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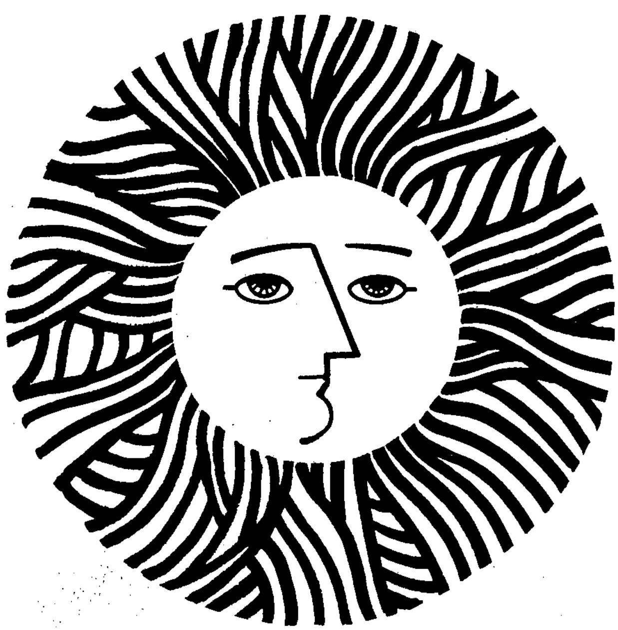
Lawrence Berkeley Laboratory
UNIVERSITY OF CALIFORNIA

ENERGY & ENVIRONMENT DIVISION

PHASE I FINAL REPORT
ENERGY EFFICIENT H.I.D. SOLID-STATE BALLAST

Jefferson Electric Division
Litton Industries, Inc.

November 1980



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PHASE I FINAL REPORT

ENERGY EFFICIENT H.I.D. SOLID-STATE BALLAST

Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

November 1980

Subcontract No. 4502310
Jefferson Electric Division
Litton Industries, Inc.
Bellwood, Illinois 60104

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1.0 INTRODUCTION

In 1977, approximately 450 billion kilo-watt hours per year of energy was expended for lighting.

TABLE I

Lighting Utilization by End Users

END USER*	PERCENT*	FLUORESCENT	INCANDESCENT	H.I.D.
Residential	20	5%	95%	---
Industrial	20	70 - 75%	10%	15%
Stores	20	80%	15%	5%
Offices and Schools	20	80%	15%	5%
Streets - Highways	4	20%	5%	75%
Commercial Outdoor	8	70%	5%	25%
Other	8	70 - 75%	5%	20%

* U.S. Bureau of Mines
The percentages for fluorescent, incandescent and H.I.D. lighting are based upon statistical and overall market data.

H.I.D. lighting accounts for approximately 12% of total lighting or 54 billion kilowatts hours per year.

1.1 Why H.I.D. Lighting? Following is a comparison of lamp efficiency (lumens per watt) for various types of lamps.

TABLE II

Lighting Efficiency

LAMP TYPE	LUMENS PER WATT W/O BALLAST
INCANDESCENT	
100 W	17.5
200 W	20
1000 W	23
H.I.D. MERCURY VAPOR	
100 W	42
250 W	45
400 W	56
1000 W	62
FLUORESCENT	
40 W	80
Slimline	84
800 MA	85
METAL HALIDE	
175 W	80
175 with energy efficient	100
400 W	84
1000 W	118
H.P.S.	
100 W	82
150 W	94
250 W	108
400 W	124
1000 W	140

In the evaluation of H.I.D. lighting, the aforementioned table catergorically illustrates the superior efficiency of high pressure sodium lighting. This fact is emphasized in that the H.I.D. lighting fixture manufacturers currently are producing and selling 20% mercury vapor, 20% metal halide and 60% high pressure sodium.

The market for H.I.D. lamps and ballasts has been changing dramatically over the last ten years. Initially, conventional mercury vapor gas lamps were the primary lamps sold from the inception of H.I.D. lighting. Many millions of mercury vapor lamps and ballasts have been sold. About 15 years ago, metal-halide lamps and ballasts were introduced for greater efficiency, ie., lumens per watt, as compared to mercury vapor lighting. Because of higher cost considerations this portion of the market approximates about 10%.

With the commercial introduction of High Pressure Sodium (HPS) lighting and the considerable energy savings per lumen output, sales of HPS lighting has grown extensively. Current product development of mercury vapor and metal-halide lighting systems is negligible, whereas high pressure sodium lamp and ballast sizes (wattages) continues to grow. At present, there are nine HPS lamp sizes available today--50, 70, 100, 150, 200, 250, 310, 400, 1000 watt.

There are matching ballast sizes for all lamps with five voltage variations, 120, 208, 240, 277, 480.
The outlook for mercury vapor and metal-halide lighting indicates negligible original equipment installations for street lighting and commercial/industrial applications. Because of the millions of existing installations, the replacement market for mercury vapor will remain strong over the next ten years, although there is a definite trend to replace conventional mercury vapor lighting with high pressure sodium lighting. The market for high pressure sodium lighting is expanding rapidly despite the higher installation cost. This cost difference can readily be recovered through lower operating costs because of significantly higher efficiency for HPS lamps. Table II list the efficacies of different light sources, not including the ballast losses. The standard ferro-magnetic H.P.S. ballast has an efficiency of 80% and a power factor of 90%. This means that a 150 watt lamp and ballast system requires a 188 watt input, ie,, the ballast dissipates 38 watts. See Jefferson Electric Engineering Test Report No. 06-TT-842-186*-047.

Subcontract 4502310 was issued to Jefferson Electric to research and develop an H.I.D. Solid State Ballast, specifically for a 150 watt high pressure sodium lamp, to be more energy efficent than conventional ferro-magnetic ballasts.

2.0 OBJECTIVES

2.1 Ballast Design Characteristics

2.1 1. Energy Efficiency:

To design a solid state 150 W high pressure sodium lamp ballast system with an efficiency of 90%; i.e., optimum 167 input watts.

2.1 2. Dimming:

The initial design will not incorporate this feature.

2.1 3. Noise:

No audible noise as opposed to the typical hum in ferro-magnetic ballasts.

2.1 4. Estimated Life:

Conventional ferro-magnetic ballasts are rated at 60,000 hours average life. Solid state devices generally are rated between 30,000 - 40,000 hours meantime betweeen failures, MTBF. By MTBF encapsulating the solid state ballast to protect it from environmental factors, the objective is to obtain 60,000 hours MTBF.

2.1 5. Power Factor:

90% or more.

2.1 6. Third Harmonic Distrotion:

No significant effect is anticipated based upon results experienced in the design and testing of solid state fluorescent ballasts.

2.1 7. Radio Frequency Interference:

Ballast will be designed to meet the criteria of M1L-STD-461.

2.1 8. Safety:

Will be designed for eventual Underwriters Laboratories recognition. Unit will be encapsulated and totally enclosed in a metal case and cover for fire hazard protection.

2.1 9. Reliability:

Reliability can be evaluated only on the total lighting system. i.e., ballast and lamp performance, and is affected by environmental conditions and component performance.

2.1 9.1. Lamp ageing and failure probably will affect ballast reliability. Lamp arc voltage increases with age or when lamp is inoperative.

2.1 9.2. Environmental conditions:

Humidity and temperature are two primary detrimental factors to ballast life. To counteract these factors the ballast will be encapsulated and protected in a metal housing.

2.1 9.3. Component selection will be a major factor in affecting reliability.

2.1 10. Ballast Cost:

The objective is to design a solid state ballast which will be competitive to ferro-magnetic ballast based upon life cycle costing.

2.2 Critical Design Targets

2.2 1. Properly start and sustain lamp in operation.

2.2 2. Special attention to following phenomenon:

a. Visual lamp flicker

b. High lamp Re-ignition voltage

c. Lamp Extinction

d. Unusual sensitivity to line voltage fluctuations

e. Minimum pulse voltage to start lamp.

f. Maximum pulse voltage to prevent lamp destruction

3.0 Engineering Report (TRIAD-UTRAD)

HIGH PRESSURE SODIUM BALLAST

FINAL REPORT

BY Robert V. Burke

ROBERT V. BURKE

TRIAD-UTRAD
Division of Litton Systems, Inc.

DATE November 21, 1980

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I. TEST SET-UP

The equipment was arranged in accordance with that schematically represented in figure one. All of the equipment used was in recent calibration and the calibration was cross-checked with instruments of the same type in the case of the Westons, Fluke, oscilliscope, J16 Photometer and J6503 Probe.

The calibration of the Clark-Hess Volt-Amp-Wattmeter was checked in two ways. First, with lamp in place and operating at 150 watts 60 Hz, a Weston 432 wattmeter was switched into the circuit in place of the Clark-Hess. Secondly, the lamp was replaced with a Precision Non-Inductive 16.66 ohm resistance. A Fluke 931B True R.M.S. differential voltmeter was placed in the circuit along with the Clark-Hess. The voltage was set at 50 volts 60 Hz, readings taken, then set to 50 volts 20 KHz, and readings retaken. The measured voltage, calculated current and wattage numbers indicated by the Fluke 931B were compared with those indicated by the Clark-Hess.

These methods indicates the instruments agree within one percent for voltage and current readings and two percent for wattage readings.

The lamp was placed into a compartment one foot, by one foot, by one foot with one end open in order to shield the high intensity lamp from eyes. The inside of the compartment was flat black, this insured that a significant amount of energy was not reflected back through the arc, which could increase the tube arc temperature and voltage, as well as providing a black back-ground to measure light output against. We have used this test method with other light sources, such as fluorescent and incandescent and have found it to produce repeatable relative light output results to an accuracy of five percent.

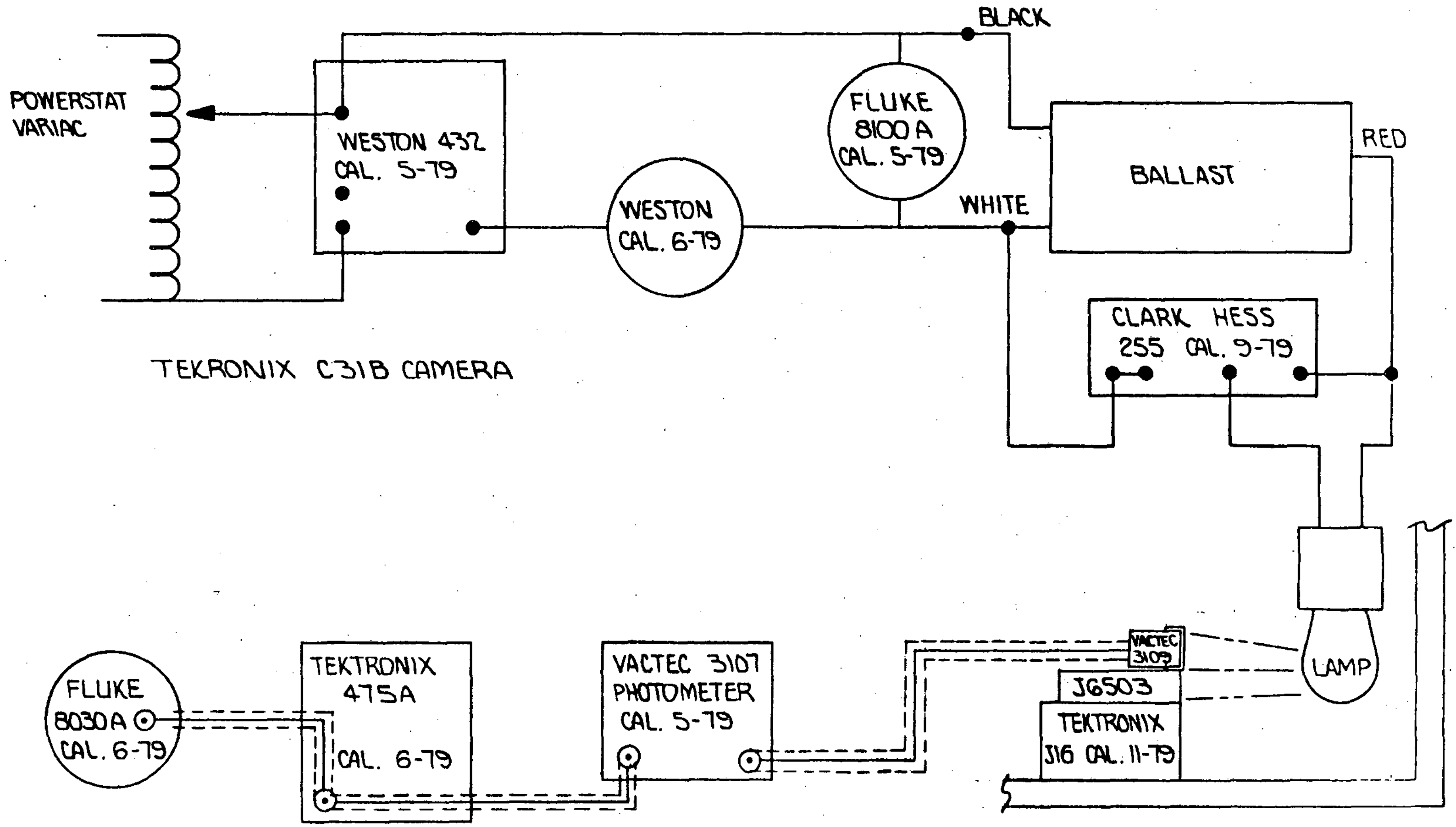


FIGURE I TEST DIAGRAM

II. TEST PROCEDURE

Each lamp used in the experiments was burned in 100 hours at 150 watts before testing began. The lamps were allowed to stabilize for 15 minutes before data was recorded.

The relative light output of the lamps was measured against a black back-ground with the J16 Photometer and J6503 7° probe withdrawn from the lamp such that a four inch circular pattern was viewed with the arc tube in the center.

Flicker was examined with the vactec 3107 photometer and 3109 probe with a 100 divider. The output of the photometer was fed to the 475A oscilliscope and 8030A true RMS voltmeter.

To obtain the point where the ballasts started the lamps, the input voltage was slowly raised until arc current was achieved and that voltage recorded.

II. EFFICIENCY

We had orginally anticipated approximately a ten percent reduction in the input power to produce a ten percent improvement in light output.

This approximation was based on two conclusions. First, we felt that a high frequency ballast could be made 90 percent efficient, this represented an increase in efficiency of just over ten percent when compared with standard 60 Hz units. Second, we anticipated about a ten percent improvement in lamp efficiency due to operation at higher frequency. We had good reason to believe this. We had seen high frequency power improve the efficiency of other types of lamps and an Illuminating Engineering Society Article written in 1969 by Mr. John Campbell indicated that there was approximately a ten percent advantage in efficiency when operating a 400 watt high pressure sodium lamp at 20 KHz as compared to 60 Hz.

The construction of the 400 watt high pressure sodium lamp is somewhat different; it's longer, it has a larger diameter, but as we understand from lamp manufacturers it's a 150 watt H. P. S. lamp made to a larger scale. The elements, as well as the methods of construction are very much the same. Therefore, based on construction, we don't see a reason for the differences in efficiency versus frequency between Mr. Campbell's results and our own. (see appendix II thru V)

The actual efficiency increase obtained was between five to ten percent. All of this was due to increased efficiency of the ballast. (see appendix XIV)

The efficiency of these ballasts was typically 85 percent. This was five percent below the target number of 90 percent. We feel the efficiency of these units can be improved from five to ten percent in future generations.

These high frequency ballast also display an improvement in power factor. Although this will not reduce the kilowatt-hours consumed, it will have the tendency of reducing peak load which is related to the maximum volt amperes used in a particular period of time. This will reduce the peak load charge and therefore, the lighting bill.

The lack of increased lamp efficacy with increased frequency indicated by our experiments does dampen our enthusiaum somewhat. What this suggests is that in the end what it will boil down to is the per unit cost of the ballast.

BALLAST	INPUT VOLTAGE	INPUT CURRENT	INPUT WATTAGE	POWER FACTOR	OUTPUT VOLTAGE	OUTPUT CURRENT	OUTPUT WATTAGE	PERCENT EFFICIENCY	LIGHT OUTPUT PERCENT	LAMP
T-U #1	120	1.63	184	94.1	50.5	3.13	155	84.2	105[1]	GE LU150/55
T-U #2	120	1.56	175	93.5	47.4	3.22	151	86.3	99[1]	GE LU150/55
T-U #3	120	1.64	184	93.5	49.0	3.19	155	84.2	103[1]	GE LU150/55
T-U #4	120	1.63	183	93.6	47.8	3.25	155	84.7	103[1]	GE LU150/55
T-U #5	120	1.57	176	93.4	48.0	3.18	152	86.3	99[1]	GE LU150/55
T-U #6	120	1.59	179	93.8	46.6	3.21	149	83.2	98[1]	GE LU150/55
T-U #1	120	1.66	187	93.9	53.6	2.96	158	84.5	105[1]	SYL LU150/55
T-U #2	120	1.61	181	93.7	52.8	2.97	155	85.6	104[1]	SYL LU150/55
T-U #3	120	1.67	187	93.3	53.6	2.95	157	84.0	105[1]	SYL LU150/55
T-U #4	120	1.66	187	93.9	54.1	2.96	159	85.0	105[1]	SYL LU150/55
T-U #5	120	1.61	181	93.7	53.1	2.95	156	86.2	103[1]	SYL LU150/55
T-U #6	120	1.62	181	93.1	52.1	2.90	151	83.4	100[1]	SYL LU150/55

100% LIGHT OUTPUT WAS LEVEL OBTAINED AT 150W 60Hz PER TEST CIRCUIT IN APPENDIX I

ELECTRICAL AND LIGHT MEASUREMENTS

TABLE I

IV. REGULATION

Regulation for the high pressure sodium lamp does not necessarily mean perfectly constant wattage. If we applied an exactly regulated 150 watts to an LU 150/55 high pressure sodium lamp the light output would be at its rated value the first few hundred hours of operation, but would continuously degrade until close to the end of its life the light output may be down over 25 percent.

