ORNL-2804
Instruments

A VERSATILE INSTRUMENT CAMERA WITH A MICROSECOND ELECTRONIC SHUTTER

C. H. Schalbe

OAK RIDGE NATIONAL LABORATORY
operated by
UNION CARBIDE CORPORATION
for the
U.S. ATOMIC ENERGY COMMISSION

Printed in USA. Price $1.50. Available from the
Office of Technical Services
Department of Commerce
Washington 25, D.C.

ORNL-2804

Contract No. W-7405-eng-26

INSTRUMENTATION AND CONTROLS DIVISION

A VERSATILE INSTRUMENT CAMERA WITH A MICROSECOND ELECTRONIC SHUTTER

C. H. Schalbe

DATE ISSUED

OCT 19 1959

OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee
operated by
UNION CARBIDE CORPORATION
for the
U.S. ATOMIC ENERGY COMMISSION

TABLE OF CONTENTS

LIST OF FIGURES

FIGURE PAGE

INTRODUCTION

Photographic recording is an important tool in the measurement and investigation of high-speed phenomena. The photographic picture provides a permanent record of an observed event permitting prolonged examination, and it furnishes an easy-to-store document for future reference and comparison. Perhaps its greatest attribute as an investigative tool is the fact that observations and measurements made photographically do not interfere with the phenomenon under examination.

The photographic technique has been used successfully in the investigation of explosion processes,[1,2] ballistic events, jet fuel injection, and in the fields of astronomy and nuclear physics among many others. Recently physicists have used this method in the identification of particles and events in experiments with high-energy accelerators and cloud chambers.[3]

Because of this wide use many techniques and special devices have been developed with the aim of decreasing the required exposure times and increasing exposure rates. Cameras using rotating mirrors[2] and drums result in high speeds (10^6 frames/second) but are expensive and have many mechanical problems besides suffering from substantial light loss.

A second group of high-speed shutters applied in the field of high-speed photography makes use of electro- and magneto-optical effects. The Kerr Cell and the Faraday shutter are examples. The Kerr Cell shutter[4] utilizes the electro-optical effect of rotating the plane or axis of light polarization by application of a field to certain fluids.

These shutters are very fast (10^{-8} seconds) but suffer from limited effective lens aperture. In addition only relatively low frame rates are possible. Another consideration, as discussed later, is that the presence of strong magnetic fields effect cell operation adversely.

Other methods of high-speed photography resort to image dissection techniques[5] which are fast but have poor definition and of course there is the stroboscopic method.

All of the methods outlined so far suffer from the disadvantages of inherent light losses and the difficulty of combining high shutter speeds with variable frame frequency. High-frequency stroboscopy and high-speed photography using the above techniques are therefore limited in exposure times or to intensely lighted objects.

Image converters offer several advantages over these methods. Single stage and multi-stage converters or image intensifiers have been under development for some time and have been used in laboratories in experimental procedures.[1,6,7] Image converter tubes make possible shutter speeds in the millimicrosecond range and can provide light amplification along with good definition.

This thesis is a discussion of a camera which was developed and built at the Oak Ridge National Laboratory and which uses a single stage image converter. The camera was designed with one particular use as its goal but an attempt was made to produce as versatile and generally useful an instrument as possible. In addition, the design was guided by the need to produce an instrument which could operate in non-laboratory environments and which could be easily operated and maintained.

The camera was developed primarily to study high current, low pressure arcs in environments encountered in controlled nuclear fusion experiments.[8] In particular, the camera is used to investigate an arc which takes place in a chamber at a pressure of 10^{-5} to 10^{-7} millimeters of mercury. The arc voltage is about 150 volts, d-c, and the current is in the range of two to three hundred amperes.[9] An important consideration is the intense magnetic field present in the vicinity of the arc. This magnetic field is generated by the containing mirror coils which produce a field of ten thousand gauss at the central plane and twenty thousand gauss at the coil centers.

Unfortunately, from the photographic viewpoint, a large part of the emitted energy of the arc is produced in the non-visible region. In the visible range the energy is peaked in the blue-white spectrum.

In this paper the image converter shutter tube will be discussed and then the associated deflection and gating systems will be described. Finally, the operating parameters and performance will be discussed.

IMAGE CONVERTER SHUTTER TUBE

The basic image converter tube was used during World War II in the snooperscope. In this application the tube was used primarily to convert infrared light to visible light for night observation purposes. Since World War II recognition of the image converter possibilities as a photographic device has caused much activity in the development of these tubes. Until recently most image converters used electrostatic focusing and electromagnetic deflection[1,7] but pure electrostatic control tubes* are now in the development stage and have been used experimentally in cameras.[10]

The image converter tube used in the camera described in this paper is controlled by electrostatic methods only. It is a developmental model produced by the Radio Corporation of America and designated "Dev. No. C73435B". Fig. 1 is a picture and schematic drawing of this tube. It consists of a semi-transparent, blue-sensitive (S11 spectral response) photocathode, a control grid for low voltage gating of the electron beam, and a pair of deflection plates for positioning a series of time-sequential frames side-by-side on the phosphor screen (P11).#

Light from the object under study is focused by the front lens (Fig. 2) onto the photosensitive surface which is deposited as a thin film on the flat glass surface which makes up the front of the tube.

---

*For a theoretical discussion of image converter tube construction see: Linder and Snell, Shutter Image Converter Tubes, Proceedings of IRE, April, 1959.

#See Appendix I for tube data.

UNCLASSIFIED
ORNL-LR-DWG. 37513
PHOTO 46425

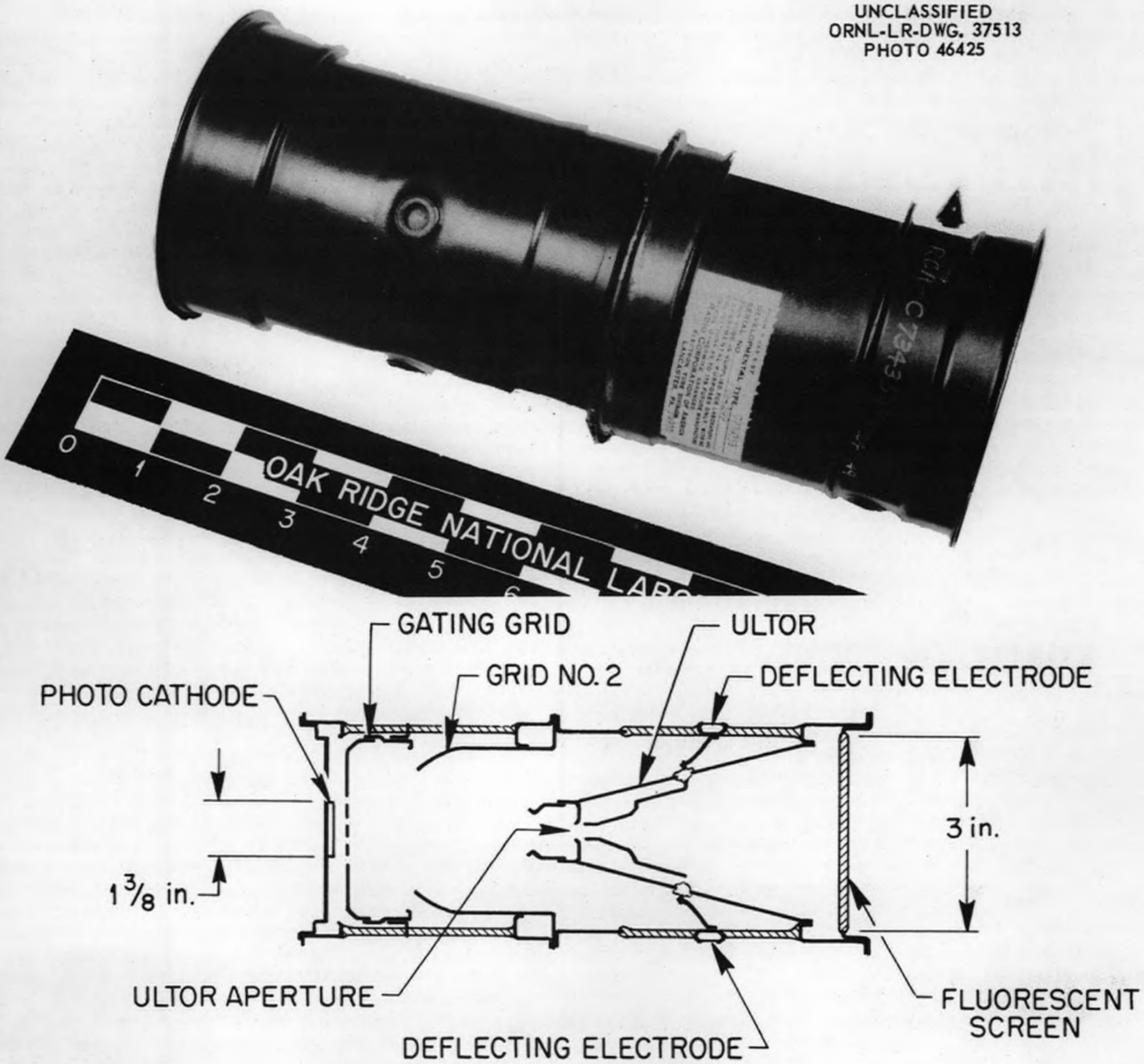
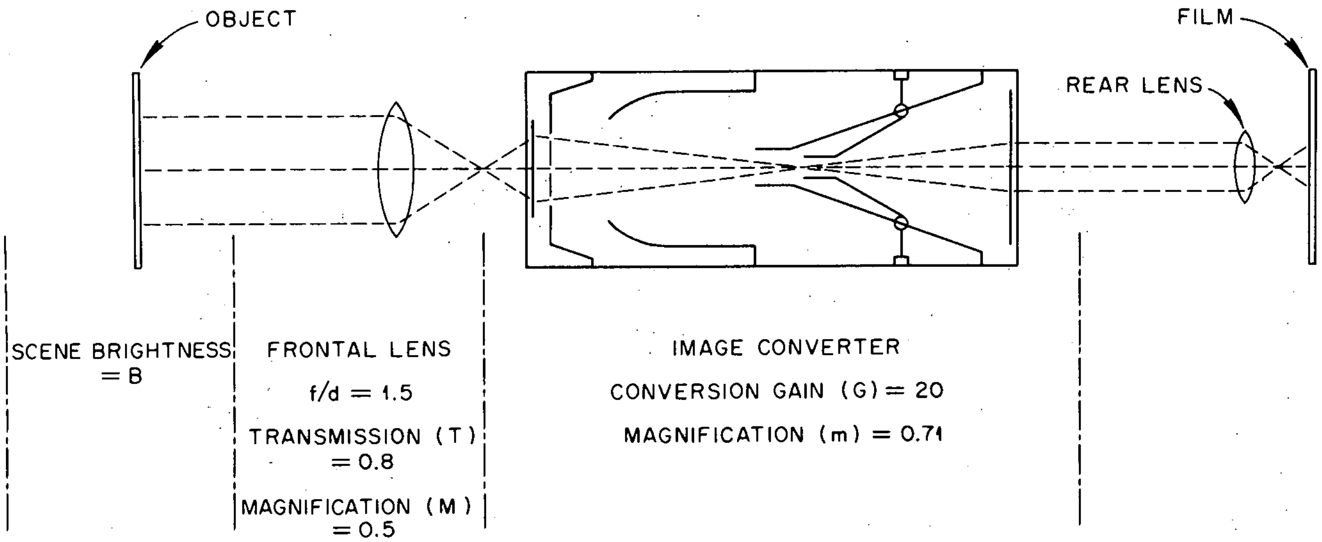


Fig. 1. Image Converter Tube — RCA C73435B

UNCLASSIFIED
ORNL-LR-DWG 39440



1. ILLUMINATION ON PHOTO CATHODE (E)

$$E = \frac{BT}{4(f/d)^2(1+M)^2} = \frac{B(0.8)}{4(1.5)^2(1+0.5)^2} = \frac{B}{25}$$

2. SCREEN BRIGHTNESS (B')

$$B' = \frac{EG}{m^2} = \frac{B \times 20}{25(0.71)^2} = 1.4B$$

3. BRIGHTNESS GAIN $\frac{B'}{B}$

$$\frac{B'}{B} = 1.4$$

Fig. 2. Ray Diagram and Calculation of Brightness Gain.

The electrons emitted by the cathode carry the picture information through the control grid, if it is biased properly, and are accelerated towards the phosphor screen. They pass through a hole in the anode where they enter the influence of the vertical deflection plates and finally strike the phosphor screen to recreate the original optical image. A thin aluminum film over the phosphor screen prevents feedback of light to the cathode and also brightens the image. Another lens then focuses the image on the recording film to produce the permanent record.

The image converter tube provides a conversion gain for illumination having a wavelength in a narrow band about 4400 Å if the proper operating voltages are present. The brightness gain of the overall system depends on the quality of the lenses and the image magnification obtained.[11] Fig. 2 illustrates the calculation of system gain under typical operating conditions. To realize the brightness gain possible with this system, the terminal photographic recording unit must be selected with care and be of the highest quality. The lenses and film transport will be discussed in a later section.

WAVEFORM REQUIREMENTS

The characteristics of the image converter tube are such that resolution deteriorates if the voltage configuration applied to the tube varies even slightly from the optimum values. To overcome defects which might be introduced through environmental changes and circuit variations, all potentials applied to the shutter tube can be adjusted by the operator. Three of these parameters, shutter pulse height, focus, and astigmatism, are controlled from the camera head itself, while the accelerating potential can be adjusted from the main power rack. (See section entitled "Camera Performance" for discussion and pictures of the physical make-up of the camera.)

Shutter pulse shape and amplitude are probably the most important factors in obtaining the best resolution. Since amplitude deviation from the optimum value by more than about one per cent will result in inferior resolution the image will be out of focus when the control grid of the shutter tube is rising or falling. This demands that the shutter gate signal have fast rise and fall times and be flat topped. The image converter tube conducts during the rise and fall of the applied exposure pulse but the contribution to the total picture during this time is insignificant except at the points where the voltage approaches the optimum exposure value, and here, assuming a reasonably well shaped pulse is used, the time of contribution is so small by comparison with the flat-topped time that little or no disturbance appears in the picture.

