Efficiency and stroboscopic effect of fluorescent lamps as affected by circuit characteristics
by Ralph B Hammerstrom

A THESIS Submitted to the Graduate Committee in partial fulfillment of the requirements for the degree of Master of Science in Electrical Engineering
Montana State University

Abstract:
The purpose of this investigation was to determine the stroboscopic effect and efficiency of fluorescent lamps as affected by circuit characteristics* The tests were made on standard two-lamp circuits with a third lamp in series, using standard 15-watt and 20-watt, white fluorescent lamps* The efficiency of the 15-watt, lamp circuits increased from 3.38 relative-lumens per watt for the 15-watt, two-lamp circuit to 3.52 relative-lumens per watt for the three-lamp circuit. The efficiency of the 20-watt, lamp circuits increased from 3.36 relative-lumens per watt for the two-lamp circuit to 4.31 relative-lumens per watt for the 20 watt three-lamp circuit* The percentage of deviation of light output or stroboscopic effect were 6 and 11 per cent for the 15-watt and 20-watt, three-lamp circuits respectively. The percentage of deviation of light output of a two-lamp circuit is 16 per cent * A secondary consideration was the harmonic content of the line current. Harmonic content was 24 per cent of the fundamental for the 15-watt, three-lamp circuit and 16 per cent of the fundamental for the 20-watt, three-lamp circuit. The harmonic content of the line current of a two-lamp circuit is approximately 20 per cent of the fundamental.

EFFICIENCY AND STROBOSCOPIC EFFECT OF
FLUORESCENT LAMPS AS AFFECTED BY
CIRCUIT CHARACTERISTICS

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RALPH B. HAMMERSTROM

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ABSTRACT

The purpose of this investigation was to determine the stroboscopic effect and efficiency of fluorescent lamps as affected by circuit characteristics.

The tests were made on standard two-lamp circuits with a third lamp in series, using standard 15-watt and 20-watt, white fluorescent lamps.

The efficiency of the 15-watt, lamp circuits increased from 3.38 relative-lumens per watt for the 15-watt, two-lamp circuit to 3.52 relative-lumens per watt for the three-lamp circuit. The efficiency of the 20-watt, lamp circuits increased from 3.36 relative-lumens per watt for the two-lamp circuit to 4.31 relative-lumens per watt for the 20 watt, three-lamp circuit.

The percentage of deviation of light output or stroboscopic effect were 6 and 11 per cent for the 15-watt and 20-watt, three-lamp circuits respectively. The percentage of deviation of light output of a two-lamp circuit is 16 per cent.

A secondary consideration was the harmonic content of the line current. Harmonic content was 24 per cent of the fundamental for the 15-watt, three-lamp circuit and 16 per cent of the fundamental for the 20-watt, three-lamp circuit. The harmonic content of the line current of a two-lamp circuit is approximately 20 per cent of the fundamental.

I INTRODUCTION

The purpose of this investigation was to determine the stroboscopic effect and efficiency of fluorescent lamps as affected by circuit characteristics.

The stroboscopic effect of fluorescent lamps is a matter of considerable discussion among illumination engineers, opthalmologists and optometrists. Morgan[1] states that Pacific Northwest opthalmologists and optometrists report that 20 to 33 1/3 per cent of all patients say eyestrain was first noticed when they started working under fluorescent lamps. Morgan[1] also wrote, "As to the stroboscopic effect, this is an obvious defect in fluorescent lighting."

The largest use of fluorescent lamps is on alternating current sources. The light output of fluorescent lamps follows the cyclic current variations. Therefore, the light output drops almost to zero, except for phosphorescent effects, when the current drops to zero. Such variations in the light output are termed the stroboscopic effect and are measured as the per cent of deviation of light output from the mean.

Commercial single-lamp installations have a per cent of deviation of 35 per cent for white fluorescent lamps and 55 per cent for daylight fluorescent lamps[2]. This has been improved by the use of two lamps operated in parallel; one leading the line voltage by 60 degrees, and one lagging by 60 degrees. The two-lamp installations reduced the stroboscopic effect to 25 per cent for daylight lamps and 16 per cent for white lamps. Operation of three daylight lamps on separate phases of a three-phase supply reduces the stroboscopic effect to 5 per cent, which is comparable to the 5 per cent deviation of 100-watt incandescent lamps and better than the 13 per cent deviation of 40-watt incandescent lamps[2]. Three white lamps on separate phases of a three-phase supply have a deviation of 3 per cent. Because of the equivalent three-phase light output of the experimental circuits, a 3 per cent deviation is theoretically possible. The three-lamps circuits investigated

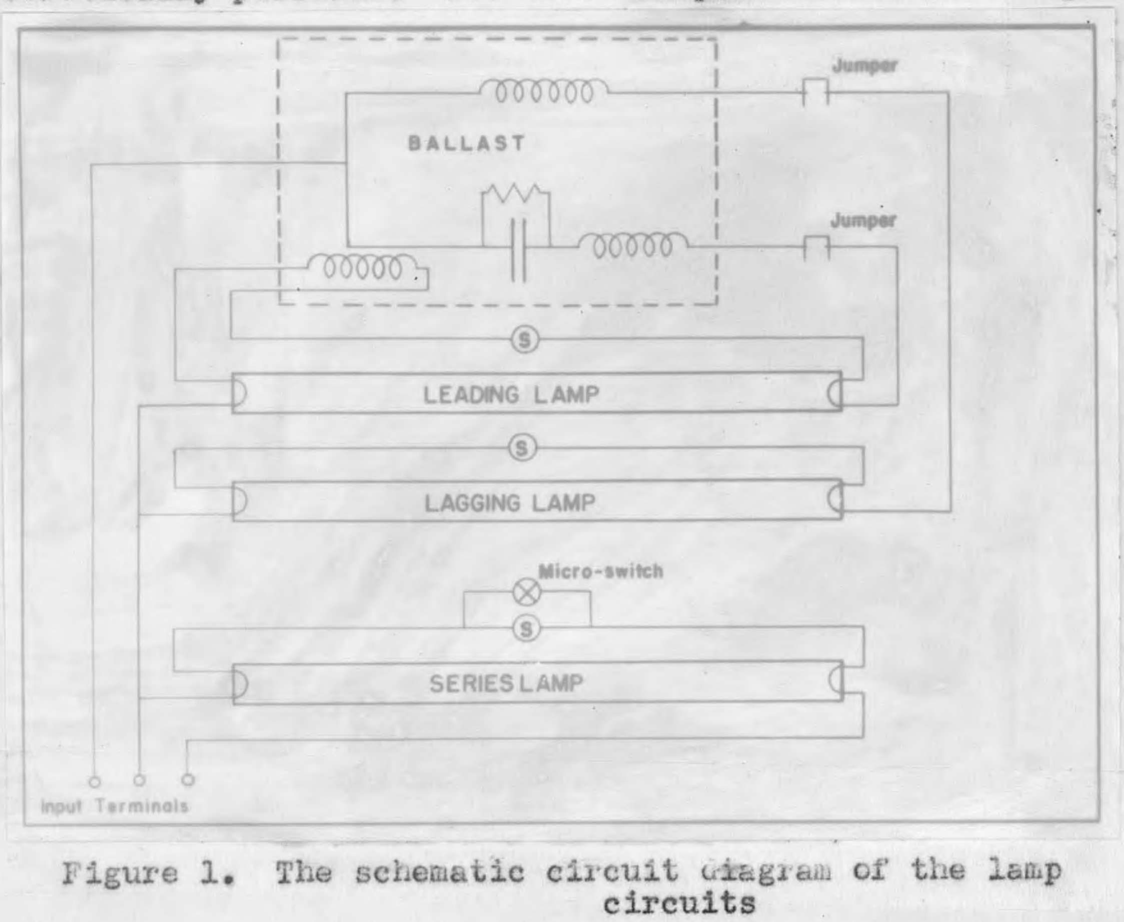


Figure 1. The schematic circuit diagram of the lamp circuits

had deviations of 6 per cent for the 15-watt circuit and 11 per cent for the 20-watt circuit.

Three-phase supply is not available at the majority of fluorescent lamp installations. Therefore, for a reduced stroboscopic effect on single-phase supply, some method of phasing lamps properly must be employed. A complicated circuit could be designed to operate satisfactorily but the primary consideration of this investigation was the use of commercially available equipment. The circuit investigated was a commercial two-lamp installation with a third lamp connected in series with the line supply and the two-lamp installation. The schematic circuit diagram is shown in Fig. 1 and the vector diagram of currents and line voltage in Fig. 2.

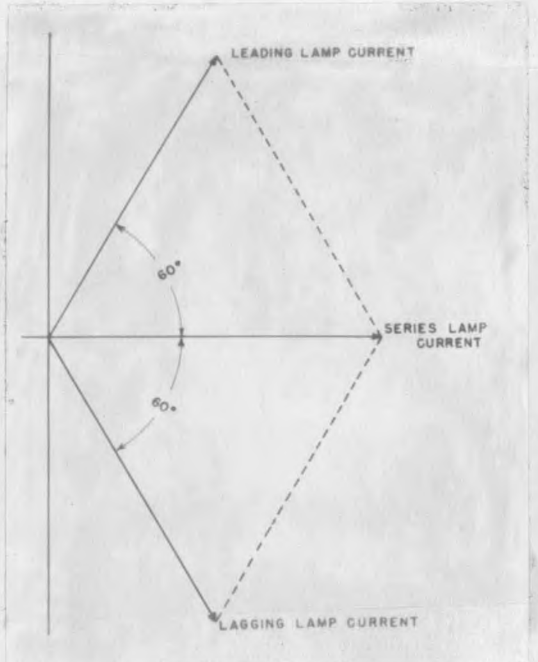


Figure 2. Vector diagram of lamp currents

The efficiency determination of the circuit that was used for this study is not a complete analysis of energy distribution. A complete analysis would involve equipment that was not available. Factors such as the conduction and convection of heat, lumen output, radiated heat and ultra-violet conversion would have to be considered for a complete analysis[2]. Therefore, an efficiency comparison of the three-lamp circuit with a commercial two-lamp circuit using white lamps constituted the efficiency study.

