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A STUDY OF

INCANDESCENT LIGHTS.

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JUNE 1902.

Master's thesis.

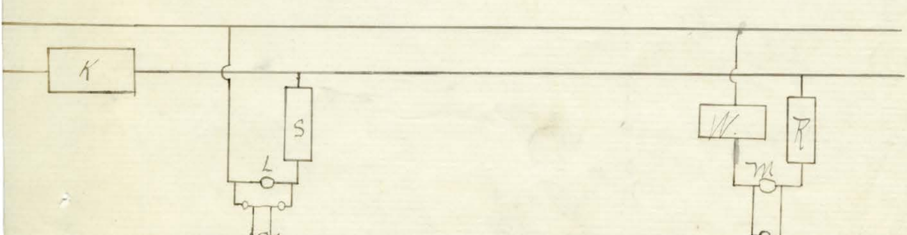
A STUDY OF INCANDESCENT LIGHTS.

This study was carried on chiefly to find in what manner the candle-power of an incandescent lamp varies with the voltage at the terminals of the lamp.

The Brodhun photometer used in these experiments had never been standardized with accuracy. The approximate positions for the lamps had been previously determined by careful measurements. Two standard 16 C.P. lamps were to be had, and were placed one at each end of the scale at such distances that the photometer balanced at 16 C.P. They were then apparently near enough to the correct position for all practical purposes, and the lamps used thereafter were put in these places.

Some difficulty was encountered because of the variations in the voltage across the mains due to the change in the load on the dynamo. The voltmeter frequently showed a change of 1 volt or more in 2 or 3 seconds. In consequence of this two observers were required in this work, one of whom devoted his time to keeping the voltage as nearly constant as possible.

The connections used during these experiments are indicated in the main by the following.



A and B are the mains from the dynamo.

L and M are the lamps used in the photometer.

R and S are resistances in series with the lamps in order that the potentials at the terminals of the lamps may be changed.

K is a sliding resistance in the main circuit to keep the voltage constant.

V is a voltmeter and W is a wattmeter.

M is the lamp which was being studied.

Having but one reliable voltmeter, a galvanometer was used as an indicator for the standard lamp L. Two lamps in series were placed across the terminals of the standard and the galvanometer was shunted around a small resistance as indicated in the figure. The reading of this was first found by using the voltmeter in parallel with it.

After finding the positions for the standard lamps, a secondary standard was made for 16 C.P. and also one for 8 C.P. and these were used in the remainder of the work.

Three lamps were studied. They were a 16 C.P., a 20 C.P. and a 25 C.P. of the Edison type, and are the three kinds of lamps used in the University. Care was taken to select an average lamp in each case. In each case the lamp was made to point in its standard position, that is, with the line, perpendicular to the shank, pointing to the center of the photometer screen.

The first lamp used was a 16 C.P., marked at 103 volts. The highest voltage obtainable that night was 102.9.

This lamp was first compared with the secondary standard 16 C.P. lamp. While one observer kept the voltage as constant as possible, the other balanced the photometer. In doing this the carriage was run one way till just a slight difference in color of the two parts of the screen could be seen. The carriage was then brought down from the other side till a similar difference could be seen; but the colors on the screen were interchanged. In this way errors due to the observer's eye were eliminated as much as possible. To correct errors of adjustment in the photometer, the screen was reversed and readings taken as before. The mean of these four readings was taken as the correct reading of the photometer. At the same time the readings of the voltmeter and wattmeter were taken.

By putting resistances into the circuit of the variable lamp its candle-power was run down by steps.

After getting as low as 8 C.P. the difference in the color of the standard and variable lamp was so great that it was quite difficult to make an accurate setting of the photometer. The 8 C.P. was then substituted for the 16 C.P. standard and the photometer readings were divided by two. The same difference of color again arose when the variable lamp reached about 4 C.P.,but it was not thought advisable to make a 4 C.P. standard because there was greater opportunities for errors and also because the results were not so important in and below that region.

The 20 C.P. and 25 C.P. lamps were studied in the sameway. Unfortunately,however,on account of the excessive drop in voltage in the main line,the voltage could not be run up to the voltage which was marked on the lamps. Each of these lamps was marked at 115 volts; but the highest voltage obtainable was about 106. The most important part of the investigation with reference to these lamps was thus lost.