Good picture quality also demands that the deflection voltages used in taking a sequence of exposures be accurately timed and stable.

Blurring of the image will result if the deflection voltage has not settled down after a step-change to a new value by the time a shutter pulse is applied.

In view of these requirements, all direct current voltages used throughout the camera including the 1750 volts for the deflection drivers and the 15,000 volts for the anode of the converter tube are obtained from well regulated power supplies.

The type of circuits used to generate the required pulses was determined by considering the following factors; pulse shape, repetition rate, ease of synchronism, reliability, circuit complexity, and, of great importance, the ease with which the operating parameters could be changed. The high shutter speed necessary and the degrading effect of vibrations excludes the use of mechanical switches. Thyratrons combined with delay lines produce fast rise-time, flat-topped pulses but only low repetition rates are possible without duplication of components. In addition, programming operations are more difficult. Because ultra-high speed (millimicrosecond range) photographs were not desired, and because sequential exposures and great flexibility were prime requisites, hard vacuum tubes were used exclusively.

DESCRIPTION OF CAMERA

Fig. 3, a simplified block diagram, and Fig. 4, a logical diagram, indicate how the camera operates. The initiating trigger causes the shutter pulse generator to produce a square pulse which is fed to the shutter driver, the counter, and the interval pulse generator. The shutter driver system amplifies it and then applies the signal to the cathode of the shutter tube; the counter totalizes these pulses; and the interval generator is triggered by it. In this way each subsystem is tied together by a common signal making for a relatively simple and automatically synchronized control system. The counting block indicates to the deflection system what position the image should occupy and also determines whether or not a signal will pass through the gate circuit to form a new trigger at the end of each exposure interval.

The logical diagram, Fig. 4, shows in more detail the control system of the camera. There are three possible sources of initiating triggers: a local start switch, an external trigger or a recurring trigger generated by a free-running multivibrator which is used in the "test" position for maintenance and focusing purposes. By means of "or" gates these triggers and the circulating trigger if it appears are used to start a one-shot and thereby trigger the shutter pulse generator. This technique was used so that the relatively sensitive generator would always see the same trigger shape and amplitude no matter what the trigger source. This contributes to pulse stability.

UNCLASSIFIED
ORNL-LR-DWG 37515

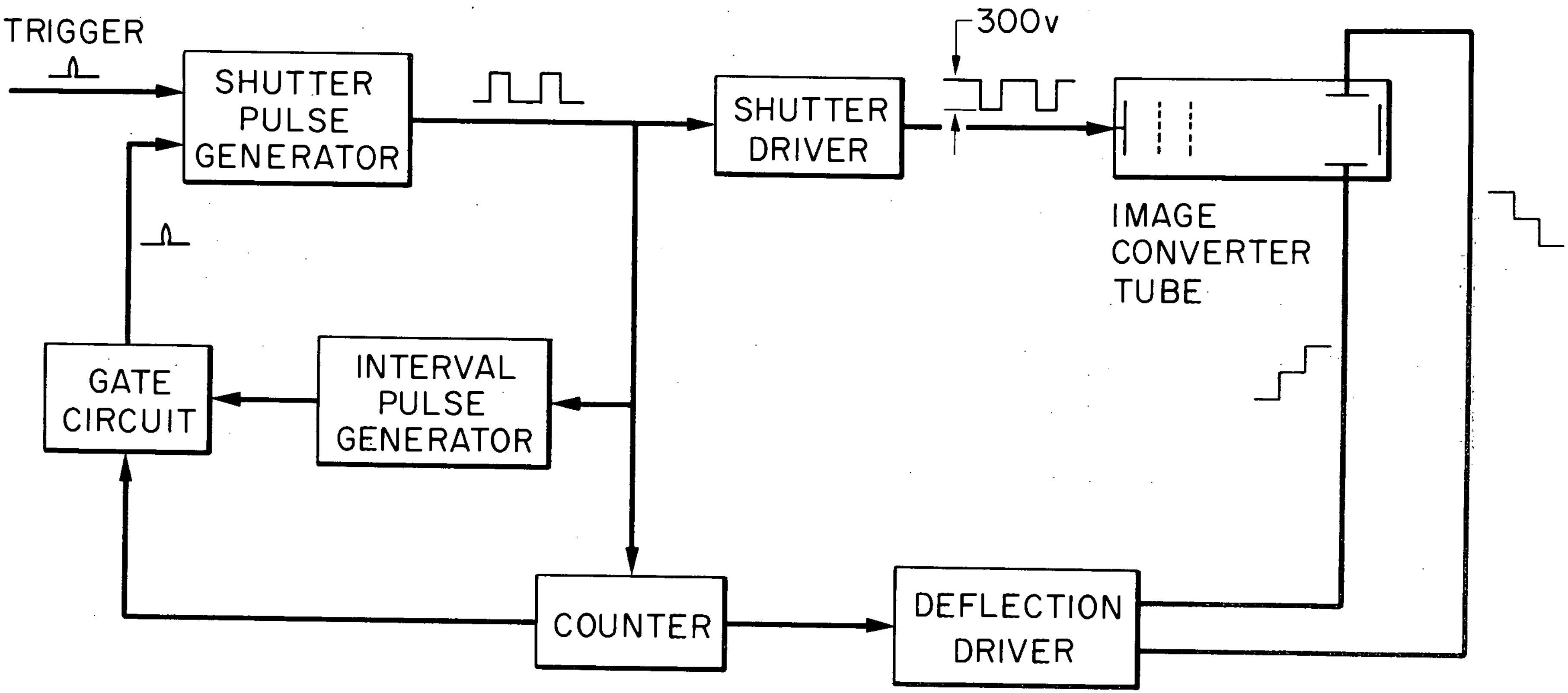


Fig. 3. Block Diagram of Camera.

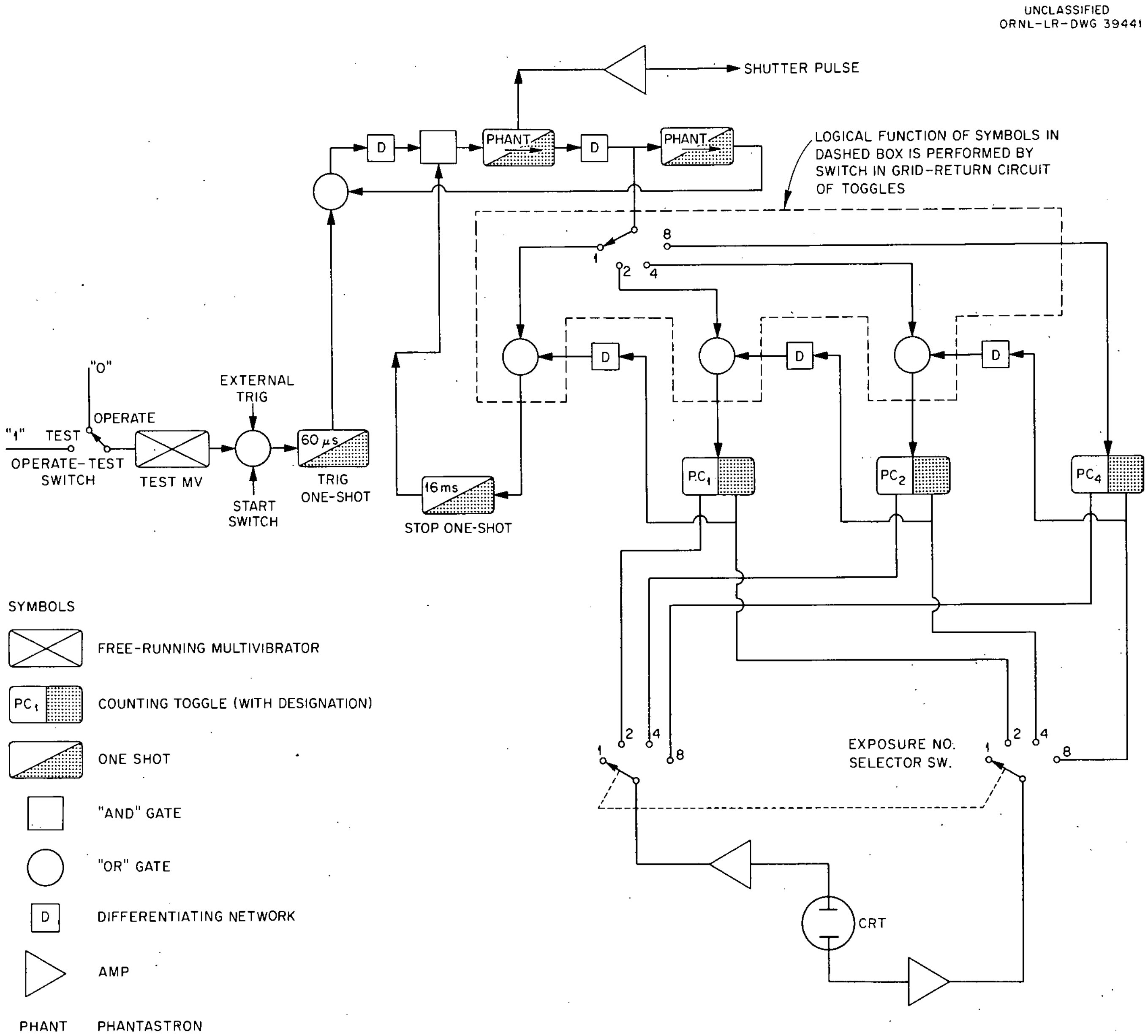


Fig. 4. Logical Diagram of Control CKT

Both the shutter pulse generator and the interval pulse generator are phantastron circuits.# This type of circuit was selected because pulse length can easily be adjusted in a linear manner. The shutter pulse can be varied from 0.6 microseconds to 100 microseconds in length and the interval pulse can be adjusted to any length between 1.0 microsecond and 1000 microseconds. A combination of decade switches and calibrated Helipots located on the operator's control panel performs this function.

The trailing edge of the shutter pulse starts the interval pulse generator which in turn forms a trigger after the selected time between exposures has elapsed and thus restarts the entire process.

The counter totals the exposures as they occur and when the preselected number is reached fires the "stop" one-shot which closes the "and" gate and inhibits the circulating trigger. One complete cycle has thus been completed and the camera is immediately ready for the next initiating trigger. A sequence of one, two, four, or eight exposures can be selected by a control on the panel. These particular numbers were chosen since a simple binary counter could then be used.

SHUTTER PULSE CIRCUIT

The shutter pulse is picked off the screen grid of the phantastron run-down tube and fed by way of a cathode follower to the shutter

---

#See Appendix II for discussion of phantastron circuit.

driver tube. See Fig. 5. This screen-coupled, positive feedback circuit provides the fast rise and fall times required in spite of the relatively large capacity presented by the cathode circuit of the shutter tube.

The 6CB5A power amplifier which is normally cut-off is driven into saturation conduction by the pulse applied to its control grid. A portion of the inverted signal which appears in the plate circuit is fed to the normally conducting 6197 thereby cutting it off and generating a positive pulse in its plate which is then coupled by means of the triode cathode follower to the screen of the power amplifier, completing the feedback loop. The diode in the grid of the 5687 tube clamps it to ground to insure that the screen signal be flat topped and also to minimize screen dissipation.

The 6W4 diode in the plate of the power amplifier (6CB5A) clamps the line at ground also and in this way insures a flat waveform. The circuit just described produces a three hundred volt pulse which has a total rise and fall time of 0.45 microseconds and is flat to within one-half of one per cent.

COUNTERS AND DEFLECTION CIRCUIT

The counter consists of three stages which will indicate totals of one, two, four, or eight counts. The exposure-number-selector-switch on the control panel biases one or more stages to a non-counting condition according to the number of exposures desired. In the non-counting state each stage acts only as an amplifier, passing the

UNCLASSIFIED
ORNL-LR-DWG 37514

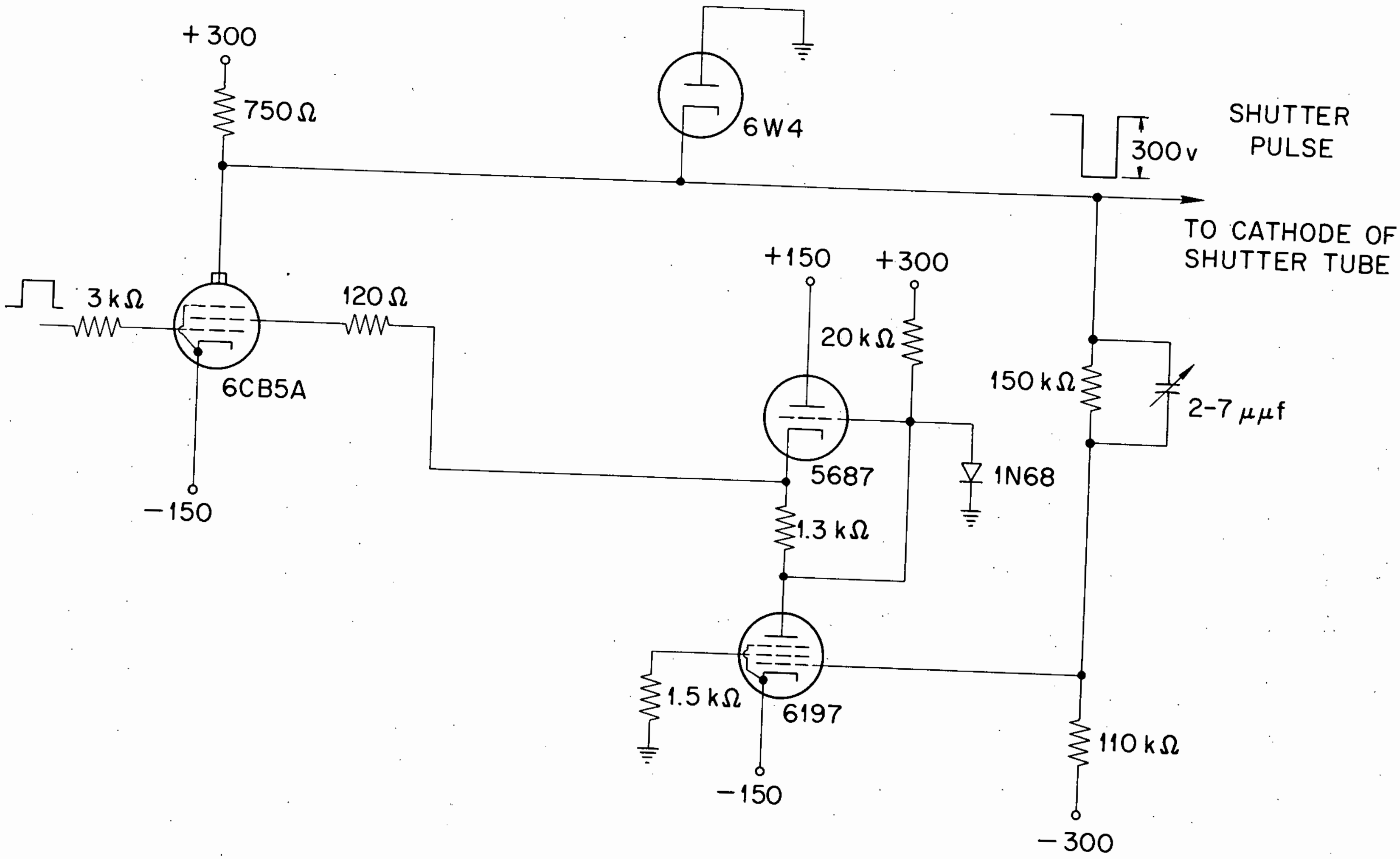


Fig. 5. Circuit of Shutter Driver.

