency was chosen as being as likely as any to give a maximum effect. Too high a frequency would not permit the filament to cool enough during the zero portion of the wave, whereas, if the frequency were too low, the rate of change of e.m.f. on the lamp would be too slow to enable the effect to be seen. The curves of current and electromotive force are shown in Fig. 1, and the phase angle between them, though small, can be clearly appreciated. In order to make the difference more effective, the tungsten lamp and the carbon lamp were connected as the two arms of a Wheatstone bridge, while the wavemeter was used to determine the wave form of the electromotive force across the diagonal of the bridge. This gave a wave which is shown in Fig. 2.

The resistance variation of the tungsten lamp during the cycle was measured, and the minimum value of resistance was found to be about 10 per cent less than the maximum value. The power factor as roughly calculated was found to be 0.99975.

John B. Taylor: Dr. Sharp has just been enlarging on what he calls a feature of merely technical interest, and that is, a slight improvement in power factor due to the substitution of tungsten lamps for carbon lamps.

I think there is a much more practical point directly connected with this matter of positive temperature resistance coefficient, in the fact that the lamp cold takes a much larger current than when in normal service. Resistance curve, Fig. 3, of Mr. Howells paper, shows a cold resistance of 50 ohms, and a hot resistance of 650 ohms, or a little more than thirteen times greater. An oscillograph actually shows a peak value of current about eight times the normal. This difference is due partly to the fact that the lamp has risen slightly in temperature before maximum deflection of the oscillograph, but mainly to reactance and resistance in the circuit. In practice the initial current may be five to eight times the normal value. Usually this large rush of current is not important, but imagine the case of a general shut down on a large interconnected Edison system. Even with carbon lamps there is difficulty in getting under way again, for the reason that all the different substations cannot be connected at the same moment, and the ones that come in first get more load than they can carry. This difficulty with carbon lamps, will be more serious with tungsten lamps. In an isolated plant, if the main breaker opens and it is attempted to throw in the load again, at this one switch, instead of breaking up the system at feeder switches, the generator will be momentarily overloaded five to eight times, depending on line drop and other matters. This may not be a serious matter with some machines, but it cannot be dismissed without investigation. Fuses are not liable to blow on account of the short interval of time during which the current has the large value, but circuit breakers with less time lag may be tripped, and the excess load may cause mechanical troubles or flashing at the commutator. These points deserve consideration.

Another point I want to bring out is more academic. Mr. Howell says: "This excessive current is of sufficient duration to cause an instantaneous rise in candle-power, which is higher than the normal candle-power; this effect has been called "overshooting." I believe I am responsible for the term "overshooting" having used it two years ago when describing the effect in one of the technical periodicals* with photographic records demonstrating that it is a real "effect" and not a mental impression. The point I want to make is that the positive temperature resistance coefficient and excess current will not explain "overshooting" unless it can be shown that there is a time

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lag between temperature of a body and its electrical resistance. The temperature is going up very rapidly, perhaps 100,000 degrees cent. per second, but that is no reason why, merely because it is rising so fast, it should continue rising beyond the ultimate temperature determined when balance is reached between energy radiated and conducted away and energy supplied. The only thing I suggested, when I showed the photographic evidence of overshooting was that it might be some secondary action, possibly connected with gases absorbed by the filament, which before begin driven out might modify the resistance for a very brief time. I think the present tungsten lamps do not show the "overshooting" to the extent that the early ones did.

Farley Osgood: I think I may be pardoned if I bring up a point which is purely financial or commercial. The discussion so far has been confined entirely to the physical side of the lamp, and the various problems, theoretical and practical, pertaining to its improvement in efficiency, but there is another point which to my mind is equally important, especially to the users of the lamp, who are quite as much to be considered as the makers of the lamp. Of course, the manufacturers advocate the use of the highest efficiency lamps of the metalized filament type, but my experience is that it is still an open question as to whether or not the metalized filament lamp is an economical proposition for an operating company using a million lamps or more per year. The product of metalized filament lamps of the not most perfect type, namely, all lamps except tungsten, is still so uncertain that the economical average life of such lamps does not from a saving standpoint warrant their introduction on a free renewal basis by operating companies. Most of the operating companies in the country have free renewals of the older type of carbon lamps among all consumers of electric current, and although the total average of metal filament lamps show such a life as to be equal to the carbon lamp, our investigation seems to show that such a result is brought about by the unusually long life of some of the lamps put under test. A few lamps will give extraordinarily long life, and a large proportion of lamps will give not so long a life in the life test, so that although the advocates of the use of this lamp, namely, the manufacturers, are able to show that these conditions are equal between carbon lamps and metalized filament lamps, the operating men are unable to realize it from a financial standpoint. If a greater portion of the lamps show shorter life, and the equal average life is occasioned by the abnormal continuance in service of a few lamps, the expense, from an operating company's standpoint, will increase greatly rather than remain the same. I think it is an open question whether the metalized filament multiple lamp should be used on a free renewal basis, unless the operating companies decide that it is desirable to spend a considerable additional sum for incandescent lamps for the sake of the various benefits which accrue to the consumer by the use of the metalized filament lamp.

In the street lighting service, the condition is almost entirely changed. The tungsten filament lamp can be safely said to average a life of 1500 hours, so that its use is equal to, or better than, the carbon series filament lamp; the renewals are less frequent per year, and the financial results, particularly on account of the lower current consumption, are beneficial to the operating company using tungsten lamps for series street lighting purposes. But I do not think these facts should be lost sight of in the consideration of a more modern or metalized filament type of lamp, and I do not think it amiss to bring out at this time some of the uncomfortable features of the metalized filament lamp as many of the consulting engineers of this Institute have before them for decision such problems for the companies which they represent.