The curves for these lamps were obtained by using the candle-power for ordinates in each case,with the volts,current,watts,resistance and watts per C.P. for abscissae. In this way a curve for the voltage was plotted and also one for the watts consumed by the lamp. Knowing the watts and volts,the current was found and a curve plotted for it. Then from the volts and currents,the resistances were found and the results plotted.

As will be seen,the curves for the different lamps are very much alike. From the curve for the voltage and the C.P. it will be seen that the candle-power drops very rapidly as the voltage drops; in fact near its capacity,the lamp changes about one C.P. per volt. As the lower candle-powers are reached the voltage drops very rapidly.

The curve for the watts and candle-power,and the current and candlepower are very similar to those for the volts and candlepower,the curve dropping rapidly near the capacity of the lamp and then making a comparatively sharp bend indicating that the watts or currents begin to drop much more rapidly.

Curves were plotted for the volts with watts,the volts with current,and the watts with current. They were very nearly straight lines showing that these three quantities change at about the same ratio with respect to each other.

Curves for resistance and candlepower were also plotted for each lamp. From these curves the conclusion is drawn that,in the vicinity worked,the resistance remains practically constant.

A much more interesting curve is that between the candlepower and the watts per candlepower. The candlepower drops rapidly when the lamp is near its capacity,but when it gets down to about one-fifth of its capacity it makes a decided turn,after which it is almost parallel to the axis for watts.

This brings up an interesting problem in incandescent lighting. It was found,by observation,that,in the lamps used in these experiments,the voltage,near the capacity of the lamp,could be lowered about 5% without a noticeable change,to the naked eye,in the strength of the light. From the voltage curve it is seen that this means a drop of about 5 candlepower in the lamp,and from the watt curve that it means a corresponding drop of from 6 to 8 watts,or over 10% of the total power consumed by the lamp at full load. From the curve for t the watts per candlepower,it is seen that the efficency of the lamp changes but slightly in a change of 5 candlepower. It may be said that the watts per candlepower is increased about 10%. In-as-much as the change in candlepower is not noticeable,a company can without discovery save at least 10% of its fuel by running its incandescent system 5 or 6 volts low. This amounts to an exceedingly important factor to a company which has many thousand lights in which the power is generated by steam. And then,to,the life of the lamp is increased by such a change. In the case where wattmeters are used there is, of course, no advantage. On the contrary there will be a slight loss due to the reduced consumption; but inasmuch as very few l-lights are run on wattmeters, this would not be an important factor.

If a certain number of candlepower is required the question arises as to whether it would be more economical to run the lamps high and thus get a greater efficency, or to run them comparatively low and so increase the life of the lamp. This would depend almost entirely on the cost of producing the power. In cases where the power is abundant and cheap, as in most waterpower plants, it would be more economical to run the lamps comparatively low; but in the case of most steam plants it would be more economical to run the lamps at a higher efficency.

It has been found, by experience, that the cost of lights and renewals is a minimum when the cost of renewals is about 15% of the total cost. If the renewals cost more than 15% the lamps are being run at to high an efficency; that is, the voltage is so high that, while the watts per candlepower is low, the lamp burns out to soon. The reverse is true, that. if the cost of renwals is less than 15% the watts per candlepower is so large that, while the life of the lamp is increased, the power required by the lamp is increased so much that it more than conterbalances the gain in life.

Lamps should not be used up to the point where they break for, although it decreases the cost of renewals, the efficiency is so low that it becomes exceedingly uneconomical to do so; both to the consumer and the producer of the light. If the lamps are run too long the consumer recieves only poor and dim lights, and the producer has to furnish this at a low efficiency. Very few lamps can be used in an economical condition for 1000 hours, and for many types it is not best to use them more than 500 or 600 hours. The best stations of today endeavor to keep the life of the lamps used down to 600 hours.

The time to use a lamp depends on the first cost of the lamp, the cost of power, and the change in efficiency. This can be shown in an interesting way as follows:

Let B = the cost of the lamp per candlepower.

" C = total cost of one candlepower of light for a given time b.

" D = average cost per hour per candlepower during the time b.

" E = cost of energy per 1000 watthours.

" a = initial power, in watts per candlepower.

" b = hours a lamp should be burned for greatest economy.

" c = increase of watts-per-candlepower for each hour of use.

