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REPORT No. 6/R/49

A High-speed Rotating Mirror Camera

E. G. Whitbread

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A High-speed Rotating Mirror Camera

by

E.G. Whitbread

This report contains information of overseas origin

Submitted by W.S. Lister
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1. SUMMARY

In order to study the build-up, propagation and, in some cases, the fading of detonation in liquid explosives a high-speed camera of the slit-type was constructed. Such studies are of basic importance to research on sensitiveness in general, and, in particular, to the design of detonation traps for rocket monopropellants.

To this end a compact rotating mirror camera has been designed and constructed. This camera has been used successfully at writing speeds of 1-2000 metres/second, and speeds as great as 3000 metres/second have in fact been achieved. One novel feature of the instrument is an electronic revolution-counter for determining mirror speeds.

The camera is being applied successfully to the problems concerned.

2. Introduction.

In connection with studies on the sensitiveness of liquid explosives to impact and on the propagation and quenching of the detonation process a high-speed camera of the slit type was constructed which would enable studies to be made of the development and, in certain systems, the fading of detonation.

High-speed photography of this kind has been used for many years at various places. The cameras used have usually been of the rotating drum type in which the film is fixed to a rapidly rotating drum and is thus moved past a fixed slit. Some cameras used a fixed drum and a rotating mirror to produce the same result. An example of the construction of a rotating drum camera and its use in studies on the detonation process in liquid explosives is described by Messerly (1). Such an instrument has the disadvantage that in order to obtain a high speed of image relative to the film a combination of a large drum and a high rotational speed is required. Elaborate precautions then have to be taken against mechanical failure which may arise at high speeds, due to inaccurate balance.

Rotating mirror cameras are usually much more compact and have the advantage that since the rotating mirror is quite small, higher speeds of rotation and therefore of image relative to film ('writing speed') are attainable. The development and application of such a camera is described by Payman et al (2) and cameras of this type are in current use at the Safety in Mines Research Station, Buxton. A smaller and more compact camera of this type was developed at the Road Research Laboratory during the late war (3). The latter camera has a semi-circular drum with a centrally mounted four sided rotating mirror. A double-lens-and-slit optical system (described fully later since this system is used on the Waltham camera) is situated so that its optical axis is parallel to the centre line of the drum and within the drum itself. A plane mirror at 45 degrees turns the light rays from this axis on to the rotating mirror and thence on to the film held in the drum. There are actually two such lens, slit and mirror systems for the one drum, and each is supposed to work on its own part of the drum. One gives a horizontal record, i.e. the progress of the detonation wave in a horizontal direction, the other a vertical record.

In view of present requirements (e.g. study of initiation by impact, as in a falling-weight impact machine, work with low temperature detonations, the close study of small parts of a detonating system) the Road Research Camera had some advantages and some disadvantages.

The disadvantages were as follows:-

As with the Buxton camera, a synchroniser was necessary. This is partly due to the use of two lens systems, which means that each optical system can use only half the drum and the camera therefore can work for only half the time, i.e. when the images from the two lens systems are on their respective halves of the drum. One of these systems could be dispensed with, i.e. by confining the camera to work in one plane. The position of the plane mirror serving to reflect the light directly between the rotating mirror and the film drum must cause a shadow on the film where there will be no image for certain rotating-mirror positions. The lens system in the R.R.L. camera, while quite suitable for high explosives at a fair distance, was found not to be of large enough aperture for closer work on detonating systems of lower luminosity.

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The advantages of the R.R.L. camera lay in its ease of construction, and the fact that its design could be altered to meet present needs. Further, it seemed likely that much higher writing speeds could be obtained from this type of design than from any other. It was therefore decided to design and construct a camera along these lines, taking into account the facts that (1) synchronisation is very difficult with a falling weight and should be avoided, (2) simultaneous recording of phenomena in two planes is not essential, (3) the camera was intended for studios of explosives supported in a vertical position.

3. Description of the Camera.

3.1. General Description.

The camera is shown in Figs. 1 to 6. and its operation is as follows:- A square prism, the faces of which form four mirrors, is mounted in ball bearings and driven by an electric motor through a system of belt and gears to a very high rotational speed. (Fig. 1D and 2D).