William L. Nodell: I wish to add to the information which Mr. Howell gives concerning tungsten automobile headlight lamps. These are now made in candle-powers ranging from 10 to 25 and operate satisfactorily at the excellent efficiency of 0.8 to 1.0 watts per c.p. They are recommended to be used at 6 volts (3 cells of storage battery) though lamps suitable for other voltages are furnished.

Mr. Howell's paper may give the impression that the normal commercial rating of tungsten lamps is still 1.25 watts per c.p. This is no longer the case, the efficiency being better in lamps of 60 watts and higher, as may be seen from the table given herewith, showing the watts per candle-power and life obtained since the 3 voltage method of rating tungsten lamps has been established:

TUNGSTEN REGULAR MULTIPLE LAMPS FOR 100-125 VOLTS

Designation total watts	At top voltage			At middle voltage			At bottom voltage			Horizontal c.p. multiplied by this re- duction factor = spheri- cal candle-power
	Watts per c.p.	Nominal mean horizontal candle-power	Hours useful and total life	Watts per c.p.	Nominal mean horizontal candle-power	Hours useful and total life	Watts per c.p.	Nominal mean horizontal candle-power	Hours useful and total life	
25-watt.....	1.33	18.8	1000	1.39	17.4	1300	1.45	16.1	1700	0.78
40-watt small bulb.....	1.25	32.0	1000	1.30	29.9	1300	1.35	28.0	1700	0.77
40-watt large bulb.....	1.25	32.0	1000	1.30	29.9	1300	1.35	28.0	1700	0.77
60-watt.....	1.20	50.0	1000	1.25	46.5	1300	1.30	43.5	1700	0.78
100-watt.....	1.15	87.0	800	1.20	80.8	1000	1.25	75.2	1300	0.78
150-watt.....	1.15	130.3	800	1.20	121.1	1000	1.25	112.8	1300	0.78
250-watt.....	1.10	227.3	800	1.15	210.0	1000	1.20	195.0	1300	0.77

Figures furnished by the N. E. L. A.

The philosophy of the three voltage plan is that formerly applied only to gem lamps. Since May 1, 1910 this method of rating is applied to all incandescent lamps, tungsten, tantalum, gem and carbon. A lamp is no longer identified by candle-power and watts-per-candle power but is designated by watts; the efficiency at which it is to burn being determined by the selection of top, middle or bottom voltage. Exceptions to this general rule are miniature lamps and the 4 watt per c.p., series-burning railway lamp, which will be known, as heretofore, by their candle-power.

Referring again to Mr. Howell's paper regarding spring supports to prevent sagging of tungsten filaments; though molybdenum supports are being used for this purpose by some manufacturers, the alleged benefit to be derived is not sustained by the general experience of the majority of manufacturers who have, after exhaustive tests with every known method of support, finally adopted the copper hook at the tip end of the lamp as giving the greatest satisfaction, particularly in the 25-watt, 40-watt and 60-watt sizes. In the larger sizes with heavier filaments the spring support is still less necessary and in the 250-watt lamp practically all manufacturers employ a rigid support. For a time a center anchor was used in one make of 25-watt lamp but this is not now recommended, as the advantages expected are not borne out by experience.

I wish to call attention to a paper on "Tests of Tungsten Lamps", by T. H. Amrine and A. Guell, giving the results of observations on three types of lamps, two of German manufacture, the third American. The results in comparison with the two foreign lamps are very much in favor of the home product.

John W. Howell: There is one characteristic of the tungsten and carbon lamps which I have omitted to mention in this paper, and that is their relative candle-powers per unit of surface. We are all familiar with the intense brightness of the tungsten lamp, as compared with the old carbon filament, and we know that it is necessary to shade the direct light of the filament from our eyes, either by shades or frosted bulbs. As a matter of figures, the tungsten filament at its normal efficiency is giving twice as much light per unit of surface as the carbon filament at its normal efficiency. If the two lamps are placed at the same efficiency, the conditions reverse; the carbon filament is then giving twice as much light per unit of surface as the tungsten filament. This is an indication of one of the reasons of the efficiency of the tungsten lamp, because when you see a carbon lamp giving twice as much light per unit of surface as the tungsten lamp, there is a strong physical indication that the temperature of the carbon lamp is much higher than the temperature of the tungsten lamp, and it is a fact, at the same efficiency, a carbon lamp is much hotter than a tungsten lamp. When you examine the same characteristic for a tantalum lamp

it is interesting, because the normal efficiency of a tantalum lamp is two watts per candle, and at that efficiency the light per unit of surface is the same as the carbon lamp, at 3.1. This marked difference between tantalum and tungsten indicates one reason for the poorer efficiency of the tantalum lamp.

G. S. Merrill, M. D. Cooper, H. D. Blake (by letter): It is well known that tungsten filaments, due to their positive temperature coefficient take more current at the instant of starting than after they become heated. The engineering department of the National Electric Lamp Association recently conducted a series of experiments to determine whether this initial current rush has the effect of decreasing the life of the lamps. Three lots of tungsten sign lamps, 6 lamps in each lot, were placed on test—the first lot was burned continuously, the second lot was flashed 3 times per minute and the third lot was flashed 30 times per minute. It was found that there was a slight decrease in

