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DEPARTMENT OF SCIENTIFIC AND INDUSTRIAL RESEARCH AND FIRE OFFICES' COMMITTEE
JOINT FIRE RESEARCH ORGANIZATION

A SOURCE OF HIGH INTENSITY RADIATION EMPLOYING AN ARC LAMP AND AN ELLIPSOIDAL MIRROR

by

P. L. Hinkley

FR Note 270

This report describes the work carried out by the Fire Research Station for the Ministry of Supply under E.M.R. contract 7/tex/104/R3.

Summary

A high intensity carbon arc lamp is used with an ellipsoidal mirror as a source of radiation giving a maximum intensity of 55 w/cm^2. The area over which the intensity of radiation is greater than 90 per cent of the maximum is 3 cm^2. A venetian blind type of shutter may be operated either by a solenoid to produce a timed pulse of radiation of constant intensity; or by a cam driven mechanism to produce a pulse having the same time intensity relationship as that from an atomic bomb. A device has been developed which will detect and record the instant of ignition of an irradiated specimen.

December, 1956.

Fire Research Station,
Boreham Wood,
Herts.

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1. Introduction

A previous paper (1) described a source of high intensity radiation employing a high current carbon arc lamp and two parabolic reflectors. The maximum intensity that could be produced was greater than 200 w/cm^2 but the area over which the intensity exceeded 90 per cent of the maximum, was less than 0·1 cm^2. This small irradiated area limited the use of the apparatus, for two reasons. Firstly heat is conducted away radially from the irradiated spot and the temperature rise at the centre will become significantly less than that obtained with a very large area after a short time (2), particularly with good conductors. Even with bad conductors such as wood, errors which could not be neglected occurred with ignition times as short as 2·5 seconds. This difficulty can sometimes be overcome by using a small specimen.

Secondly in experiments on ignition a further source of error was the limited amount of flammable gas produced by the very small irradiated area. This greatly increased the minimum intensity of radiation at which ignition occurred and also tended to increase the ignition times at higher intensities (3).

The wide angle through which the beam converged on the specimen necessitated the accurate positioning of the specimen along the axis of the system; an error of as little as 1 mm resulted in a 10 per cent loss of intensity. The positive carbon of the lamp did not rotate and this meant that the image was irregularly shaped.

Several methods of obtaining relatively large and uniformly irradiated areas by means of an arc lamp are used in studio background and cinema projectors. The simplest employs a single ellipsoidal mirror to obtain a magnified image of the arc crater (Fig. 1). This has been adapted as a high intensity source (4) to produce intensities of up to 150 w/cm^2, with an area of 1 cm^2 receiving more than 88 per cent of the maximum intensity. Another type of studio background projector employs a condenser relay lens system (5). This has been adapted for use as a high intensity source in an apparatus built in the U.S.A. which will give 120 w/cm^2 over a circular area 0·8 in. in diameter or 60 w/cm^2 over an area 1·4 in. in diameter.

A system based on an ellipsoidal mirror was selected for the apparatus described in this report because of its greater simplicity. The mirror has the same diameter and focal lengths as in the system mentioned above (4) but by using a large positive carbon, a larger irradiated area was obtained at the expense of a reduced intensity.

2. Apparatus

2.1. General description

The apparatus is shown diagrammatically in figure 1 and its general appearance in plate 1. The arc lamp and mirror are enclosed in the lamphouse at the rear of the apparatus (plate 2). Two shutters are mounted over the hole in the front of the lamphouse through which the beam emerges. The first shutter (plate 3) is air cooled and has its blades horizontal. It can be controlled by a solenoid to give a pulse of radiation of constant intensity for a period set by an electronically controlled switch. The shutter can also be controlled by a cam mechanism to produce a pulse of radiation having the same intensity-time relationship as that produced by an atomic explosion [6]. The second shutter (plate 4) is used for attenuating the beam and is provided with a hand control enabling the blades to be set at any angle. It has its blades vertical to prevent the two shutters interacting to produce a striped pattern on the image.

The equipment for controlling the operation of the shutter is contained in a rack mounted unit.

The specimen is mounted at the focus, 2 ft from the lamphouse on a suitable holder which is carried on a sliding table (plate 5). The sliding table also carries a radiometer [7] so that measurements of the intensity of radiation can be made before and after each exposure. The mounting of the specimen in the correct position is facilitated by marking the focus by a plumb line.

A photo-electric device is provided which detects the ignition of a specimen and enables the time required to ignite the specimen to be recorded by an electrically controlled stop watch.

2.2. Power supply

Power is provided by a three phase rectifier system producing 150 amps at 90 volts [8].

2.3. Arc lamp

The arc lamp mechanism is that used in a Mole Richardson type 170 150 amp film studio arc. The positive carbon rotates at about 12 r.p.m. The lamp is of the semi-automatic type in which the carbons are fed forward at approximately their correct burning rates, but slight adjustments to the positions of the carbon must be made by hand about every five minutes. To facilitate this adjustment a magnified image of the arc and white hot carbon tips is formed on the wall by a pinhole in the side of the lamphouse with correct positions of the carbons marked on the wall.

The lamp is mounted on a stand with provision for adjustment in three directions. The manual controls for the carbons are brought to a control panel on the outside of the lamphouse (plate 6) by flexible drives. The control panel also carries an arcing switch and meters for measuring the arc voltage drop and current. An 0-0·25 ohm ballast resistor is placed in series eith the lamp and power supply and is adjusted to give a current of 150 amp when the carbons are burning correctly. The carbons used are a 16 mm positive (Link PTB) and an 11 mm copper plated negative (Link PCN).

The hot gases from the arc are collected by a hood fitted inside the lamphouse and escape through a chimney.

2.4. The mirror

The mirror is ellipsoidal having a diameter of 24 in. and focal lengths of 11 and 55 in. It is made by Clarke Chapman and Co. Ltd. of cast aluminium with an electrolytically brightened surface, stated by the manufacturers to have an absolute specular reflectivity of 84 per cent. This surface has the advantage that it can be cleaned with a suitable metal polish. A this deposit of material from the arc forms at the top of the mirror but this is easily removed and, although no dowser is used, there have been no signs of damage to the surface from material ejected by the arc after 250 hours use.

The mirror is fitted in a frame mounted in a three point suspension allowing it to be tilted in two directions. This mounting remains stable in spite of fairly high temperatures attained in the lamphouse and no movement of the focal spot occurs when the equipment becomes warm.

2.5. Shutters

The main shutter is attached to the front of the lamphouse (plate 3) and is about 31 in. from the pole of the mirror. The design is based on that of shutters used with studio arc lamps and is a modified venetian blind in which alternate blades turn in opposite directions (Fig. 2). The blades are one inch wide and three quarters of an inch apart, they are made of steel, chromium plated to give a durable reflecting surface. The blades and bearings are cooled by blowing air along channels at either side of the shutter and through annular aperatures surrounding the blade spindles. The shutter is normally held open by a spring fitted internally.

A sheet of asbestos wood is slid behind the shutter to protect it from the radiation when it is closed for long periods.

About 30 per cent of the beam is obscured by the lamp and when the shutter is fully open a further 15 per cent is obscured by the shutter blades. About half this obscuration is caused by the effect of the width of the blades on the converging beam (see Fig. 3).

When the shutter is partially open it is effectively a system of parallel slits and the beam is divided into a number of strips of light. However, these overlap near the focus and no change in the intensity distribution of the useful central portion of the beam can be detected even when the shutter is nearly closed.

A second shutter is used to attenuate the beam when the first shutter is used to provide a shaped pulse of radiation. This second shutter is similar to the first except that it is fitted with a worm drive operated by a handle to enable the blades to be held at any angle.

The two shutters must have the blades of one at right angles to those of the other, otherwise the two systems may interact to change the intensity distribution of the image. A very simple case is illustrated in Fig. 4. The top of the image is receiving all the light passing through two slits in the first shutter whereas the bottom half is receiving light through one only. In general a striped image is produced. For the same reason a foraminated screen cannot be used to reduce the intensity of radiation when the shutters are in use.

2.6. Solenoid

A diagram of the solenoid and return spring is shown in Fig. 5. The coil has 12,000 turns of wire and has a resistance of about 2,500 ohms. When there is a half inch gap the solenoid produces a thrust of 18 lb wt with a potential across the coil of 90 volts. Rapid operation of the solenoid is obtained by using a 200 volt power supply. This would, however, result in an unduly long time lag between switching off the current and opening the shutter and a micro-switch is arranged to put a resistance in series with the power supply when the shutter is closed. This reduces the potential across the coil to 50 volts, sufficient to hold the solenoid closed against the return spring.

Fig. 5 shows the variation in intensity during the opening and closing of the shutter. The opening and closing delay periods were made equal by adjusting the tension of the return spring. The time interval between switching on and off the solenoid current is measured by an electromagnetically operated stop watch having an 0.01 second escapement. This time interval is 0·02 sec. longer than the effective time of irradiation of the specimen (1) but this error can be neglected.

The attenuating screw fitted to the solenoid can be used to reduce the intensity of radiation by preventing the shutter from opening fully (5).

2.7. Cam mechanism

The main shutter may be operated by a push rod driven by a cam to give a pulse of radiation having an intensity time relationship similar to that obtained from an atomic weapon (6). The mechanism is shown in plates 4 and 7.

The cam is driven by a geared D.C. shunt motor unit having a speed practically independent of the torque applied to it. The power is obtained from the main arc lamp supply. A potentiometer in the armature circuit enables the speed of the cam to be varied from about 0·2 r.p.m. to 20 r.p.m. The calibration of this potentiometer in terms of pulse length is shown in Fig. 7 but this is approximate as the motor speed progressively increases as the potentiometer and motor become warmer and the potentiometer must periodically be reset in the course of a series of experiments. A diagram of the cam is shown in Fig. 8. The greater part (270°) of the periphery is shaped to produce the required pulse of radiation. Part of the remainder is cut away so that in the "rest" position the push rod falls clear of the shutter actuating lever. In this position the shutter is controlled by the solenoid. On pressing the main contact push button the cam completes one revolution and is then rapidly stopped by short circuiting the armature of the motor with the field energized. The solenoid is released immediately before the beginning of the pulse and energized immediately after it is finished. This is arranged by three timing cams on the same shaft which stop the motor, operate the stop watch for measuring the length of the pulse, and synchronise the solenoid with the motor.

A graph of intensity of radiation against push rod movement is shown in Fig. 9. Using this graph a chart was prepared showing the push rod movement for any given angle of the cam to give the required pulse shape. The cam was then cut on a milling machine using a cutter having the same diameter as the cam follower ($\frac{1}{4}$ inch). It was found that the peak intensity of the pulse could only be 96 per cent of the maximum intensity since the push rod movement from 96 to 100 per cent of maximum is disproportionately large and would have resulted in too steep a slope on the cam. The maximum allowable gradient is about 50°, otherwise the push rod will bend.

Since the radiometer (7) had too slow a response it was necessary to use a photocell to measure the shape of the pulse. The arc lamp was replaced by a car headlamp bulb. The output from the photocell was recorded on a drum camera for the shorter times and on a high speed pen recorder for the longer times.

Corrections to the cam were made to improve the shape of the pulse and it was found that the required shape was obtained with an error in the integrated curve of less than 5 per cent at all cam speeds.

2.8. Ignition detector

An ignition detector has been developed in order to eliminate human error in recording the moment of ignition of the specimen. The detector is a lead sulphide photoconductive cell having the spectral response shown in Fig. 10. This is more like the spectral distributions of the radiation from a black body at 800°C, (the temperature of the flame) than that from the arc lamp also shown in Fig. 9. The cell will thus have the greater response to the flame. The cell is enclosed in a tube which is pointed at the position where ignition is likely to occur (Fig. 11). This is usually in the gas stream just above the specimen (9). Changes in the intensity of the radiation scattered by smoke from the beam usually occur relatively slowly but ignition usually results in a sudden increase in radiation. The detector is therefore arranged to respond only to rapid increases in radiation. The circuit is shown in Fig. 12. The pulse produced by the differentiating circuit when there is a sudden decrease in the resistance of the photocell triggers a thyratron. A relay in series with the thyratron can be arranged to close the shutter and stop the stop watch. The bias on the thyratron and hence the sensitivity of the device may be changed by varying the setting of the potentiometer.