An image of the explosion is formed on an optical slit (Fig.1) by an objective lens (Fig.1A) and the resulting very narrow image re-projected by a second lens ('projection lens' Fig. 1B) via the rotating mirror, on to a roll of film held in a semi-circular drum (Fig.1E and 2E). A surface reflecting plane mirror (Fig. 1C and 2C) is interposed between the projection lens and the rotating mirror. This arrangement produces from a vertical slit, an image at right angles to the length of the film. Since the mirror has four sides and is (approximately) at the centre of curvature of a semi-circular drum then irrespective as to when the slit is illuminated it will produce an image on the film, thus removing the need for an explosion - camera synchroniser.

There are two major disadvantages with a square mirror. First, at the position where the diagonal of the square is vertical, the cone of light from the inverting mirror is split giving two images, one at either end of the film. If the object or its illumination is of low luminous intensity this can be troublesome since each of these images is formed with only half the available light. However, a 50% reduction in light quantity will only reduce the density of the photographic image by about 35% even at the high values for gamma (1.2) to which the film is normally developed, and unless the camera is used with very feeble light sources (e.g. low-temperature, low-order detonations) this phenomenon of image splitting, which only occurs at the ends of the film, is not objectionable.

The second disadvantage of a square, or rather any thick, mirror is that the total distance from the projection lens to the film, measured along the optical axis, varies as the mirror rotates. This affects the speed of the image as it moves over the film and can also affect the focus of the projection lens. The focus is not important unless the variation is greater than that permitted by the optics of the lens, and even with the large lens employed (8 inch focal length, f 2.9) the variation allowed is ± 0.3 inch which is more than ample. The variation in the speed of the image is more important as will be discussed later, but in this case the errors involved have been reduced to a small amount which can be calculated. (see Appendix I).

The camera was designed mainly for use with liquid explosives, and these are usually contained in tall cylindrical vessels, which means that the slit should be vertical. The rotating mirror bearings however, are much less likely to give trouble if the mirror shaft is horizontal, and the use of the inverting mirror allows the use of a vertical slit with a horizontal rotating mirror axis. It also results in a camera of much more compact design.

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It will be appreciated that if the central ray of the light cone from the rotating mirror is to fall normally on to the film, the inverting mirror must be placed between the rotating mirror and the film drum. This would mean that the inverting mirror would shield part of the film from the light from the rotating mirror and either the operation of the camera would have to be synchronised with the explosion to ensure that an image did not occur at this point, or a percentage of the results would be lost.

This defect is overcome by the present arrangement, which, however, requires the inverting mirror to be of an angle greater than 45 degrees, and this, together with the use of a 'thick' rotating mirror results in a curved path for the end of the central light ray where it reaches the film. The consequences of this are not serious since with the normal record, the deviation of the image from its true position amounts to no more than a few thousandths of an inch and this can be calculated if necessary.

3.2. The Lens system and Focusing.

The lens system in use at the present time consists of a pair of F. 2.9, 8-inch focal length Dallmeyer "Pentacs". The double lens plus optical slit arrangement, though complicated and relatively inefficient in light transmission, is very flexible and readily permits alteration of equivalent focal length, field etc., apart from the almost overriding consideration that it permits the separation of the slit and the explosion.

The inner or projection lens is at present set so that the image of the slit is magnified 2.56 times on the film. With the camera at 14 feet from the charge this gives an overall reduction or 'demagnification' of about 8 times, and enables the average velocity of detonation to be matched (i.e. produce a trace at an angle of 45 degrees to the edge of the film) with a very convenient rotational speed of 18,000 r.p.m. for the mirror shaft.

Focusing is carried out in two stages, namely (1) for the inner or projection lens and (2) for the outer or objective lens. The former is done when the slit holder guide and inner lens is fitted by the following process. The outer lens is removed, the inner lens is fitted and screwed down, and with the slit in place and illuminated from the objective lens side, the whole shutter-slit panel is moved until a sharp image of the slit is formed on the film drum. The shutter-slit panel is then screwed down in this position. The outer lens is focused just before a firing or series of firings. The slit is removed giving a wide field. A small electric bulb, (actually a motor car side lamp bulb) is placed in the plane to be occupied by the charge, and the outer lens moved in its screw mount until the image, projected by the inner lens on to the film drum, is sharp. This setting holds good for any number of firings in the same plane.