Then according to Foster we have,

$$C = B + (a + c\frac{b}{2})E\frac{b}{1000}$$

$$D = \frac{C}{b} = \frac{B}{b} + (a + c\frac{b}{2})\frac{E}{1000}$$

Differentiating in respect to b we have,

$$\frac{dD}{db} = -\frac{B}{b} + \frac{cE}{2000}$$

or D is a minimum when $b = \sqrt{\frac{2000B}{cE}}$

when $c = .001 \qquad b = 1410\sqrt{\frac{B}{E}}$

when $c = .002 \qquad b = 1000\sqrt{\frac{B}{E}}$

when $c \doteq .003 \qquad b \doteq 815\sqrt{\frac{B}{E}}$

We assume in this that for any one lamp c is a constant.

The cost of power per kilo-watt-hour is difficult to find. It depends on several exceedingly variable quantities. One of them is the cost of fuel. In water-power plants the cost is, of course, much less than for steam plants. The size of the plant also makes a material difference in the cost of power.

A few cases are cited here to give an idea of the cost of electric power.

As worked out from a thesis of R.H.Dearborn, the cost of coal alone, with coal at $2.50 per ton, is .73 cents per K.W.hour. The actual cost of the power is probably 4 or 5 times this amount. The particular plant studied in this thesis was a 5000 H.P. plant. According to Buckley the cost of power is about 5.5 cents per K.W. hour when used for electric lighting. According to Chas. T. Main the cost of power for 1000 H.P., noncondensing engines, in which the exhaust steam is used for heating, is 4.2 cents per K.W. hour. Probably a fair average would be 4.5 cents per K.W. hour. Large plants go as low as 3. cents and small isolated plants to about 7.5 cents per K.W. hour. According to Dr. Friedel the total cost of power, when running in the Gymnasium with poor machinery, was 7.5 cents per K.W. hour. Under the conditions this was very good.

The following results were obtained from readings taken by Mr. Converse in the University power plant. The boilers were used all day, and the dynamo was run till 5:00 P.M., after which it was shut down till 7:00 P.M. The results are taken from the readings for ten nights in which the exhaust steam alone is used to heat the dormitory.

Total wood used was 1.6 cords.

Average current was 46.5 amperes.

Voltage was 115.

Number of hours run in the ten nights was 37.

Total output was 198 K.W. hours.

Cost of wood, labor, etc., was estimated at $15.00.

Cost of power was $\frac{1500}{198} =$ 7.6 cents per K.W. hour.

This, however, is the cost of running the dynamo and heating the dormitory.

The average amount of wood used for 24 hours from 7:00 A.M. on Sunday is 1.25 cords.

.7 cords is required to heat up before 7:00 A.M. Monday morning and .15 for running the dynamo on Sunday night. This leaves .4 cords to heat the dormitory fob 16 hours on Sunday. For 37 hours this would cost about 3:00 dollars.

The cost of electric power would then be reduced by this amount, that is, the cost of 198 K.W.hours would be \$12.00.

Therefore the cost of power is $\frac{1200}{198} = 6.08$ cents per K.W. hour.

This, of course, does not include the interest on the money invested in the plant or thedepreciation in the machinery.

While this is not a very high efficiency it is fairly good for so small a plant.

Returning to the problem of finding the maximum number of hours which a lamp should be burned, we will substitute the value 6.06 for E in the expression for $b = \frac{2000\ B}{c\ E}$

The cost of the 25 candlepower lamps is 20 cents or .8 cents per CP.

Therefore if c = .001	b = 512 hours.
" c = .002	b = 363 "
" c = .003	b = 296 "

The cost of the 20 C.P. and the 16 C.P. lamps is 20 cents.

For the 20 C.P. lamps B = 1

Therefore if c = .001	b = 572 hours.
" c = .002	b = 406 "
" c = .003	b = 331 "

For the 16 C.P. lamps B = 1.25

Therefore if c =.001	b = 640 hours.
" c =.002	b = 454 "
" c =.003	b = 372 hours

The value of C for these lamps is not known but it is probably about .002. If this is the case the most economical length of time to run these lamps would be

for the 25 C.P. lamps about 375 hours

for the 20 C.P. lamps about 400 hours.

" " 16 C.P. " " 450 "

From the curves it is seen that the lamps have an efficiency, at their marked voltage, of about 3.1 watts per candlepower. If the voltage is lowered the efficiency drops also.

