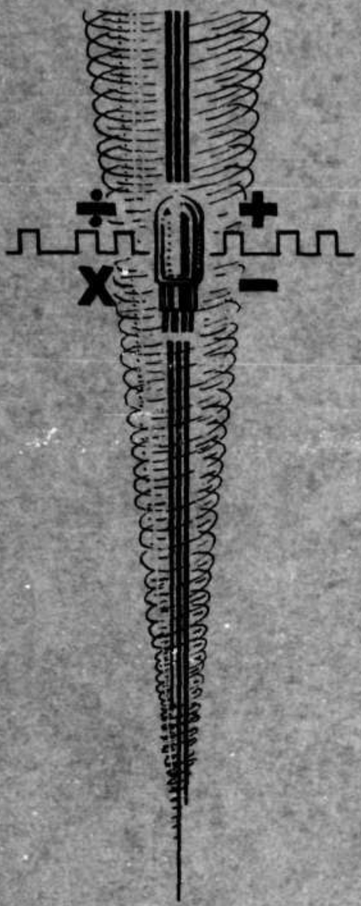

PROJECT

WHIRLWIND

Contract N5ori60

SUMMARY REPORT NO. 2

VOLUME 21

PULSED LIGHTS

(PART I)

SERVOMECHANISMS LABORATORY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

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PROJECT WHIRLWIND
Summary Report No. 2
November, 1947

PULSED LIGHTS

Volume 21 of 22 volumes

Servomechanisms Laboratory
Massachusetts Institute of Technology
Cambridge, Massachusetts

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INTRODUCTION

Volumes 21 and 22 present data obtained in thesis research using the facilities of Project Whirlwind under the faculty supervision of Professor Harold E. Edgerton. The work was originally encouraged as part of the general investigation of storage techniques. For the storage of information the electrostatic tube has been chosen by Project Whirlwind. However, the use of controlled short pulses of light at high repetition rates may in the future prove valuable in high-speed recorders using photographic film. The material is included in the Summary Report as research results which may have future usefulness in computers or other scientific fields.

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PULSED LIGHT SOURCES FOR PRESENTATION OF STORED DATA IN ELECTRONIC COMPUTERS

by

PAUL CHARLES GROSSE
S.B., Massachusetts Institute of Technology
(1944)

SUBMITTED IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE OF
MASTER OF SCIENCE

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
(1947)

Signature of Author /S/ Paul C. Grosse . . . .
Department of Electrical Engineering, January 17, 1947

Certified by ./S/. Harold E. Edgerton . . . .
Thesis Supervisor

. . . . /S/. Harold L. Hazen . . . .
Chairman Department Committee on Graduate Students

PREFACE

This research was begun early in July, 1946 and was carried out in the Massachusetts Institute of Technology Servomechanisms Laboratory as a part of Project WHIRLWIND, D.I.C. 6345 which is under the direction of Jay W. Forrester.

I wish to express my appreciation to Dr. Harold E. Edgerton, who kindly consented to supervise the thesis work and to Kenneth J. Germeshausen. I wish also to thank the personnel of Servomechanisms Laboratory who were associated with the work. In particular, I am indebted to Patrick Youtz who suggested the problem and to Richard L. Brown who greatly expedited its solution. I owe thanks also to Margaret I. Florencourt, who made a large part of the calculations, John O. Ely, who investigated the properties of the Strobotron and several arc tubes, Timothy Leary, Jr., who made the layouts of the circuit diagrams, and Robert H. Murch, who built much of the equipment.

Paul C. Grosse

Cambridge, Massachusetts
January 1947

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CRATER GLOW TUBES

CHAPTER ONE

INTRODUCTION

The broad object of this research is to begin a program of surveying, investigating, and testing of pulsed light sources which may prove appropriate for use in electronic computers for the ultra-high-speed flash illumination of cards, slides, or films. On these cards will be stored data, such as instructions or function tables. The light flashes will make a selected portion of the data available to a light-sensitive pick-up device for use in the computation.

The Computer Problem

In the past, calculating machines were designed to perform small parts of calculations or operations which recur frequently. These were the four processes of addition, subtraction, multiplication, and division. A human operator put material into the machine and took it out at the appropriate time. The operator carried the instructions in his head and consulted function tables and other aids to the computation problem as required.

An automatic computer must receive, store, manipulate, and deliver numerical data in accordance with a prescribed program. This program is a series of control orders in the form of coded signals which select and initiate the operations within the computer. The program orders and numerical data are very similar in many respects since both are represented by the same sort of coded signal and are used similarly. They must be supplied to the computer, stored within it, and must be available individually for use as required.

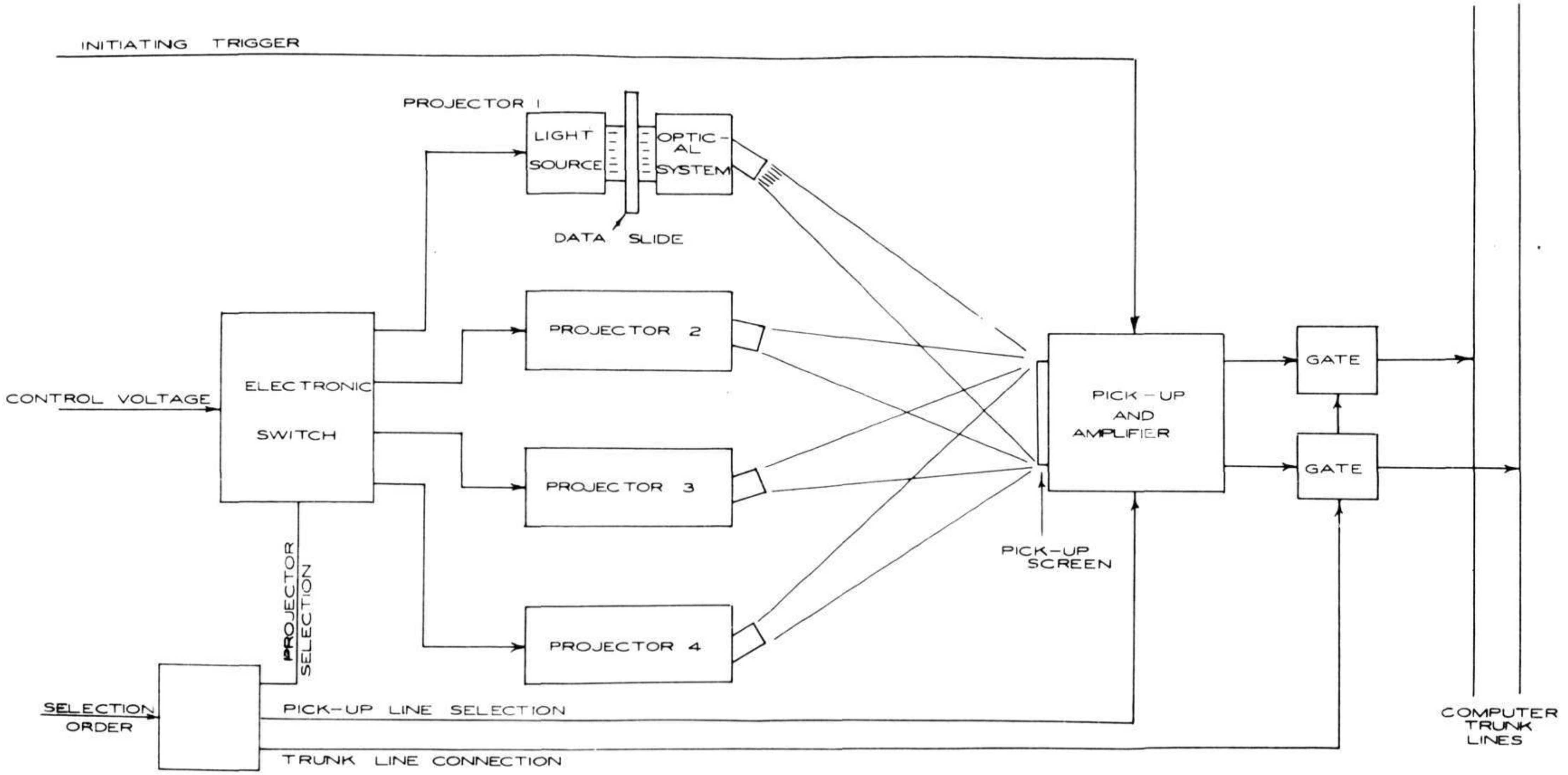
Professor Hartree of the University of Manchester, Manchester, England, said in a recent seminar at the Massachusetts Institute of Technology that a general purpose computer requires a storage capacity of ten thousand numbers. This is the order of three hundred thousand binary digits. In the past it has not been possible to store very large quantities of information economically in such a way that the required portions of it are readily available at a rate compatible with the desired computing speeds. This has been the main problem in the design of high-speed electronic computers. The design of the other circuits of the computers is comparatively straightforward.

It has been suggested that this program data and numerical data be stored on a magnetic tape, on punched paper tape, or on cards. With these methods at the present state of the art, the time required for taking the appropriate data out of storage increases with the storage capacity and places a definite limit on the computing speed.

One other method of supplying data fast enough has been developed in the Massachusetts Institute of Technology Servomechanisms Laboratory. A perforated opaque data card is placed across the face of a cathode-ray tube and the beam is swept across a selected row of perforations. The resulting pulses of light are picked up by a multiplier phototube and are converted into a series of electrical pulses for use in the computer. Unfortunately, the investigation indicated that this system requires an excessive number of cathode-ray tubes and auxiliary equipment.

The Proposed Data Reader

Another proposed system is diagrammed in Figure 1. It uses one pick-up system and a battery of projectors each containing a slide on which is stored data in the form of many rows of clear and opaque areas.



31 JULY 1946

FIGURE 1. PROPOSED DATA READER – SIMPLIFED BLOCK DIAGRAM

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Proposed pick-up devices under investigation by the Massachusetts Institute of Technology Servomechanisms Laboratory are:

1) A matrix of miniature phototubes
2) A matrix of ordinary phototubes
3) A matrix of multiplier phototubes
4) A Farnsworth Image Dissector
5) An RCA Iconoscope

The optical system of each projector will focus a data card upon the pick-up device. The computer will select any of a large battery of projectors by means of the electronic switching system. The light source of the projector selected will then be modulated so as to flash the required data onto the pick-up device and, at the same time, the pick-up device will be set to scan a line (i.e. read a word) of the displayed data. The time required to read a word will be less than 50 microseconds.

The requirements of a light source for each projector now become manifest. If it is to present the data in a time compatible with the reaction time of the switching system, it should be desigend so that it can be turned on within 1 to 2 microseconds and, for at least one of the above pick-up devices, off within 1 to 2 microseconds. It must, furthermore, be able to operate at a frequency of 20 kilocycles per second or higher. Unfortunately, because the computer may require that the same light be flashed indefinitely, the light source must be designed for continuous pulsed operation. The intensity of the light source and its pulse waveform will depend on the characteristics of the particular pick-up device and system selected. The intensity of the light source also depends upon the efficiency with which the projection system conveys the light from the source onto the pick-up device.

Projector Efficiency

A starting point in the determination of orders of magnitudes of light intensities required by each pick-up device must be an estimation of the efficiency of a projector in converting light output from a lamp into light on the screen of the pick-up device. This was obtained experimentally and checked by theoretical computations.

A projector, a small 35 millimeter slide model, having a 100 watt tungsten projection lamp, a hemispherical mirror, a double condensing lens, and a double projection lens, was acquired. The lens, unfortunately, was not coated and also, not very fast. The results of one run by coincidence gave average data. In this run the projector was placed 108 inches from a screen 20 x 30 inches in dimensions. This screen had an area, therefore, of 0.39 square meters. A Weston, model 603, illumination meter indicated 66 lumens per square meter in the picture area. The light on the area was therefore 26 lumens. Then, all the lens elements including the reflector were removed and the light intensity from the unaided lamp in the direction of the screen was measured. This was 14 lumens per square meter at 108 inches. A simple calculation involving the inverse squdre law shows that the light had 106 candle power in the direction of the lens. The efficiency of the projector is then 0.25 lumens per candle power. This figure is used because it relates useful light energy on the screen to the effective intensity of the lamp (i.e. the intensity in the direction of the lens). It is of interest to add that, if one were to make the unusual assumption of a light source which radiates uniformly in all directions, the above efficiency may be expressed as about 2 per cent. Theoretical calculations[1] involving the areas of the lens elements and an arbitrary assumption of 50 per cent absorption of light by them checked the above experimental result within 50 per cent. Because of the low quality of the projector, the above figure is undoubtedly decidedly conservative.

Estimated Light Intensity Requirements for Each Contemplated Pick-up Device.

With this rough measure of the efficiency of the projector it is now possible to determine the light intensity of the projection lamp required by each of the pick-up devices under consideration.

1) Matrix of Miniature Phototubes

As now visualized the phototube matrix will be actuated by short pulses of light (perhaps 1 microsecond), having a low duty cycle. The information will be passed on to "flip-flop" circuits where it will be preserved until the word is read. Responses of phototubes are practically instantaneous depending principally on circuit design so that steady-state sensitivities apply. Measurements made at the Massachusetts Institute of Technology Servomechanisms Laboratory indicate that an intensity of 120-foot candles is necessary to obtain the maximum rated current (0.5 microamperes) from the type RCA-C7112A Miniature Phototube. Including space necessary for mounting, the area of a matrix of 30 rows and columns of these tubes is approximately $(3/8" \times 30)^2 = 127$ inch^2 (the diameter of a cell is 1/4 inch). The light requirement is, therefore, $\frac{120 \times 127}{144 \times 0.25} = 430$ candle power. A figure of merit of .0012 microamperes per candle power results.

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[1] Hardy and Perrin, *Principles of Optics*, McGraw-Hill, New York, 1932.

2) A Matrix of Ordinary Phototubes

Similar measurements on type RCA-929 phototubes show that 320 foot-candles are necessary to give a reasonable output current (51 microamperes). The dimensions of the tube are such that a matrix of 50 rows and columns measures 45 x 45 inches. The light requirement is, therefore, $\frac{320 \times 45 \times 45}{144 \times 0.25}$ 18,000 candle power. A figure of merit is, therefore, 0.0029 microampere per candle power.

3) A Matrix of Multiplier Phototubes

A noise-free operating condition is obtained at and under 75 volts per dynode stage of the type 931-A tube. Figure 12, which will be considered later, indicates that the tube used in the laboratory has a sensitivity of 10 amperes/lumen at 75 volts per stage. The rated maximum current of 1000 microamperes is, therefore, obtained with only 10^{-4} lumens on the cathode. Since the cathode area is 0.29 square inches,[2] the required light intensity on the matrix is $\frac{10^{-4}}{0.29}$ lumens/in.^{2} The dimensions of each cell including the mounting socket are such that the matrix would be about 90 x 60 inches. The light requirement is, therefore, $\frac{10^{-4} \times 90 \times 60}{0.29 \times 0.25} = 7.5$ candle power. A figure of merit of 133 microamperes per candle power results.

4) A Farnsworth Image Dissector[1]

The screen area is 5 square inches. The manufacturer quotes a necessary light level of 50-foot candles for "noise-free" operation.

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[1] Madison Cawein, "Farnsworth Image Dissector", Research Report 44 Farnsworth Tel. and Rad. Corp., Fort Wayne, Indiana, December 30, 1944.

[2] See RCA Tube Manual

This results in a light requirement of $\frac{50 \times 5}{144 \times 0.25} = 6.4$ candle power. The response of this tube is theoretically practically instantaneous. There exists no energy storage in it. Therefore, a flat-topped pulse lasting for the length of time required to read a word(i.e. 50 microseconds) would be required. This means a nearly 100 per cent duty cycle for the light.

5) An RCA Iconoscope

The number 1846 iconoscope is under consideration. It has a screen size of 2-3/16 x 2-7/8 inches or 6.3 inches^2. Little quantitative information is available about the response of the iconoscope to suddenly applied light; however, it is generally accepted that the charge on the mosaic builds up exponentially over a period of time which is long relative to the pulse lengths with which this investigation is concerned. As ordinarily used, the tube is scanned in 33,000 microseconds and a light level of 5 foot-candles is quoted by the manufacturer for "noise-free" operation. Inasmuch as the time constant of build up of charge on the screen is not known, a very rough estimate is ventured that this time constant is 1000 microseconds. For steady operation with one sweep cycle each 33,000 microseconds the light requirement is $\frac{5 \times 6.3}{144} = 0.219$ lumens, but to build up this same charge from a light pulse of only 1 microsecond length 1000 times as much light is required. The projection lamp must then supply 1 microsecond pulses of light $\frac{1000 \times 0.219}{0.25} = 877$ candle power.

Summary of Light Specifications

The iconoscope may possibly require about 1000 candle power in 1 microsecond pulses or perhaps 500 candle power in 2 microsecond pulses at a correspondingly low duty cycle from the projection lamp, if the many assumptions both stated and implied in the above calculations hold true. On the other hand, the image dissector, less sensitive as ordinarily used, needs only 6.4 candle power but at a nearly 100 per cent duty cycle.

The three types of vacuum phototubes considered required short pulses of light at low duty cycles. If used, the ordinary and miniature types must work into amplifiers to gain enough output to trip the single-shop multivibrator with the required rise time of 1 to 2 microseconds; although the multiplier phototube is its own amplifier and will work well with a pulsed light source of as little as 5 candle power. This tube is used as a part of the light measuring device in this investigation and will be condiered in detail.

Emphasis is placed on the "noise-free" condition for each device because the loss of even one light pulse would be disastrous to the computer. The above calculations undoubtedly do not adequately consider this limitation for "noise-free" is interpreted in the usual communications sense by the manufacturer of each tube.

In the above analysis and throughout this paper the spectral distributions of light energy from each lamp and those of the sensitivity of the various pick-up devices have not been included in the analysis. This was the practical procedure to take. Data on the spectral responses are readily available from manufacturers' specifications for each pick-up device, and it is assumed that a surface will finally be selected to match closely the energy distribution from the selected light source.

On the conservative side is another uncertainty, the low value of efficiency for the projector. The use of a high quality lens will reduce each light requirement considerably. The figures arrived at are only orders of magnitude; therefore, the certainty that a given lamp will properly excite a given pick-up device can only be attained by the actual operation of the combination.

CHAPTER II

POSSIBLE LIGHT SOURCES

A survey of the literature conducted at the beginning of this research indicated that there had been no gaseous discharge device operated under the conditions required by this project. There are two very general categories of lamp which seemed, nevertheless to have possibilities. These are glow-discharge tubes and arc-discharge tubes.

The glow tubes used as light sources in the past had been designed to be modulated linearly at audio frequencies for the recording of sound and other information on film and, less recently, for use in television receiving equipment.[1] It is true that these tubes produce little light under steady conditions,[2] yet it was felt that they might prove ideal when pulsed at high energies, especially as they had been used as stroboscopic light sources (pulsed by condenser discharges) at frequencies as high as 15,000 cycles per second.[3,4] Furthermore, the use of very high potentials can lead to a small ignition time according to theory.[4] Presumably, also, these tubes are not subject to rapid deterioration except for sputtering. With these factors in mind, the following tubes were procured and tested:

1) Crater Glow Modulator Tube 1B59/R1130B
2) Crater Glow Modulator Tube 1B59/R1131B
3) Strobotron SN4

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1. Dinsdale, First Principles of Television, John Wiley, New York, 1932.
2. Cobine, J. C., Gaseous Conductors, McGraw-Hill, New York, 1941, 57.
3. Ingram, S.B., A.I.E.E. Transactions, 58 (1939) 342.
4. Reich, H.J., Theory and Applications of Electron Tubes, McGraw-Hill, New York, 1944, 427.

4) Strobotron 1D21

The strobotrons were included principally because of their availability. The arc discharge of their normal operation deionizes so slowly that the maximum repetition rate on arc discharges is much less than a hundreith that required by the project. They are also poorly adapted for use as high energy glow discharge tubes, for the principal feature of their design is a cup-shaped cathode containing a cesium compound to permit easy transfer from glow to arc at low cathode temperatures.[1] The greatest portion of the time has, therefore, been assigned to work on the crater lamp.

As the work progressed, it became apparent that a glow tube of the large flat-plate type would have interesting possibilities. It was planned to design and construct one or more of this type possibly with water-cooled cathodes to permit high energy glow operation, but lack of time and facilities prevailed.

The possibility of supplying exciting energy to the gases of a tube from a high-frequency field was considered. One of the references read describes such a tube for early television use.[2] In it temperature-controlled mercury vapor was excited by a radio frequency carrier modulated at audio frequencies. The author reports "no tube discoloration" and "no time lag when the current is cut-off or when the tube is started". It would be interesting to determine how nearly correct are these statements by the use of the pulse techniques made available in recent years. Very

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1. Germenshausen, K. J., and Edgerton, H. E., Electrical Engineering, 55 (1936) 790.