count-pulse directly through to the following stages. For example, if eight exposures are desired all three stages act as counters and therefore no "stop" signal is generated until eight pulses have been applied to the shutter tube grid. However, if only four pictures in one series are desired the first of the three counting stages acts as an amplifier passing the count-pulse on to the two remaining counting stages which will therefore produce a "stop" signal after four exposures. Similarly, in the "two exposure" mode, the first two stages are amplifiers while the third is a normal counter. In order to obtain only one exposure all three stages act as amplifiers and the first count-pulse then passes through the entire counter and prevents further exposures.

A second function of the counter is that of determining the position each electron image in a series will occupy on the phosphor screen and also to properly synchronize deflection voltage steps with the exposures. This is accomplished by a current-adder stage connected to each of the three counting stages. In this way, each count-pulse which is accumulated by the counter is also directly converted through the current-adder circuitry to a new deflection voltage in preparation for the next exposure. Timing in this system is therefore automatic, insuring that the deflection voltage has stabilized before the next exposure pulse is generated. Fig. 6 illustrates the time relationship existing between the shutter pulses and the deflection voltage. This photograph was taken while the electronic camera was operating in the mode in which a series of eight exposures is made. The upper waveform, a series of eight negative-going pulses, is the signal seen on the plate of the

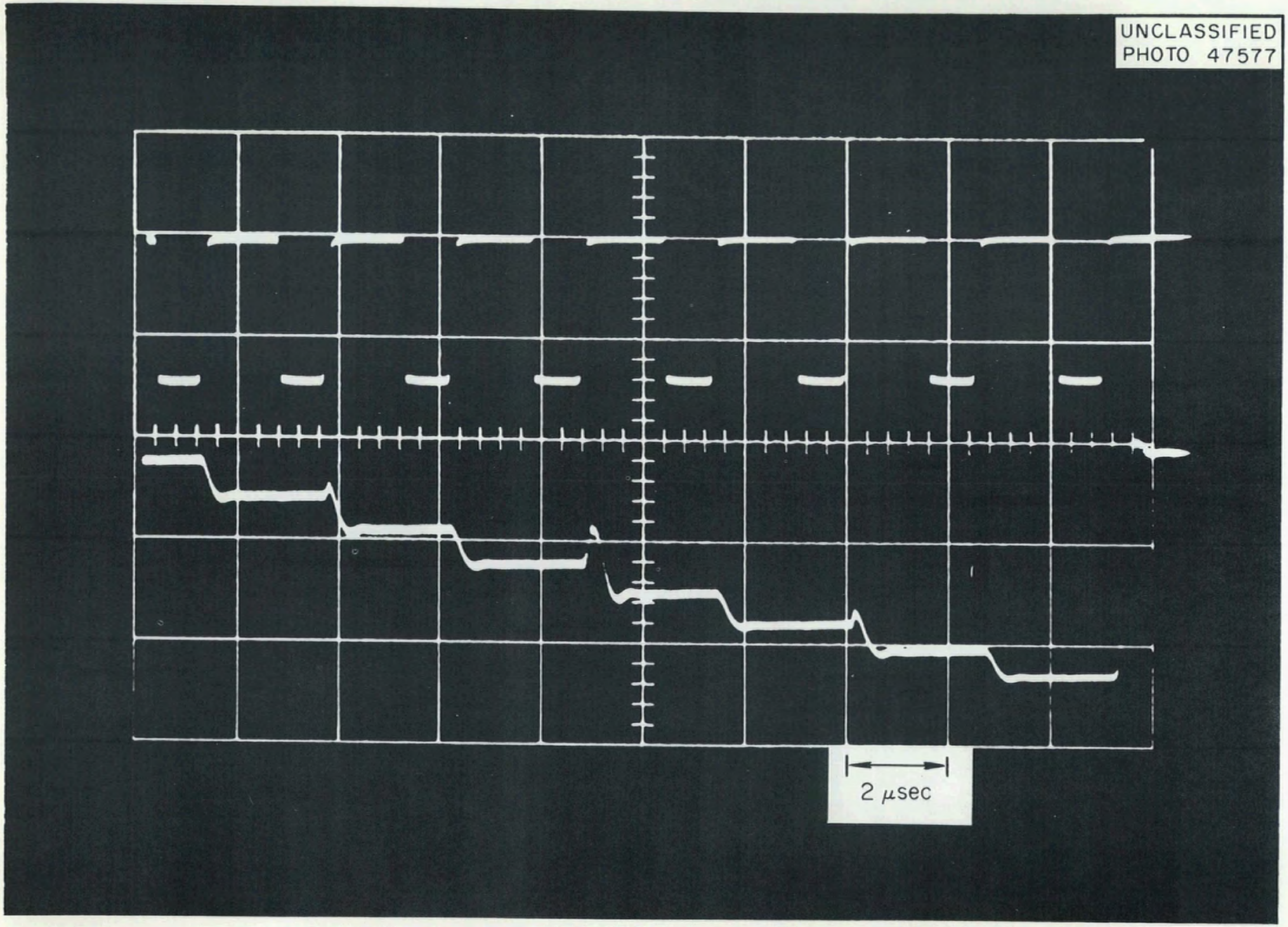


Fig. 6. Shutter Pulse and Deflection Waveforms.

shutter driver. (The 6CB5A in Fig. 5.) Each major vertical scale division represents 200 volts for this waveform.

The lower, or step waveform, is the voltage appearing on the upper deflection plate. (The voltage on the lower deflection plate is similar but inverted.) In this case each major vertical scale division represents about 500 volts. The horizontal or time scale is the same for both signals, 2 microseconds per major division. As shown in this picture, each shutter pulse occurs immediately preceding a step in the deflection voltage, allowing some stabilizing time after each step before the next shutter pulse appears.

The total deflection voltage variation per plate is approximately 1300 volts but this change is not required in any one step. The greatest separation between successive images and therefore the greatest voltage step required of the deflection system occurs in the "two exposure" mode of operation. Here the change in voltage per plate is about 600 volts.

The deflection driver, like the shutter driver, must effect these voltage changes rapidly in the face of relatively high circuit capacity. The driver used is a push-pull system with two tubes operating in parallel in each leg to handle the high currents.

One further advantage of using the counter-current-adder configuration to generate deflection voltages is that each series of pictures, whether there be one, two, four, or eight exposures, will be centered on the screen automatically. Moreover, the separation between images on the phosphor screen is also automatically adjusted for the number of exposures involved.

CAMERA PERFORMANCE

The camera in its final form is shown in Figs. 7, 8, 9, and 10. In Fig. 7 the large rack contains the low voltage supplies and regulators which are in the two top panels, the 15,000 volt supply and regulator located behind the third panel from the bottom, and the 1750 volt, one ampere supply and regulator which occupies the lower two sections. The a-c distribution system and power control section are located behind the third panel from the top. This includes a voltage sensing system to prevent application of high voltage in the absence of lower voltages. The rack is mounted on casters to facilitate movement.

Fig. 7 also shows the camera head which is mounted on a standard black-and-white television camera tripod and dolly, again for reasons of mobility.

Fig. 8, a close-up view of the camera head, shows three of the four control panels. The four controls at the bottom right are for selecting exposure and interval times while the single control towards the left-center is to select the number of images. The third panel contains the operate-test control (top), a connector for external synchronization, and a local shutter control button. The front lens is a f/1.5, 180mm lens.

The remaining control panel is shown in Fig. 9. It contains the intensity, focus, and astigmatism controls. Photographs of the phosphor screen are taken with a 35mm oscilloscope camera also seen in this figure. This camera which has an electrically operated shutter and film

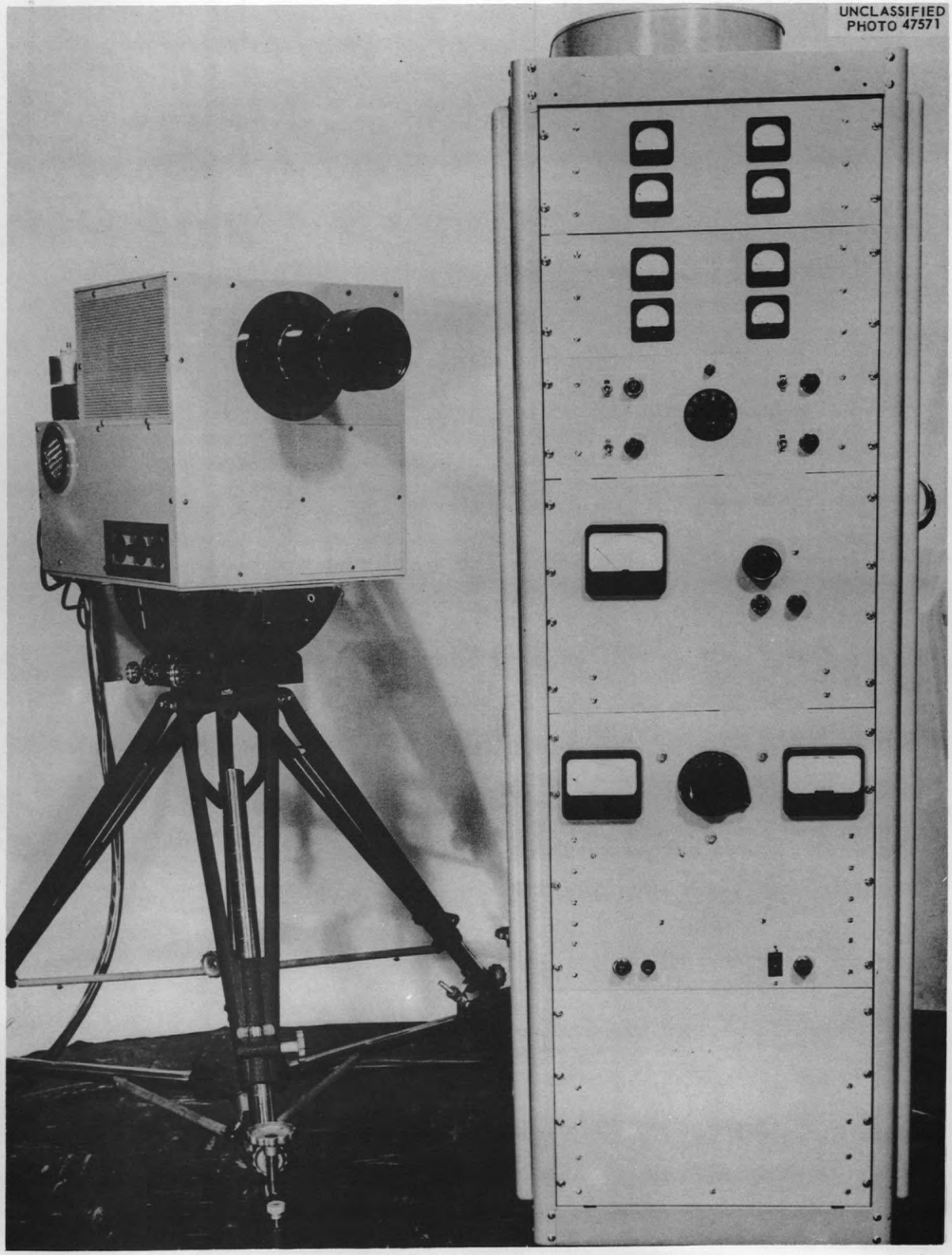


Fig. 7. Electronic Camera Head and Power Rack.