In the 16 C.P. lamp the efficiency at its capacity is 3.1 watts. If the lamps are run at avoltage of 98, or 5 volts below the normal, the efficiency of the lamp is 3.6 watts per candlepower. The cost of power to furnish the same amount of light in the former case is only 86% of what it is in the latter case. In the case of the 16 C.P. lamp with an efficiency of 3.1 the watts consumed is 49.6. From the curve for the 20 C.P. lamp the efficiency, when the candlepower is 16 and the voltage is 108, is 3.8 or the power consumed for 16 C.P. is 61 watts. If we take the power consumed in the former case as 100%, for the 20 C.P. lamp it will be 123% and for the 25 C.P. lamp it will be 161%.

This shows the great importance of running the lamps at their highest efficiency. The advantage gained in the increased life obtained by running a 25 C.P. lamp at 105 volts is much more than counterbalanced by the increase in the power required to furnish the light.

In conclusion it may be said that if a plant is to be run economically the lamps should be used at such a voltage that they will give the amount of light for which they are made; and in such a way that the cost of renewals will be about 15 % of the cost of producing the light; and that they should not be used to long because of the decrease in the efficiency of the lamps.

It is very necessary that a station shall be supplied with accurate instruments, particularly reliable voltmeters; and that the drop in the main shall be known, so that the voltage at the terminals of the lamp can be kept at its proper value. And finally it should be the endeavor of all plants to work for a satisfactory efficiency of 3 watts per candlepower.

Following are the readings which were taken for the different lamps. The readings for the Volts, the Watts per lamp, and the Candle-power were read directly from the instruments. The current was obtained by dividing the volts into the watts. The resistance was then obtained by dividing the current into the volts. The watts per candle-power was obtained by dividing the candle-power into the watts required by the lamp.

---16 CANDLE-POWER LAMP.---

Edison Type. Marked 103 volts.

Volts.	Current.	Resistance.	Watts per lamp.	Watts per C.P.	Candle-power.
102.9	.632	162.9	65.0	3.23	20.15
99.8	.601	166.0	60.0	3.51	17.10
97.3	.586	166.1	57.0	3.83	14.90
96.0	.580	165.5	55.7	4.02	13.85
93.7	.572	163.8	53.6	4.36	12.30
91.8	.556	165.2	51.0	4.72	10.80
90.3	.549	164.4	49.6	5.06	9.80
87.8	.531	165.4	46.6	5.58	8.35
85.5	.522	164.0	44.6	6.15	7.25
83.3	.509	163.6	42.4	6.84	6.20
81.2	.498	163.2	40.4	7.48	5.40
78.0	.472	165.3	36.8	8.86	4.15
74.3	.453	163.8	33.7	10.70	3.15
69.7	.430	161.9	30.0	15.00	2.00
64.2	.394	162.9	25.3	20.24	1.25
59.7	.372	160.6	22.2	31.71	.70
		Mean = 164.0			