Because of the effect of a distorted current wave upon the efficiency and light output, a secondary consideration of this investigation is the distortion factor of the current waves. The distortion factor is a ratio of the effective value of the harmonic content of a wave to the effective value of the total wave[3]. Peterson and Blakeslee[3] say that the distortion factor should be 0.25 or less. Using the Fourier graphical method of wave analysis, distortion factors of 0.24 for the 15-watt, three-lamp circuit and 0.16 for the 20-watt, three-lamp circuit were determined.

II EQUIPMENT AND PROCEDURES

A. Equipment

The equipment used in this investigation consisted of the following: two, three-lamp chassis shown in Fig. 3; one single-lamp chassis; a variable auto-transformer; three a-c ammeters; an a-c voltmeter; a wattmeter; a vacuum-tube voltmeter; an electronic phototube circuit; a three-stage amplifier; an icosohedron photometer; a Macbeth illuminometer;

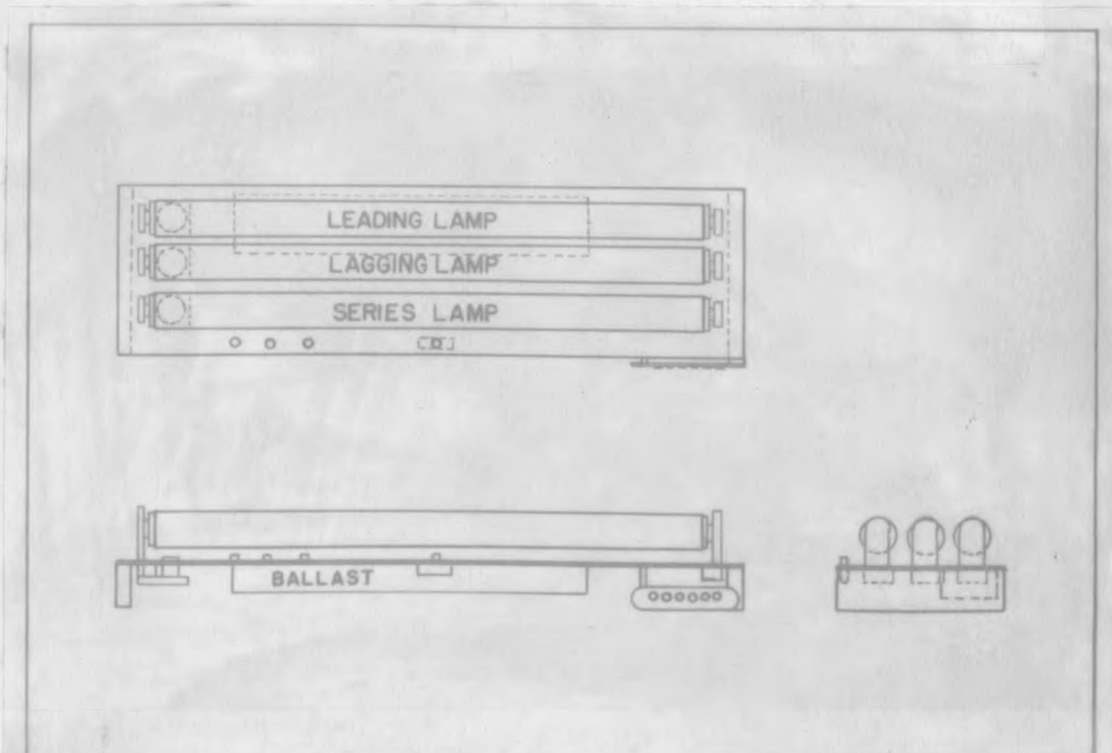


Figure 3. Lamp chassis assembly

three one-ohm shunts; and a magnetic oscillograph.

The lamp chassis were cut from masonite with wooden supports at each end. The circuit components necessary for operation were mounted on the lamp chassis as shown in Fig. 3.

General Electric TU-Lamp ballasts were used in the two, three-lamp circuits. The 20-watt lamp ballast is rated 0.45 line amperes at 118 line voltage, 60 cycle, with a full-load loss of 9 watts and a full-load power factor of over 90 per cent. The Catalog Number of the 20-watt, two-lamp ballast is 58G678. The 15-watt-lamp ballast is rated 0.35 line amperes at 118 line volts, 60-cycle, with a full-load loss of 9 watts. The Catalog Number of the 15-watt, two-lamp ballast is 58G679. The single-lamp circuit used a Jefferson Electric Corporation, 15-watt-lamp ballast. The ballast is rated at 0.16 line amperes at 118 line volts. The ballast is 218752.

The two, three-lamp chassis were supplied with three power-input terminals. One is common, and is connected to the line input of the ballast. The other two terminals are connected so that either the three-lamp series circuit or the conventional two-lamp circuit may be used. Other terminals on the lamp boards. are jumper connection terminals between the ballast and lamps. FS-2, glow-type starters were installed for starting the two parallel lamps. A microswitch was installed for starting the series lamp. Provision was also made for the use of a glow starter with the series tube. For the complete schematic circuit diagram of the three-lamp chassis, see Fig. 1.

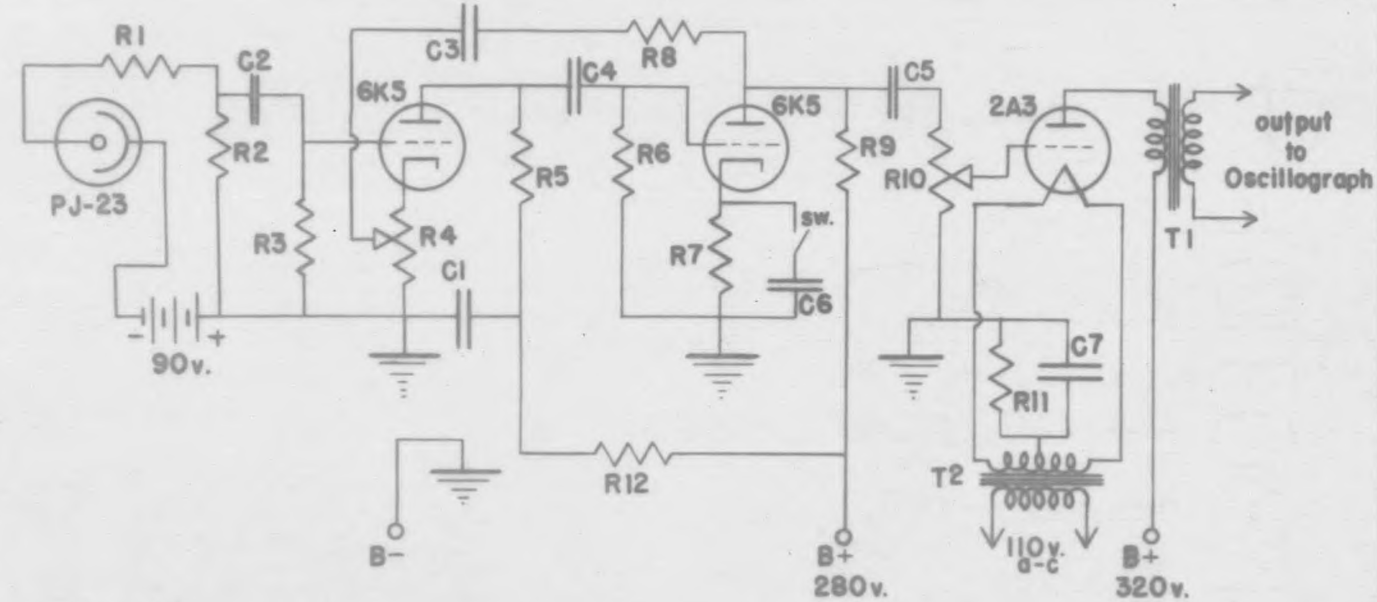
The single-lamp circuit was constructed in a similar manner as the preceding three-lamp circuits. Two line-input terminals and a jumper connection between the lamp and ballast were provided. The single, fluorescent lamp was supplied with a microswitch and a glow starter connection for starting.

The variable auto-transformer was a 220-volt, three-phase, open-delta variac.

The a-c ammeters used had a range of 0-1 amperes. Standards for calibrating the ammeters were not available, but the ammeters were checked with several available ammeters and the deviation was found to be one per cent or less from the average of all ammeter readings.

The a-c voltmeter used had two voltage ranges. The two scales were 0-150 volts and 0-300 volts. The voltmeter was calibrated with a standard and was found to have less than 0.5 per cent error per reading.

The a-c wattmeter used had two voltage ranges and two current ranges. The two voltage ranges were 0-100 volts and 0-200 volts. The two current ranges were 0-0.5 amperes and 0-1 amperes. The wattmeter was checked against a standard. Reading errors of three per cent were found. On the basis



Parts List

PJ-23 - Gas Photo Tube
R1, R2 - 1 Megohm Resistor
R3 - 50,000 ohm Resistor
R4 - 1000 ohm Potentiometer
R5 - 0.10 Megohm Resistor
R6 - 0.47 Megohm Resistor
R7 - 1000 ohm Resistor
R8 - 0.15 Megohm Resistor
R9 - 0.12 Megohm Resistor
R10 - 1 Megohm Resistor
R11 - 800 ohm Resistor

T1 - Output Transformer, Pri - 8000 ohm, Sec - 15 ohm
T2 - Filament Transformer

C1 - 8 mfd. Cond.
C2 - 0.25 mfd. Cond.
C3 - 0.5 mfd. Cond.
C4 - 0.006 mfd. Cond.
C5, C6 - 0.1 mfd. Cond.
C7 - 50 mfd., 120 volt Electrolytic Cond.

Figure 4. Schematic circuit diagram of the electronic phototube and amplifier.