2. A. P. Peck, "White Light for Television," Television, 6 (Jan 1933) 15-16.

interesting indeed, is the 3,000 candle-power output which he reports. No work was done in the development of this idea for lack of time.

The various arc tubes which were considered seemed less promising than the glow tubes because of the very long ionization and deionization times of the familiar types. However, Mr. K. J. Germeshausen of the Massachusetts Institute of Technology was consulted and agreed to cooperate in the design of a three-element discharge tube for test purposes. This tube, consisting of two main electrodes (made of a low-sputtering tungsten alloy) spaced 5/8ths of an inch apart with a third starting electrode interposed, was filled with argon at a low pressure. On one-shot condenser discharge, it fired at a minimum potential of 500 volts with a starting pulse of the order of 4000 volts on the third electrode. To test this lamp under conditions of pulsed operation, a Model 12 radar modulator was borrowed from the Basic Research Laboratory, M. I. T. This modulator uses a hydrogen thyratron tube as a switch and an artificial line to form the pulse. The circuit was modified by the addition of 2 parallel 2X2 diodes in series with the line charging choke to permit pulsing the tube at low frequencies. An artificial 50-ohm load was constructed to match the output impedance of the modulator. To permit measuring the output pulse voltage, a capacitor voltage divider was also constructed. The modulator would not fire the spark tube. Tests were then made in the Basic Research Laboratory which indicated that 10-15 kv are necessary to <u>pulse</u> the tube with 5 kv on the main electrodes. This suggested the use of a lower gas pressure and decreased electrode spacing. Theoretical calculations indicated that the Model 12 modulator could not possibly supply the required amount of pulse current. Further experimentation with this type of lamp was then deferred. If this type tube is to serve the purpose of the project the energy per pulse must somehow be very much reduced to meet the high-frequency, continuous-duty requirement.

Another arc tube which is being investigated is the constricted arc type used in flash photography. A tube of this type, the R4330 , has been pulsed in the laboratory from an artificial line in single-shot operation. The results of this investigation are not available for inclusion in this report, except to observe that the amount of energy used to pulse the tube (10 microsecond pulses) precludes its use at high frequencies and that the time delay from the application of the exciting trigger to the ignition of the tube is thus far poor (sometimes as much as 40 microseconds) and not at all constant. Development work with similar tubes will continue.

The possibility of using an electro-optical light valve, the Kerr Cell, to modulate an unvarying light source such as a tungsten lamp or a mercury arc to obtain the desired light pulses has been considered. Such a device has an ultimate response time of 10^{-10} seconds and may be an ideal solution to the problem. However, consultation with Professor Mueller of the Physics Department, M.I.T., and through him with engineers of the Polaroid Corporation, and separately with several military research projects indicated that these cells are not available in the United States. It was thought impractical to construct one in the time available for the research, primarily because of the difficult chemical problems involved in refining commercial nitrobenzene to an extent where it can safely be subjected to high voltages.[1,2] Because of the considerations outlined above, the bulk

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1. Dunnington, F. G., "The Electro-optical Shutter - Its Theory and Technique," Physical Review, 38 (1931), 1506-1534.

2. Kingsbury, E.F., "The Kerr Electrostatic Effect", Review of Scientific Instruments, 1 (1930) 22-32.

of the experimental part of this research has then been devoted to the crater glow tubes. This will be described in the following chapters.

CHAPTER THREE

EXPERIMENTAL PROCEDURE - GLOW LAMPS

History of the Work

The first tubes to be studied were the small crater lamp, R1130B and the Strobotron SN4. These were available when the research began. Later, a larger crater lamp, the R1131B, and another Strobotron were obtained. Still later other tubes mentioned in Chapter II were obtained, but the bulk of the time spent by the author has, however, been devoted to the study of the two crater glow tubes, the R1130B and the R1131B.

The first step in the study of the glow tubes was to decide on a suitable light-measuring circuit. A choice lay between an ordinary high-vacuum phototube used with a load resistance low enough to achieve good high-frequency response and a wide-band amplifier necessary to get enough voltage to drive a synchroscope amplifier, and a multiplier phototube which requires only the scope amplifier.

The multiplier phototube possessed many advantages. Great gain is achieved with no noticeable noise. The gain is adjustable over extremely wide ranges (see Figure 12) through the use of a variac to control the power supply voltage. This factor means that extremely wide variations of light intensity can be handled by the single pick-up device. A 931-A multiplier phototube and power supply were on hand, having been used in the study of the cathode-ray tube data reader mentioned in Chapter I. One disadvantage lay in the need of keeping the tube in a light-tight box, whenever energized; for there is no way to prevent a steady tube-destroying overload in the presence of ordinary light.

The first modulator built for the crater lamp consisted simply of a switch tube, a 6L6, connected in series with a crater lamp and a 100 ohm resistor, across which a voltage proportional to the current in the tube could be observed. A regulated power supply of 300 volts was used. The grid circuit was the same as that used in the final experimental modulator, Figure 12. A variable negative bias was used to cut the 6L6 off between the positive gate pulses, which were supplied from a Forbes-Dane Pulse Generator. This generator can operate at only one repetition rate, 2000 pulses per second; although it gives a 150 volt gate having the excellent rise time of 0.1 to 0.2 microseconds. A master oscillator for the system was provided by the trigger output of a type P4 synchroscope. The light-measuring circuit used in the preliminary studies was the multiplier phototube without modification with a 6800-ohm load resistor and no cathode follower. The output voltage of the 931-A was fed into the amplifier of a Dumont Type A/N 256-B Synchroscope on which the light waveform was viewed. Final conclusions after modifications which greatly improved the frequency response of the 931-A circuit are that this original circuit was almost adequate to reproduce all the frequencies present in the light waveforms.

A circuit was designed which reversed the current in the crater lamp momentarily after the current pulse was over (a series R-L branch in parallel with the tube) with the hope of decreasing the time constant of the light decay; however, no effect was noticed except that if enough current was sent through the tube for long enough in the reverse direction, the light again increased.

The light-measuring circuit was early tested for frequency response by observing its response to the light output of a General Radio Strobotac. This was synchronized at line frequency. In order to see the waveform on the screen of the A/N256 Synchroscope, it was necessary to devise a circuit to shift the phase of the synchronizing trigger by a considerable amount. The final arrangement, in which the sizes of the circuit elements were determined by experiment, used the circuit in Figure 2, to shift the phase of the line voltage by the required amount. The variac adjusted the voltage level so that the correct voltage (14 volts rms.) to synchronize the master oscillator of the P4 synchroscope was obtained across the capacitor. This instrument provided triggers to the A/N 256 synchroscope sweep circuit.

The idea is to compare the waveform as seen on the synchroscope with similar ones previously taken with ordinary high-vacuum phototube circuits by graduate students who thoroughly checked them for adequate high-frequency response. Later, a circuit similar to the one they had used with a 10,000-ohm load resistor was tested at the Servomechanisms Laboratory and found to have an upper half-power frequency of approximately 2 megacycles per second. This means a rise time to a step of light of about 0.5 microseconds or a time constant of about 0.08 microseconds. The waveform as seen on the synchroscope is shown in Figure 3. The rise at the end of the 5 microsecond pulse takes about 1 microsecond and the trail off is sharp; however, the dip immediately before the 1 microsecond rise does not seem deep enough.

The substitution of a 1000-ohm load resistor in the 931-A circuit had no apparent effect on the waveshape. Variation of the 931-A power supply voltage over wide ranges also had no visible effect on the waveshape. This test provided only a rough check which at the time

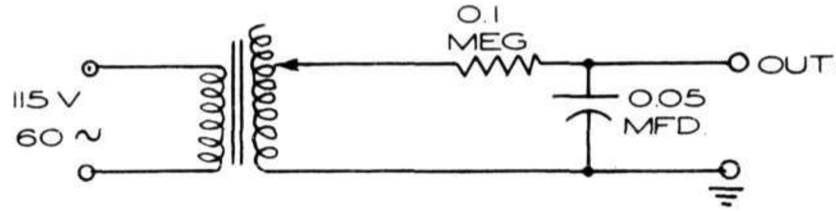

FIGURE 2. PHASE SHIFTING CIRCUIT

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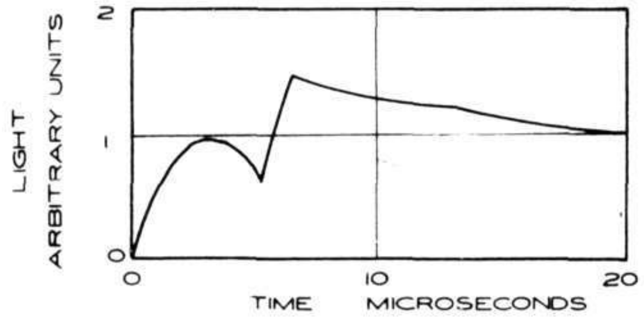

FIGURE 3. STROBOTAC LIGHT OUTPUT BY MULTIPLIER PHOTOTUBE

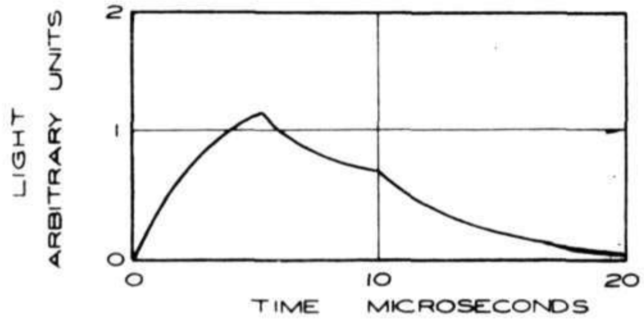

FIGURE 4. STROBOTRON SN4 LIGHT OUTPUT FOR 10 MICROSECOND CURRENT PULSES

seemed adequate enough to warrant proceeding to a study of lamp characteristics. Later, the question of frequency response of the photocell circuit was reconsidered and some modifications were made to improve it greatly.

After completing preliminary studies of the operation of the glow tube, it was decided that more pulse current was needed. That previously obtained (250 milliamperes) was doubled by the connection of another 6L6 in parallel with the first. Resistors placed in the leads to the grids and to the screens as shown in the circuit diagram, Figure 12, eliminated high-frequency oscillations. The two tubes passed a pulse current up to 500 milliamperes.

It was found that increasing the power supply potential greatly decreased the time constant of increase of current in the tube (as is to be expected from theory) so that all subsequent studies were conducted with potentials greater than 400 volts except where they were designed to show the effect of a lower voltage.

Some time was also spent designing, building, and testing modulators to operate the Strobotron tubes on a glow discharge. The first circuit designed did not cut the tube off between pulses. Others did not work for a variety of reasons. A final successful attempt used a 6L6 to apply a large negative gate voltage to the first grid of the Strobotron at the same time that two other 6L6's gated the circuit. It was observed that the Strobotron, although operated at only a 3/4 ampere pulse current, had a tendency to change from a glow to an arc. This is a reasonable condition because it was designed so that this transfer is easily made.[1] It was further noted that most of the light seemed to come in a pulse of about 5 microseconds duration at the beginning of the gate independently of the length of the gate. Figure 3 shows the light waveform for a 10 microsecond current pulse. This study was conducted before the light measuring circuit had been calibrated, at a time when it was proposed to measure the average light with a Weston, Model 603, Illumination Meter and to determine the peak light from a waveform analysis. This method was time consuming and awkward at the best and also inaccurate because the response of the illumination meter to pulsed light is in doubt. Calculations using this method will not be presented in this report.

Because the Strobotron had a much greater tendency to arc than the crater lamps, it was decided to devote full time to the study of the characteristics of the latter. Later, J. O. Ely of the Servomechanisms Laboratory, made some further studies of the Strobotron. Some of his results are included in this report.

Overall Test Circuit for Glow Tubes

The first experimental set-up was limited to a single frequency, 2,000 cycles per second, and to pulse widths of 0 to 20 microseconds. It was felt, however, that a thorough study of the crater tube would involve varying the pulse repetition frequency from 0 to at least 20,000 cycles per second, as well as varying the pulse current over as wide a range as possible, and varying the supply potential over wide ranges. To achieve these conditions several circuits had to be designed and constructed. These will be described later.

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[1] K. J. Germeshausen, H. E. Edgerton, "The Strobotron", Electronics February, 1937, 12-14.

A block diagram of the final overall test circuit is given as Figure 5. This system was designed to test any type of pulsed light source with the single exception that a separate modulator must be built for each different type of tube. Note that the voltage waveforms are sketched on the diagram where they occur. The Hewlitt-Packard Audio Oscillator produces a sine-wave voltage at frequencies adjustable from nearly zero to little over 20,000 cycles per second. This unit synchronizes a multivibrator which supplies square pulses to a pulse shaping circuit which, in turn, generates sharp triggers to drive the sweep synchronizing circuit of the Dumont Type A/N 256-B Synchroscope and, also, to trigger a delay box included to delay the signal so that the desired waveforms can be seen on the synchroscope screen in their entirety. The pulse frequency divider shown is necessary because the synchroscope sweep circuit does not synchronize from external pulses at a frequency greater than 2,000 pulses per second. The delay trigger pulse is applied to a gate generating circuit which produces a delayed positive gate (60 volts) of variable width (with, unfortunately, a minimum width of 5 microseconds) to gate the 6L6 modulator tubes. The gate is applied to the grids of the 6L6's of the modulator to pulse the crater lamps. Single-shot pulses were obtained by removing the audio oscillator and the driven multivibrator and substituting for them a simple circuit incorporating a microswitch and an RC peaking circuit to provide a positive trigger each time the switch is closed. This trigger is processed by the other elements of the block diagram in the same manner as are repeated triggers.

Figure 6 is a photograph of the test bench with all the connections of the final test circuit in place. The oscillator is at the extreme right

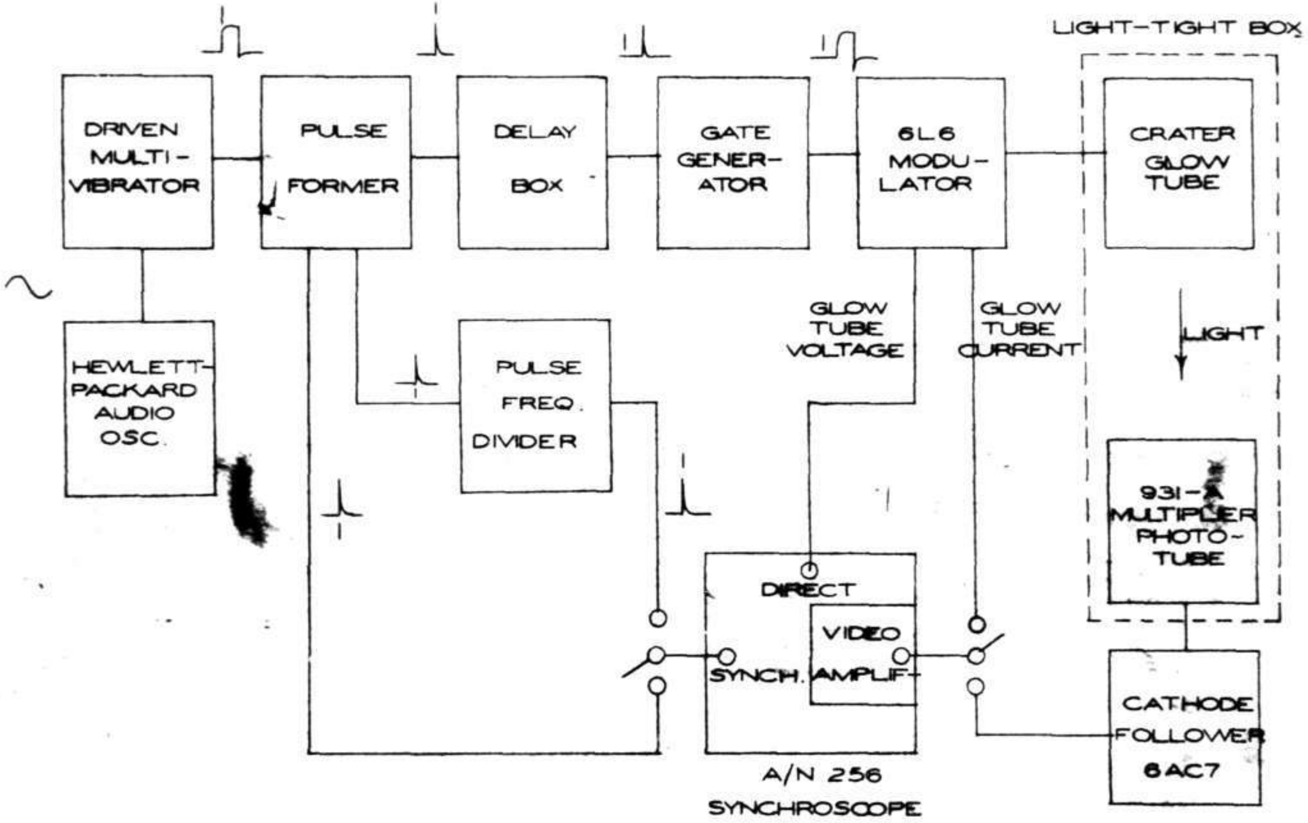

FIGURE 5. BLOCK DIAGRAM OF OVERALL TEST CIRCUIT FOR CRATER GLOW LAMPS

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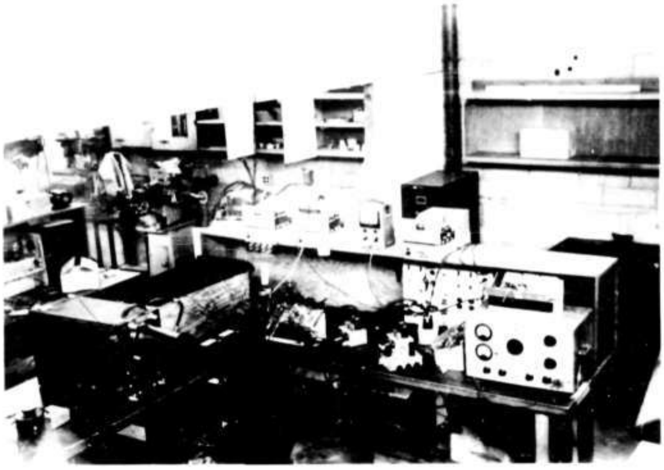