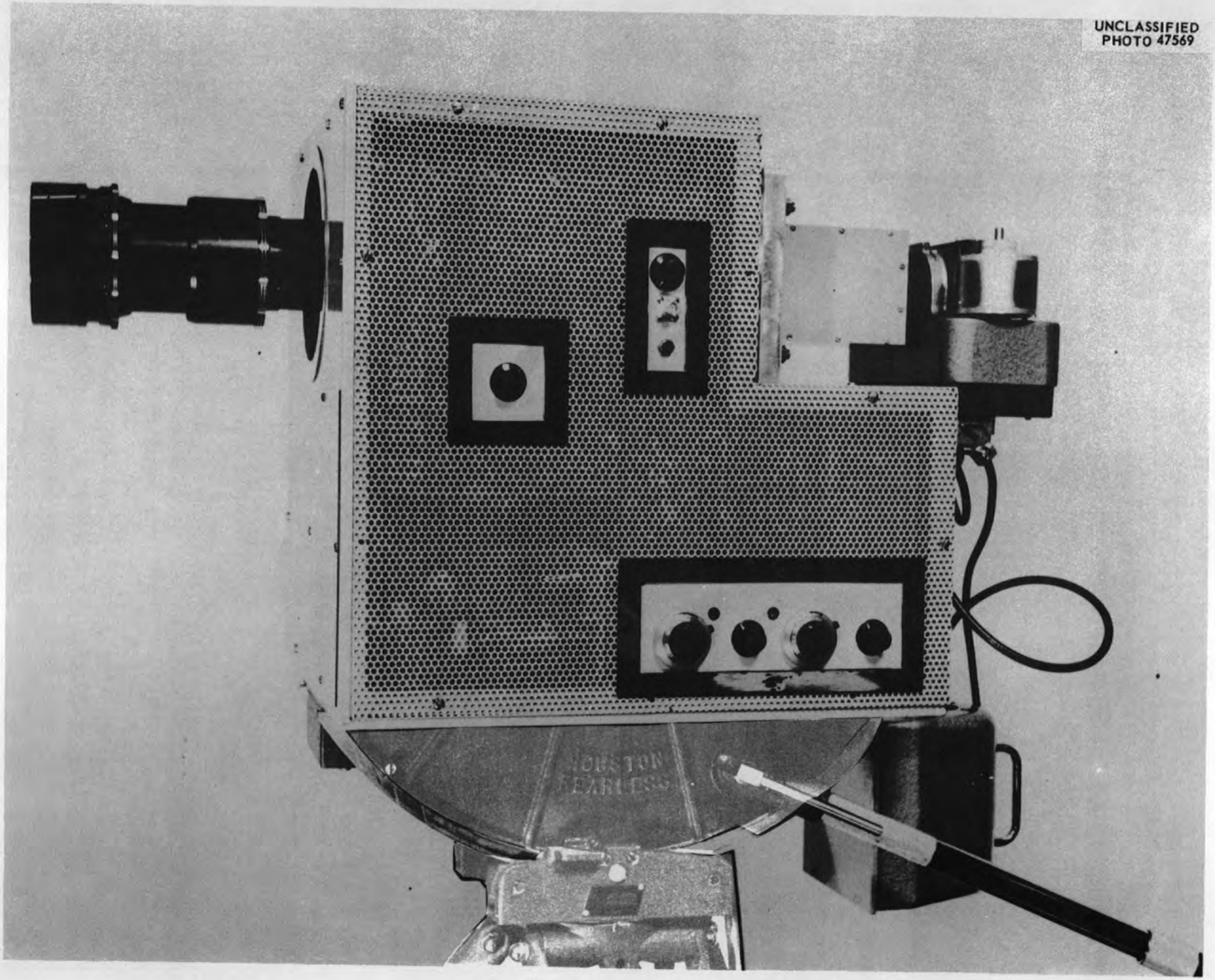


Fig. 8. Left-Side View of Camera Head.

UNCLASSIFIED
PHOTO 47570

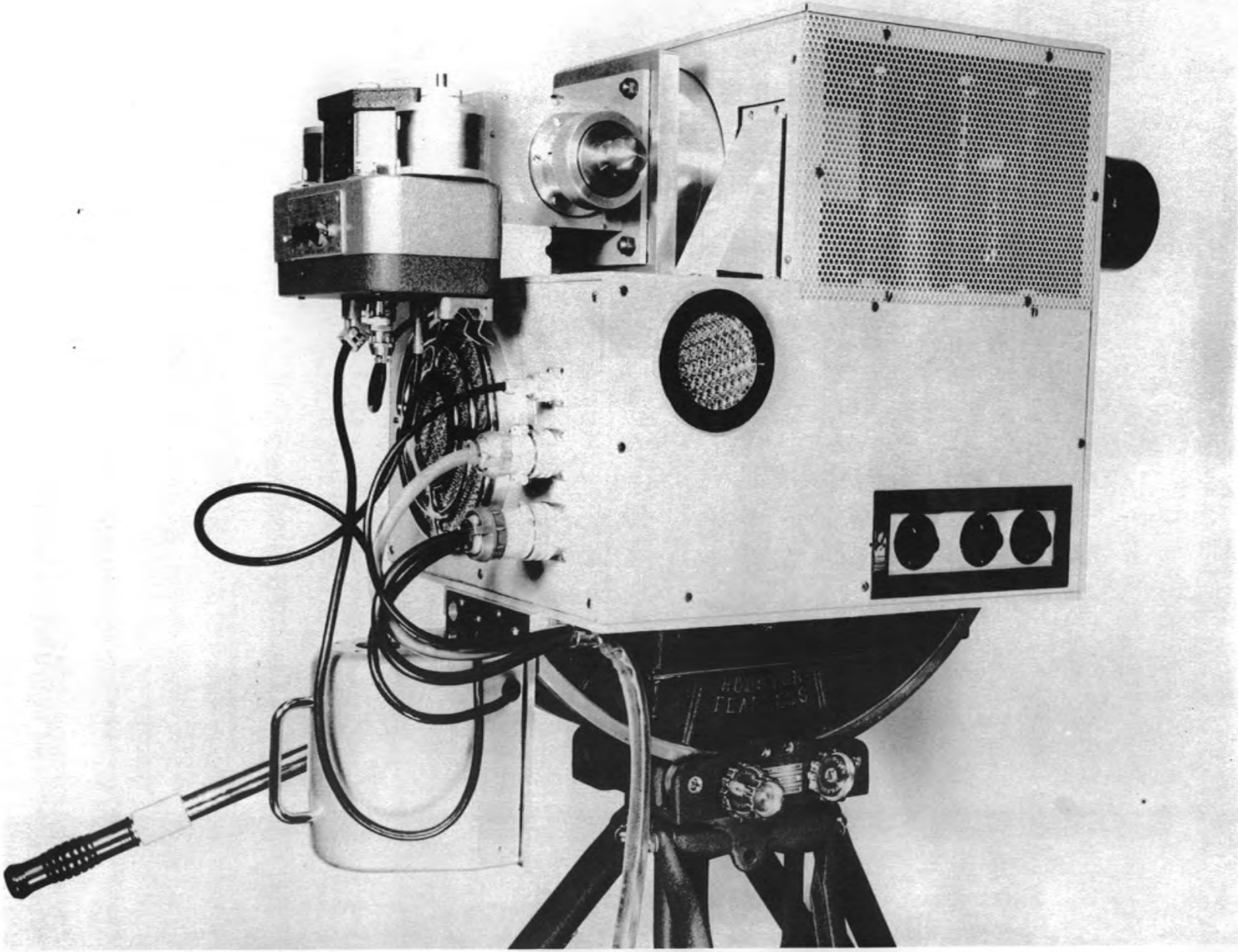


Fig. 9. Right-Side View of Camera Head.

transport permits either single exposure or continuous film motion operation. Two high quality lenses are available for use with this camera; a f/1.5 50mm lens, and for maximum light transfer, a f/1.0 50mm lens. The film used is Linagraph Ortho roll film which is most sensitive in the blue region. It is given a speed rating of 160 for tungsten light by the manufacturer, Kodak Corporation.

Fig. 10 indicates some of the construction techniques and the method of mounting the image converter tube. The tube is mounted within the cylinder which extends through the top half of the camera head. This cylinder is made of layers of co-netic, fer-netic shielding materials and is adequate protection for the image converter tube in fields up to one thousand gauss.

Table I summarizes the operating parameters of the camera along with listing some of the more important features.

SHUTTER TUBE PERFORMANCE

A test of light gain obtained with the image converter tube was made with a General Electric PSP2 Photospot lamp which has a color temperature of 3200° Kelvin as a light source and an accelerating potential of 13,000 volts. The gain in light flux was found to be about 10. Brightness gain should be somewhat more, since it also depends on the amount of demagnification in the system.

The image converter tube being use arced over internally at about 13,500 volts and therefore the gain obtainable is limited to

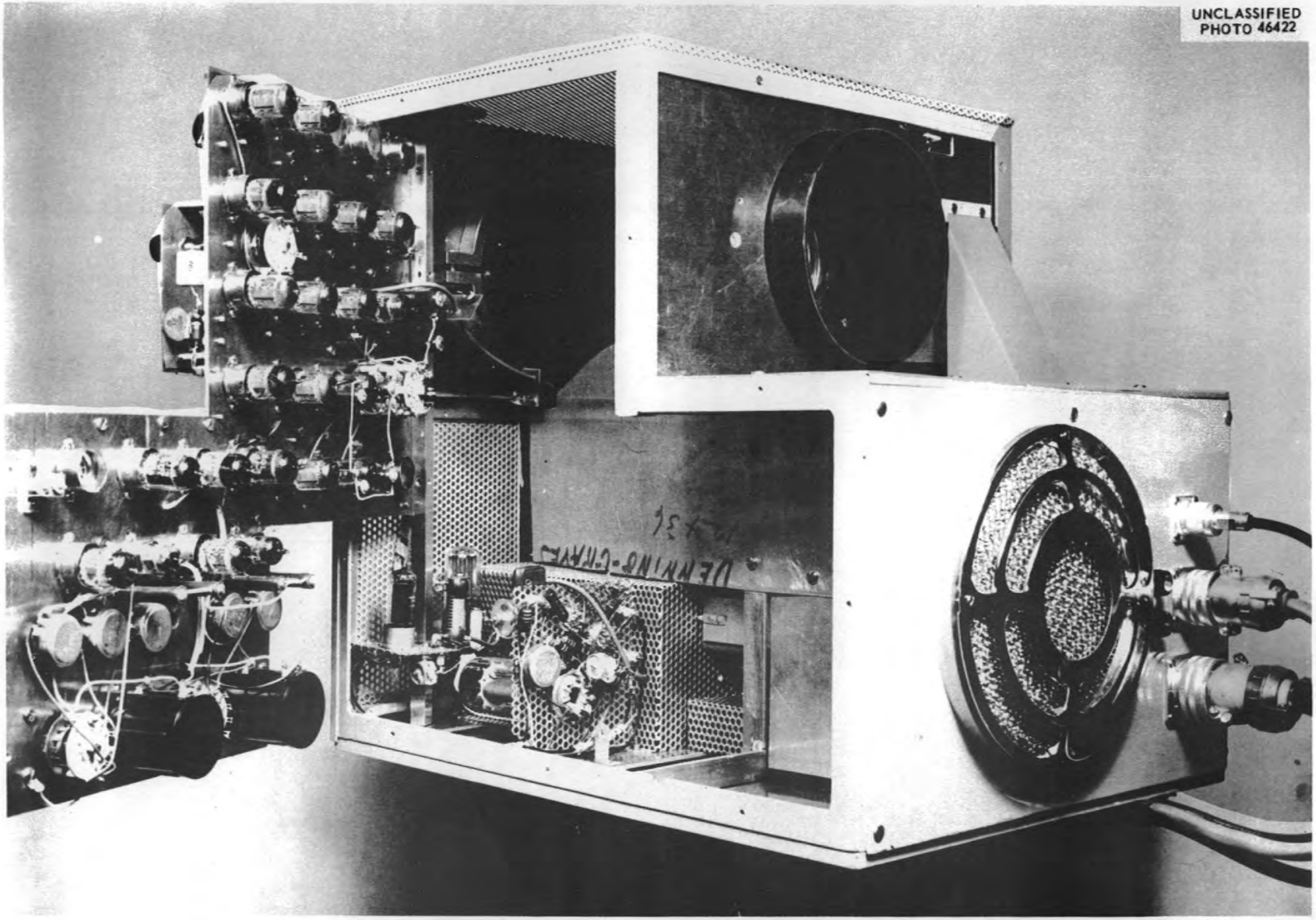


Fig. 10. Internal View of Camera Head.

Table I. Performance Characteristics of Camera

Exposure time	0.6 to 100 microseconds
Exposure spacing	1.0 to 1000 microseconds
Number of Exposures	1, 2, 4, or 8
Frontal lenses	50mm f/0.8
	90mm f/1.5
	180mm f/1.5
	310mm f/2.5
Rear lenses	50mm f/1.0
	50mm f/1.5
Synchronization	External trigger or local control
Conversion gain (measured)	Approx. 10 at 13 KV anode voltage using photospot PSP2 as light source.

something less than possible with the normal 15,000 volt accelerating potential. At present the tube is operated with about 12,000 to 13,000 volts applied to its anode.

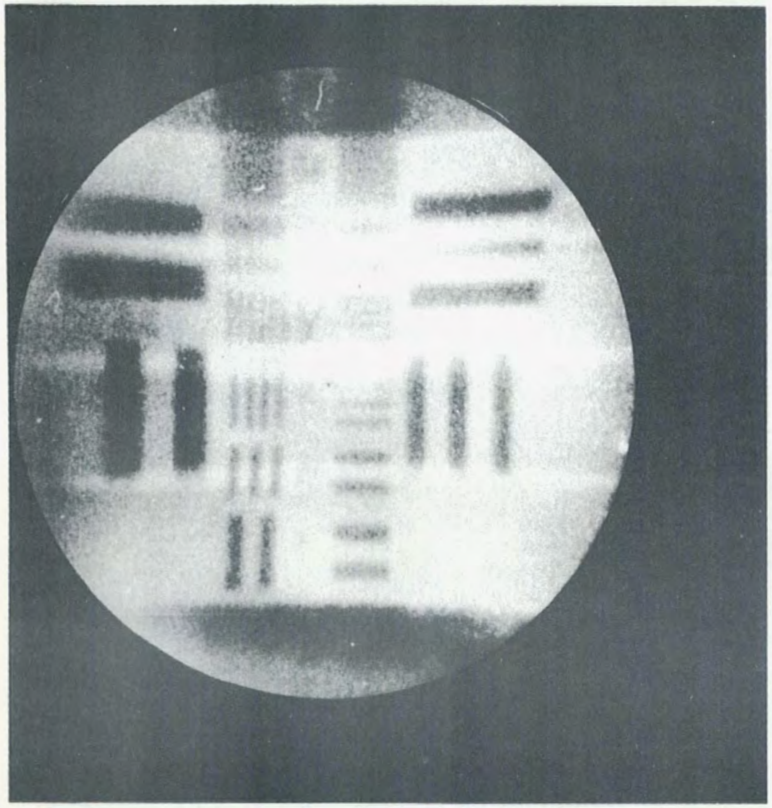
It was also found that adjustment of the operating voltages on the shutter tube would not completely prevent the image of the control grid from appearing on the phosphor screen. Voltage settings which presented the sharpest focus were not the same as those which minimized control grid image. These lines can be seen in some of the photographs on the following pages.