The detector may possibly be triggered by the sudden increase in the radiation scattered by the specimen when the shutter is opened. The detector can therefore be suppressed by connecting the grid of the thyratron to earth during the time the shutter is being opened. The detector must be reset once it has been triggered. This is done by pressing a button which interrupts the anode current through the thyratron.

2.9. Timer

The circuit of the electronic process timer is shown in Fig. 13. This incorporates a Miller Circuit. It has two ranges, 0-2·5 seconds, and 0-12 seconds.

2.10. Shutter control unit and power supplies

The equipment for controlling the operation of the shutter is contained in a rack mounted unit. The circuit of this is shown in Fig. 14 and diagrams showing the positions of the main components in Fig. 15. A list of the switch positions and terminals is given in Appendix I. The solenoid power supply (Fig. 16) and the power supplies for the timer and ignition detectors are contained in two separate units.

The push button initiating the exposure of the specimen is attached to terminals on the front panel by a cable of sufficient length to enable the operator to watch the specimen. For safety, the shutter closes immediately the push button is released whatever method of exposure is being used.

The changeover from a square pulse of radiation to a shaped pulse is made by turning a switch. Provision is made in the switching arrangements for the timer to be triggered by the ignition detector. This facility is intended for use in experiments on continued burning. Both the timer and ignition detector can be disconnected from the shutter controlling circuit and used independently.

In the event of failure of the solenoid power supply, the solenoid is held closed by the arc lamp power supply and at the same time a warning lamp on the front panel is illuminated.

The number of times the shutter has been opened is shown on a P.O. ratemeter.

3. Performance of apparatus

3.1. Intensity of radiation

The volume round the theoretical focus was explored using a radiometer (7) mounted on a three dimensional movable table. The best exposure plane was found to be 1·5 inches inside the focus. The area of approximately uniform radiation was a maximum in this plane but the maximum intensity was about 10 per cent lower than at the focus. The distribution of intensity of radiation along the axis of the mirror is shown in Fig. 17 and a map of lines of constant radiant intensity in the best exposure plane is shown in Fig. 18.

The rotation of the positive carbon results in a cyclic variation in intensity. The amplitude of this varies with different carbons but is generally about 4 per cent of the mean intensity. The maximum intensity is about 55 w/cm^2.

3.2. Effective irradiated area

The area over which the intensity is greater than 90 per cent of the maximum is about 3 cm^2. Experimental work which will be described elsewhere suggests that the system behaves as a uniformly irradiated area of about 2 cm^2. This is less than the area at which the ignition behaviour is unaffected by the small amount of gas evolved from the irradiated area. The correction which must be made to ignition times with this apparatus is, however, much less than that necessary with the previous apparatus (1) which had an effective area of 0·1 cm^2. Work is being carried out to determine the actual corrections required.

The effect of radial conduction on the temperature at the centre of the irradiated area is negligable for bad conductors such as oak or fibre board (2), but must be considered when irradiating metals.

3.3. Effect of draughts

The shutter cooling arrangements result in some turbulence near the specimen. This is reduced by placing an 18 inch square sheet of asbestos millboard about 2 inches behind the specimen. This disturbance near the specimen is not severe enough for it to have any effect on the ignition times but it may reduce the minimum intensity at which ignition occurs (11).

3.4. Spectrum of radiation at exposure plane

The spectrum of the radiation falling on the centre of the exposure plane has been measured using a quartz monochromator with a lead sulphide cell as a detector (Fig. 19). The intensity was not measured in absolute units so that the emissivity of the source cannot be calculated. The spectrum consists of a background of black or grey body radiation characteristic of 4000°K presumably from the hot crater, with additional radiation in the ultra violet region, presumably from the ball of hot gas. This gives the arc its colour temperature of 6000°K.

3.5. Efficiency of optical system

The rate of transfer of energy across the exposure plane was found to be about 1,100 watts while the rate of transfer across the area where the intensity was greater than 90 per cent of the maximum was only about 150 watts. Thus only about 14 per cent of the energy crossing the exposure plane was at a useful density.

The ellipsoidal mirror is thus a very inefficient optical system for use in a high intensity source and this explains the superiority of the condenser relay system (5) in spite of the smaller angle subtended at the arc by the condenser lens and the reflection and absorption losses associated with lenses.

It might be possible to compensate for the loss of intensity away from the axis by using a specially figured mirror.

4. Acknowledgements

1. The author would like to thank Mr. C. Shore and members of the workshop staff for their assistance with the design and construction of the apparatus.

2. The electronic process timer was designed by Mr. J. H. McGuire who gave much advice in the design of the other electronic equipment.

3. The main shutter was made by the Chemical Defence Experimental Establishment, Porton who have kindly loaned it to us.

4. The spectrum of the arc was determined by Dr. T. F. Moss of The Royal Aircraft Establishment.

5. Miss M. Weston and Miss P. Cheshire plotted the intensity of radiation near the focus. Miss P. Cheshire also assisted in the construction of the electronic equipment.

5. References

1. Lawson, D. I., Pickard, R. W. and Simms, D. L. The development of the carbon arc source of high intensity radiation. Joint Fire Research Organization F.R. Note No. 128, 1954. Restricted.

2. Thomas, P. H. and Simms, D. L. Some practical limitations to the use of small irradiated areas on solids for the study of thermal damage. Joint Fire Research Organization F.R. Note No. 163, 1955.

3. Effect of size of an irradiated specimen on the time taken to ignite (note in course of preparation).

4. Davis, T. P., Krolak, L. J., Blakney, R. M. and Pearse, H. E. Modification of the Carbon Arc, Searchlight for Producing Experimental Flashburns. Journal of the Optical Society of America, 1934. 44, 766-769.

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9. Report of the Fire Research Board for the year 1954. London, 1955. H. M. Stationery Office.

10. Report of the Fire Research Board for the year 1956. London, H.M. Stationery Office.

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APPENDIX 1

TABLE 1

Switches in shutter control unit

Number	Use	Position	Setting	Notes
S.1	Main switch	Up	Off	Switches both 240 volt mains and 90 volt D.C.
		Down	On	
S.2	Pulse type selector	1	Square	
		2	Cam	
S.3	Open shutter	Up	Closed	Used to open shutter for intensity measurements
		Down	Open	
S.4	Timer trigger	1	Off	
		2	Test	Timer is triggered by pressing "test" push button.
		3	Shutter	Timer is triggered when shutter opens on square pulse or when timing cam closes on cam pulse.
		4	Ignition	Timer is triggered by ignition detector.
		5	External	Timer is triggered by shorting timer trigger terminals on rear panel.
S.5	Timer range	Up	Short	0-2·5 seconds
		Down	Long	0-12 seconds
S.6 (on rear panel)	Timer output	1	Shutter and external	Shutter will close when timer relay closes.
		2	External only	Shutter is disconnected from timer relay.
S.7	Ignition detector	1	Off	
		2	Clock and shutter	Stop clock will stop and shutter close when detector is triggered.
		3	Clock only	Stop clock will stop when detector is triggered.
		4	External only	
S.8 (rear panel)	Ignition detector time constant	Up	Short	0·02 seconds
		Down	Long	0·05 seconds
S.9 (rear panel)	Ignition detector suppresion	1	Off	
		2	Shutter	Ignition detector is suppresed while shutter is closing with square pulse or on rising portion of pulse with cam pulse.
		3	External	Ignition detector is suppressed when suppresion terminals are shorted.

TABLE 2

Terminals on shutter control unit

Number	Description	Notes
T.1	Main control	Connected to push button which indicates exposure of specimen.
T.2	To ignition detector head	
T.3	External suppression	Ignition detector is suppressed when terminals are shorted if S.9 is set to position 3.
T.4	Timer external trigger	The timer will be triggered when terminals are shorted if S.4 is set to position 5.
T.5	Timer output	Terminals are connected internally when timer is triggered.
T.6	To stop clock	
T.7	Ignition detector relay	Terminals are normally connected internally but connection is broken when ignition detector is triggered.
T.8	Timing Cam	Terminals are connected internally during cam pulse.
T.9	Shutter relay	Terminals are connected internally when shutter is open.