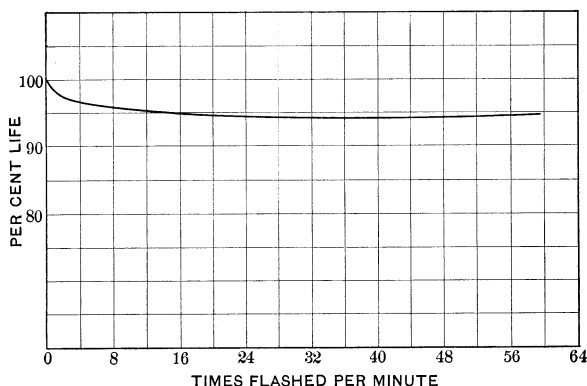


FIG. 1

life with the lamps that were flashed, but that this decrease was so slight as to be practically negligible. The curve of Fig. 1, plotted between frequency of flashing and the per cent of normal total life, shows a decrease of about 6 per cent in life up to 35 flashes per minute. For higher frequencies the life rises toward normal value. This test, due to the small number of lamps used, is not, of course, absolute proof that the initial current rush may not have a greater effect in decreasing the life, but it indicates that the effect is not as great as might be supposed.

That the above should be the effect becomes evident on consideration of the "cooling curves" given in Fig. 2. These curves show the per cent of cold resistance of tungsten lamps at various time intervals after the lamp has been turned off. If the lamp is allowed to cool completely before being again lighted, the initial current rush will be as severe as at the first lighting. If, however, it is turned on when the resistance is

still considerably above cold value, the current will not rise to as high an initial value. For instance, if a sign lamp is flashed six times per minute (5 seconds on, 5 seconds off), it will be re-lighted when the resistance is still $2\frac{1}{4}$ times the cold value, and as the hot resistance is about ten times the cold value, we would expect only about one-fourth as great a rush of current as when the lamp had fully cooled.

Flashing at very high frequencies would correspond to operation on alternating current, which would give the same life as when burned without interruptions.

Mr. Howell's mention of spring supports brings up the question of the adaptability of tungsten lamps to burning in a horizontal position. The complaint is sometimes made that tungsten lamps do not prove satisfactory when burned horizontally because the filaments sag.

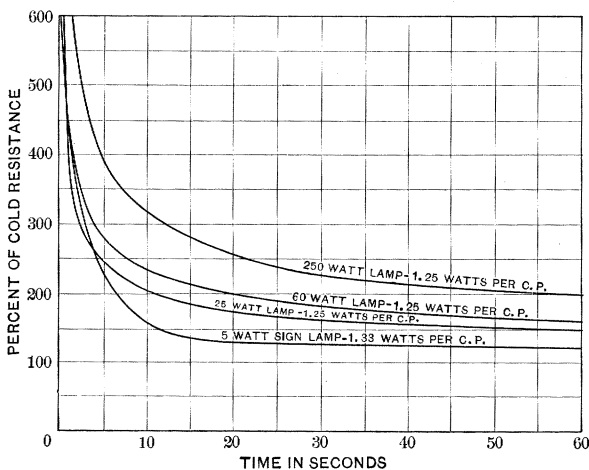


FIG. 2

The sagging filament in a horizontally burning lamp will conform closely to the catenary curve, for the filament is comparatively heavy and after continued heating will respond to the force of gravity nearly as well as a perfectly flexible string or chain.

The accompanying curves were derived on the assumption of this catenary curve. The equation of the catenary is:

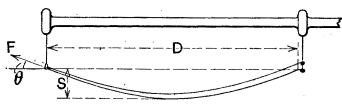


FIG. 3

$$y = \cosh x$$

and in this form the y intercept is 1. For a given distance, D , between supports, the sag will be

$$s = \cosh \frac{D}{2} - 1 \quad (1)$$

$$\text{or the per cent sag} = \frac{100}{D} S = \frac{100 \left(\cosh \frac{D}{2} - 1 \right)}{D} \quad (2)$$

Fig. 3 shows in an exaggerated manner, the way in which a filament will droop and as there shown, D is only the distance between the ends of the freely sagging portion of the filament. Due to the rigid weld at the base, the whole filament will not sag freely, hence D will not be the whole of the distance between supports.

The slope of the curve will be

$$\frac{dy}{dx} = \sinh x$$

The angle θ , which the filament makes with the horizontal through the end of the freely sagging portion will be given by the equation,

$$\tan \theta = \frac{dy}{dx} = \sinh \frac{D}{2}$$

If the weight of the filament is W , the supporting force F will be given by

$$F = \frac{W}{\sin \theta}$$

from which

$$\frac{F}{W} = \frac{1}{\sin \tan^{-1} \cosh \frac{D}{2}} \quad (3)$$

Using the parametric equations (2) and (3), curve A of Fig. 4 was plotted, showing the "stress ratio", F/W , for any given sag.

When a lamp hangs vertically, the maximum force is equal to the weight of the filament, hence the above ratio is the same as the ratio between the filament stress when the lamp burns horizontally and that when it burns vertically.

To investigate the effect of contraction on cooling, it is necessary to get some relation between length of filament and corresponding sag.