FIGURE 6. TEST BENCH

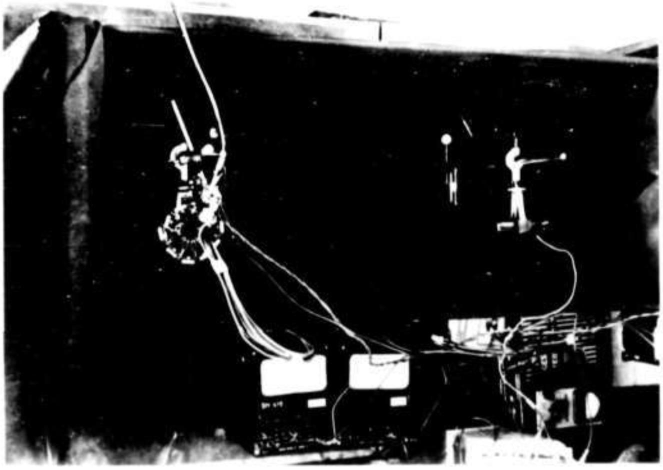


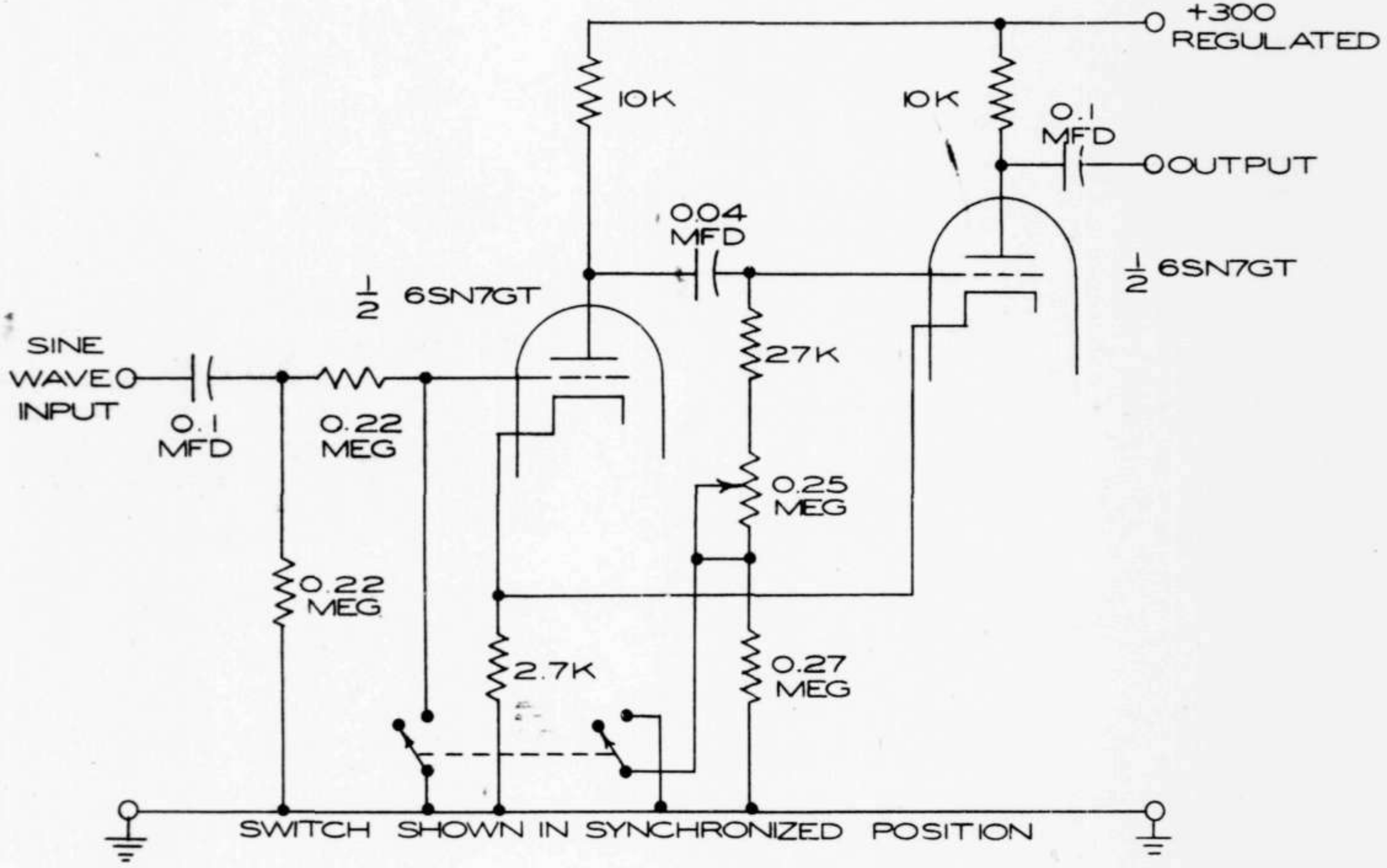
FIGURE 7. LIGHT-TIGHT BOX

end of the bench. The driven multivibration unit is built on the chassis resting on top of this. The next unit to the left is the pulse former. Resting next to this is the frequency divider unit in front of the delay box. Connected to the delay box is the pulse former. The next chassis (on the wooden stand) is the experimental modulator unit. Back of this is the power supply for the phototube. The light-tight box (with cover removed) extends from behind the synchroscope. Three power supplies are on the shelf above the bench; two others, on the shelf below it.

Figure 7 is a photograph of the interior of the light-tight box which houses the phototube (connected to the end of the cable of wires - and a cathode-follower tube on one stand and a test lamp (R1130B) on the other.

Driven or Squaring Multivibrator

The circuit diagram of this unit is given by Figure 8. Built for this application on a separate metal chassis, it gives a stable gate output over a wide range of frequencies. The first half of the 6SN7 tube is normally off; the second half, normally conducting. When the sine wave raises the grid of the first half to cut-off potential, a sudden flow of plate current through the load resistor drops the plate voltage abruptly. The drop is, of course, applied simultaneously to the grid of the second half of the tube, cutting it off. The 0.04 microfarad capacitor discharges through the grid circuit resistors (about 0.52 megohms total) until the grid voltage of the second half rises to cut-off, at which time it again conducts. When this happens, the common cathode potential momentarily rises and cuts off the first tube, restoring the original conditions. During this operation a positive voltage gate is generated at the output terminals.



SWITCH SHOWN IN SYNCHRONIZED POSITION

FIGURE 8. CIRCUIT DIAGRAM OF THE DRIVEN MULTIVIBRATOR

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Pulse Former

This unit was also designed and constructed specifically for this project. Figure 9 is the circuit diagram. The first two tubes limit and amplify the gate pulse. (Actually they were designed to square up a sine wave input, for the unit was originally designed to work without the multivibrator, but it is more stable with it.) Between the plate of the second tube and the grid of the third one is a peaking circuit that gives positive peaks at the start of the gate and negative ones at the end of the gate. Only the positive ones pass through the third tube, for the negative ones are below cut-off. Therefore, negative pulses are applied to the first 6AG7 which amplifies them and passes them on as positive triggers to the last 6AG7. This tube is connected as a cathode follower so that positive output triggers result. These triggers are used to drive both the delay box and either the pulse frequency divider or the synchroscope sweep circuit. This unit provides trigger pulses from 20 to 20,000 per second.

Pulse Frequency Divider

In use at the Servomechanisms Laboratory for another project, this circuit was easily modified so that it reduces the trigger frequency from values over 2,000 pulses per second to ones under that limit in order to drive the sweep circuit of the synchroscope. Figure 10 is the circuit diagram of the modified unit. The first tube, a 6AG7 is connected as a conventional blocking oscillator. If a trigger pulse applied to the input is effective in raising the grid of the tube to cut-off, one cycle of plate current flows which is fed back to the grid circuit causing a heavy grid current to flow and charge the 720 micromicrofarad capacitor

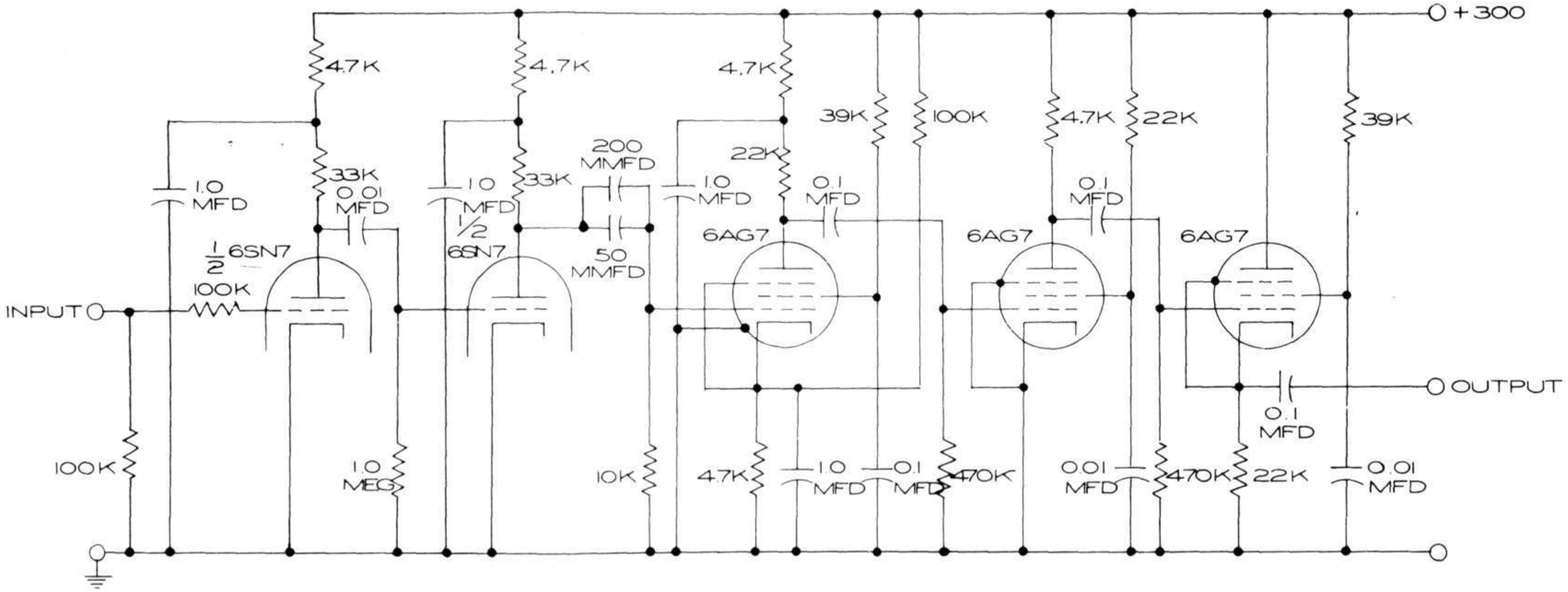

FIGURE 9. CIRCUIT DIAGRAM OF THE VARIABLE-FREQUENCY PULSE FORMER – 20 TO 20,000 TRIGGER PULSES PER SECOND

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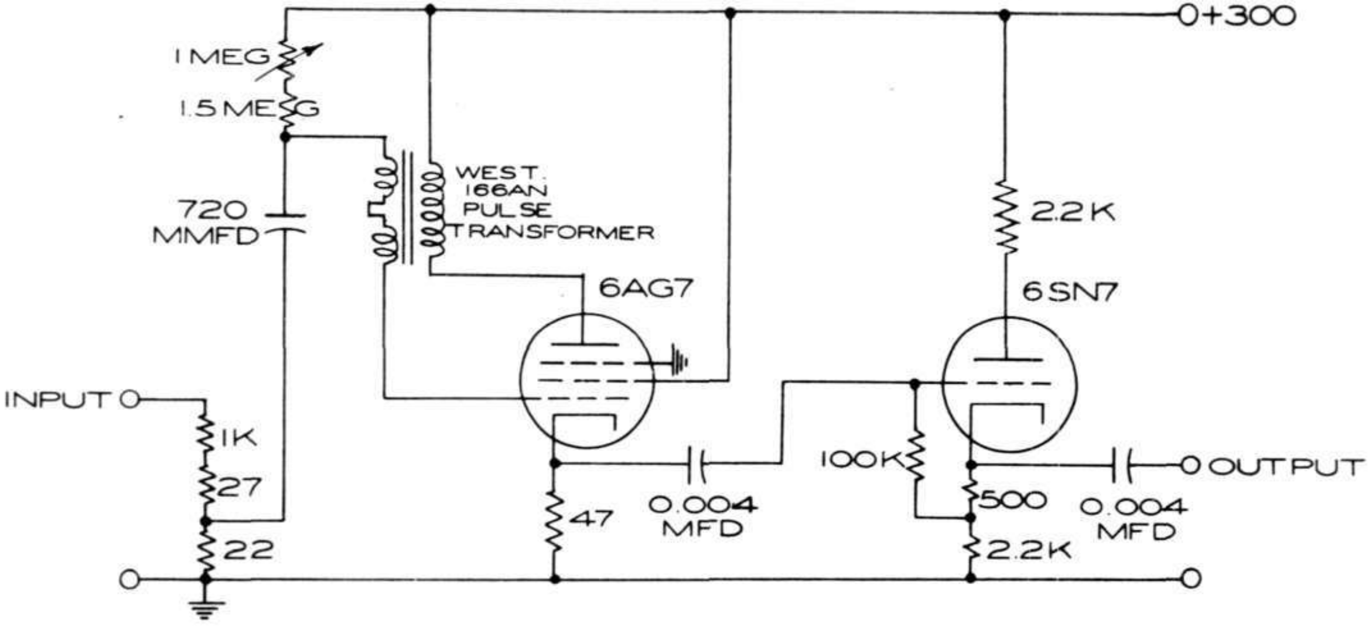

FIGURE 10. CIRCUIT DIAGRAM OF PULSE FREQUENCY DIVIDER

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to cut off the tube. The plate current flowing through the 47-ohm cathode resistor forms the output pulse which remains positive as it passes through the 6SN7 output cathode follower. The time constant of the grid circuit of the blocking oscillator, which controls the frequency division ratio, is adjustable by means of the 1 megohm rheostat.

Delay Box

This unit, whose circuit diagram is given by Figure 11 was available in the laboratory and used without modification. The voltage waveforms at important points in the circuit are given on the diagram. The output is a delayed trigger. The delay is controlled by the switch at the left as a rough control and the 1.0 megohm rheostat above it as a fine control.

Gate Generator

This is exactly the same as the delay box except for the position of the second switch. The controls mentioned above, now, obviously control the length of the output gate pulse.

6L6 Experimental Modulator

Figure 12 is the circuit diagram of the final set up of the test modulator for the crater lamps. The development of this circuit has been partially described. Additional features will now be considered.

All the current waveform is obtained as the voltage drop across a 5-ohm non-inductive resistor, one end of which is connected to the power supply. This voltage is passed through a calibrated attenuator and then to the amplifier of the synchroscope. The reason for using 5 ohms instead of the original 100 ohms is to reduce the voltage drop across it to a value small enough compared with the crater lamp voltage that it will not distort this voltage. The resistance is connected to the power supply.

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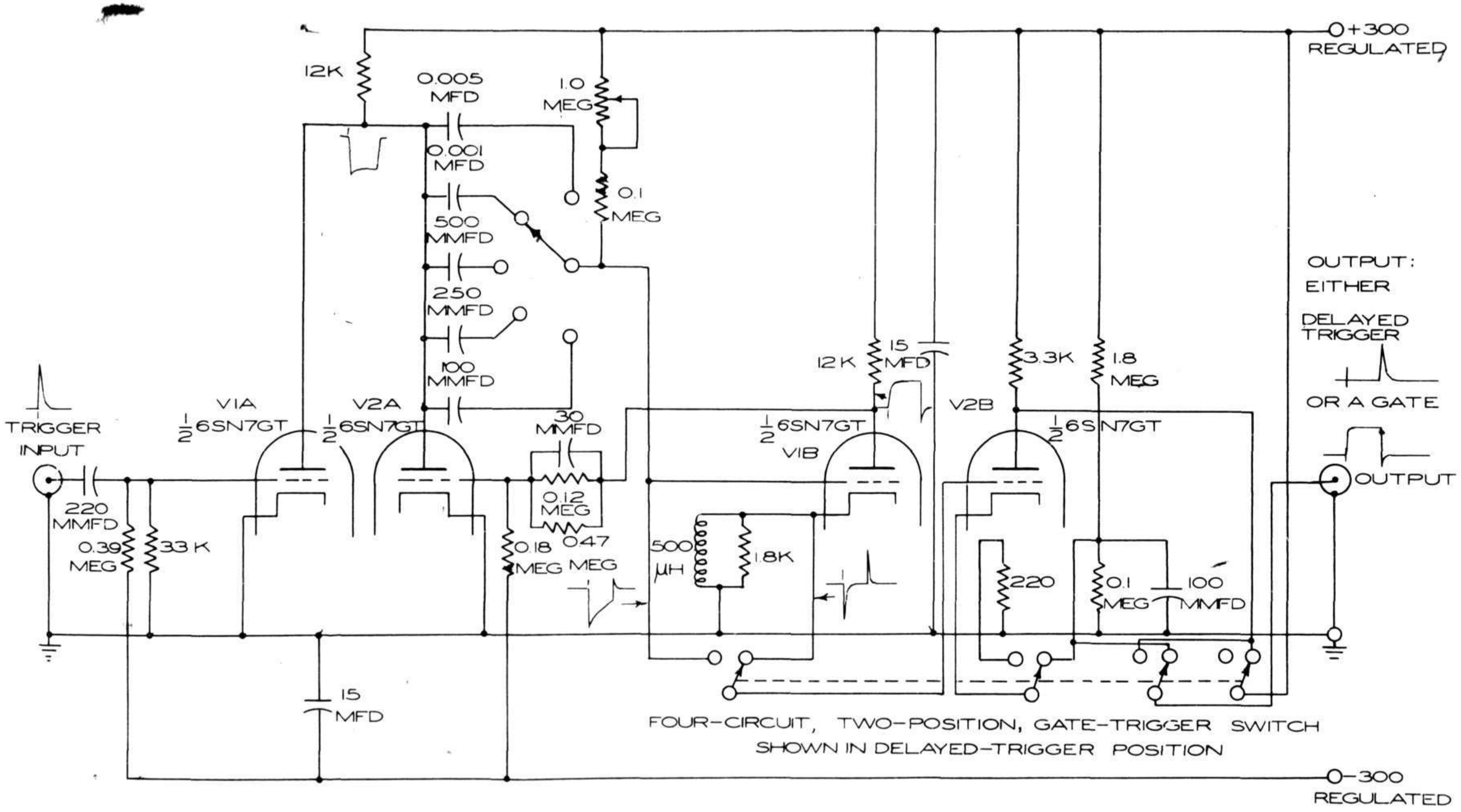

FIGURE 11. GATE GENERATOR
ALSO DELAY BOX

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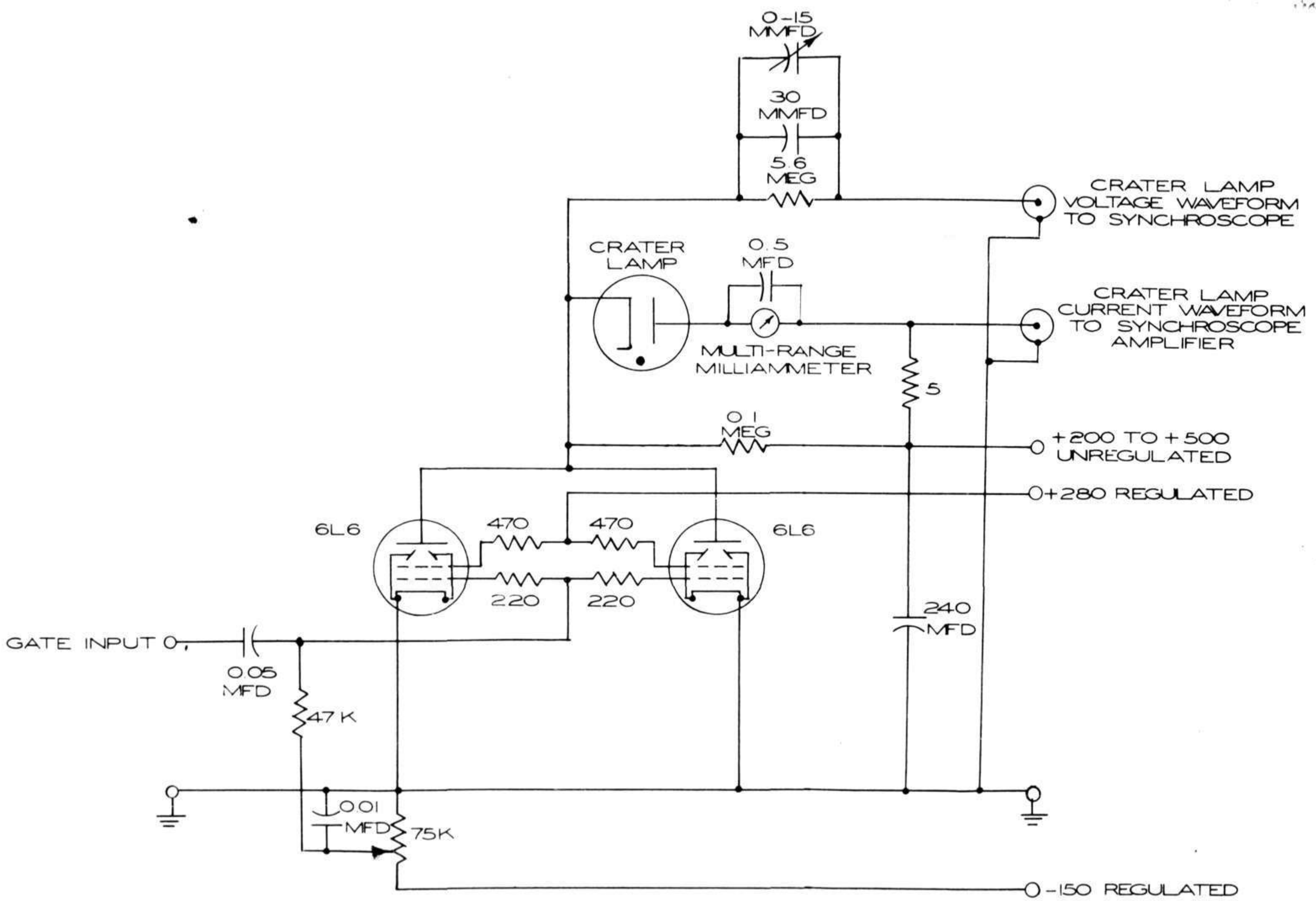

FIGURE 12. CIRCUIT DIAGRAM OF EXPERIMENTAL CRATER LAMP MODULATOR

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SERVOMECHANISMS LABORATORY
DRAWING NUMBER

rather than in the cathode leads of the 6L6's where one end of it could have been grounded, so that the current measured would be only the crater lamp current. This reduction in the size of the resistor made the ripple from the power supply relatively much larger and necessitated the connection of 240 microfarads of capacitance to ground. With this connection about 0.1 volt of ripple remained but was tolerably small.