No test of resolution under steady-state (non-pulsed) conditions was made but under pulsed conditions the resolution was approximately 6 line-pairs per millimeter (referred to the cathode). As in other cameras resolution is affected by light intensity.

Figs. 11 and 12 are photographs of a resolution chart which was placed about 17 inches away from the electronic camera and illuminated with a photospot lamp. As indicated exposure time in Fig. 11 was 10 microseconds and in Fig. 12 it was 100 microseconds. Both pictures were made using the 180mm lens at f/1.5. The horizontal lines in the pictures are the shadows of the control grid.

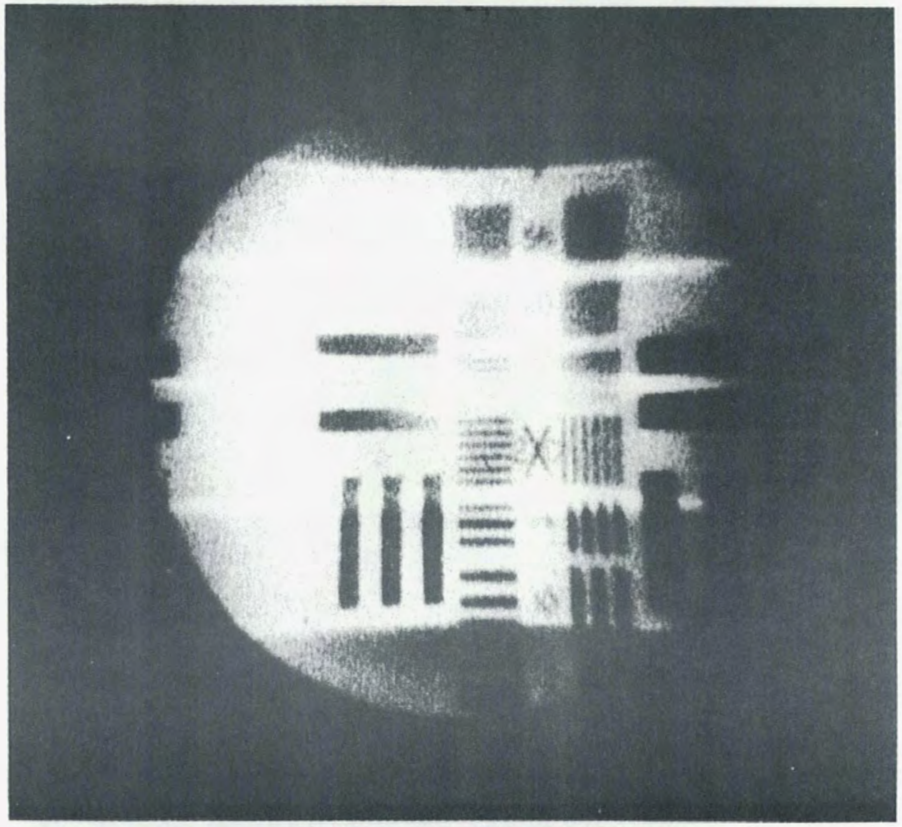
Fig. 13 was made with the same physical conditions but in the mode of operation which produces two images in sequence. Exposure times in this case were 20 microseconds. Resolution is poorer in this picture because both images are off the center of the phosphor screen.

UNCLASSIFIED
PHOTO 47581



EXPOSURE TIME – 10 μsec

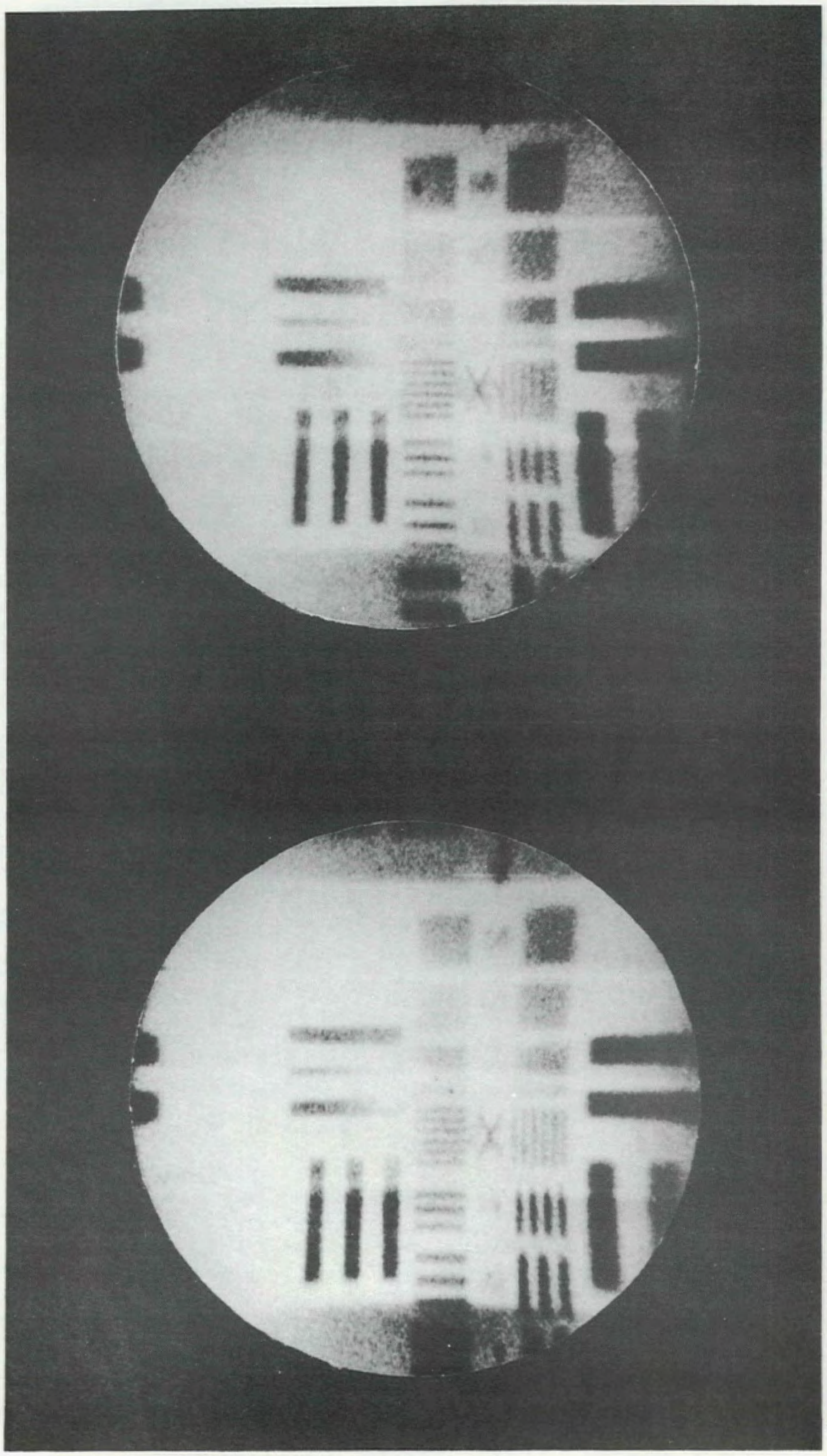
Fig. 11. Resolution Chart.



EXPOSURE TIME – 100 μsec

Fig. 12. Resolution Chart.

UNCLASSIFIED
PHOTO 47707



EXPOSURE TIME – 20 μsec

Fig. 13. Series of Exposures of Resolution Chart.

TEST RESULTS

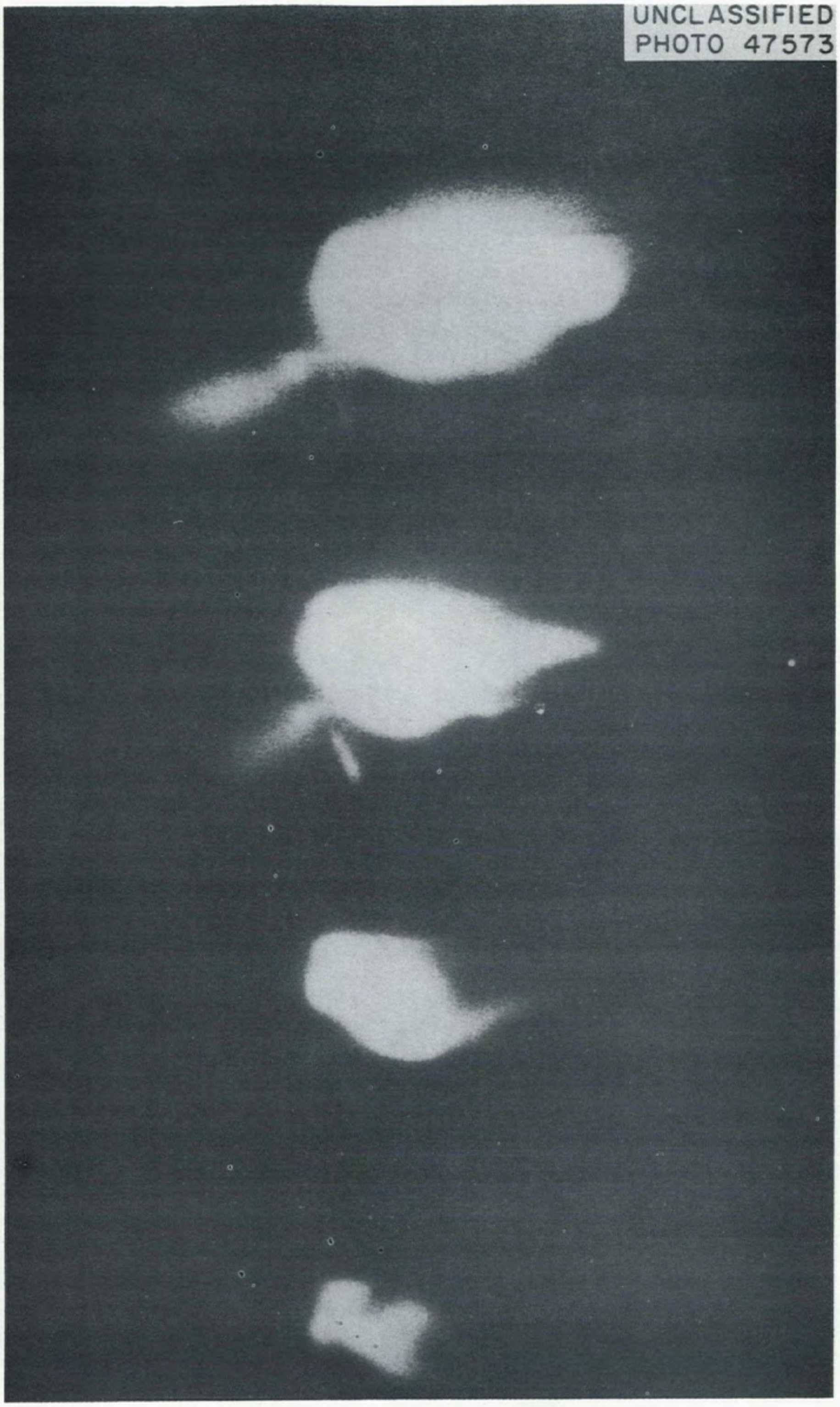
Preliminary testing of the electronic camera was performed by photographing electrical discharges. Two carbon electrodes were mounted in a tube to which a vacuum pump and gauge were connected so that the arc could be fired at various air pressures. A variable direct current high voltage supply furnished the driving power for a 0.2 μf high voltage condenser which was discharged to form the arc.

In all of the following pictures the anode is located on the left side and the cathode on the right. Both electrodes were 1/8th inch in diameter. Also, each series of images starts at the top and progresses downward with time. The 180mm f/1.5 lens was used for all photographs.

The photograph shown in Fig. 14 is that of a 1-1/4 inch long arc. The air pressure was about 200mm of mercury and 8 KV was impressed across the electrodes. Exposure time and exposure interval are listed on the figure. The photograph was taken with the lens stopped down to f/16. The form of the arc as it decays can be seen and several corona discharges are also evident at the anode.

