THE EFFECTS OF NON - SINUSOIDAL WAVE FORMS

ON INCANDESCENT LAMP CHARACTERISTICS

by

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I. INTRODUCTION

From an electrical engineering viewpoint,[1]

> An incandescent lamp filament is a
> resistance of such value that it will
> comsume specified wattage and operate at
> such a temperature that the life will have
> a predetermined value when short circuited
> across a given voltage.

The problem of the lamp engineer is to design the
filament so that the lamp life, temperature, and efficiency
will be corrolated to give the maximum economical operation
as well as an energy output favorable to the visible spectrum.

Although the tungsten-filament may be considered as a
unity power factor load, incandescent lamps, more so than
other power consuming devices, are peculiarly sensitive to
relatively small variations in voltage. An increase of ten
per cent in voltage results in a decrease of average life of
nearly thirty per cent, while a ten per cent decrease in
voltage will reduce the lumen output by thirty per cent when
operating on a sinusoidal alternating voltage.

While the commercial electric power companies strive
to achieve a pure sine wave of voltage, this condition can
be realized only to a limited degree. Quite often, conditions
may exist which cause a pronounced deviation from the pure
sine wave. Variations in the voltage wave may be the result
of alternator construction due primarily to the variation of
gap permeance with time and to the effects of damper wind-
ings. Even in cases where the voltage wave form generated is

theoretically sinusoidal, certain circuit and transient conditions may cause the wave actually utilized to vary considerably from a pure sine wave.

Even though the distortion of commerical voltage wave forms may be negligible, especially any distortion due to harmonics other than the third, the question resolves to one of whether or not the operating characteristics of incandescent lamps are effected by variations in the wave form employed.

It is the purpose of this study to determine what effect, if any, wave distortion has on typical operating characteristics of lamps, especially average life, lamp efficiency, and lumens output.

II. LITERATURE REVIEW

A. <u>Historical Development of the Incandescent Lamp</u>.

The history of the development of incandescent lamps covers one and one-half centuries beginning with the early experiments of Sir Humphry Davy, who passed current through a number of thin strips of various metals to obtain a white heat. Most of the metals tested oxidizied so rapidly in the air that they were literally burned up. However, he discovered that platinum did not oxidize so rapidly and could be maintained at a white heat for some time while emitting a usable intensity of light. These experiments which took place in 1802, are generally considered to be the first suggestion of the commercial practicability of the incandescent lamp.

In 1809, De La Rue made the first recorded attempt at making an incandescent lamp. This was constructed with a coil of platinum wire for a burner which was enclosed in a piece of glass tubing, the ends of which had brass caps. There is no evidence of any evacuation of the glass tubing.[2]

In 1840, Grove introduced an incandescent lamp consisting of a coiled platinum wire burner which was covered by a glass tumbler surrounded by water in a glass dish to protect the burner from draughts of air.[2]

The first patent on an incandescent lamp was granted by the British government to Frederick De Moleyns. This

lamp contained powdered charcoal which filled and bridged the gap between two coils of platinum wire mounted in a globe from which the air had been exhausted. The current flowing from one platinum wire to the other through the bridge of powdered charcoal made the latter incandescent. The air in the glass globe was removed by means of hand air pumps increasing the life of the charcoal.[3]

Other early investigators were: J. W. Starr, William E. Staite, J. W. Draper, and M. J. Roberts. The lamps they experimented with consisted of either platinum or iridium operating in air but covered by a globe to protect the burners from draughts, or of carbon or graphite operating in the vacuum then obtainable. Although patents were granted on many of these lamps, none were more than laboratory experiments.[2]

During the period from 1860 to 1870, the lamp scientists concentrated their attention on the arc lamp with the result that the development of the incandescent lamp was retarded. By 1878, the arc lamp was commercially established and was rather widely used for street lighting.[3] Since the arc lamp was too large a unit for household use, the scientists became interested in developing a smaller electric light. As a result of the sucess of the arc lamp, most of the early attempts at perfecting a smaller lamp were endeavors to operate a carbon rod in nitrogen gas or in vacuum.[3]

On October 21, 1879, Thomas A. Edison exhibited the first practical carbon filament lamp.[2] This experimental lamp

embodied all of the basic features of lamps made at that
time. It consisted of a carbonized piece of ordinary
sewing thread operating in a one piece all glass globe
which had been exhausted to a high vacuum. The lamp burned
steadily for 45 hours before it failed.[2]

Immediately after this exhibition, everything con-
ceivable was carbonized in an effort to find a better filament.
It was found that carbonized paper increased the life of the
lamp to several hundred hours. In 1880, it was found that
carbonized bamboo increased the life as well as being sturdier
than the carbonized paper filaments and was therefore adopted
for the filament.

It was on January 27, 1880, that the basic lamp patent
was awarded to Edison.[3]

> This patent was not for the invention of the
> incandescent lamp but for a particular kind
> of lamp which combined four elements - (1) a
> high resistance filament of carbon, in (2) a
> chamber made entirely of glass and closed at
> all points by fusion of the glass, which con-
> tained (3) a high vacuum and through which
> (4) platinum wires passed to carry current to
> the filament.

From this period until 1905, most of the developments
were in the actual construction of the lamp rather than in
changing any of the constituent parts. The shape of the base,
the method of fastening the ends of the filament to the
platinum lead-in wires, the method of forming the filament,
and the method of exhausting the lamp were all improved upon
by various designers. During this period a filament was

produced by squirting a cellulose solution through a die. This solution was then dried and carbonized.

In 1905, Dr. W. R. Whitney developed a metallized carbon filament. This filament consisted of a graphite coating on a treated carbon filament which had been heated to a high temperature in an electric furnace. The high temperature increased the positive temperature coefficient of the graphite coating to such an extent that the treated filament as a whole had a positive temperature coefficient.[3] This lamp was more efficient than carbon filament lamps but not as rugged in construction.

During the development of the carbon-filament lamp experiments were being performed on metal filament lamps. The first commercial metal filament lamp, the Osmium lamp, had a filament made by mixing powdered osmium with a binder, such as syrup or sugar, the resulting paste being squirted by pressure through a die. The filament was fragile, and its resistance so low that it was practical only for low voltage lamps. This lamp could be operated at a higher temperature than the carbon lamp as the filament did not vaporize so easily. The cost of osmium made it impossible to manufacture these lamps in large quantities.[3]

Dr. W. Von Bolton, a Russian Chemist, invented the tantalum lamp around 1902. Tantalum in the pure state even though very hard is extremely ductile and can be drawn out into a fine wire having a very high tensile strength. The resistance of the metal is relatively low hence the filament

had to be long. When operating on direct current the properties were superior to those of the metallized carbon filament lamp. However, when burned on alternating current, the filament rapidly crystallized and the life was greatly decreased.

Two Austrians, Just and Hanaman, invented the tungsten filament lamp in 1902.[2] Tungsten is very hard and brittle, and no process was known for wire drawing it. Consequently, the first tungsten lamps used filaments made by mixing finely divided tungsten powder with a binder into a paste, and squirting the paste through a hole drilled in a diamond, forming a thread. Hair pin loops of this thread were treated to remove the binder and make what was called a pressed filament. This filament was very efficient, but so fragile that the lamps had to be handled with extreme care.

Dr. William D. Coolidge, after much experimenting developed a new metallurgical process for making tungsten ductile. The technique enabled the filament to be a continuous uniform filament which is one of the basic elements of all incandescent lamps manufactured at the present time. Drawn tungsten wire filaments were very strong and could be readily coiled thus the new filament permitted the lamp to be used in a large number of new applications. The tungsten filament when operated on alternating current tended to crystallize causing an "offsetting" which decreased its life. This problem was reduced by the addition of small particles of thoria to the filament.

Prior to Dr. Coolidge's invention all filament lamps were of the evacuated bulb type. Attempts at decreasing the bulb blackening due to the evaporation of the filament were confined to placing chemicals in the bulb which decomposed as the lamp burned and combined with the vaporizing filament to form a light colored deposit on the globe. About this time Dr. Irving Langmuir became interested in filament evaporation and bulb blackening.

Dr. Langmuir discovered that the evaporation of the filament was the result of the low pressure existing at the bulb filament. This discovery led him to put inert gases into the lamp to observe the effects of the gas upon blackening. The addition of this inert gas greatly increased the efficiency of the tungsten filament lamp and along with Dr. Coolidge's drawn tungsten filament is one of the basic elements of present day lamps.

Many additional improvements were made in the connection of lead-in wires to the filament, in the shaping of the filament, in the type of "getter" used to retard blackening, and in the coating of the bulb. These advancements have lead to a considerable improvement in efficiency and maintenance of candlepower.

Although no change in the basic features of the incandescent lamps have occured in the past forty years there have been many developments in their construction and in the process used in their manufacture. At the present time

are nearly 9000 different types of lamps manufactured for varied applications. Nearly all of these lamps embody the same basic elements, the great adaptability being obtained by altering the design features. In 1947, the market value of lamps manufactured for these varied uses was $385,944,000.

Incandescent lamp development and manufacture is an ever-expanding industry. There is a continuous stream of new lamp types being produced for consumer use. However, there is a very great opportunity for science and research to continue their program toward a better and more economical light to serve the needs of mankind.

B. Review of Related Literature.

Although there is available an abundance of literature on the general subject of incandescent lamps, the author was not able to discover any articles pertaining to the specific subject of this investigation. The literature referred to in the remainder of this section will be from related articles which have some bearing on the discussion of the results obtained from the tests performed.

Tests conducted at the University of Illinois Engineering Experiment Station in 1909[4] proved quite conclusively that the life of tungsten filament lamps depended to a large degree upon the actual operating conditions of the tests. Variations in the mountings for the lamps effected the life as did a variation in the regulation of the supply source. These tests also indicated that the life was effected by the source being changed from direct current to alternating current.

Dr. Langmuir[5] while studying the flicker of incandescent lamps on alternating current arrived at the conclusion that flicker was a physiological effect caused by fluctuations in the intensity of the light source. The fluctuation of intensity was the direct result of the heating effect varying very rapidly with time. Dr. Langmuir also showed experimentally that the per cent variation of the light intensity from the average intensity was inversely proportional to the frequency and the diameter of the filament.

W. E. Forsythe,[6] writing in the General Electric Review in 1934 states that a very high degree of accuracy is necessary in filament construction since the uniformity of the filament diameter is one of the principal factors effecting the life of the bulb. A thin spot of only one per cent variation in the diameter may result in the life being only one-third of normal.

In an article pertaining to the calculation of the filament resistance of tungsten lamps,[7] Preston S. Millar states that the incandescent lamp may be considered as a unity power factor load which may be computed from the following equation.

$$(1) \quad R_r = \frac{V_r^2}{W_r}$$

He also develops the following empirical equation to express variation of operating resistance with operating voltage in a gas filled tungsten filament lamp.

$$(2) \quad \frac{V_o^{3.4}}{V_r} = \frac{R_o^{7.4}}{R_r}$$

In these two equations,

Rr = rated resistance

Wr = rated watts

Vr = rated voltage

Vo = operating voltage

Ro = operating resistance

In an article appearing in the Westinghouse Engineer in 1939,[8] S. G. Hiblen describes one of the principal disadvantage of the early tungsten filament lamp as being a tendency for the pure tungsten to form large crystals when burned on alternating current. As a result of this recrystallization, the position of the crystals may become altered and a change in the effective cross-section of the filament results.

Lamp life is defined as;[9]

> The average laboratory life of a large number of similar lamps when burned under a carefully controlled conditions. For design purposes the life may be designated as that period of time required to evaporate a certain percentage of the original filament.

III. INVESTIGATION

The investigation described herein was the outgrowth of a suggestion by Professor G. C. Barnes of the V. P. I. Electrical Engineering Department.

A. <u>Objectives</u>. After a careful consideration of the problems involved, the writer formulated the following objectives:

(1) To determine the variation of lamp characteristics with life for various wave forms.

(2) To determine the variation of lamp characteristics with voltage for various wave forms.

(3) To attempt to correlate the variation of lamp characteristics to the crest factor of the voltage wave employed.

B. <u>Equipment</u>. This investigation was performed on 100 watt, type A21 115 - volt lamps manufactured by Sylvania Electric Products Inc.. The following information obtained from the lamp manufacturer was used as a basis for all calculations.

Initial Lumens	Initial Lumens Per Watt	Rated Average Hrs. Life
1635	16.35	750

The wave forms used were produced by means of a General Electric Sine Wave Generator, Model 15A224, consisting of a 10 horsepower, 3600 rpm, direct current motor directly coupled to five alternators. These alternators produced frequencies of 60, 120, 180, 300, and 420 cycles per second respectively. The output of the alternators were connected in series as desired by means of a specially designed switch board. The alternator fields were excited directly from the output of a 3 phase, half wave, 250 volt, 75 ampere, ignitron manufactured by the Westinghouse Electric Corporation.

The value of the lamp intensity in foot-candles was read by means of a Westron photronic cell. The photronic cell used was equipped with a visual-correction filter so that its response is closely similar to the visibility curve of the human eye.

