

THE CONCENTRATED-ARC LAMP AS A SOURCE OF MODULATED RADIATION*

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Summary.—*The concentrated arc is a new type of lamp whose radiation emitting source is a thin film of molten zirconium and a cloud of excited and ionized zirconium vapor and argon gas which forms on and very close to the end of the specially prepared negative electrode. By modulating the lamp current, the radiation may be modulated at audio frequencies.*

The continuous radiation from the molten zirconium can be only partly modulated, the per cent modulation decreasing with increase in modulating frequency and in spectral wavelength. The line radiation from the cathode-glow region close to the electrode modulates almost completely at all audio frequencies. It is particularly strong in the near-ultraviolet and infrared.

By using suitable modulator circuits, which are adapted to the rather unusual impedance characteristics of these lamps, and by using optical filters to select the spectral region used, the light output may be made to follow the lamp current modulation with good fidelity.

During the war, information about concentrated-arc lamps was restricted for security reasons. After the war, security restrictions were at first only partly removed so that the original public announcement of the lamps^{1,2} could refer only to their static characteristics and the lamps were discussed as simple light sources. Now, all restrictions have been removed, so the dynamic or modulation characteristics of the lamps may be disclosed.

Western Union's concentrated-arc lamps are made in sizes ranging from 2 to 100 w. The smallest, or 2-w lamp, is the most satisfactory for modulation purposes because of its very small source diameter, only 0.003 in., its high brightness, about 100 candles per sq mm, and its superior modulation characteristics. The larger wattage lamps can be modulated, and they will give many more lumens of modulated radiation than the 2-w size, but their light can be less completely modulated; their modulated light output is less constant with frequency,

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and their modulated intensity or brightness is less than that of the 2-w lamp. For applications where a high intensity rather than a large quantity of modulated radiation is required, the 2-w lamp is superior. Large lamps are finding their major application in photographic enlarging, photomicrography, spot lighting, and projection.

The lamps are made* with the two arc electrodes permanently sealed into a glass bulb which is filled with argon gas. The cathode or negative electrode is made by packing zirconium oxide into a tantalum or molybdenum tube. The positive electrode or anode is a simple plate of molybdenum with a hole in the center, through which the light coming from the end of the cathode can pass. After the lamps have been evacuated, the bulbs are filled with argon to almost atmospheric pressure, and the lamps are processed or "formed". In this process the exposed oxide surface at the end of the cathode tube is converted to metallic zirconium. When the lamp is operating, this extremely thin layer of zirconium metal is melted and maintained as an incandescent pool by the intense argon ion bombardment of the arc. Most of the visible radiation of the lamp comes from this white-hot surface. It has a continuous spectral distribution of the black body type peaking near 10,000 A.

Directly above this zirconium film is a layer of excited and ionized zirconium vapor and argon gas in the cathode-glow region of the arc. This layer extends for only a few thousandths of an inch from the cathode. The radiation from this region is very intense and shows three principle spectra, a continuum reaching from the ultraviolet to about 5000 A, and the line spectra of zirconium and argon. The majority of these zirconium lines occur at wavelengths shorter than 4500 A, peaking around 3500 A. Strong argon lines are scattered throughout the spectrum, the strongest occurring in the near-infrared around 8115 A. The continuous radiation from the cathode surface and the continuum and line radiation from the cathode-glow region combine to produce the complete spectral distribution characteristic of concentrated-arc lamps.

When the current through the lamps is changed or varied slowly, the candlepower of all of the various sizes of lamps changes in almost exact proportion and the modulation ratio is nearly 100 per cent. Modulation ratio is defined as the ratio of the per cent candle-power change to the per cent current change which produced it. The linear

* [Ed. Note.—See references for more detailed description of lamp construction.]

relationship and high modulation ratio are not maintained exactly as the frequency of the current variation is increased into the audio frequency range.

That part of the radiation which comes from the incandescent cathode surface shows a rapid decrease in modulation ratio with increase in frequency and with increase in spectral wavelength. Thus, measurements made in the continuum of a 100-w lamp at 3500 Å in the ultraviolet show per cent modulation ratios of 78 at

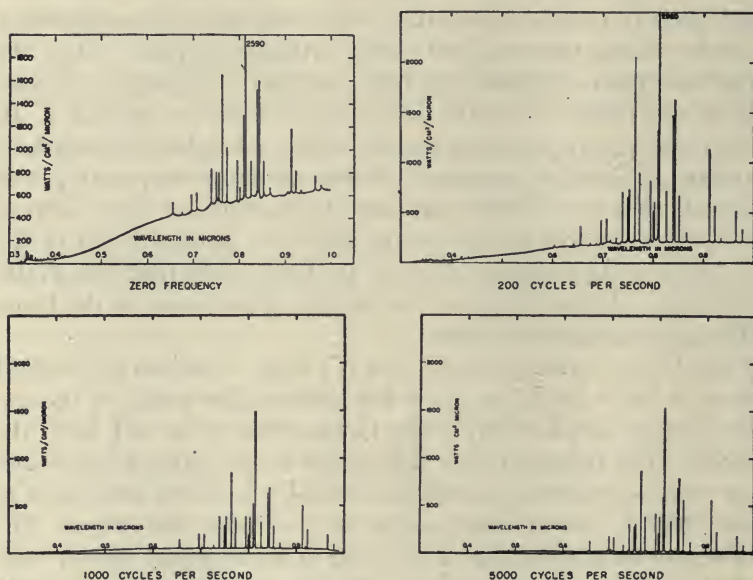


FIG. 1. Spectral distribution of the modulated radiation of a 100-w argon-filled concentrated-arc lamp.