It would appear to us that a solution to this phenomena would be to begin lamp wattage at -10 percent rated or light output at -12.5 percent of rated value. (see appendix X for light output in relation to lamp power) If the voltage rise and lumen depreciation of the lamp tracked well, and + 12.5 percent of power was obtained near the end of the lamp life, a fairly constant light output of -12.5 percent rated would be provided to the environment.

This system would use the same kilowatt hours as the constant wattage system with a 12.5 percent light output improvement near the end of the lamp life.

The regulation scheme utilized in the six samples provided represents an adaptation of the general theme just described. General Electric lamps are the most abundant and in general run on the low side of 55 volts, as we understand from our associates from Jefferson Electric, added to this is the decrease in voltage due to the higher frequency power, (see appendix VI). It would appear that the majority of lamps will run between 45 and 50 volts at 150 watts. This places the majority of lamps on the rising portion of the regulation curve, which is shown in figures two through seven. This is basically what we would like to have happen.

Figures two thru seven demonstrate the line and load regulation curves for the six prototypes. Line-load regulation curves are useful because they illustrate the envelop of possible wattage levels for all lamp and line voltage combinations within specified limits. Examination of figures two thru seven show that the wattage peaks between 55 and 60 volts. It may have been better to have this occur five or ten volts higher in order to allow the wattage to peak further into the life cycle of the lamps. The most desirable voltage for the peak wattage to occur will probably be different for General Electric and Sylvania lamps, because these lamps appear to start their life cycles at slightly different voltages (see appendix VIII). There remains the need to test more of these lamps for longer periods of time in order to determine the extent of the differences between lamps manufactured by the various companies as well as to determine the optimum lamp voltage for the peak wattage to occur.

Figure eight illustrates the line-load regulation we believe should be simulated. The curve is characterized by a gradual slope from the lower voltage levels to the higher voltages and a leveling off of wattage at the higher voltages. The upper wattage limit was selected because it's plus ten percent of rated which is the upper limit we desire. The slope of the curve is necessarily shallow because lamp voltage also increases due to factors other than age (see appendix VI, VIII, and XI). If the slope was much steeper, there would be a tendency to drive the lamp to the upper wattage rail. For example, an increase in ambient temperature would cause an increase in lamp voltage which would cause an increase in lamp wattage which would cause both an increased lamp voltage and temperature. Not exactly what we want. We selected the slope down because we felt it would provide satisfactory regulated light output with time, yet not allow these other factors to significantly effect stabilization.

Appendices two thru eleven illustrate some of the lamp characteristics that necessarilly have to be taken into consideration when designing a ballast to regulate light output based on a lamp electrical parameter, rather than some type of light level feedback.

One particular item not taken into consideration was the increase in arc voltage that occures when the lamp is placed into certain fixtures. We understand that this voltage rise is due to absorption of the light energy reflected back through the arc tube. The voltage rise due to this could be significant. The arc tube absorbs some of the returned energy which causes increased arc tube voltage as well as temperature. We don't have specific data at this point in time,but will need to generate it for future ballast generations. This may detract from the light output regulation provided by the ballast.

UNIT	minus 10% rated Input Voltage		plus 10% rated Input Voltage	
	GE LU150/55	SYL LU150/55	GE LU150/55	SYL LU150/55
UNIT I				
INPUT POWER	-13.0%	- 8.6%	+ 1.6%	0%
OUTPUT POWER	-11.0%	- 7.6%	0%	- 1.9%
LIGHT OUTPUT	-12.0%	- 8.0%	0%	2.0%
UNIT 2				
INPUT POWER	- 7.4%	- 8.3%	+ 2.2%	0%
OUTPUT POWER	-11.9%	- 5.8%	+ 0.7%	- 1.9%
LIGHT OUTPUT	-13.0%	- 6.0%	0%	- 2.0%
UNIT 3				
INPUT POWER	- 9.2%	- 4.5%	2.2%	+ 0.1%
OUTPUT POWER	- 7.7%	- 3.2%	0.6%	- 0.1%
LIGHT OUTPUT	- 8.0%	- 4.0%	0%	0%
UNIT 4				
INPUT POWER	- 7.1%	- 5.9%	+ 1.6%	+ 0.5%
OUTPUT POWER	- 5.8%	- 5.0%	+ 0.6%	- 0.6%
LIGHT OUTPUT	- 6.0%	- 6.0%	+ 1.0%	0%
UNIT 5				
INPUT POWER	-10.8%	- 8.3%	+ 2.8%	+ 1.1%
OUTPUT POWER	-11.8%	- 6.4%	+ 0.6%	- 1.3%
LIGHT OUTPUT	-12.0%	- 7.0%	+ 1.0%	- 1.0%
UNIT 6				
INPUT POWER	- 5.6%	- 3.3%	+ 1.7%	2.2%
OUTPUT POWER	- 3.3%	- 2.0%	- 0.6%	- 1.3%
LIGHT OUTPUT	- 4.0%	- 3.0%	0%	- 1.0%