The multirange ammeter contributes a very small direct voltage drop which is negligible. It is suitably by-passed by a 0.5 microfarad capacitor. The voltage across the crater lamp is too large to be applied to the synchroscope plates directly. To reduce it so that a reasonable deflection results, a voltage divider was contrived. This divider consists of resistance and capacitance in parallel being tuned experimentally to insure good frequency response. It should be noted that the use of this divider increases the input impedance to the synchroscope leads and, therefore, decreases the influence of this unit on the circuit. The input impedance to the cable and synchroscope is apparently 1 megohm (manufacturer's catalog) in parallel with appreciable cable and amplifier input capacitance. The 5.7 megohms was chosen to give a good division ratio and the capacitance was adjusted experimentally to preserve the shape of a waveform having many high-frequency and low-frequency components (a long, crater lamp, voltage pulse). The actual division ratio was determined experimentally from the relative sizes of this waveform on the oscilloscope screen without and with the divider in the circuit. It was 7.5/1. It is interesting to observe that between pulses the glow tube remains in a conducting circuit because of the synchroscope voltage lead. This gave much trouble until the 0.1 megohm resistor was connected across the crater lamp, acting as one element in a voltage divider. This resistance is large enough to have a negligible effect on the operation of the crater lamp during the pulse; yet small enough to short out the lamp during the rest of the cycle.

931-A Multiplier Phototube Circuit

The reasons why the multiplier phototube was chosen as the basic component of the light-measuring device have already been presented. Figure 13, is the circuit diagram of the final arrangement of the circuit, including a cathode follower stage. The 931-A is a high-vacuum multiplier phototube in which the photocurrent produced at the light-sensitive cathode is multiplied many times by secondary emission occurring at the dynodes. The output current is a linear function of the incident light under normal operating conditions. These do not include the conditions of operation during this research. The linearity, theoretically proven, was experimentally checked at several reduced dynode potentials by taking runs of output current at various intensities of exciting illumination. The results of one of these runs is presented as Figure 14. There was also a question that the dynode signal currents which flow in the bleeder resistors of the power supply possibly upset the voltage division per dynode stage enough to affect the gain of the tube and, therefore, its linearity. Calculations, however, indicated that with the present 10,000-ohm resistors across the dynodes the overall change in gain from zero to

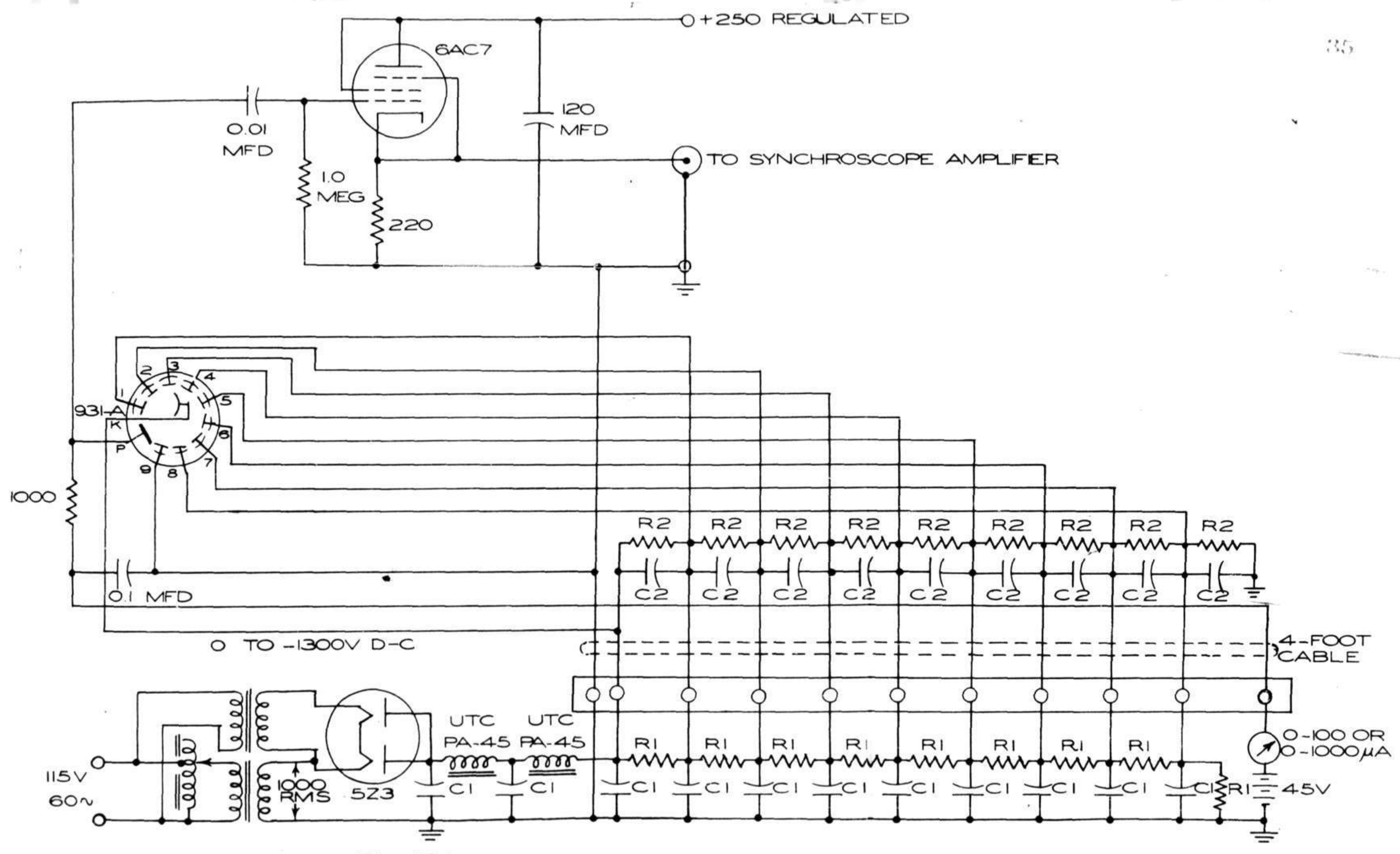

FIGURE 13. CIRCUIT DIAGRAM OF 931-A MULTIPLIER PHOTOTUBE AND 6AC7 CATHODE FOLLOWER

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SERVOMECHANISMS LABORATORY
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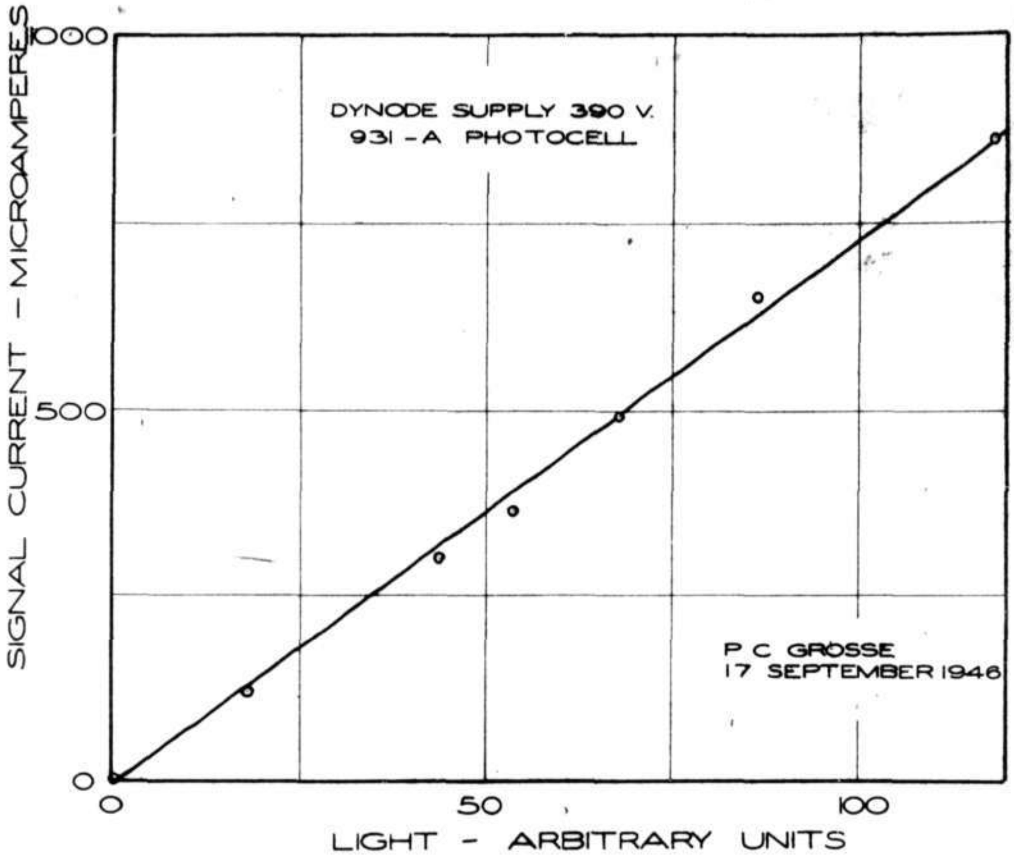

DYNODE SUPPLY 390 V.
931-A PHOTOCELL

P C GROSSE
17 SEPTEMBER 1946

FIGURE 14. EXPERMENTAL CHECK OF PHOTOCELL LINEARITY

nected by means of a four-foot-long bundle of cables to the power supply at which point each is by-passed to the negative side of the power supply by a 1 microfarad high-voltage capacitor. Voltage division between the 9 dynodes was accomplished by connecting them to taps of a series of nine 47,000 ohm resistors connected across the power supply. This circuit was in existence at the start of the research. The author was not entirely satisfied that the impedance of the four-foot-long cable was not affecting the high-frequency response, especially after an unexplained time delay of about 1/2 microsecond was observed between the start of the current through the crater lamp and the start of the light output. The dynodes were then by-passed with 10,000-ohm resistors across each of them as shown in Figure 13. Observation of the waveforms afterward showed no apparent change. It was then concluded that any multiple time delay introduced by the cable impedances is negligible at the frequencies involved in the waveforms. The 10,000-ohm resistors were matched by use of an ohmmeter to within two per cent. The fact that these 10,000-ohm resistors are much smaller in resistance than the original 47,000-ohm resistors, which were left in place, makes them the determining factor in the voltage distribution among the dynodes. The 47,000-ohm resistors had not been so closely matched and therefore a more uniform voltage distribution per stage was probably achieved. This condition results in more perfect focusing fields within the multiplier and greater overall gain. A recalibration of the circuit showed that the gain had increased in a ratio of 1.3/1 at all values of dynode voltage. It is an interesting and convenient coincidence that the overall gain of the circuit was exactly the same after as it was before the 10,000-ohm resistors and the cathode follower were added.

After all doubt has been removed that the dynodes hold constant voltage during the pulse, the only other cause of poor frequency response is the time constant of the plate circuit of the tube. It should, however, be mentioned that there is no measurable time lag in the process of secondary emission of the dynode surface[1], and that rough calculations show that the transit time through the tube by the electrons is only a few hundredths of a microsecond even with much lower voltages on the dynodes than used in this research. The original circuit employed a 6,800-ohm load resistor coupled by a cable two feet long into the amplifier of the synchroscope. The distributed capacitance associated with the output resistor alone has been measured by the original designer of the circuit and found to be 12 micromicrofarads. The cable adds another 26 micromicrofarads and the input to the synchroscope, another 20 micromicrofarads. This makes a time constant of 0.4 microseconds and leads to a rise time (time from the start of a step to nearly constant conditions obtained) of about $2\pi \times 0.4 = 2.5$ microseconds. The preliminary waveforms were taken with this circuit. Later, a 1000-ohm resistor was used instead of the 6,800-ohm resistor. Following the above reasoning, this change would reduce the rise time to 0.4 microseconds and the time constant to about 0.06 microseconds.

From Fourier analysis considerations it can be shown[2] that the pulse rise time, as previously defined, is approximately inversely proportional to the upper half-power point of the sinusoidal frequency

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1. M.A. Pomerantz, "Secondary Emission From Oxide-coated Cathodes", J.F.I., 61 (July, 1946) 44-61.
2. See Principles of Radar, Staff, M.I.T. Radar School, The Technology Press, 1944, 4-16.

response of the circuit. The sinusoidal responses of several output circuits were measured by inserting a low resistance (70 ohms) in series with the load resistance of the 931-A phototube between it and the filtered 50-volt battery connection (see Figure 13). A model LP-5, Radio-Frequency Standard Signal Generator, excited this resistor at a 1 volt potential over a wide range of frequencies. Response was measured by the size of the trace on the oscilloscope screen. The LP-5 was duly checked with a radio-frequency vacuum-tube voltmeter and found to have a voltage output flat to beyond 10 megacycles per second. The results, Figure 15, give the upper half-power frequency of 2.1 megacycles per second for the condition of no cathode follower and revised output circuit (1000-ohm load resistor). This figure indicates a rise time of 0.48 microseconds and a time constant of 0.077 microseconds. It should be noted that this was taken after the 10,000-ohm resistors and the 100-micromicrofarad capacitors had been soldered in place at the base of the tube. This small added capacitance probably accounts for the trifling difference in rise times. The use of the cathode follower increases the upper half-power frequency to 6.2 megacycles per second. This means a rise time of 0.16 microseconds and a time constant of 0.025 microseconds.

A comparison of pictures taken with the 1,000-ohm resistor and with the original circuit shows no detectible differences. This seems reasonable since the time constant of the light waveforms observed are of the order of whole microseconds. It may now be concluded that the original circuit was adequate for the purpose.

An additional check on the validity of the above analysis is

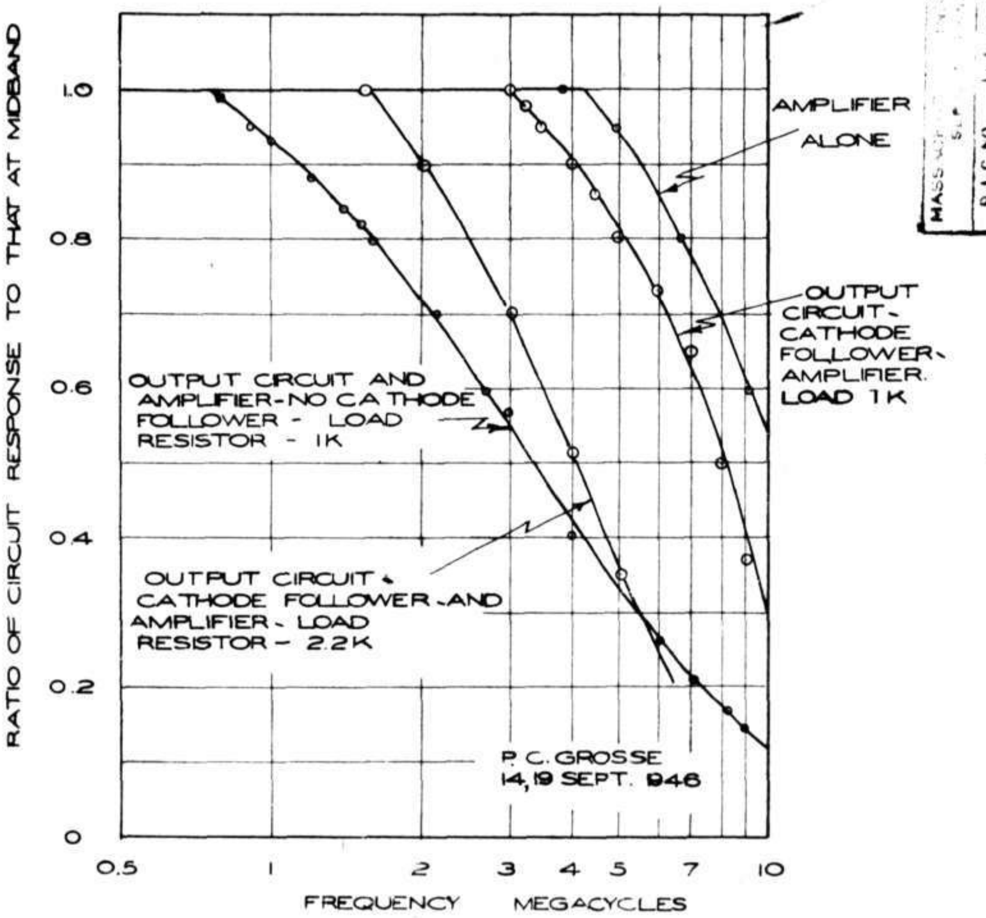
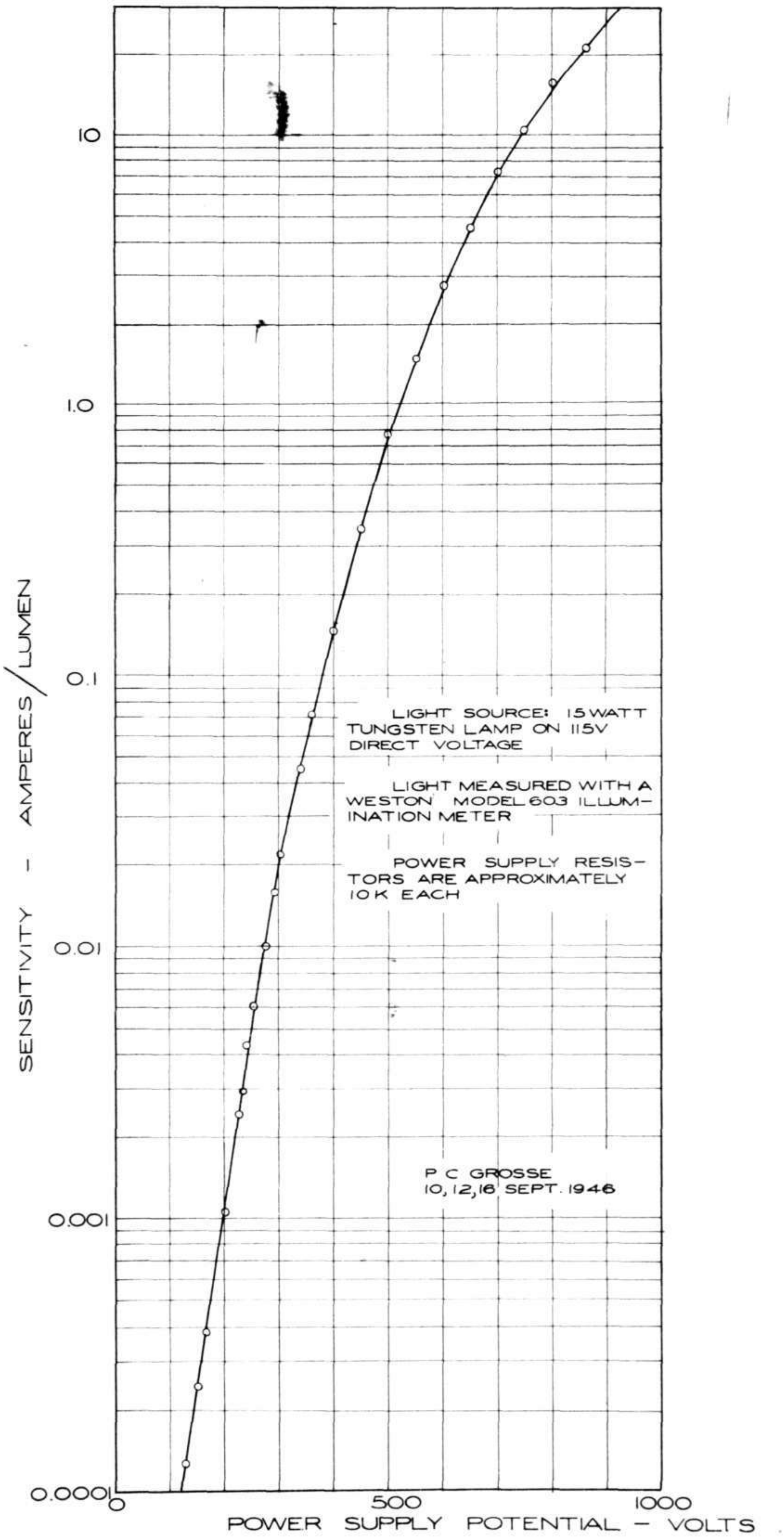


FIGURE 15. MEASURED FREQUENCY RESPONSES OF SEVERAL OUTPUT CIRCUIT ARRANGEMENTS OF THE RCA 931-A PHOTOCELL

given by the frequency response of the amplifier alone and its response to a suddenly applied fast-rising pulse. The upper half-power frequency for the amplifier alone is 7.8 megacycles per second. This indicates a rise time of 0.128 microseconds. This was roughly checked by noting that the response of the amplifier to pulses from the Forbes-Dano Pulse Generator was at least this good. The type of analysis given applies strictly to circuits having a single time delay; however, it is used here as a good approximation.