C. Voltage Wave Forms Employed. For this investigation the choice of voltage wave forms employed were somewhat limited by the equipment available. The composite wave forms employed were chosen to obtain as wide a range of crest factors as possible. Since the lamp filament may be considered as a pure resistance, it was not considered necessary to investigate the effects of waves having a leading or lagging peak. For this same reason the effect of the frequency of the various harmonics utilized in obtaining the resultant wave could be considered to be negligible. When waves of

different frequencies are referred to as being in phase, it is implied that these waves pass through their zero value increasing in a positive direction at the instant time is considered to be zero. The wave forms employed were those shown in appendix I.

For simplicity in indentifying them, the wave forms employed will be designated as follows:

Wave Form A - This wave form consists of a fundamental and a fifty per cent third harmonic component in phase with each other. The equation of this wave was e= 240.4 sin 377t +120.2 sin 1131t. The crest factor was 1.357 and the effective value 190 volts. See oscillogram 1 and curve sheet I-1, appendix I.

Wave Form B - Sinusoidal wave or e= 260.66 sin 377t. The crest factor was 1.414 and the effective value 190 volts. See oscillogram 2 and curve sheet I-2, appendix I.

Wave Form C - This wave form consists of a fundamental and a fifty per cent third harmonic. The third harmonic lags the fundamental by 60 degrees referred to the fundamental. The equation of this wave was e = 240.4 sin 377t - 120.2 sin 1131t. The crest factor was 1.90 and the effective value 190 volts. See oscillogram 3 and curve sheet I-3, appendix I.
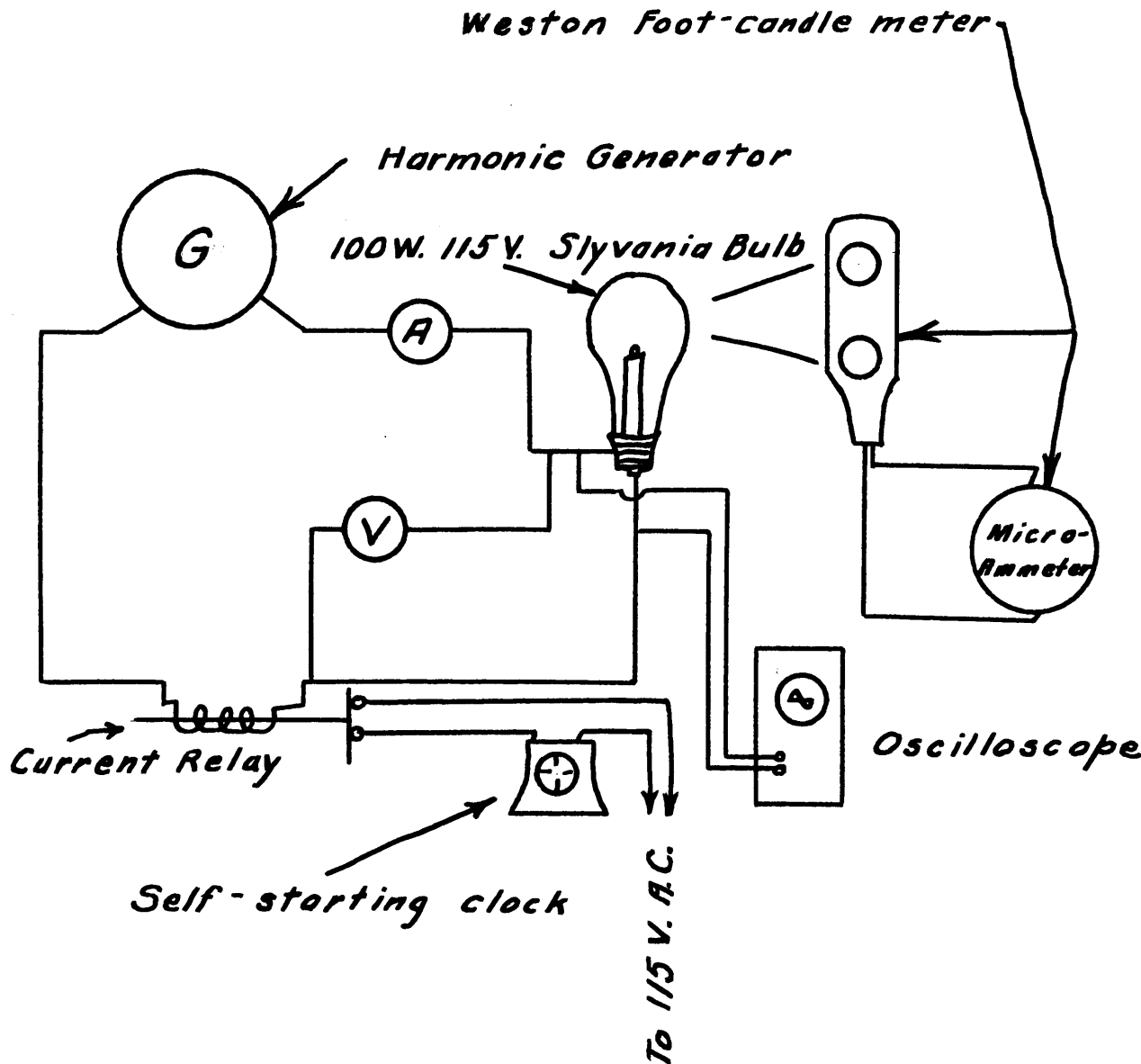
Wave Form D - This wave form consists of a fundamental, a 32 per cent third harmonic, a 20 per cent fifth harmonic, and a 20 per cent seventh harmonic. The fundamental and the

fifth harmonic are in phase. The third harmonic lags the fundamental by 60 degrees referred to the fundamental. The seventh harmonic lags the fundamental by 25.71 degrees referred to the fundamental. The equation of this wave was $e = 247.5 \sin 377t - 79.2 \sin 1131t + 49.5 \sin 1885t - 49.5 \sin 2639t$. The crest factor was 2.24 and the effective value 190 volts. See oscillogram 4 and curve sheet I - 4, appendix I.

Wave Form E - This wave form was the output of the ignitron rectifier. The harmonic content of this wave was too complex for detailed analysis. The ratio of the peak to effective voltage was 1.58 and the effective value 190 volts. See oscillogram 5.

In all of the wave forms employed the composite wave was obtained by superimposing the various harmonics upon the fundamental, and so positioning the harmonics to produce the wave desired.

D. Test Procedure. The test circuit was arranged as shown in the circuit diagram, Fig. 1, page 17. The lamps being tested were enclosed base down in a wooden container which was lined with black cardboard to keep the reflected light to a minimum. The average illumunation of the lamps was measured by means of a Weston photronic cell. The readings obtained were taken in the horizontal plane passing through the luminous center of the lamp. Since the readings were taken at a distance of three feet from the lamp center,

Weston Foot-candle meter

Harmonic Generator

100 W. 115 V. Slyvania Bulb

G

A

V

Micro-Ammeter

Current Relay

Self-starting clock

To 115 V. A.C.

Oscilloscope

WIRING DIAGRAM

FIG. 1

laws governing a point source were applicable. A cathode ray oscillograph was connected across the terminals of the lamp for the purpose of checking wave form.

In the first series of tests, the variation of lamp characteristics with life were determined. Readings of voltage, current, and average illumination were taken at regular intervals during the life of the bulb. Twenty bulbs were tested on each of the wave forms A, B, C, D, and E. During this test the effective voltage was maintained at 190 volts neglecting the regulation of the supply which was nearly two per cent. This value of voltage was limited by the range of the sine wave generator and was chosen to reduce the average life of the bulbs to a satisfactory value.

For this test, the general procedure was as follows: The output of the sine wave generator was gradually applied to the lamp by means of a potentiometer. If the 190 volts had been applied directly to the lamp, the large inrush of current to the cold filament would have been sufficient to destroy the filament. When 190 volts was approached, the current relay contacts closed which started the electric clock. When the filament of the lamp burned out, the current relay contacts opened and stopped the clock.

As the values of luminous flux, efficiency, and wattage were plotted with per cent of average life as an abscissa, it was not necessary to take readings at definite intervals during the life of the bulb. The results of these tests are

best shown by the actual curves, (Curve sheets 1 through 7), which are to a large extent self explanatory. Any mathematical equation for these curves would involve a great number of variables which could not be determined with the equipment available. Those effects which merit consideration will be discussed later.

In the second series of tests, the variation of lamp characteristics with voltage was determined. The effective value of voltage was varied by adjusting the alternator fields. Readings of voltage, current, and average illumination were recorded for each value of voltage. The relative per cent of each harmonic in the composite wave and the relative position of these harmonics were maintained as shown in wave forms A, B, C, and D, appendix I. Therefore the crest factor was constant throughout the voltage range covered. Values of filament resistance, power, lamp efficiency, and total lumens emitted were calculated from the meter readings.

The results of these tests are shown on curve sheets 8 through 14. The values used for plotting these curves are averages for five lamps. Curve sheets 8 through 11, are typical characteristics curves for tungsten-filament lamps. A consideration of these curves and equations expressing the relationship between the various characteristics will be included in the discussion. Curve sheets 12 through 14 summarize the results of this second series of tests.

Curve sheets 15 and 16 are included as a graphical solution to object 3 of this investigation.

IV - DISCUSSION

In this investigation, values of average illumination were measured by the photronic cell which was placed perpendicular to the light rays. The distance from the center of the lamp to the measuring cell was greater than ten times the diameter of the lamp. Values of horizontal candlepower could therefore be calculated from the Inverse Square Law which is expressed by the following equation.

$$(3) \quad I = ED^2$$

where I = Intensity in candles

E = Average illumination in footcandles

D = Distance in feet

In the calculation of the total flux emitted the assumption was made that the flux was directly proportional to the mean horizontal candle power and that the flux emitted when operating at rated voltage on a sinusoidal wave was 1635 lumens. This assumption is in error if the spherical reduction factor of the lamp is not unity. This ratio of the mean spherical candlepower to the mean horizontal candlepower cannot be unity because of the filament construction and the mountings used to support the filament. However, in quality manufactured lamps the deviation from unity is very slight. Therefore, this assumption results in negligible error, especially when relative results are to be considered.

The results of these tests show that as the crest factor

of the applied voltage wave is increased, the lumens output throughout life is increased. See curve sheet 1. The lumens output of a tungsten filament is a direct function of the filament temperature. As the filament temperature increases the energy output becomes more favorable to the visible spectrum. When operating on alternating current of frequency f, the filament temperature fluctuates periodically with a frequency of 2f. The variation of temperature from a mean value is inversely proportional to the frequency. For a 100 watt lamp operating at 60 cycles this variation is approximately 12 per cent.[1] Even though this variation in intensity is not noticeable to the human eye at frequencies above 7 cycles per second, it appears reasonable to assume that as a result of the higher instantaneous temperature obtained with increased crest factors the lumens output should increase. This effect should be less pronounced as the mass of the filament is increased.