HIGH FREQUENCY BALLAST LINE REGULATION
LAMP LOAD

TABLE II

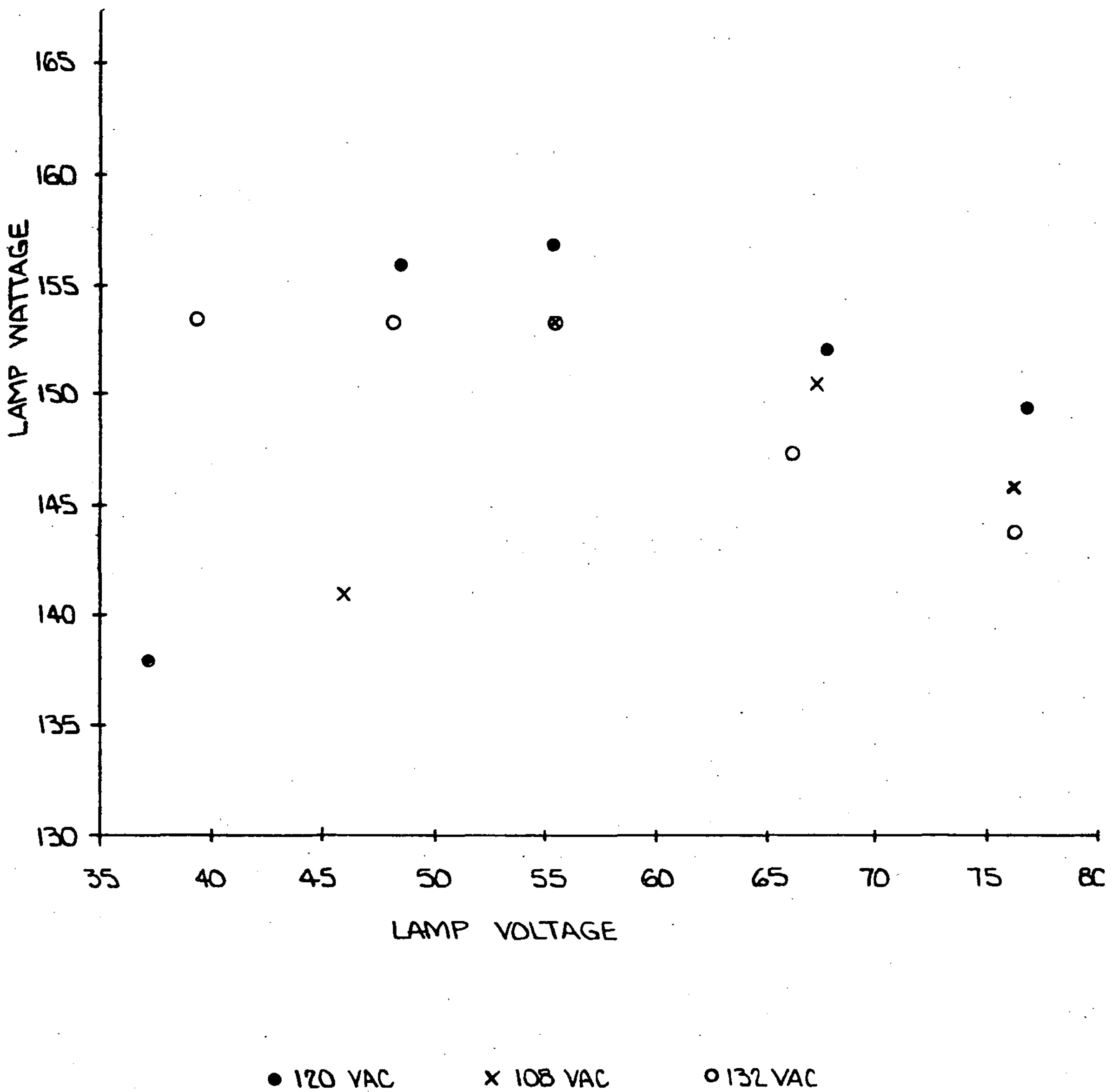


FIGURE II LINE-LOAD REGULATION UNIT # 1

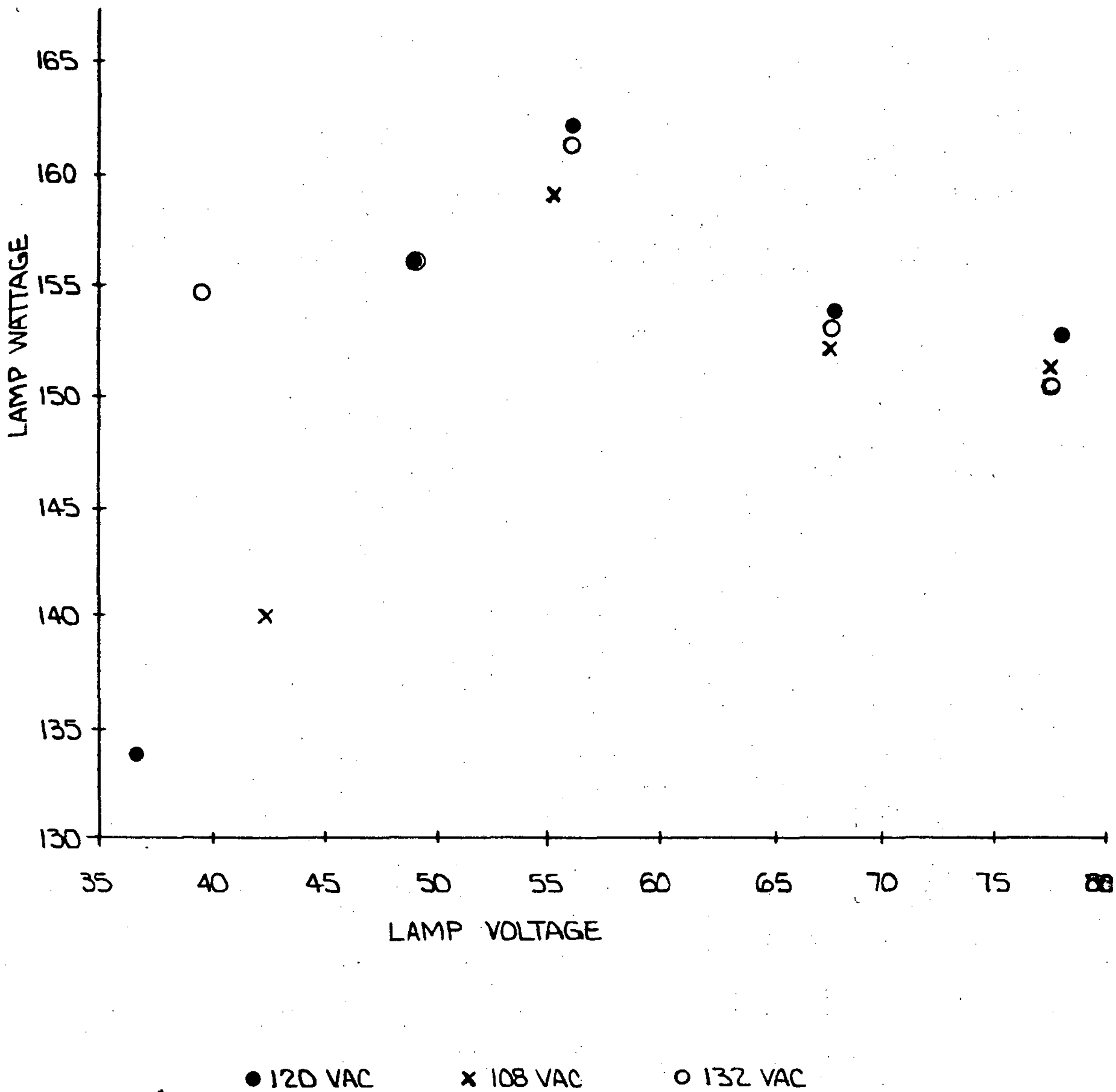


FIGURE III LINE-LOAD REGULATION UNIT # 2

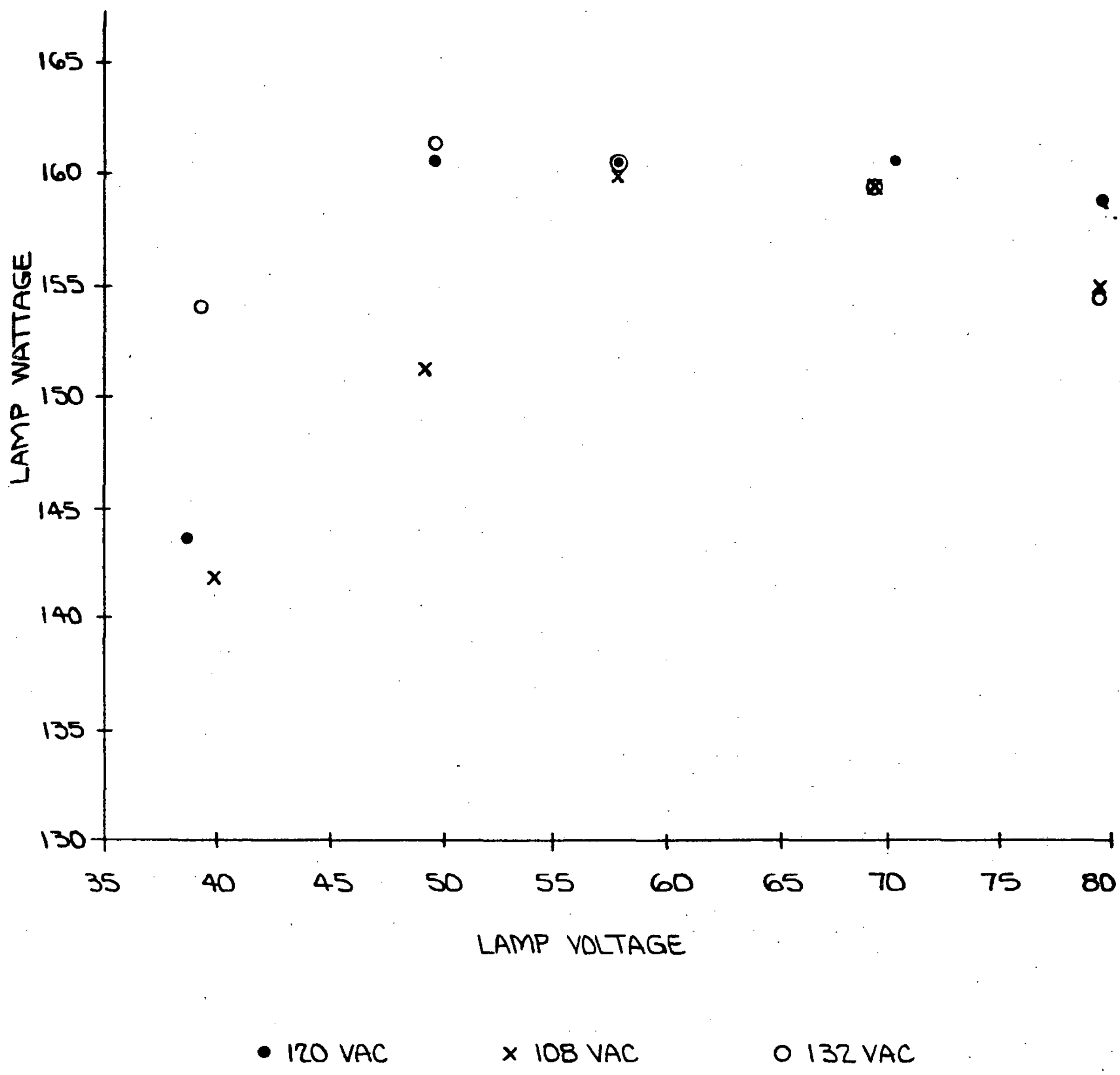


FIGURE IV LINE-LOAD REGULATION UNIT # 3

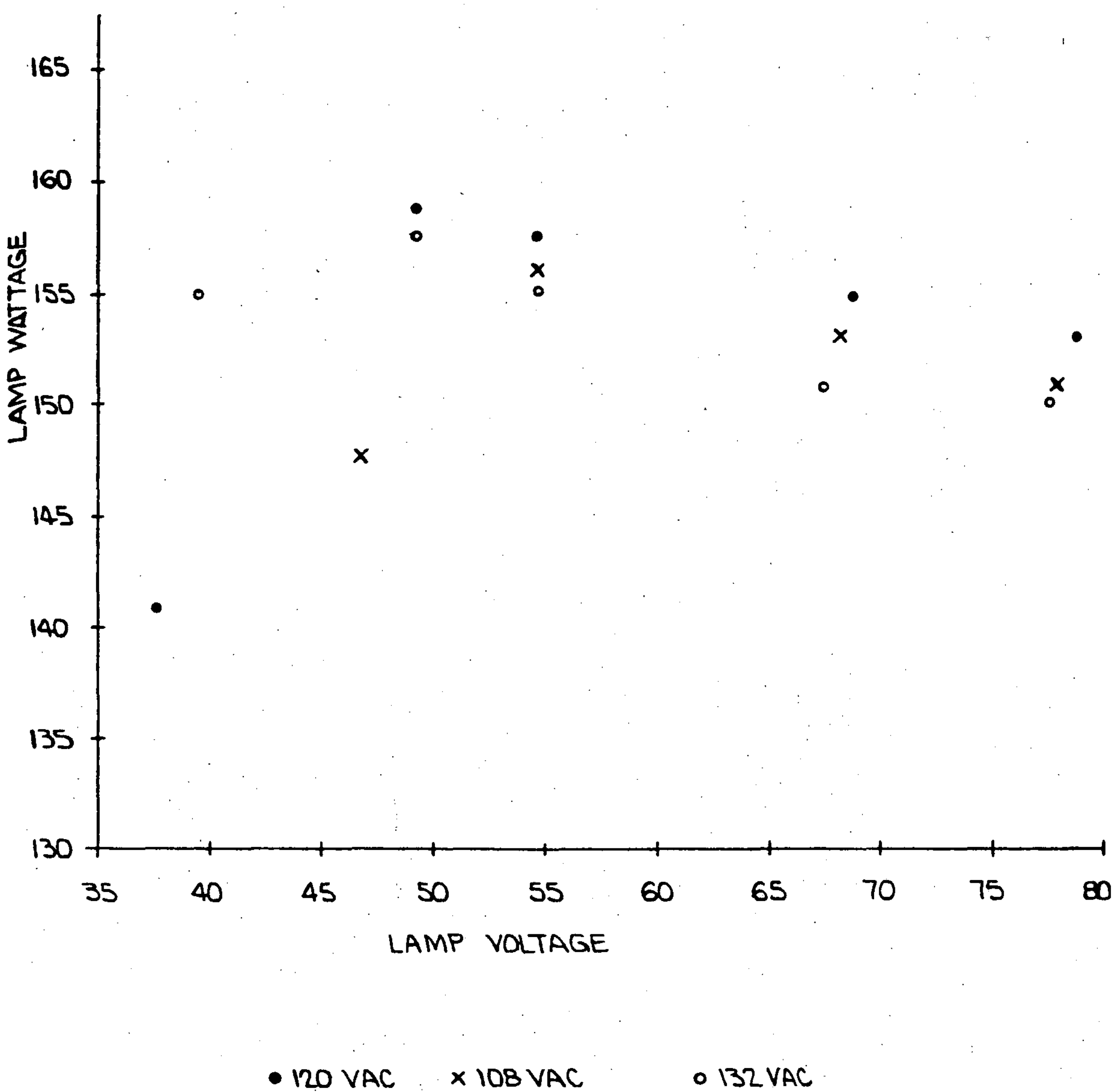
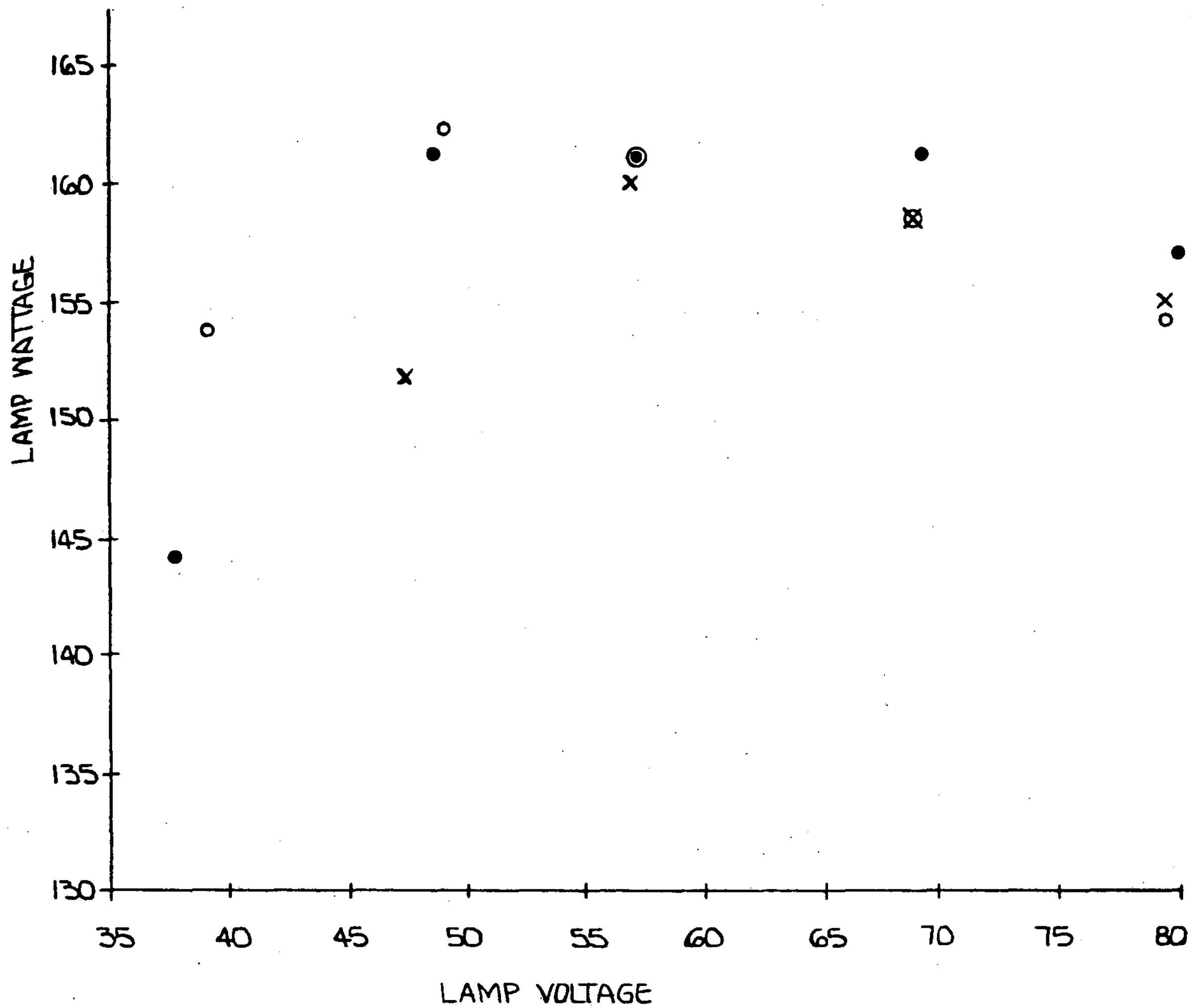


FIGURE V LINE-LOAD REGULATIONS UNIT # 4



● 120 VAC × 108 VAC ○ 132 VAC

FIGURE VI LINE-LOAD REGULATIONS UNIT # 5

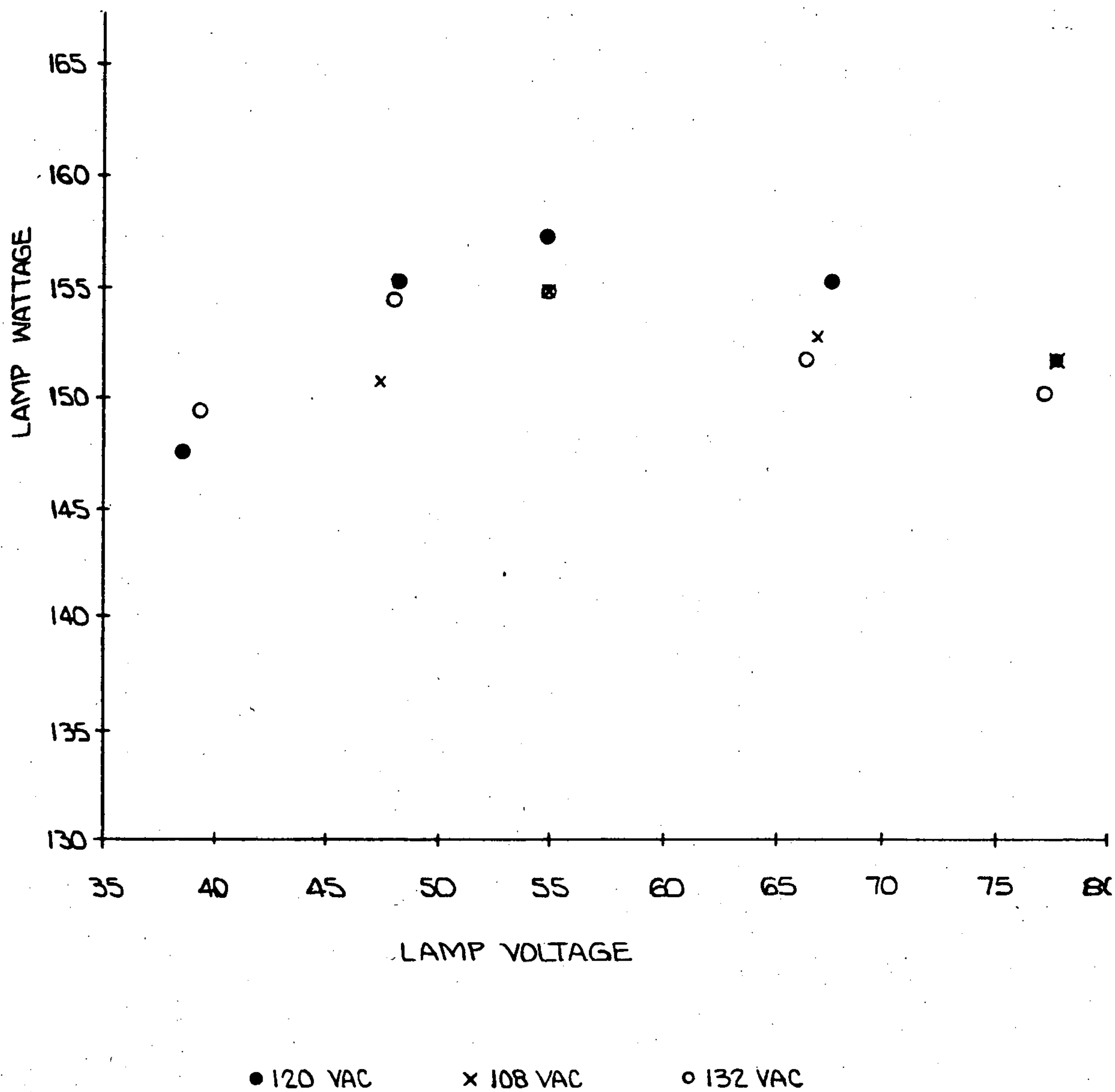


FIGURE VII LINE-LOAD REGULATIONS UNIT #6

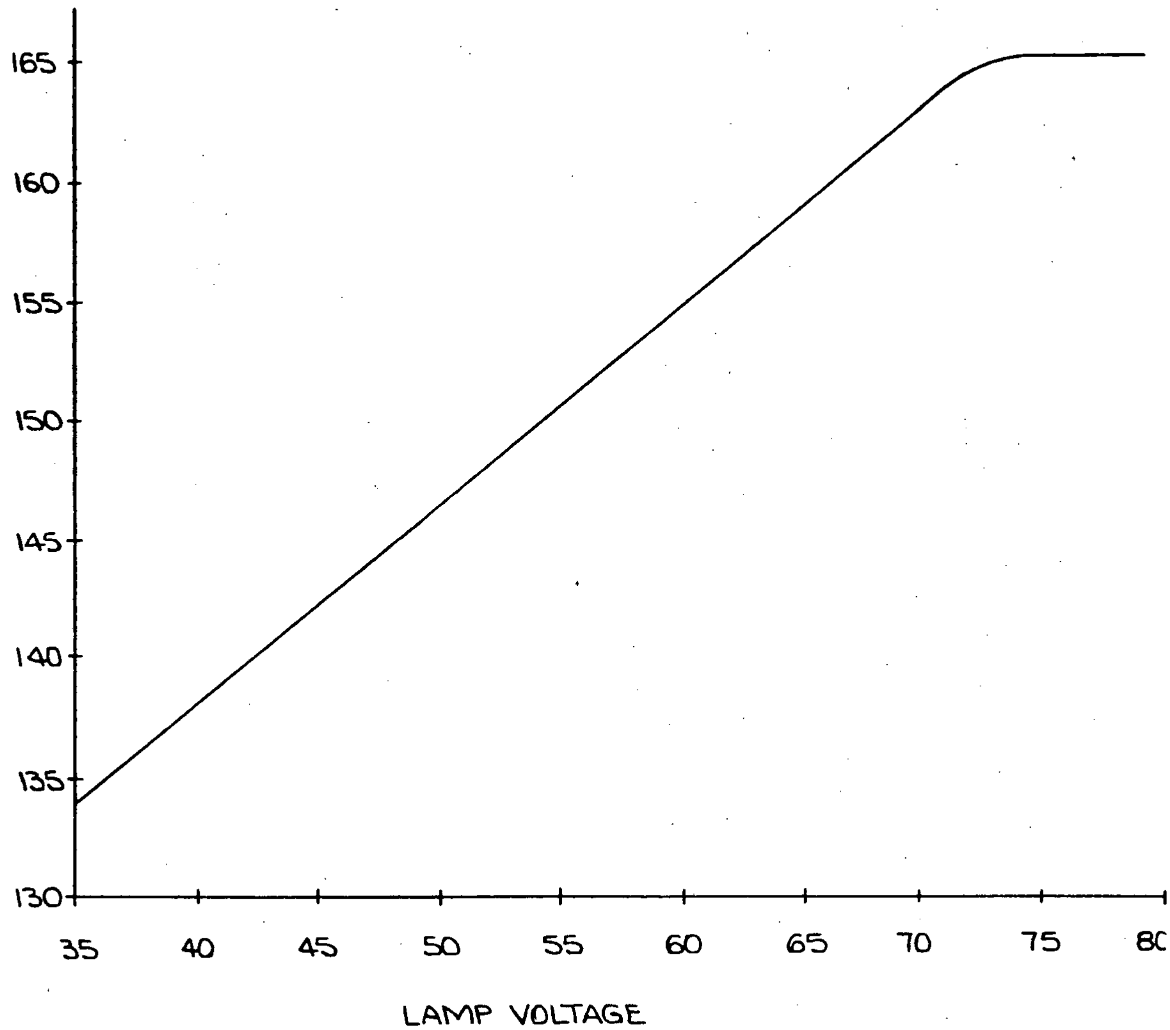


FIGURE VIII OPTIMUM LINE-LOAD REGULATION

V. FLICKER

Cyclic variations in the light output of a lamp is called flicker. With a 60 hertz ballast the flicker frequency is 120 cycles per second. Which, in general, is to quick to be noticed by the eye. However, rapid moving objects may be strobed causing ghost like images. This effect is called stroboscopic effect and the higher the flicker index, the more noticeable the effect.

The cyclic variations of high frequency ballasts generally consists of two components, a 120 Hz ripple and a 40 KHz or greater power frequency.

Examining the light output of the lamps with a fast responding silicone photocell indicates that 40 KHz is to fast for the lamp to respond. This suggests that the light output variations will be dominated by the 120 Hz ripple component. This is interesting, but we don't know that it's important. Any 40 KHz flicker that would exist, even if the lamp could respond to it, would be over 330 times quicker than the 120 Hz variations. Therefore, we doubt that the high frequency component would add significantly to the stroboscopic effect.

Examination of Table III, figure XII, and appendix XIII indicates that a lamp driven with the high frequency ballast displays significantly lower light output cyclic variations and lower flicker index than when driven with a single phase 60 Hz unit. This suggests that for application where rapid movement is present a high frequency ballast system would be more desirable than their 60 Hz counterparts. You'll note that Table III includes information regarding the flicker percentile and flicker index, as well as percent AC RMS / DC AVE.

We included the percent AC RMS / DC AVE because this type of information can be particularly useful.

The photocell, used to measure light, produces a voltage that is linear and directly proportional to the level of light striking its surface.

The denominator of the expression, or DC AVE, is an average of the photocell's voltage output and therefore an average light measurement. This can be used as a relitive, or calabrated for absolute light output measurement.

The numerator, or AC RMS number, of the expression is a measure of the root mean square value of the light output variations. This AC RMS number and the ratio of the AC RMS to DC AVE can be used to examine the filtering action of the lamp, or the effect of ballast low frequency ripple on lamp light output. We did not do this during this examination.

We should note that power supply ripple voltages are typically rated in AC RMS values and the ratio of AC RMS ripple to the DC AVE value is termed ripple factor. When this ratio is converted to percent it's termed ripple percent. Therefore, this measurement allows direct comparison of light output ripple to commonly used power supply terms.

The AC RMS / DC AVE number is waveform related to the flicker index. The percent AC RMS / DC AVE numbers given in Table III can be divided by 100 and 2.2 to produce a flicker index number that we have found to be generally more accurate than those produced by oscillicope measurements. For further explanation of this refer to appendix XIII.

	UNIT 1	UNIT 2	UNIT 3	UNIT 4	UNIT 5	UNIT 6
FLICKER %	16	8	10	17	14	15
FLICKER INDEX	.04	.02	.02	.04	.04	.04
% AC RMS/DC AVE*	11.0	5.6	6.5	11.7	9.3	11.0

* WAVEFORM AC RMS DIVIDED BY WAVEFORMS DC AVERAGE

MEASURED WITH TRUE RMS DIGITAL VOLTMETER

HIGH FREQUENCY BALLAST

FLICKER

TABLE III

VI. LAMP STARTING

The starting of a high pressure sodium lamp consists of two steps. First, the ionization of the gas must be initiated by high voltage. Second, a sufficient amount of arc current must be provided in order to bring the lamp's light output up to rated value in as short a time as possible, yet not go outside the manufacturer's ratings.

We chose a symmetrical high frequency high voltage AC to start the lamp because it appeared to cause less arcing than a single non-symmetrical high voltage pulse normally used for high pressure sodium lamps. We felt this had the potential of extending lamp life. We have not confirmed this with on - off cycle testing. Appendix XII gives additional information on the starting of 150 watt high pressure sodium lamps with symmetrical AC voltages. Table IV shows that the low input voltage starting capability of the high frequency ballast is comparable to the Jefferson 841-1862 ballast which started GE LU150/55 at 82 volts input.