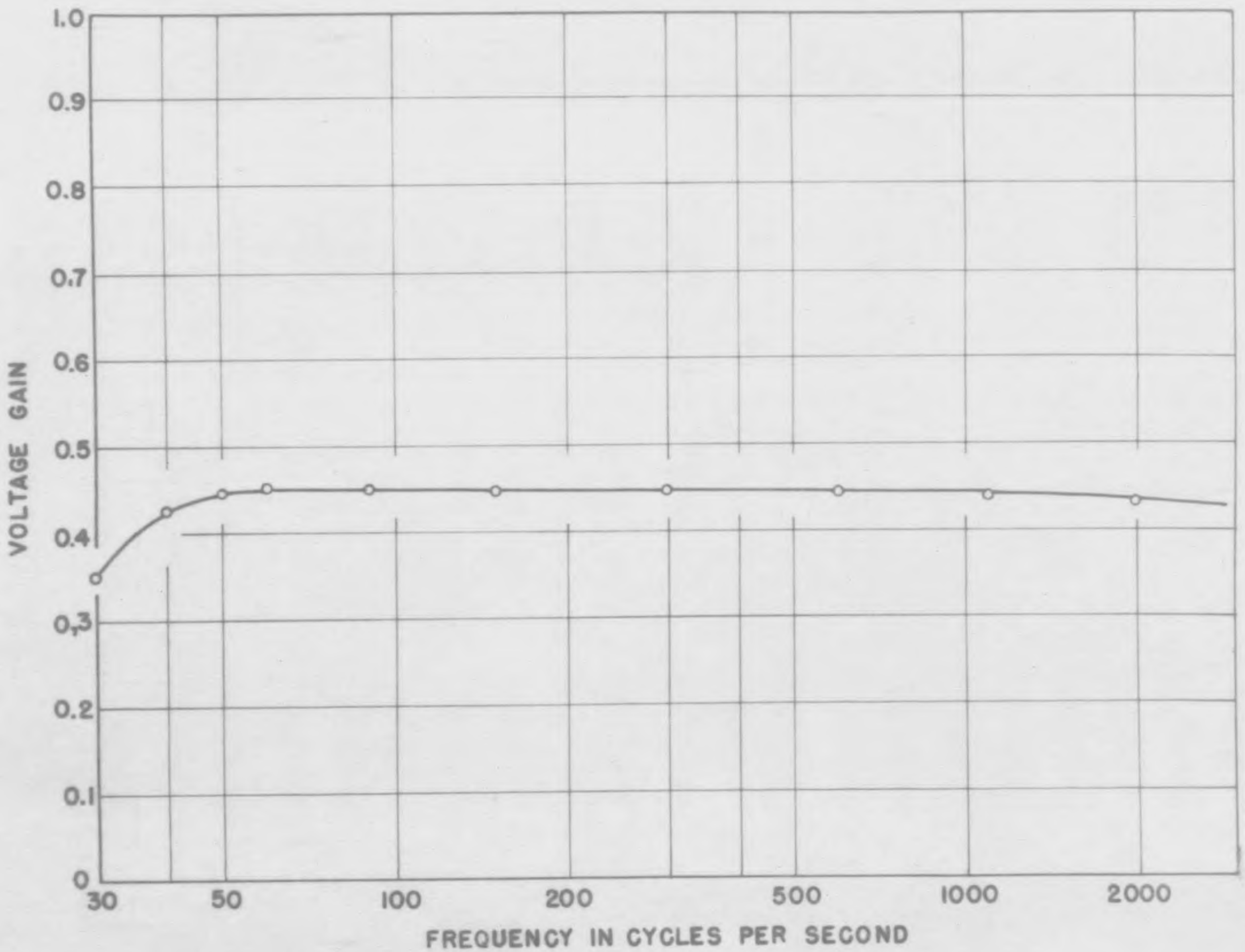


Figure 5. Frequency characteristic of the amplifier.

of the determined error per reading, the power data was corrected.

The vacuum-tube voltmeter used had a-c scales of 0-.5, 0-2.5, 0-10, 0-50, 0-250 and 0-1000 volts. The vacuum tube voltmeter was not calibrated.

The electronic phototube and three-stage amplifier circuits, as shown in Fig. 4, are one unit. The voltage-gain curve of the amplifier, as shown in Fig. 5, is flat from 60 cycles to 2000 cycles per second. The amplifier was designed for a voltage input and by means of a power tube and step-down output transformer, provided a current output. The tubes used were a PJ-23, 2-6K5's and a 2A3 output tube. The various components are marked on the schematic circuit diagram in Fig. 4.

A General Electric, type PM-10-B2, magnetic oscillograph, serial number 2581755, was used. The oscillograph has six G-1 galvanometer elements, each rated at 500 milliamperes maximum current, and each with a variable resistance, variable in steps from zero to 5000 ohms, in series with the galvanometer element and the input terminals.

The icosohedron photometer was constructed of sheet metal, painted a buff color in the interior and was four feet and seven and one-half inches between faces.

The Macbeth illuminometer, used in conjunction with the icosohedron for determining the relative-lumen output of the lamps, was calibrated with the standard lamp and reflection plate[3].

The three one-ohm shunts were wound with 19 1/4 inches of Manganin resistance wire with 0.625 ohms resistance per foot and calibrated with a Kelvin double bridge.

The fluorescent lamps tested were commercial 15 and 20 watt, white lamps. The 15-watt lamps were manufactured by the General Electric Corporation and the 20-watt lamps were manufactured by the Westinghouse Electric Corporation. Seven, 20-watt lamps were used and ten, 15-watt lamps.

B. Procedures

1. Determination of the Electrical Characteristics of the Circuits.

The meters were connected according to standard procedure[3] to provide readings of the input power, line voltage and line current. The leading-lamp current and the lagging-lamp current were obtained by replacing the jumper connections with ammeters in each of the two, ballast lamp-leads. This connection gave the effective value of each lamp current. Lamp voltage drops were obtained by measuring the potential difference across each lamp with the vacuum-tube voltmeter. A vacuum-tube voltmeter was necessary for these measurements because a standard a-c voltmeter caused a lamp operational change when shunted across the respective lamp. The preceding procedure was repeated several times with the different lamp circuits and average sets of data are shown on Tables I, II, III, IV and V in the Appendix.

The lamp-current phase relationships are shown by the waveshapes that were recorded by making oscillograms. For these data, the one-ohm shunts were used as jumper connections and the voltage drop due to the current through them was used to operate the oscillograph galvanometers. The oscillograph was then adjusted for good deflection and trace intensity. The film magazine was loaded with Tri-X pan film and installed