It is also seen from curve sheet 1, that the lumens output decreases at nearly the same rate regardless of the wave forms employed. The reason for this decrease in lumens with life is two-fold. First, as the filament incandesces it sublimates slowly and becomes smaller in diameter. Its resistance therefore, increases and allows less current to pass through the wire, thereby producing less light. Secondly, the sublimated filament material is deposited on the inside of the bulb in the form of "blackening" which interferes with the transmission of
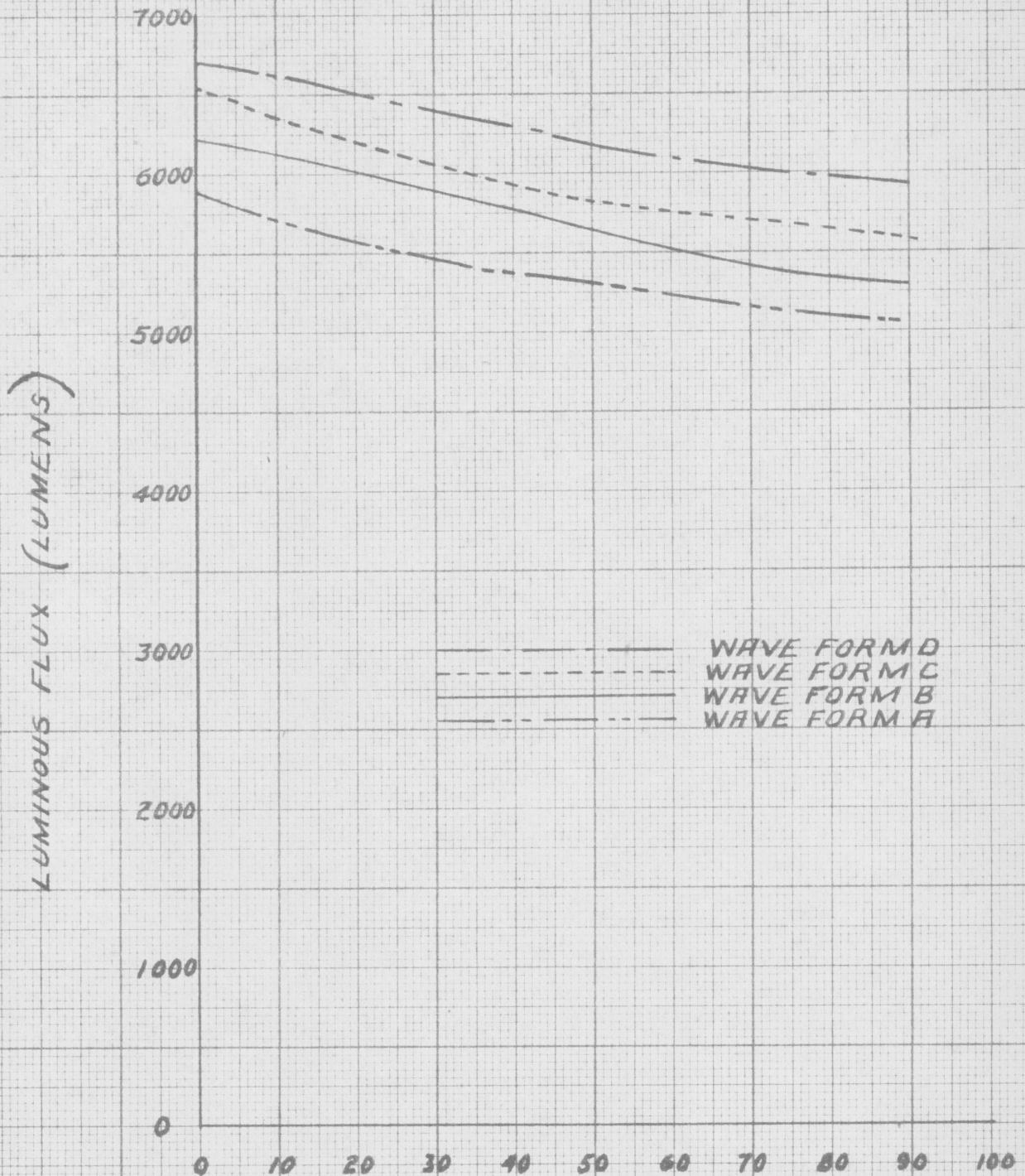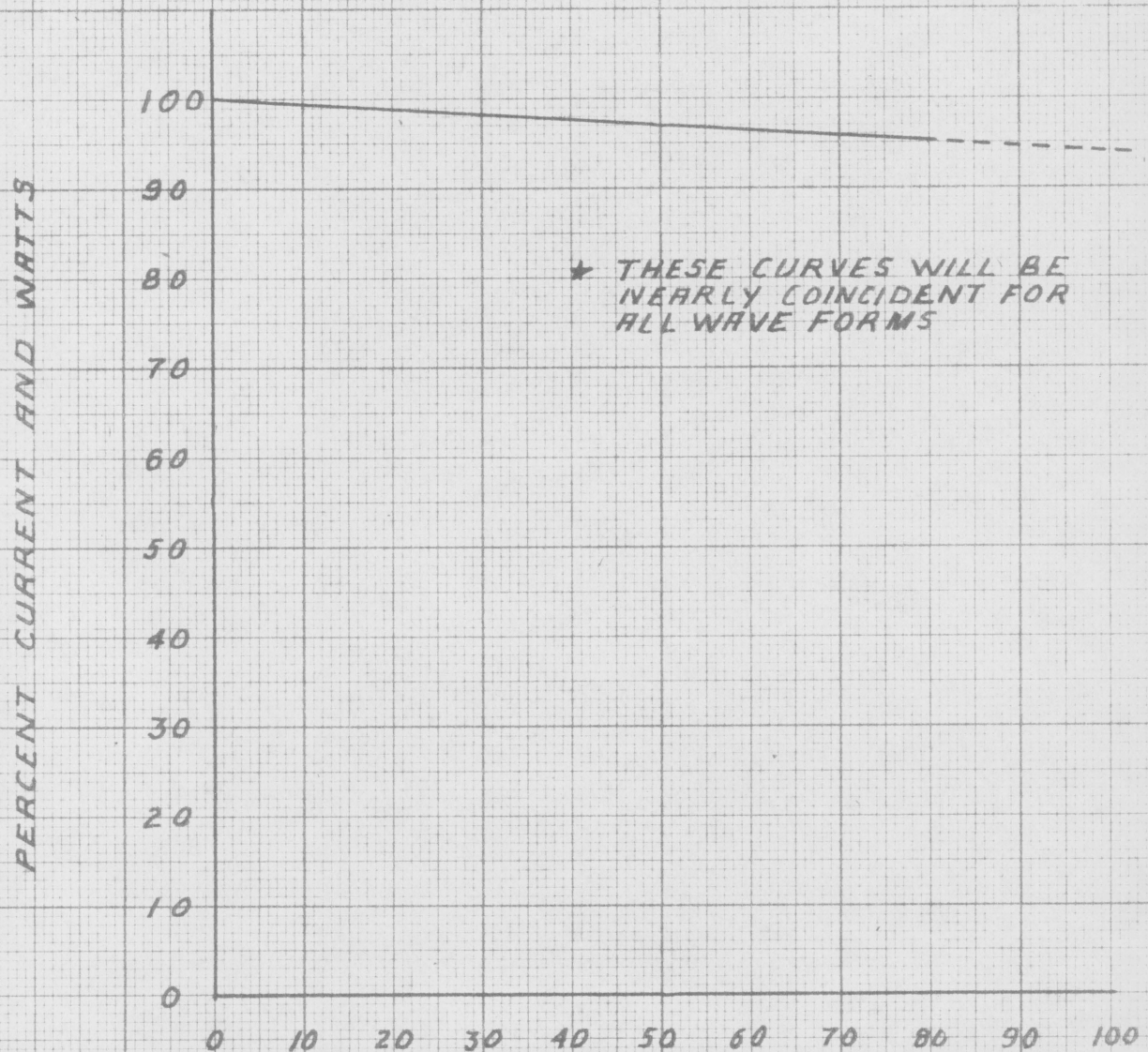
VARIATION OF EFFICIENCY
OPERATING AT 190 VOLTS

EFFICIENCY (LUMENS PER WATT)

32
30
28
26
24
22
2
0

0   10   20   30   40   50   60   70   80   90   100

WAVE FORM D
WAVE FORM C
WAVE FORM B
WAVE FORM A
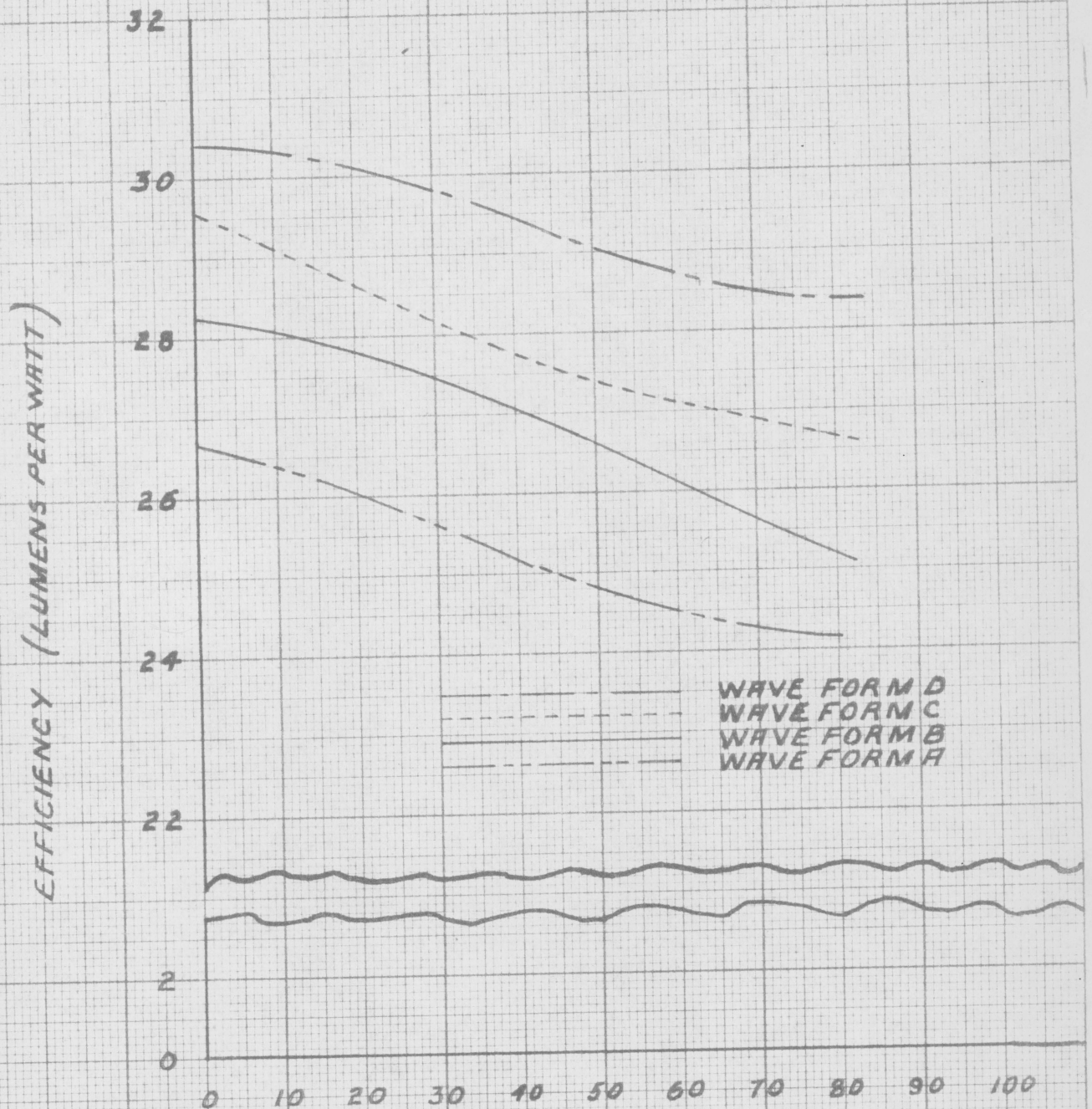
PERCENT OF AVERAGE LIFE
CURVE SHEET 1

4-25-51
WCB

VARIATION OF LUMINOUS FLUX
OPERATING AT 190 VOLTS

WAVE FORM D
WAVE FORM C
WAVE FORM B
WAVE FORM A

LUMINOUS FLUX (LUMENS)