200 cycles, 44 at 1000 cycles, and 18 at 5000 cycles. In the infrared part of the spectrum at 9000 Å, modulation ratios drop to 33 at 200 cycles, 8 at 1000 cycles, and practically zero at 5000 cycles.

The radiation from the gas and vapor cloud, of the cathode-glow region of the arc, can be almost completely modulated. It shows a modulation ratio of 85 per cent or better, a factor which holds for all audio frequencies and for line radiation in all parts of the spectral range. The spectral distribution of the modulated portion of the total radiant energy of a 100-w concentrated-arc lamp when modulated at 0, 200, 1000, and 5000 cps is shown by the curves of Fig. 1.

These curves show that, as the modulating frequency is increased, the amplitude of the continuum, in any spectral region, decreases by a much larger factor than the amplitude of the lines. Also, the modulation ratio appears to be more favorable in the ultraviolet and blue end of the spectrum.

That such is actually the case, for a 2-w lamp, is shown by Fig. 2 which plots the average per cent modulation ratio, in spectral bands 0.1 micron or 1000 Å wide, at a 1000-cycle modulating frequency. This shows that, in the ultraviolet, ratios of better than 80 per cent may

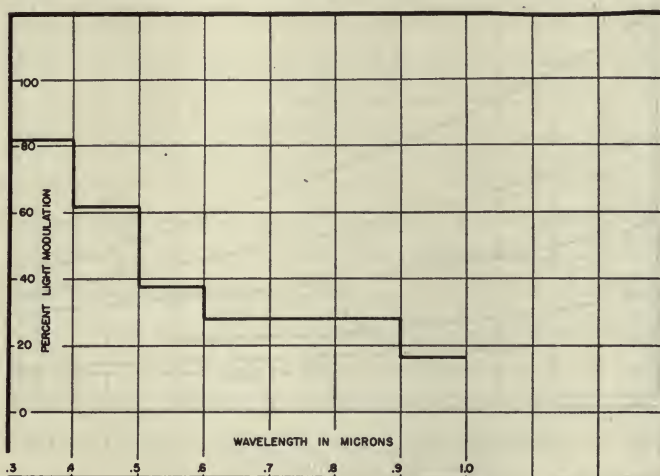


FIG. 2. Average per cent modulation ratios in spectral bands for a 2-w concentrated-arc lamp modulated 100 per cent at 1 kc.

be obtained while, in the infrared, values drop to less than 20 per cent. The flat portion of the characteristic at around 0.8 micron results from the strong argon gas lines, with their high modulation ratios, which occur in this region. The strong downward trend is caused by the modulation characteristic of the continuum.

The radiant output of the lamps is so much greater in the infrared that there is actually more modulated radiation given off in the longer wavelengths than in the ultraviolet, but its degree of modulation is less complete. The choice of which spectral region is to be used will depend upon which factor, quantity or quality, is the most important for the particular application.

In many cases the part of the spectrum employed will be determined by the spectral sensitivity of the receiving device. Thus, if a red-sensitive caesium-silver-oxide type of photoelectric cell is used to measure the modulated light coming from a concentrated-arc lamp, the system will exhibit an entirely different over-all frequency-light characteristic than it would if a blue-sensitive antimony type of photocell or an ultraviolet-sensitive photographic film is employed. Optical filters can be used to further select or restrict the spectral region covered.

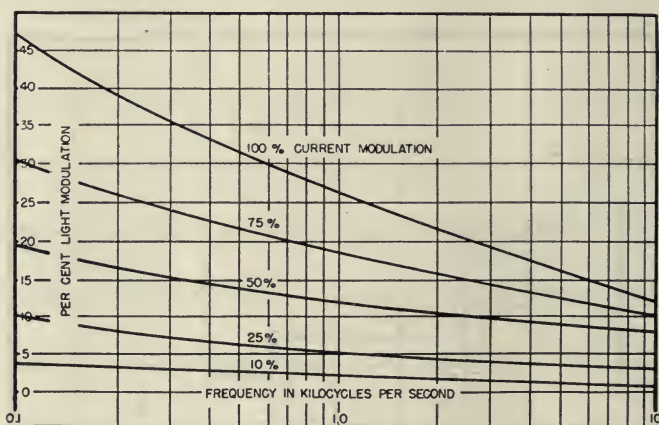


FIG. 3. Frequency characteristic for 2-w concentrated-arc lamp taken with a caesium phototube.

The effect on the over-all modulation ratios of systems using these two different types of photoelectric cells is shown by the figures of Table 1. This shows, for example, that a 2-w argon-filled lamp,

TABLE 1
MODULATION RATIOS

Per Cent Modulation Ratios at 75 Per Cent Current Modulation

Lamp Rating Watts	Gas Filling	Antimony Cell (Freq.)			Caesium Cell (Freq.)		
		200	1000	5000	200	1000	5000
2	Argon	76	63	49	35	25	17
10	Argon	63	57	31	28	23	14
25	Argon	52	35	15	27	18	8
100	Argon	39	22	12	19	12	7
100	Krypton	50	40	24	21	16	9

75 per cent current modulated, if measured with an antimony-type photocell, will show a modulation ratio of 76 per cent at 200 cycles, 63 per cent at 1000 cycles, and 49 per cent at 5000 cycles. If a caesium cell is used, the ratios will be 35 per cent at 200 cycles, 25 per cent at 1000 cycles, and 17 per cent at 5000 cycles.