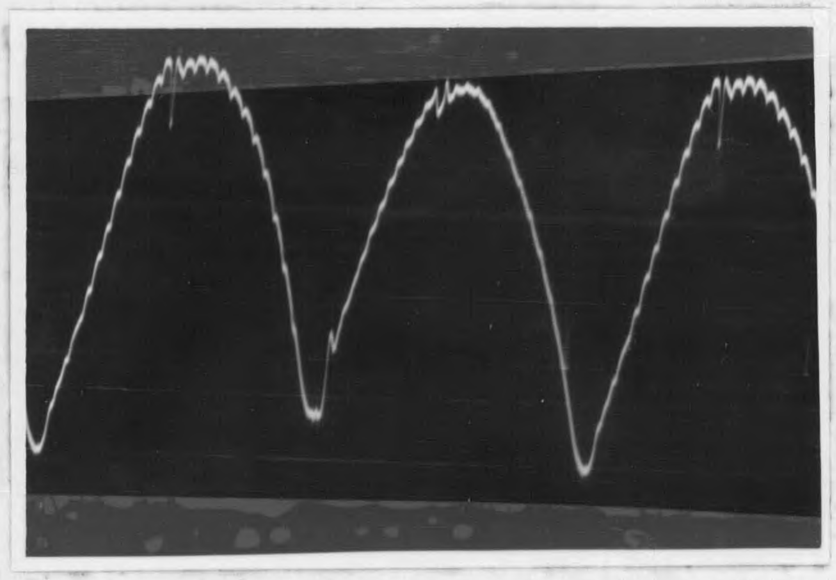


Figure 6. The light-output waveshape of a single, 15-watt lamp

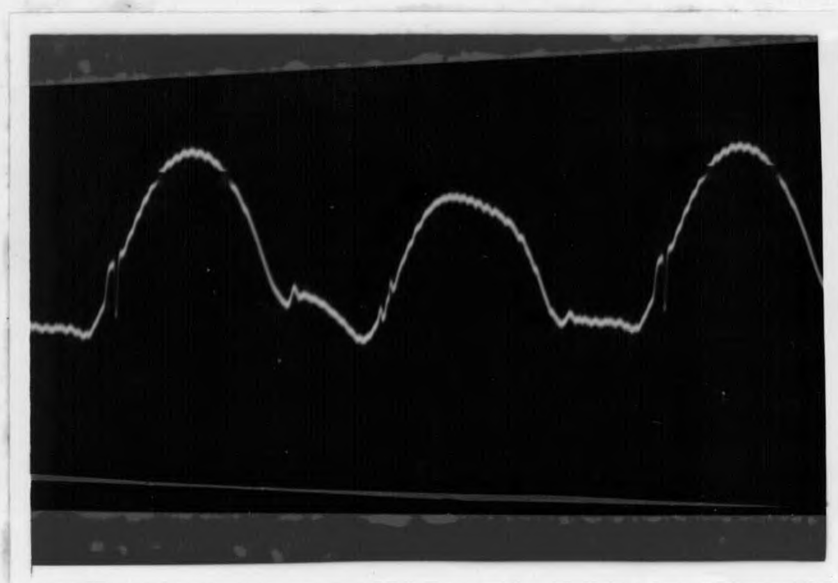


Figure 7. The light-output waveshape of a 15-watt, two-lamp circuit

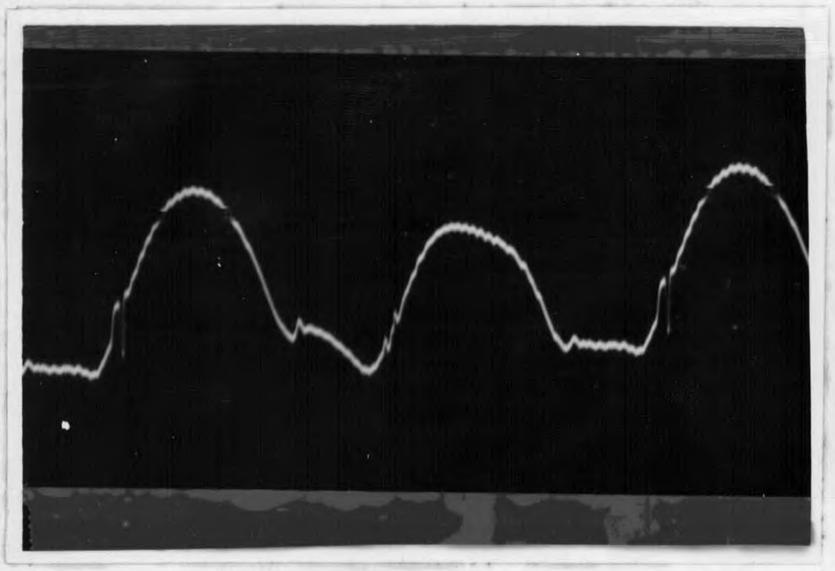


Figure 7. The light-output waveshape of a 15-watt, two-lamp circuit

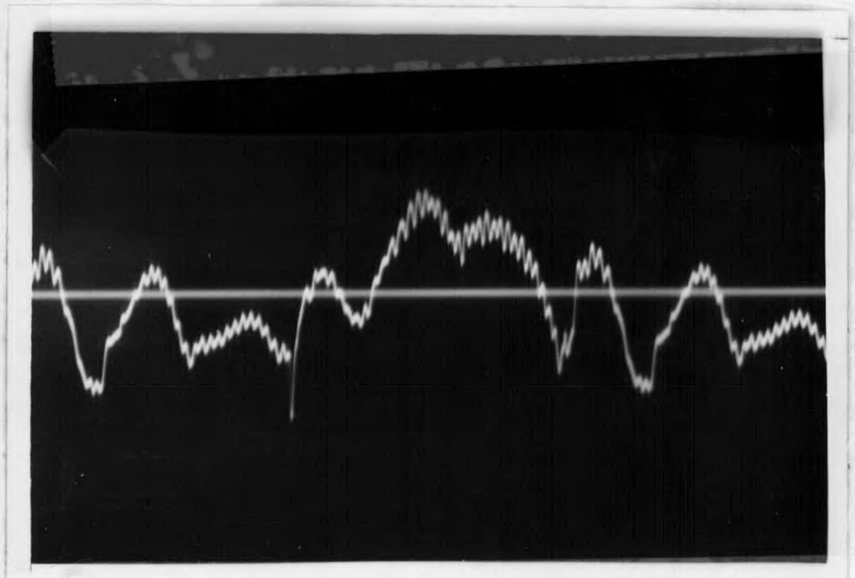


Figure 8. The light-output waveshape of a 15-watt, three-lamp circuit

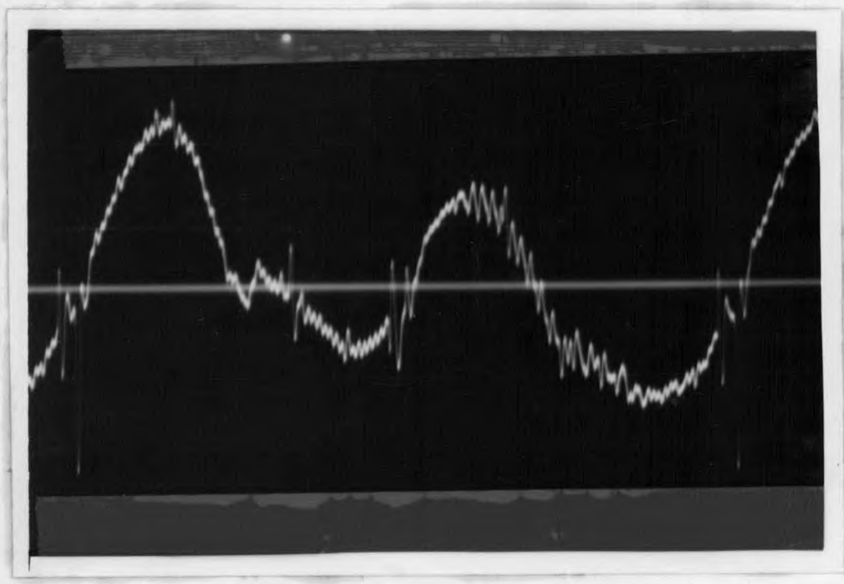


Figure 9. The light-output waveshape of a 20-watt, two-lamp circuit

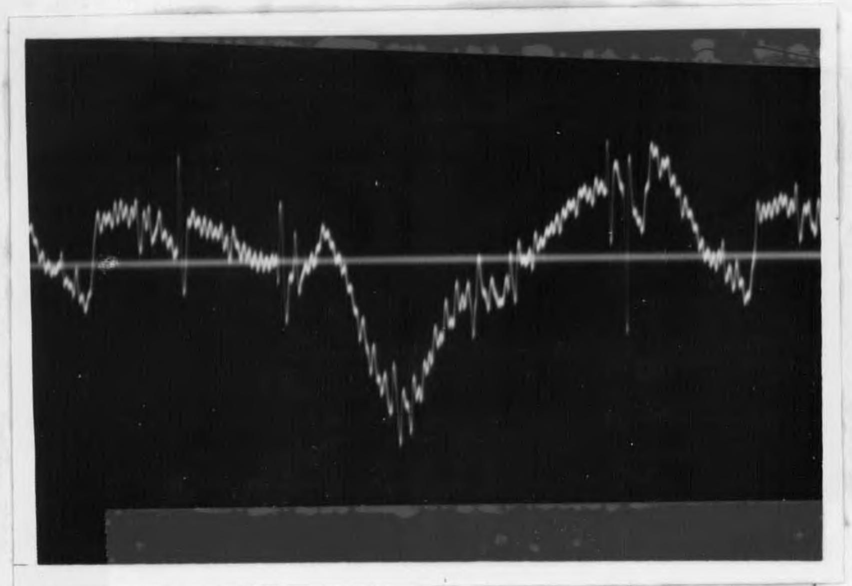


Figure 10. The light-output waveshape of a 20-watt, three-lamp circuit

in position on the oscillograph. Several exposures were made with different input voltages for each lamp circuit. Film magazine speed of rotation was adjusted so that a 60-cycle wave would be 3.3 inches in length on the oscillogram.

2. Determination of the Relative-Lumen Output of the Lamps.

The lamp boards were mounted inside the icosohedron, with standard meter connections outside the icosohedron. The Macbeth illuminometer was used to measure the relative-lumen output of the various lamps in their respective circuits. Lumen outputs for various voltage ranges were obtained for a single 15-watt lamp, two parallel 15-watt lamps, three 15-watt lamps, one in series, two parallel 20-watt lamps and three 20-watt lamps, one in series. Tables VI, VII, VIII, IX and X give sample sets of data.

3. Obtaining the Light-Output-Deviation Waveshapes.

Oscillograms of the light-output deviation of the fluorescent lamps were obtained by using the photo-tube circuit and amplifier. Calibration of the oscillograph for deviation per lumen output of the lamp was effected by measuring the foot-candles produced at the phototube by a single 15-watt lamp and noting the deviation on the oscillograph scale. Figure 6 shows the deviation of the light output for a single, 15-watt, white-lamp circuit. The three-lamp-circuit light waveshapes obtained are shown in Figures 8 and 10. The waveshapes of the light deviation of two-lamp circuits are shown in Figures 7 and 9. A barrier cell light meter and a meter stick were used to maintain a mean light output at the photocell for each lamp circuit. The photocell was overloaded with respect to incident light, but such a procedure was necessary to obtain sufficient galvanometer deflection with the available amplification. An oscillogram was made showing the interference produced by the ionization effect of the electromagnetic fields of the lamp arcs[4], and by the variac on the phototube. This interference could not be eliminated with the equipment available, but is taken into account when measuring the lamp, light-output waveshapes.