Calibration of the Light-Measuring Circuit

Figure 16 is the sensitivity characteristic of the 931-A multiplier photocell. It gives the ratio of output current to light energy incident on the cathode as a function of the dynode supply voltage. This characteristic was much used in the calculations, for the gain of the unit was adjusted to get optimum screen size for each waveform. It can be noted that the calibrating light source was a new 15-watt tungsten lamp operated on 115 volts direct potential at all times. The voltage was not changed as that procedure would alter the spectral distribution of the light energy coming from the lamp. Direct voltage was used to avoid a 120-cycle ripple in the light. The intensity of the light was varied by changing the distance to the lamp and was determined from the reading of a Weston, Model 603, Illumination Meter, the probe of which was placed very close to the 931-A window. The 15-watt lamp was at all times far enough from the tube to make the intensity distribution there uniform. For several distances, the supply voltage was varied in steps and this voltage (read from a 0-1000 voltmeter) and the 931-A output current (read from the 0-1000 microampere ammeter permanently connected in the circuit) were recorded. The readings of the illumination meter



LIGHT SOURCE: 15 WATT TUNGSTEN LAMP ON 115V DIRECT VOLTAGE

LIGHT MEASURED WITH A WESTON MODEL 603 ILLUMINATION METER

POWER SUPPLY RESISTORS ARE APPROXIMATELY 10K EACH

P C GROSSE
10, 12, 16 SEPT. 1946

FIGURE 16. D-C SENSITIVITY CHARACTERISTIC OF THE RCA 931-A MULTIPLIER PHOTOTUBE

were in units of lumens per square meter. The manufacturer of the 931-A gives the cathode area as 0.29 square inches. It was then a simple matter to compute the number of amperes per lumen for each setting of the variac. The results were presented as Figure 12. This curve was checked on several occasions to gain assurance that the sensitivity of the tube had not changed because of inadvertent overloading.

Light Waveform Calibration

The dynode supply potential was read and recorded in the research notebook for each frame of film on which a light waveform was taken. This information and the calibration curve, Figure 12, allows a determination of the 931-A sensitivity for that particular frame, i.e., X amperes per lumen. The gain of the cathode follower as measured over wide ranges of power supply voltage was constant at 0.75. The sensitivity of the synchroscope, including the amplifier, was measured as 0.67 volts per inch deflection. The output load resistor of the 931-A phototube was 1000 ohms (measured by an ohmmeter). There are ten grid divisions per inch. The standard distance to the test lamp from the phototube was 19 inches. These data can now be combined to obtain a very convenient calibration constant as follows:

$$\frac{0.67 \times 144 \times (19)^2}{1000 \times 0.75 \times X \times (12)^2 \times 0.29} = \frac{0.111}{X} \text{ candle power per grid division.}$$

The above figure was easily used in calibrating the many waveforms photographed. It is emphasized that the candle power mentioned is that in the direction of the phototube.

Precision of Data Taken by Light Measuring Circuit

The usual sources of error enter directly in the above constant.

The 1000 ohms was measured with an ohmmeter and is good to ±1 per cent. The gain of the cathode follower was measured by a comparison method and is good to ±2 per cent. The 0.67 volts per inch involved a meter reading and measurement of deflection on a grid covering the screen; it is perhaps good to ±2 per cent. The size of the cathode area enters both the calculation of the above constant and the determination of the calibration curve and is therefore irrelevant. But, the determination of X involves the reading of the power supply voltage by means of a 0-1000 voltmeter and entering a curve with this reading. If the accuracy of the meter is ±1 per cent, there is an uncertainty of ±10 volts. Add to this the inability of the observer to read the scale to better than 2 volts; and, if the same meter is not used at all times, an uncertainty of ±12 volts results. The sensitivity changes 2.8 per cent per volt in the working range (Figure 16) so that a precision of only ±34 per cent is obtained in finding the value of X. If, however, the same voltmeter used to obtain the calibration curve is permanently assigned to finding the dynode supply voltage, then the precision in finding the value of X is about ±8 per cent, and the above variable constant is good to within ±11 per cent. To this must be added errors in taking data from the waveforms which are estimated to vary from about 5 per cent for large deflections to much higher values for the smaller deflections. Any small error in reading the voltage of the dynodes, however, is always a serious one.

Photographic Technique - Date Taking

Originally the method of recording of waveforms in use in the laboratory was that of painstakingly drawing a reproduction of the pattern of the screen. This proved too inefficient a method to use in recording the hundreds of waveforms involved in this research, and some thought was given to devising an improved technique. The obvious answer was photography of the synchroscope screen.

At first, the screen photographs were made without the benefit of grids or using a black grid on transparent plastic. However, during the course of the research, a grid was constructed by the laboratory consisting of lines scratched with an awl on a piece of lucite. This was illuminated by incandescent lamps through its edges and gave excellent service in the recording of the waveforms in this research.

The camera unit used is a 35 millimeter, f 3.5 Argus, Model C3, mounted in an adapter which fitted over the face of the cathode-ray tube. Provision was made for illuminating a card inside the adapter so that an identifying serial number could be photographed on each frame, together with another card with the author's name, notebook page, and the date. It was found that the lens was not sufficiently fast to record single sweeps at the trace speeds used, even though the fastest film available, Eastman Super-XX and the Agfa equivalent was used and the negatives were developed in process developer for maximum contrast. Much work was then originated by members of the Servomechanisms Laboratory staff toward improving the photographic equipment of the laboratory to allow the recording of single traces at speeds of inches per microsecond. The results of this work were not available at the time that the experimental part of this research was completed.

The method of obtaining data from the waveform negatives for use in the computations is of interest. It was clearly out of the question economically to make enlarged prints of the hundreds of waveforms needed to obtain the data for the curves. As an alternative method, it was suggested that the negatives be projected by means of a small microfilm unit and the data read from the projection. This was tried, but it was found that the job of reading the data from the projected negatives is an extremely slow one - one clearly not applicable to a large number of negatives. It was then that the author hit upon the method of recording the waveforms on sheets of tracing paper by inking in the projected waveforms. A typical worksheet illustrating this technique is presented as Figure 17. The enlarged grid is not traced, for all the waveforms are enlarged to the same degree. The two crosses on the sheet are benchmarks recorded to allow the placing of several related waveforms on the same sheet in nearly perfect register. The tracing is easily and accurately done and the tedious, painstaking job of obtaining data is performed later with much less strain by placing the transparent worksheet over a ruled grid.

Photographs of the synchroscope screen for the same three waveforms of the worksheet are presented as Figures 18, 19, and 20.

CLASSIFICATIONS
1. RUN ON AVERAGE CURRENT, 1.5MA.
2. RUN ON PULSE LENGTH, 5μS.
3. RUN ON FREQUENCY, 400 CPS.

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APP. | A-30230

R1130B
NEW TUBE
19 SEPT. 1946, 1-PCG-104
#7, 8, 9 (FRAMES)
400 CPS, 5μS, 6L6'S ON 450V
DYNODES ON 350V
CURRENT ATTENUATOR ON 10

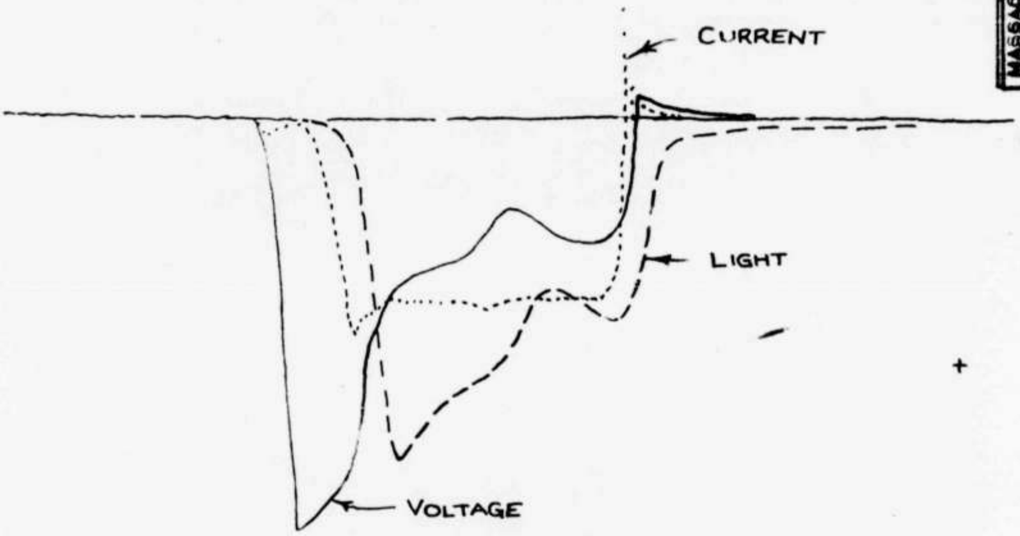

FIGURE 17. A WORKSHEET TYPICAL OF THOSE USED FOR MAKING WAVEFORM DATA FROM PHOTOGRAPHIC NEGATIVES AVAILABLE ECONOMICALLY FOR COMPUTATIONAL PURPOSES

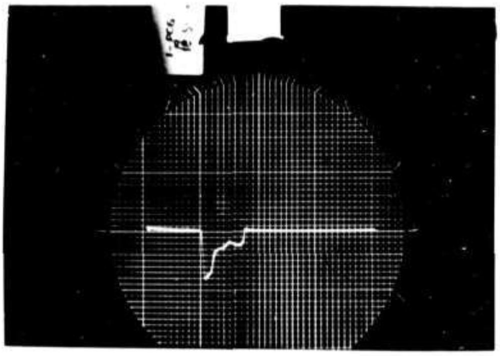

FIGURE 18. R1130B CRATER LAMP
VOLTAGE WAVEFORM DURING 5 MICROSECOND
PULSES AT 400 PULSES PER SECOND

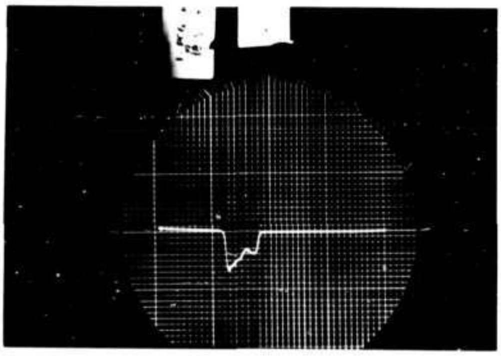

FIGURE 19 R1130B CRATER LAMP
LIGHT WAVEFORM DURING 5 MICROSECOND
PULSES AT 400 PULSES PER SECOND

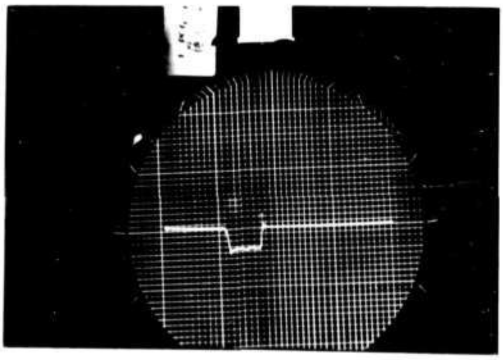

FIGURE 20 R1130B CRATER LAMP
CURRENT WAVEFORM DURING 5 MICROSECOND
PULSES AT 400 PULSES PER SECOND

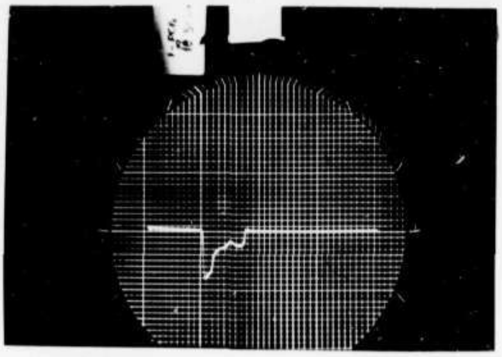

FIGURE 18. R1130B CRATER LAMP
VOLTAGE WAVEFORM DURING 5 MICROSECOND
PULSES AT 400 PULSES PER SECOND

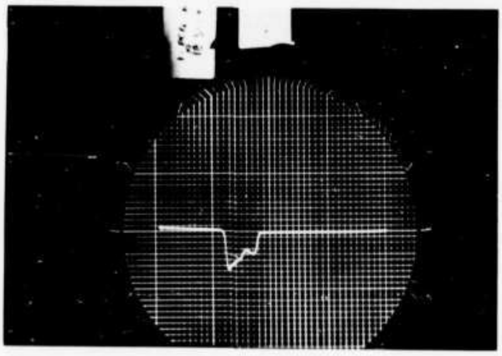

FIGURE 19. R1130B CRATER LAMP
LIGHT WAVEFORM DURING 5 MICROSECOND
PULSES AT 400 PULSES PER SECOND

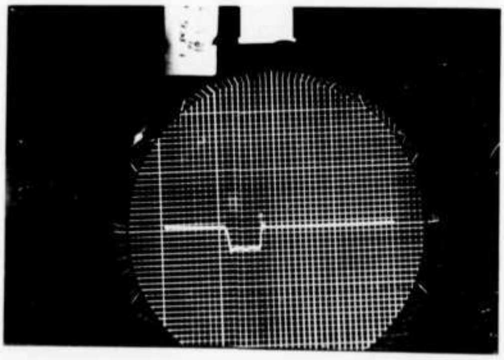

FIGURE 20. R1130B CRATER LAMP
CURRENT WAVEFORM DURING 5 MICROSECOND
PULSES AT 400 PULSES PER SECOND

CHAPTER FOUR

CRATER GLOW TUBES

This chapter will present the results of the investigation of the abilities of the commercial crater lamps studied to meet the requirements of the project. An understanding of these results must rest on a knowledge of the mechanism of the glow discharge.

The Glow Discharge [1,2,3]

The theory of the steady-state glow discharge is presented in numerous texts. A glow discharge is a self-maintaining conduction of electricity through a gas characterized by a high fall in potential between the cathode and a cloud of positive ions gathered a short distance from it. The size of this fall in potential is a function of the gas in the tube and of the material of the cathode, and is many times the ionization voltage of the gas. It makes up the larger part of the tube voltage drop, the remainder being across a region of low potential gradient and small net charge called the positive column. The region of the cathode fall is frequently composed of a series of relatively light and dark regions called the Aston dark space, the cathode glow, the Crookes dark space, the negative glow, and the Faraday dark space. The positive column is usually softly luminous.

When the current is small, the discharge concentrates on a part of

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1. Applied Electronics, E.E. Staff, M.I.T., John Wiley, New York, 1943, CH III.

2. Reich, H.J., Theory and Applications of Electron Tubes, Ed. II, McGraw-Hill, New York, 1944, Ch. III.

3. Loeb, L.B., Fundamental Processes of Electrical Discharges in Gases. John Wiley, New York, 1939, 408-595.

the cathode and the tube voltage drop varies little with the current. A discharge under these conditions is termed a normal glow. The cathode area covered increases with the current until the cathode is blanketed and then the current density and the tube voltage must increase with the current. In this region, called an abnormal glow, the total voltage drop rises appreciably. As the current is further increased, the cathode current density increases and considerable heating of the cathode from positive ion bombardment results. Suddenly the voltage across the tube decreases to a much lower value (of the order of the ionizing potential of the gas), the current concentrates on a small spot on the cathode, and an arc occurs. In this discharge the cathode is subject to intense heating and violent sputtering.

There exists a time lag following the application of voltage to a tube and the formation of a glow discharge. This time lag decreases with increased applied voltage and with an increase in any residual ionization which may be present in the tube. It results partially from the time necessary for a heavy positive ion to move to the cathode and to gain the energy necessary to produce ionization by collision.

The light produced by a glow discharge is thought to result from the release of photons of light energy from atoms of the gas 10^{-8} seconds[1] after they have absorbed a quantums of energy from bombarding particles in a process called excitation.

The Crater Glow Tube

The crater tube is one of many different designs of glow tubes. It is characterized by a solid, axial, cylindrical cathode with a cone-shaped

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1. Applied Electronics, 137

depression in the outer end. This electrode is purposely massive to dissipate heat and to impede the formation of arc discharges. Separated by mica insulation from this cathode is a thin cylindrical anode. When the tube is energized, a glow discharge takes place between the cone-shaped crater and the outer surface of the anode. This design results in a high current density at the center of the crater and a bright, concentrated negative glow. The current density in the positive column is too low to produce much light under ordinary operating conditions; although when the tube is pulsed at 20 times normal operating current the glow was observed to spread. During a glow discharge there is an appreciable amount of material sputtered from the cathode onto the walls of the tube, where it forms, in time, an opaque coating. To lengthen the useful life of the tube two mica sputter shields are placed between the cathode and the end of the tube. These act as cool surfaces upon which the sputtered material may condense; although small, centrally located holes allow an unimpeded passage of a small cone of light. The measured beam angle of this cone is 26°. This small beam angle is a decided disadvantage in the design of a projector using the crater lamp as a light source. The necessity of the sputter shields, however, was demonstrated by the blackening of the ends of the test lamps. These lamps were operated at high current densities and inadvertently, at times, with arc discharges of several amperes. The rate at which the deposit built up was not investigated under controlled conditions.

Static Characteristics

The static characteristics of the two types of crater lamps studied are presented in Figure 21. These experimentally determined characteristics are carried to, but not beyond, the point where the discharge became an arc. They show clearly that the tubes normally operate in what is called an abnormal glow region.

As far as could be determined from a survey of the literature, radar pulse techniques have not previously been applied to the study of glow discharges. In this investigation the tubes were energized in short pulses at low duty cycles that permitted large instantaneous current densities, while operating the tube in an extension of the abnormal glow region. The experimental results seem to indicate that after a transient period of a few microseconds the tube voltages settle down at values on extensions of the static characteristics.

Transition to Arc

Many times during the investigation when the tube was being operated at unusually high duty cycles the formation of an arc discharge was noted. This was characterized by a great increase in the intensity of the light. by a substantial drop in the pulse voltage, and by a great increase in current (theoretically limited to the emission current of the filaments of the two 6L6 modulator tubes). Sometimes the voltage waveform on the screen of the synchroscope indicated that the tube was continually changing from glow to arc. After a tube had been allowed to arc it became very hot and would operate on glow discharge only with unusually low currents. The exact point at which arcing occurs depends on many factors, most important among them the ability of the cathode to dissipate heat. It is thought that the tubes studied can be operated at much higher peak currents than the 500 milliampere limit imposed by the experimental modulator if the

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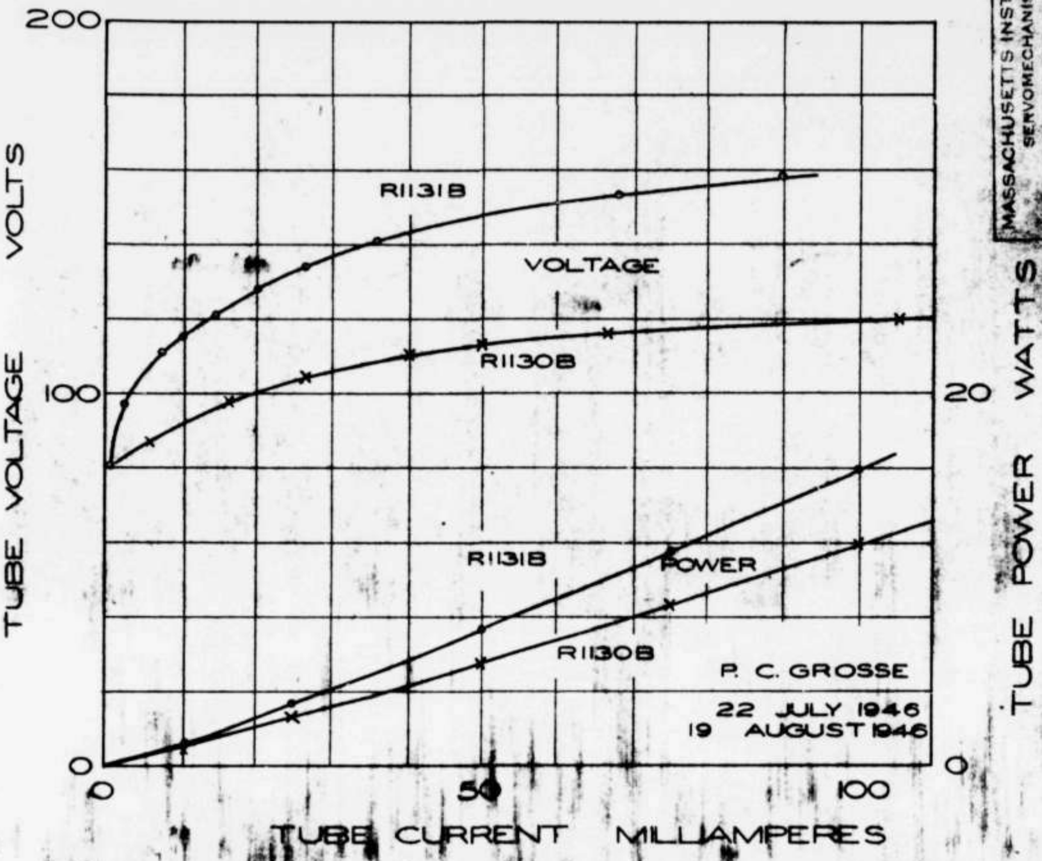

FIGURE 21. STATIC CHARACTERISTICS OF
SYLVANIA CRATER LAMPS
R1130B & R1131B

pulse length is made shorter. This increase of current is desirable, for the light output of the tube increases exponentially with this current.[1]

Conditions of the Test

In order to make a thorough study of the crater lamps, it was desired to determine the effects of each of the following variables on the operation of the tubes:

1) Power-supply potential
2) Tube current
3) Frequency
4) Pulse length

Four sets of runs were planned. In each run of a set, one of the above was varied over a wide range while the others were maintained constant. For example, one run of the set investigating the effects of frequency involved five frequencies between 0 and 20,000 pulses per second while the power-supply potential was held at 450 volts, the pulse current at 500 milliamperes and the pulse length at 5 microseconds. Each reading was made by photographing three waveforms: voltage, current, and light.