In this camera, apart from the loss of light at the numerous glass-air surfaces, the double lens system suffers from the defect that owing to the rectilinear propagation of light the angle of acceptance of the second lens does not include all the cone from the first lens. For it to do so would require one of two conditions to be satisfied:-

- (i) the object must be nearer to the outer lens than the final image is to the inner lens, (this is almost impossible in practice); or
- (ii) the inner lens must be of greater aperture than the outer. The ratio of the apertures for lenses of equal focal length, expressed in the usual 'f' notation, must in fact, be in ratio:-

$$\frac{f \text{ outer}}{f \text{ inner}} = \frac{\text{Distance of film to inner lens}}{\text{Distance of object to outer lens.}}$$

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In practice, because of (ii) above, the largest available lens was used for the inner or projection lens and since another lens of the same type was available this was used for the objective.

An attempt was made to concentrate all the available light to a cone acceptable by the inner lens by placing a thin lens next to the slit, where it would interfere least with the focus of the image. The resulting distortions however, more than offset the gain in light.

3.3. The Slit.

The slit is non-adjustable and consists of two blackened razor blades clamped between two sheets of brass. The blades are set by feeler gauges. The separation in use at present is 0.003 inch. This is magnified on the film to a line 0.009 inch wide. This is not the width of the image since the latter is moving over the film at at least a millimetre in a millionth of a second. Therefore if the luminosity is sufficiently intense to record for (say) one millionth of a second the width of the image is the magnified image of the slit (0.009 inch) plus the movement in this time, 1 mm. or .040 inch. The result is that with detonations which have a long reaction time, or if there is considerable after-luminosity of the products of detonation, the image is very wide and appears out of focus. This fault, if it can be described as such, is inherent in high speed cameras and must become worse as the speed increases.

An adjustable slit was tried for a time but proved so troublesome that it was abandoned.

3.4. The Shutter.

A shutter is used to make the body of the camera light-tight between firings. This is placed at the position where the light rays between the two lenses have the smallest cross-sectional area, i.e. next to the slit. A commercial 'Epsilon' shutter was used at first but for continuous and heavy use a shutter of a more robust type is needed and has in fact been made.

In both the commercial and laboratory shutters the trigger is operated electrically by means of a solenoid. In order to ensure that the charge is fired when the shutter is open, a pair of electrical contacts has been fitted and these are closed by the shutter winding lever as it makes its return movement when shutter opens, these contacts completing the electrical circuit which fires the charge. Where initiation of the charge is by means other than an electric detonator a 'bulb' system is used, i.e. the solenoid is energised opening the shutter, the charge is fired e.g. by falling weight, then the shutter is closed.

3.5. The Film.

The film used is standard Ilford Selo H.P. 3 size 20. The bulk of the work so far has been with 'low' temperature detonation waves and a film with a high red-sensitivity is essential; Ilford .H.P.3 is the fastest film of this type available. There may be a use for an emulsion sensitized right down to the infra red but so far it has been considered that the difficulties which would occur outweigh the advantages which might be gained.

The films are developed with Kodak D.82 to a gamma of 1.2 or 1.3. This has been found to give the best results where there is only a minimum of light, but where adequate light is available, e.g. from the detonation of nitroglycerine, 'Quinol-Caustic' gives better results.

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The above value of gamma is derived from results with the D.82 developer using normally exposed film, but the films from the mirror camera are often at the foot of the exposure-density curve and are always exposed under conditions such that the reciprocity law does not hold good. Thus gamma in itself for such films has little meaning.

3.6. The loading mechanism.

The winding gear is extremely simple, consisting of two standard No.20 film take-up systems such as are found in any box camera of this size. Two are fitted, one each end of the film drum, because the film moves easier if it is fed into the drum as well as pulled out. To load in daylight the film is prepared with an extra leader, marked at a definite distance from the end of the film. This is put in the drum, the mark brought opposite a reference mark in the camera, and the back closed. The film is then wound on a predetermined number of spool revolutions, bringing the film into place. It has been found so easy to put an ordinary unprepared film straight into the drum, by touch in the dark, that this is preferred when possible, (e.g. in the light-tight camera room).