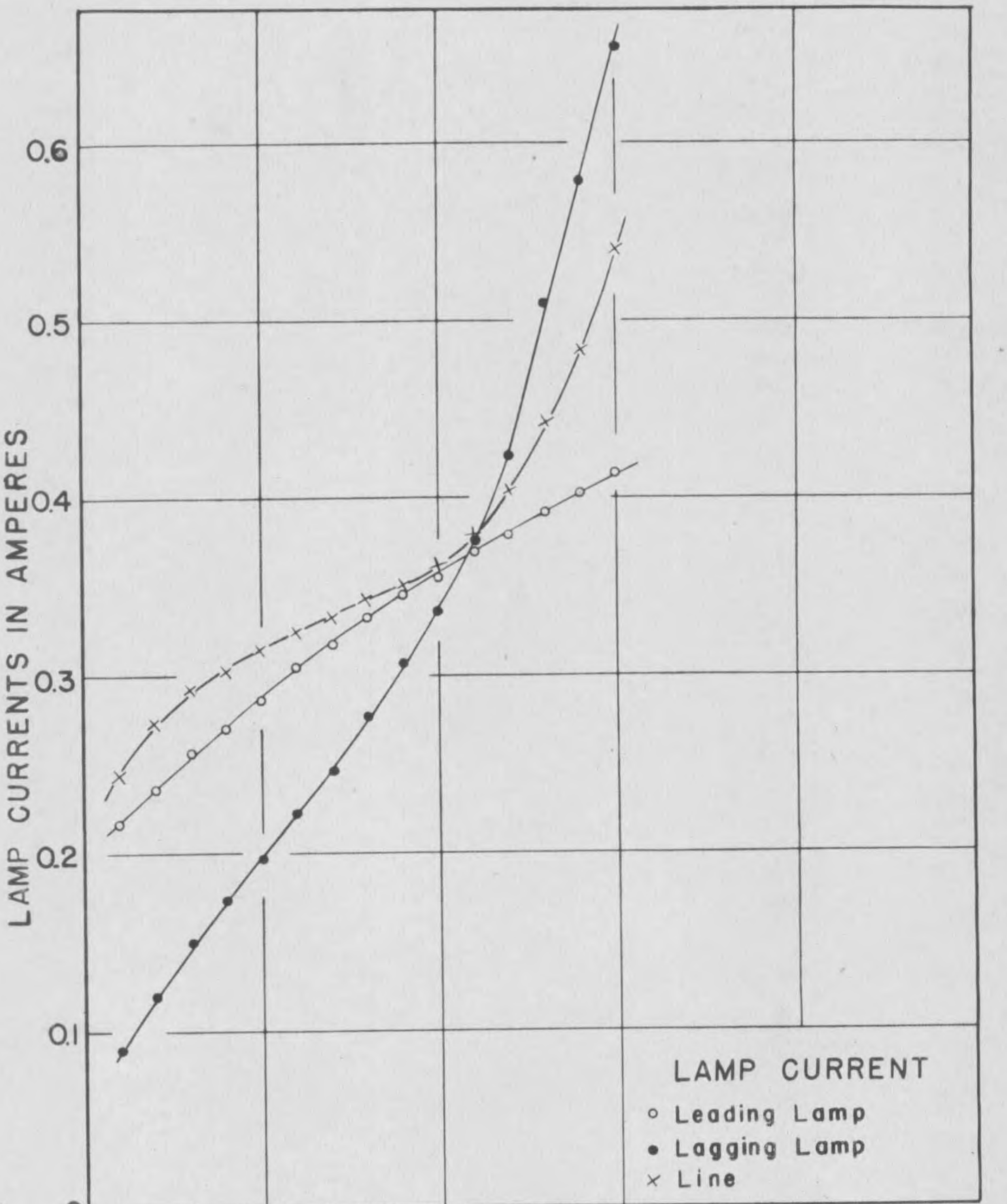


Figure 11. Lamp currents and line current in a 15-watt, two-lamp circuit

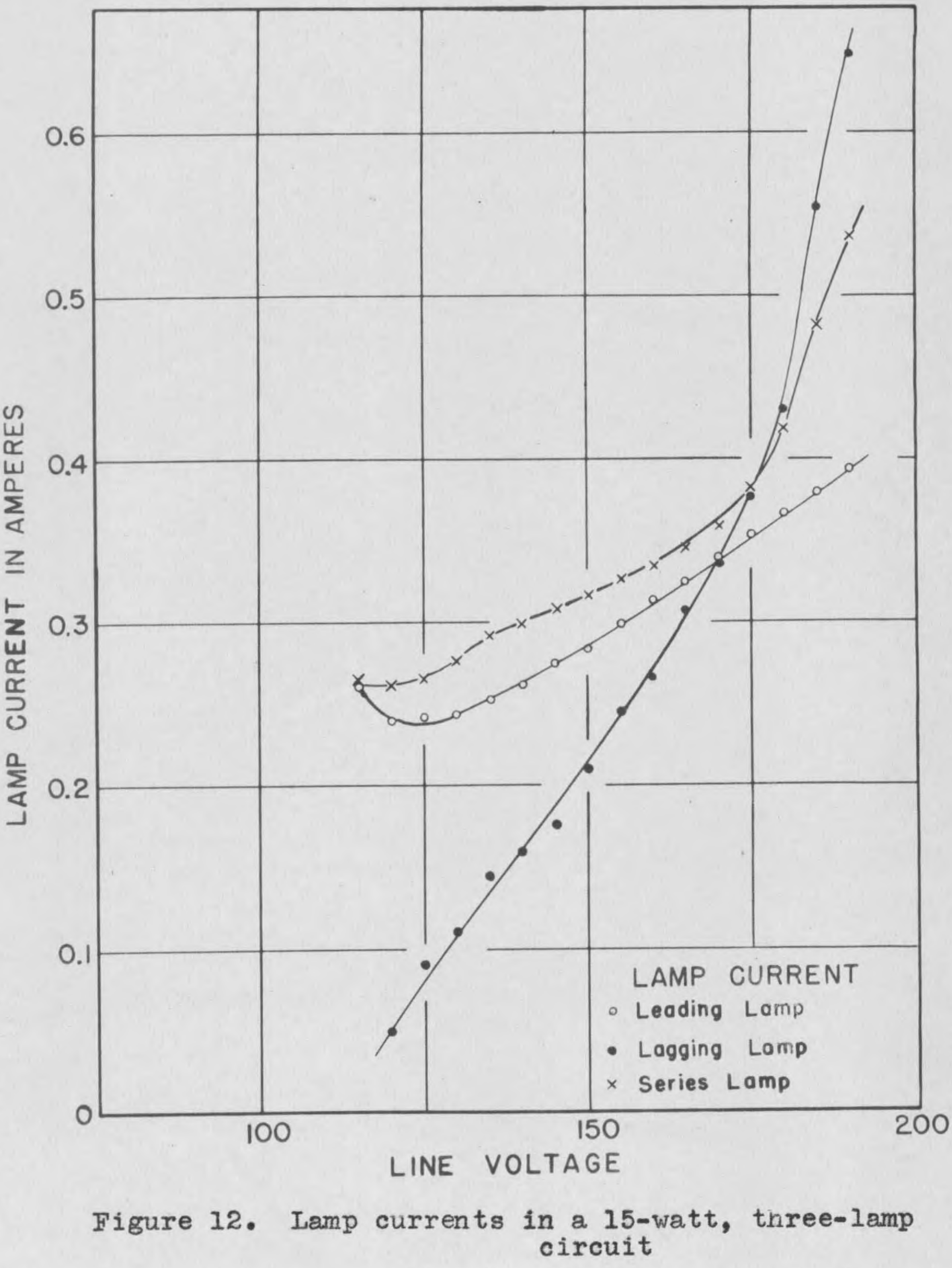


Figure 12. Lamp currents in a 15-watt, three-lamp circuit

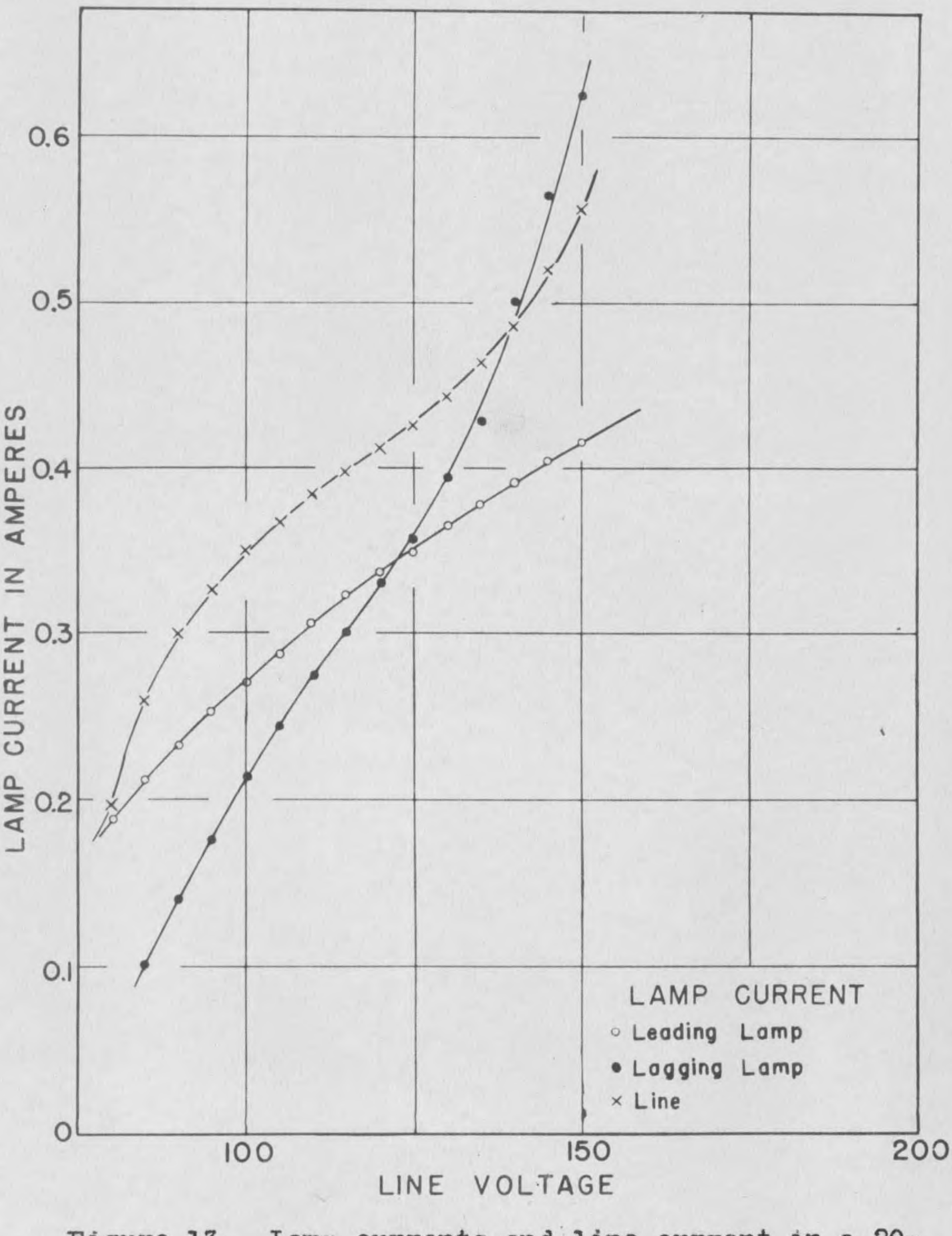


Figure 13. Lamp currents and line current in a 20-watt, two-lamp circuit

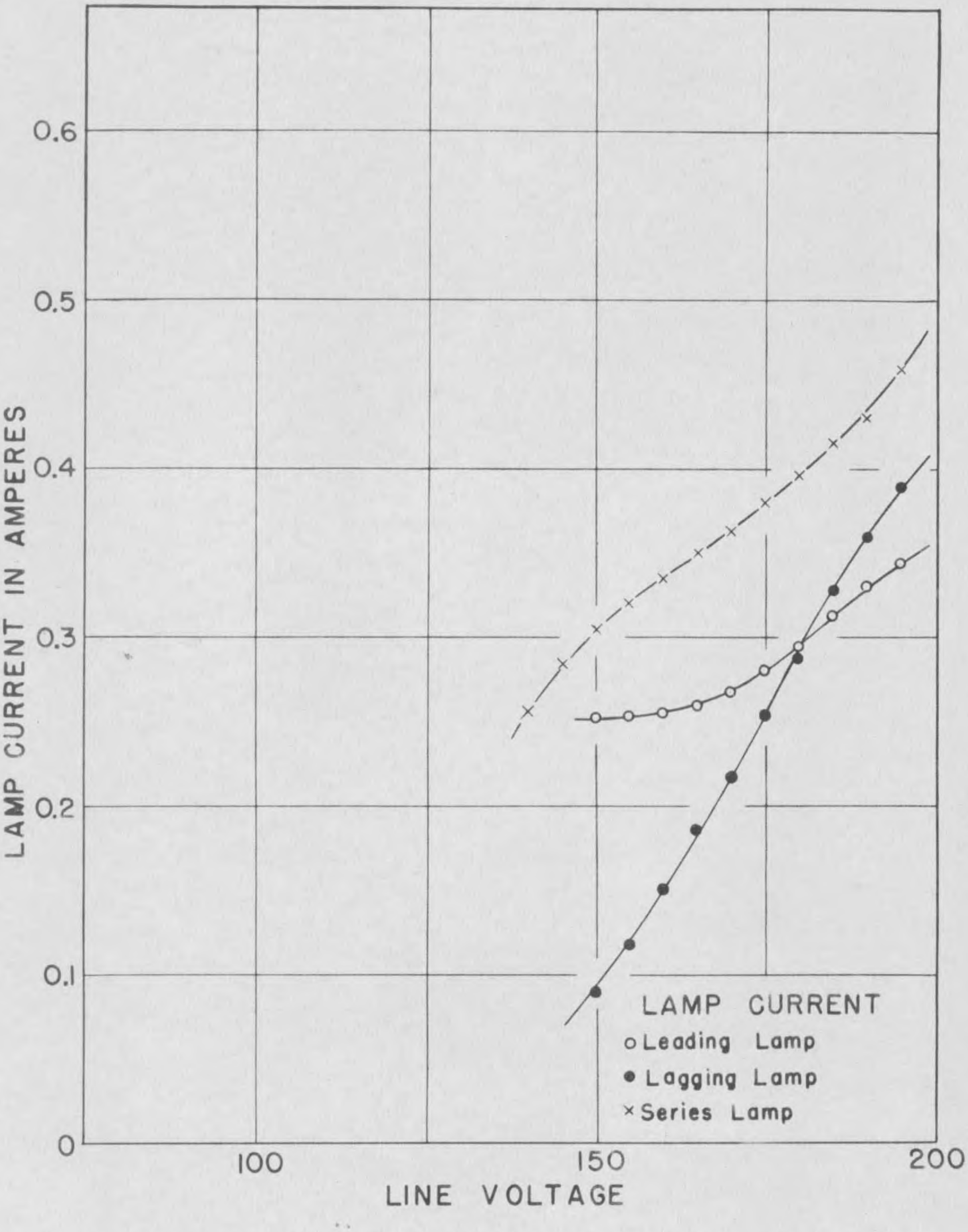


Figure 14. Lamp currents in a 20-watt, three-lamp circuit

III ANALYSIS OF DATA

1. Selection of Operating Voltages by Current Analysis.

The vector diagram in Figure 2 shows that the series lamp, leading lamp and lagging lamp currents should all be equal in magnitude. The production of harmonics due to the arc characteristics of the lamps change the effective values of the currents. The changes in current magnitudes with a change in line voltage are shown in Figures 11, 12, 13 and 14.

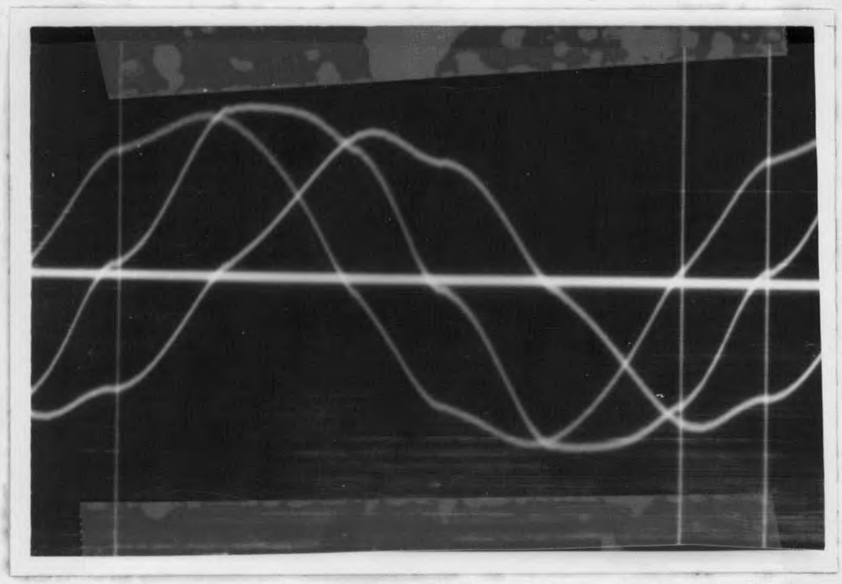


Figure 15. Current oscillogram for a 15-watt, three-lamp circuit