Results

Unfortunately, available time has limited the number of waveforms reproduced in this report to a few for each of the three types of tubes tested. Figures 22 through 26 present typical waveforms. These figures also present the calculated quantities of resistance and efficiency during the pulses. The resitance is defined as the ratio of instantaneous voltage to instantaneous current, and the efficiency is defined as the ratio of instantaneous light to instantaneous power. These quantities are of special

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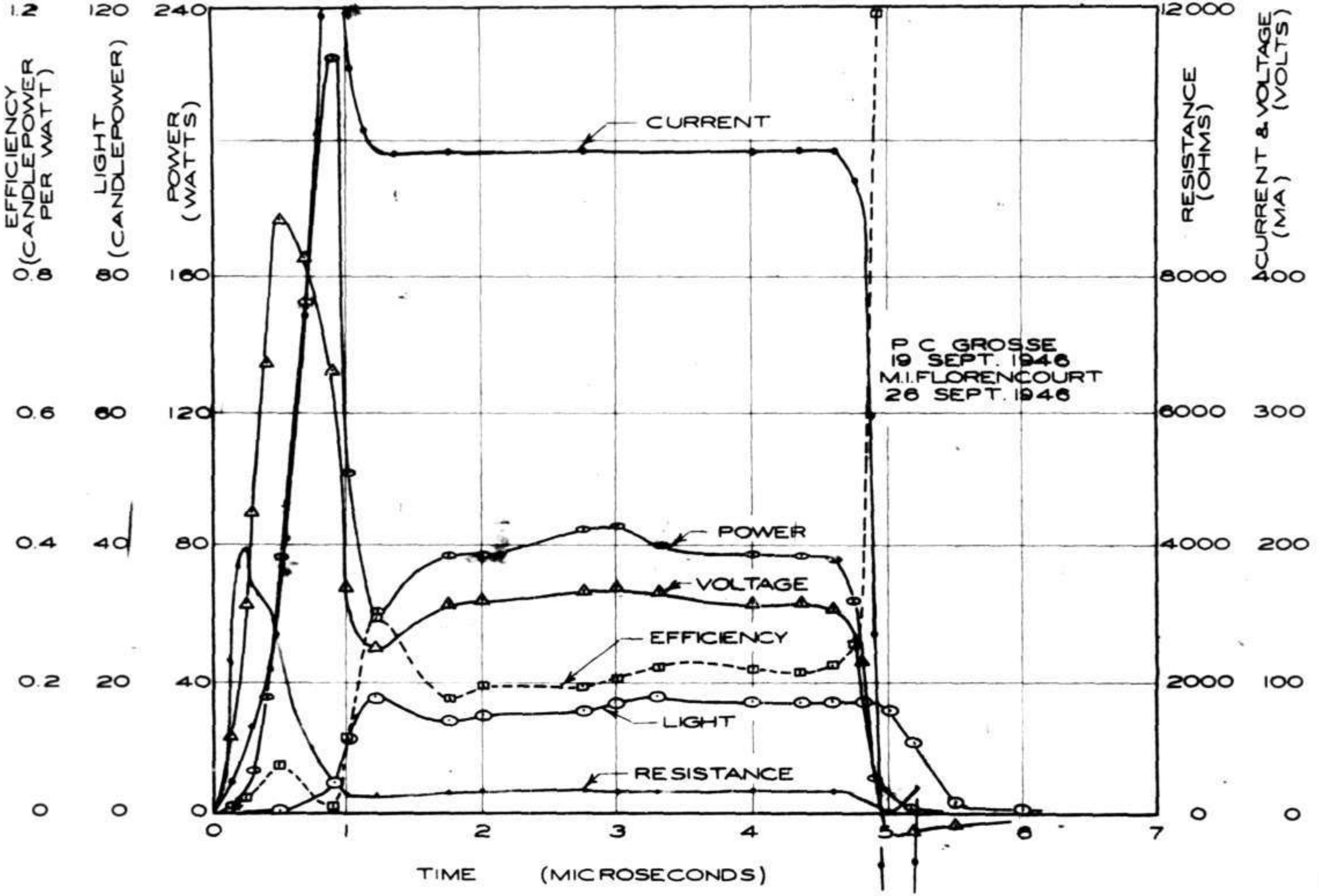
1. See Figure 36.



P C GROSSE
19 SEPT. 1946
M.I. FLORENCOURT
26 SEPT. 1946

FIGURE 22. R1130B CRATER TUBE WAVEFORMS DURING 5 MICROSECOND PULSES AT 10,000 PER SECOND REPETITION RATE WITH POWER SUPPLY POTENTIAL OF 470 VOLTS

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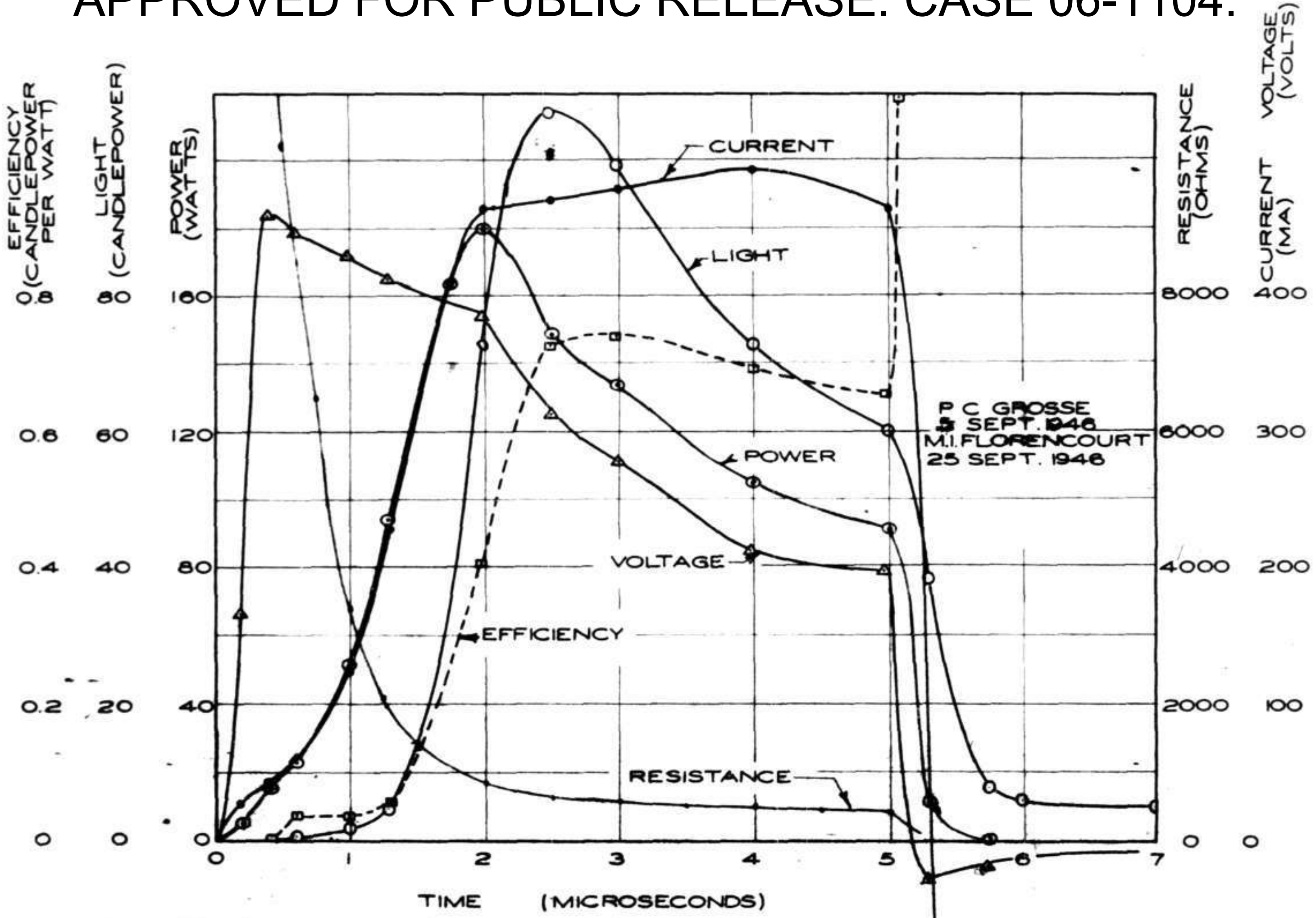

P C GROSSE
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25 SEPT. 1946

FIGURE 24. R1131B CRATER TUBE WAVEFORMS DURING 5 MICROSECOND PULSES AT 20,000 PER SECOND REPETITION RATE WITH POWER SUPPLY POTENTIAL OF 450 VOLTS

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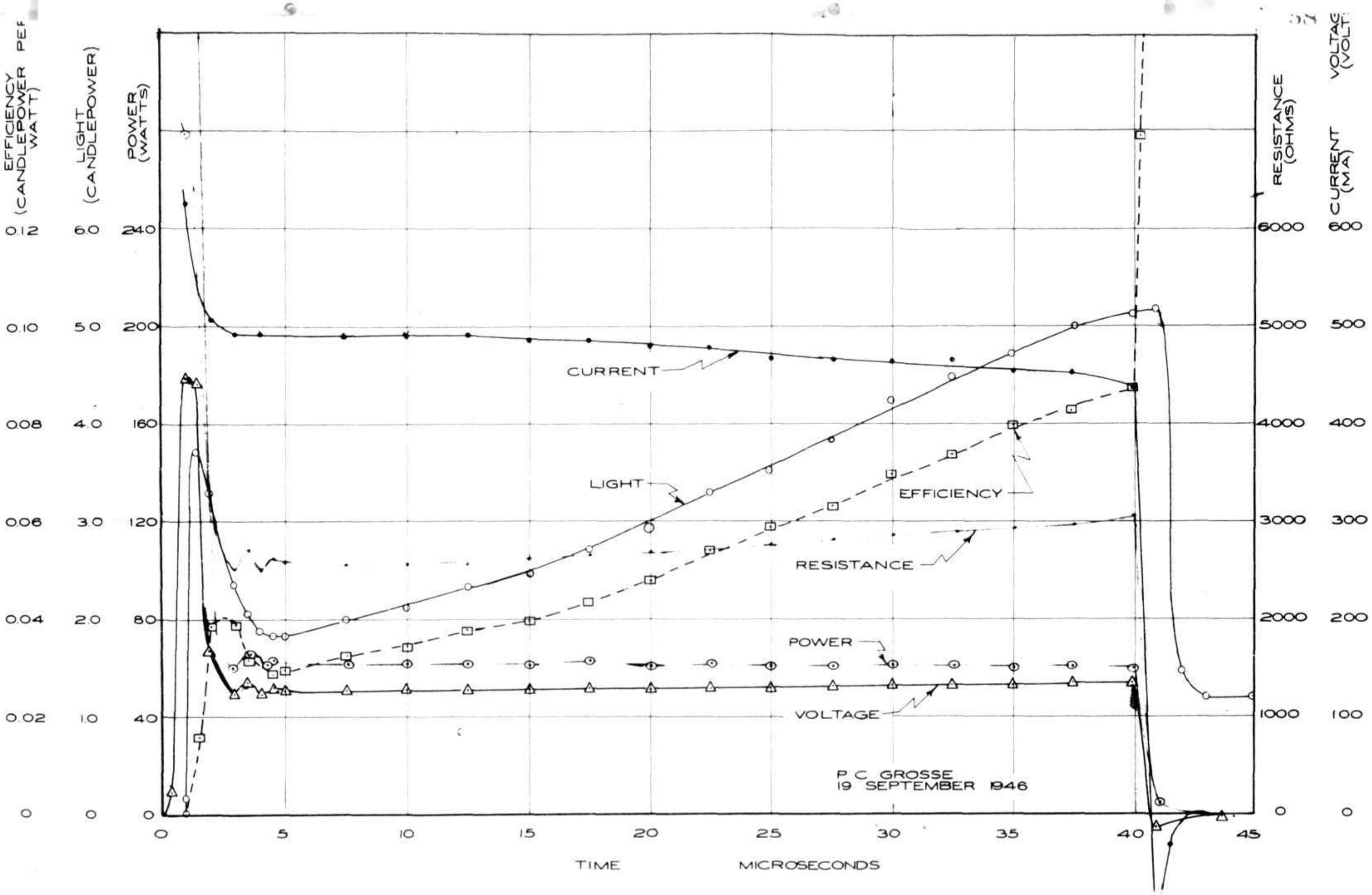

P. C. GROSSE
19 SEPTEMBER 1946

FIGURE 23. R1130B
CRATER TUBE WAVEFORMS
DURING 40 MICROSECOND
PULSES AT 400 PER SECOND
REPETITION RATE

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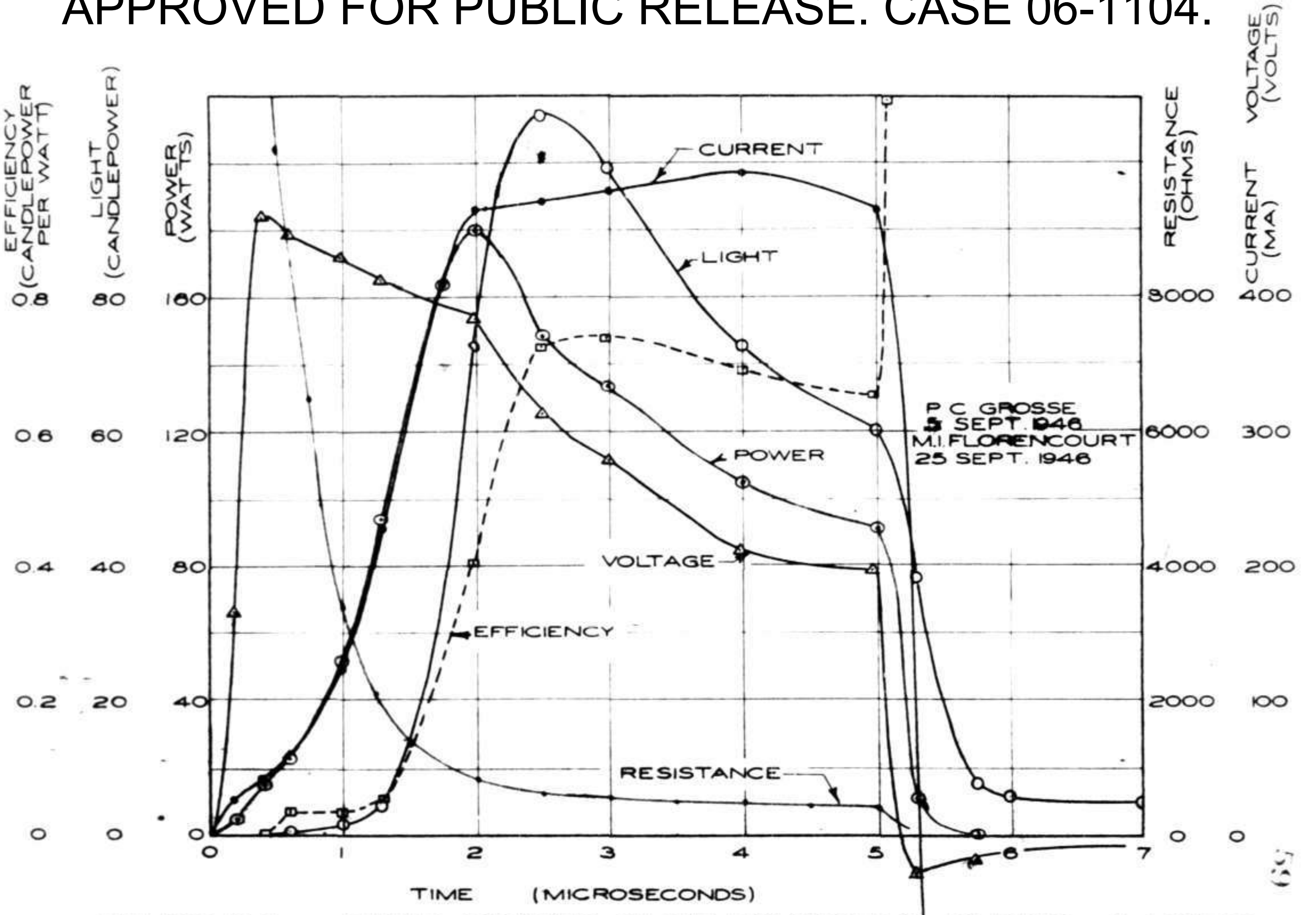

P C GROSSE
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25 SEPT. 1946

FIGURE 24. R1131B CRATER TUBE WAVEFORMS DURING 5 MICROSECOND PULSES AT 20,000 PER SECOND REPETITION RATE WITH POWER SUPPLY POTENTIAL OF 450 VOLTS

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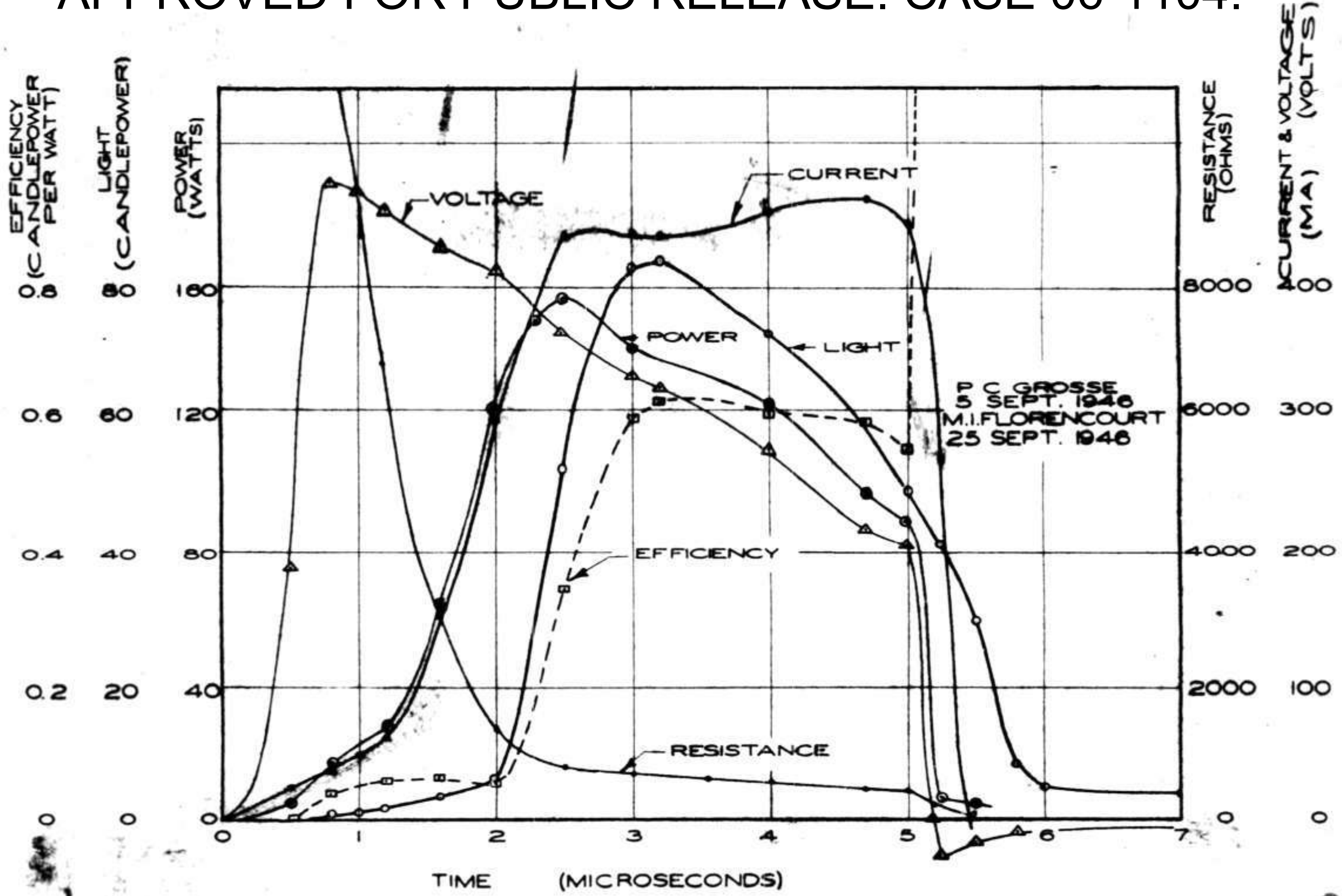

FIGURE 25. R1131B CRATER TUBE WAVEFORMS DURING 5 MICRO-SECOND PULSES AT 2000 PER SECOND REPETITION RATE WITH POWER SUPPLY POTENTIAL OF 450 VOLTS

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DRAWING NUMBER A-30236

interest.