PERCENT OF AVERAGE LIFE

CURVE SHEET 2

9-25-51
WEB

VARIATION OF CURRENT AND WATTAGE
OPERATING AT 190 VOLTS

★ THESE CURVES WILL BE
NEARLY COINCIDENT FOR
ALL WAVE FORMS

PERCENT CURRENT AND WATTS

PERCENT OF AVERAGE LIFE
CURVE SHEET 3

1-25-51
WEB

WAVE FORM A
OPERATING AT 190 VOLTS

PERCENT SURVIVING

DEPRECIATION OF LIGHT

MORTALITY CURVE
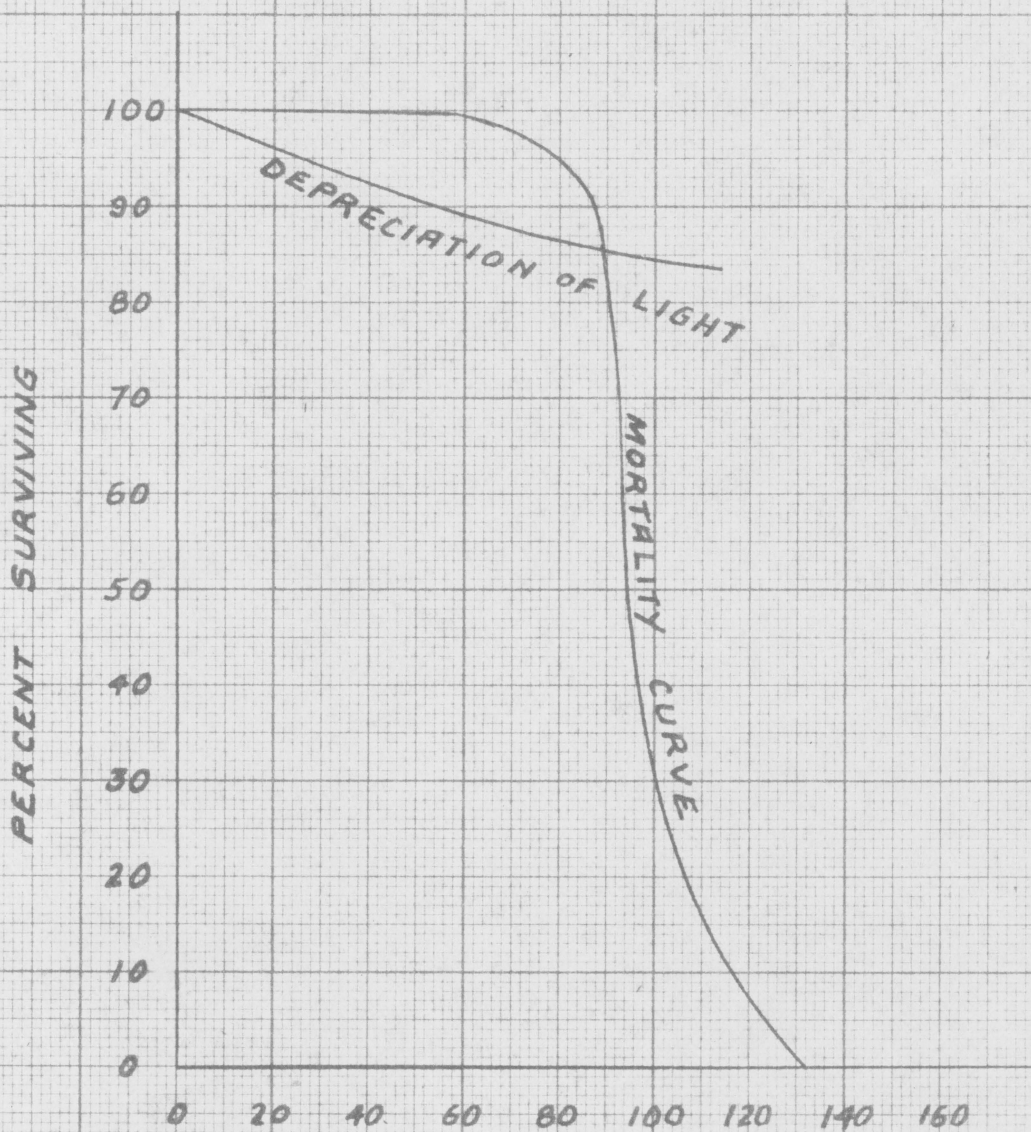
PERCENT OF AVERAGE LIFE

CURVE SHEET 4

4-30-51

WAVE FORM B
OPERATING AT 190 VOLTS

PERCENT SURVIVING

DEPRECIATION OF LIGHT

MORTALITY CURVE

PER CENT OF AVERAGE LIFE
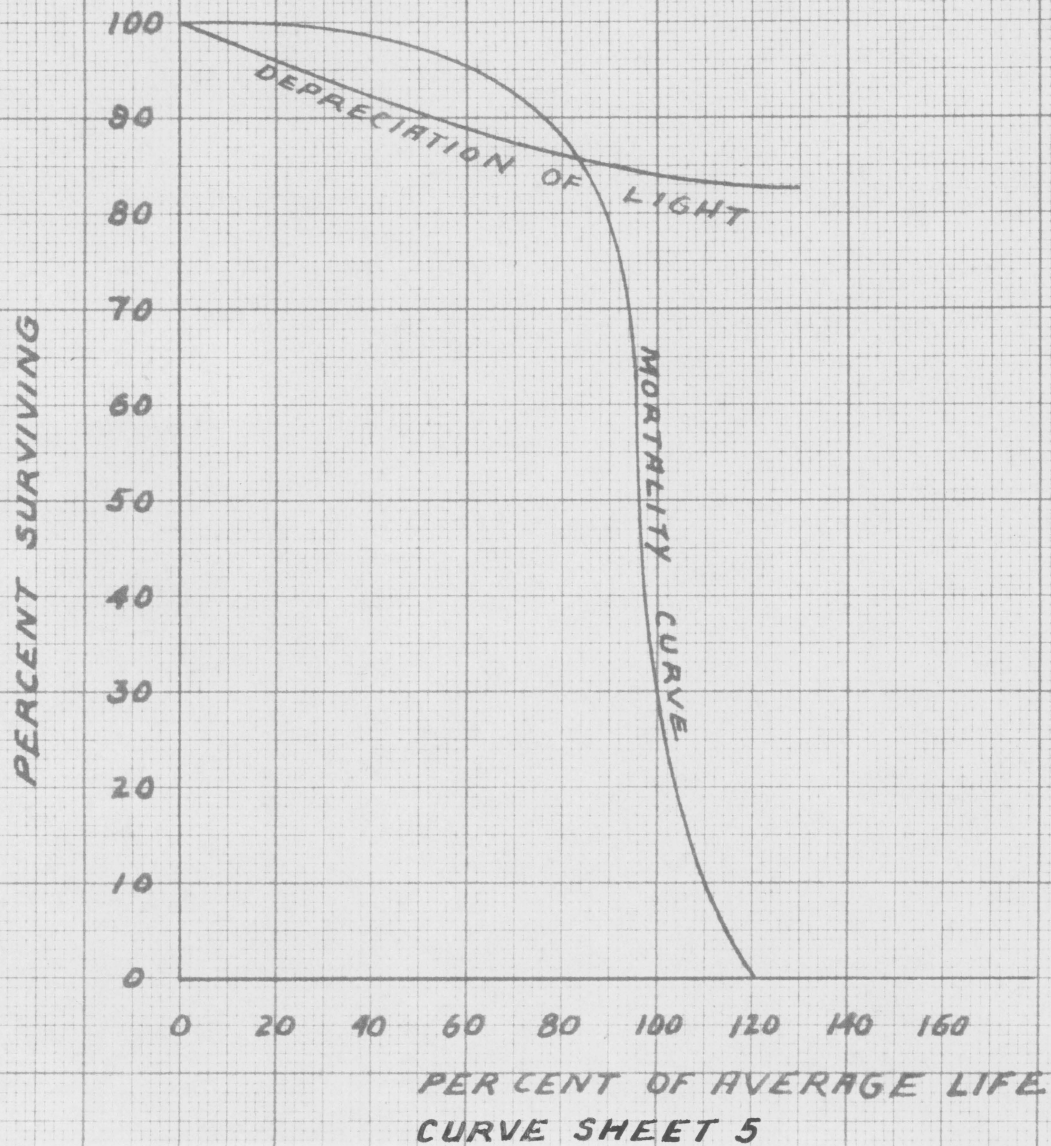
CURVE SHEET 5

4-30-51
WEB

WAVE FORM C
OPERATING AT 190 VOLTS

PER CENT SURVIVING

DEPRECIATION OF LIGHT

MORTALITY CURVE
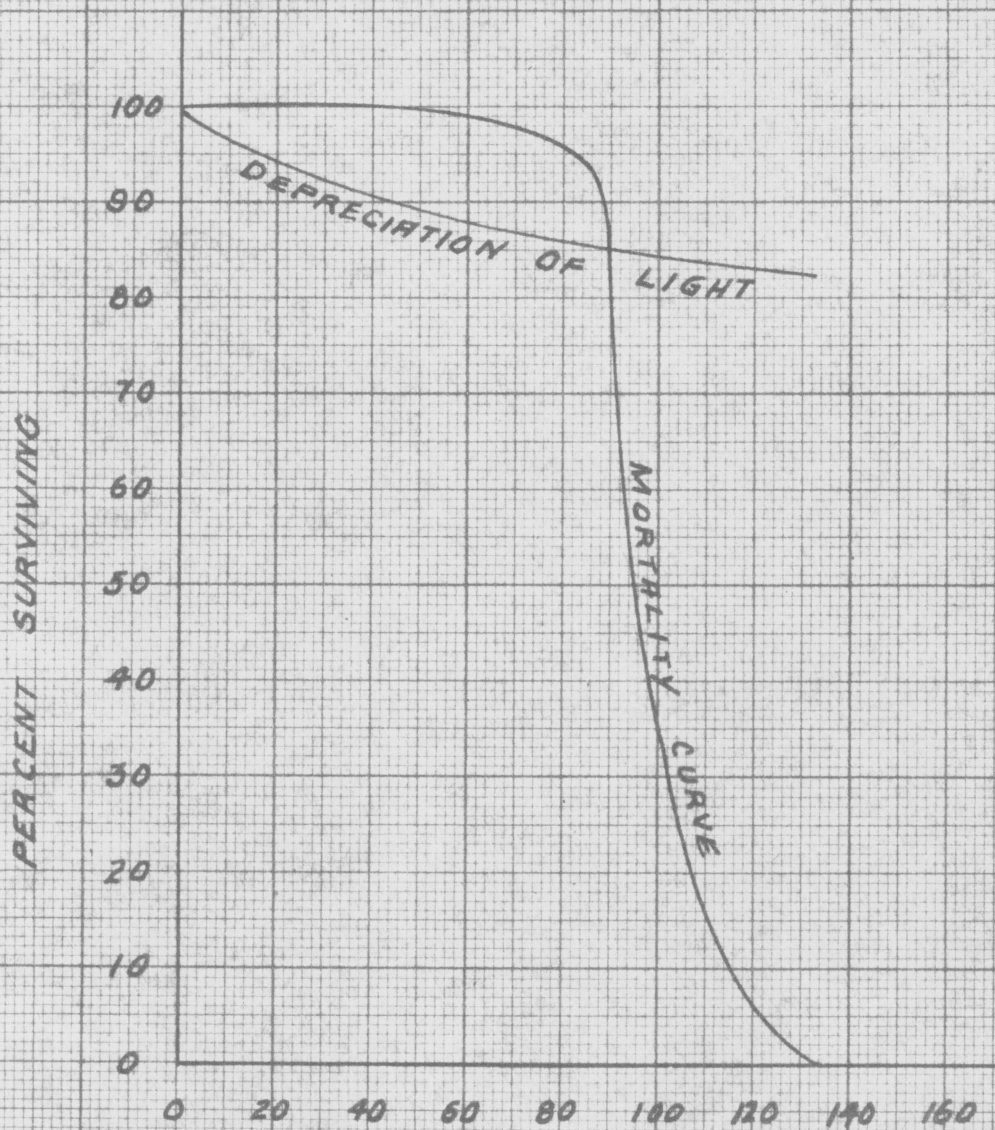
PER CENT OF AVERAGE LIFE

CURVE SHEET 6

9-30-51

WAVE FORM D
OPERATING AT 190 VOLTS

PERCENT SURVIVING

DEPRECIATION OF LIGHT

MORTALITY CURVE

100
90
80
70
60
50
40
30
20
10
0

0   20   40   60   80   100   120   140   160
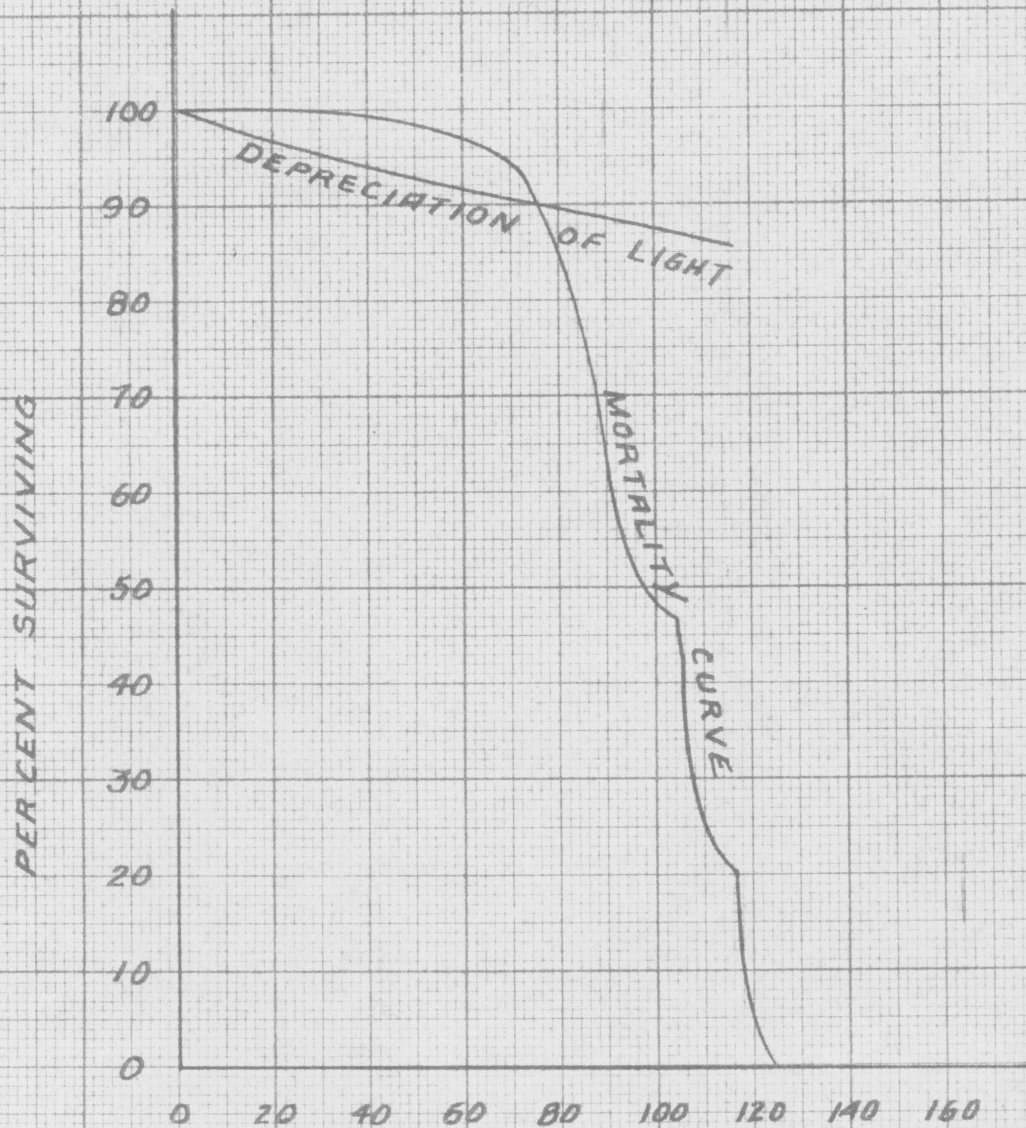
PERCENT OF AVERAGE LIFE
CURVE SHEET 7

4-30-51
JWEB

light through the glass. The effect of the second reason was very pronounced in this test as could be substantiated by observation of the burned out lamps. This was the result of the lamps being tested in a base down position. Much of the sublimated tungsten was deposited by gas convection on the light producing surface of the lamp. Had the lamps been tested in a base up position, much of this material would have been deposited in the stem of the lamp producing very little "blackening."