Examination of Figures 11 and 12 show that for 15-watt lamps, the currents vary with the voltage in a similar manner. The oscillogram in Figure 15 shows the three current waveshapes of the three-lamp circuit. Harmonic content is high and, therefore, the difference in current readings is accounted for. The correct operating line voltage for the three-lamp, 15-watt circuit was selected as 160 volts. This selection was made by the examination of Figures 11 and 12.

Figure 11 shows the current magnitudes for the conventional two-lamp circuit. The highest branch current is the leading current with a magnitude of .345 amperes at a line voltage of 120 volts. Then from a line or series lamp current of .345

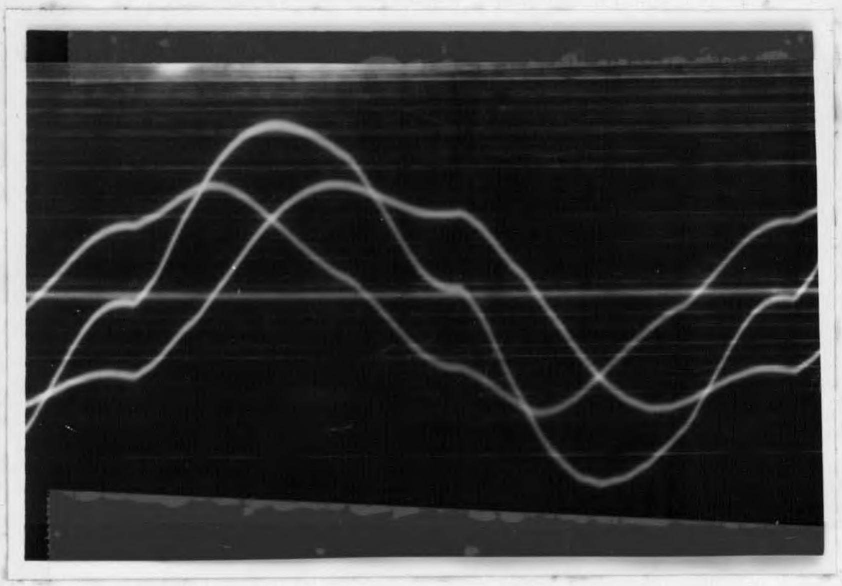


Figure 16. Current oscillogram for a 20-watt, three-lamp circuit

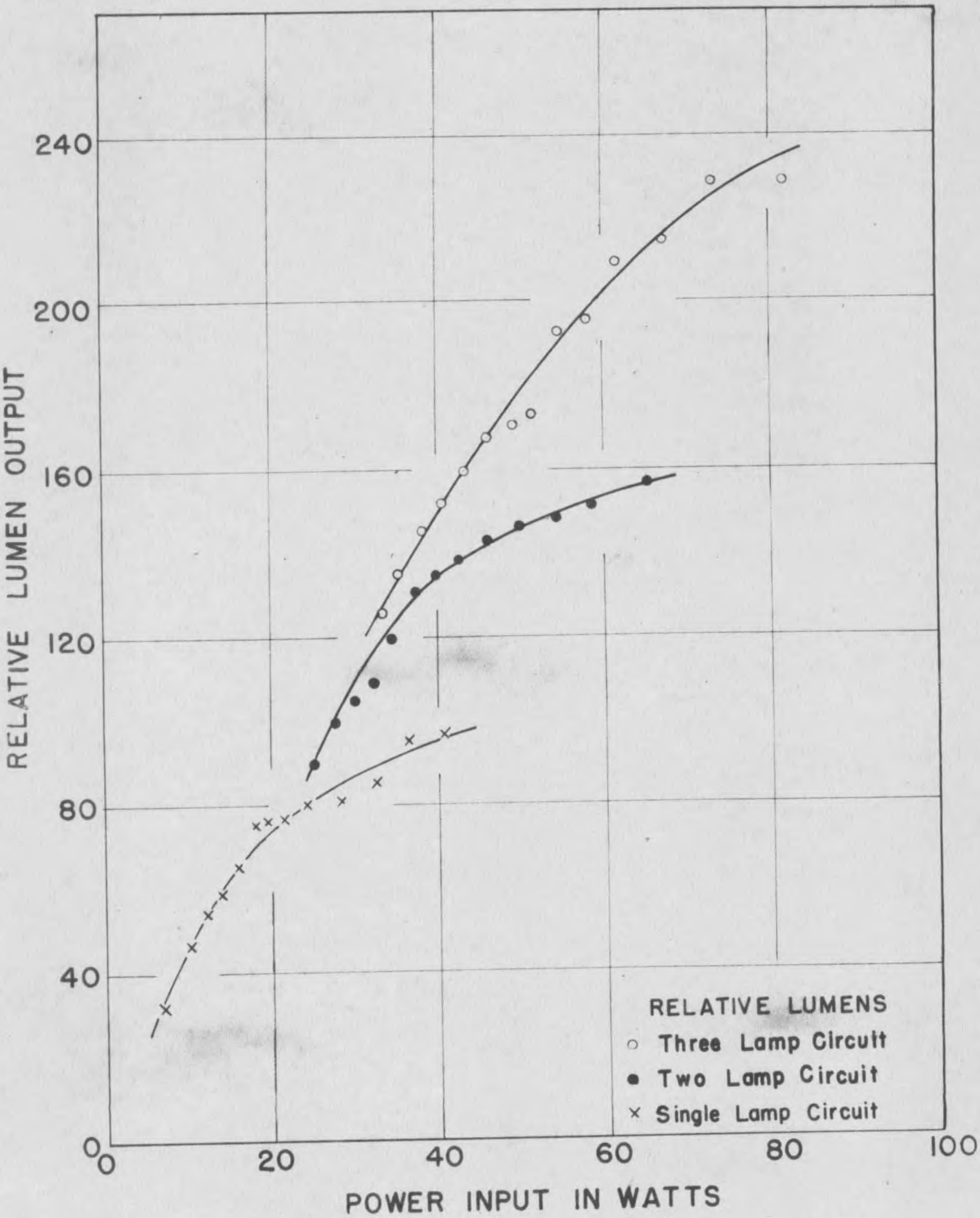


Figure 17. Relative-lumen output as a function of input power for 15-watt, lamp circuits