Table IV also shows that the high frequency ballast brings the light output of the lamp up to its rated value in a period that compares favorably with the Jefferson 841-1862, which brings a GE LU150/55 up to 90 percent of its rated light output in 3.5 minutes with 120 VAC input.

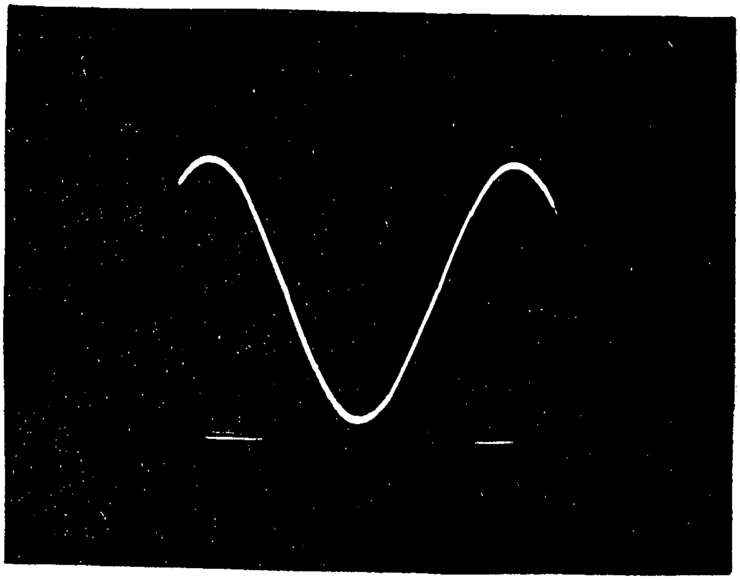
Rated light output was considered, that level obtained when the lamp was operated at 150 watts 60 Hz.

	UNIT 1	UNIT 2	UNIT 3	UNIT 4	UNIT 5	UNIT 6
LAMP START VOLTAGE GE LU150/55	72VAC	86VAC	82VAC	78VAC	68VAC	76VAC
LAMP START VOLTAGE SYL LU150/55	72VAC	86VAC	82VAC	78VAC	68VAC	76VAC
TIME IN MINUTES TO 90% RATED LIGHT OUTPUT 120V INPUT	3.0	3.0	3.0	3.0	3.0	2.5

MINIMUM INPUT STARTING VOLTAGE
AND TIME TO RATED LIGHT OUTPUT

HIGH FREQUENCY BALLAST

TABLE IV



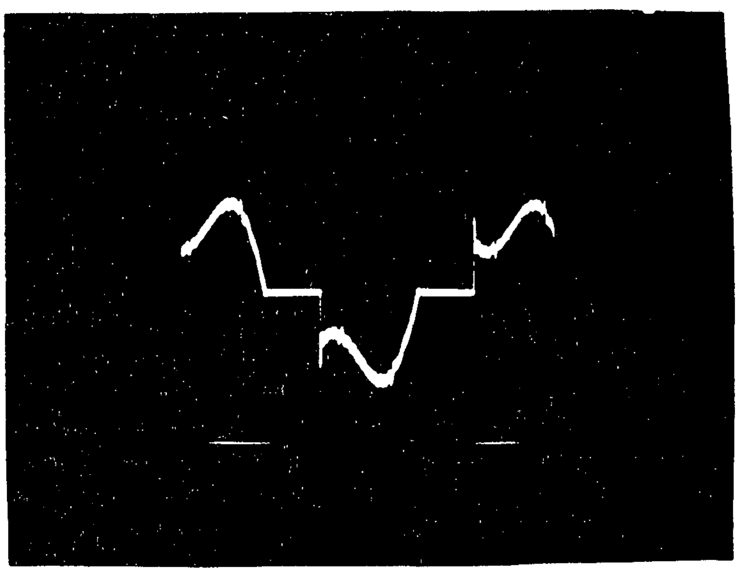
INPUT VOLTAGE

AT 120 VAC 60 Hz

INPUT

50V/div

2ms/div



INPUT CURRENT

AT 120 VAC 60 Hz

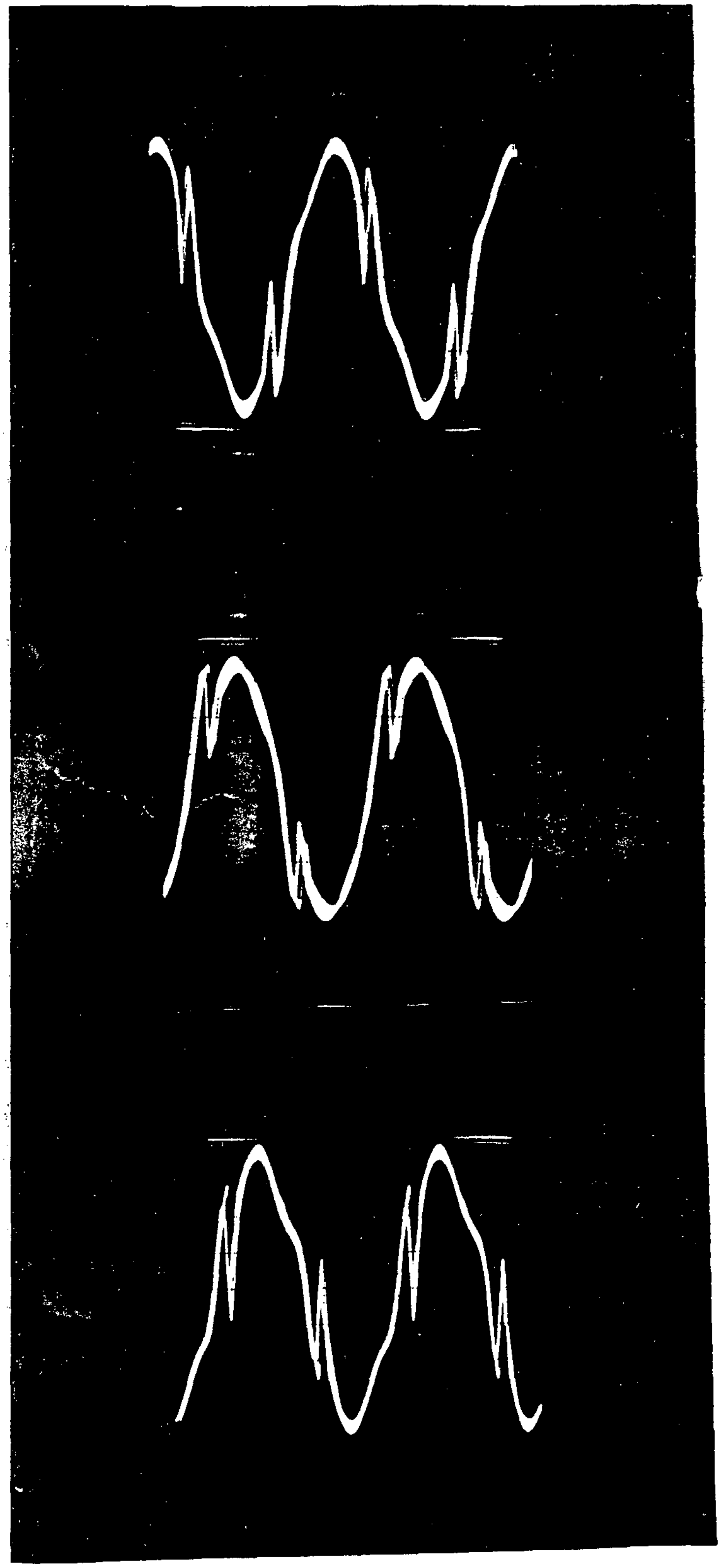
INPUT

0.5A/div

2ms/div

TYPICAL INPUT WAVEFORMS
HIGH FREQUENCY BALLAST
GE LU150/55

FIGURE IX



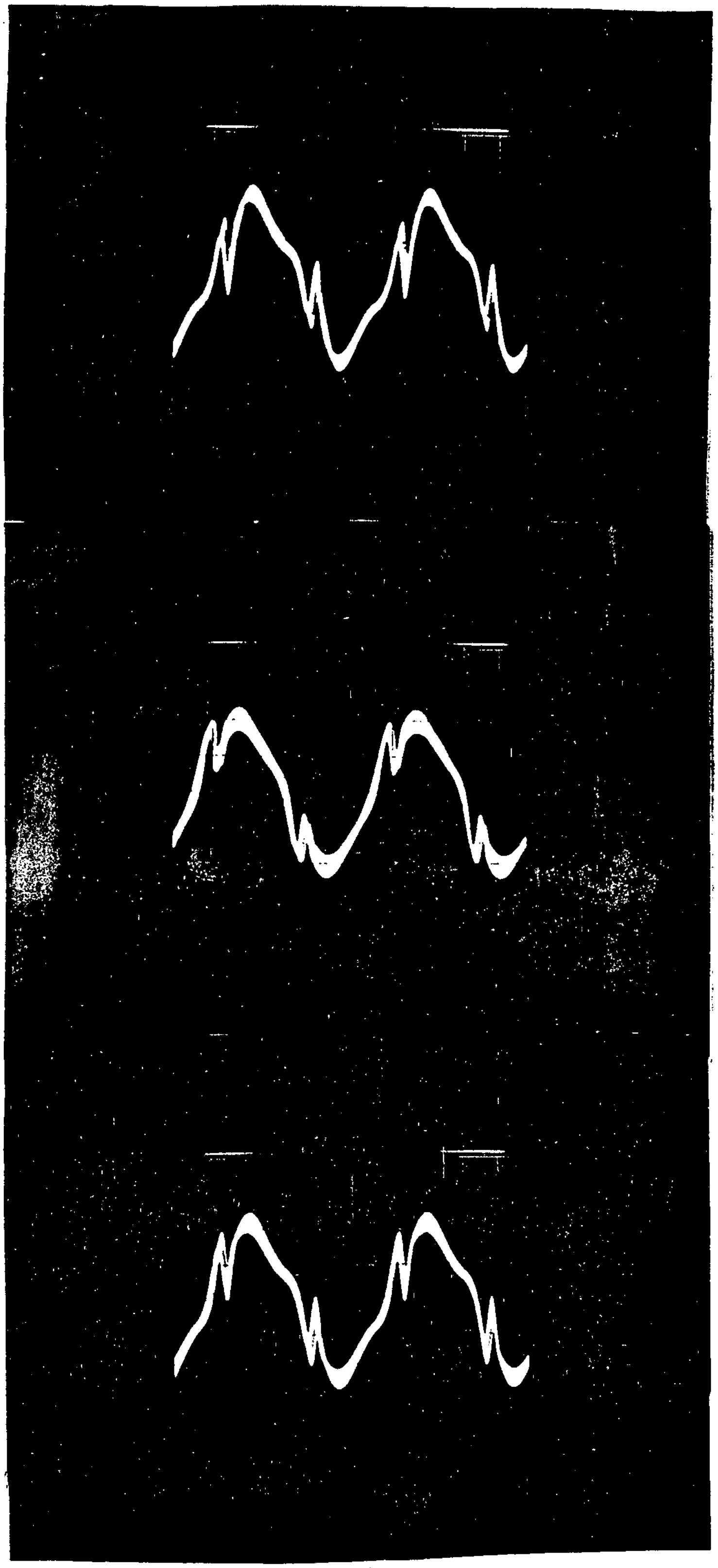
LAMP VOLTAGE
120 VAC INPUT
20V/div
10US/div