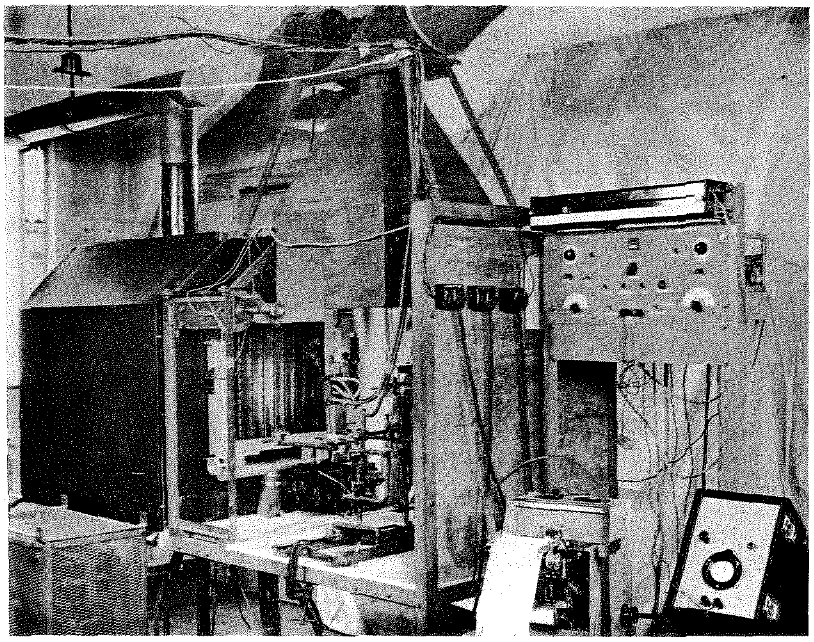

PLATE. I. GENERAL VIEW OF APPARATUS

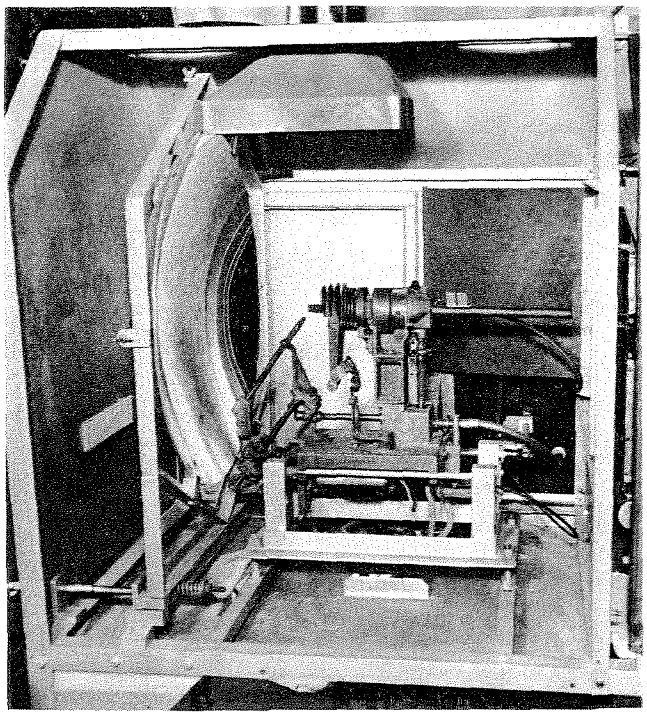

PLATE. 2. INSIDE OF LAMPHOUSE

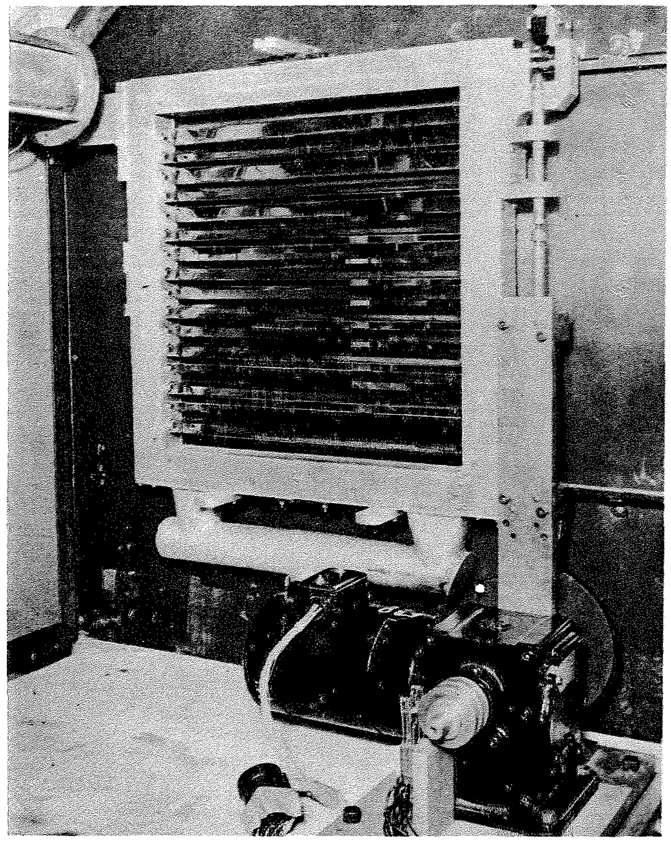

PLATE. 3. AIR COOLED SHUTTER

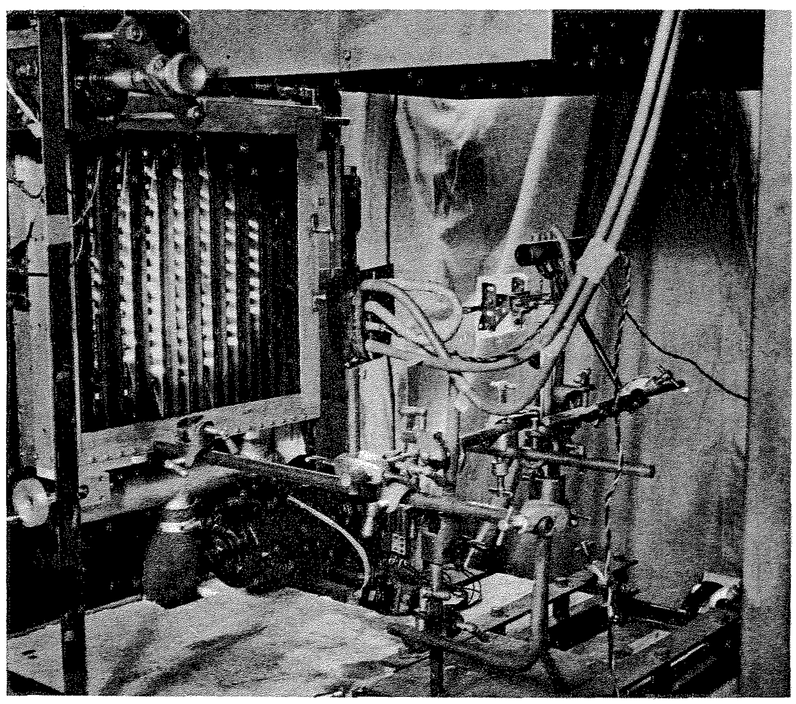

PLATE. 4. ATTENUATING SHUTTER IN USE

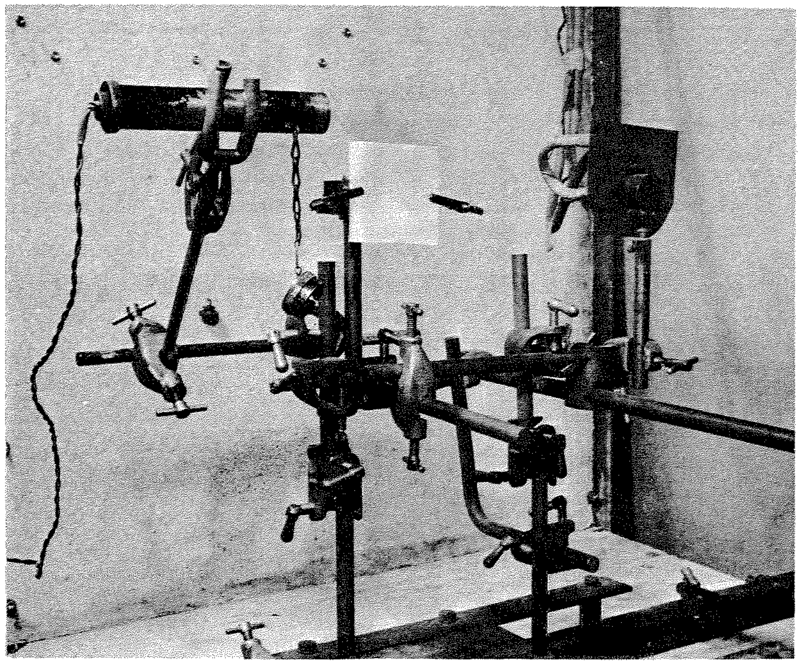

PLATE. 5. SLIDING TABLE CARRYING RADIOMETER, IGNITION DETECTOR AND SPECIMEN

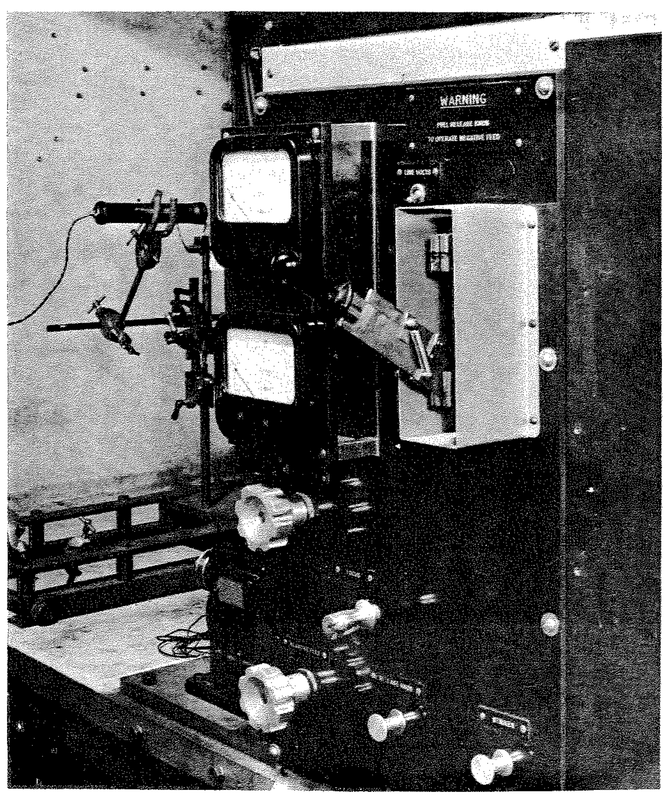

PLATE. 6. ARC LAMP CONTROL PANEL

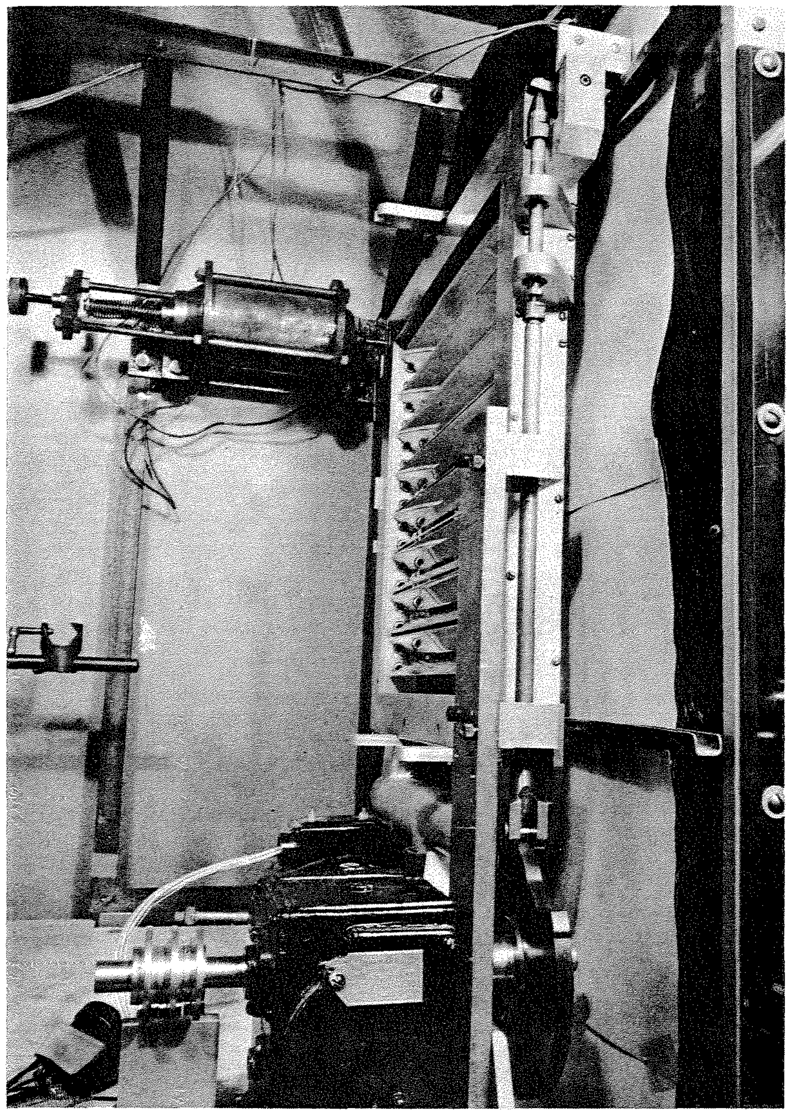

PLATE . 7. CAM MECHANISM FOR CONTROLLING SHUTTER

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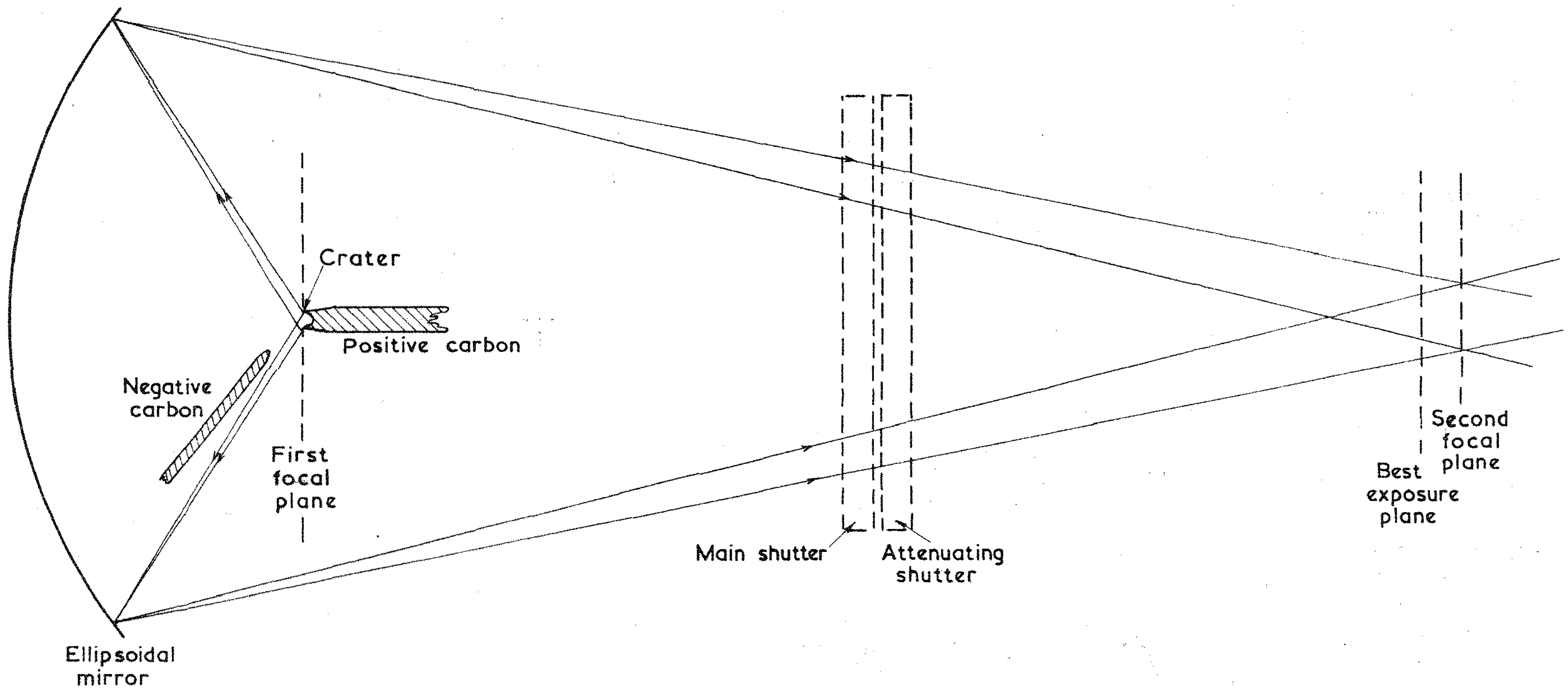