Curve sheet 3 shows that the current decreases throughout life as previously explained. This decrease in current was the same for all wave forms. Since the voltage was maintained constant, it follows that the wattage should decrease directly with the current. The efficiency of the lamps decreased as a result of the effect of decreased output being more pronounced than the decrease in wattage. This is shown on curve sheet 2.

The mortality curves (see curve sheets 4 through 7) indicated that the variation of wave form had the same general effect on the life of the lamps. The depreciation curve superimposed on the mortality curves indicate that those lamps which last beyond rated life become so inefficient that replacement may be economically justifiable before burnout. The per cent decrease in lumens for all wave forms was nearly the same at 70 per cent of average life. A summary of the results of the first series of test is given in table 1.

TABLE I

Wave Form	Initial Lumens	Initial Efficiency Lumens Per Watt	Average Life In Minutes	Maintenance Lumens Per Watt at 70% Average Life
A	5910	26.70	235	24.40
B	6220	28.25	220	25.50
C	6540	29.60	204	26.85
D	6680	30.40	172	28.50
E	6300	28.60	220	26.10

The results shown on curve sheets 8 through 11 are self-explanatory. The following relations were derived to express the performance under varying conditions. (Capital letters represent normal rated values and the small letters those other then normal.) The value of exponents were calculated for a 10 per cent variation from rated values.

$$(4) \quad \frac{w}{W} = \left(\frac{v}{V}\right)^a$$

$$(5) \quad \frac{f}{F} = \left(\frac{v}{V}\right)^b$$

$$(6) \quad \frac{f}{F} = \left(\frac{w}{W}\right)^c$$

$$(7) \quad \frac{E}{e} = \left(\frac{V}{v}\right)^d$$

$$(8) \quad \frac{E}{e} = \left(\frac{F}{f}\right)^e$$

INCANDESCENT LAMP CHARACTERISTICS
WAVE FORM A
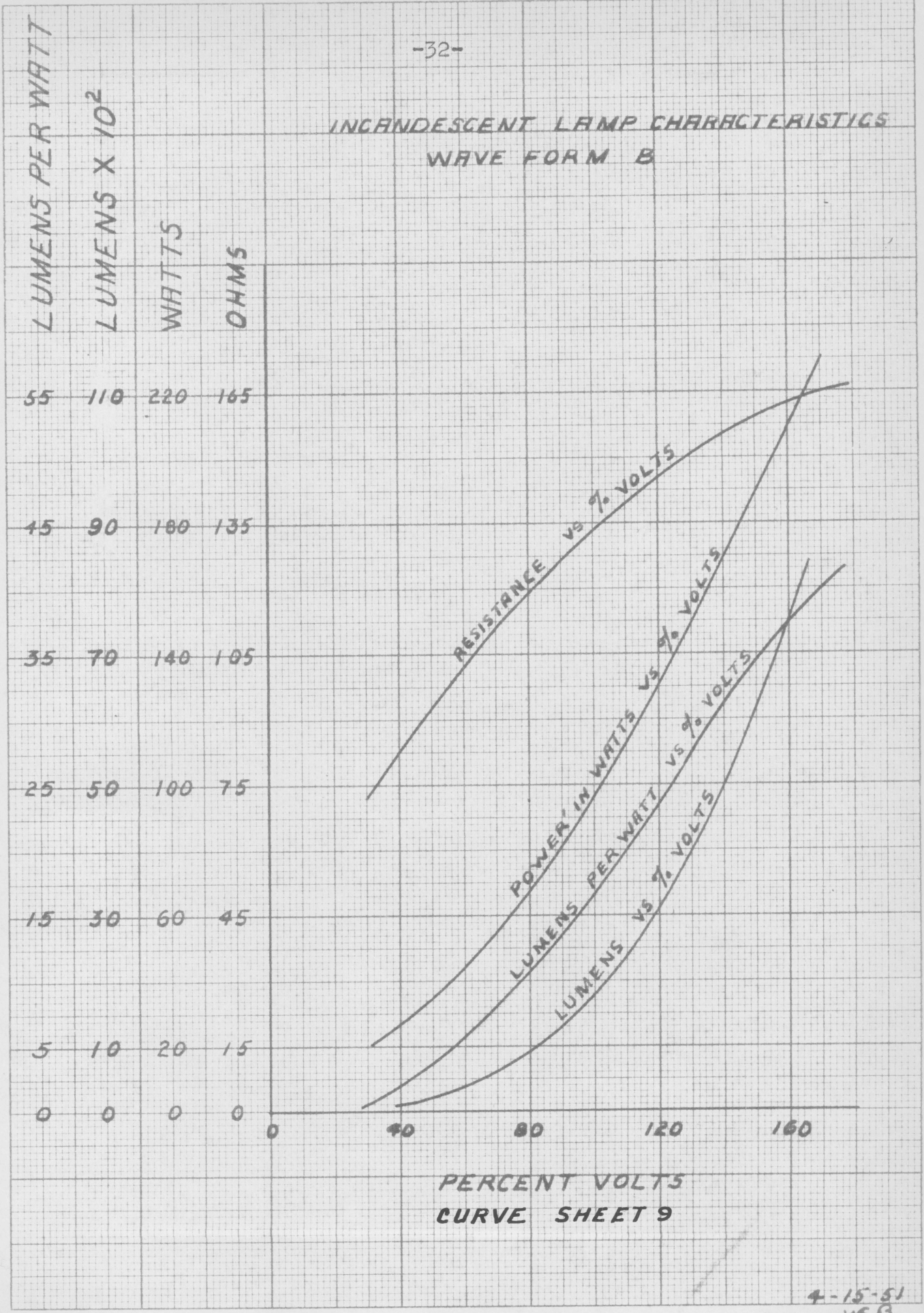
LUMENS PER WATT

LUMENS X 10²

WATTS

OHMS

RESISTANCE VS % VOLTS

POWER IN WATTS VS % VOLTS

LUMENS PER WATT VS % VOLTS

LUMENS VS % VOLTS

PERCENT VOLTS

CURVE SHEET 8

4-15-51

INCANDESCENT LAMP CHARACTERISTICS
WAVE FORM B

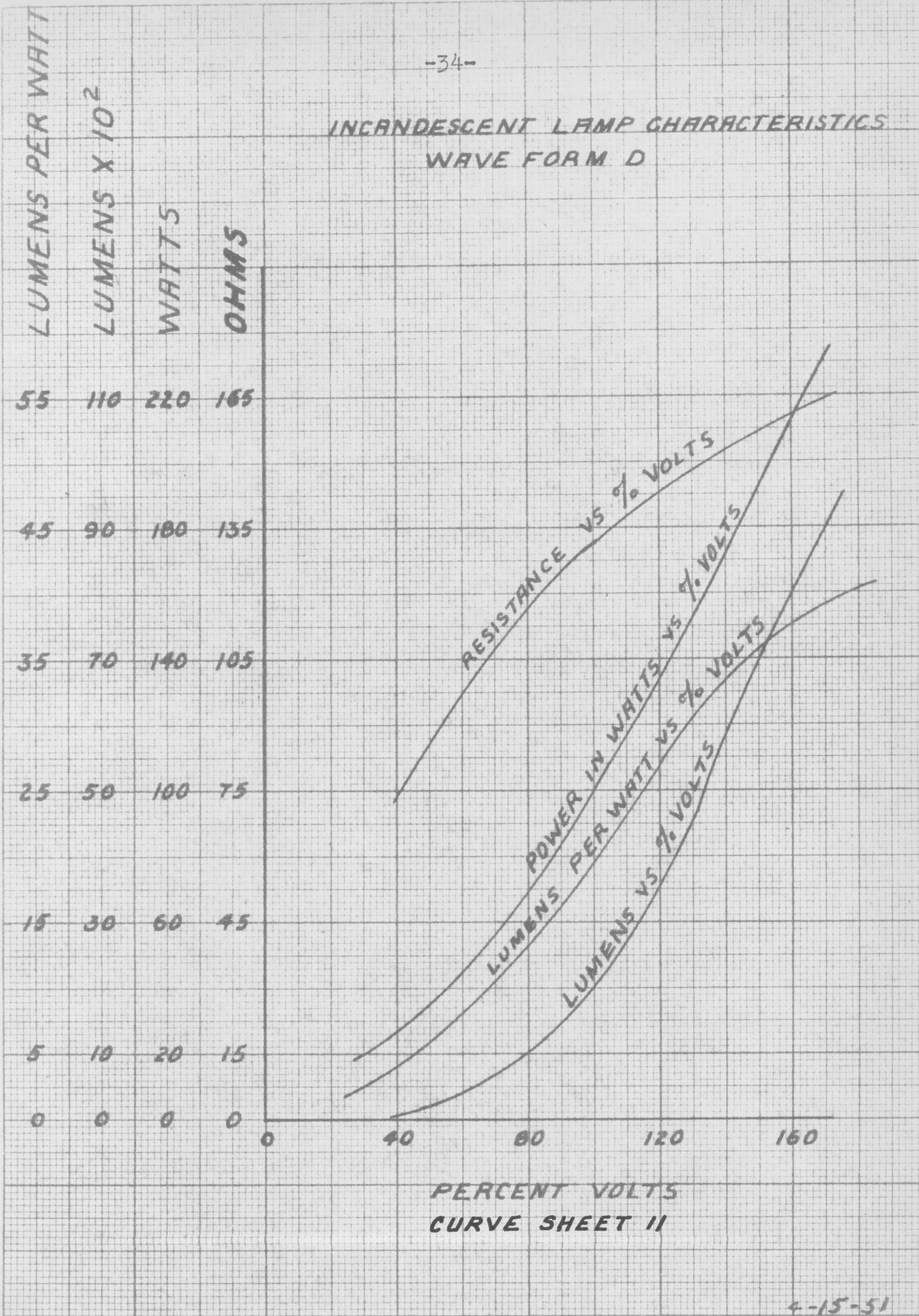CURVE SHEET 9

INCANDESCENT LAMP CHARACTERISTICS
WAVE FORM C
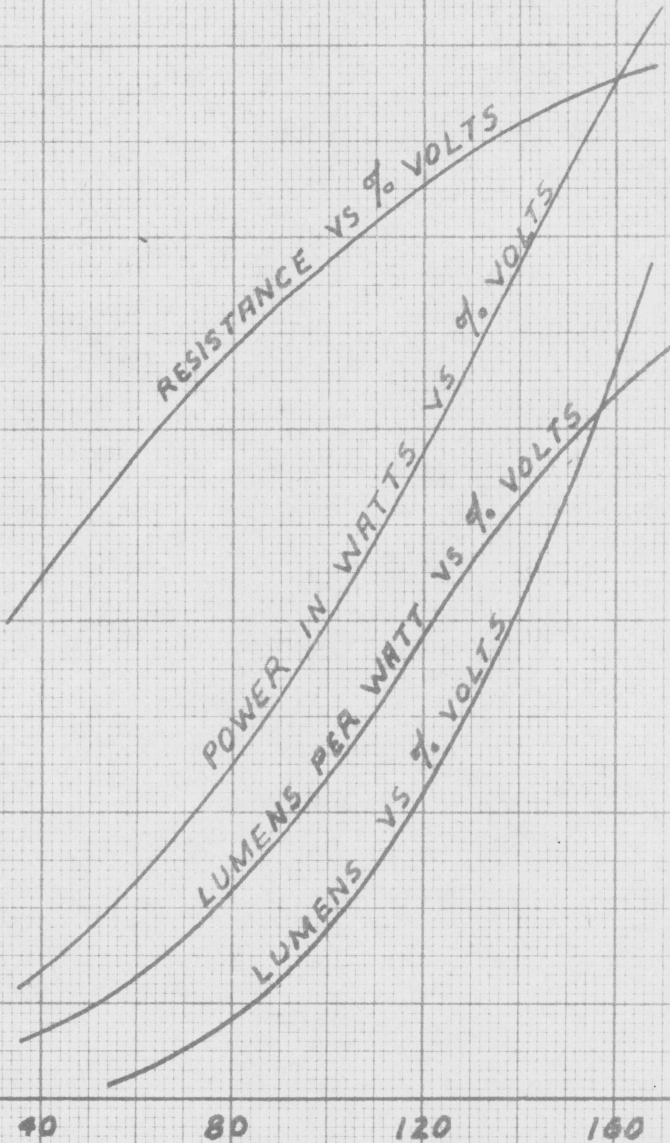
PERCENT VOLTS

CURVE SHEET 10

INCANDESCENT LAMP CHARACTERISTICS
WAVE FORM D

LUMENS PER WATT

LUMENS X 10²

WATTS

OHMS

RESISTANCE VS % VOLTS

POWER IN WATTS VS % VOLTS

LUMENS PER WATT VS % VOLTS

LUMENS VS % VOLTS

PERCENT VOLTS

CURVE SHEET 11

4-15-51

In the above equations:

W = watts

V = volts

F = lumens

E = lumens per watt

It was not possible to develop relationships between the various characteristics and life since there was no available information on the rated life employing wave forms that were not sinusoidal.

The exponents calculated are given in table 2.

TABLE 2

Wave Form	A	B	C	D	E
A	1.61	3.790	2.355	2.15	.574
B	1.61	3.785	2.350	2.16	.576
C	1.61	3.790	2.355	2.16	.576
D	1.61	3.785	2.350	2.15	.574

It should be stated that the theoretical results calculated by the exponential relationships cannot always be realized in practical installations since such factors as cleaning, handling, and vibration are not considered in the laboratory ratings.