LAMP VOLTAGE
108 VAC INPUT
20V/div
10US/div

LAMP VOLTAGE
132 VAC INPUT
20V/div
10US/div

LAMP VOLTAGE WAVEFORMS
HIGH FREQUENCY BALLAST
GE LU150/55

FIGURE X



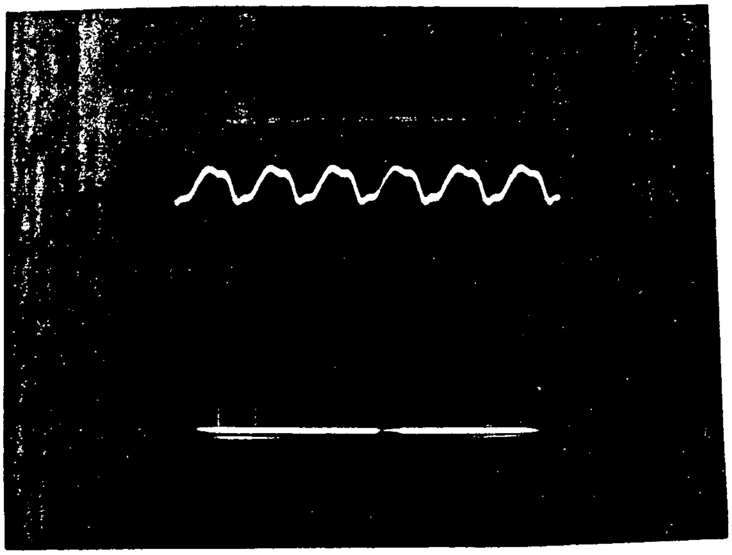
120 VAC INPUT
10US/div
2A/div

108 VAC INPUT
10US/div
2A/div

132 VAC INPUT
10US/div
2A/div

LAMP CURRENT WAVEFORMS
HIGH FREQUENCY BALLAST
GE LU150/55

FIGURE XI

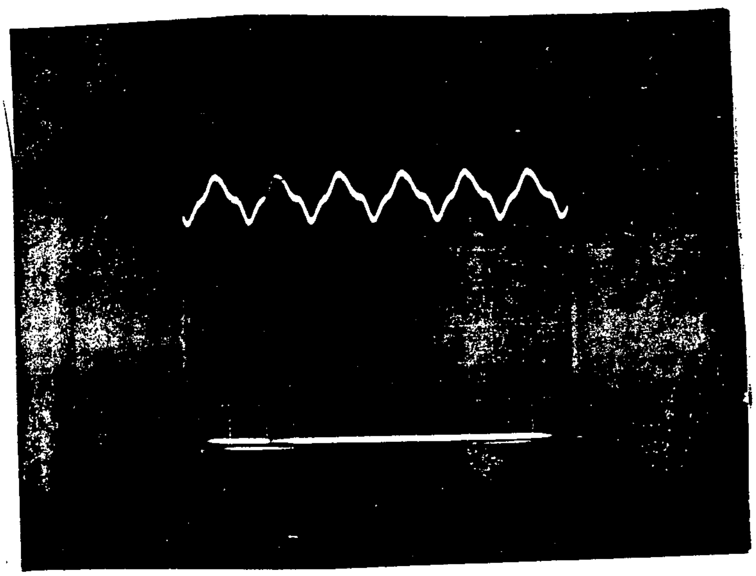


120 VAC INPUT

5ms/div

.1V/div

FLICKER INDEX .02

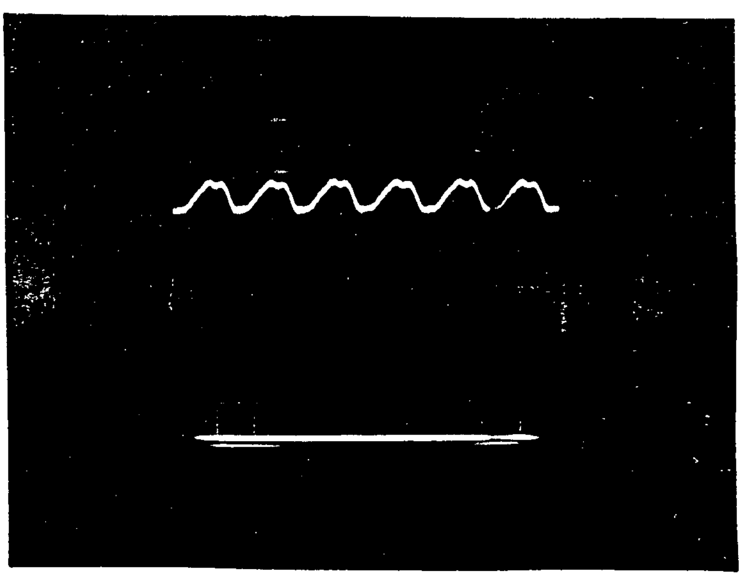


108 VAC INPUT

5ms/div

.1V/div

FLICKER INDEX .03



132 VAC INPUT

5ms/div

.1V/div

FLICKER INDEX .02

FLICKER WAVEFORMS
HIGH FREQUENCY BALLAST
GE LU150/55

FIGURE XII

APPENDIX

I. Test Circuit

II. Constant Wattage Light Output With Frequency GE LU150/55 #3

III. Constant Wattage Light Output With Frequency GE LU150/55 #5

IV. Constant Wattage Light Output With Frequency Sylvania LU150/55 #2

V. Constant Wattage Light Output With Frequency Sylvania LU150/55 #8

VI. Lamp Voltage Variations With Frequency

VII. Power Factor Variations With Frequency

VIII. Lamp Voltage Versus Lamp Wattage

IX. Lamp Current Versus Lamp Wattage

X. Light Output Versus Lamp Wattage

XI. Constant Wattage Lamp Voltage Variations With Ambient Temperature

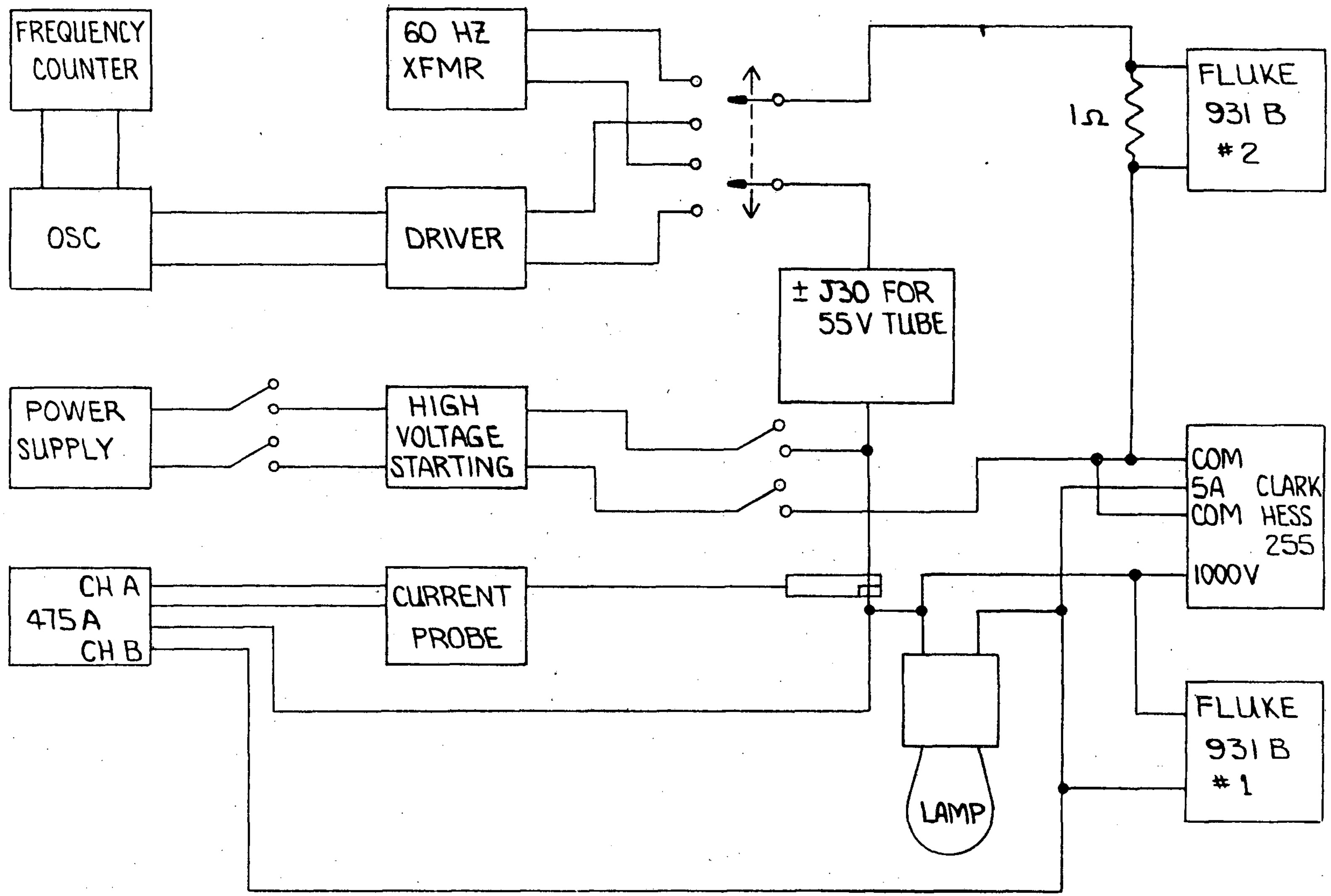
XII. Lamp Starting Voltage Versus Frequency And Temperature

XIII. Standard Ballast Flicker And A Look At AC RMS / DC AVE

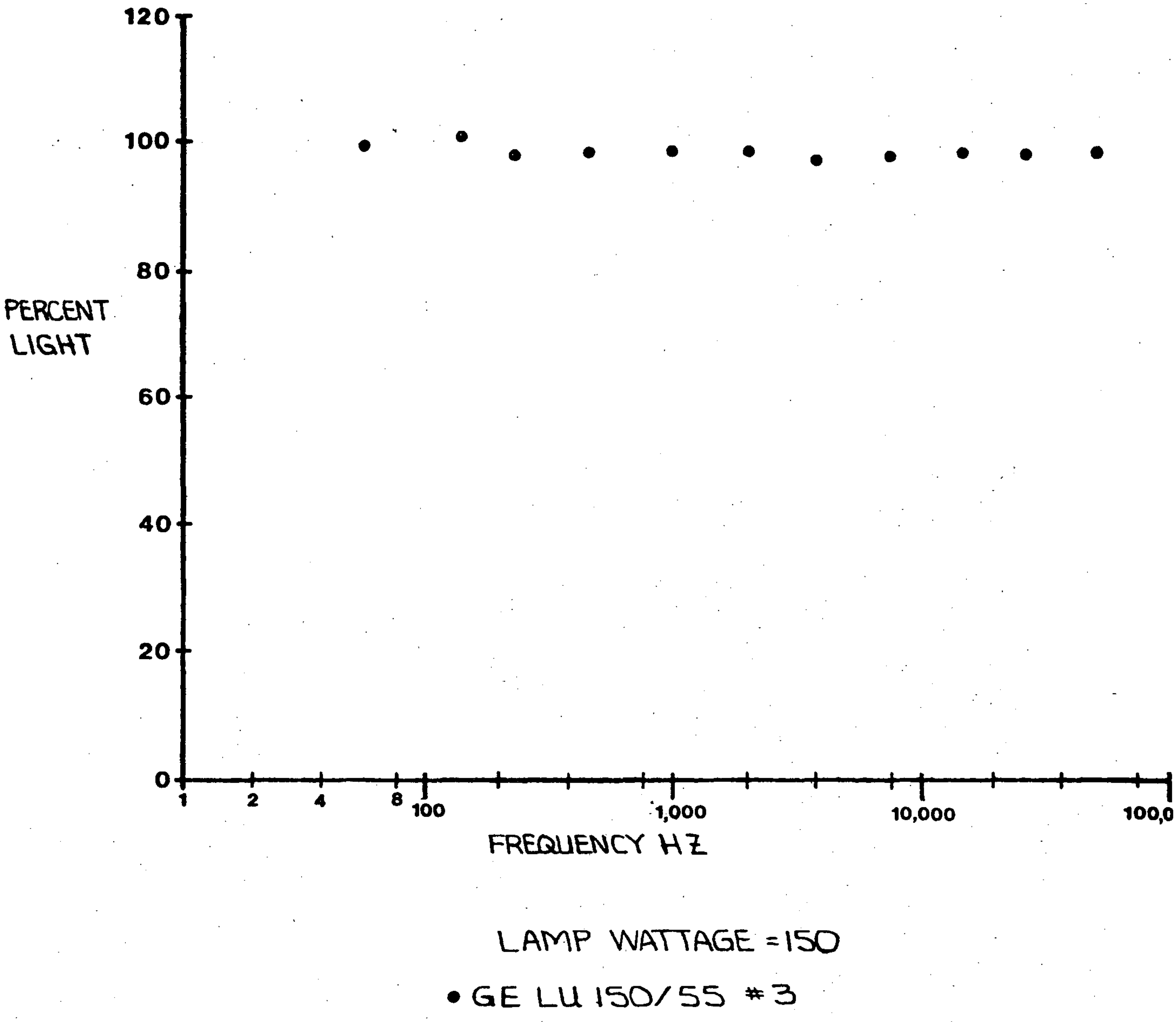
XIV. Standard And High Frequency Ballast Comparison

XV. Standard Ballast Line Regulation GE Lamp LU150/55

XVI. Recommended Lamp Operating Limits



APPENDIX I FIG. 1 SCHEMATIC USED TO OBTAIN DATA IN APPENDIX II THRU XII



APPENDIX II CONSTANT WATTAGE LIGHT OUTPUT VARIATIONS WITH FREQUENCY

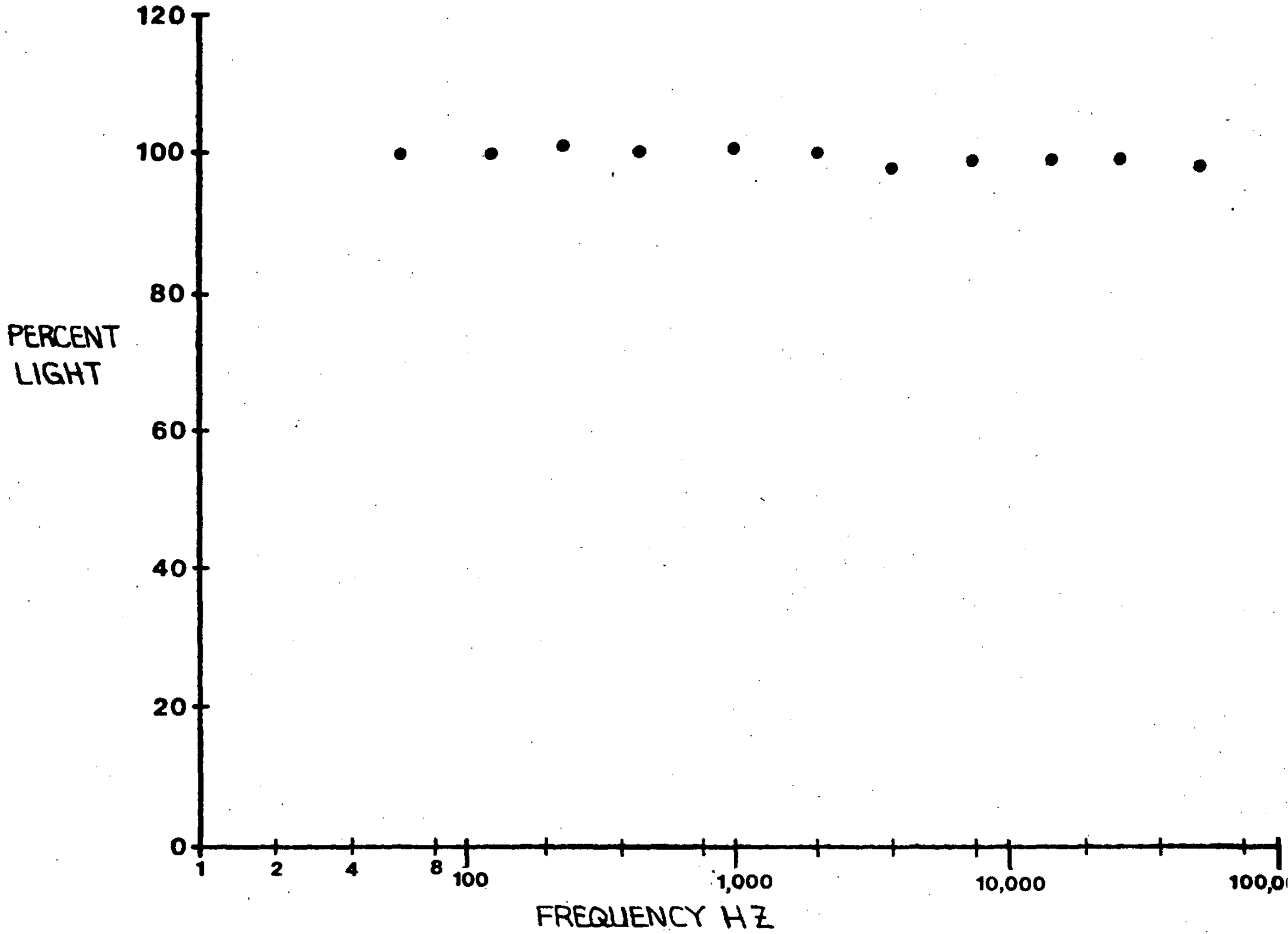
The light measurements for Appendix II through V were taken per that discribed in the test procedure of the text.

We wanted to find the frequency that produced the highest lamp efficacy.

Series reactance was maintained at $\pm$ J30 + 10 percent throughout the range of frequencies. The frequency where the reactance changed from + J 30 to - J 30 was 8 KHz, below that frequency + J 30 was used. Current crest factor was monitored and maintained below 1.6.

The fact that we did not use an integrating sphere sheds some doubt on the results but the consistancy, linearity and the sensitivity to changes in light output (see appendix X), speak well for the results.