Among the various sizes of lamps, the per cent modulation ratios show a decrease as the lamp size increases. The tabulation shows that a 100-w concentrated-arc lamp has less than one-half the per cent modulation ratio of a 2-w lamp. The 100-w lamp has about

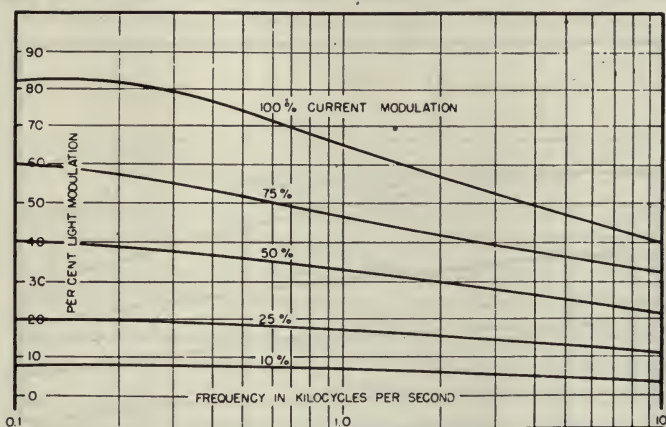


FIG. 4. Frequency characteristic for 2-w concentrated-arc lamp taken with an antimony phototube.

250 times the light output of a 2-w lamp; thus, even with its lower modulation ratio, the modulated light output of the 100-w lamp will be many times that of the 2-w.

Table 1 also shows the effect of a change in the gas used to fill the lamp. The first four lamps listed are argon-filled, while the last is filled with krypton gas. By comparing it to the 100-w argon-filled lamp, it can be seen that there is a considerable advantage in the krypton filling; the average gain in modulation ratio being 56 per cent for the antimony cell, and 21 per cent for the caesium cell. Other gases have been tried in the lamps, but these two are the most satisfactory.

The complete frequency characteristic for a system consisting of a 2-w argon-filled lamp and a caesium-type photoelectric cell is given in Fig 3. This shows the effect on the per cent light modulation of

different modulating frequencies and different percent current modulation. For this particular combination, the maximum per cent light modulation shown is slightly less than 50 per cent. A linear relationship between modulated light output and modulating current is indicated by the uniformity of the spacing of the curves for the various percentages of current modulation.

Fig. 4 shows the same characteristic for a 2-w lamp when combined with an RCA 931 A antimony-type photocell. These curves also show a linear light-current relationship with an increase in the per cent light modulation, whose maximum now exceeds 80 per cent.

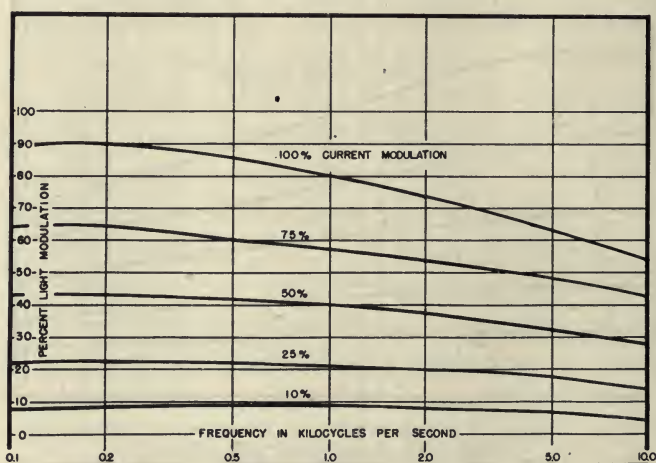


FIG. 5. Frequency characteristic of 2-w concentrated-arc lamps as seen by an antimony phototube through a CG587 filter.

If the spectral region used is restricted further by the addition of a Corning No. 587 ultraviolet-passing glass filter so as to employ radiation which peaks around 3750 Å, which might be suitable for photographic film, a characteristic such as shown in Fig. 5, will be obtained. The use of this filter raises the modulation ratio by amounts ranging from 10 per cent at low audio frequencies to 35 per cent at 10 kc. As a result, the 100 per cent current modulation curve of this combination shows a modulated light output which is flat to within less than 5 db from 100 cycles to 10 kc.

Some gain in the depth of modulation and flatness of the light-frequency characteristic shown in Fig. 4 can be obtained by using a krypton-filled 2-w concentrated-arc lamp with the RCA type 931 A

photocell as is shown in Fig. 6. Further gains result from the addition of the ultraviolet glass filter to produce the curves of Fig. 7. These curves show a maximum light modulation of 93 per cent and a drop with frequency of only 2.3 db between 100 cycles and 10 kc.

The total amount of modulated radiation emitted by concentrated-arc lamps can be more than doubled by increasing the gas pressure of argon or krypton from one to ten atmospheres as is shown by the curve of Fig. 8. Because of the possible danger of explosion, such lamps have not been made commercially.