3.7. Driving mechanism.

The camera is driven by a 0.4 H.P. electric motor. This carries on its shaft a 6 inch diameter (nominal) Vee pulley which is connected by a belt to a $1\frac{3}{4}$ inch Vee pulley on the gear box countershaft. The whole of the gear box is inside the camera, and the countershaft is extended and projects through the side of the camera box to carry the $1\frac{3}{4}$ inch pulley previously noted. This shaft drives the mirror by a single stage of step-up gearing in the ratio of 6 to 1. The belt has a spring loaded 'jockey' or tension device.

4. Constructional Details.

4.1. The camera box.

The box containing the film drum etc. is made of $\frac{1}{2}$ inch thick multi ply wood built in a frame of teak. The base board is of 1 inch plywood. The door is carried on three hinges and the edges are formed on a 'tongue and groove' principle to act as a light trap. The door is fastened by two lever-operated cams which squeeze it shut. The inside of the box is painted 'dead' black.

4.2. The Film Drum.

The film drum was made by rolling a strip of brass to a circle of the appropriate radius, brazing on the fixing lugs and turning in a lathe to the cross section shown (Fig. 1). The exact radius, $9\frac{1}{2}$ inches was turned on the inner (as it is mounted in the camera, the top) face of the side grooves since the film is pulled against these in use. After turning, a little more than a semi circle was cut out. The finished drum is not rigid when unsupported but tends to spring. Therefore it was carefully fitted to lines scribed inside the camera box.

4.3. The Inverting mirror.

The inverting mirror holder is on a universal ball joint and is located by three locking screws. The mirror itself is a 3 by 4 inch optical flat, the surface of which is aluminised. The mirror is $\frac{1}{4}$ " thick and care is taken not to introduce distortions by bending.

4.4. The Rotating mirror.

The rotating mirror, which is integral with its shaft, is made from

/solid

solid stainless steel bar, and is ground and polished to 'optical flat' accuracy and finish and finally surface aluminised. The faces measure 1 inch by $1\frac{1}{2}$ inches, the $1\frac{1}{2}$ inch side being parallel to the axis of rotation.

4.5. The Gears and Pulleys.

In view of the high speeds involved and the difficulties of either fitting an oil bath or gear cover, it was decided to run the gears dry. Any lubricant on the gear teeth would soon be flung off on to the film and spoil it. For this reason aluminium and Tufnol were chosen as gear materials.

The large gear is made of aluminium, has 120 teeth and is of 20 'diametral pitch'. The pinion of Tufnol, 20 teeth, made from sheet material with the grain across the face of the pinion in order to minimise the risk of tooth-breakage. Both wheels are fixed to their shafts by means of taper pins, as this method of fixing affects the balance less than a key. It has been found necessary to hammer over the small end of the mirror (pinion) pin since on one occasion the pin was squeezed out when the camera was being driven hard. The axles are supported in dual purpose (i.e. thrust type) ball races since this type permits easy dismantling of the gear box even with both inner and outer members a driving fit on the shaft and gear box respectively.

The pulleys are standard 'Vee' belt types, 6 inch and $1\frac{3}{4}$ inch nominal diameter. The actual ratio is a little over 4 to 1 since a $\frac{3}{8}$ inch laced leather belt is used which sits closer to the pulley than the normal Vee belt. A $1\frac{3}{4}$ inch pulley with a ball bearing centre, mounted on an arm with a light spring to tension it is used to 'jockey' the belt and prevent the expansion due to centrifugal force causing the belt to ride off.

4.6. The Speed control system.

A wide range of controllable speed is essential for the accurate determination of detonation velocities. It was expedient to use an A.C. motor and this led to the adoption of a system of control which is somewhat unusual and has features which may first appear undesirable.

A single phase induction motor with a rotor-centrifugal switch starter, r.p.m. 2850, H.P. = 0.4, was chosen. This is belted and geared as described with the deliberate intention of seriously over-gearing it (actually 24 to 1 on the mirror). Under these conditions, at least up to mirror speeds between 40,000 and 50,000 r.p.m, the switch will not operate and since the motor is running under conditions of high slip and with the starting device working the speed is sensitive to voltage control. A system of variacs and a fixed transformer provide this (Fig.7).