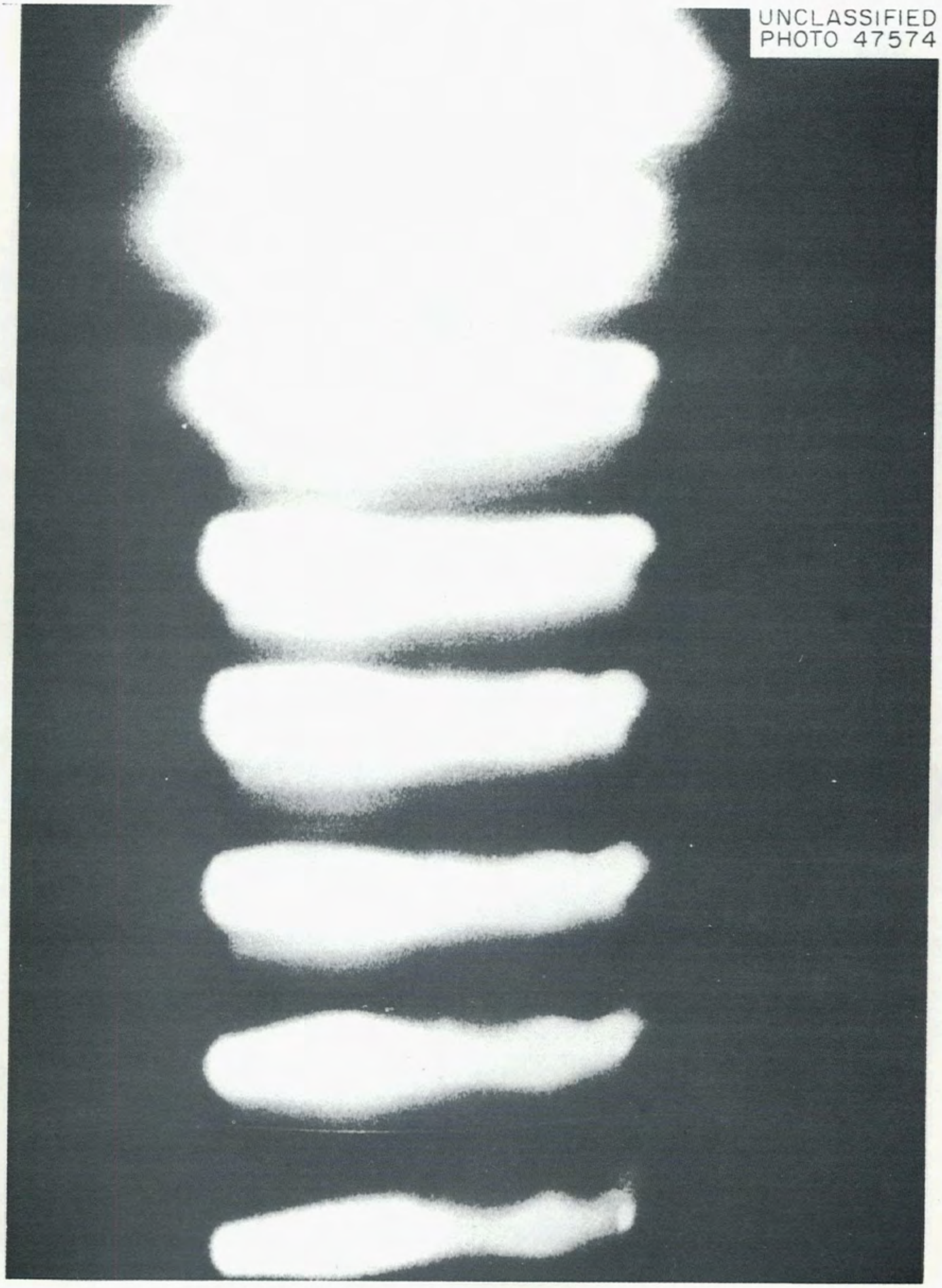
Figs. 15 and 16 were taken under the same physical and electrical conditions except for the aperture of the front lens. Here the arc was 2.5 inches long and occurred at a pressure of about 90mm. The voltage impressed across the electrode was again 8 KV. The front lens was opened to f/1.5 for Fig. 15 and set at f/8.0 for Fig. 16.

Fig. 17 is a photograph taken with the same arc characteristics as in the previous two pictures. The lens was adjusted to f/8.0. The time covered by this series of exposures is 29.6 microseconds, about 5



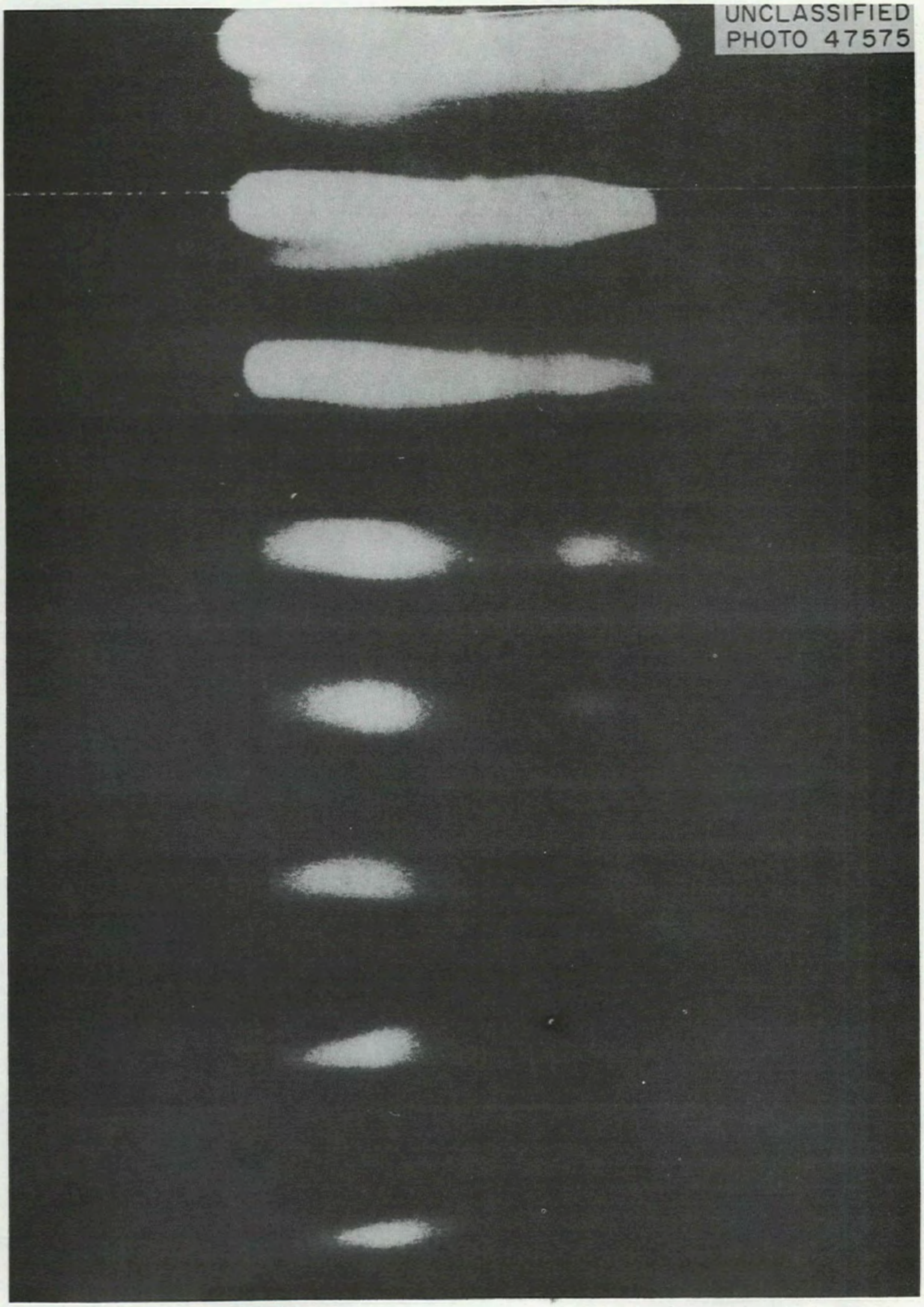
EXPOSURE TIME – 1 μsec
EXPOSURE INTERVAL – 3 μsec
FRONT LENS – f/16.0

Fig. 14. Arc Discharge.



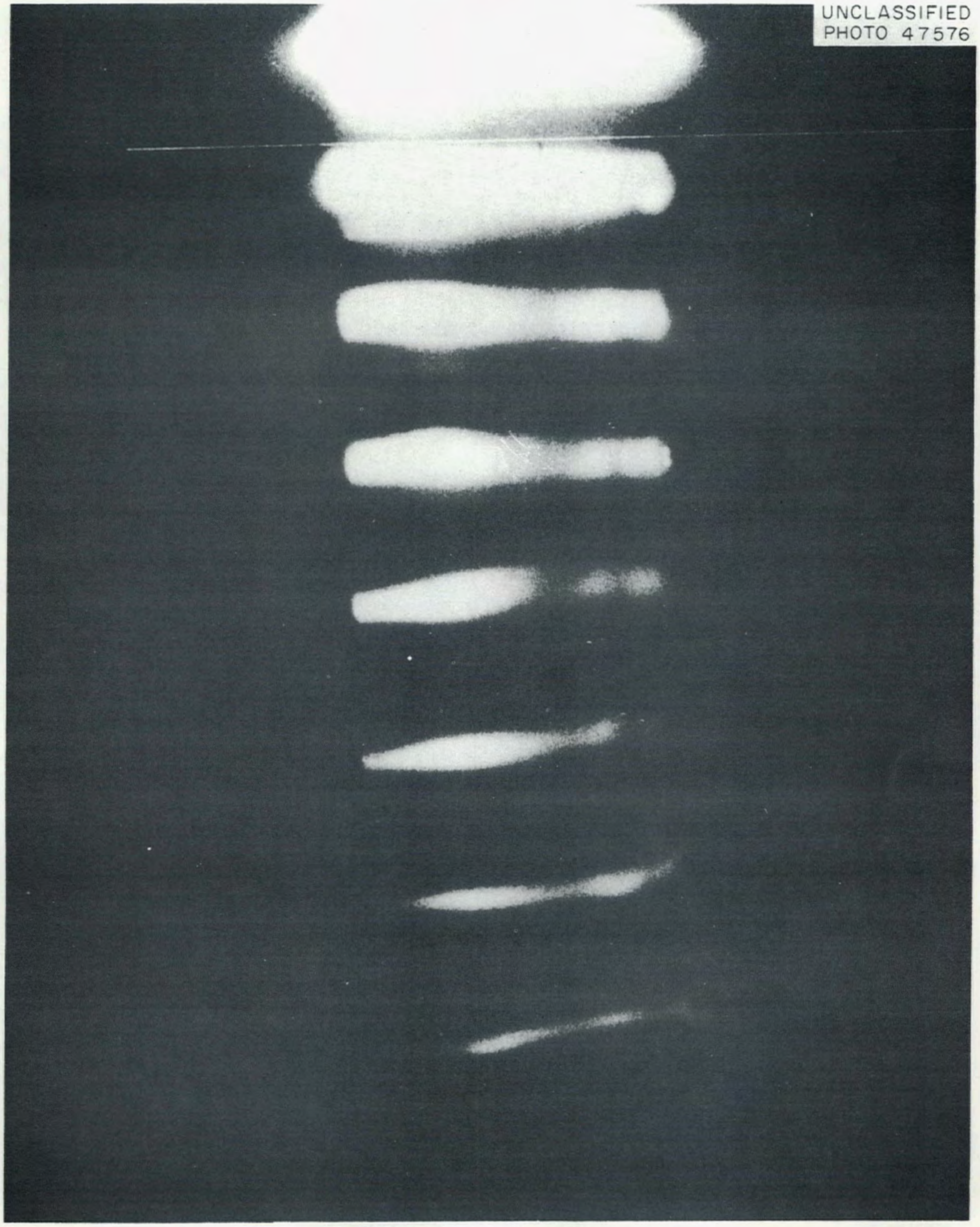
EXPOSURE TIME - 1.25 μsec
EXPOSURE INTERVAL - 1.75 μsec
FRONT LENS - f/1.5

Fig. 15. Arc Discharge.



EXPOSURE TIME - 1.25 μsec
EXPOSURE INTERVAL - 1.75 μsec
FRONT LENS - f/8.0

Fig. 16. Arc Discharge.



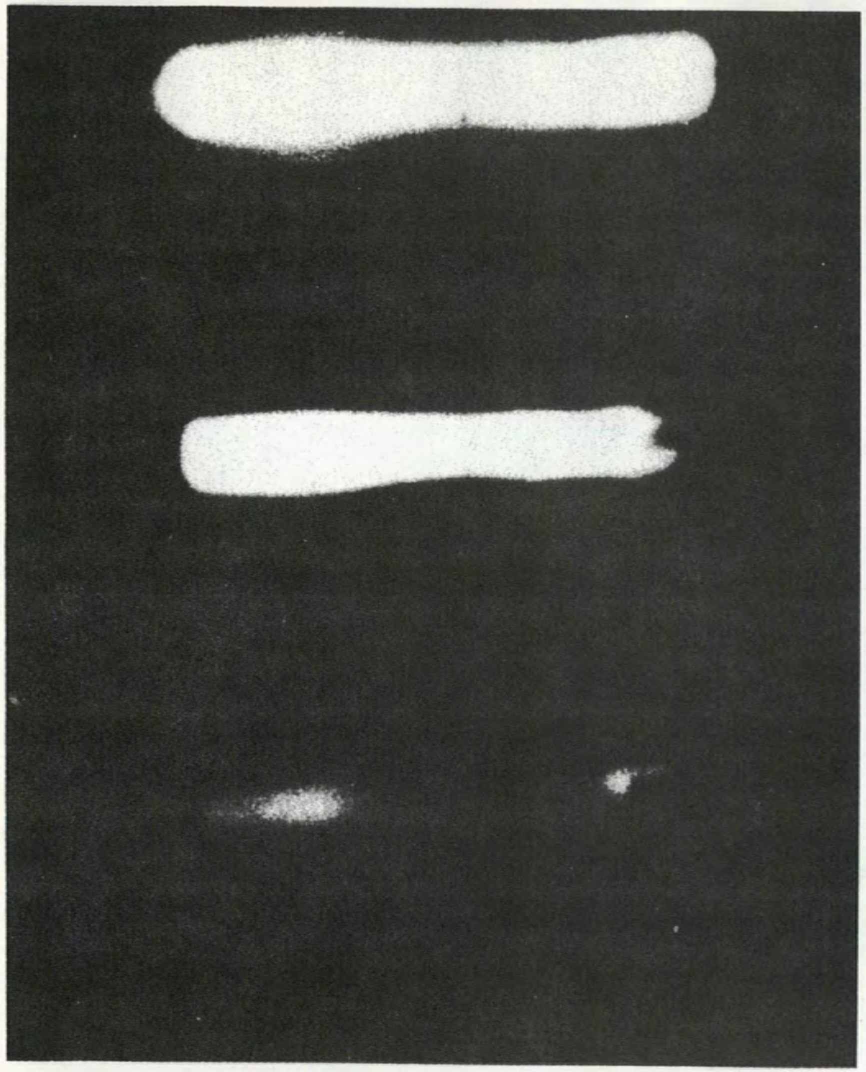
EXPOSURE TIME - 1.6 μsec
EXPOSURE INTERVAL - 2.4 μsec
FRONT LENS - f/8.0

Fig. 17. Arc Discharge.

microseconds longer than in Figs. 15 and 16. An interesting characteristic of this particular arc can be seen in the fourth exposure from the top where the two bright spots on the cathode apparently indicate the main points from which the arc emanates.