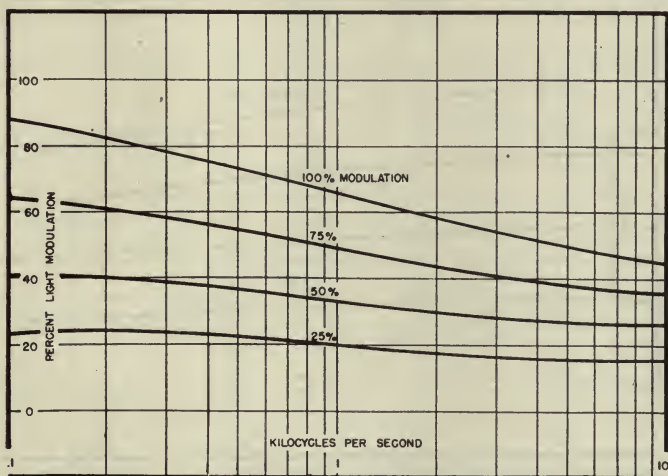


FIG. 6. Frequency characteristic for 2-w krypton-filled concentrated-arc lamp as seen by an antimony phototube.

The dynamic relationship between lamp current and lamp light is not absolutely linear. At the peak of a cycle of modulation, the lamp may be driven to give high light output with good fidelity. On the opposite half of the cycle, as the light output approaches zero, the response becomes nonlinear. This results in a flattening of the negative peaks, which analysis shows to consist largely of second-harmonic distortion. For this reason the percentage of second-harmonic frequency in the modulated light wave is used as a measure of the distortion of the lamps.

A typical distortion characteristic for a 2-w argon-filled concentrated-arc lamp taken with an antimony type of phototube is given in Fig. 9.

Table 2 gives the percentage of second-harmonic distortion of the modulated light output of the several sizes of lamps taken at 75 per cent current modulation and at various frequencies. Percentage of distortion tends to rise with an increase in the percentage of current modulation, the lamp wattage, and the frequency.

The random fluctuations in the light output of the lamps result in background noise in the systems in which they are used. When the 2-w argon-filled lamp is used with an RCA 931 A photocell and Corning No. 587 ultraviolet filter, the noise level is more than 50 db below

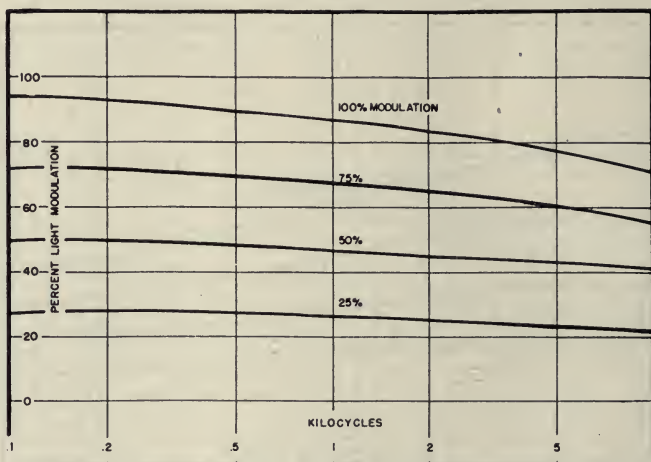


FIG. 7. Frequency characteristic for 2-w krypton-filled concentrated-arc lamp taken with an antimony phototube through a CG587 filter.

the maximum output of the lamp when it is 100 per cent current modulated. The majority of this noise seems to occur in the very low audio and subaudio frequency range and, in radio frequencies, between 100 kc and one megacycle.

TABLE 2
DISTORTION

Per Cent Second-Harmonic Distortion at 75 Per Cent Current Modulation

Lamp Rating Watts	Gas Filling	Antimony Cell (Freq.)			Caesium Cell (Freq.)		
		200	1000	5000	200	1000	5000
2	Argon	1.8	2.2	4.1	10.0	7.7	9.0
10	Argon	4.2	10.5	11.5	4.3	6.8	6.4
25	Argon	5.2	10.5	12.5	4.1	6.1	7.4
100	Argon	7.5	14	22.5	6.2	12.8	15.0
100	Krypton	10.0	17.5	18.8	7.8	12.3	13.0

Over a period of time, the lamps show small changes in modulated light output, as shown by the trace of Fig. 10. The amplitude of these changes in a good lamp is usually of the order of 2 db or less. The relative amplitude of these changes can be reduced if the lamps are operated at slightly higher than normal currents. This will tend to reduce the average life expectancy of the lamps, which for the 2-w lamp, operating on unmodulated direct current, is 175 hrs. When the lamp current is modulated, the life of the lamp may also be reduced. This is probably because of loss of zirconium vapor from the cathode-glow region of the arc during the extreme excursions of the modulation cycle, particularly if the polarity actually reverses.