The total length L is given by the equation

$$\begin{aligned}
 L &= 2 \int_0^{\frac{D}{2}} \sqrt{1 + \frac{d y^2}{d x}} d x \\
 &= 2 \int_0^{\frac{D}{2}} \sqrt{1 + \sinh^2 x} d x \\
 L &= 2 \sinh \frac{D}{2}
 \end{aligned} \tag{4}$$

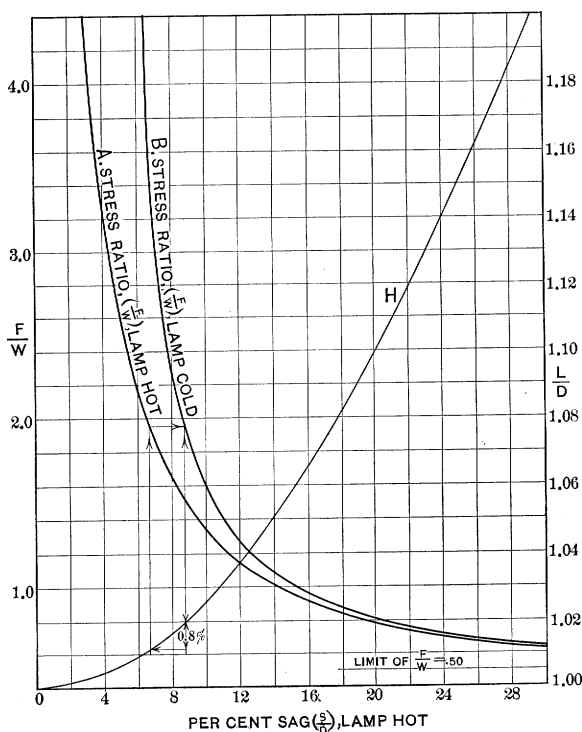


FIG. 4

Using this equation in connection with (2), curve H was plotted showing the per cent sag for a given value of L , expressed as a percentage of D .

A point on curve A shows the stress in a horizontally burning filament for a given sag when the lamp is burning. At the same point, the ordinate of curve B shows to what extent this

stress is increased by the shrinkage of the filament on turning off the lamp. In deriving this second curve a shrinkage of 0.8 per cent was used, as determined by experiment. Curve *B* was derived from *A* as follows: For example, at 8.8 per cent, sag *L* is 102 per cent of *D*. On turning off the lamp, *L* decreases 0.8 per cent, hence the sag will be reduced to 6.8 per cent, corresponding to a stress ratio of 1.90, which is plotted over the "hot sag" of 8.8 per cent.

The curves show that a certain amount of sag is necessary if excessive filament stresses are to be avoided. If a lamp were so designed that when burning horizontally the filament would sag but 7 per cent, the stress would be 1.85 times as great as when burning vertically, and when turned off, the stress ratio would rise to 3.0.

The effect of burning a lamp is to cause the filament to disintegrate gradually. This disintegration, moreover, is not absolutely uniform, but is liable to localize at any weak points on the filament, if such there are. As the lamp continues to burn, the weak spots disintegrate more and more rapidly, till they can no longer withstand the imposed mechanical stress and a burn-out results. It is therefore apparent that, although the filament as a whole could withstand a stress many times greater than its weight, yet, due to its non-uniform disintegration, an early burnout will be the inevitable result of insufficient sag and consequent high stress ratio.

A number of lamps, of the 25, 40 and 60-watt sizes and of the most recent design, showed from 10 to 15 per cent sag after they had burned for some time. The curves show that for this range of sag, the filament stress ratio, even when cold, will not rise above 1.60.

The curves cannot be rigorously applied to lamps larger than the 100 watt, for in these the filaments are larger and stiffer and do not sag freely.

The investigation of the flickering of incandescent lamps on alternating current can be separated into two divisions; first, the determination of the effect on the cyclic variation in candle-power produced by varying the size, length and material of the filament; and second, the determination of the relations between cyclic variation in candle-power, intensity of illumination, and "critical frequency" (or the frequency at which the sensation of flicker just disappears).

We have recently conducted some experimental work on the second division of the subject—the relation between cyclic candle power variation, illumination intensity and critical frequency. We found that for a cyclic variation *M*, equal to $\frac{\text{variation in c.p.}}{\text{max. c.p.}}$, and an illumination *I*, in foot candles, the

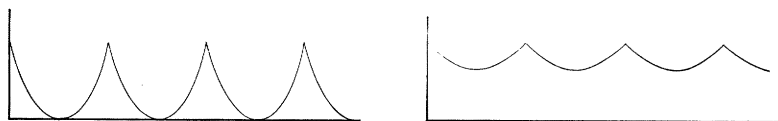
critical flicker frequency *f*, in cycles per second (twice the current frequency) is given by the relation

$$f = 43 (I M)^{0.13}$$

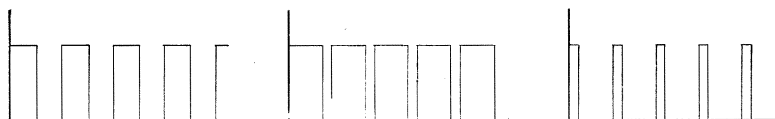
The constants in this equation were derived from five sets of data taken by two different observers, and the average deviation from the mean is about 7.8 per cent for each constant.

The cyclic variation in illumination was produced by a vane rotating at variable speed in a beam of light. In front of the vane was an opaque screen with a hole in it, the hole being covered with a ground glass diffusing plate. By using vanes of different sizes, we obtained different ratios of variable to maximum illumination. The flicker was viewed on the test plate of an illuminometer placed eight inches from the ground glass. Simultaneous readings were taken of the illumination and of the speed of the rotating vane at which the flicker sensation disappeared.

The rotating vane gives a cyclic variation in illumination about like the following curves:



Experiments show that the cyclic variation in candle-power of a lamp on alternating current very closely approximates a sine wave raised up above the axis. Dr. Kennelly conducted some experimental work on flicker using cyclic light waves of the following shapes, and his results tend to show that the critical



frequency is a function only of the maximum and minimum illumination, and is not affected by wave shape. His equations when put in the form expressed above, agree closely with ours. His results were published in the 1907 Proceedings of the National Electric Light Association.