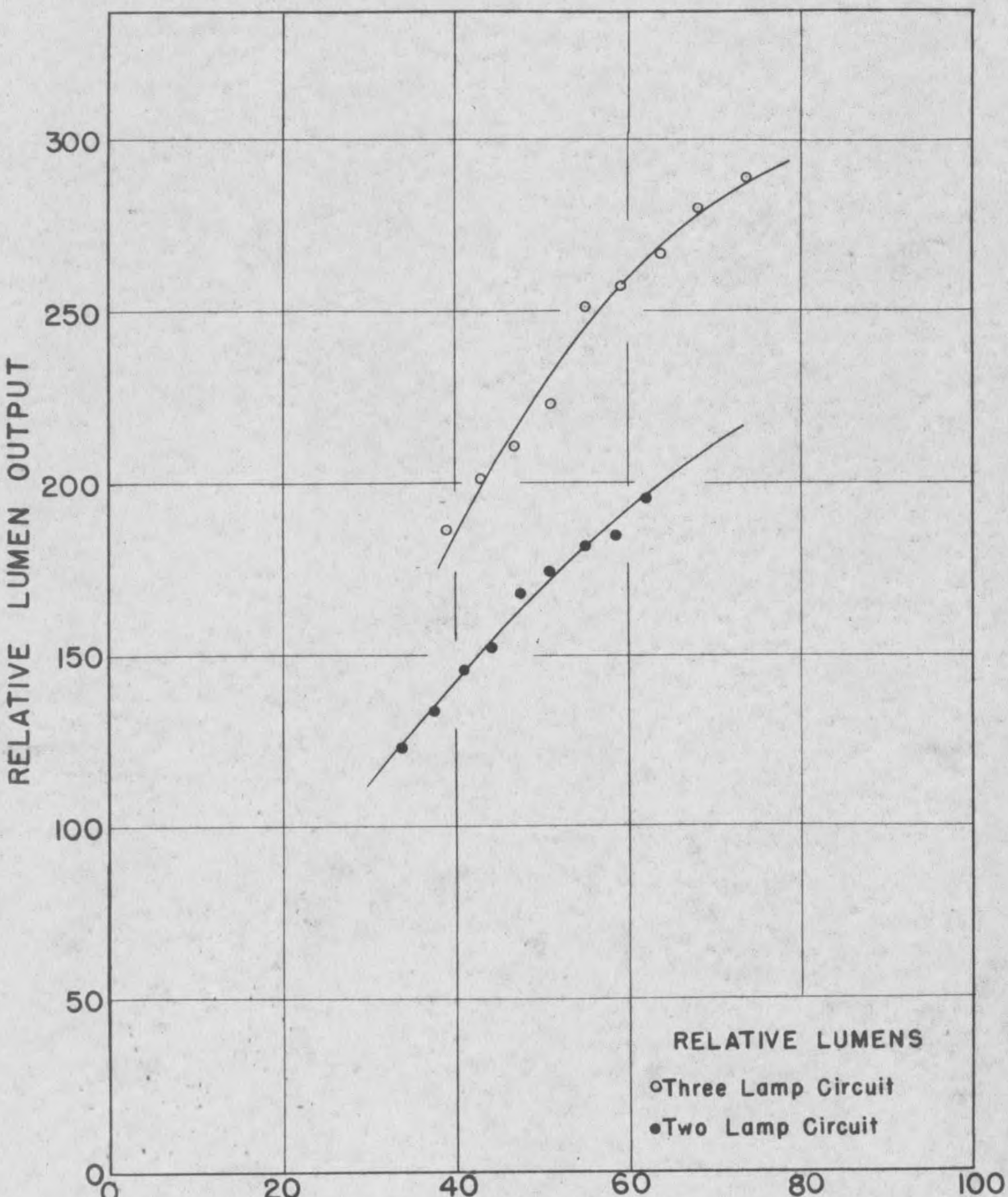


Figure 18. Relative-lumen output as a function of input power for 20-watt, lamp circuits

amperes, in Figure 12, the operational line voltage of 160 volts is determined.

The 20-watt, three-lamp circuit, operating voltage was determined by first examining Figure 13. The leading current has the largest magnitude of .338 amperes at a line voltage of 120 volts. The corresponding series lamp current in Figure 14 gives an operating voltage of 153 volts at .338 amperes. A line voltage of 153 volts reduces the leading and lagging lamp lumen outputs considerably. Therefore, a compromise was effected and the operating voltage of 170 volts was selected. The series lamp current is increased somewhat above the standard value for a 20-watt, fluorescent lamp, but the leading and lagging currents are increased also, giving a better balanced light output. Figure 16 shows the current waves of the three-lamp, 20-watt circuit at an operating voltage of 170 volts.

2. Analysis of Relative Efficiency.

The efficiency of a fluorescent lamp cannot be changed except by redesign. The over-all efficiency of a fluorescent lamp circuit can be changed considerably by the design of the circuit. The three-lamp circuits investigated, show an increase in efficiency when auxillary losses are included in the ratio of lumen output to power input.

The power input of the standard, 15-watt, two-lamp circuit operated at 120 volts, line voltage, is 40 watts. The power input of the 15-watt, three-lamp experimental circuit at 160 volts, line voltage, is 52 watts. The increase of power input with the addition of the third lamp is 12 watts; Figure 17 shows for the two-lamp circuit with 40 watts input, a lumen output of 135 relative-lumens. The efficiency is then 3.38 relative-lumens per watt input. Similarly, Figure 17 shows for the three-lamp circuit with 52 watts input, a lumen output of 183 relative-lumens. The calculated efficiency for the three-lamp circuit is 3.52 relative-lumens per watt. The relative efficiency increase of the three-lamp circuit based on the standard two-lamp circuit is 4 per cent.

The power input of the standard, 20-watt, two-lamp circuit operated at a line voltage of 120 volts is 47.9 watts. The power input of the 20-watt, three-lamp experimental circuit at 170 volts, operating voltage, is 59.4 watts. The increase of power input with the addition of the series, 20-watt lamp is 11.5 watts. Figure 18 shows for the two-lamp circuit with 47.9 watts input, a lumen output of 161 relative lumens. The efficiency of the two-lamp circuit is 3.36 relative-lumens per watt. Figure 18, shows for the three-lamp circuit with 59.4 watts input, a lumen output of 256 relative-lumens. The efficiency of the three-lamp circuit is 4.31 relative lumens per watt of input power. A comparison of the 20-watt lamp circuits show an increase in relative efficiency of 28 per cent.

3. Comparisons of Stroboscopic Effect.

The stroboscopic effect for the three-lamp circuits is determined by the method shown by Amick[2]. Amick's method is based upon the light-output waveshape of a single, fluorescent lamp with a sine current wave. Analysis of the three-lamp, vector diagram in Figure 2 and the three-lamp-circuit, current waveshapes of Figures 15 and 16 show that if the currents were sinusoidol, the light-output waveshape of each lamp of a three-lamp circuit would have a phase difference of 60 degrees for the entire cycle and would give equivalent three-phase light output. Because of the similarity of the three-lamp circuit, light wave phasing with that of three lamps, one per phase, on a three-phase supply, the same deviation should be expected.

Amick[2] gives the theoretical per cent of deviation for daylight lamps on three-phase operation as 5 per cent. By plotting three, single, white-lamp light-output waveshapes, each 60 degrees apart and adding the ordinates, a three-phase white-lamp deviation of 3 per cent was obtained. This also gave the three-phase mean as 329 units, with the single lamp mean as 100 units. In a similar manner the two-lamp mean was determined as 220 units for white lamps.

The light-output-wave oscillogram for a single, 15 watt, white lamp is shown in Figure 6. The total deflection is 19 units. The maximum deviation is, therefore, 9.5 units from the mean. Amick gives the per cent deviation for white lamps as 35 per cent[2]. The mean output is 9.5 ÷ .35 or 27.2 units above zero output. The theoretical mean output for three, white lamps, one operated in each phase of a three phase supply, is 329 units above zero output or 3.29 times the mean output of a single lamp, which is based on 100 units. Multiplying 27.2 by 3.29 gives 89.5 units as the mean output of three lamps with the lamp light-waves phased 60 degrees apart. Figure 8 shows the deviation of light output of the 15-watt, three-lamp circuit. The deviation measured from the oscillogram is 5 units. Dividing 5 by 89.5 results in a percentage of deviation of 6 per cent.

Figures 9 and 10 are used in determining the stroboscopic effect of the 20-watt, three-lamp circuit. The light-output waveshape of the 20-watt, two-lamp circuit is used as the calibrating factor. The deviation of the 20-watt, two-lamp circuit, light-output waveshape is measured as 5.85 units. Amick gives the two-parallel-lamp circuit stroboscopic effect as 16 per cent. Dividing 5.85 by .16 gives a mean output of 36.5 units. The ratio of the two-lamp mean output to the single lamp mean output for white lamps is 2.20. Therefore, the three-lamp mean output is 3.29/2.20 x 36.5 or 54.7 units above the base. The deviations measured on the oscillogram of the 20-watt, three-lamp circuit, light-output waveshape is 6.25 units. The stroboscopic effect is $6.25 \div 54.7$ or 11 per cent.

4. Determination of the Distortion Factor.

An analysis of the 15-watt, three-lamp circuit line current by the graphical Fourier method provided the necessary data for the determination of the distortion factor. The analysis showed that the third harmonic current was 3.0 per cent, the fifth, 6.5 per cent and the seventh, 3.7 per cent of the fundamental. The total effective harmonic value was determined by subtracting the fundamental ordinates from the total wave, and finding the root-mean-square value of the harmonic components remaining. The effective or rms value of the total wave was 12.7. The effective value of the harmonics was 3.0. This gives a distortion factor of 0.24 for the operating conditions used.

The 20-watt, three-lamp distortion factor of the line or series tube current was determined in a manner, similar to that of the 15-watt, three-lamp, line current distortion factor. The distortion factor of the 20-watt, three-lamp-circuit, series-lamp current was 0.16. Both distortion factors computed are less than 0.25.