5. Determination of Writing Speed.

5.1. General considerations.

The velocity of the final image, relative to the film, is known as the writing speed of the camera.

Considering the normal case of a narrow detonation zone moving so as to produce a point of light which moves along the slit-image, it is clear that the result of the simultaneous movement of the slit-image will be to produce a line at some angle to the film edge. Since this angle is a function of the writing speed and the velocity of the point in the image, the latter may be determined from a knowledge of the former.

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As the charge is brought nearer to the camera, the speed of the light-point for a given velocity of detonation, will increase since the dimensions of the final image relative to the object have increased. As the most accurate determinations are made when the image angle is about 45 degrees to the film edge it follows that as the charge is brought nearer the camera the writing speed should be increased. Thus a high maximum writing speed, provided that it can be measured accurately is an essential in a good instrument of this type.

The accurate measurement of writing speed presents exceptional difficulties since it directly involves the rotational speed of the mirror. Standards of speed are not so easily obtained as (say) length. The best of Tachometers compares badly in accuracy with even a cheap foot rule.

The first method used to determine rotational speeds was stroboscopic, because it was known that this type of control had already been employed successfully at the Safety in Mines Research Station, Buxton. Later the same principle was adapted to permit of remote control of the camera.

5.2. The Stroboscope 'Rev counter'.

When a stroboscope is used as a 'rev-counter' it is not usual actually to determine the speed of an uncontrolled shaft. The method is to decide first on the speed to be obtained, set the stroboscope by some frequency standard, and then adjust the speed of the shaft until it 'locks' with the stroboscope.

In the present camera the fundamental standard is the tuning fork of a 'Tinsley' chronoscope. This fork is set to ± 0.02 per cent of 25 cycles per second by the makers who state that the temperature variation is 0.02 per cent per degree centigrade. In order to keep the equipment dry the camera hut is heated by a thermostatically controlled heater and this helps to maintain the constancy of the fork frequency.

An extra pair of contacts on this fork acts as the interrupter of an induction coil. The output of this coil is intended to drive a neon lamp direct, but the power available was hopelessly small and the pulses far from sharp. In order to improve this a 'cathode-follower' type of amplifier was devised (Fig. 8).

The operation of this amplifier is as follows:- the bias resistor R is so large that the 6L6 amplifier valve is practically at 'cut off', the current being so small that the potential drop on R is below the extinguishing voltage of the neon lamp N, which is therefore dark. On the arrival of a pulse from the 'Tinsley' fork-induction-coil the current will rise slowly until the potential difference on R reaches the firing voltage of N. Then, owing to the voltage stabilising effect of these lamps, the cathode of the 6L6 will be held at approximately this voltage, the grid will be driven to zero and the 6L6 will jump to a high value of anode current. As the intensity of the pulse falls, the reverse occurs with an almost equally sharp cut-off. The lamp N is a 5 watt 'Osglin' with the base resistor removed and so connected as to make the wire spiral the cathode since this has been found to give the maximum light.

The intermittent light is used to illuminate the pulley on the gear box. This pulley is painted black except for a bright radial streak. As the speed increases, various steady patterns are seen on the pulley (when viewed by the intermittent light) for speeds which are multiples of the tuning fork frequency (i.e. 25 c.p.s.); thus a cross is seen at $\frac{1}{4}$, $\frac{3}{4}$ and $1\frac{1}{4}$ times 25 revolutions per second, a diametral line is seen at $12\frac{1}{2}$, $37\frac{1}{2}$, $67\frac{1}{2}$ r.p.s. and the radial line is seen at 25, 50 and 75 r.p.s.

/the

the last corresponding to writing speed of roughly 425, 850, 1275 metres per second.

5.3. An Electronic rev. counter.

It became apparent with experience that it would be advantageous to remove the control from the vicinity of the camera itself, and the stroboscope method was modified to permit this.