--- 20 CANDLE-POWER-LAMP.---

Edison Type — Marked 115 volts

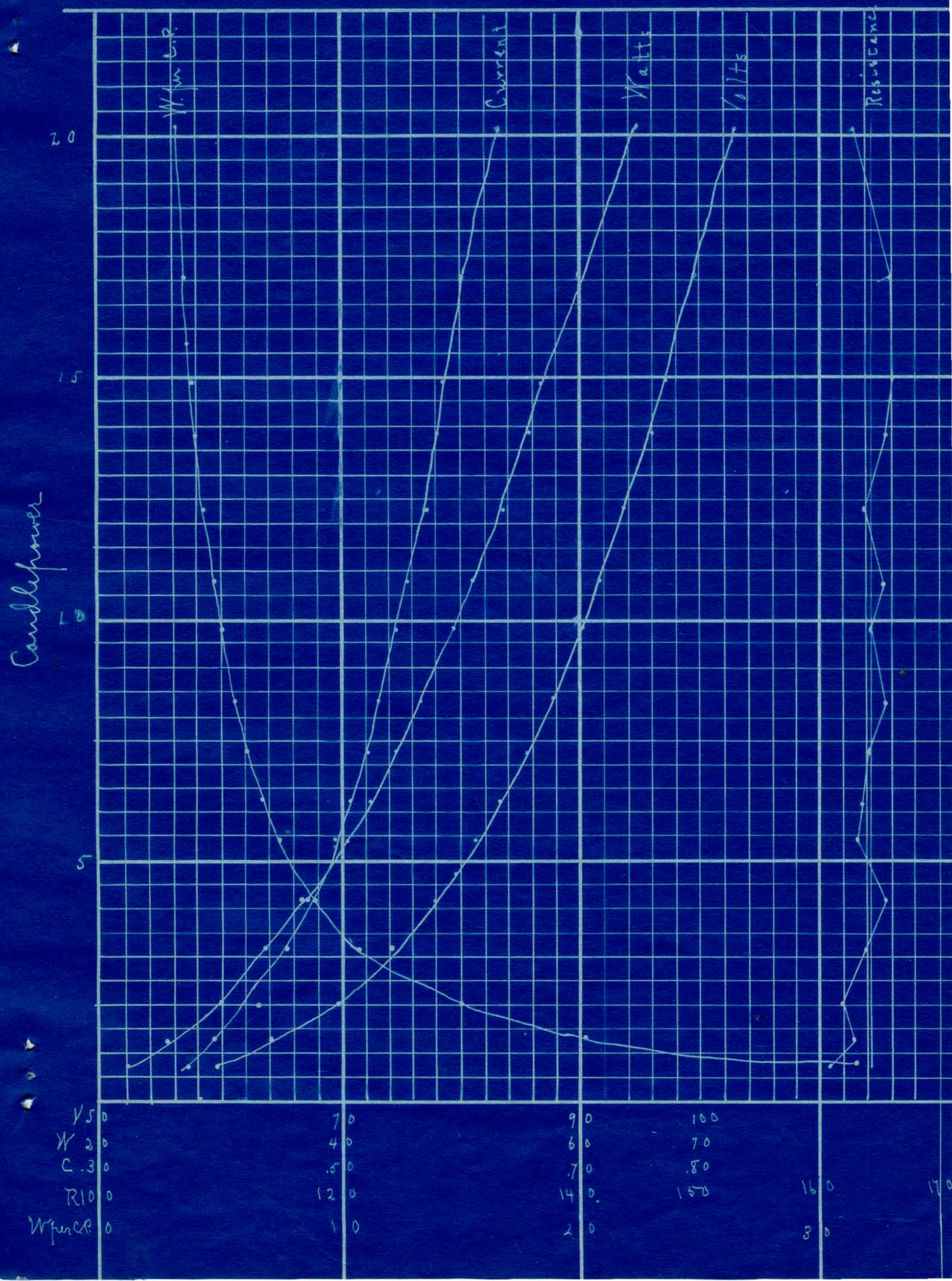
Volts.	Current.	Resistance.	Watts per lamp.	Watts per C.P.	Candle-power.
106.0	.561	188.8	59.5	4.02	14.45
103.8	.547	189.7	56.8	4.50	12.62
101.6	.541	187.7	55.0	4.93	11.15
99.3	.530	187.4	52.6	5.37	9.80
98.4	.523	188.0	51.5	5.66	9.10
97.2	.511	190.1	49.7	5.85	8.50
95.5	.504	189.6	48.1	6.41	7.50
91.0	.479	189.8	43.6	7.58	5.75
87.6	.457	191.9	40.0	8.08	4.95
83.8	.408	205.3	34.2	10.00	3.42
79.8	.418	190.7	33.4	13.36	2.50
75.0	.400	187.6	30.0	18.19	1.65
69.9	.365	191.7	25.5	24.28	1.05
65.1	.346	188.3	22.5	34.62	.65
	Mean	190.5			

--- 25 CANDLE-POWER.---

Edison Type — Marked 115 volts

Volts.	Current.	Resistance.	Watts per lamp	Watts per C.P.	Candle-power.
106.2	.768	138.3	81.5	4.88	16.85
103.3	.744	138.7	76.9	5.23	14.70
101.1	.732	138.2	74.00	5.74	12.90
98.9	.710	139.3	70.2	6.26	11.22
96.8	.699	138.4	67.7	6.87	9.85
94.3	.681	138.5	64.2	7.66	8.38
91.0	.651	139.8	59.2	8.80	6.73
87.8	.631	139.0	55.4	10.3o	5.38
84.8	.612	138.5	51.9	11.93	4.35
80.3	.570	140.8	45.8	15.02	3.05
74.6	.527	141.6	39.3	21.82	1.80
69.4	.484	143.4	33.6	29.22	1.15
66.5	.472	140.9	31.4	36.94	.85
	Mean	139.6			

16 C.P. lamp. marked 103 V.



Candlepower.