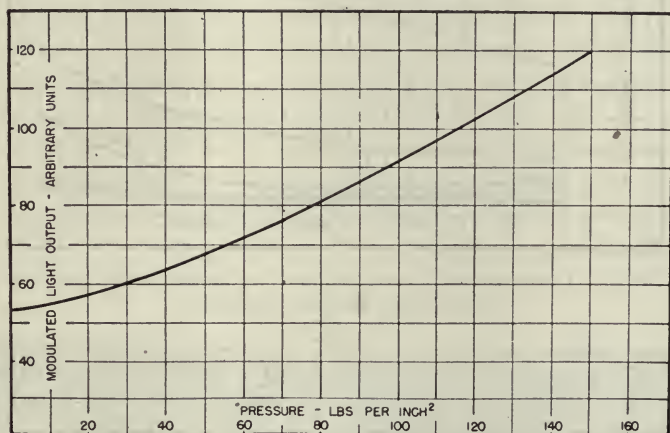


FIG. 8. Relative modulated-light output of concentrated-arc lamps at various gas-filling pressures.

The intensity of the modulated component of the radiation is not constant over the face of the cathode spot. Fig. 11 shows the relative values of modulated light intensity at different frequencies and at different positions in the cathode spot of a 100-w argon-filled lamp as measured with a caesium-type photocell. This diagram shows that the highest modulation intensities are found at the center of the spot.

If the current through a lamp is increased slowly, the diameter of the cathode spot will also increase, with some slight time lag, so that the unit brightness of the surface tends to remain almost constant. If the current is varied at a frequency of a few cycles per second or higher, the spot diameter remains constant, and the variations in current produce an almost linear change in the unit brightness of the

cathode spot. The fact that the dynamic relationship between the modulating current and the light output is linear, at various audio frequencies, is shown by the oscillograms of Fig. 12. These traces also show that there is a phase lag between the current and light,

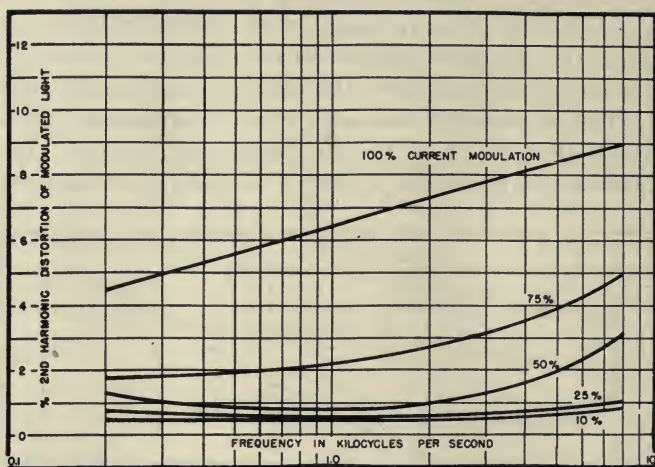


FIG. 9. Distortion characteristics of a 2-w concentrated-arc lamp taken with antimony phototube.

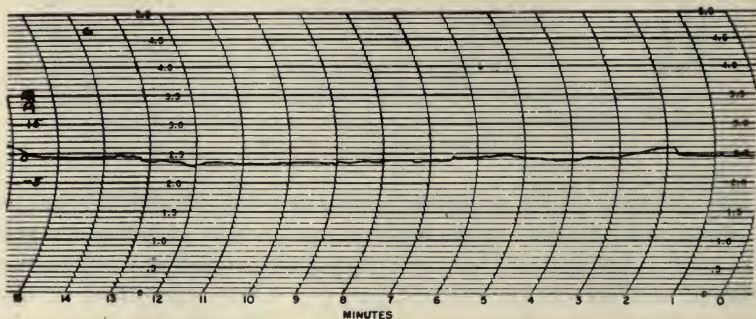


FIG. 10. Slow changes in modulated light output of a 2-w concentrated-arc lamp.

which increases with frequency. In the 2-w lamp, this lag rises to about 35 deg at 10 kc.

In their static characteristic, concentrated-arc lamps, like most arcs, show a negative volt-ampere curve. Thus, as the current is increased, the voltage across the lamp drops, giving the electrical

effect of a negative resistance. For stable operation, positive resistance must be added to the circuit in an amount sufficient to match the negative resistance of the arc and leave a positive surplus.

Fig. 13 shows oscillograms of the volt-ampere characteristic of a 2-w lamp at various audio frequencies. At 10 cycles, the negative slope is quite similar to that of the static characteristic; but, as the frequency increases, the pattern opens up, showing a negative characteristic over only a part of the cycle.



FIG. 11. Relative modulated brightness at various frequencies and at different parts of the light-source spot of a 100-w concentrated-arc lamp.

Impedance and phase characteristics of 2-w lamps are shown by the curves of Fig. 14. When operated at rated current and 50 per cent current modulation, the lamp acts as an inductive load with an average impedance, over the audio-frequency range, of about 200 ohms. As the frequency increases, this impedance Z at first decreases, reaches a minimum of 150 ohms at 1200 cycles, and then increases to 270 ohms at 10 kc. The resistive component R of this impedance has a value of minus 260 ohms at 100 cycles, reaches zero at 2600 cycles, and rises to 200 ohms at 10 kc. The voltage-current phase-angle curve θ_{EI} shows that the current lags the voltage, the lag decreasing as the frequency increases. The light always lags the current, the amount increasing with frequency, as shown by the current-light phase-angle curve θ_{IL} .

The impedance and phase characteristics of the larger wattage lamps show similar trends. Fig. 15 shows that the impedance of the 10-w lamp is 7 ohms at 1000 cycles, and that its resistive component becomes positive at 900 cycles.