The question of flicker comes up most often in connection with the operation of metal filament lamps on 25 cycle current. Letting f in the above equation be 50 (the flicker frequency corresponding to a current frequency of 25 cycles) there results

$$IM = 3.18$$

The table below is computed from this equation and shows the maximum permissible cyclic variation in candle-power allowable with various intensities of illumination. If in any case the variation is greater than that given in the table, a flicker will be perceptible. With an illumination of less than

about 3 foot candles, flicker will not be discernible, no matter how great the cyclic variation.

Intensity of illumination I	Maximum allowable cyclic variation on 25-cycle current M
10.....	31.8%
8.....	49.8
6.....	53.0
5.....	63.6
4.....	79.5
3.18.....	100.0

We thoroughly agree with Mr. Howell in his statement that lamp testing is absolutely necessary to lamp making and also a very necessary adjunct to proper lamp using, but one should not understand from Mr. Howell's remarks that the necessity of testing in any case extends beyond the manufacturers or other thoroughly equipped lamp testing bureaus. Unless lamps are tested under the most rigid conditions the results are worse than useless and this applies with particular force to tests run at higher than normal efficiencies in order to shorten the time of testing. In such "forced" testing the effects of errors in test voltage are multiplied many times in reducing the results to normal performance and if the forcing is carried to an excessive point the extremely high temperature produced may create abnormal conditions which tend to make the lamps appear better or worse than tests at actual rated efficiencies would have indicated. Do not understand for a moment that we wish to undervalue the importance of forced testing, for when conducted under proper conditions and with proper knowledge of the limitations and errors to which it is subject, the forced test forms a very valuable means of rapidly attaining comparative results and has proved of inestimable service to the manufacturers. The Engineering Department of the National Electric Lamp Association has been devoting a great deal of study to the forced testing of metallic filament lamps, principally because the extremely long life attained at normal efficiencies served to severely tax the testing capacity and because urgent demand was being continually made by the factories for quicker test results. In spite of the fact that this problem has been before the engineers of the department for some time, no correction figures have yet been decided upon which can be regarded as final. Since Mr. Howell has brought the subject before you and as some may endeavor to proceed with forced tests upon the figures he has given, he will give some data in connection with this matter.

The earlier attempts to secure a correction figure for forced tests were based upon the average life of numerous lamps, run at various efficiencies. Tests conducted on such lines were not fruitful of results of the accuracy it was desired to attain. A study of the results of such tests, and previous experience with performance of the older and better known carbon filaments led to the following conclusions.

Steinmetz* has stated that "tungsten filaments do not ordinarily fail by evaporation as is the case with carbon, but by melting at some weak spot;" and also that "blackening of tungsten lamps is not gradual, as with carbon, but occurs simultaneously with impaired vacuum and appears rapidly." Our experience would indicate that there is a certain slight amount of normal blackening of tungsten lamps. The fact that this blackening deposit is found to consist largely of tungsten, and that the current after the initial rise tends to decrease gradually leads us to believe that the filament actually is vaporized to a limited extent.

A perfect filament would have a perfectly uniform temperature throughout practically its entire length. Near the supporting wires, the cooling effect due to these supports, would demand consideration. This filament could be conceived to be disintegrating at a uniform rate throughout its entire length except near the supports, with an ultimate result somewhat as shown in Fig. 5, which

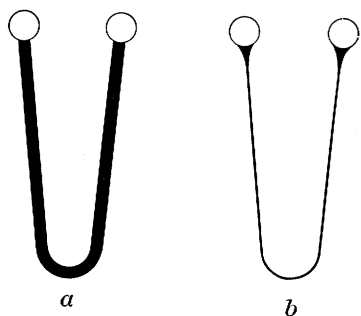


FIG. 5

represents in an exaggerated way a short length of filament.

The candle-power of such a filament when burned at a constant normal voltage would probably show a slight initial rise due to changes in the physical characteristics of the filament material and to changes in the condition of the residual gases in the bulb (which of course are at extremely low pressure). After an initial rise the candle-power would drop gradually at a dimin-

ishing rate, until the radiation within the limits of the visible spectrum had become incapable of producing the sensation of light. During this period the value of the current flowing through the filament would have changed in a somewhat similar manner to the luminous radiation, but even after the filament had ceased to emit visible radiation the current would still flow and the filament would never burn out.

The decrease in candle-power would be due essentially to two things:

1. The temperature would decrease as the filament material evaporated and the diameter decreased. Neglecting possible changes in physical characteristics after the initial changes already noted, the energy expended in the filament would decrease as the square of the diameter of cross section. Obviously the surface of the filament would decrease directly as the diameter, so that as the filament evaporated the energy expended

* "Radiation, Light and Illumination" pp. 80, 81.

therein would decrease more rapidly than the radiating surface and the temperature would decrease.

2. The total radiating surface would be decreased. As a third, though secondary effect blackening of the bulb by condensation of evaporated filament material upon the interior surface would cause a decrease in candle-power of the lamp as a whole.