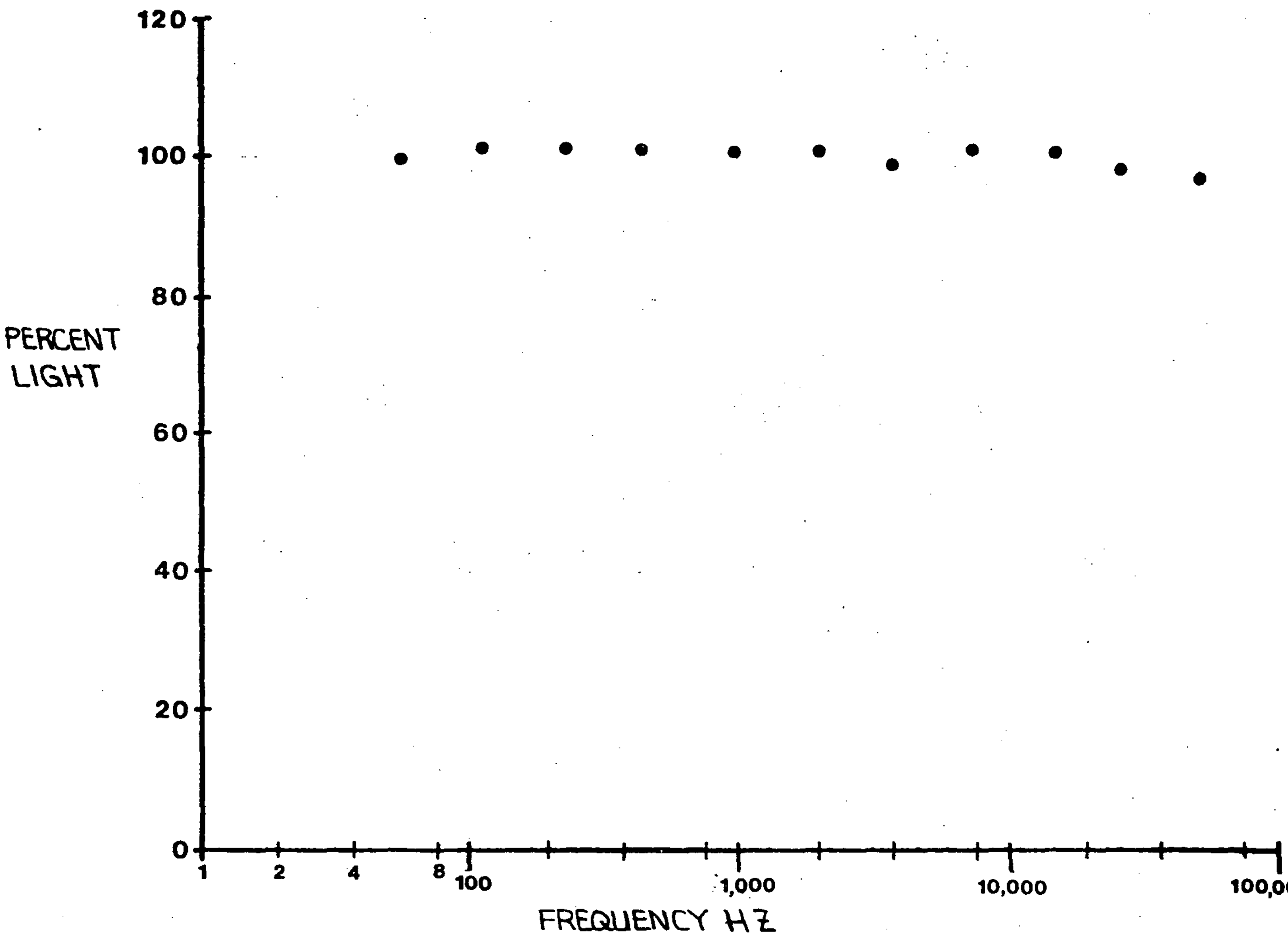
Appendix II



LAMP WATTAGE = 150

• GE LU 150/55 # 5

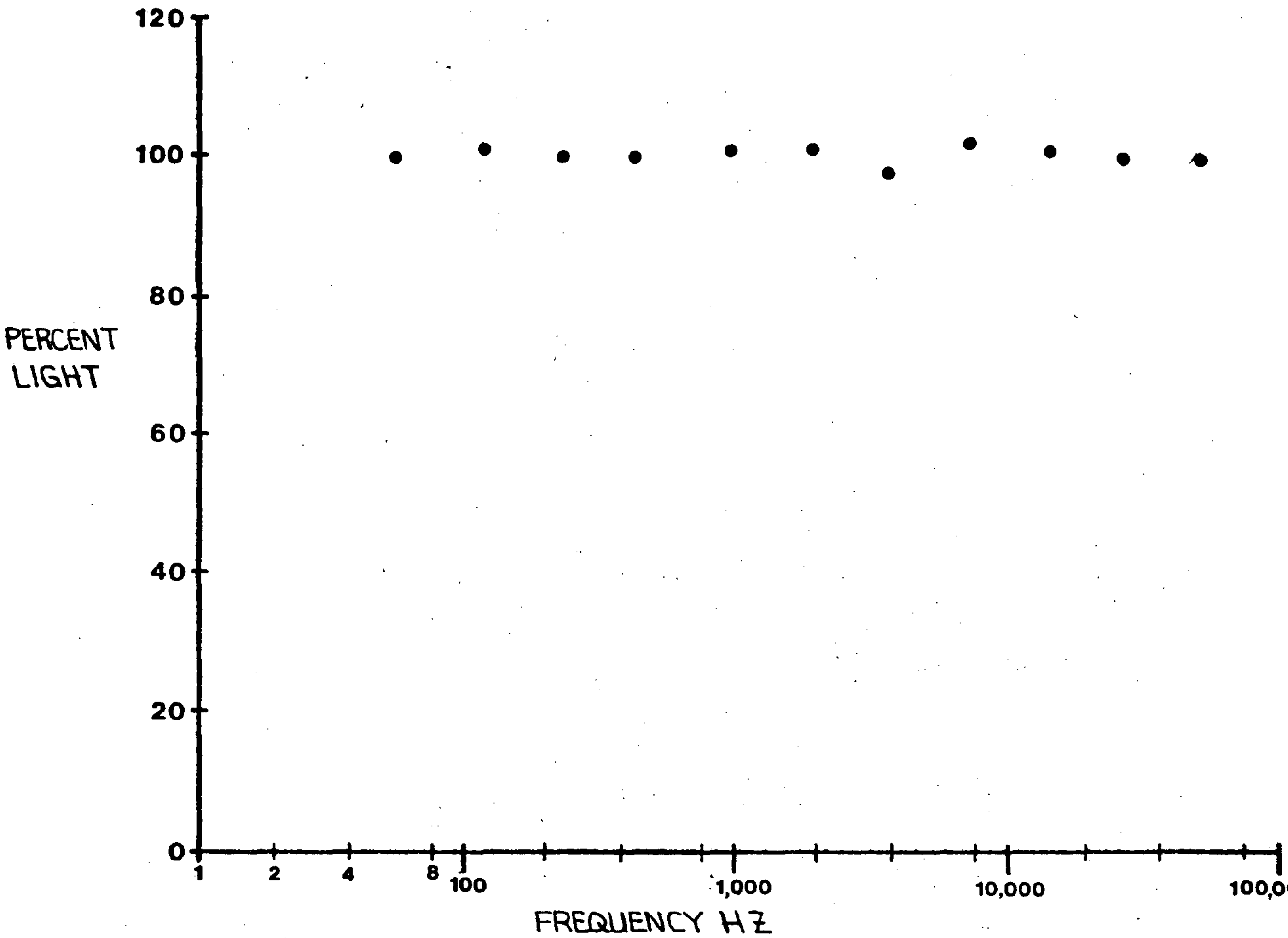
APPENDIX III CONSTANT WATTAGE LIGHT OUTPUT VARIATIONS WITH FREQUENCY



LAMP WATTAGE = 150

• SYL LU 150/55 # 2

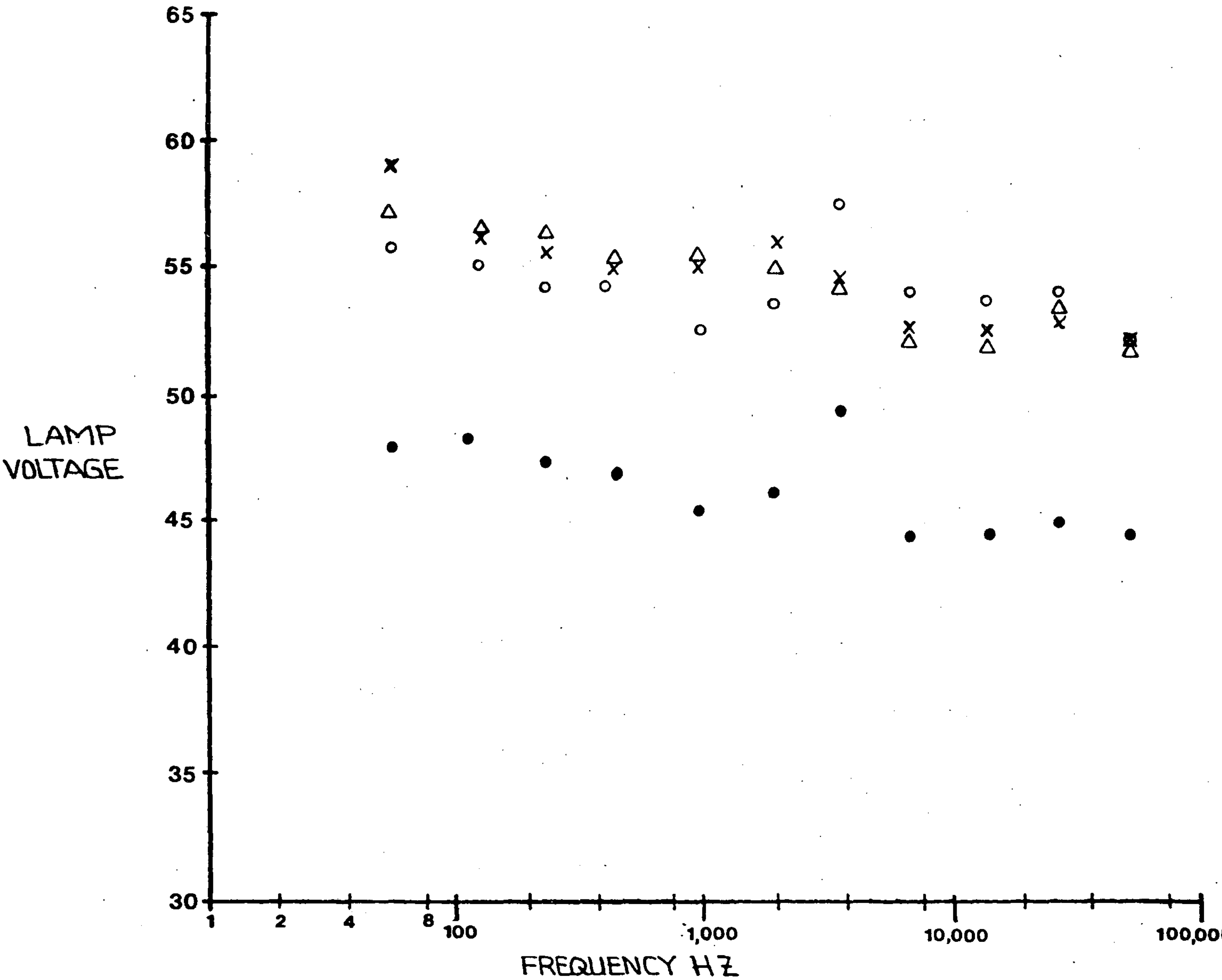
APPENDIX IV CONSTANT WATTAGE LIGHT OUTPUT VARIATIONS WITH FREQUENCY



LAMP WATTAGE = 150

• SYL LU 150/55 #8

APPENDIX V CONSTANT WATTAGE LIGHT OUTPUT VARIATIONS WITH FREQUENCY



LAMP WATTAGE = 150

● GE LU150/55 # 3
○ GE LU150/55 # 5
× SYL LU 150/55 # 2
△ SYL LU150/55 # 8

APPENDIX VI LAMP VOLTAGE VARIATIONS WITH FREQUENCY

This chart clearly illustrates the longitudinal acoustic resonant point for the General Electric LU150/55 lamps.

We found the resonance was strong enough in the case of the General Electric lamps to crack the arc tube of the two lamps we operated in that region.

The Sylvania lamps also display an acoustic resonance around the four kilohertz region, although the voltage rise is not as evident from the chart.

The acoustical resonance of the Sylvania LU150/55 was not strong enough to destroy the lamp samples we tested. We did notice a chiming noise made by the Sylvania lamp around 16 to 18 kilohertz, this sounded much the same as shaking an incandescent light bulb. We didn't note a change in

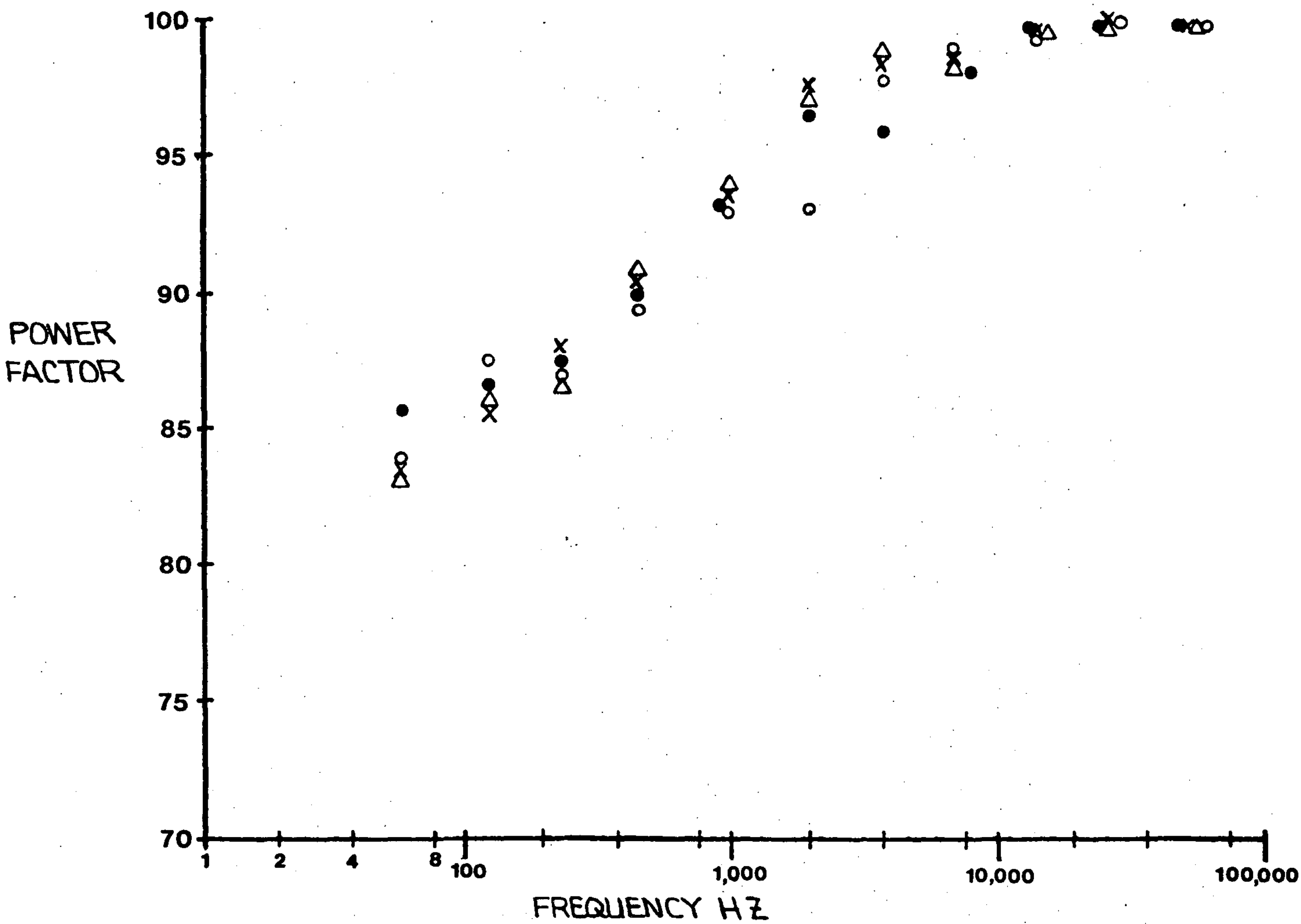
Appendix VI

operating voltage or current though and this was not noted with General Electric lamps.

The chart shows that there is a decreasing lamp voltage characteristic with frequency for both the General Electric and Sylvania lamps.

An artical by Mr. Charles F. Scholz in the December 1970 issue of Illuminating Engineering Society provides additional information on the subject.

Appendix VI



LAMP WATTAGE = 150

● GE LU150/55 # 3
○ GE LU150/55 # 5
× SYL LU150/55 # 2
△ SYL LU150/55 # 8

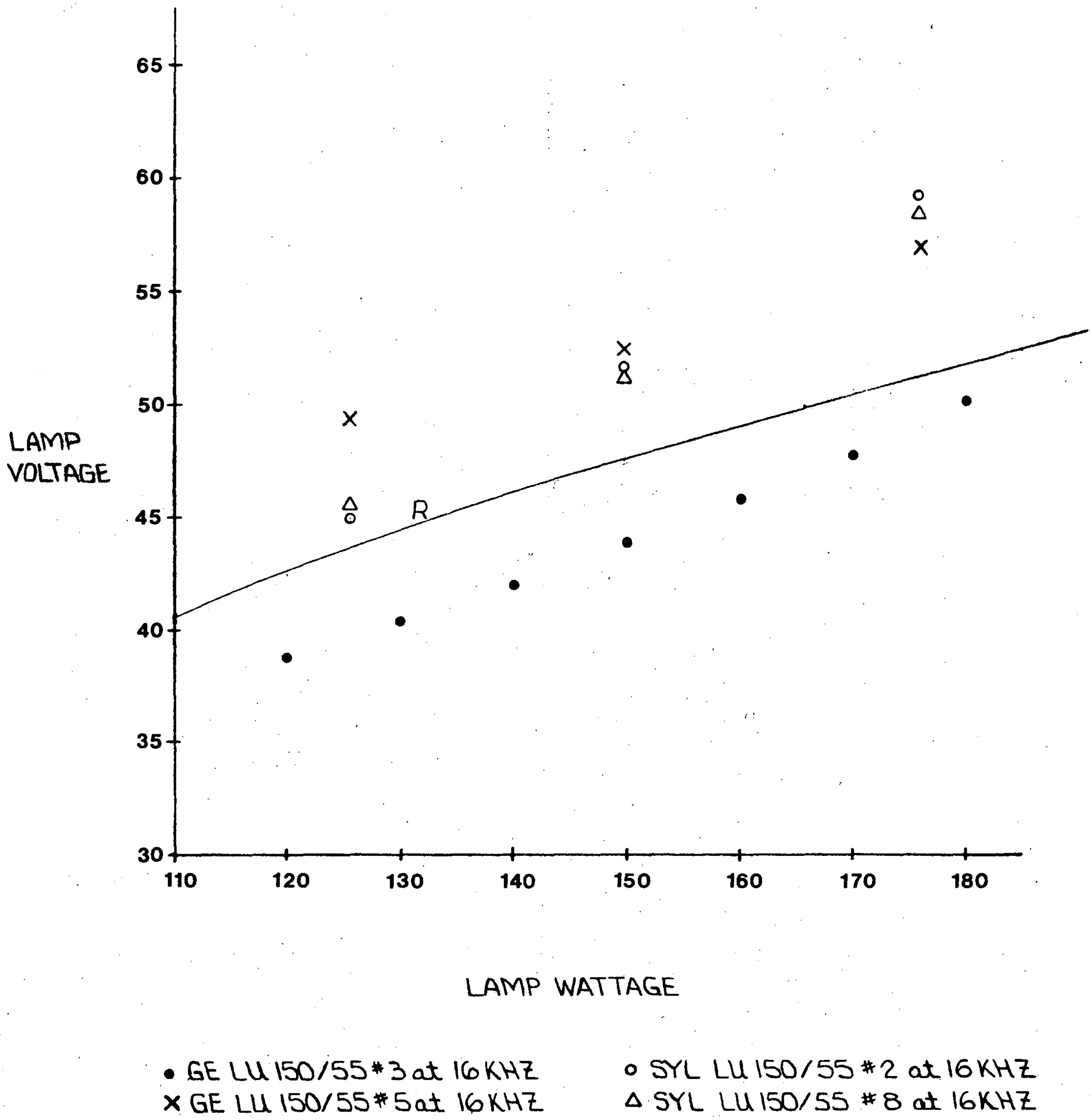
APPENDIX VII POWER FACTOR VARIATIONS WITH FREQUENCY

The graph in this appendix shows that the circuit loading effect of the high pressure sodium lamp changes with frequency.

At the low frequency end, the current waveform is a sine wave but the voltage is a square wave. At the high frequency end, both the current and the voltage are sine wave.

The harmonic content of the voltage waveform decreases with increasing frequency until about eight kilohertz, where the transition from square wave to sine wave is basically complete.

Appendix VII



APPENDIX VIII LAMP VOLTAGE VERSUS LAMP POWER

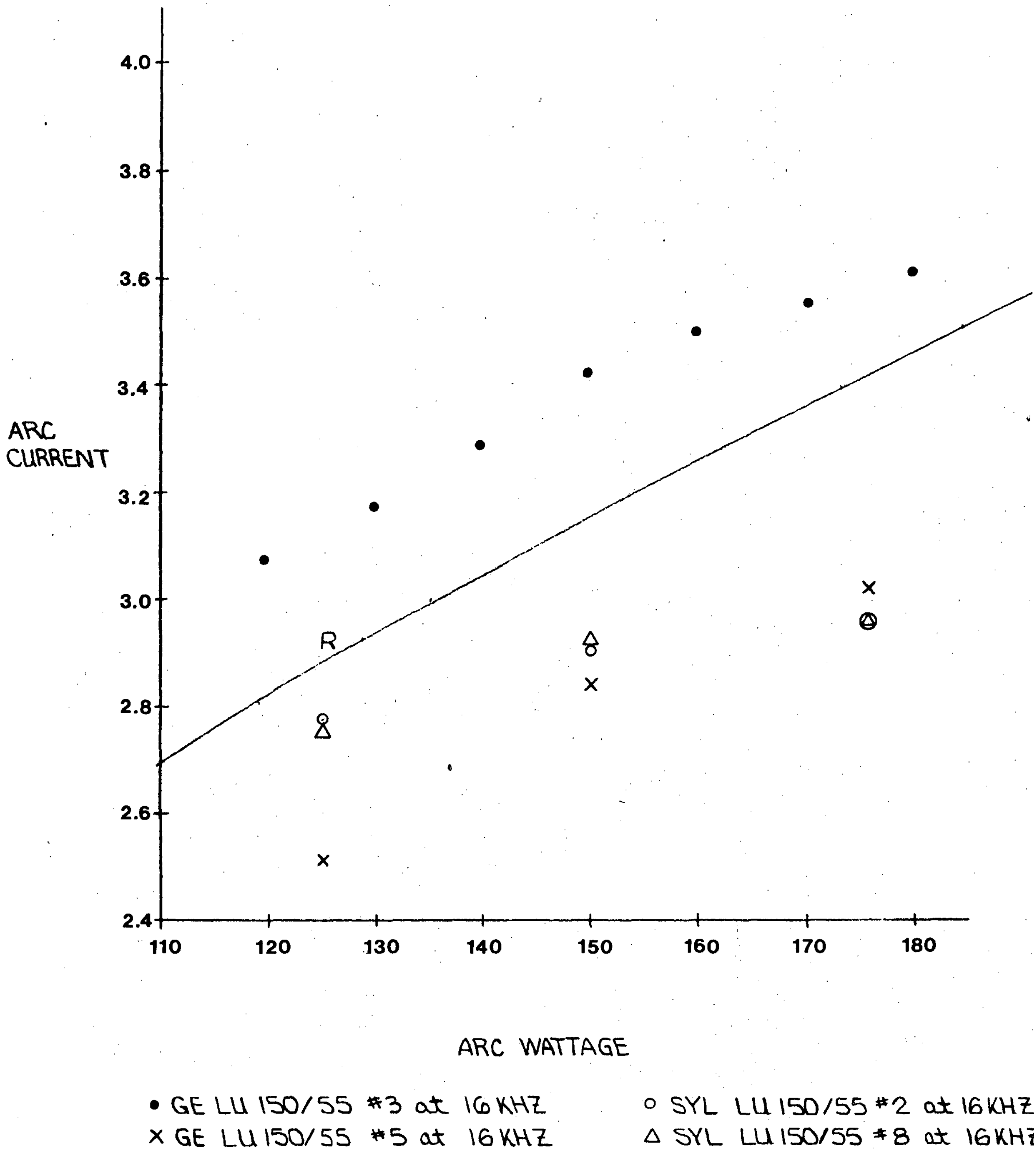
Although the power factor of the lamps are near unity at the higher frequencies, the circuit loading effect is not resistive because the impedance of the lamps changes with lamp power.