Instead of the radial streak there is an electrical brush fixed to the pulley and this completes an electrical circuit, by means of a spring contact, once per revolution. The result of this contact is brought out on to a cathode ray tube in the form of a vertical pulse on a horizontal time base (Fig. 9A). Now if the time base (which is a thyatron 'saw-tooth' generator) is running at exactly the same frequency as the pulley, only one pulse will be seen and this will be stationary. If the pulley is asynchronous with respect to the time base, then the pulse will move to left or right according to the sign of the difference. If the pulley is running at some multiple n of the time base frequency then n pulses will move to seen. For reasons of accuracy, discussed later, n should equal 1.

This arrangement as stated is not quite satisfactory since the pulley may be running at some sub multiple or some fractional multiple, say $1\frac{1}{3}$ of the time base frequency and still give stationary pulses. Thus suppose the pulley is rotating at one third the time base frequency, the sequence is as follows:- the pulse is generated, then the time base will make two complete sweeps without a pulse and on the third sweep will generate a pulse which will be superimposed on the first, and the pattern on the screen will be indistinguishable from the case when $n = 1$.

From similar reasoning, when $n = 1\frac{1}{3}$ it can be shown that three pulses will be seen, the separation between them being $\frac{1}{3}$ of a sweep, identical with the case of $n = 3$.

In order to prevent confusion the pulses are 'shaped' by a condenser resistor net work to that shown in Fig. 9b. Now, for cases where the pulley speed is a sub multiple or a fractional multiple of the time base frequency the pulse will be underlined (Fig. 9c) while for whole number multiples the pulses will be as shown in Fig. 9b.

The Cathode Ray tube is part of an oscilloscope which follows conventional lines. Amplifiers for either axis are unnecessary, and a small (3 inch) tube working on the comparatively low anode voltage of 700 is used.

The time base is adjusted to an approximate multiple of 25 by means of a sine-wave pattern obtained from the A.C. mains. This pattern is then synchronised from the out-put of the Tinsley fork (unamplified) by injection of this voltage, correctly poled, into the grid of the time base thyatron. The sine-wave is switched out and the pulse circuit then switched in.

With this method the errors in setting can be estimated as follows:-

if N = nominal speed and

S = time, in seconds, for a pulse to move to the position previously occupied by its successor or predecessor then the error = $\frac{100}{SN}$ per cent

The distance moved, $D = \frac{WT}{N}$

/where

where T = time base frequency in cycles/sec

W = tube width.

(Correctly W = time base amplitude but in practice this is set so that the sweep fills the tube).

The usual procedure is not to time the movement of the pulse but to hold as steady as possible. This is done with the best advantage when the apparent speed of movement of the pulse is greatest for a given error, i.e. D should be as great as possible. Since when $\frac{T}{N} > 1$ the pattern on the Cathode Ray tube is confused by the multiple underlinings, $\frac{T}{N}$ should equal 1. Thus for a pulley speed of 50 r.p.s. equivalent to a mirror speed of 18000 r.p.m. the time base is set to 50 c.p.s.

5.4. Conversion of rotational speed to writing speed.

A length of paper, corresponding to the film is inserted in the film drum. The shutter is opened and the slit illuminated from the front. The rotating mirror is set so as to produce a split image, i.e. a line at both ends of the paper in the drum. These lines are marked on the paper with pencil, the paper removed from the drum and the separation measured.

If R is the rotational speed of the mirror and L is the separation of the images, $4RL$ is taken as the writing speed. The errors involved, particularly those due to the thickness of the mirror, are discussed in Appendix 1.

6. Procedure for determining detonation velocity.

6.1. Setting up and firing procedure.

The camera is located in a light-tight room built on the side of the armoured firing chamber. A small safety glass window is pierced in the common wall for the camera.

In the firing chamber is a large girder frame 5 feet by 6 feet, securely held in a vertical plane at right angles to the optical axis of the camera so that this axis passes approximately through its centre. The camera is focused (as previously described) on the plane occupied by this frame. The charge must then be located so that it occupies the object position corresponding to the image slit in the camera, and this has been done in two different ways:-

- (i) the slit is replaced after focusing, and with the shutter open, a 100 watt lamp is placed in the camera over the inverting mirror. This causes a projected image of the slit to appear in the firing chamber;
- (ii) with the old shutter, i.e. the 'Epsilon' the aperture was such that it had to be placed against the slit. With the laboratory made one however they can be separated by about $\frac{3}{4}$ inch. The shutter is fixed this distance behind the slit and in the intervening space is a guide for a small tubular lamp, size about $7\frac{1}{2}$ mm. diameter by 30 mm. in length. This lamp can illuminate the slit from behind while the shutter is closed. The advantages are that the film can be in position while the charge is lined up, and that several charges can be lined up and fired in succession without changing the film. The latter is only practicable when a number of identical charges are being fired. The tubular lamp is a 'fostoon' lamp as used in a car 'trafficator'.