The 25-w lamp of Fig. 16 shows an impedance of 5 ohms at 1000 cycles, and its resistance is positive at frequencies above 200 cycles.

Fig. 17 shows the same trends for the 100-w lamp. Here the 1000-cycle impedance is 1.5 ohms and its resistance becomes positive at a frequency less than 100 cycles.

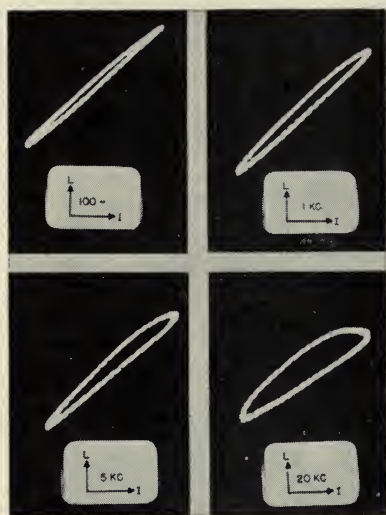


FIG. 12. Oscillograms of the dynamic light-current characteristic of a 2-w concentrated-arc lamp at various frequencies.

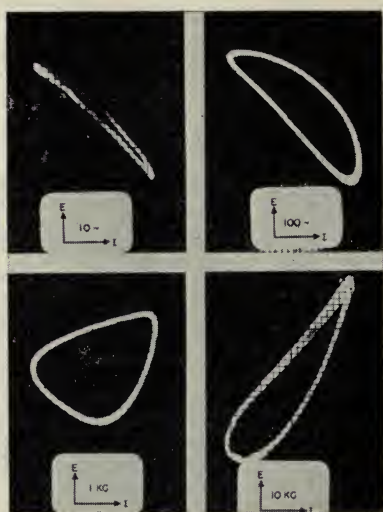


FIG. 13. Oscillograms of the dynamic volt-ampere characteristics of a 2-w concentrated-arc lamp at various frequencies.

Modulating circuits for concentrated-arc lamps are of two general types. The first, shown in Fig. 18, is applicable to 2-w lamps only. The impedance of this lamp is high enough so that it can be connected directly into the plate circuit of a vacuum tube, such as a 6L6, the modulating voltage being applied to the grid. Only 0.055 amp of direct current is required to maintain the arc, and this can be supplied by the normal plate current of the modulator vacuum tube.

In this circuit, the lamp is started automatically by a small spark coil, which is controlled by a relay in series with the lamp. In

practice, a pentode connection for the modulator tube would be preferred because of the stabilizing effect of the higher plate impedance

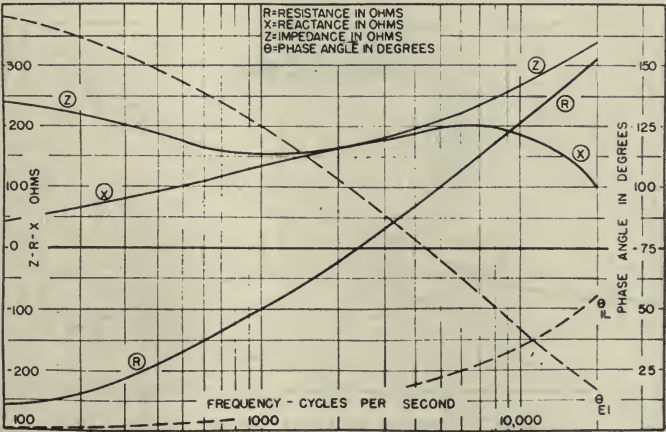


Fig. 14. Impedance and phase characteristics of 2-w concentrated-arc lamps.

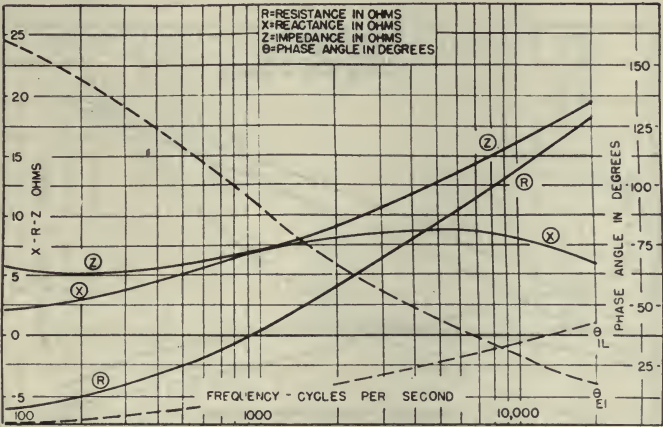


Fig. 15. Impedance and phase characteristics of 10-w concentrated-arc lamps.

and its more nearly constant current characteristic. There are also advantages in the use of negative current feedback.