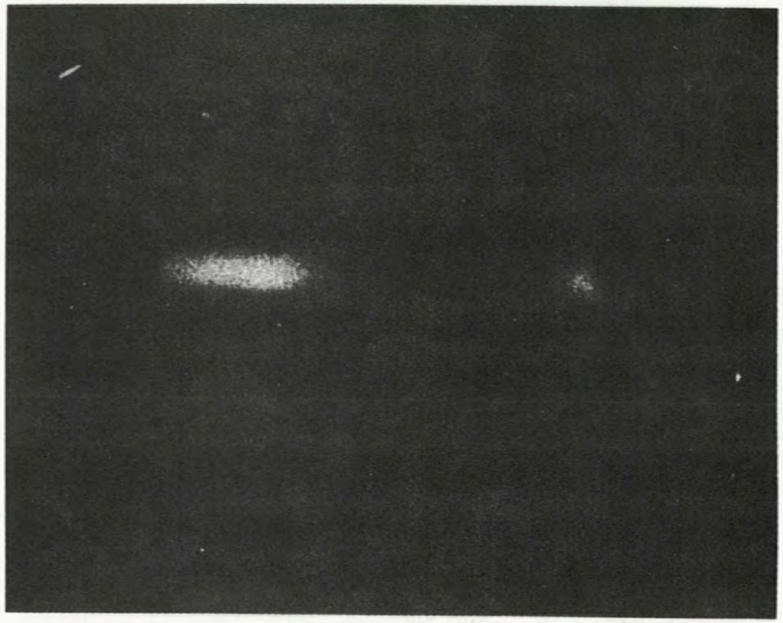
The last two photographs of arcs, Figs. 18 and 19, were taken with an aperture setting of f/1.5. The arc, about 2.25 inches long, occurred at a pressure of 6.5mm with an impressed voltage of 7 KV. Fig. 18 is a multiple-exposure picture of the arc showing quite clearly the outline of the cathode in the third image from the top. Fig. 19 is a single exposure photograph. Again the outline of the cathode can be seen.

UNCLASSIFIED
PHOTO 47583



EXPOSURE TIME - 2.5 μsec
EXPOSURE INTERVAL - 3.0 μsec

Fig. 18. Arc Discharge at 6.5 mm Hg Pressure.



EXPOSURE TIME - 2.5 μsec

Fig. 19. Arc Discharge at 6.5 mm Hg Pressure.

CONCLUSIONS

There are three features of an electronic camera which set it apart from other high-speed photographic techniques. The first is that the shuttering problem is transformed from the mechanical realm to the control of an electron beam. This is an almost inevitable step in the development of high-speed devices since ease of control and freedom from jitter and vibration are such attractive qualities.

Second, the acceleration of the electrons provides a mechanism for introducing energy into the image. An image converter can produce an image of greater intensity than the object being photographed. This is a great advantage since high-speed photography is frequently hampered by the lack of brightness of the image due to the short time in which the film must be exposed.

The third feature of an electronic camera is that synchronism to the event being photographed or generating a synchronizing pulse when the shutter is "tripped" is relatively simple.

Summarizing the more outstanding features of the camera described in this paper:

1. Exposure time and intervals between exposures can be accurately and continuously selected as opposed to the more usual selection of times in steps.

2. A conversion gain of approximately ten is possible in the image converter tube and a system brightness gain of up to one or more can be obtained as opposed to a loss of 50 per cent or more in other systems.

3. The camera is simple to operate and all operating parameters can be changed rapidly with practically no "dead-time".

4. The camera is relatively small and highly mobile. Setting up at a new location is simple and rapidly performed.

REFERENCES

1. IMAGE-CONVERTER CAMERA FOR STUDIES OF EXPLOSIVE PHENOMENA, F. C. GIBSON, et. al., Review of Scientific Instruments, Vol. 25, No. 2, Feb. 1954, pp. 173-176.

2. PHOTOGRAPHIC INSTRUMENTATION IN THE STUDY OF EXPLOSIVE REACTIONS, M. SULTANOFF, Journal of SMPTE, Feb. 1953, pp. 89-97.

3. 1958 SYMPOSIUM ON PHOTOELECTRIC IMAGE DEVICES AS AIDS TO SCIENTIFIC OBSERVATIONS, D. J. SAFFARANO, Office of Naval Research Technical Report (To be published summer of 1959).

4. KERR-CELL SHUTTER HAS SUBMICROSECOND SPEED, W. G. NICHOLSON and I. ROSS, Electronics, June 1956, pp. 171-173.

5. HIGH SPEED CAMERAS, J. S. COURTNEY PRATT and D. THACKERAY, Journal of Photographic Sciences, Vol. 5, No. 2, March/April 1957, pp. 32-42.

6. IMAGE CONVERTER - A NEW HIGH SPEED SHUTTER DEVICE, R. W. KING, I.R.E. Transactions on Telemetry and Remote Control, Vol. TRC-1, pp. 8-12.

7. SHUTTER IMAGE CONVERTER TUBE FOR MULTIPLE-FRAME PHOTOGRAPHY, W. O. REED and W. F. NIKLAS, Journal of the Society of Motion Picture and Television Engineers, Vol. 68, No. 1, Jan. 1959, pp. 1-5.

8. INTENSE GASEOUS DISCHARGES, J. S. LUCE, Proceedings of the Second United Nations International Conference on the Peaceful Use of Atomic Energy, Vol. 31, Theoretical and Experimental Aspects of Controlled Nuclear Fusion, United Nations Publication, Geneva, Switzerland, 1958, pp. 305-314.

8. THE OAK RIDGE THERMONUCLEAR EXPERIMENT, C. F. BARNETT, et. al., Proceedings of the Second United Nations International Conference on the Peaceful Uses of Atomic Energy, Vol. 31, Theoretical and Experimental Aspects of Controlled Nuclear Fusion, United Nations Publication, Geneva, Switzerland, 1958, pp. 298-302.

10. MILLIMICROSECOND PHOTOGRAPHY WITH AN IMAGE CONVERTER CAMERA, R. C. MANINGER and R. W. BUNTENBACH, Paper Published by Precision Technology, Inc., Livermore, California, March 1957, 14 pages.

11. AN IMAGE-CONVERTER TUBE FOR HIGH-SPEED PHOTOGRAPHIC SHUTTER SERVICE, R. G. STOUDENHEIMER and J. C. MOOR, R.C.A. Review, Sept. 1957, pp. 322-331.

12. AN ELECTRONIC FRAMING CAMERA FOR MILLIMICROSECOND PHOTOGRAPHY, G. L. CLARK, 1958 IRE Wescon Convention Record, Part 5, pp. 189-195.

13. PRELIMINARY AND TENTATIVE DATA RCA IMAGE CONVERTER, DEV. NO. C73435B, STAFF, Radio Corporation of America, Harrison, New Jersey, Jan. 8, 1958, 8 pages.

14. DESIGN OF PHANTASTRON TIME DELAY CIRCUITS, R. N. CLOSE and M. T. LEBENBAUM, Electronics, April, 1948, pp. 100-107.

APPENDIX I

IMAGE CONVERTER TUBE SPECIFICATIONS[13]

Table II lists some of the more important electrical and optical characteristics of this tube. All voltages are referred to the cathode and an anode voltage of 15,000 volts, the maximum rating, is assumed. An acceleration potential of 30,000 volts can be used if the anode is pulsed with this voltage for periods of time not exceeding one second.

Shutter speeds attainable with this tube are limited by the ability of the external circuitry to supply good square-wave pulses of sufficiently short time. With adequate pulse-forming circuits, the minimum exposure time is limited by electron transit time. The calculated transit time of electrons between cathode and ultor for 15 kilovolts on the ultor is about 5×10^{-9} seconds. Since the electrons are defocused if they are not beyond the influence of the gating grid when its voltage returns to the cut-off value, loss of resolution becomes noticeable at exposure times in the order of 10^{-8} seconds.

The distortion characteristics and the spectral response of the photocathode and phosphor screen are shown in Fig. 20 and Fig. 21. The phosphor screen has a short persistence, decaying to ten per cent of maximum in about 0.4 milliseconds.

Table II. Specifications of C73435B Image Converter Tube

Photocathode	
Diameter	1.375 inches
Sensitivity, at 4400 Å	0.016 μa/mw
Control Grid	
Cut-off Potential	-100 volts
Operating Potential	170 to 190 volts
Cathode to Grounded Grid	28 μμf
Electronic Lens	
Type	Electrostatic
Magnification	0.71
Nominal Operating Potential	1400 V
Deflector System	
Type	Electrostatic, one axis only
Deflection Factor	1100 to 1200 volts per inch per plate
Anode (Phosphor Screen)	
Diameter	3 inches
Operating Potential	15 KV (max)
Phosphor	P11
Resolution (referred to cathode)	17 line-pairs/mm
Conversion Gain at 4400 Å	12 min.

UNCLASSIFIED
ORNL-LR-DWG 39438

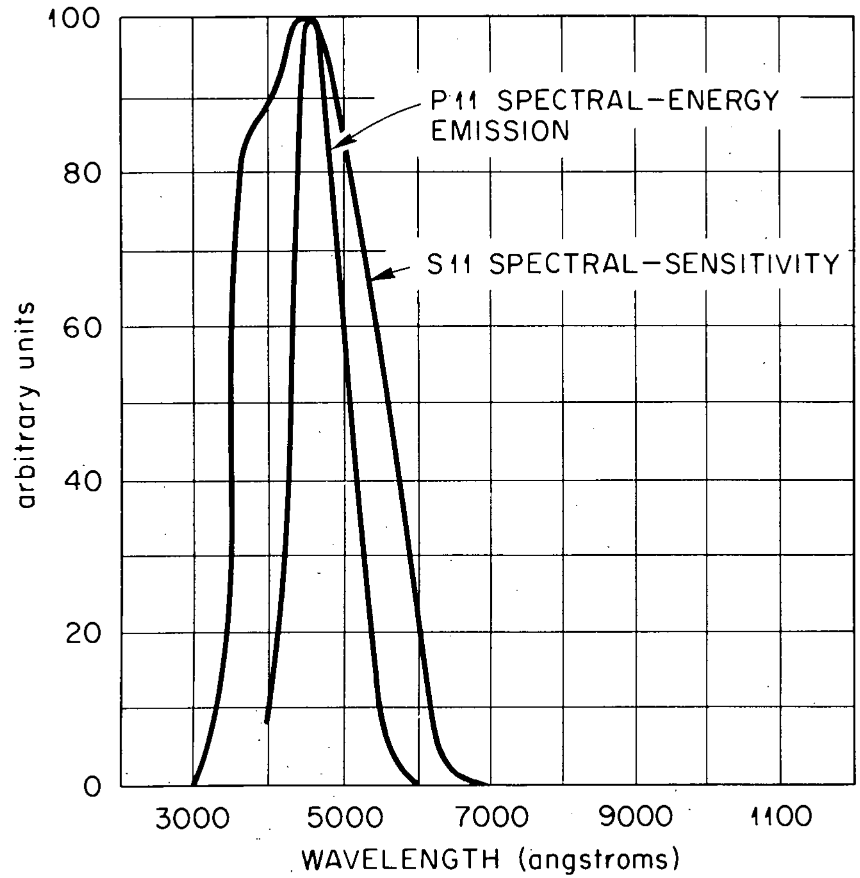


Fig. 20. Spectral Characteristics of the Photocathode and Fluorescent Screen Used in the Image-Converter Tube.

UNCLASSIFIED
ORNL-LR-DWG 39439

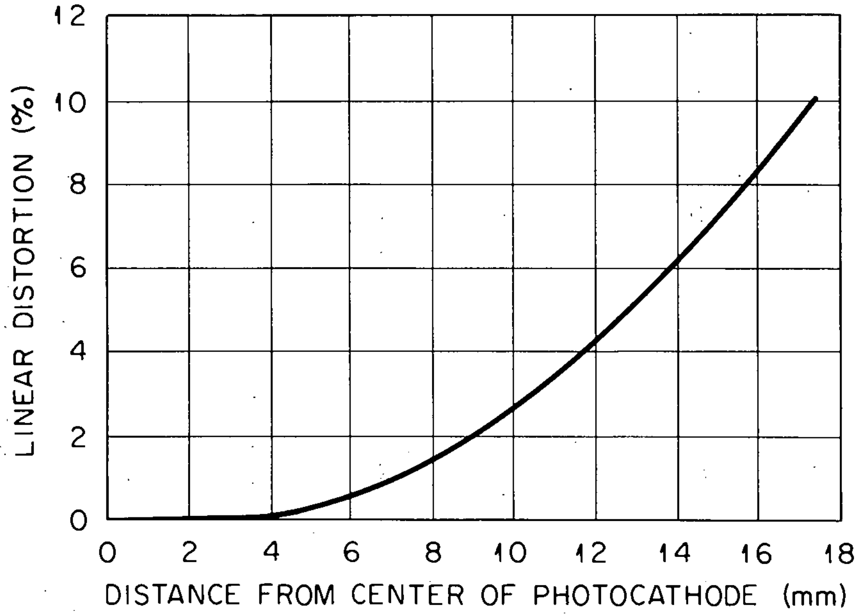


Fig. 21. Distortion Characteristics of the C73435 Converter Tube.

APPENDIX II

PHANTASTRON TIMING CIRCUITS[14]

The phantastron circuit shown in Fig. 22 is used to generate the shutter pulse and the pulse which determines the interval between successive shutter pulses. The linear decrease in plate voltage with time of the 6AS6 tube is used as a time base.

In the quiescent condition, the suppressor grid is sufficiently negative to cut off the plate current and the control grid is at zero bias, approximately, because of the positive grid return. Except for a very small grid current all of the space current goes to the screen. If the suppressor is suddenly brought up to zero by the trigger, the time base is initiated.