Ignition time

The effect of increasing the supply voltage is not shown by the waveforms reproduced in this report. These were all taken at maximum supply potential. It was observed that as the potential is increased, the time constants of the build-up of tube current and light output decrease materially. For example, an increase of the supply potential from 300 volts to 400 volts decreases the time delay before maximum current is reached by about 1 microsecond.

A comparison of Figure 24 and Figure 25 indicates that at 20,000 pulses per second there is about a 1/2 microsecond decrease in the time delay before maximum current is reached over that at 2,000 cycles per second. This is explained by greater residual ionization at the higher frequendy.

Figure 30 shows that the pulse resistance is less at the beginnings of the pulses at the higher frequencies. Since the inverse of this quantity is a measure of the effectiveness of a voltage in producing current, it also illustrates the effect of residual ionization.

Figure 33 shows clearly the fact that an increase of pulse current at a constant frequency decreases the time required for the resistance to settle to a steady value. It is proposed that the assumption of a steady value by the instantaneous resistance is an indication that transient conditions are over and the tube is operating in the conventional manner of a steady-state glow discharge.

Light Output

It is a curious fact that the light output of the crater lamps increases slowly with the current at first, but very rapidly as the resistance begins to assume a constant low value. This rapid increase in light follows the rapid increase in tube current by about a half microsecond. It can also be seen from the waveforms that the time required for the light to decrease to substantially zero is about 1 microsecond, but that a further decay of light output which has a very long time constant then occurs. This effect is most apparent in Figure 23, where the tube was operated at a high average power and remained luminous during the entire part of the cycle in which there was no current.

Figures 27 through 29 are dynamic voltage-current curves taken from pulse data. These illustrate in a conventional manner[1] the effect of frequency and pulse current on the operation of the tubes.

Figures 30, 31 and 32 present resistance-time curves of the crater lamps. Figure 33 presents similar characteristics of the Strobotron under a variety of conditions. The positive slopes at the beginnings of these curves probably result from capacitance charging currents.

Figures 34 and 35 are additional dynamic characteristics of the Strobotron operated as a glow lamp.

Figure 36 presents a summary of the light outputs of the two crater lamps for both steady and pulsed operation. It is very interesting that the light output increases exponentially with the tube current. The fact that these characteristics apply only for the conditions given in Figure 36 is emphasized by Figure 37, which shows how the efficiency of the tubes increases with frequency, if the instantaneous tube power is held constant.

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[1] See Reich, op. cit., 433-435.

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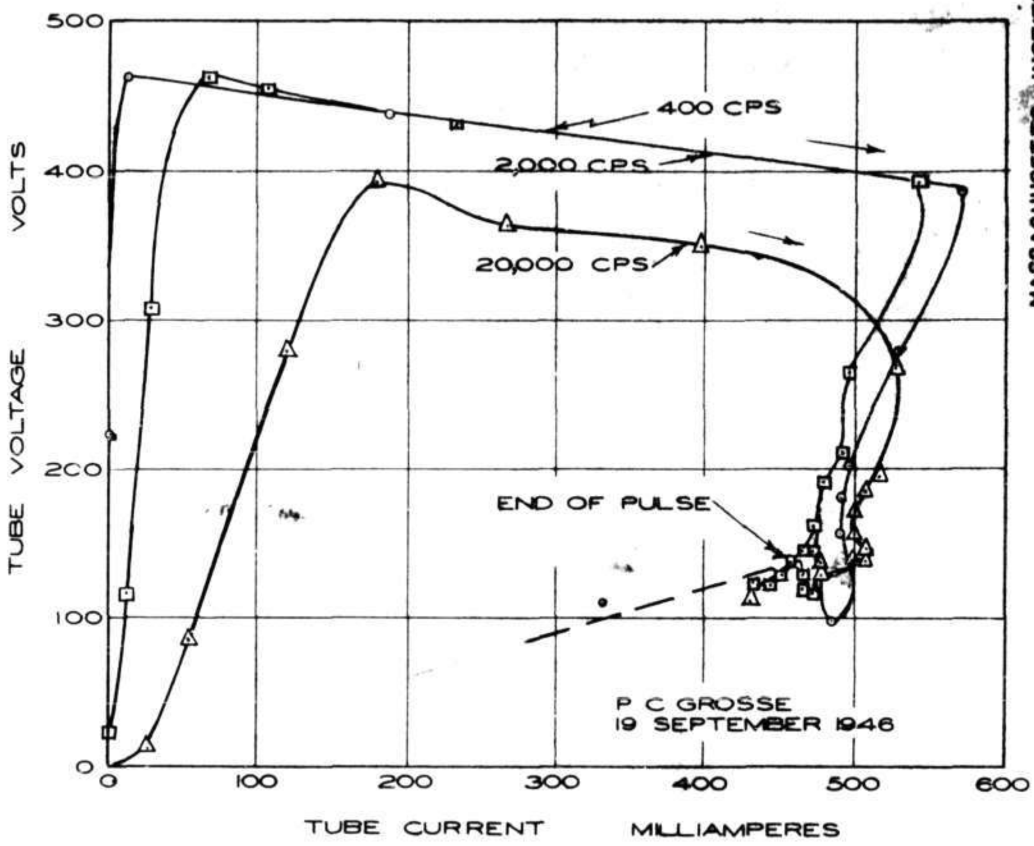

FIGURE 27. DYNAMIC CURRENT-VOLTAGE CHARACTERISTIC OF SYLVANIA CRATER LAMP R1130B. POWER SUPPLY POTENTIAL IS 450 VOLTS FOR 400 AND 2000 CYCLES BUT 390 VOLTS FOR 20000 CYCLES. PULSE LENGTH 5 MICROSECONDS.

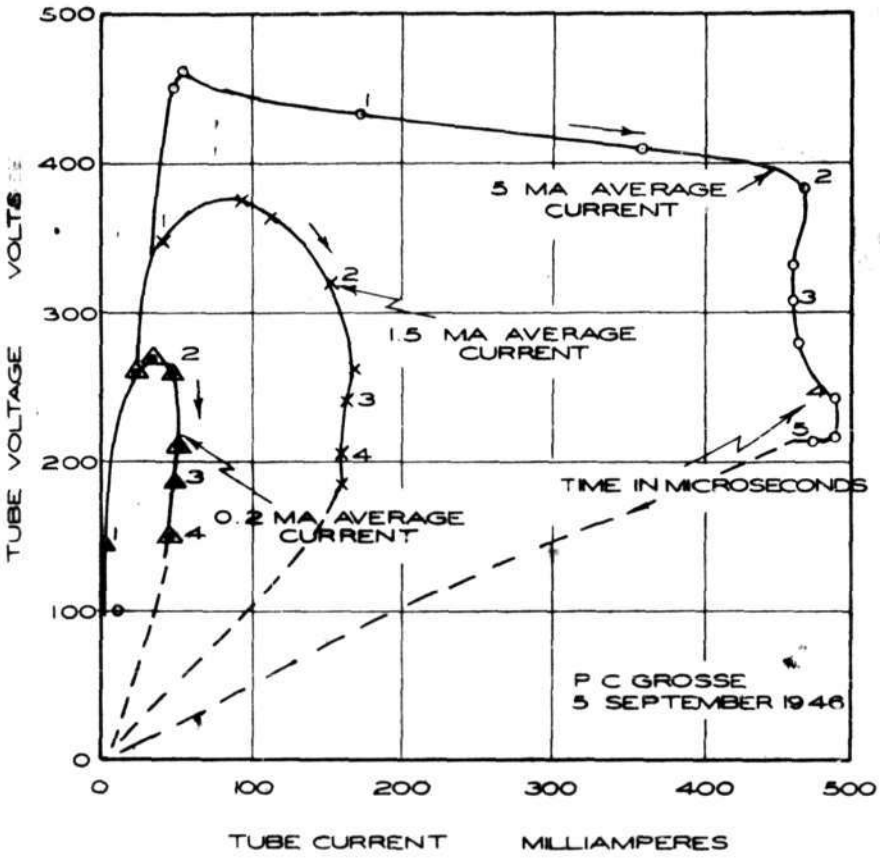

FIGURE 28. DYNAMIC CURRENT–VOLTAGE CHARACTERISTIC OF SYLVANIA CRATER LAMP R1131B. PULSE LENGTH, 5 MICROSECONDS. FREQUENCY, 3000 CYCLES PER SECOND.

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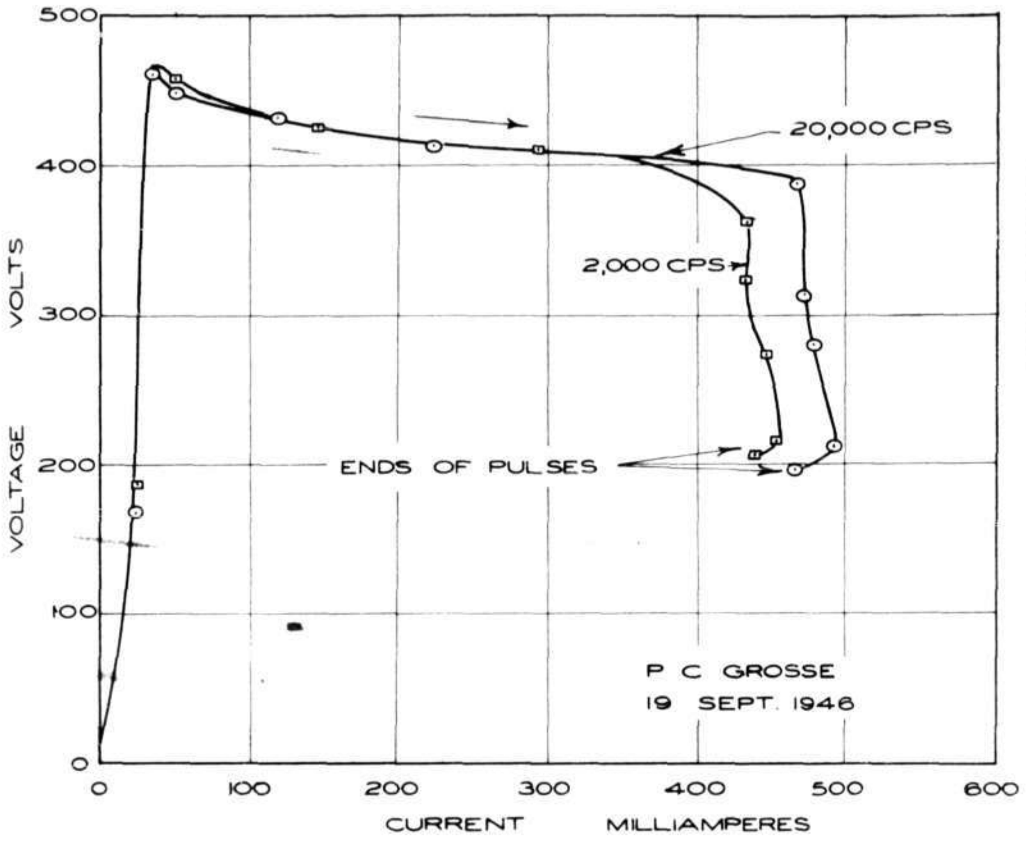

FIGURE 29. R1131B CRATER TUBE VOLTAGE-CURRENT PULSE CHARACTERISTICS FOR 5 MICROSECOND LONG PULSES

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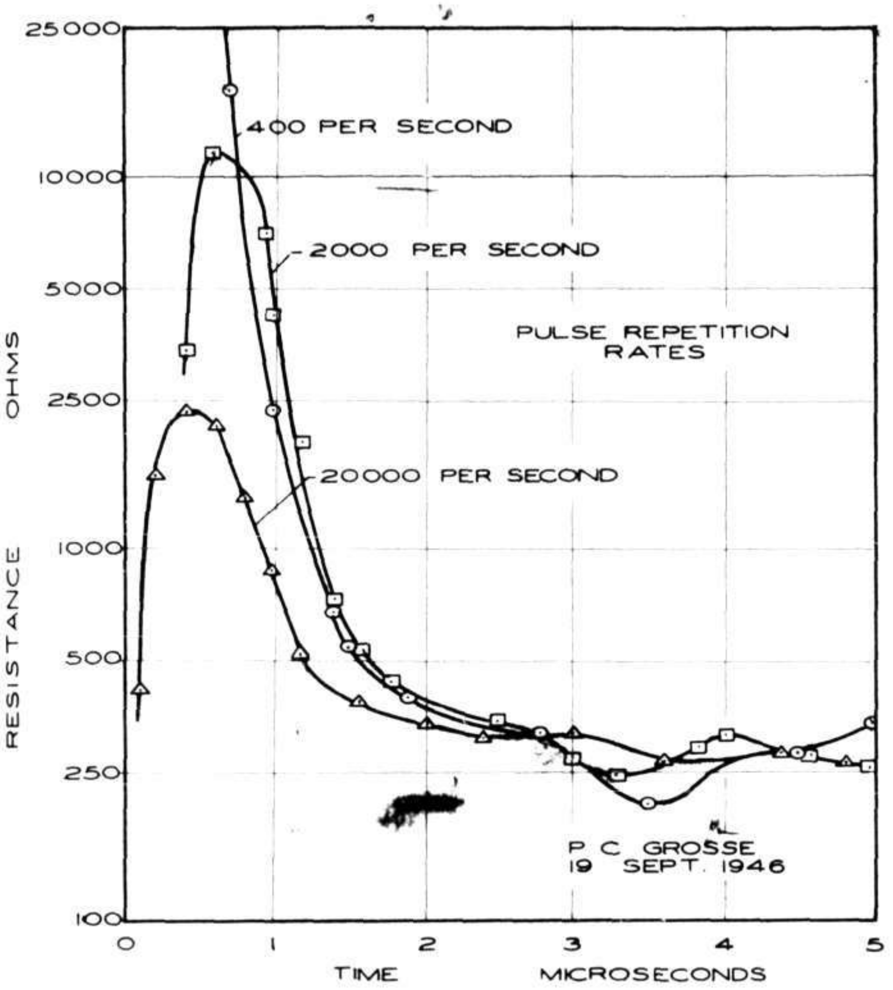

FIGURE 30. R1130B CRATER TUBE RESISTANCE-TIME PULSE CHARACTERISTICS FOR SEV-FREQUENCIES WITH 5 MICROSECOND PULSE LENGTHS

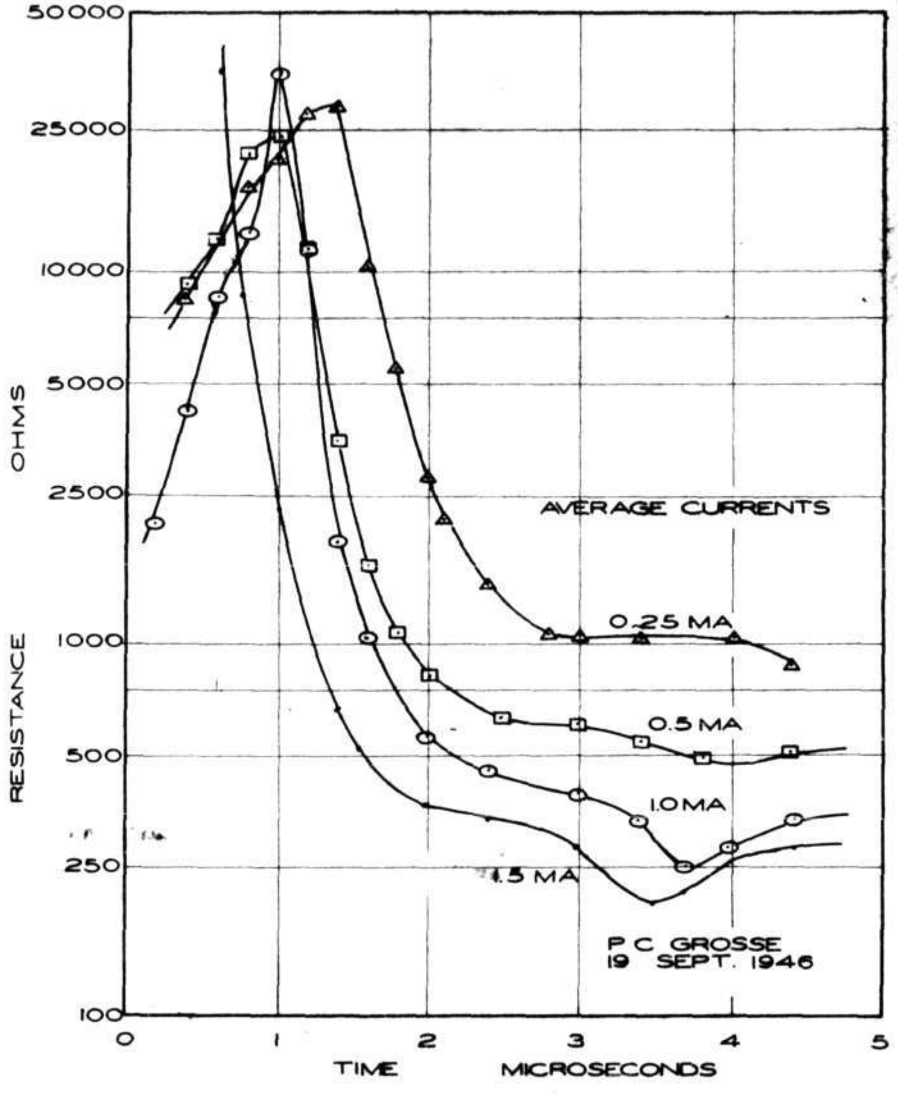

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FIGURE 31. R1130B CRATER TUBE RESISTANCE - TIME PULSE CHARACTERISTICS FOR SEVERAL AVERAGE CURRENTS AT A PULSE FREQUENCY OF 400 PER SECOND AND A 5 MICROSECOND PULSE WIDTH