Curve sheets 12 through 14 indicate that even though

the horizontal candlepower, luminous flux, and efficiency are higher at a given voltage for a higher crest factor, the rate of increase of these characteristics is nearly the same for all wave forms. This is also shown by the correlation of the exponents derived for the various wave forms.

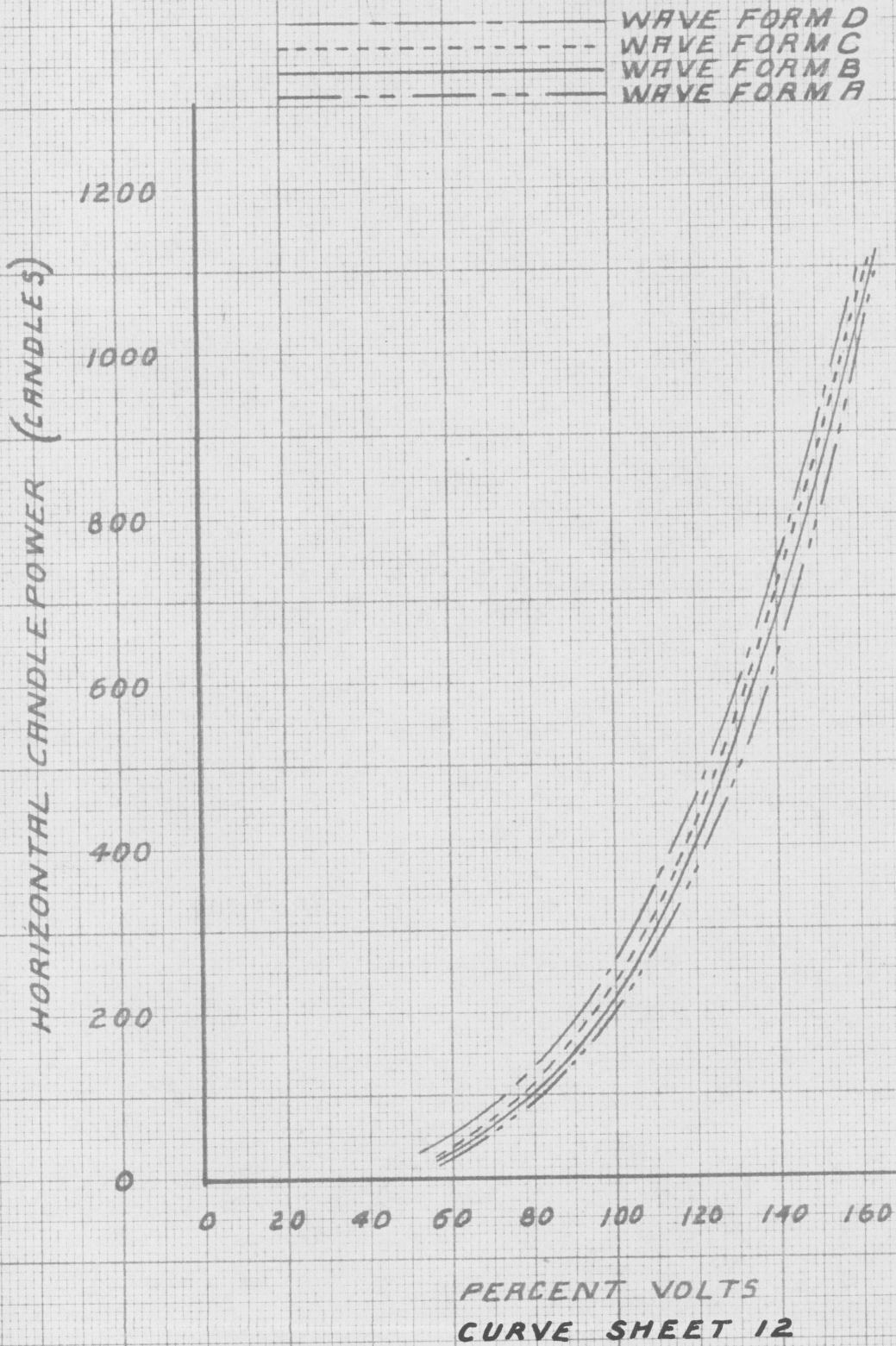The results of object 3 are shown on curve sheets 15 and 16 and summarized in table 3.

TABLE 3

Crest Factor	Average Life Minutes	Initial Efficiency
1.357	235	26.70
1.414	220	28.25
1.900	204	29.60
2.240	172	30.40

It is evident from curve sheet 16 that as the crest factor is increased the life of the lamp is decreased. When a lamp is first lighted,[3]

> The long fibrous grains of the drawn wire, heated above their annealing temperature, are changed to the equiaxed grains of an annealed metal. These grains, during this transition, absorb each other, gradually growing in size until further growth is retarded or stopped. The cessation of the growth of the grains may be attributed to several causes, not the least of which is the presence of impurities in the

VARIATION OF HORIZONTAL CANDLEPOWER
WITH WAVE FORM

——— — — — ——— WAVE FORM D
— — — — — — — — — WAVE FORM C
——————————— WAVE FORM B
—— — — —— — — —— WAVE FORM A

PERCENT VOLTS

CURVE SHEET 12

4-15-51

VARIATION OF LUMINOUS FLUX
WITH WAVE FORM

WAVE FORM D
WAVE FORM C
WAVE FORM B
WAVE FORM A

LUMINOUS FLUX (LUMENS)

PERCENT VOLTS

CURVE SHEET 13

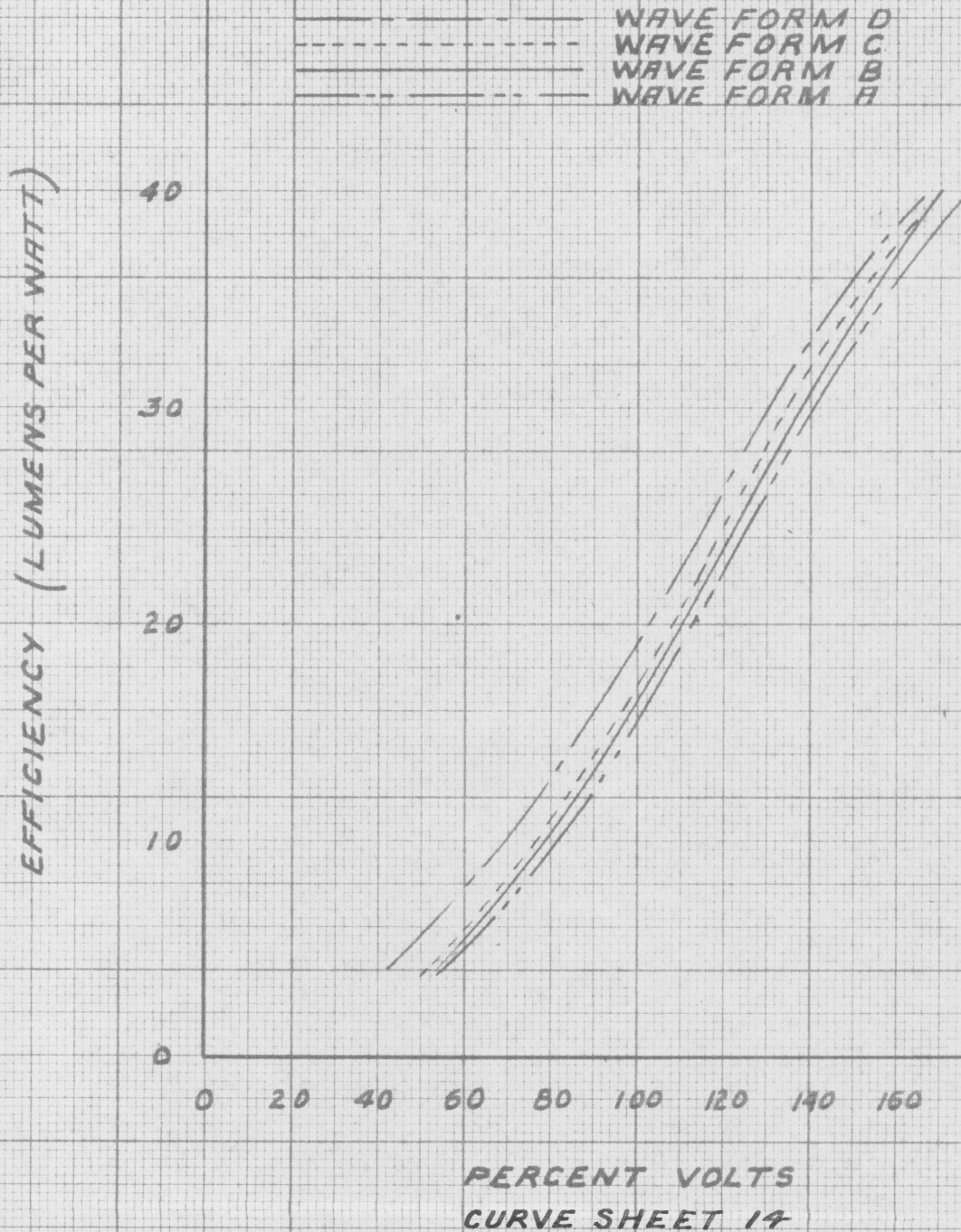4-20-51

VARIATION OF EFFICIENCY
WITH WAVE FORM

——— · ——— · ———   WAVE FORM D
——— - - - - ——— - - -   WAVE FORM C
——————————   WAVE FORM B
——— - · — — — · —   WAVE FORM A

EFFICIENCY (LUMENS PER WATT)

40

30

20

10

0

0   20   40   60   80   100   120   140   160

PERCENT VOLTS
CURVE SHEET 14

4-20-51
WEO

VARIATION OF LUMENS WITH CREST FACTOR
OPERATING AT 190 VOLTS

AVERAGE INITIAL LUMENS

7000		
6000		
5000		
4000		
3000		
2000		
1000		
0		

0   1   1.2   1.4   1.6   1.8   2.0   2.2   2.4
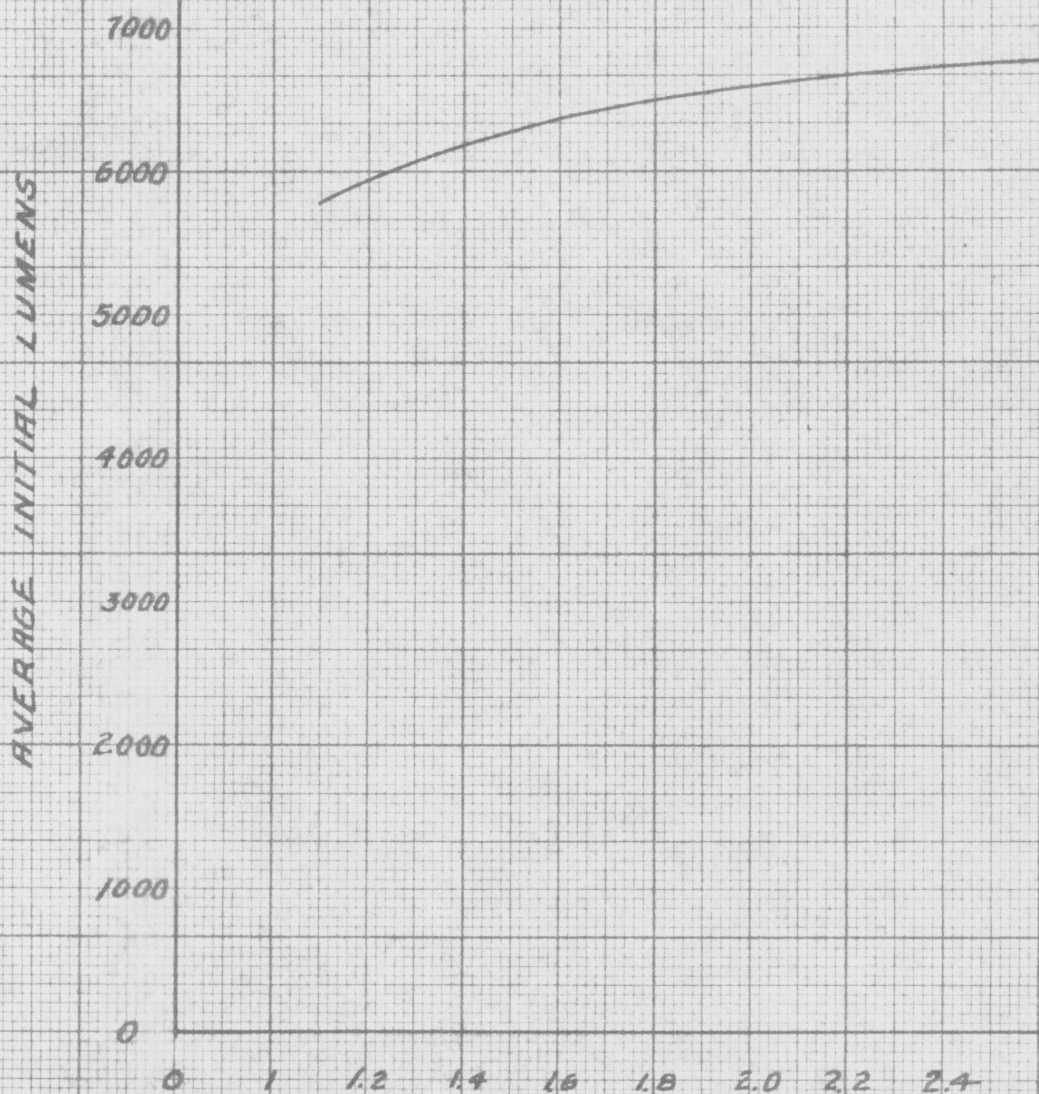
CREST FACTOR
CURVE SHEET 15