Such would be the performance of a filament without defect. In actual filaments defects exist and the magnitude of the defects is a variable quantity which follows to some extent the laws of probability for a given lot of lamps. For example, out of a large number of lamps started on life test under the same conditions, a few would probably fail rather early in life due to large defects or imperfections in the filament itself. As the burning continues the "mortality" rate would increase as the average size defects would begin to cause failures. Then with

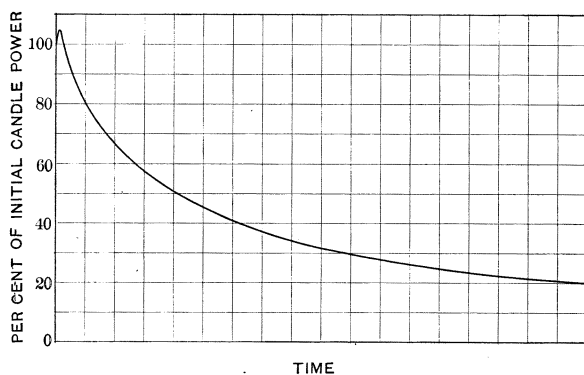


FIG. 6

the number of lamps burning considerably reduced, the rate of failure would decrease, for there would then be left only lamps having defects of less than average size. Finally there would be left only a few lamps which would give a very abnormal life, because they might happen to be particularly free from imperfections in structure. During this period the candle-power would have been undergoing the general changes previously noted which may be illustrated by the actual performance curve obtained from a test of 115, 16-c.p., 3.5-watts per c.p. carbon lamps as shown in Fig. 6. The average total life to burnout of the lamps represented on this test was several times the so-called "useful life", to 80 per cent of initial candle-power. The average candle-power corresponding to the average life gives us a means of judging the magnitude of physical imperfections which exist in the filament. On this basis it appears that at the present the carbon filament is more highly developed than

the tungsten filament, inasmuch as the carbon lamps reach a relatively lower candle-power value before failure than the tungsten lamps. This shows that there is still room for enormous improvement in the tungsten filament and that there are possibilities for obtaining still higher efficiencies than those at present attainable.

From the above considerations, it was decided that the correction figure to be applied to the life of metal filament lamps burning at other than normal efficiency could be determined more accurately from the time required by lamps operating at various efficiencies to reach the same percentages of initial candle-power or of initial current than from the actual time to failure or burnout. This should be true whether the changes in candle-power and current are due entirely to disintegration of the filament or whether they result from some other physical change which takes place during life.

It is manifestly impossible to obtain results on a single individual lamp at more than one efficiency, consequently for the purpose of arriving at the proper figure a special lot of lamps were made.

The following condensed report of the test on these lamps will be of interest in indicating what precautions have been taken in order to arrive at a proper correction factor for tungsten filament lamps.

Fifty 40-watt, 109-volt lamps were formed and assembled with the greatest possible care, in order to produce a lot of lamps which should be similar in all characteristic qualities. The work was started with over 1000 filaments from which 200 of the most perfect were selected after several rigid and careful inspections. Upon measuring the lamps made from these carefully prepared and selected filaments at 1.25 watts per c.p. the voltage with two exceptions was found to fall between 108.8 and 109.2 volts inclusive, a range of but 0.4 volts.* Aside from indicating a close selection, this uniform rating simplified to a large extent some of the work of testing, and has, we believe, eliminated the possible source of several small errors.

The test was divided into five sets of ten lamps, which were burned on 60-cycle alternating current at efficiencies of 1.25, 0.97, 0.85, 0.75 and 0.67 watts per mean horizontal candle

* If lamps can be made by commercial processes and in an ordinary factory which come within 0.2 of one per cent of the rating for which they were designed, it might be possible, by using more refined methods of manufacture, to produce a primary standard of light with tungsten filament.

An ordinary commercial lamp would not, of course, serve the purpose. It might, however, be possible to make a single loop lamp under rigid specifications as to size, length, and processes of manufacture of filament, dimensions of leading in wires, size and shape of bulb, etc., that could be exactly reproduced at any time. Such a lamp could be not only a primary standard, but an absolute standard as well, for it is well within the range of possibility to compute as well as measure the luminous intensity of such a source.

power respectively. According to the best correction figures available at the time the test was started each set was measured at approximately equivalent intervals. Readings were made with a contrast Lummer-Brodhun screen at rated voltage and

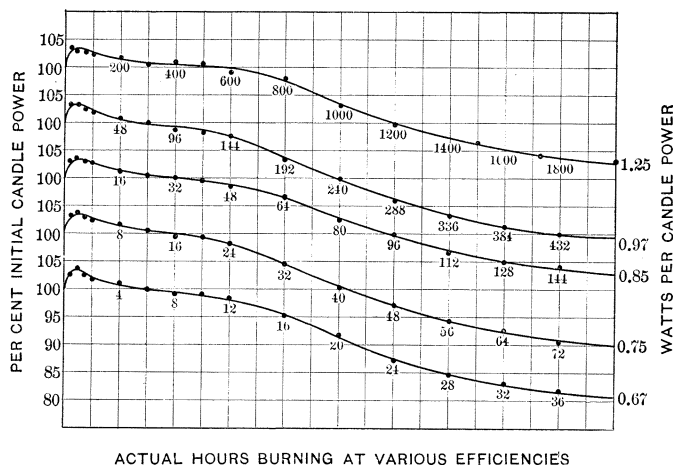


FIG. 7

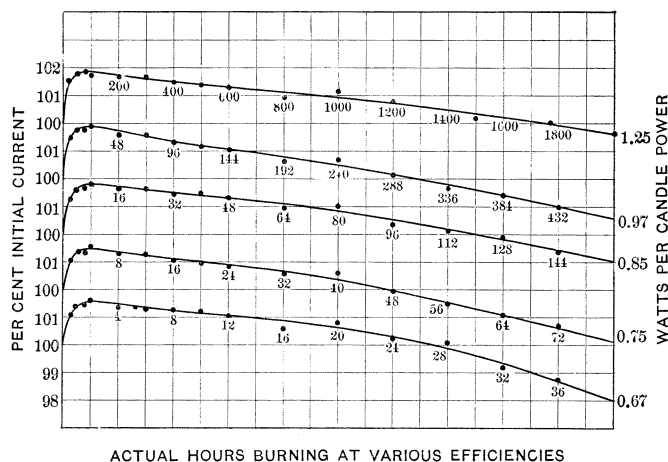


FIG. 8

all currents were checked in each instance with accurately calibrated standard laboratory meters.