A large fraction of the space current must now flow to the plate as in a normal pentode. At the first instant the stray capacities supply most of the plate current. As these discharge the plate voltage drops and current flows through the plate load resistor. This drop is transmitted to the grid by the grid to plate capacity (in this case augmented by an external capacitor) and as a result space current is reduced. An equilibrium point is soon reached where the plate current is the normal fraction of the existing space current, and the fall of the plate voltage is arrested.

The plate voltage continues to fall (but at a slower rate) because the control grid voltage rises and increases the space current and therefore the plate current. This continuous drop of the plate voltage

UNCLASSIFIED
ORNL-LR-DWG 39795

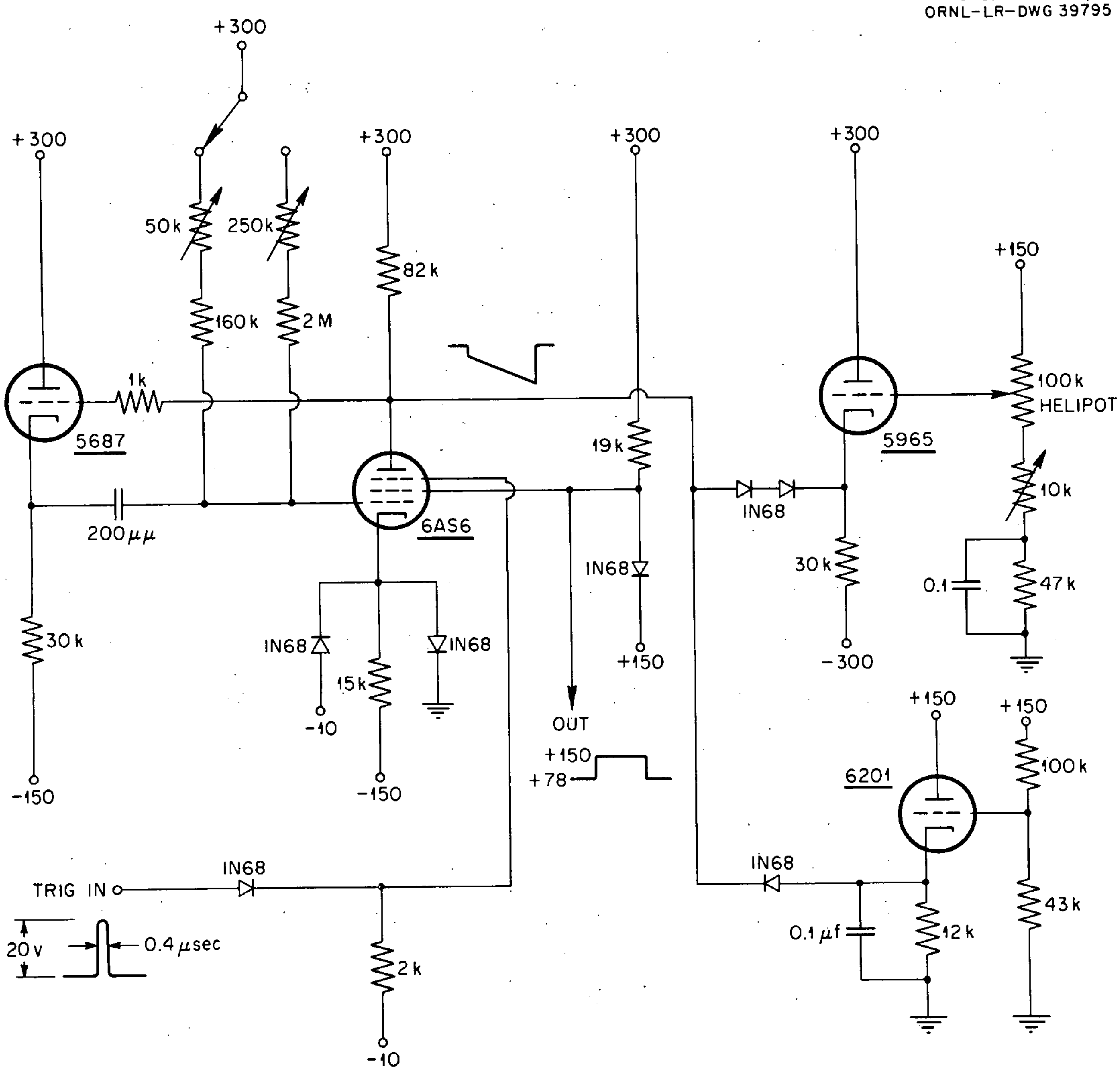


Fig. 22. Phantastron Circuit.

reflected to the grid retards the rise of grid voltage and it is this feedback which is responsible for the linear fall of the plate voltage after the initial jump.

Basically the phantastron is a Miller run-down circuit. A simplified drawing of this circuit, Fig. 23, can be used to explain its operation. The input capacity of the tube is

$$C_{in} = C_{gk} + C_{gp}(1 + A) \qquad (1)$$

where C_{gp} has been increased by the addition of C_g. Since A >> 1, the input capacity is very closely AC_g and the input time constant is AR_gC_g.

For small grid variations the variation in the plate current of a pentode may be expressed as

$$i_p = g_m(e_g + e_{sg}/\mu_{sg} + e_p/\mu_p) \qquad (2)$$

where e_g, e_{sg}, and e_p are the instantaneous control grid, screen grid, and plate potentials, and μ_{sg} and μ_p are the screen grid and plate amplification factors, and g_m is the plate-control grid transconductance. If v_c is the voltage across C_g at any instant, then from equation (2)

$$i_p = g_m \left[(E_{BB} - R_L i_L - v_C) + e_{sg}/\mu_{sg} + (E_{BB} - R_L i_L)/\mu_p \right] \qquad (3)$$

Solving for i_L and noting that $i_p = i_L + i_s + i_c$

$$i_L = \frac{g_m[E_{BB} - v_C + e_{sg}/\mu_{sg} + E_{BB}/\mu_{sg}] - i_c - i_s}{1 + g_m R_L + g_m R_L/\mu_p} \qquad (4)$$

In order that di_L/dt, and therefore de_p/dt, be constant each term of the denominator of equation (4) must be constant and the terms

UNCLASSIFIED
ORNL-LR-DWG 39796

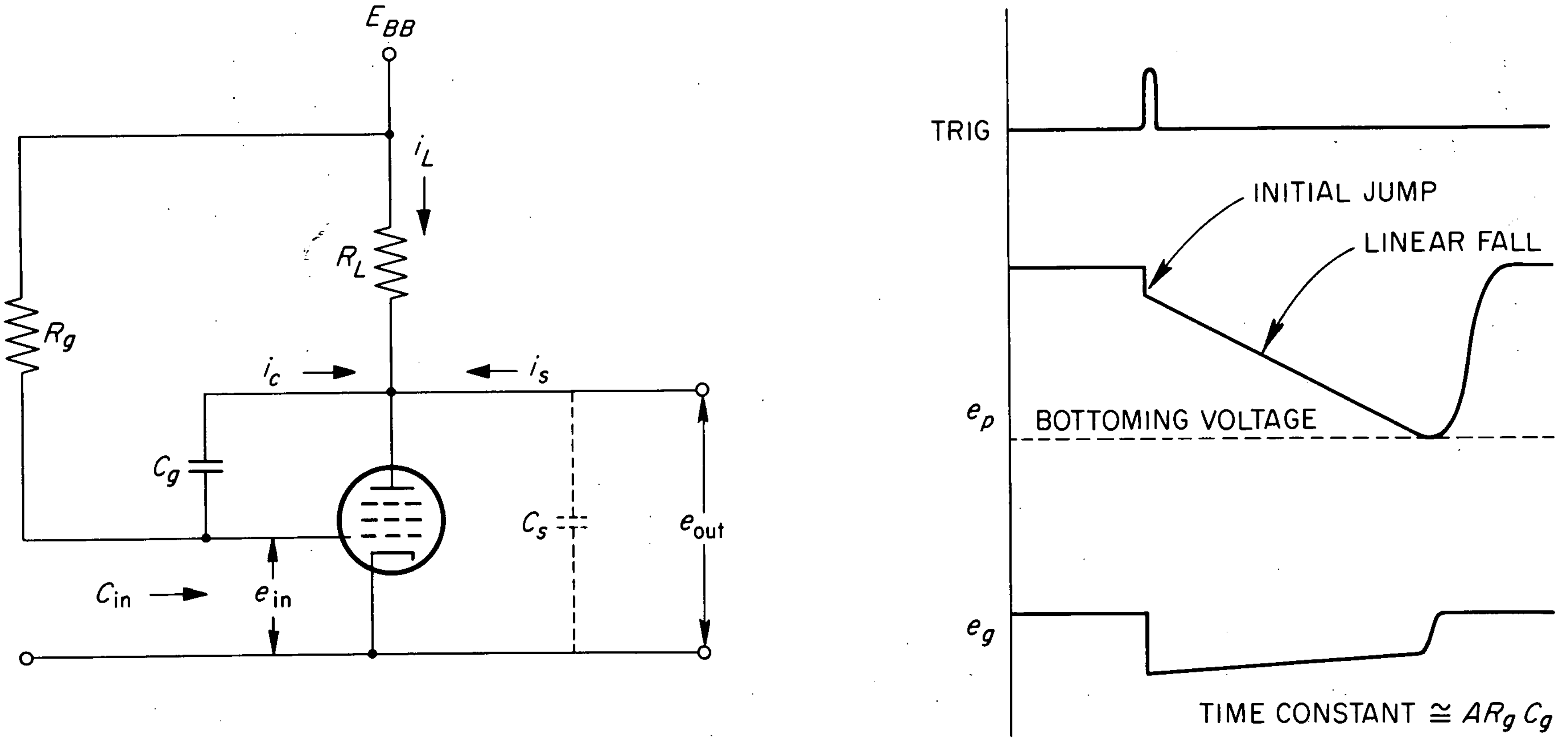


Fig. 23. Equivalent Run-Down Circuit

of the numerator must be constant or vary linearly with time. With a large R_L and small grid changes, and assuming operation is above the knee of the $e_p i_p$ characteristic of the tube, g_m, μ_p, e_{sg}, and μ_{sg} are relatively constant. The current i_c flowing into C_g is $(E_{BB} - e_g)/R_g$ and since the change in e_g is small, i_c can be expressed

$$i_c = (E_{BB} - e_g)/R_g \tag{5}$$

Also, $dv_c/dt = i_c/C_g$, so from equation (5) we have

$$dv_c/dt = (E_{BB} - e_g)/R_g C_g \tag{6}$$

During this phase of operation, e_p falls slowly and i_s is small compared to i_c if $C_g >> C_s$.

Differentiating equation (4) and multiplying both sides by R_L,

$$R_L \frac{di_L}{dt} = \frac{de_p}{dt} = - \frac{g_m R_L}{1 + g_m R_L(1 + 1/\mu_p)} \frac{E_{BB} - e_g}{R_g C_g} \tag{7}$$

Assuming that $\mu_p >> 1$ and $g_m R_L >> 1$, equation (7) reduces to

$$de_p/dt = (E_{BB} - e_g)/R_g C_g \tag{8}$$

This indicates that the fall of plate voltage is linear.

When the plate voltage falls to a very low value, the plate "bottoms", the net plate current no longer changes and there is no feedback to the grid. The circuit then recovers to its original conditions.

In the phantastron circuit of Fig. 22 the plate runs down from a voltage determined by the setting of the Helipot to a voltage determined by the bleeder circuit in the grid of the 6201. This arrangement, along with the 5687 cathode follower driving the grid capacity of the 6AS6, provides a variable run-down time, ensures fast recovery to initial conditions after each time-base has been generated, and stabilizes the circuit against tube and circuit parameter drift.

ORNL-2804
Instruments
TID-4500 (15th ed.)

INTERNAL DISTRIBUTION

1. C. E. Center
2. Biology Library
3. Health Physics Library
4-5. Central Research Library
6. Reactor Experimental Engineering Library
7-26. Laboratory Records Department
27. Laboratory Records, ORNL R.C.
28. A. M. Weinberg
29. L. B. Emlet (K-25)
30. J. P. Murray (Y-12)
31. J. A. Swartout
32. E. H. Taylor
33. E. D. Shipley
34. C. S. Harrill
35. M. L. Nelson
36. W. H. Jordan
37. S. C. Lind
38. F. L. Culler
39. A. H. Snell
40. A. Hollaender
41. M. T. Kelley
42. K. Z. Morgan
43. T. A. Lincoln
44. A. S. Householder
45. C. E. Winters
46. H. E. Seagren
47. D. Phillips
48. J. L. Lovvorn
49. P. R. Bell
50. C. J. Borkowski
51. G. S. Hurst
52. R. S. Livingston
53. E. Fairstein
54-58. C. H. Schalbe
59. C. W. Sheppard
60. W. G. Stone
61. C. P. Keim
62. C. D. Susano
63. J. V. Francis
64. M. J. Skinner
65. R. W. Johnson
66. D. J. Fisher
67. E. G. Struxness
68. J. R. McNally
69. J. L. Gabbard
70. R. A. Charpie
71. T. V. Blosser
72. E. L. Olson
73. J. A. Auxier
74. R. K. Abele
75. J. R. Tallackson
76. H. E. Banta
77. E. W. Burdette
78. R. R. Dickison
79. C. A. Mossman
80. D. S. Toomb
81. R. G. Affel
82. H. J. Stripling
83. E. P. Epler
84. F. W. Manning
85. J. L. Blankenship
86. L. D. Roberts
87. J. W. T. Dabbs
88. J. Walter
89. S. H. Hanauer
90. R. H. Dilworth
91. P. M. Reyling
92. ORNL - Y-12 Technical Library, Document Reference Section

EXTERNAL DISTRIBUTION

93. Division of Research and Development, AEC, ORO
94-710. Given distribution as shown in TID-4500 (15th ed.) under Instruments category (100 copies - OTS)