4-30-51

VARIATION OF LIFE WITH CREST FACTOR
OPERATING AT 190 VOLTS
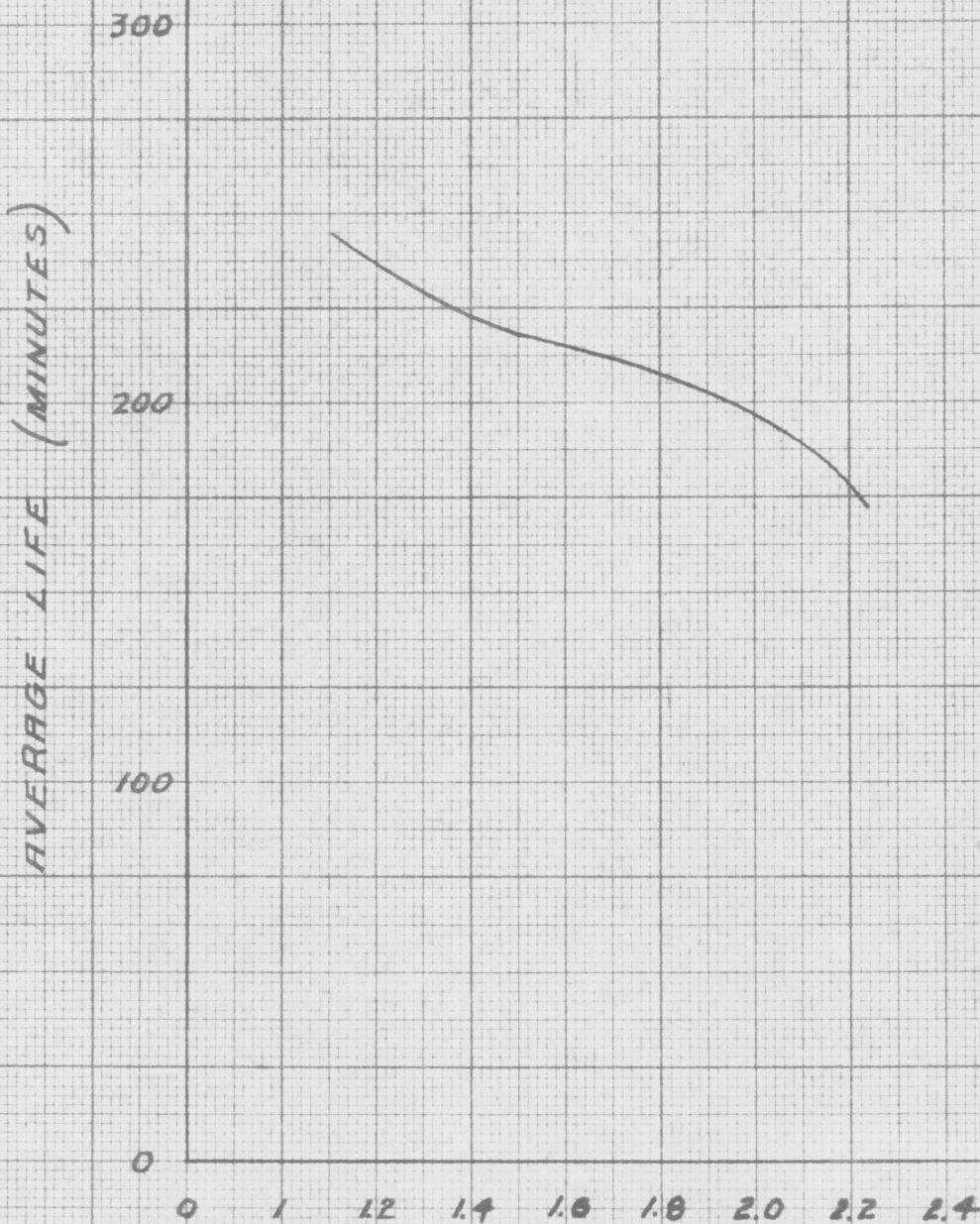
CREST FACTOR
CURVE SHEET 16

4-30-31

metal.

The crystals composing the wire are, to
the best of present knowledge, held together
by amorphous tungsten. This material acts as a
binder to hold them together and in place, but,
at very high temperature, it is not as rigid as
the crystals themselves, consequently the posit-
ions of the latter may become altered.

Should the faces of one or more crystals
fall in one plane across the diameter of the fil-
ament, offsetting will occur, that is, sections of
the filament will slide side ways and it will
soon burn out due to the decrease in cross-section
at this point.

The effect introduced by existence of temperature grad-

ients in tungsten is important.[10]

Since the rate of grain growth increases
rapidly with the temperature it is possible for
one part of the filament to be above the grain
growth temperature whilst another part is below
it. The large crystals formed in the hotter part
of the filament are then able to absorb their
smaller neighbors when the temperature is raised,
exaggerated grain growth takes place, and very
large crystals are formed. This is particularly
the case when any obstruction to grain growth is
present, such as thorium oxide or other refractory
oxide.

Although thoria restrains the growth of
smaller grains, it has less effect upon grains
which, owing to favorable conditions, such as
local absence of thoria or temperature gradients,
have become comparatively large. By restraining
the growth of smaller grains it may increase the
grain size contrast and produce exaggerated growth.

The author believes that the temperature gradients re-

sulting from the variation in crest factor may be sufficient

to produce such a recrystallization process and result in

" offsetting," thus reducing the life. Evidence of this

was indicated in several cases when the lamps were being tested

on wave forms C and D. The average illumination after a

pronounced decrease in value actually increased with life which could be explained by an increase in filament diameter in the same plane where the readings were being taken.

The question arises whether or not the advantage of increased efficiency resulting from a higher crest factor outweighs the disadvantage of decreased life. The cost of one million lumen hours of light was calculated for each wave form using the following assumption.

Cost per lamp = 15 cents

Cost of electricity = 2 cents per kilowatt-hour

Operating voltage = 190 volts

Average lumens output during life equal to original lumens output.

Average watts consumed through life equal to initial watts consumed.

The results of this calculation are shown in table 4.

TABLE 4

Wave Form	Cost Per Million Lumen Hours
A	$ 7.21
B	$ 7.28
C	$ 7.42
D	$ 8.49

From this it can be seen that the loss of life resulting

from increased crest factor is far more important economically than the increase in lumens. Therefore, if conditions are present that result in a peak wave form, it would be advisable to investigate the economical advantage of correcting them.

V - CONCLUSIONS

Based on the specific results of this investigation, the following conclusions are drawn.

1. The lumens output and efficiency of an incandescent lamp are increased as the crest factor of the applied voltage wave form is increased.

2. The average life of an incandescent lamp is decreased as the crest factor of the applied voltage wave is increased.

3. As the crest factor increases, the detrimental effect of decreased life outweighs the advantage of increased output as far as an economical consideration of light energy is concerned.

The author wishes to, stress the importance of local conditions upon the results obtained and would like to list the following as possible methods of improving the results of any future tests of this nature.

1. The use of permanent mountings for the lamps to keep the effects of local vibrations to a minimum.

2. The use of a spherical photometer to determine the mean spherical candlepower of the source.

3. The use of an accurate voltage regulating device.

4. The use of pre-tested bulbs. Even though quality manufactured bulbs were used the horizontal intensity varied over a considerable range. The bulbs

could have been tested for the same horizontal candlepower on the sine wave source.

5. The use of a more continuous direct current to excite the alternator fields.

6. The use of wider selection of crest factors.

VI - ACKNOWLEDGEMENT

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IX - APPENDIX I

Wave Forms

Shown herein are the wave forms used in determing the effect of voltage wave forms on the operating characteristics of incandescent lamps. Wave forms are shown by both oscillograms and actual ploting of the equations for the instantaneous values. All oscillograms are photographs of the resultant standing waves. The plotted waves show the magnitude as well as the phase relationship of the components of the composite waves.
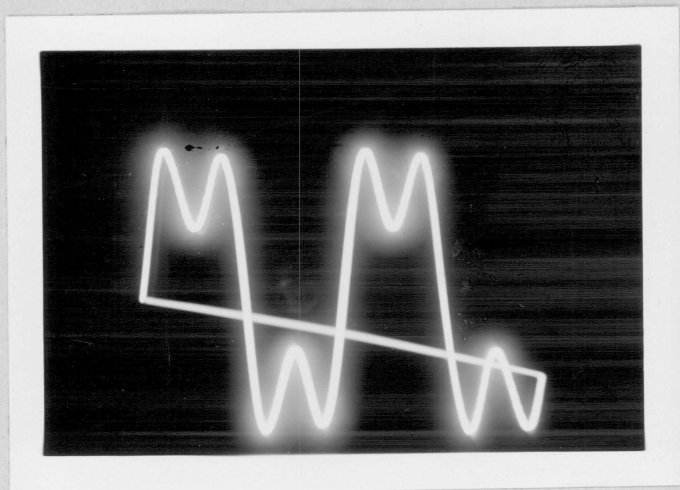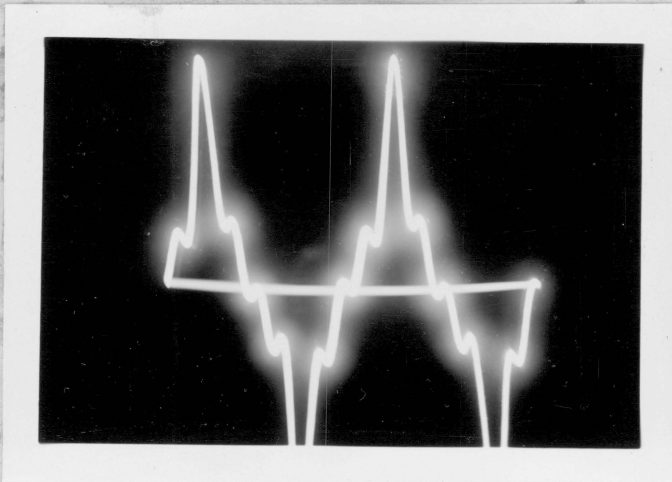
Oscillogram 1
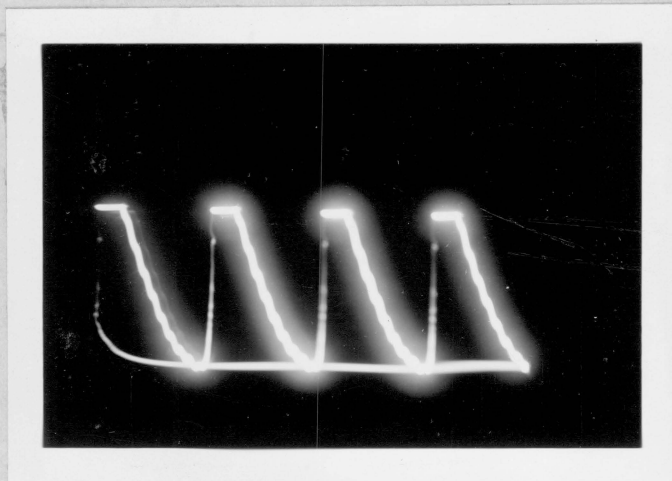Wave Form A.
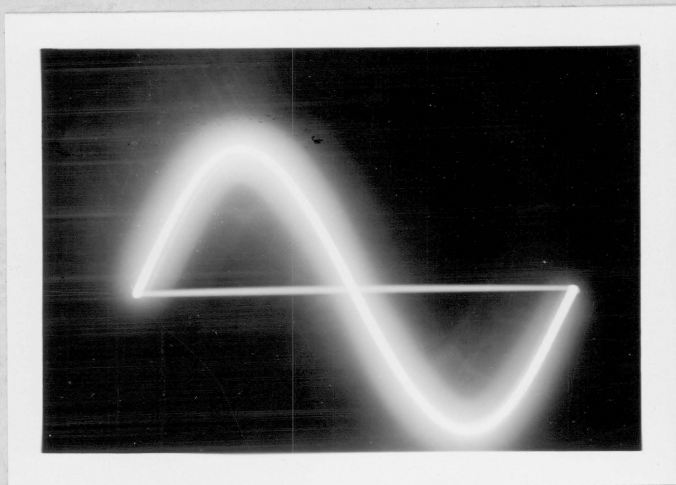
Oscillogram 2
Wave Form B.
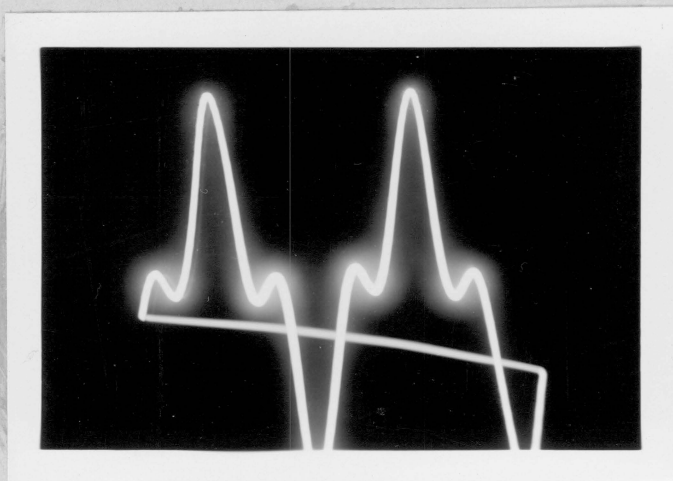
Oscillogram 3
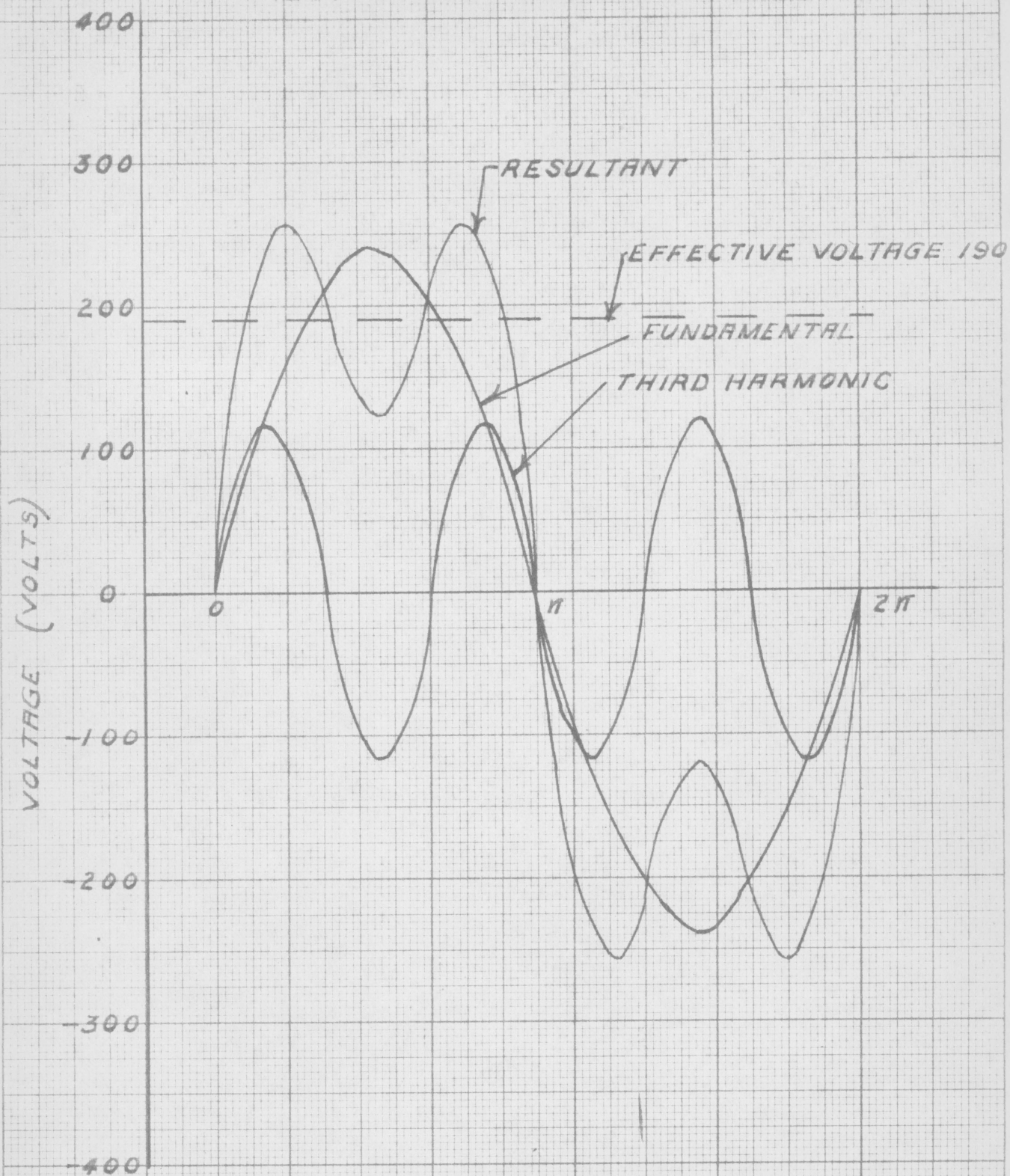Wave Form C.