FIG. 1. DIAGRAM OF ELLIPSOIDAL MIRROR OPTICAL SYSTEM

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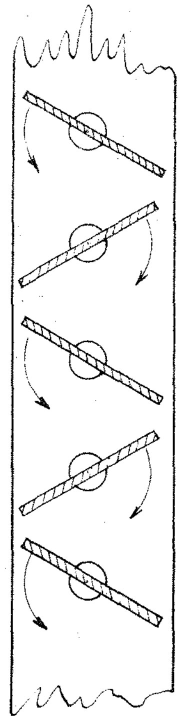

FIG. 2. SECTION OF SHUTTER

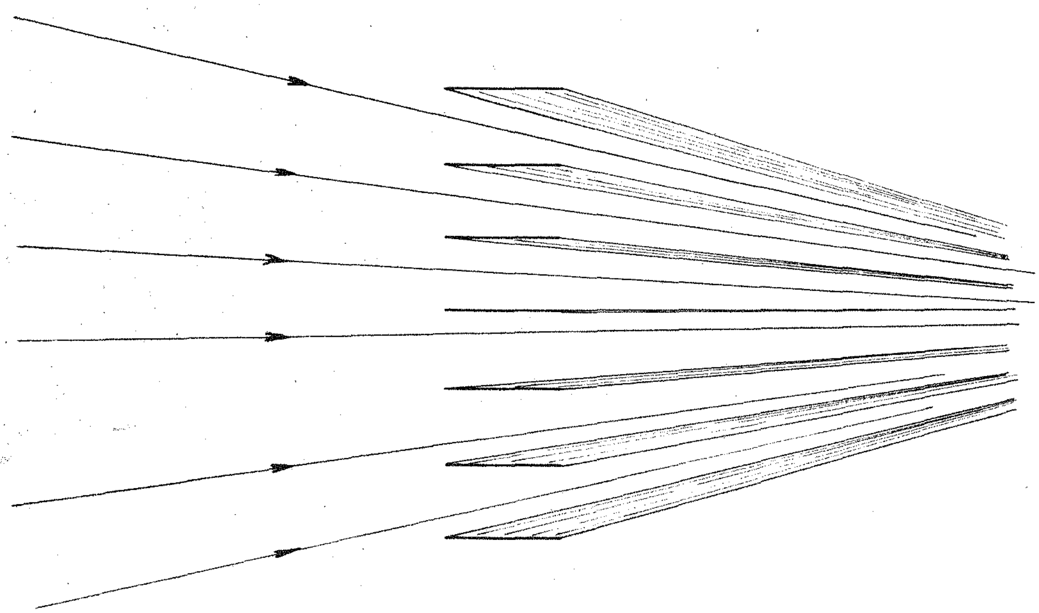

FIG.3. DIAGRAM TO ILLUSTRATE OBSCURATION OF CONVERGING BEAM BY PARALLEL BLADES

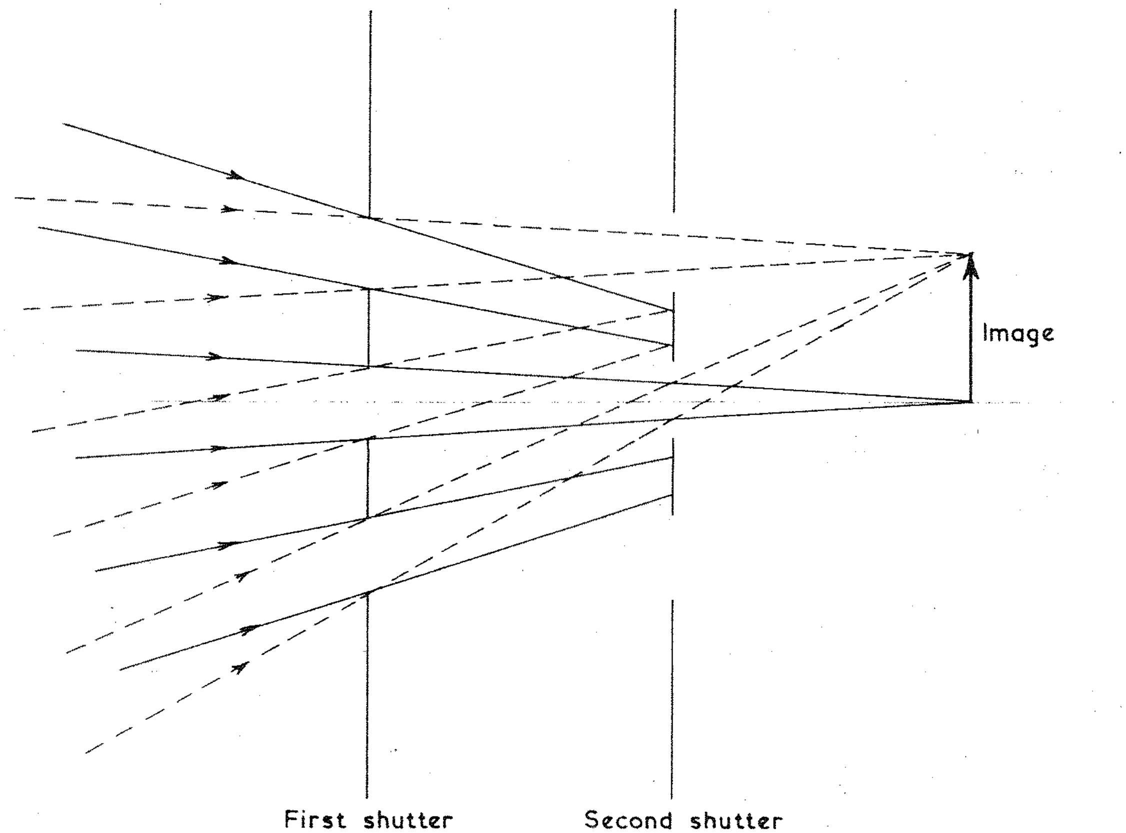

FIG. 4. DIAGRAM TO ILLUSTRATE INTERACTION OF TWO PARALLEL SYSTEMS OF SLITS IN A CONVERGING BEAM

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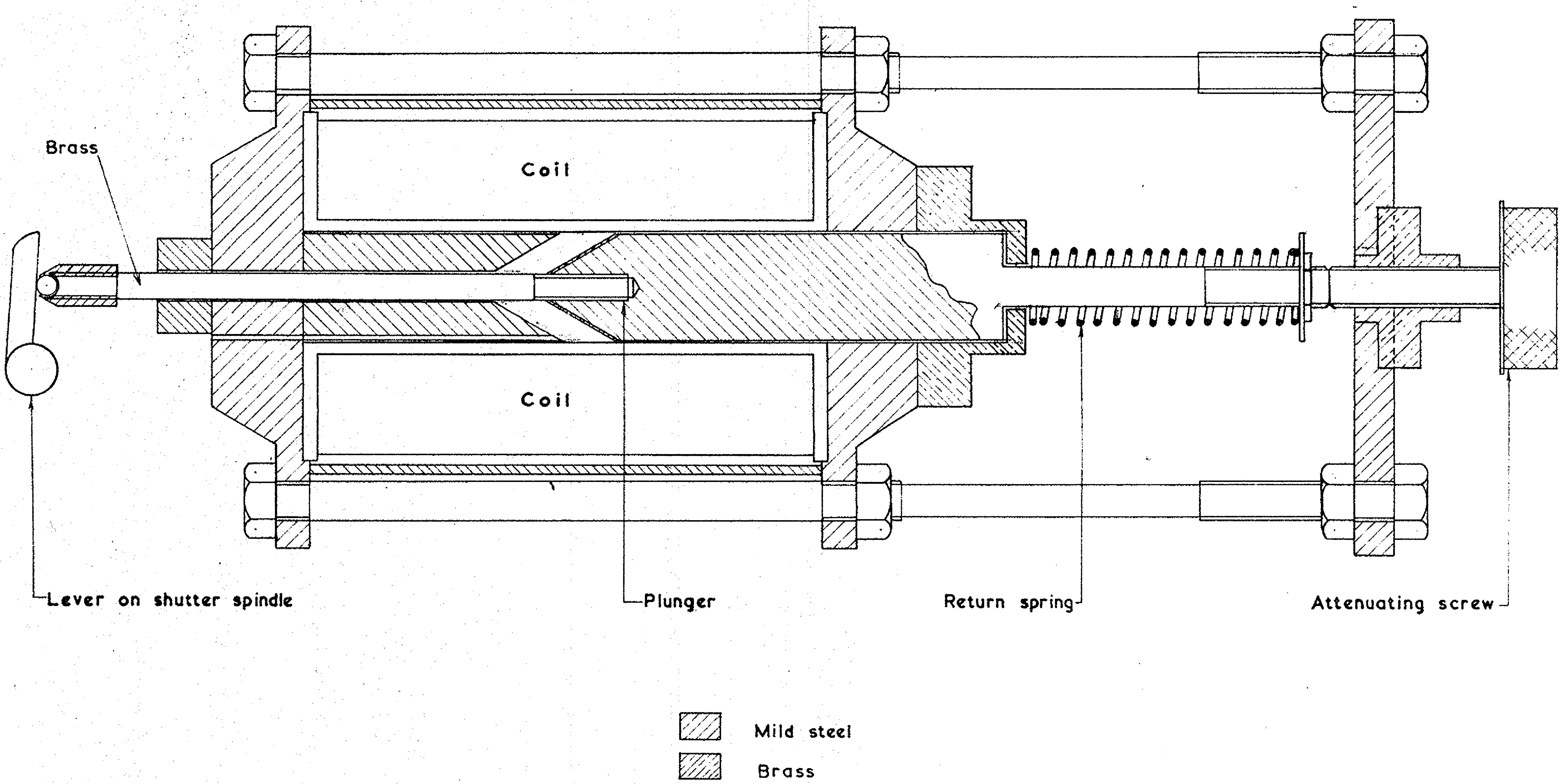