Fig. 19 shows a type of modulator circuit which can be employed with all sizes of concentrated-arc lamps. Here, the lamp is coupled

to the modulator tube through a suitable impedance matching transformer, and the direct current for the arc is drawn from a separate supply. Manual starting is used in this circuit. The high voltage

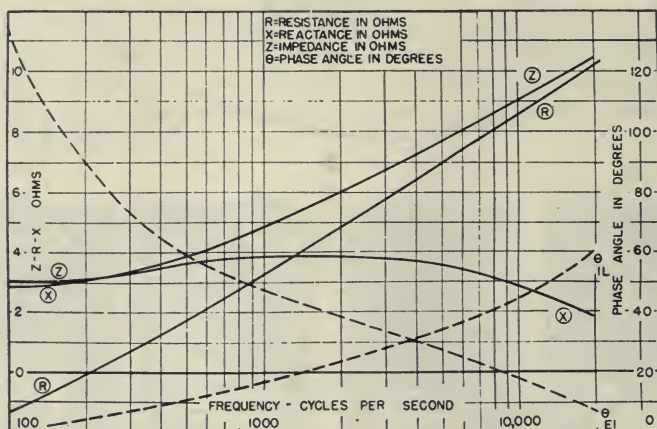


FIG. 16. Impedance and phase characteristics of 25-w concentrated-arc lamps.

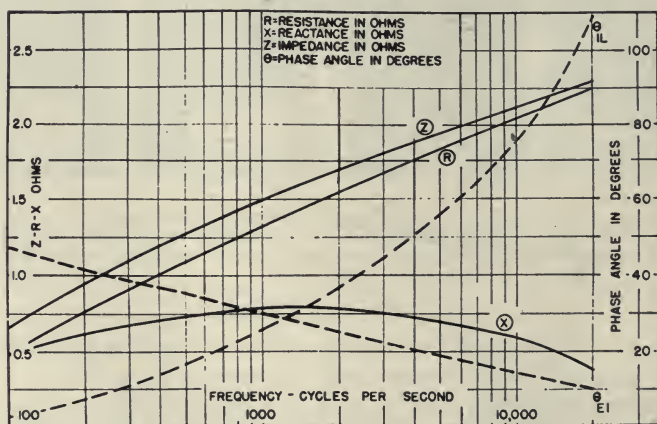


FIG. 17. Impedance and phase characteristics of 100-w concentrated-arc lamps.

necessary to start the arc is obtained from an inductive surge produced when a vacuum-type shorting switch is opened in the highly inductive direct-current supply circuit.

In the design of such modulators, consideration must be given to the unusual impedance characteristics of the lamps. For example, the 2-w lamp has a negative resistance at frequencies lower than 2600

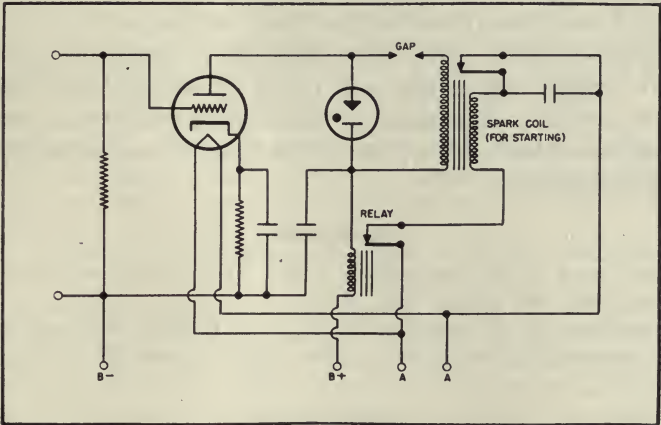


FIG. 18. Direct-coupled modulator circuit for 2-w concentrated-arc lamps.

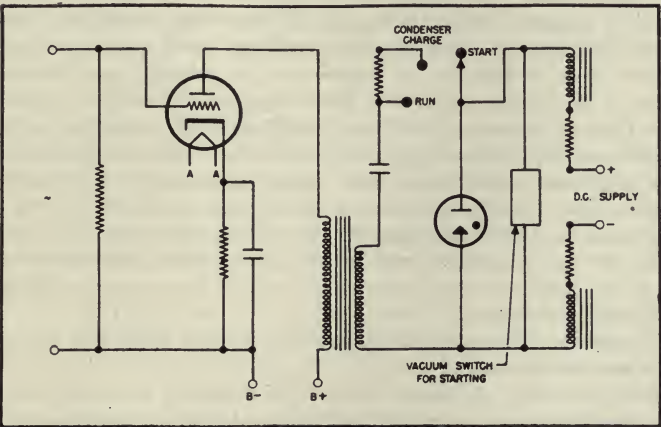


FIG. 19. Transformer-coupled modulator circuit for concentrated-arc lamps.

cycles. If this lamp is put into a circuit whose natural resonance is less than 2600 cycles, and if the positive resistance of the circuit is less than the negative resistance of the lamp, the circuit will oscillate. Thus, resistance must be added to some circuits to secure stability.

The actual power required to modulate the lamps, with the necessary circuit and stabilizing resistance, varies from about 2 w for a 2-w lamp to 50 w for a 100-w lamp. Modulating power requirements, for a given percentage of current modulation, rise with the increase of modulating frequency for all sizes of lamps.

A concentrated-arc lamp thus furnishes a source of modulated radiation which has unique and useful characteristics. The 2-w lamp, in particular, is adapted to applications requiring a source of high brightness, high percentage of light modulation, low background noise, and high fidelity.

REFERENCES

¹ BUCKINGHAM, W. D., AND DEIBERT, C. R.: "The Concentrated-Arc Lamp," *J. Opt. Soc. Amer.*, **36**, 5 (May 1946), p. 245.

² BUCKINGHAM, W. D., AND DEIBERT, C. R.: "Characteristics and Applications of Concentrated-Arc Lamps," *J. Soc. Mot. Pict. Eng.*, **47**, 5 (Nov. 1946), p. 376.