The changes in lamp voltage with power can be compared with that of a 15 ohm resistor which is shown in this appendix and the following one as the R curve.

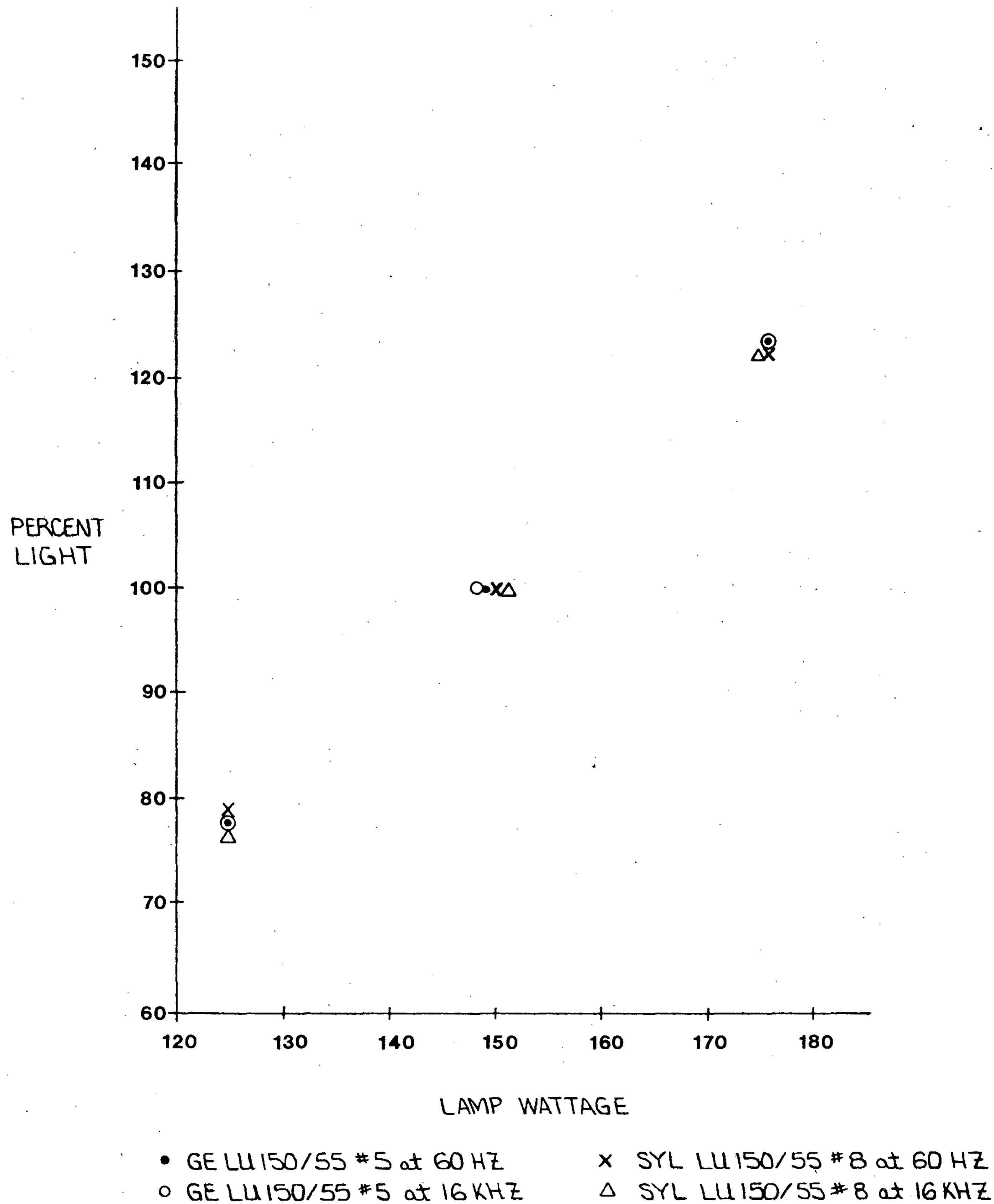
The graphs in this appendix and the following shows that the voltage increases more quickly and the current increases more slowly with increasing power than a resistive load.

There also appears to be quite a variation from lamp to lamp which makes regulation somewhat difficult.

Appendix XIII



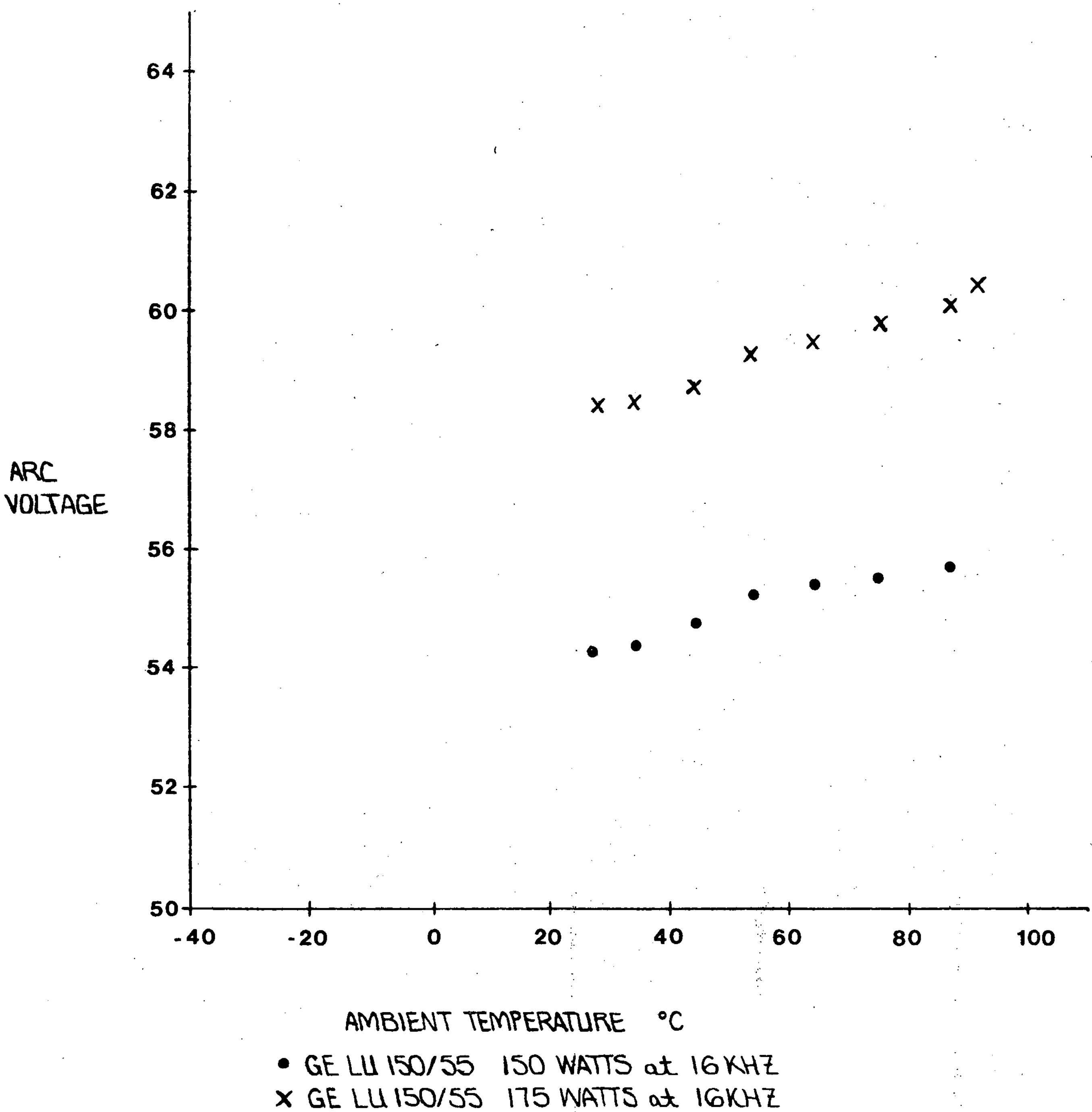
APPENDIX IX LAMP CURRENT VERSES
LAMP POWER



APPENDIX X LIGHT OUTPUT VERSES
LAMP WATTAGE

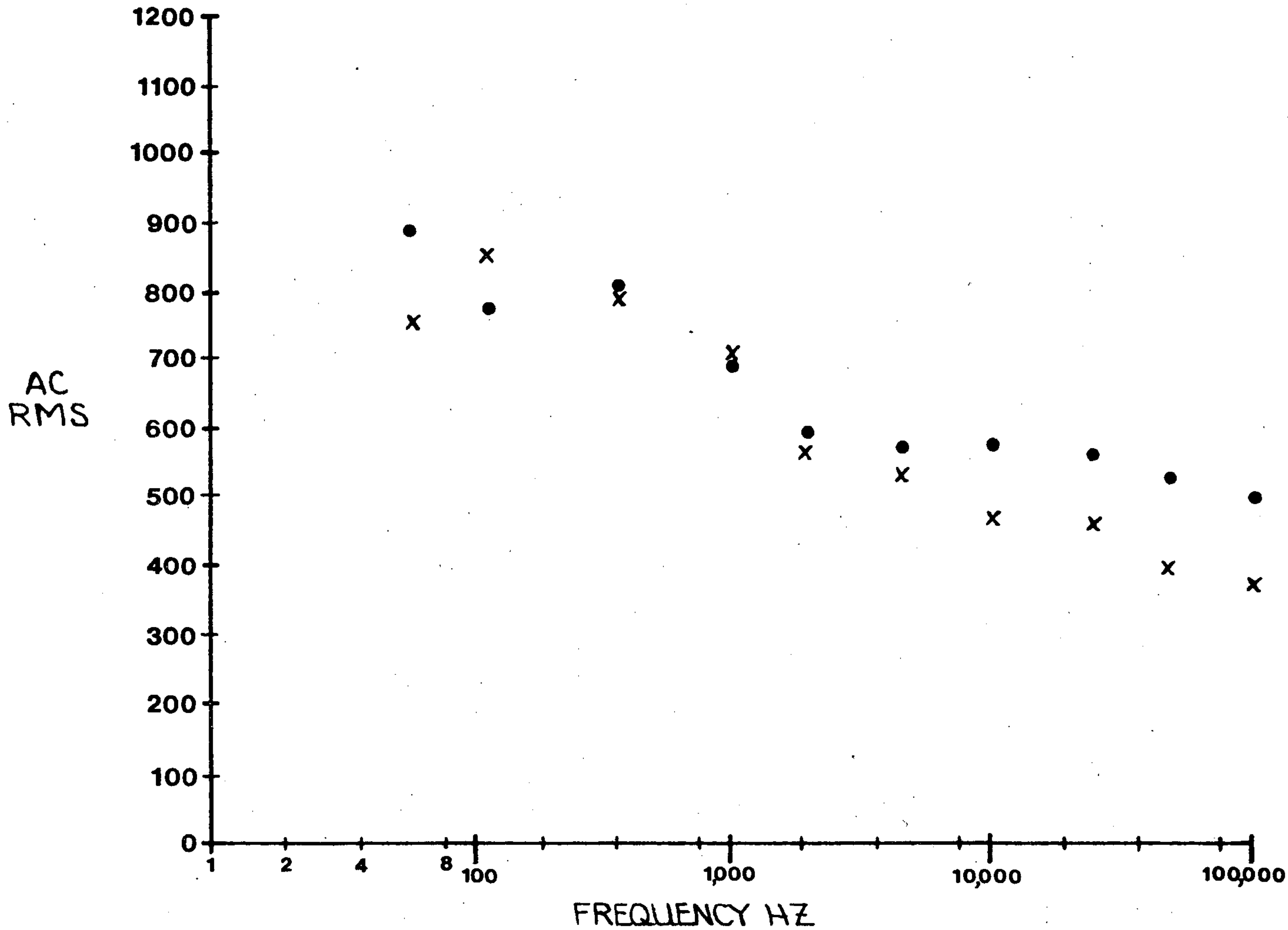
The efficacy of the lamp increases with increasing input power. This suggests that you should operate the lamps near the upper end of their rating in order to have a system that will produce the most light output per dollar.

Appendix X



APPENDIX XI CONSTANT WATTAGE LAMP VOLTAGE VARIATIONS WITH TEMPERATURE

Arc voltage increases with lamp temperature. This effect will have a tendency to detract from the light output regulation with increasing age of the lamp, although the voltage only varies about four percent over range of 60 degrees celsius.



• GE LU 150/55 × SYL LU 150/55

TA = 25°

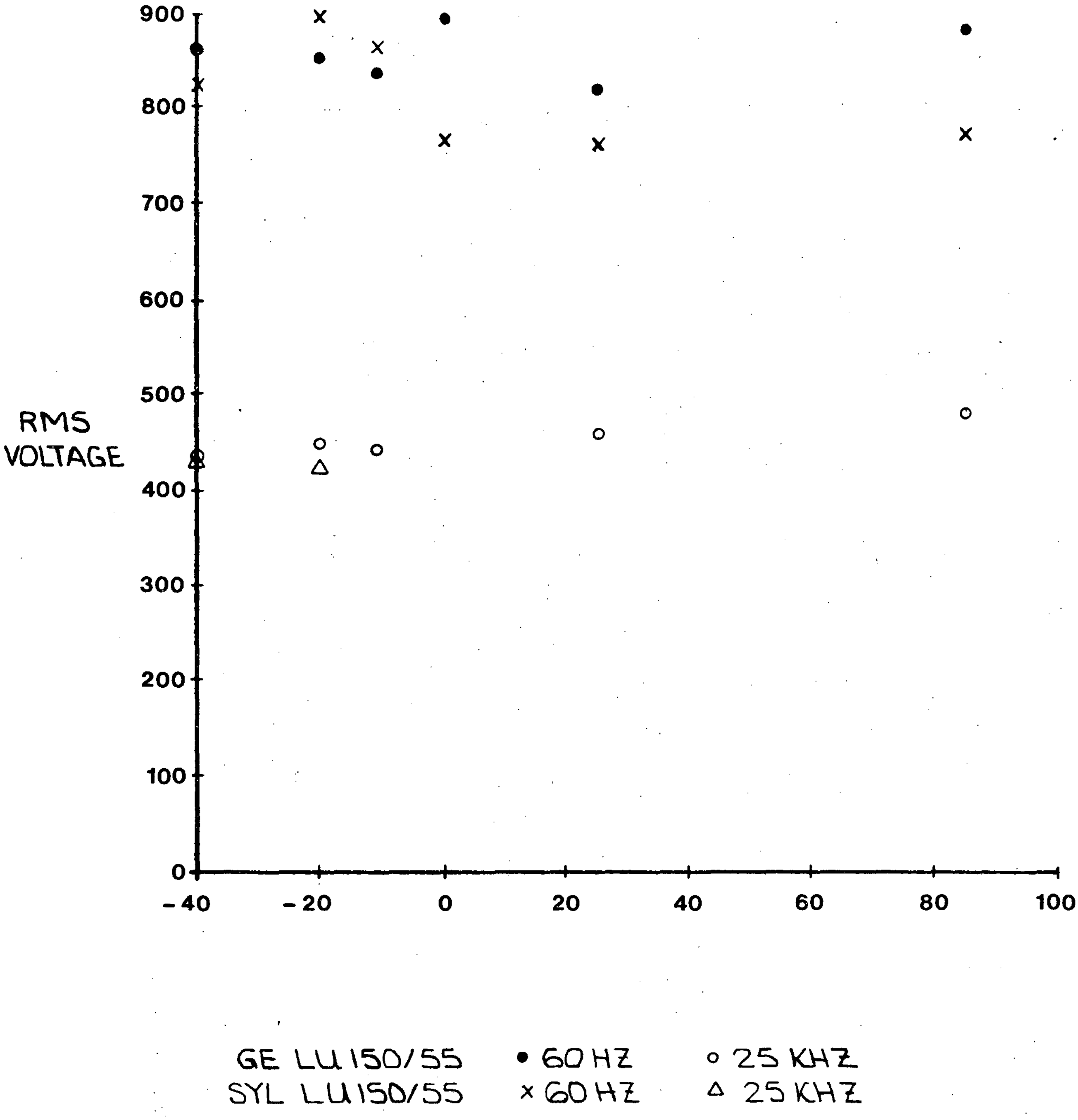
APPENDIX XII LAMP STARTING VARIATIONS WITH FREQUENCY

New lamps, and lamps that have been burned-in 100 hours, exhibit the starting characteristics shown in this and in the following appendix. This data indicates, as does Mr. John Campbell's December 1969 Illuminating Engineering Society article, that the starting voltage decreases with increasing frequency.