FIG. 5 SECTION OF SOLENOID

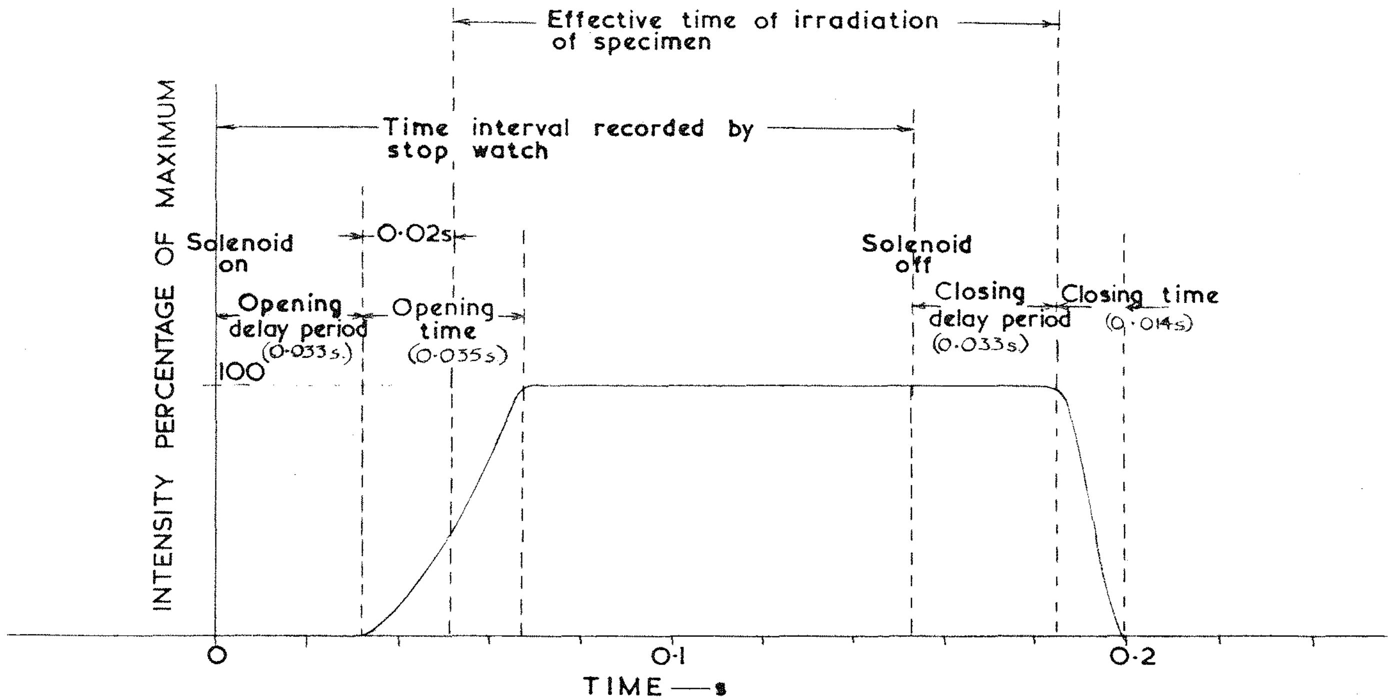

FIG. 6 OPENING AND CLOSING TIMES OF SHUTTER

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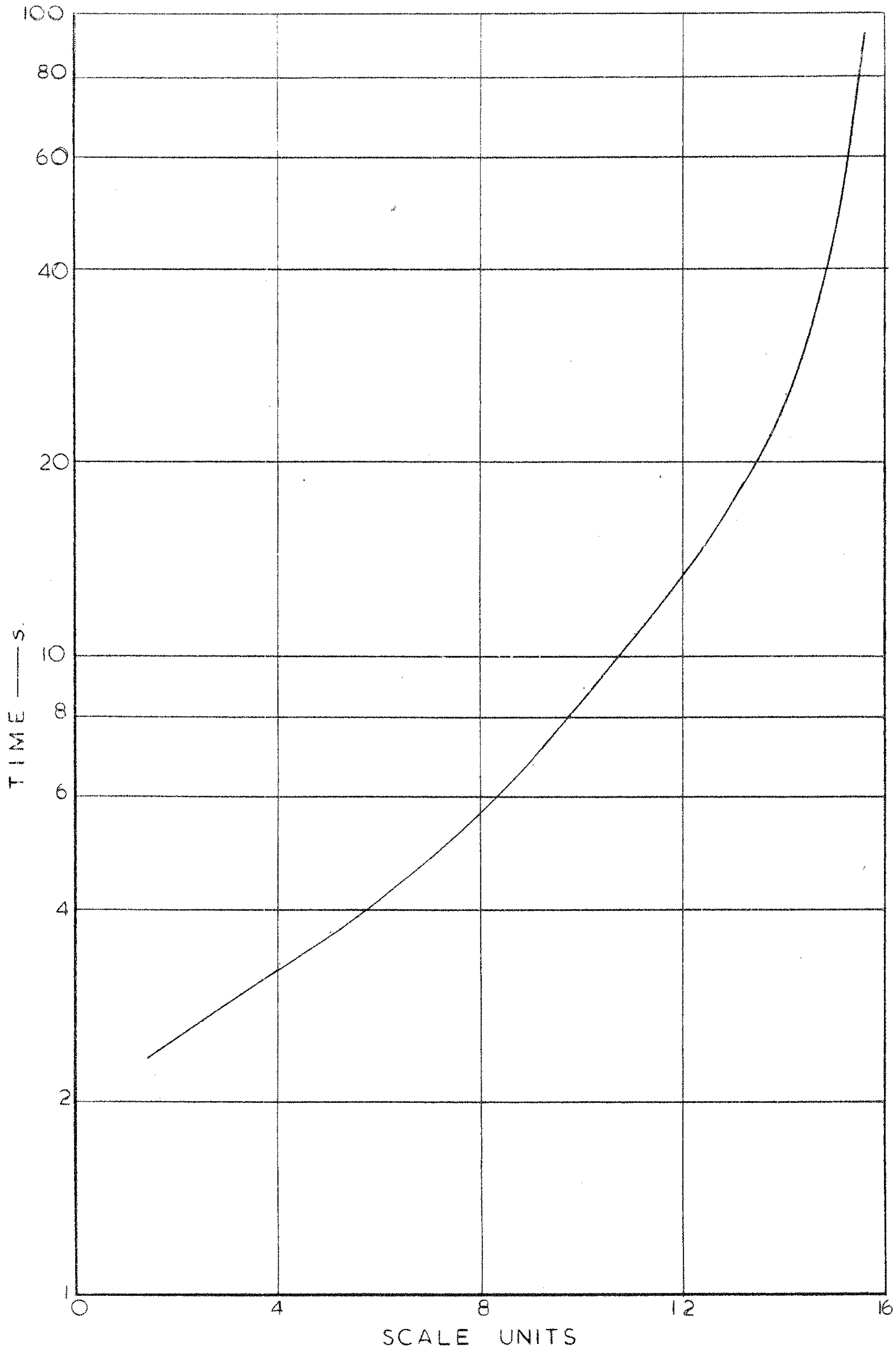

FIG.7. CALIBRATION OF MOTOR SPEED AGAINST SCALE ON POTENTIOMETER.

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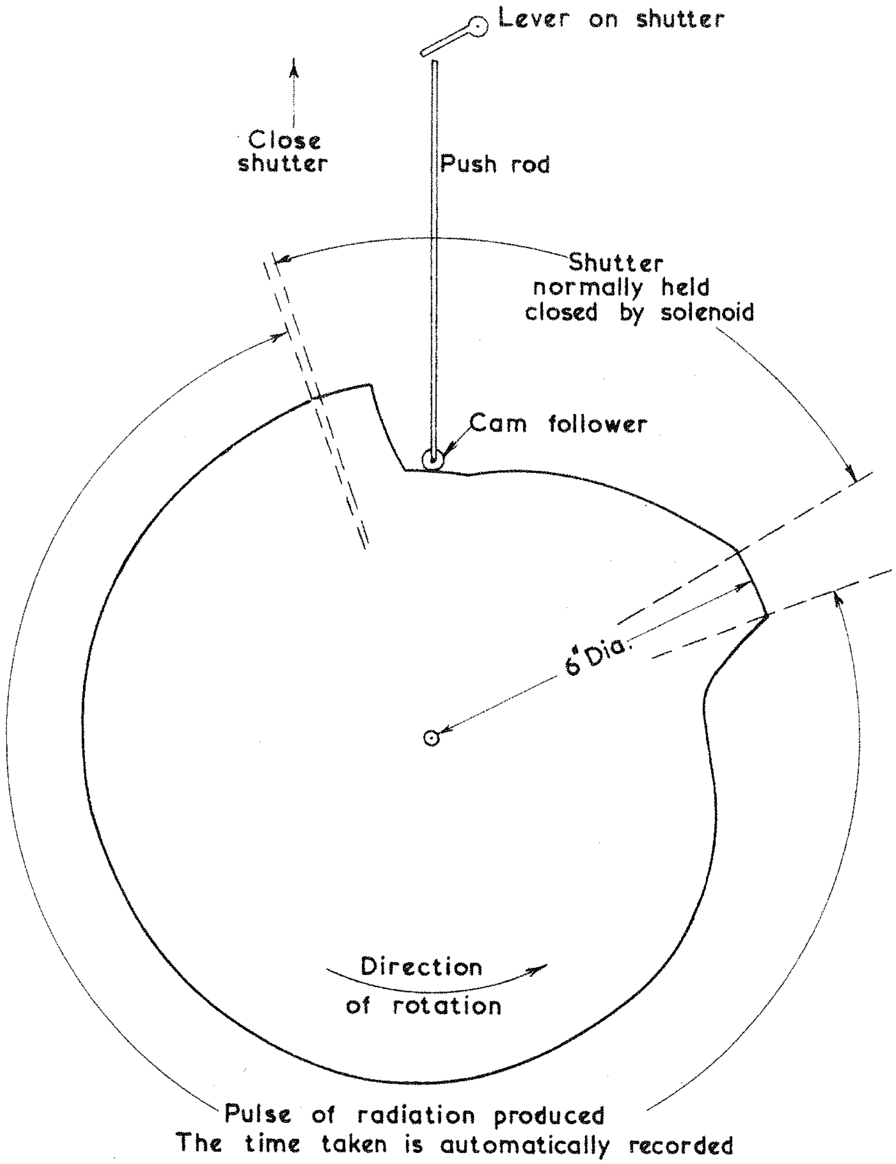