DISCUSSION

MR. R. S. LEONARD: What is the output of the 100-w lamp in lumens?

MR. BUCKINGHAM: On a candlepower basis, the 100-w lamp is quite similar to the 100-w tungsten filament lamp, giving about one candlepower per watt. Since the lamps have a cosine spatial distribution rather than spherical, when you convert from candlepower to lumens, you can multiply only by π instead of four π , so the lumen output of a 100-w lamp is π times 100, or about 300 lumens. That is the reason we do not recommend these lamps for applications where total quantity or lumen output is important. Their use is indicated where the high brightness of the source is of major importance. The brightness is several times that of a tungsten filament and in many places that is very useful. Also, the source is so extremely small that in optical systems it has the advantage of forming the stop of the system in many applications to give unusual results. But the lumen output is only one-fourth of that of the corresponding tungsten lamp with equal efficiency.

MR. LEONARD: What would be the expected life at 3000-cycle operation of the 100-w size—continuous?

MR. BUCKINGHAM: We do not know. We have had some experience that indicates that the life is less under conditions of modulation than it is when operated with direct current, but now and then we have a lamp that comes along and lasts and lasts and lasts, under conditions of modulation, which I guess only proves that our lamps are not all exactly alike. For example, we have a 10-w lamp operating in New York City now which has been going steadily for over six months. I do not know the number of hours that would figure out, but since we expect a life of about 800 hr for the 10-w lamp, something is wrong there. So I do not know what length of life you would get in a 100-w lamp.

MR. LEONARD: Would you estimate in terms of hours just roughly?

MR. BUCKINGHAM: I would guess you would get somewhere near the normal length of life, which is 1000 hr. We think if you over-modulate the lamp so as to reverse the polarity, you may carry away enough of the active material to shorten the life very greatly.

DR. J. G. FRAYNE: What is the signal-to-noise ratio, approximately?

MR. BUCKINGHAM: It was not on the curve, but I gave it as being better than 50 db below the maximum output of the lamps. We do not know the exact figure because when we got 50 db below, we ran into 60-cycle hum which we were picking up because of an inadequate filter in the power supply.

DR. FRAYNE: Have you made any recordings on film?

MR. BUCKINGHAM: We have not. Being a communication company we do not have those facilities. That was one of the reasons for coming out here. We are hoping that somebody with those facilities will make the test and see what actually turns up.

MR. L. G. DUNN: Can you tell us the progress being made with high-wattage lamps?

MR. BUCKINGHAM: There has been a great deal of interest in the higher wattage lamps, and we have had them up to about 1500 watts in operation in the laboratory. The 1500-w lamp, for example, has a source spot about $\frac{3}{8}$ in. or a little less in diameter, giving about 4000 cp. This means that it has a unit brightness which figures out about 70 candles per sq mm. That is a large enough spot size so that it could be used in a 35-mm projector with an ordinary condensing system. We have been working hard on this particular phase of the lamp development, because there is so much interest in it, and expect shortly after the first of the year to have something that we can show people. The lamps so far have been of a highly experimental nature, but very, very promising in their performance.

MR. DUNN: What specific applications have been made?

MR. BUCKINGHAM: The applications that have been made so far have been, of course, with the smaller lamps, which are now available, the 2- to 100-w sizes. The major applications have been perhaps in the field of photography and microscopy. In a photographic enlarger the use of the point source lamp in a condenser system acts as a stop of the lens system so that the pictures you get are extremely sharp in comparison to those you would get on the same system using a larger source lamp.

MR. P. A. WILLIAMS: Mention was made of the appreciable radiation of these lamps in the ultraviolet and infrared regions and it would seem that the latter would be a rather important factor in the heat radiation and necessary cooling equipment. It would be interesting to learn whether or not it has been found necessary to provide forced air or other means of cooling when these lamps are used in enclosures.

It is also suggested that some information be provided regarding the effects of operating temperature on the light output. Several attempts have been made in the past to use gaseous discharge tubes for photographic printing but the variability of light output with temperature has made the practical use of such sources rather difficult.

MR. BUCKINGHAM: The spectrum of the concentrated-arc lamp differs from that of the tungsten-filament lamp only in that it shows a few sharp peaks of

line radiation which originate in the gas discharge and also in that the concentrated-arc lamp is several times as bright as the tungsten-filament lamp.

There is no greater proportion of ultraviolet or infrared in the output of a concentrated-arc lamp considering its increased brightness in the visible. It has the same advantages in these spectral regions as it has in the visible, those of high brightness or concentration of energy and small-source size.

From a practical standpoint, 100 w of electrical energy put into a concentrated-arc lamp will produce no more heat than 100 w put into a tungsten-filament lamp. However, because of the high brightness of concentrated-arc lamps, it is possible in some applications to substitute a 100-w concentrated-arc lamp for a 500-w tungsten-filament lamp without decreasing the useful light output of the equipment. In this case, there will be only one-fifth as much heat given off by the concentrated-arc lamp as by the tungsten lamp.

The second question has to do with the effect on lamp operation of the room or operating temperature. We have been unable to detect any difference in the lamp operation or light output as the external temperature is varied over a range of several hundred degrees. The lamps are not critical in this respect.