Average candle-power curves for the various efficiencies, together with the actual hours burning, are plotted in Fig. 7, and average current curves for the same lamps are plotted in Fig. 8. We are able to show these only out to 2000 equivalent

hours, at 1.25 watts per c.p., because the test is still in progress with over 80 per cent of the lamps still burning.

We wish to call attention to the peculiar shape of the candle power curves of Fig. 7. Their peculiarity is the unexpected maintenance of candle-power during the interval corresponding to 300 to 700 hours on the 1.25 watts per c.p. curve.

We are at a loss for an explanation of this peculiar curve form but the accuracy of the timing and the photometry of the test leads us to believe that the results are correct.

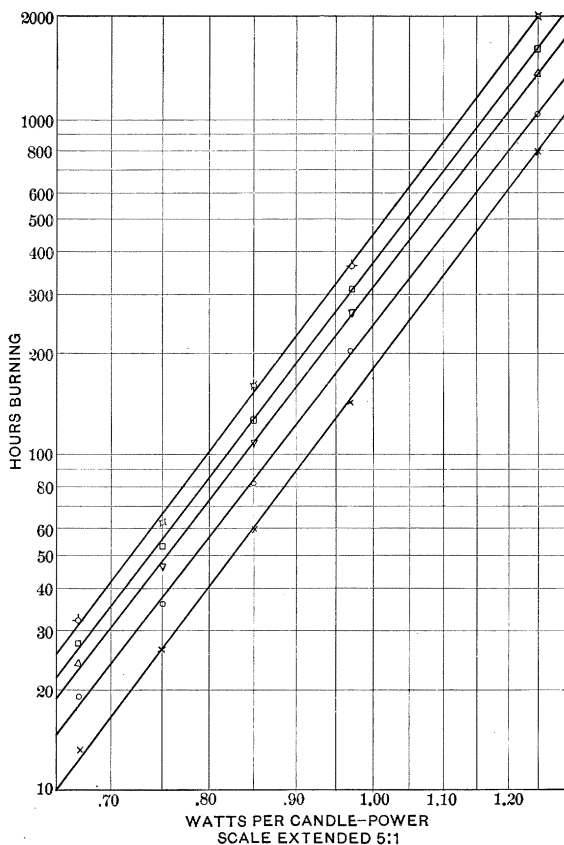


FIG. 9

From previous experience we assumed that the equation between life and efficiency is of parabolic form:

$$\frac{\text{Life}_1}{\text{Life}_2} = \left(\frac{\text{Watts per c.p.}_1}{\text{Watts per c.p.}_2} \right)^b$$

the object of this test being to determine the exponent b . In Fig. 9 and Fig. 10, we have shown several logarithmic graphs

between watts per c.p. and hours life obtained by comparing the interval of time required to reach various percentages of the initial values of candle-power and current. The results show that the life equations for tungsten lamps conform very rigidly to a pure parabolic law over the range investigated. The candle-power curves and the current curves appear to give slightly different values of exponent b . We believe that the

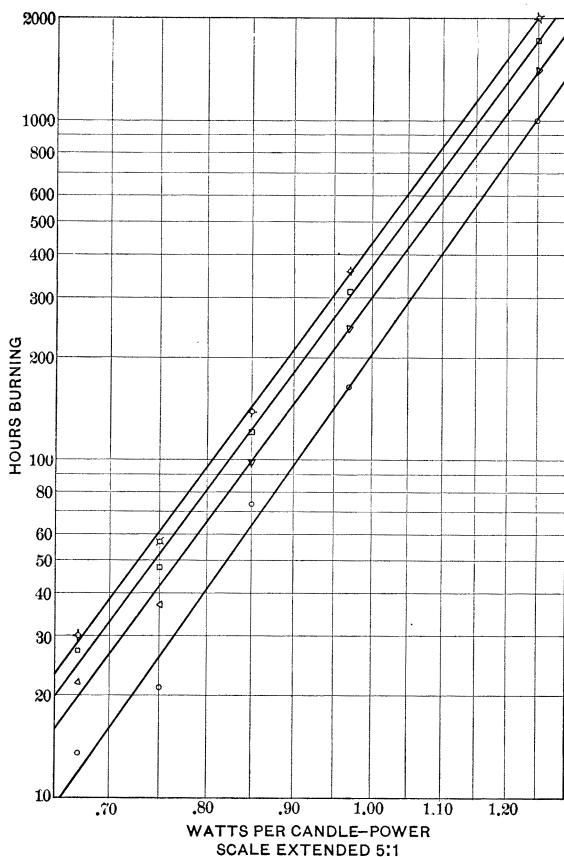


FIG. 10

exponent derived from the candle-power curves is the more accurate, where total life values are to be determined. In Fig. 11 we have shown curves between the watt per candle-power life exponent, b , and hours burning at normal efficiency (1.25 watts per c.p.).

The correction figure for tungsten filament lamps is still in some doubt, which may be evident from the results of the test previously described, and also from the fact that in his

paper Mr. Howell seems to have used two different values for the exponent of the life-efficiency equation. Mr. Howell states that the life was found to vary universally as the -3.65 power of the candle-power. This exponent was derived from experiments on lamps with untreated bamboo filaments, but he says it was later found to hold for treated carbon and metal filament lamps. If the candle-power is taken to vary as the 1.75 power of the efficiency, as careful work would indicate, the exponent connecting the life and efficiency would be 6.4 . From the life factors in the table given by Mr. Howell the value of the exponent through the normal working range is found to vary from 6.7 to 6.8 .