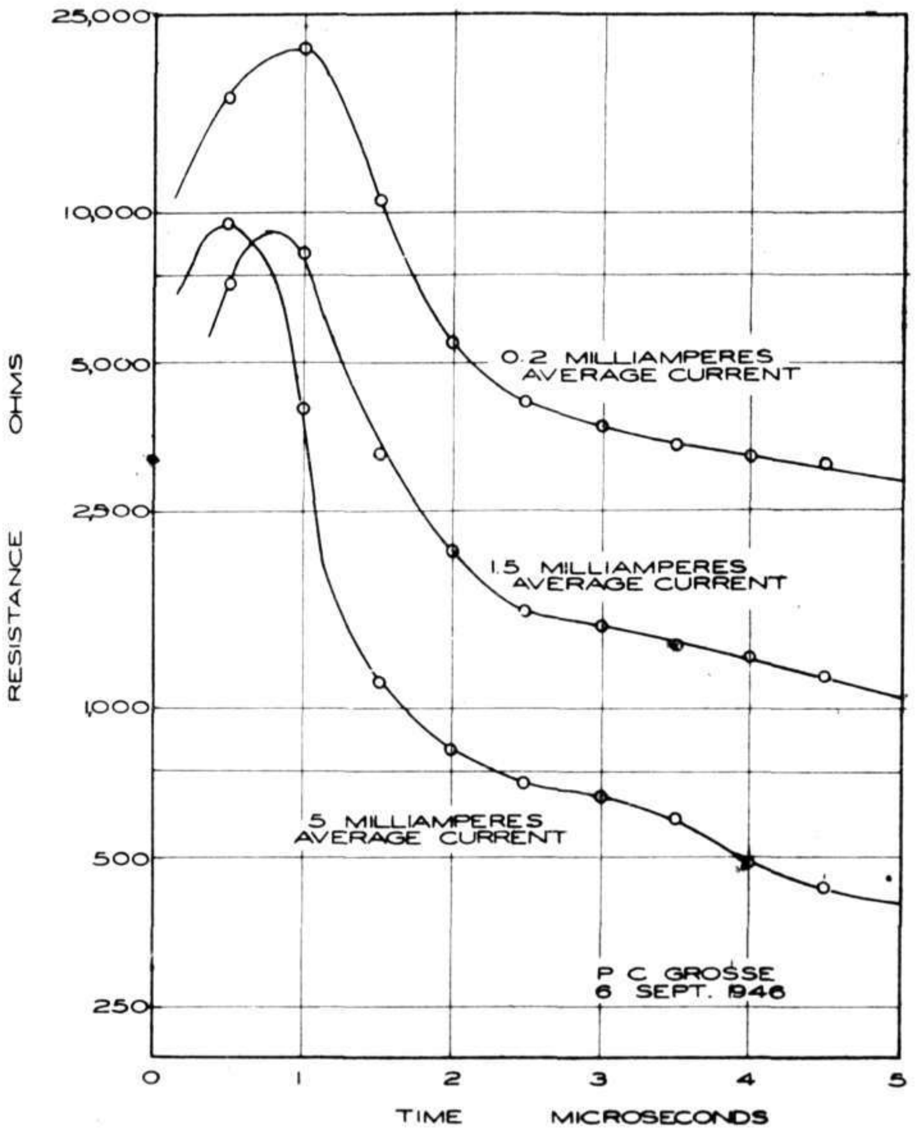

FIGURE 32. R1131B CRATER TUBE RESISTANCE-TIME PULSE CHARACTERISTICS FOR SEVERAL AVERAGE CURRENTS AT A PULSE FREQUENCY OF 3000 PER SECOND

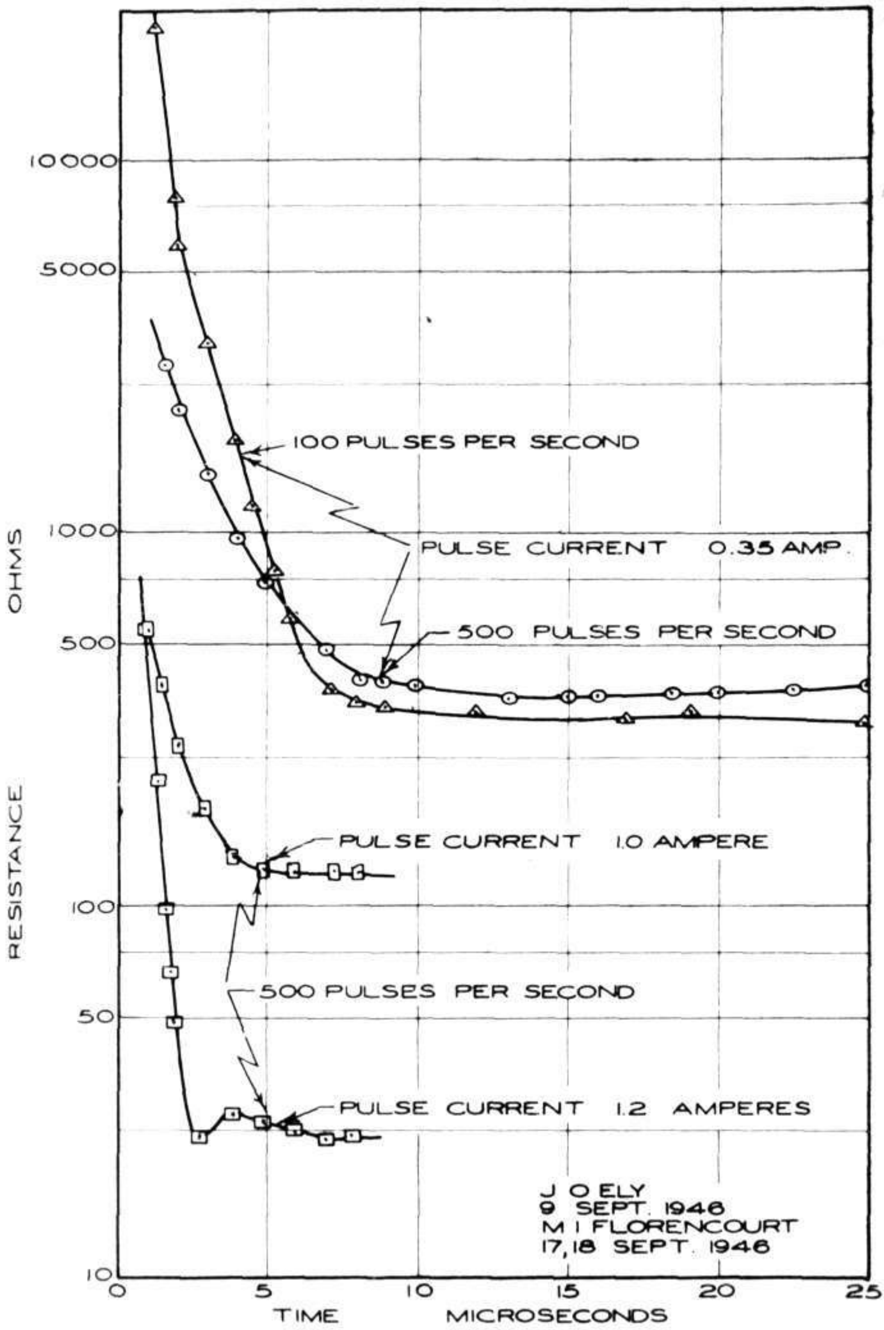

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FIGURE 33. SEVERAL RESISTANCE – TIME CURVES FOR STROBOTRON SN4

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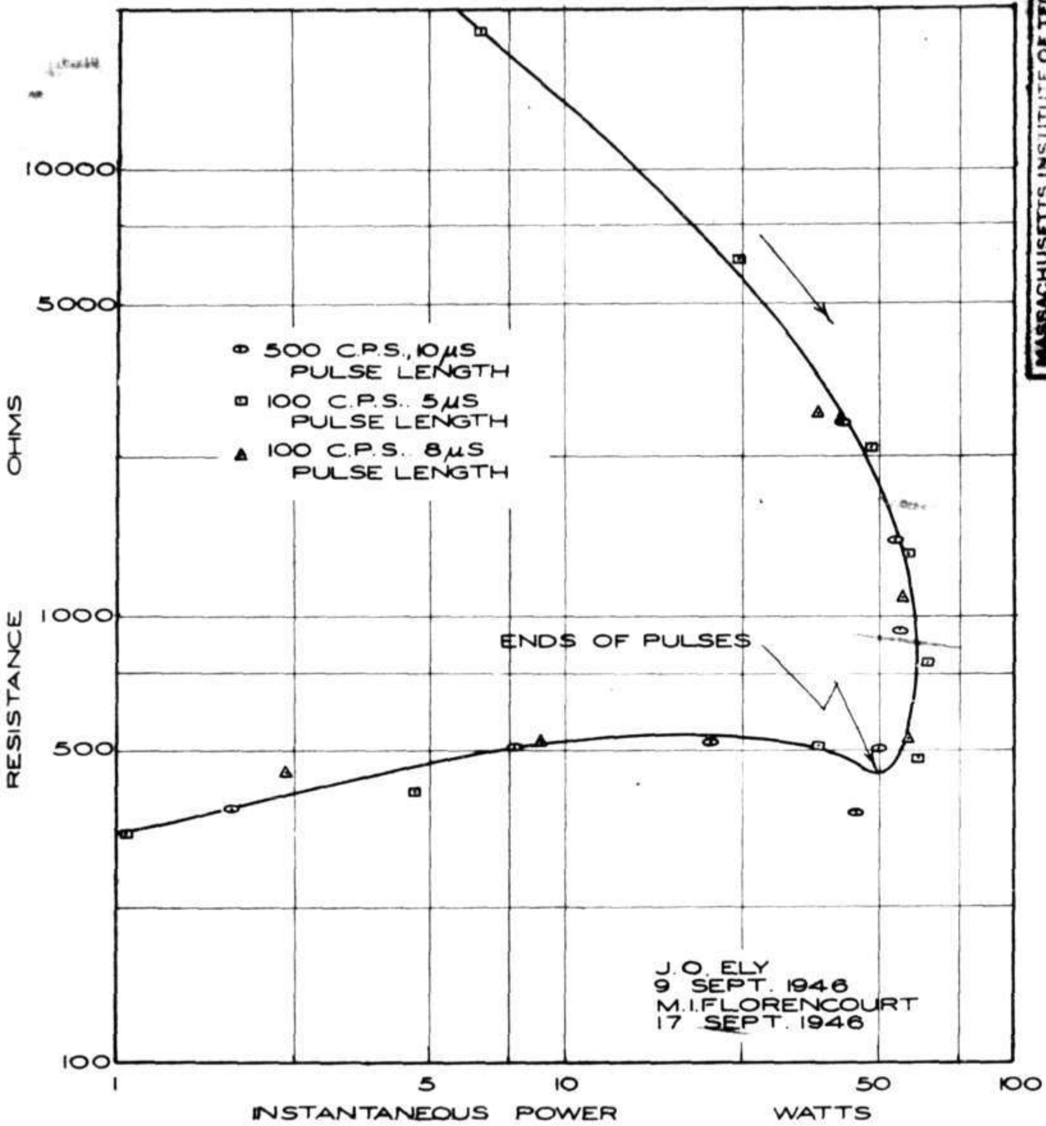

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FIGURE 34. RATIO OF VOLTAGE TO CURRENT AS A FUNCTION OF POWER FOR THE SN4 STROBOTRON DURING PULSES

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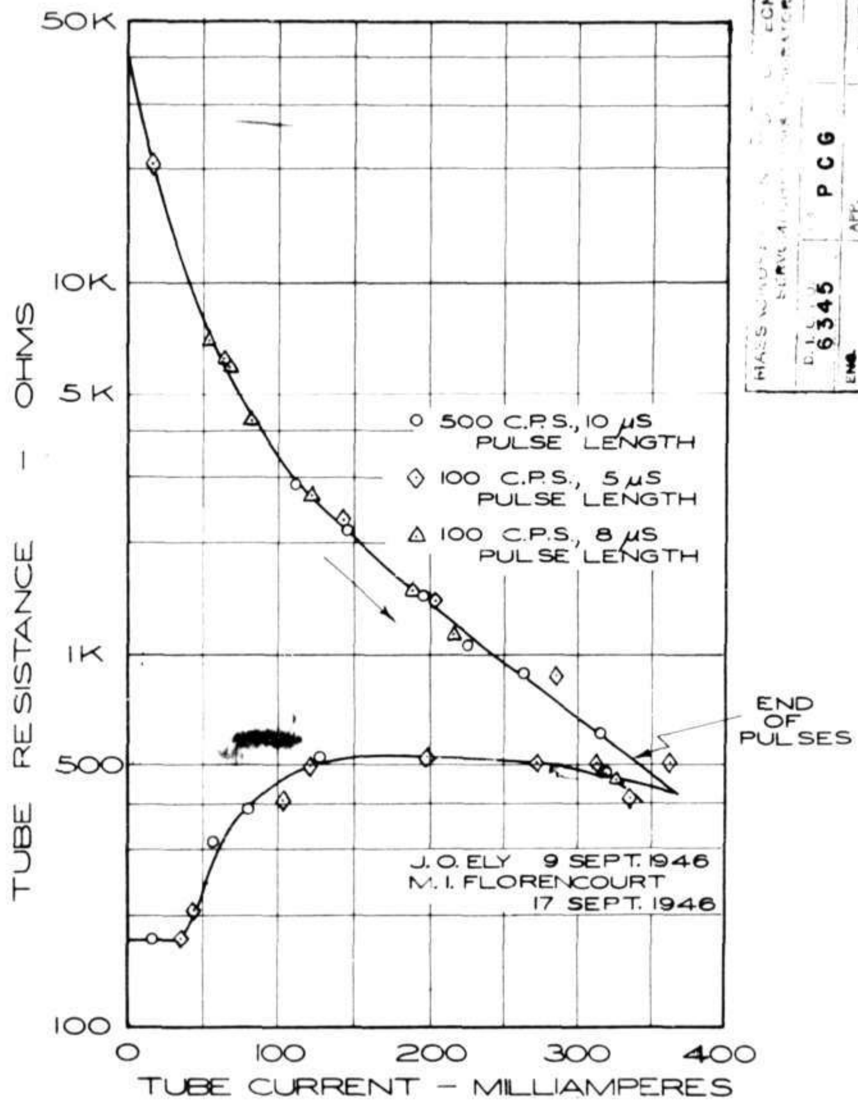

J. O. ELY 9 SEPT. 1946
M. I. FLORENCOURT 17 SEPT. 1946

FIGURE 35. PULSE CHARACTERISTIC OF THE TYPE SN4 STROBOTRON

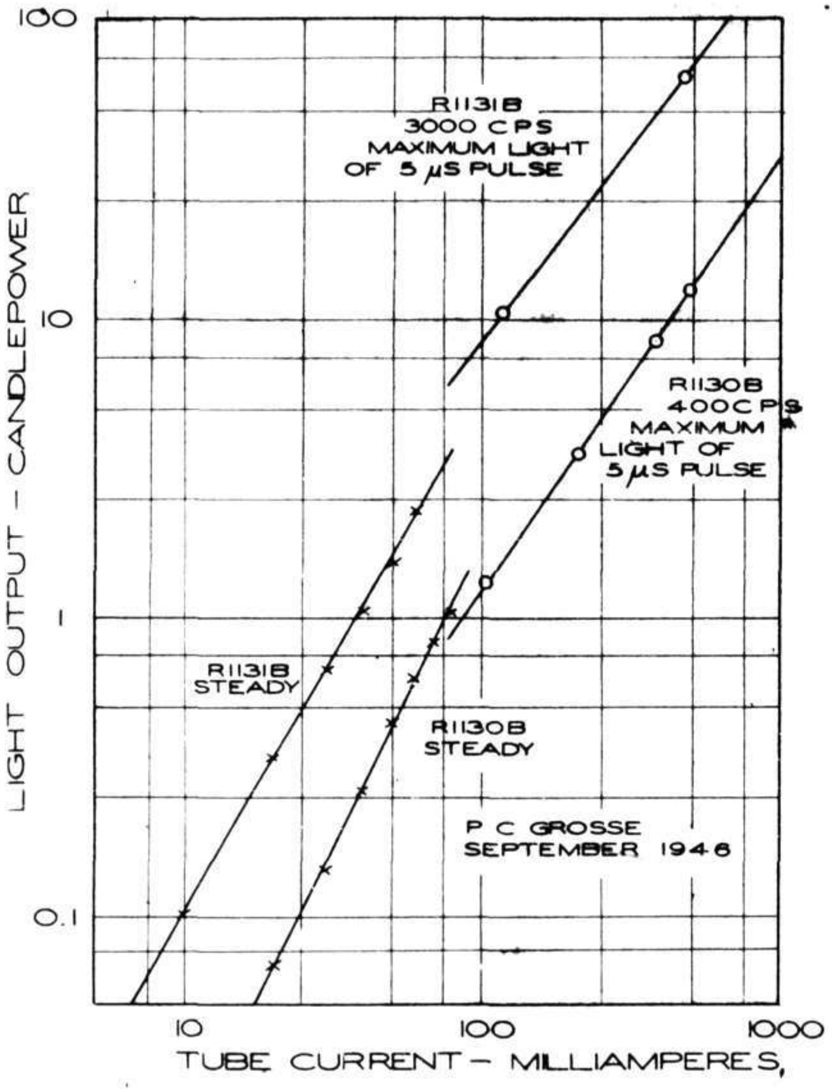

FIGURE 36. STEADY AND PULSED LIGHT-CURRENT CHARACTERISTICS OF SYLVANIA CRATER LAMPS R1130B & R1131B

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DRAWING NUMBER A-3024 8

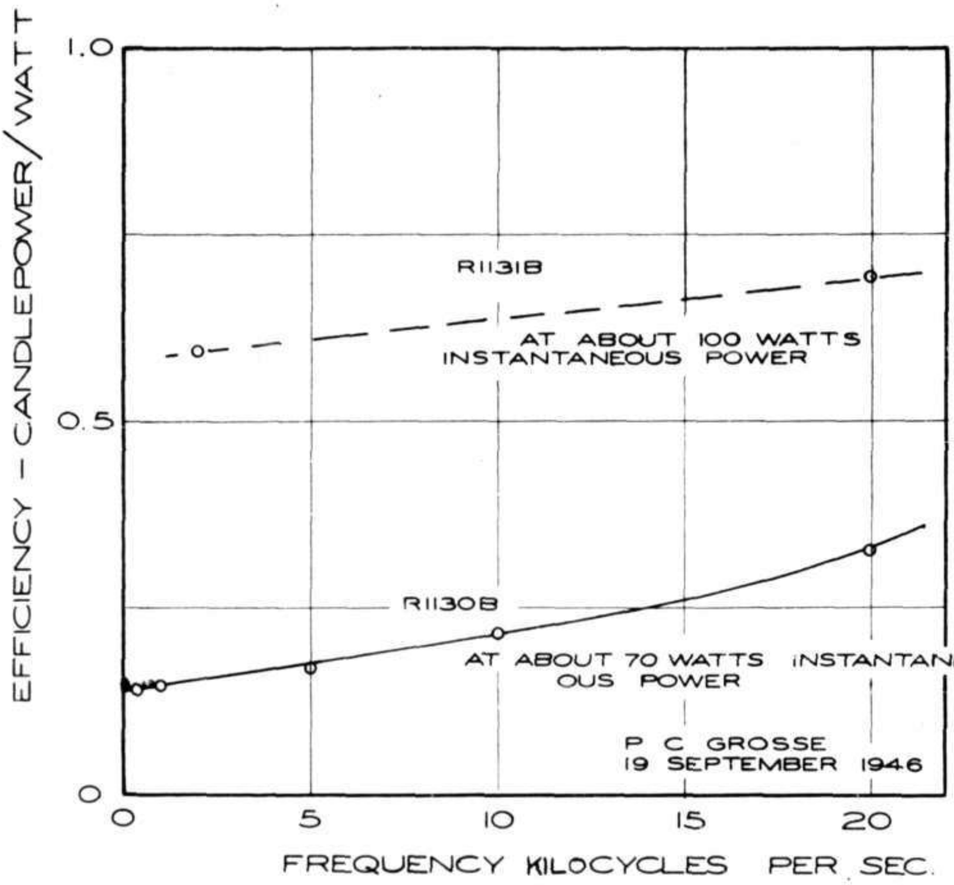

FIGURE 37 LIGHT OUTPUT - POWER INPUT RATIOS (TAKEN AT 4 MICROSECOND POINTS OF 5 MICROSECOND LONG PULSES) AS FUNCTIONS OF FREQUENCY FOR R1130B AND R1131B CRATER TUBES

Conclusions

From a consideration of the light output waveforms and from Figure 36 it is evident that the R1131B crater lamp meets the light level requirements of the multiplier phototube and of the image dissector tubes as calculated in Chapter I. The time delay to the maximum light output during the pulse is of the order of 1.5 microseconds for the R1130B and 3.0 microseconds for the larger R1131B at the lower frequencies. These are of the right order of magnitude and may be further decreased by the use of a higher power-supply potential.

The results of this investigation indicate that the glow type of discharge will meet the requirements of the project as far as light output, time delays, and ease of control are concerned. If it is to be used in preference to the arc discharge, much additional design work will be required to obtain the best possible tube for the project. Further developmental work with pulsed arc tubes should also be undertaken.

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS

Figure Number

M.I.T.
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Laboratory Drwg. No.