FIG. 8 DIAGRAM OF CAM SHOWN IN THE "REST" POSITION

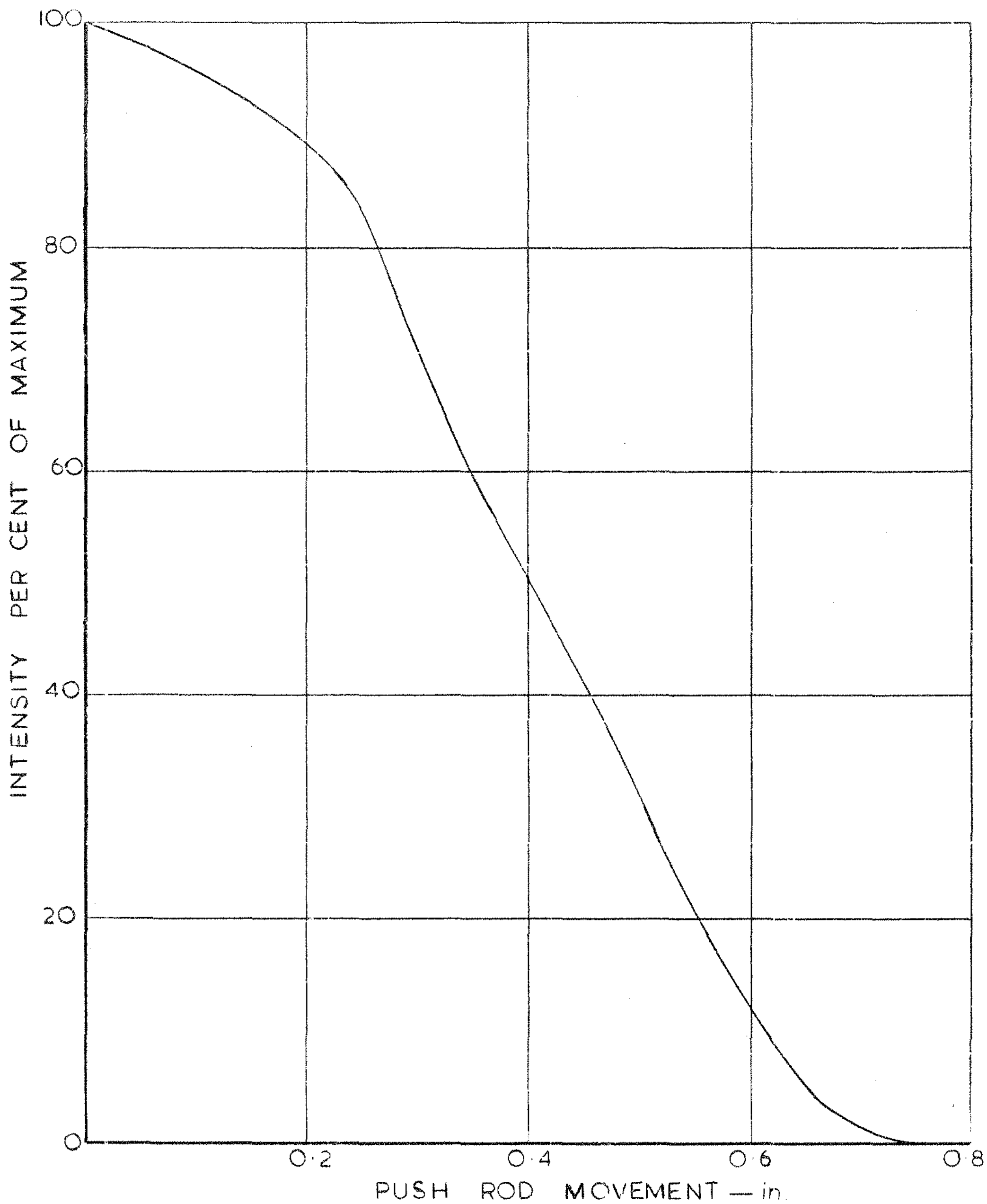

FIG. 9. INTENSITY OF RADIATION AGAINST PUSH ROD MOVEMENT

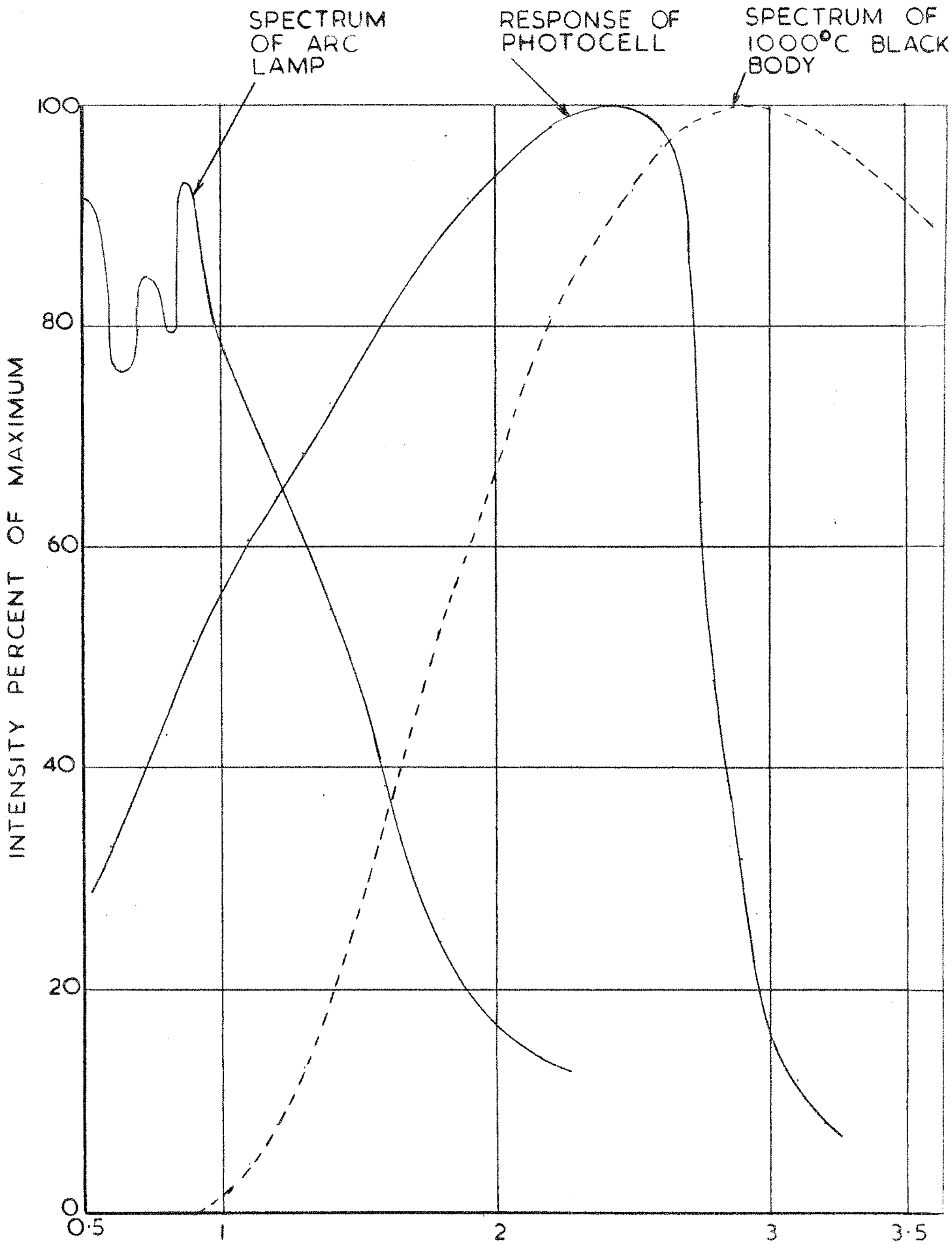

FIG.10. SPECTRAL RESPONSE OF PHOTOCELL IN IGNITION DETECTOR COMPARED WITH SPECTRUM OF 1000°C BLACK BODY AND SPECTRUM OF ARC LAMP

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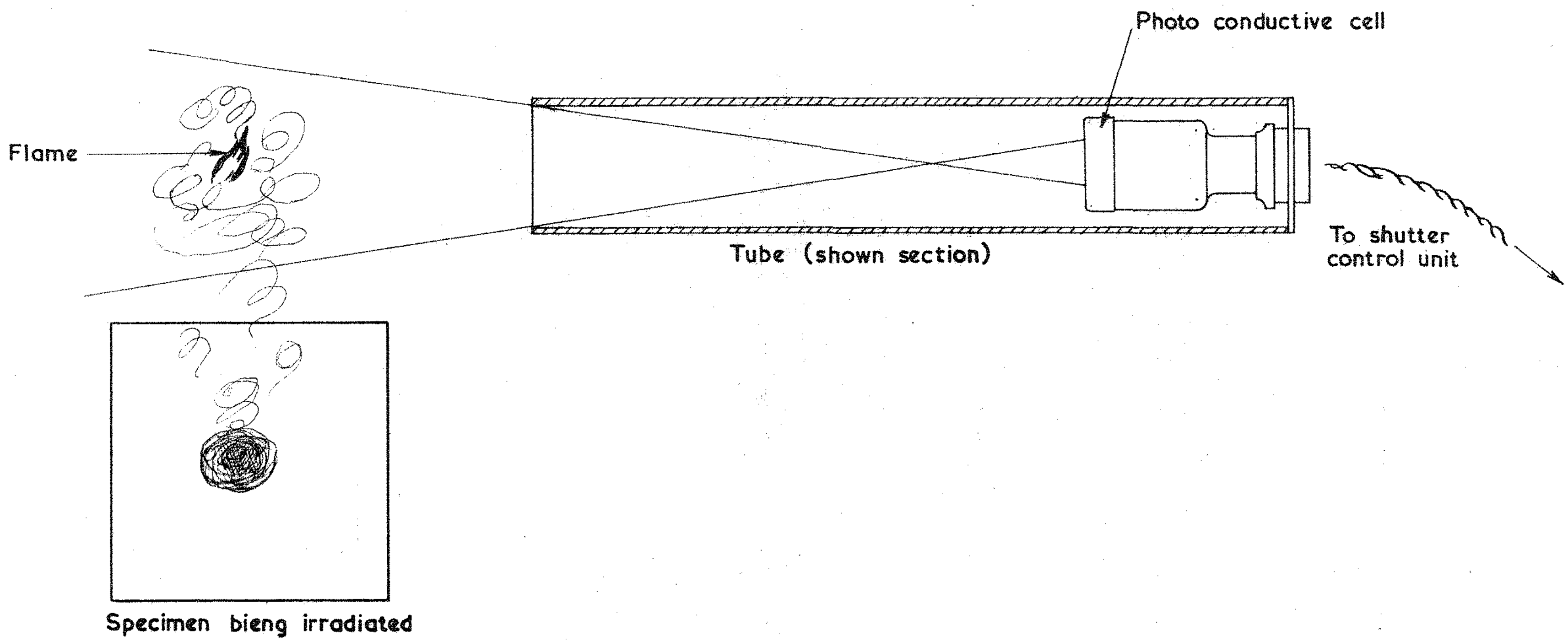