In connection with the work we have done on forced testing of tungsten filament lamps, we might mention that a similar line of work is now being carried out on the tantalum filament lamps on both alternating current and direct current for a

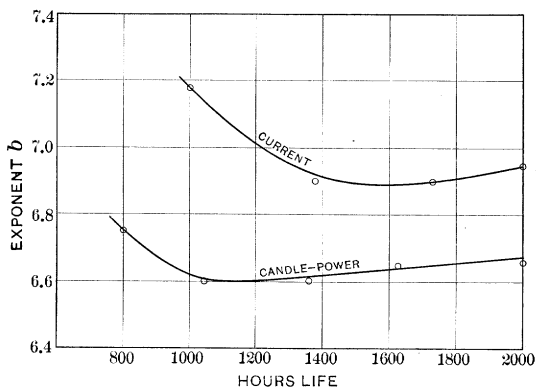


FIG. 11

similar purpose. Here interesting developments are expected on the alternating current, as from previous tests there is much to indicate that below a certain temperature the life is not affected greatly by the efficiency, being, we believe, more dependent upon the effect of frequency. However that may be, we will undoubtedly be in a position to throw considerable light upon the matter in the near future.

As to the relation between life and watts or watts per candle power being very nearly the same for all different lamps we cannot agree. The exponent by which we express the relation between life and efficiency varies from 6.65 for the tungsten filament lamps to about 5.43 for untreated carbon. The first mentioned figure may be changed somewhat in view of later developments, but we find that the treated carbon, gem, and tantalum exponents, in so far as we have been able to determine them, are scattered between these limits.

In the table below are given our determinations of the exponents of the following equations, in which L = hours life, C = candle-power, W = total watts, e = watts per candle, V = voltage, I = current and R = resistance.

$$\frac{L_1}{L_2} = \left(\frac{C_2}{C_1} \right)^a \left(\frac{e_1}{e_2} \right)^b \quad \frac{C_1}{C_2} = \left(\frac{e_2}{e_1} \right)^h = \left(\frac{V_1}{V_2} \right)^k$$

$$\frac{W_1}{W_2} = \left(\frac{V_1}{V_2} \right)^n \quad \frac{V_1}{V_2} = \left(\frac{I_1}{I_2} \right)^x \quad \frac{R_1}{R_2} = \left(\frac{V_1}{V_2} \right)^q$$

Exponent.....	a	b	h	k	n	x	q
Tungsten.....	3.80	6.65	1.75	3.68	1.59	1.718	0.418
Tantalum.....	†*3.73	†*6.30	1.69	4.20	1.72	1.382	0.276
Gem.....	*3.7	*5.8	1.6	4.9	1.8	1.25	0.20
Treated carbon.....	3.65	5.83	1.59	5.55	2.07	0.930	-0.075
Untreated carbon.....	*3.62	*5.43	1.50	6.89	2.31	0.763	-0.310

(*) Computed from the dotted curve of Fig. 12.

(†) Direct current.

The values given for h , k , n , x , and q are correct within the limits of accuracy of photometers and electrical instruments, therefore are correct within 1 per cent. The values of a and b , however are subject to much greater error, probably at least 5 per cent.

In applying correction figures to forced tests, we have found the exponent b to be the most convenient one to use, hence we call this the *fundamental* life exponent. The exponents k and x are also *fundamental* exponents, k being determined from photometric relations, and x from electrical relations. Given these three fundamental exponents, it is possible to determine the relation between *any* two of the variables, life, candle-power, watts, watts per candle, volts, current and resistance.

A curve plotted between x and k brings out some interesting considerations. As shown in Fig. 12, the points for all the lamps, except the gem fall on a very smooth curve. This is rather surprising, in view of the fact that the metal filaments exhibit more selective radiation than those made from carbon. The point shown in Fig. 12 for "old treated carbon" was obtained from performance curves of some treated carbon lamps which had burned for several thousand hours. The effect of this burning was to evaporate part of the graphitic layer deposited on the filaments in the treating process, or to partially "untreat" them. As could be anticipated, the point representing these lamps falls between those for treated and untreated lamps.

By using the curve of Fig. 12 it is possible to determine the

relation between any two of the variables, but the life (excepting for lamps of the gem class) when either of the fundamental exponents, k and α , is known. The exponent α of the voltage-current equation is obviously the easier of these two to determine, as it can be obtained from voltage and current measurements of a lamp.

It is within the range of possibilities that future experiments may give a smooth curve between α and one of the life exponents.

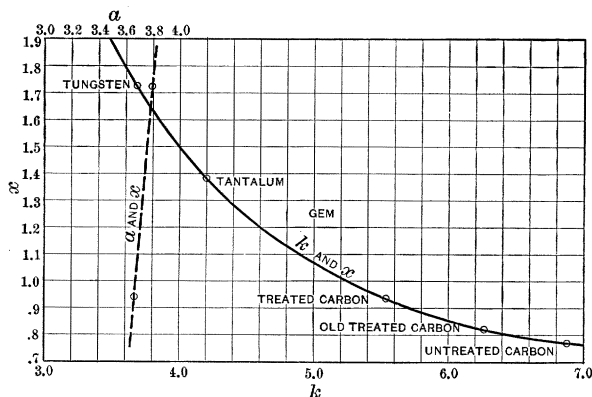


FIG. 12

If such proves to be the case, it will be possible to predetermine the *entire* performance of a lamp from its volt-ampere curve. The dotted curve of Fig. 12 is plotted between α and x . As only two points on this curve are known, it is drawn in as a straight line. Future developments may show that it has a slight curvature, but in the meantime it will serve as a good basis for calculations.