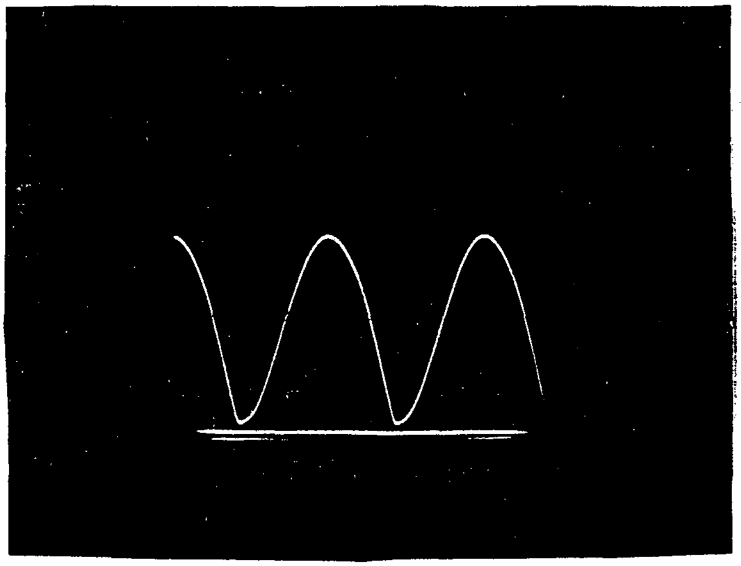
This would be a very useful design advantage for high frequency ballasts. Unfortunately, this characteristic is inconstant. The lamps will, at times, hang up and will not ionize unless a voltage equivalent to that required to start the lamp at 60 Hz was applied.

This characteristic could probably be stabilized with some work with the lamp manufacturers.

Appendix XII



APPENDIX XII LAMP STARTING VOLTAGE VARIATIONS WITH TEMPERATURE



JEFFERSON

841-1862 BALLAST

AT 150 WATTS

0.2V/div

2ms/div

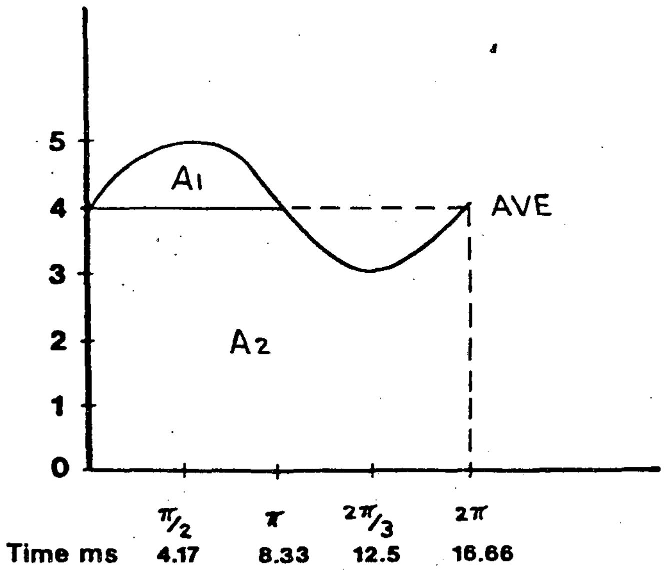
% FLICKER 89

FLICKER INDEX 0.33

WAVEFORM AC RMS/DC AVE 0.57

STANDARD BALLAST FLICKER

APPENDIX XIII



FLICKER INDEX = $\frac{A_1}{A_1 + A_2}$ =

0.32/(0.32+3.68) = 0.080

DC AVE = 4.0

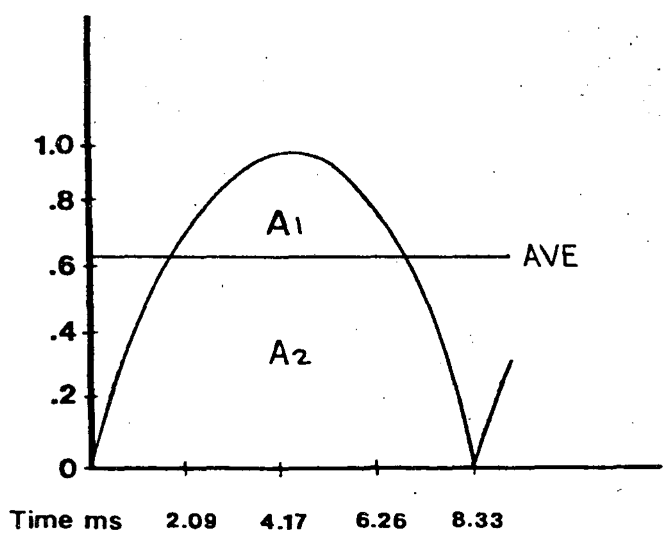
AC RMS = $\sqrt{\frac{\int_0^{2\pi} \sin\theta^2 \, d\theta}{2\pi}}$

= 0.707

AC RMS / DC AVE = 0.707/4

= 0.177

FLICKER INDEX = .177/2.2 = 0.08



FLICKER INDEX = $\frac{A_1}{A_1 + A_2}$ =

0.0011/(0.0042+0.0011) = 0.21

DC AVE = 0.636

AC RMS = 0.307

AC RMS / DC AVE = 0.48

FLICKER INDEX = 0.48/2.2 = 0.22

APPENDIX XIII

The previous page shows that AC RMS / DC AVE can be used to measure flicker index.

We would like to point out that the 2.2 divisor we use is waveform dependent. For example, for a square wave the number would more correctly be 2.0 and for a pure sine wave it would be 2.22.

The number is generated by the ratio of calculated flicker index and AC RMS / DC AVE for the waveform under consideration.

Appendix XIII

BALLAST	Vin	Iin	Pin	PF	LIGHT OUTPUT	LAMP	LUM/WATT
Jefferson 841-1862	117	1.86	196	90.0%	100% (16000LUM)	GE LU150/55#3	81.6
Triad-Utrad #5	117	1.62	176	92.9%	100% (16000LUM)	GE LU150/55#3	90.9
Jefferson	117	1.86	197	90.0%	100% (16000LUM)	GE LU150/55#3	81.6

STANDARD AND HIGH FREQUENCY

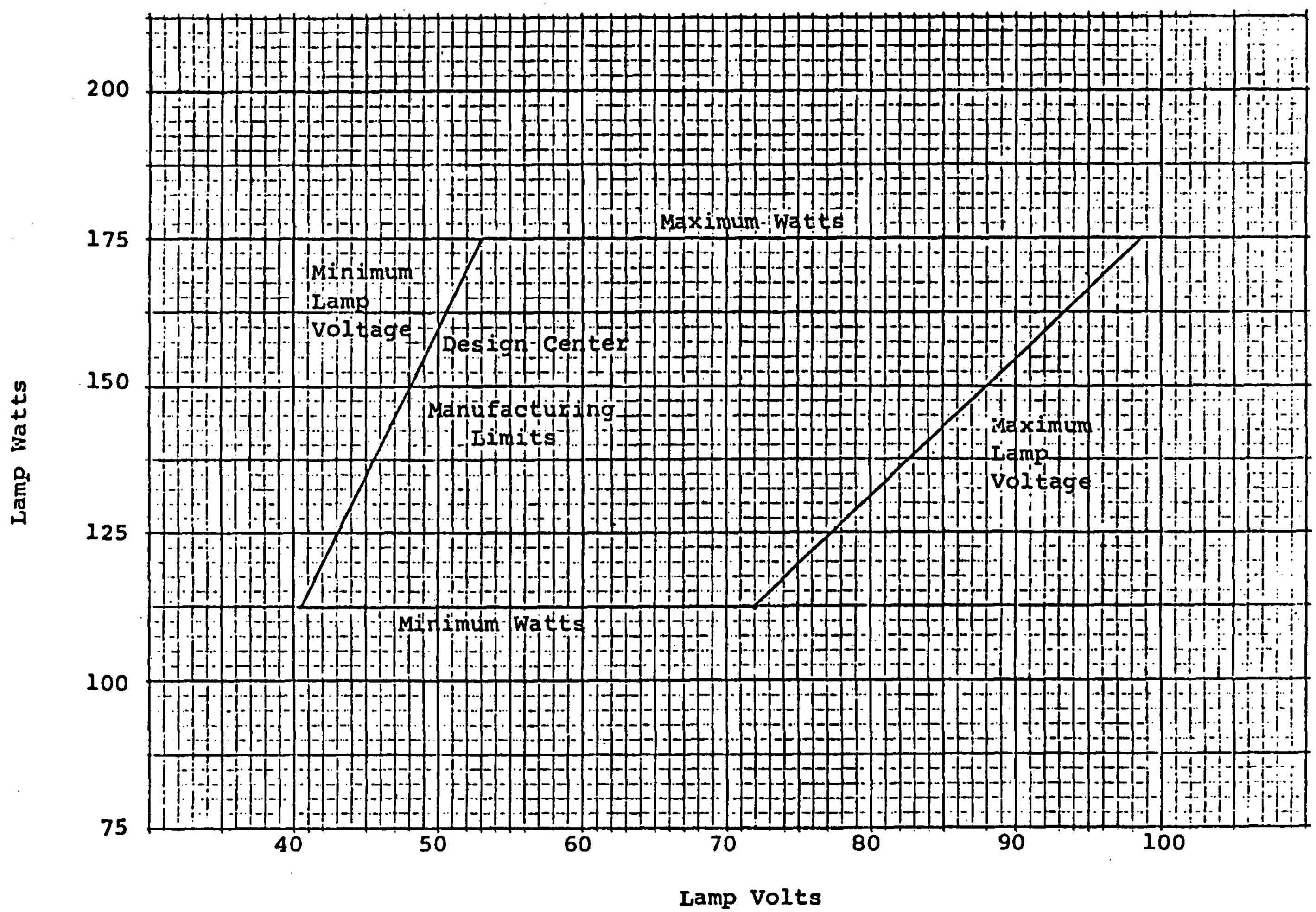
BALLAST COMPARISON

APPENDIX XIV

JEFFERSON 841-1862
GE LU150/55 LAMP

Line Voltage Change From Rated	- 5%	-10%	+ 5%	+10%
Input Power Change	-10%	-22%	+11%	+23%
Output Power Change	-10%	-20%	+11%	+23%
Light Output Change	-12%	-23%	+13%	+27%

Appendix XV
Line Regulation Standard Ballast



Appendix XVI Lamp Operating Limits GE LU150/55

The decrease in lamp voltage with frequency may cause some lamps to operate slightly to the left of the recommended operating limits. The manufacturer indicates this will be no problem as long as the power and crest factor is maintained within limits.

4.0 CONCLUSION

A. Efficiency

The average efficiency of the six prototype ballasts when operated with G.E. and Sylvania lamps is 84.8%.

The average efficiency of conventional high reactance autotransformer core/coil ballasts is 80%.

B. Regulation

With plus or minus 10% rated input voltage the ballast output power varied from -11.9% to +0.7%.

Standard core/coil ballasts have a ±11% regulation with a ±5% rated input voltage. See Jefferson Electric Engineering Test Report No. 06-TT-842-186*-047.

C. Power Factor

Power factor increases from 85% at 60 HZ to 100% at approximately 15,000 HZ. See section 3.1 appendix VII. However, resonant frequencies occur above 1000 HZ which will cause destruction of the lamp. See section 3.1, appendix VI. For safe operation, ballast output frequencies below 1000 HZ are recommended.

The standard core/coil ballast operates at 90% power factor.

D. Annual Cost Savings
Life cycle costs

1. Annual cost savings
   To determine the annual cost savings, average efficiencies must be used.

   Solid state Ballast -
   120 V 83.2 - 86.3% Avg. 85%
   $\frac{150W}{.85}$ = 176 input watts

Core and coil ballast
120 V 79.8 - 80.0% Avg. 80%

$\frac{150W}{.8}$ = 188 input watts

4000 Hrs./Yr. X $.06/KWH X (.188 - .176) = $2.88/Yr.

2. Life cycle costs
Initial costs + replacements costs + operating costs

a. Core/coil ballasts

Expected life - 40000 Hrs.	
Initial cost -	$30.00
Operating cost -	
4000 Hr./Yr. X $.06/KWH X .188 KW X 10 Yrs.	=$451.20
LCC	=$481.20

b. Solid state ballast

Expected life - 30000 Hrs.		
Initial costs	Approx. -	$35.00
Replacement cost - $70.00 X 1/3 unit		$23.00
Replacement labor		
$21.00/Hr. X 1 Hr. X 1/3 unit		$ 7.00
Operating cost		
4000 Hrs./Yr. X $.06/KWH X .176 KW X 10 Yrs.	=	$422.40
	LCC =	$487.40

5.0 PROGNOSIS

As indicated on Table I of Section III, Engineering Report, the percent efficiency, ballast output wattage divided by input wattage averaged 85%.

Conventional HRS core/coil ballast average 80% efficiency.

Analysis of the Phase I data and circuit design indicates that additional efficiency can be obtained through improved circuit deisgn, i.e., eliminating inherent internal losses by improved component selection, redesigning portions of the circuit, and selection of the frequency for optimum efficiency and power factor.

It is believed that a ballast efficiency of 88% can be obtained through the aforementioned improvements. At this level, the commercial use of solid state ballasts is justifiable.

Report No. 06-TT-842-186*-047
Page 1
May 1980
480V Design Added
October 1980

JEFFERSON ELECTRIC
Jtton
840 S. 25th Avenue, Bellwood, Illinois 60104 312 626-7700

6.0 ENGINEERING TEST REPORT

PURPOSE OF TEST:

To measure thermal and electrical performance characteristics of the Jefferson 150 Watt High Pressure Sodium (Low Arc Voltage Lamp) High-Reactance ballast operating on test bench in open air.

BALLASTS:

Jefferson Catalog No.:	842-1860-047	120/208/240/277 Line Voltage
	842-1861-047	120/240 Line Voltage
	842-1862-047	120 Line Voltage
	842-1863-047	240 -"- -"-
	842-1864-047	208 -"- -"-
	842-1865-047	208/277 Line Voltage
	842-1866-047	277 Line Voltage
	842-1868-047	480 Line Voltage

All ballasts are employing the same primary and secondary coils, the same lamination and stack except 480V design which has different coils and stack, but the same lamination.

Each Hi-Rx ballast is utilizing Class "H" (180°C) "H565" Jefferson insulating system. The ballasts are using starting circuit Catalog No. 232-088 and for H.P.F. correction 14 mfd at 280 V.A.C. Capacitor for all ballasts except 480V which is utilizing 4 mfd at 480 V.A.C.

GENERAL TEST CONDITIONS:

Each Hi-Rx ballast core & coil selected at random was placed on test bench and operated in open air as free of drafts as practicable at an ambient temperature of 25°C ± 2°C. A standard 150 Watt H.P.S. (S55) lamp was chosen at close to nominal arc voltage.

Complete electrical performance data was recorded after lamp and ballast had operated for 15 minutes at rated line voltage and the power factor corrected.

Coil temperature was determined by change of resistance method after lamp and ballast had operated over night with regulated rated line voltage. Final reading was taken after thermal stability of core and coil was indicated by thermocouple method.

Basic electrical performance and individual component temperature and ambient air were measured and recorded immediately prior to shutting ballast down for change of resistance measurements.

TEST RESULTS:

Complete electrical and thermal performance data for the ballast operating the 150 HPS (S55) lamp in a vertical position at nominal line, is shown in attached table.

CONCLUSION AND COMMENTS:

Results are typical only when all test conditions such as ballast position, environment, capacitor value, lamp and component position, lamp arc voltage, etc. are reproduced. Test data does show typical performance variations that exist on units of various voltage design. Slight additional variation should be expected from unit to unit on any production run.

Marion Rosiak
H.I.D. Proj. Eng. Manager

MR/bp

ELECTRICAL DATA

Catalog No.	842-1860				
Catalog No.	842-1861		842-1865		
Catalog No.	842-1862	842-1863	842-1864	842-1866	842-1868
Line Voltage	120	240	208	277	480
Line Current	1.71	0.85	0.90	0.74	0.43
Line Wattage	185	186	173	185	186
Power Factor	90%	91%	92%	90%	90%
Watt Loss	35	36	33	35	36
Lamp Voltage	53	53	50	53	55
Lamp Current	3.5	3.5	3.4	3.5	3.3
Lamp Wattage	150	150	140	150	150
Capacitor MFD/Voltage	14/276	14/276	14/270	14/277	4/480
Regulation*	11%	11%	10%	11%	11%
Max. Leakage Current	0.12	0.18	0.16	0.20	0.34
O.C.V. RMS	125	125	121	125	128
I [illegible]e O.C. (With Cap.)	2.85	1.43	1.52	1.20	0.6
I Line Sec Short Circuit	1.70	0.90	0.90	0.80	0.5
Start/Exting. Line Volt	71/72%	69/71%	73/74%	70/72%	73/70%

THERMAL DATA

Line Voltage	120	240	208	277	480
Line Current	1.74	0.86	0.90	0.75	0.44
Line Wattage	190	190	175	190	190
Power Factor	91%	92%	93%	91%	90%
Watt Loss	40	40	35	40	37
Lamp Voltage	52	52	49	52	58
Lamp Current	3.52	3.52	3.42	3.52	3.3
Lamp Wattage	150	150	140	150	153
Temperatures:					
Pri Rise (Tap-Com)	70°C	73°C	69°C	74°C	71°C
Pri Rise (Tap-Line)	76°C	85°C	78°C	82°C	79°C
Pri Rise (Line-Cap)	82°C	72°C	73°C	-"-	-"-
Sec Rise (Tap-Lamp)	72°C	74°C	69°C	72°C	71°C
Core Surface Temp.	91°C	92°C	89°C	91°C	88°C
Room Ambient Temp.	25°C	25°C	25°C	25°C	25°C

B3 *Regulation given as mean average with a ± 5% line voltage variation.

TECHNICAL INFORMATION DEPARTMENT
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