The total harmonic content of the line current of a two-lamp circuit is 20 per cent of the fundamental.[5] The magnitudes of the harmonics in per cent of the fundamental of a two-lamp line current are as follows: third, 27 per cent; fifth, 1.0 per cent; seventh, 0.8 per cent; and ninth, 0.3 per cent[6].

IV CONCLUSIONS

The following conclusions may be drawn concerning the electrical and light output characteristics of the 15-watt and 20-watt, three-lamp circuits:

1. The effective values of the currents are approximately the same for the experimental three-lamp circuits as the corresponding two-lamp circuits.
2. The relative efficiencies, as measured by relative-lumens per watt, are increased over the corresponding relative efficiencies of the two-lamp circuits.
3. The strobscopic effect of the three-lamp circuits closely approaches the three-phase stroboscopic effect and is also comparable to that of incandescent lamps.
4. The distortion factors of the three-lamp circuits are less than the 0.25 specified as denoting maximum harmonic content allowable.
5. The operating voltage necessary for a three-lamp circuit is 40 to 50 per cent greater than the normal supply voltage of 118 volts. This difficulty may be overcome by the use of a combination ballast and auto-transformer.
6. The third harmonic magnitude is reduced by 80 to 90 per cent but the higher harmonic magnitudes are

increased. The decrease in the third harmonic overbalances the increase in higher harmonics. This improves the power factor.

7. The phase relationships of the lamp currents and consequently the light outputs could be improved by a redesign of the ballasts to compensate for the increased harmonic content of the branch currents caused by the series lamp.

8. The three-lamp circuits analyzed were started successfully with FS-2 glow-type automatic starters at the selected operating line voltages. The time delay was five to ten seconds compared to four seconds or less for the two-lamp circuits.

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VII APPENDIX

TABLE I

Electrical Characteristics of a 15-Watt, Single-Lamp Circuit

Line V (volts)	Input Power (watts)	Line I (amperes)	Lamp V (volts)
150	40.4	.393	69
145	34.6	.350	68
140	31.0	.295	67
135	27.4	.250	66
130	24.6	.220	65
125	21.8	.193	67
120	20.0	.179	66
115	18.0	.170	67
110	16.5	.160	67
105	14.8	.153	67

TABLE II

Electrical Characteristics of a 15-Watt, Two-Lamp Circuit

Line V (volts)	Input Power (watts)	Line I (amperes)	Leading Lamp I (amperes)	Lagging Lamp I (amperes)	Leading Lamp V (volts)	Lagging Lamp V (volts)
150	65.5	.540	.415	.655	56	50
145	58.9	.183	.402	.580	56	51
140	54.5	.443	.392	.510	57	52
135	50.1	.404	.380	.422	56	52
130	46.1	.380	.370	.378	56	54
125	42.7	.363	.356	.338	57	55
120	40.0	.351	.346	.308	57	57
115	37.5	.342	.332	.276	57	57
110	34.9	.333	.319	.248	58	59
105	32.5	.325	.304	.221	58	61
100	30.1	.316	.287	.197	59	62
95	27.7	.303	.270	.172	60	63
90	25.1	.293	.256	.150	61	65
85	22.1	.275	.239	.120	62	67
80	----	.245	.218	.090	62	69

TABLE III

Electrical Characteristics of a 15-Watt, Three-Lamp Circuit

Line V (volts)	Input Power (watts)	Line I (amps)	Leading Lamp I (amps)	Lagging Lamp I (amps)	Leading Lamp V (volts)	Lagging Lamp V (volts)	Series Lamp V (volts)
190	82	.506	.392	.595	57	51	52
185	73.2	.445	.377	.505	57	53	54
180	67.4	.403	.363	.41	57	54	55
175	62.0	.373	.350	.360	56	55	55
170	58.4	.360	.338	.325	57	56	56
165	55.0	.345	.324	.298	57	57	57
160	52.0	.336	.310	.270	57	58	57
155	49.6	.330	.297	.245	58	60	58
150	46.4	.320	.280	.219	59	62	59
145	43.8	.311	.266	.198	59	63	59
140	41.0	.301	.253	.171	61	65	61
135	38.6	.293	.243	.15	61	67	61
130	35.8	.285	.239	.125	62	69	62
125	33.6	.279	.238	.109	62	72	62
120	31.2	.270	.243	.090	62	77	62

TABLE IV

Electrical Characteristics of a 20-Watt, Two-Lamp Circuit

Line V (volts)	Input Power (watts)	Line I (amperes)	Leading Lamp I (amperes)	Lagging Lamp I (amperes)	Leading Lamp V (volts)	Lagging Lamp V (volts)
150	74.3	.558	.415	.625	64	58
145	69.9	.520	.403	.565	62	58
140	62.1	.486	.389	.500	63	61
135	58.9	.463	.378	.429	62	62
130	55.1	.445	.363	.393	62	62
125	51.1	.428	.349	.356	63	63
120	47.9	.412	.336	.330	63	63
115	44.5	.399	.321	.300	64	66
110	41.1	.384	.305	.273	64	66
105	37.9	.369	.288	.242	66	67
100	33.9	.350	.270	.212	67	68
95	30.1	.328	.251	.175	68	70
90	26.5	.300	.231	.140	67	71
85	21.5	.260	.211	.100	68	74

TABLE V

Electrical Characteristics of a 20-Watt, Three-Lamp Circuit

Line V (volts)	Input Power (watts)	Line I (amps)	Leading Lamp I (amps)	Lagging Lamp I (amps)	Leading Lamp V (volts)	Lagging Lamp V (volts)	Series Lamp V (volts)
195	84.4	.459	.343	.390	64	65	73
190	78.4	.430	.330	.361	64	67	73
185	73.8	.415	.313	.327	64	68	74
180	68.4	.396	.293	.288	65	68	76
175	64.0	.380	.280	.254	66	71	78
170	59.4	.363	.268	.219	67	73	81
165	55.4	.350	.260	.186	67	74	81
160	51.2	.335	.255	.150	66	76	82
155	47.0	.320	.254	.118	67	78	83
150	43.0	.304	.253	.090	65	82	85

TABLE VI

Relative-Lumen Output and Power Factor of a 15-Watt, Single-Lamp Circuit

Relative-Lumen Output	Power Input (watts)	Relative-Lumen per Watt	Line V (volts)	Line I (amperes)	Power Factor
97.2	40.4	2.4	150	.412	.653
95.3	34.6	2.75	145	.36	.663
85.6	31.0	2.76	140	.31	.714
81.4	27.4	2.97	135	.265	.766
80.1	24.6	3.26	130	.221	.857
76.5	21.8	3.51	125	.194	.899
77.3	20.0	3.86	120	.179	.930
75.8	18.0	4.21	115	.166	.943
65.7	16.5	3.98	110	.158	.949
59.3	14.8	4.00	105	.151	.934
54.7	13.0	4.21	100	.149	.873
46.9	11.4	4.11	95	.148	.810
32.6	9.4	3.47	90	.152	.686
34.8	7.7	4.52	85	.140	.647
25.2	5.0	5.04	80	.140	.446

TABLE VII

Relative-Lumen Output and Power Factor of a 15-Watt, Two-Lamp Circuit

Relative-Lumen Output	Power Input (watts)	Relative-Lumen Per Watt	Line V (volts)	Line I (amperes)	Power Factor
157.3	65.5	2.4	150	.54	.809
151.5	58.9	2.57	145	.483	.832
148.8	54.5	2.73	140	.443	.879
146.2	50.1	2.92	135	.404	.917
143.5	46.1	3.11	130	.380	.933
138.1	42.7	3.24	125	.363	.942
135.1	40.0	3.38	120	.351	.950
131.0	37.5	3.49	115	.342	.953
120.0	34.9	3.44	110	.333	.953
109.0	32.5	3.35	105	.325	.953
104.8	30.1	3.48	100	.316	.953
99.4	27.7	3.58	95	.303	.963
89.7	25.1	3.57	90	.293	.951

TABLE VIII

Relative-Lumen Output and Power Factor of a 15-Watt, Three-Lamp Circuit

Relative-Lumen Output	Power Input (watts)	Relative-Lumen per Watt	Line V (volts)	Line I amperes	Power Factor
229.0	82.0	2.79	190	.506	.854
229.0	73.2	3.13	185	.445	.890
215.0	67.4	3.19	180	.403	.929
210.0	62.0	3.39	175	.373	.950
196.0	58.4	3.38	170	.360	.953
193.1	55.0	3.52	165	.345	.967
173.9	52.0	3.35	160	.336	.968
171.0	49.6	3.45	155	.330	.970
168.2	46.4	3.62	150	.320	.967
160.0	43.8	3.65	145	.311	.972
151.9	41.0	3.71	140	.301	.974
147.6	38.6	3.83	135	.293	.975
135.0	35.8	3.77	130	.285	.967
125.5	33.6	3.74	125	.279	.964

TABLE IX

Relative-Lumen Output and Power Factor of a 20-Watt, Two-Lamp Circuit

Relative-Lumen Output	Power Input (watts)	Relative-Lumen per Watt	Line V (volts)	Line I (amperes)	Power Factor
196	62.1	3.16	140	.486	.913
185	58.9	3.14	135	.463	.941
182	55.1	3.31	130	.445	.952
174	51.1	3.41	125	.428	.955
168	47.9	3.51	120	.412	.970
152	44.5	3.42	115	.399	.970
146	41.1	3.56	110	.384	.973
144	37.9	3.80	105	.369	.979
133	33.9	3.92	100	.350	.969

TABLE X

Relative-Lumen Output and Power Factor of a 20-Watt, Three-Lamp Circuit

Relative-Lumen Output	Power Input (watts)	Relative-Lumen per Watt	Line V (volts)	Line I (amperes)	Power Factor
289	73.8	3.92	185	.415	.962
280	68.4	4.10	180	.396	.960
267	64.0	4.17	175	.380	.963
256	59.4	4.31	170	.363	.963
251	55.4	4.53	165	.350	.960
233	51.2	4.55	160	.335	.956
211	47.0	4.50	155	.320	.948
202	43.0	4.70	150	.304	.944
187	39.2	4.77	145	.285	.950