FIG. 11. IGNITION DETECTOR

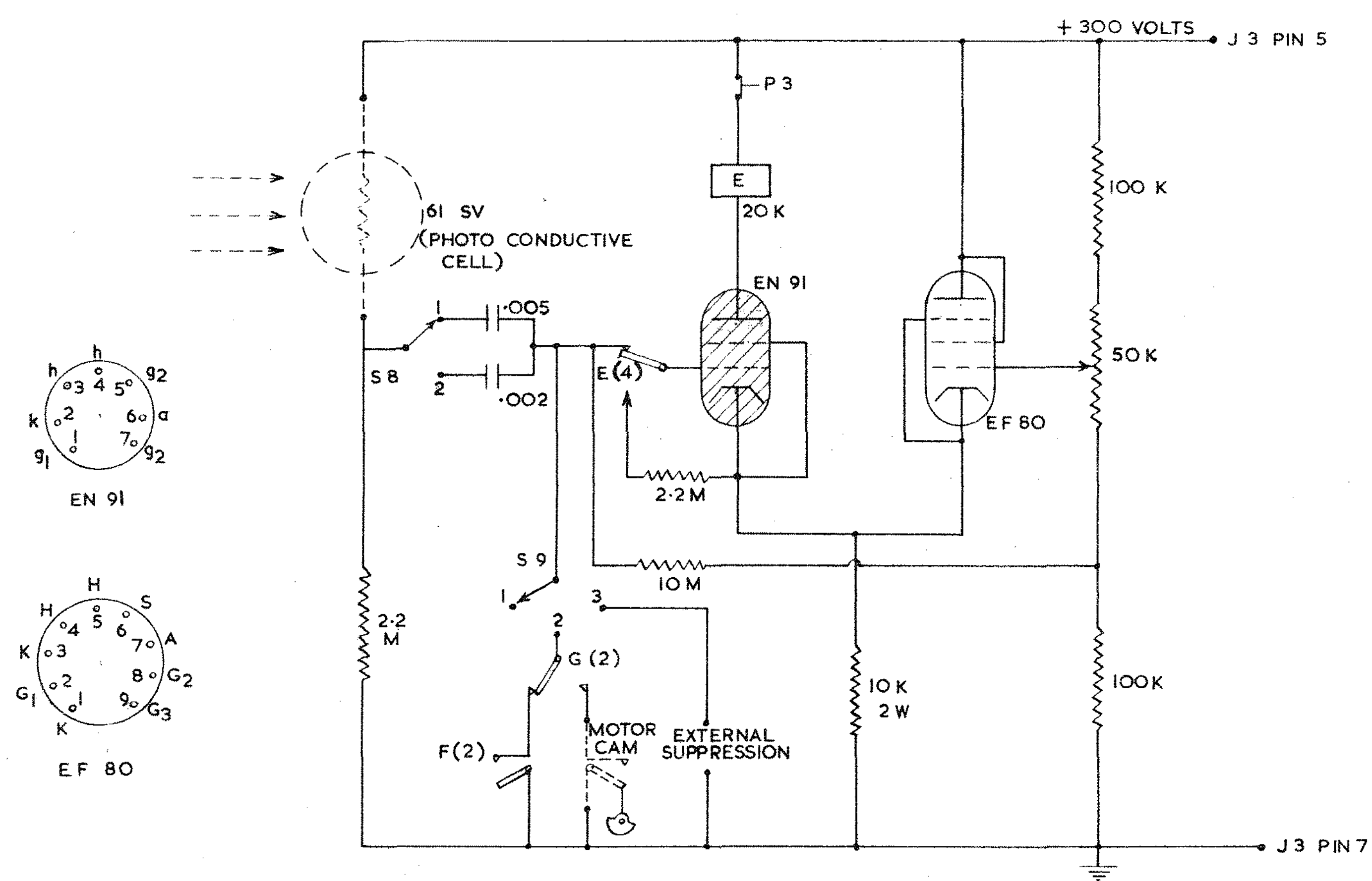

FIG. 12. CIRCUIT OF IGNITION DETECTOR

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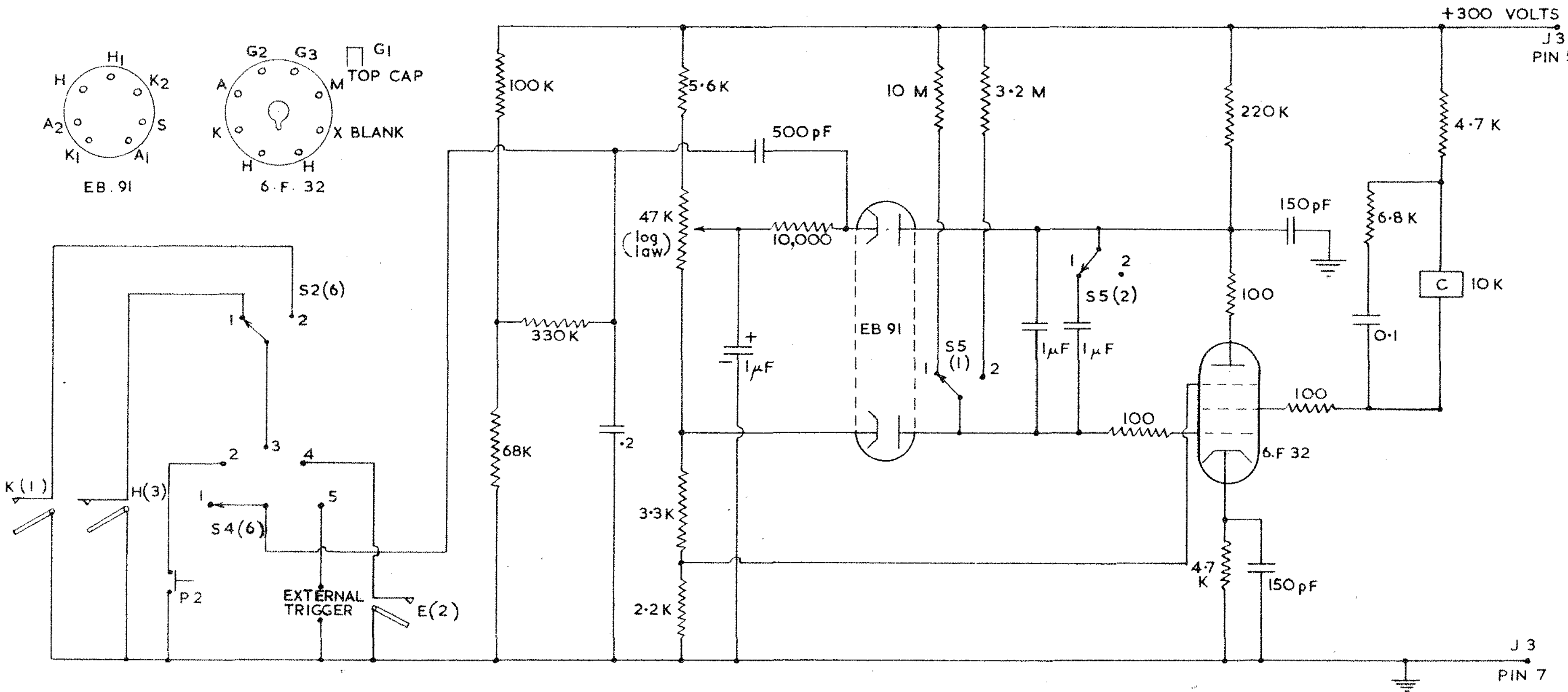

FIG. 13. CIRCUIT OF TIMER

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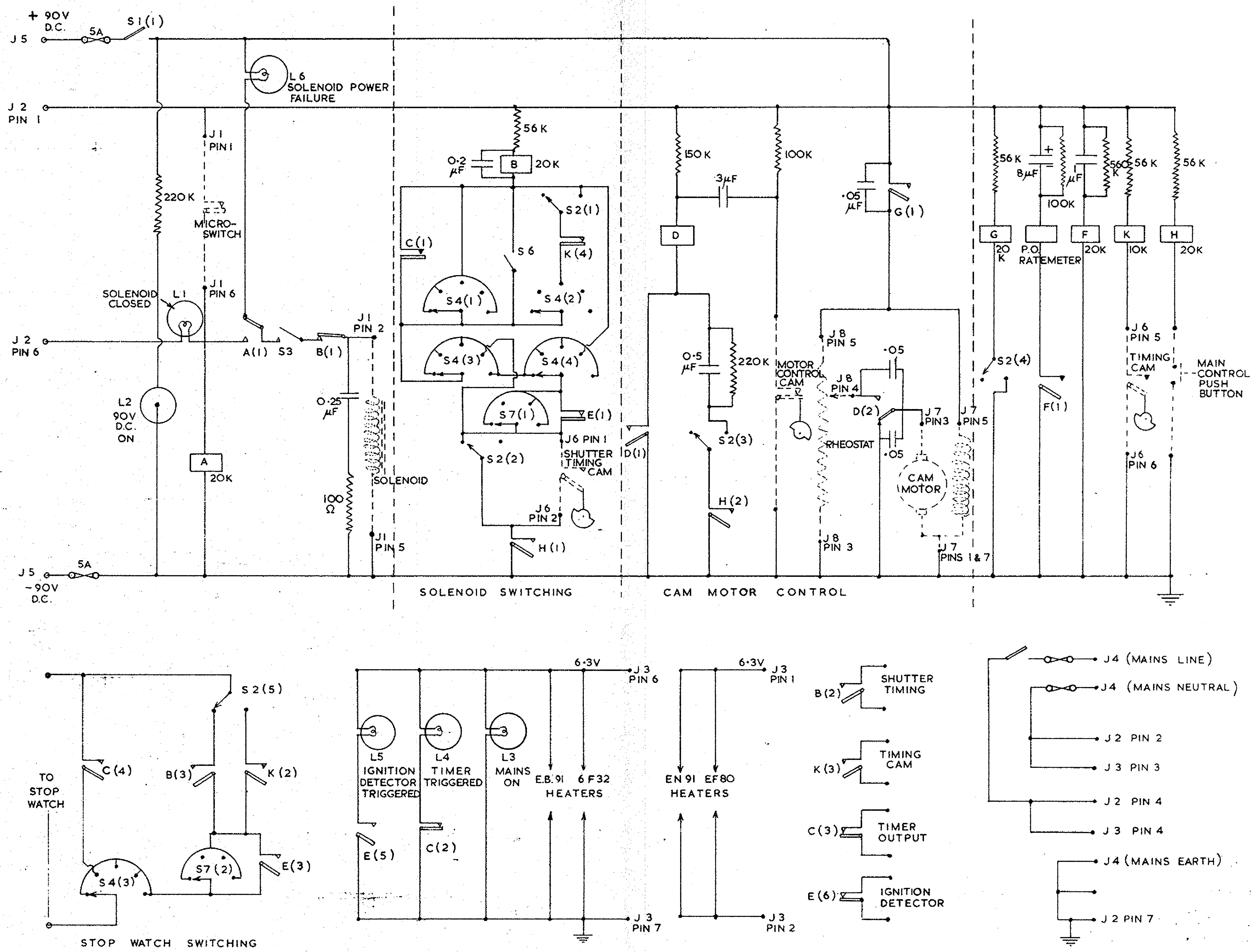

FIG. 14. SHUTTER CONTROL UNIT

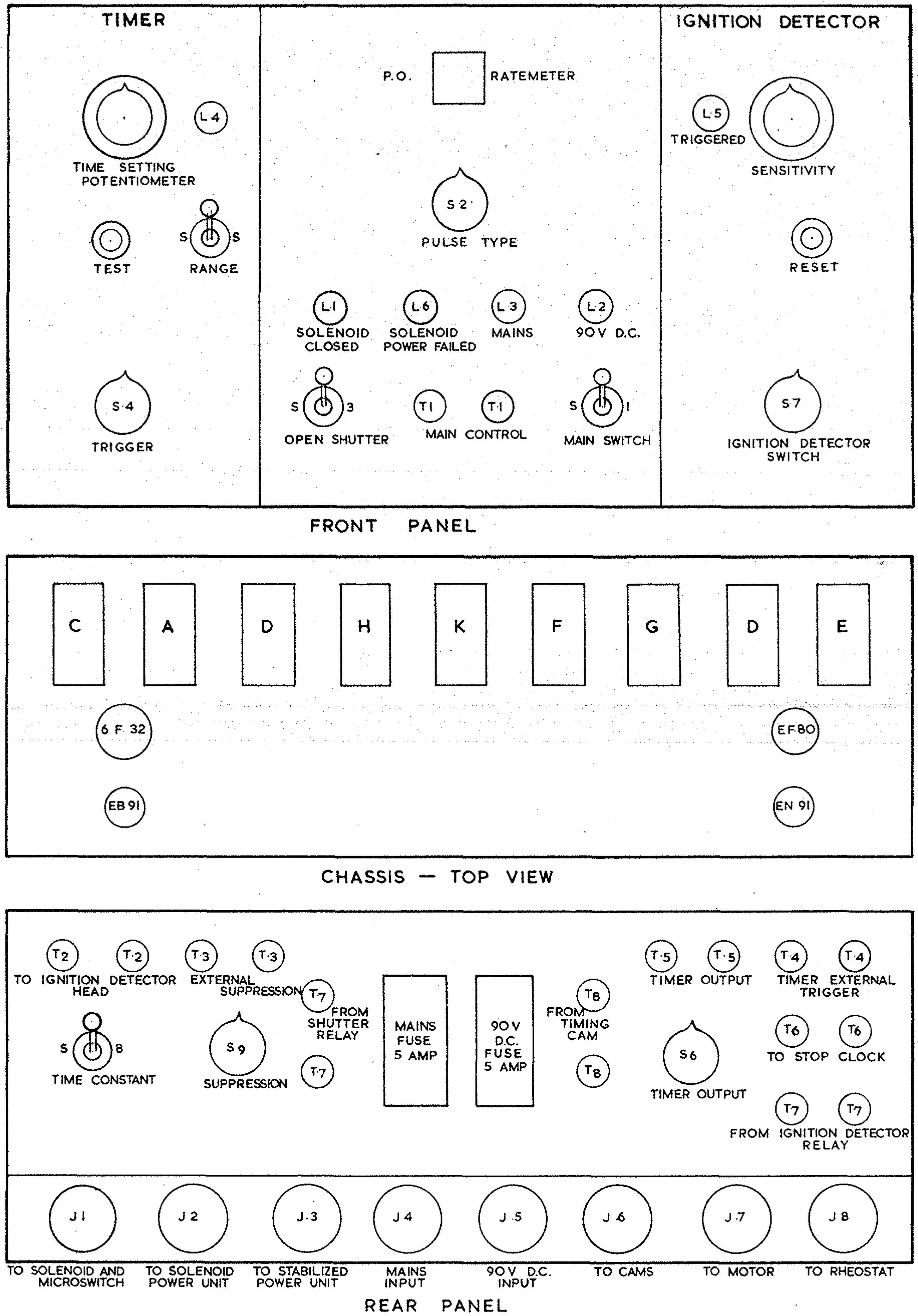

FIG. 15. DIAGRAM OF SHUTTER CONTROL UNIT SHOWING POSITION OF MAIN COMPONENTS

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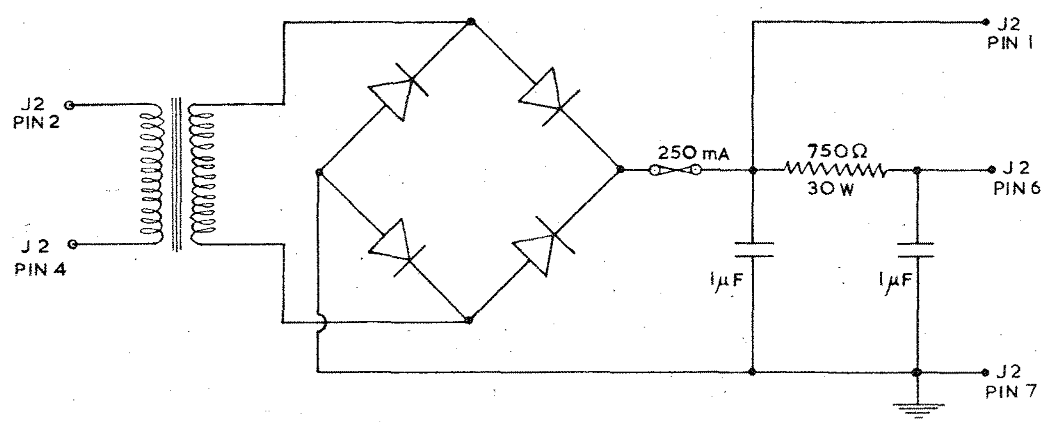