Oscillogram 4

Wave Form D.

Oscillogram 5

Wave Form E.

-55-

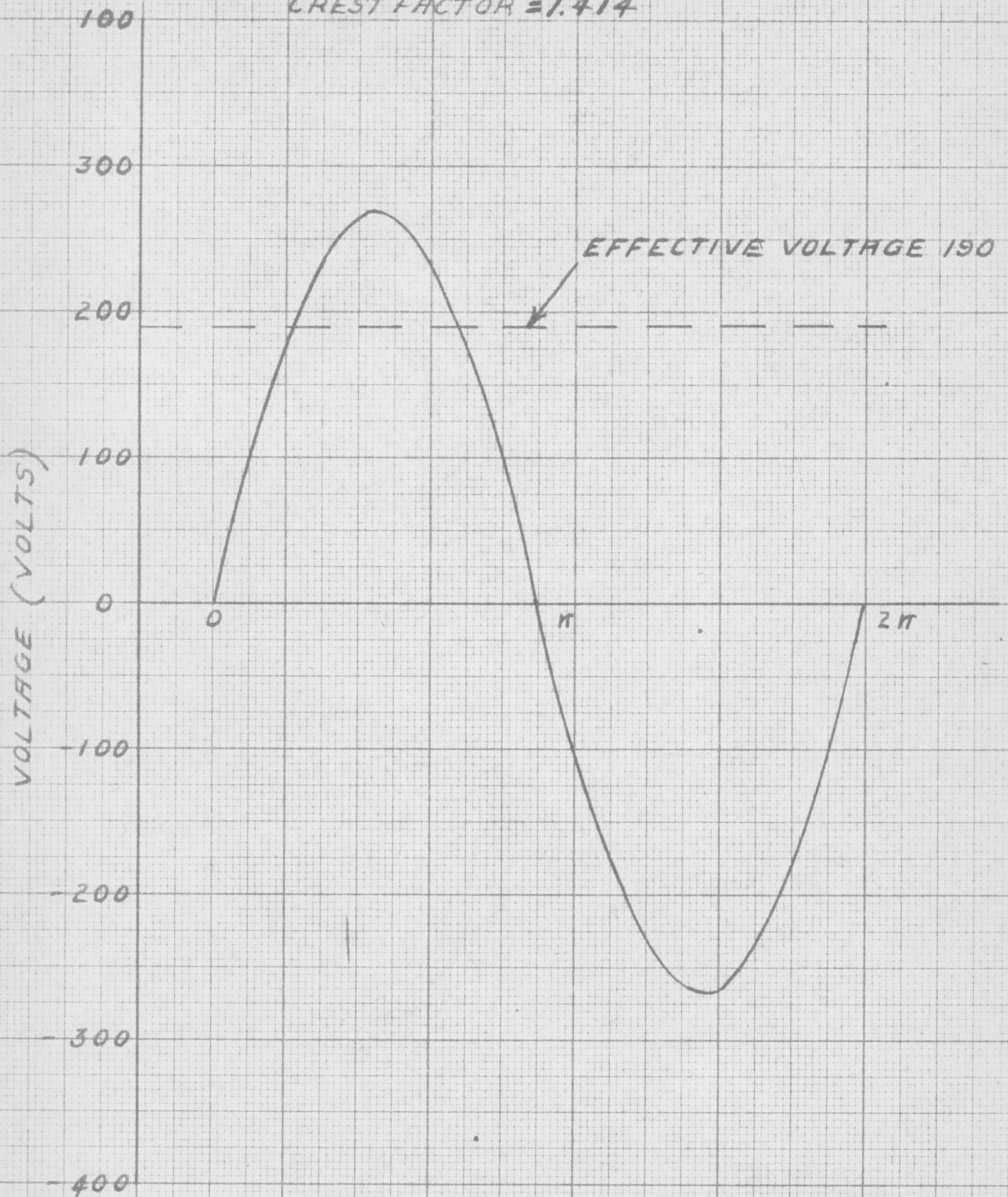EQUATION = 240.4 SIN 377t + 120.2 SIN 1131t

CREST FACTOR = 1.357

RESULTANT

EFFECTIVE VOLTAGE 190

FUNDAMENTAL

THIRD HARMONIC

VOLTAGE (VOLTS)

WAVE FORM A

CURVE SHEET I-1

4-15-51

EQUATION = 268.66 SIN 377t
CREST FACTOR = 1.414

EFFECTIVE VOLTAGE 190

WAVE FORM B
CURVE SHEET I-2

4-15-51

EQUATION = 240.4 SIN 377t - 120.2 SIN 1131t

CREST FACTOR = 1.9

RESULTANT

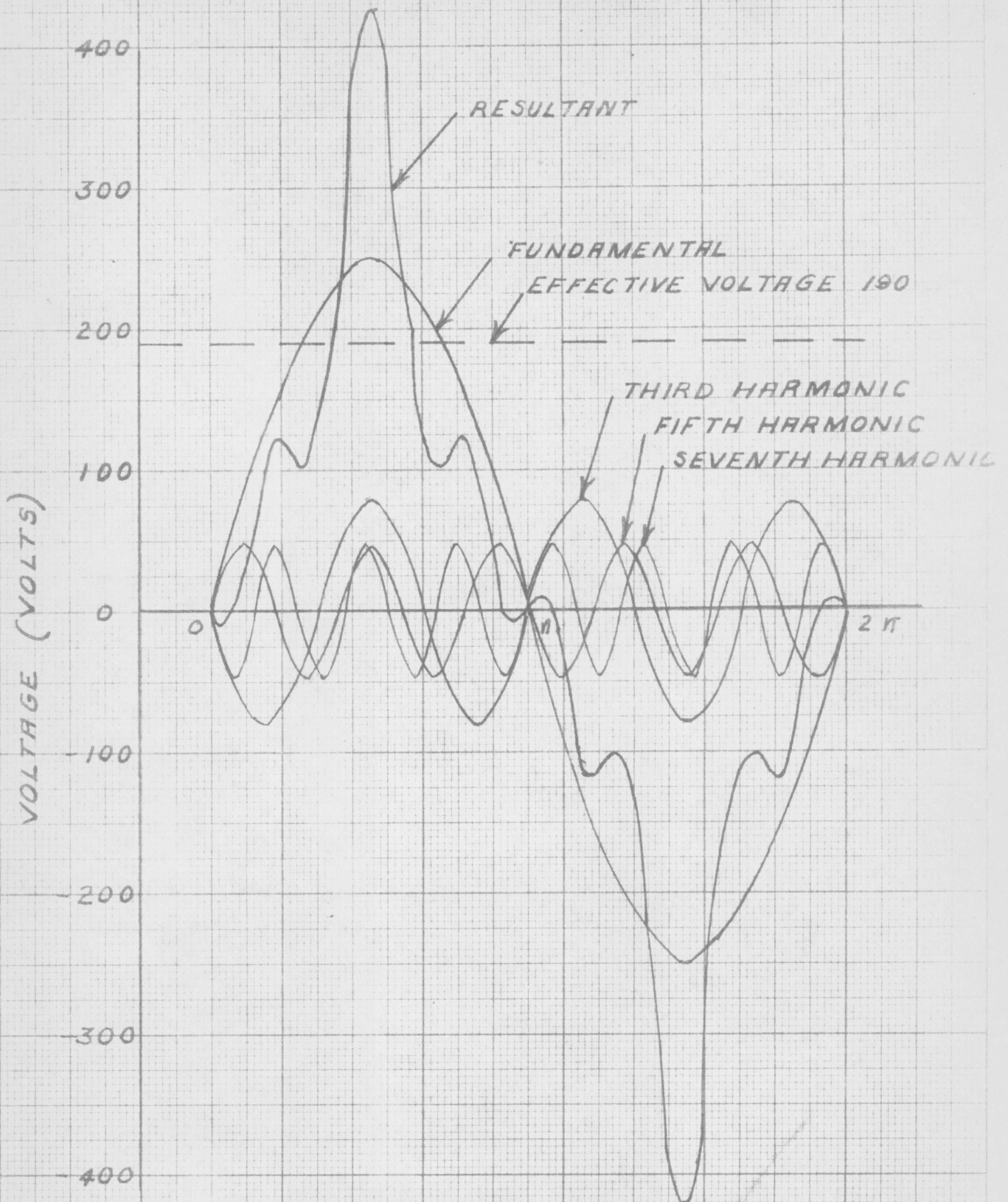EFFECTIVE VOLTAGE 190

FUNDAMENTAL

THIRD HARMONIC

VOLTAGE (VOLTS)

0   π   2π

WAVE FORM C

CURVE SHEET I-3

4-15-51

EQUATION = 247.5 SIN 377t - 79.2 SIN 1131t + 49.5 SIN 1885t - 49.5 SIN 2639t
CREST FACTOR = 2.24

RESULTANT

FUNDAMENTAL
EFFECTIVE VOLTAGE 190

THIRD HARMONIC
FIFTH HARMONIC
SEVENTH HARMONIC

WAVE FORM D
CURVE SHEET I-4

4-15-51
WEB