FIG. 16. SOLENOID POWER UNIT

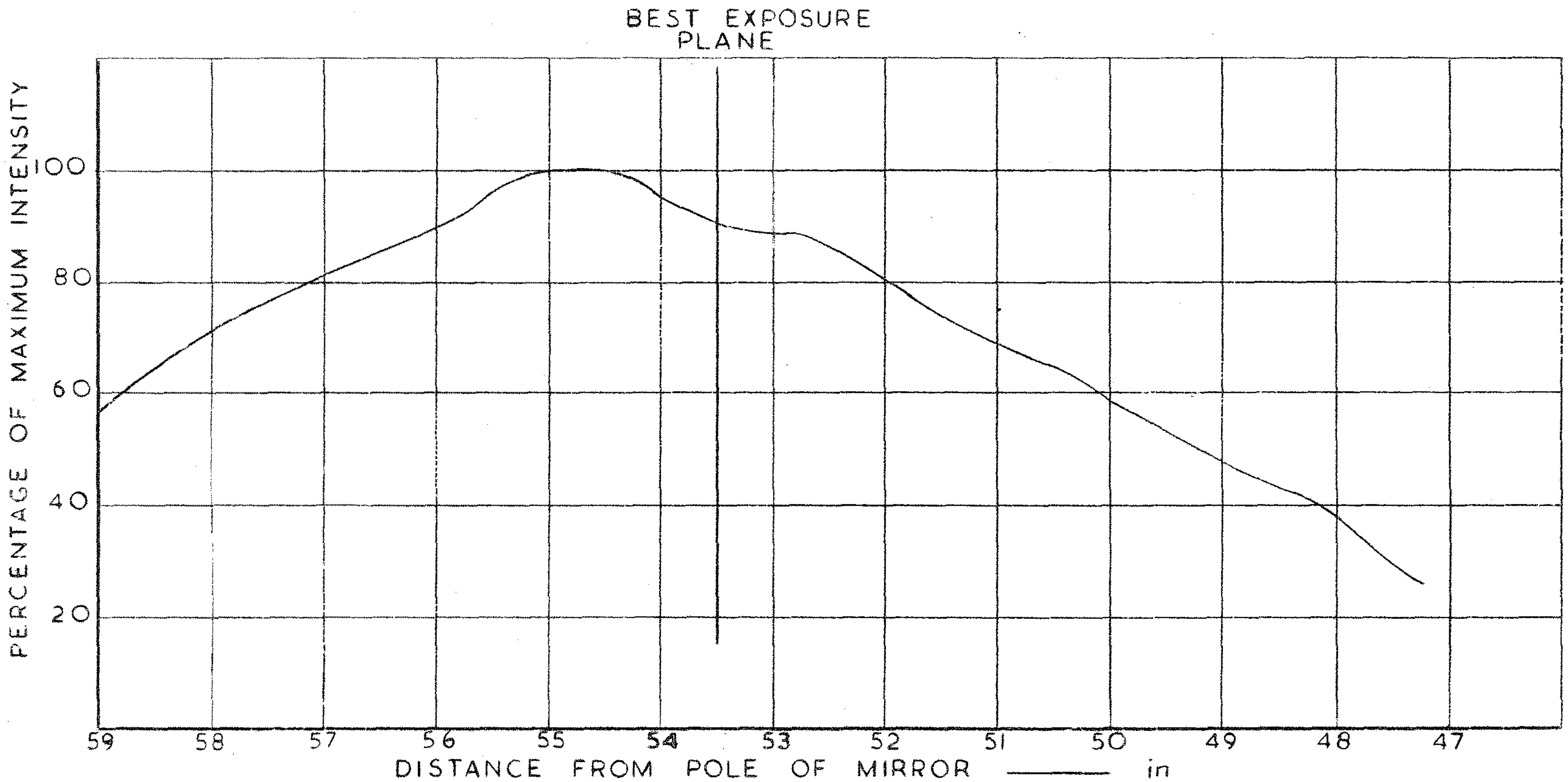

FIG. 17. INTENSITY DISTRIBUTION ALONG AXIS

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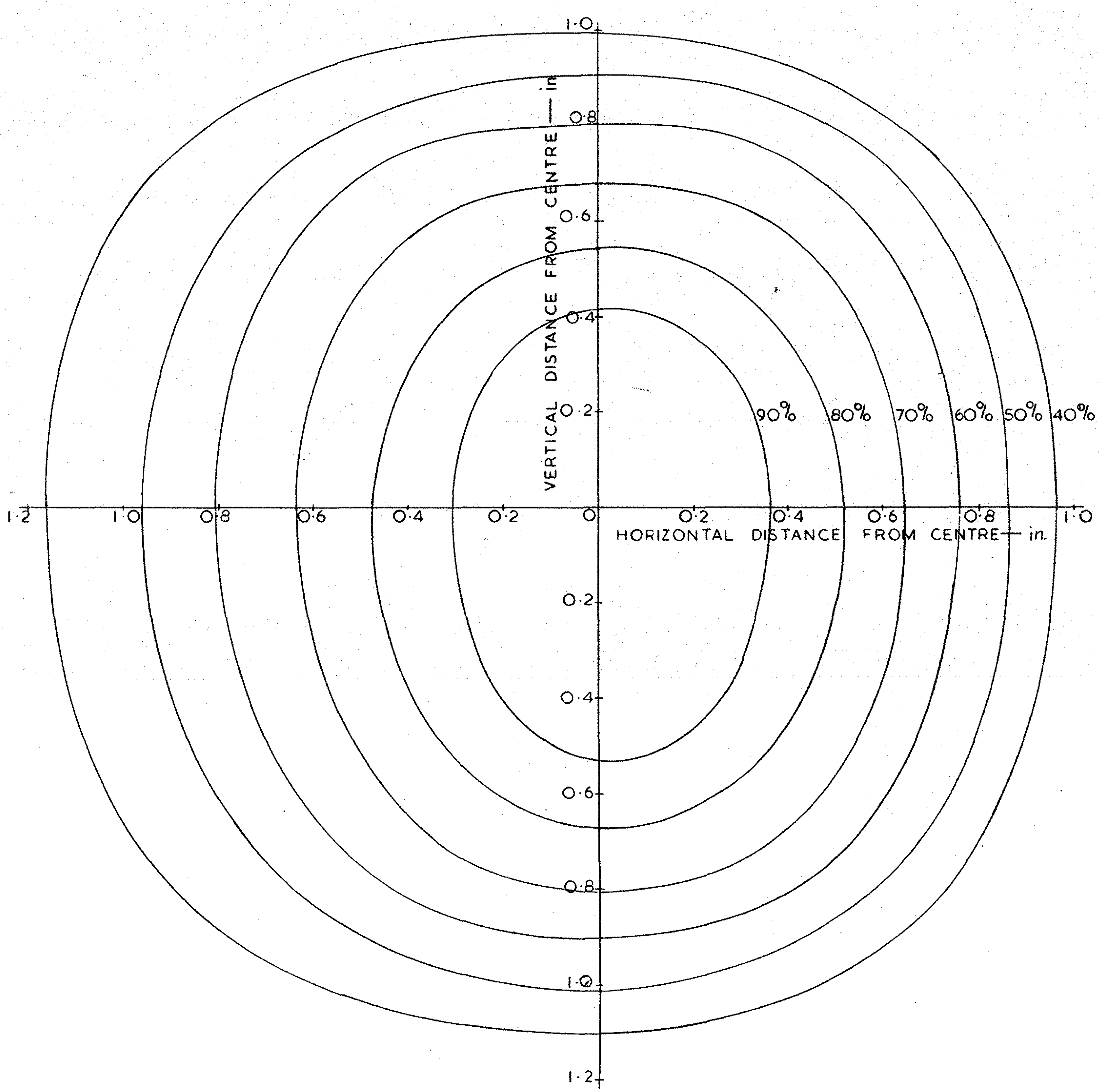

FIG.18 LINES OF CONSTANT INTENSITY OF RADIATION IN THE EXPOSURE PLANE

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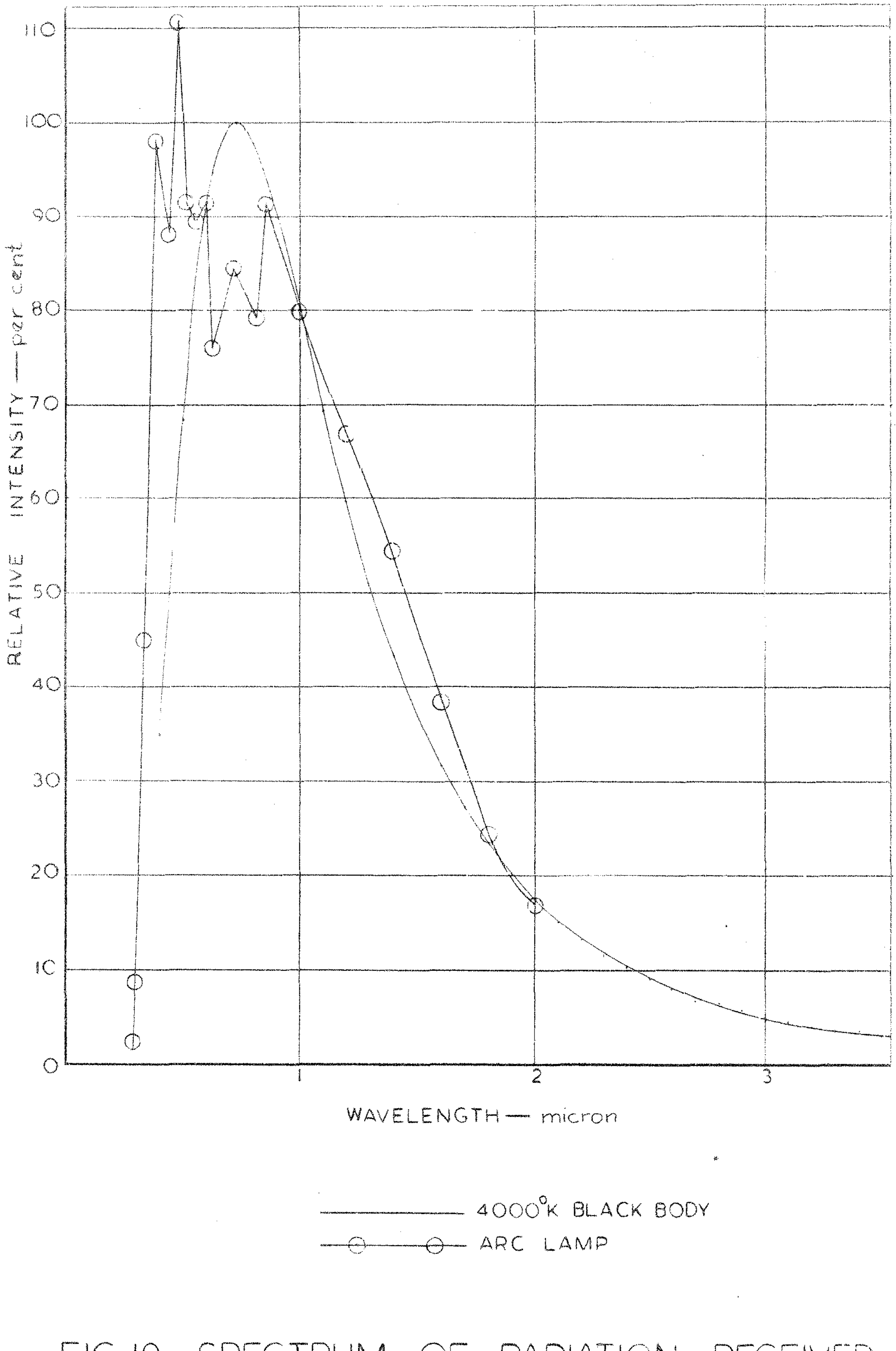

FIG. 19 SPECTRUM OF RADIATION RECEIVED IN FOCAL PLANE COMPARED WITH THAT OF 4000°K BLACK BODY.

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