/Having

Having obtained the image inside the chamber, by either means, a vertical cross string is fixed to the frame in line with this image, and the charge fixed to this string and steadied by means of two horizontal cross strings.

Where necessary, a point of particular interest, e.g. a change in diameter of the explosive charge, can be marked on the film by placing the lamp used for focusing with its filament crossing the slit at the point to be marked. The camera is run and an exposure made, thus giving a line marker for the whole film.

The actual initiation of the charge is by an electric detonator. The sequence of events is as follows:- The camera is run at the required speed and the shutter is tripped. On reaching the 'open' position the shutter mechanism closes a pair of contacts which 'fire' a thyatron controlling the discharge of a condenser through the detonator. The capacity is 8 MFD and the voltage on the detonator approximately 1 KV. The panel containing the thyatron, condenser etc. is only connected immediately before a firing, in addition there is a 'safety plug', the removal of which prevents the operation of the firing panel, and this, together with the shutter-operating key, is always taken into the firing chamber when the charge is being set up.

6.2. Measurement of Photographic Image.

An enlarger is set so that the negative holder is parallel with the base board. The negative is placed in the holder so that its edges are visible and their images lined up with one ordinate of a sheet of millimetre graph paper. Several points on the 'straight' part of the trace image are marked with a pencil and a line drawn through. The velocity is then determined by counting squares, from a knowledge of the constants applicable.

The demagnification, and any correction due to the lack of 'uprightness' of the slit with respect to the film, are determined by the use of a special firing as follows:-

A charge is set up consisting of an explosive known to give a bright image, e.g. nitroglycerine, with two opaque bands a known distance apart. This is fired by the shutter in the usual way but with the mirror stationary. This gives a line which can be used to check the uprightness of the slit and the breaks in the line give the demagnification.

7. Results.

Some typical traces.

A typical high explosive record is shown in Fig.10 (Nitroglycerine in a glass tube, $12\frac{1}{2}$ mm. internal, $15\frac{1}{2}$ mm. external diameter). It is seen that the record is bright and clear with a sharp leading edge (on the left). The trailing edge is not so sharp, presumably because the duration of the luminosity of the products of detonation is not constant. The faint, almost horizontal lines on the right are probably the debris of the explosion burning in air.

With explosives which give a detonation zone of lower temperature, the trace is much less clear and bright. Figs. 11 to 14 show typical records obtained from Dithokite (20% water). An enlargement of the 'head' of one of these is shown in Fig.12. This shows the way in which the initial axial detonation zone, after proceeding for some distance in the middle of the charge, changed into a spherical zone expanding both up and down the charge giving the Y shaped record. The gradual decrease in the width of the trace is due to the increasing radius of the spherical wave-front, i.e. the width of the trace decreased as the zone flattens.

/Fig.13

Fig. 13 shows the effect of introducing a constriction into a cylindrical charge. The luminous mass at the top is probably the aluminium detonator case burning in the nitric acid from the Dithekite. The lower luminous mass may be an end effect from the upper large diameter part of the charge.

Fig. 14 is a 'close up' (not a greater photographic enlargement) of the constriction in a charge, similar to that used for Fig. 13. The horizontal line is a marker showing the beginning of the constriction. The thickening of the trace and its subsequent narrowing in the lower part of the trace is what would be expected if a small, axial, flat detonation wave expands spherically out of the narrow tube into the wider, and then as the distance travelled by the zone increases its radius also increases (i.e. it flattens) giving a narrow trace once more.

8. Conclusions.

The instrument described will be of value in the solution of problems associated with detonation zone shapes and velocities. It is extremely fast judged by mechanical standards, and its definition, in view of these high speeds is good.

It is difficult to estimate the overall accuracy of the time-resolution since all the work so far has been with liquid explosives. Variations of some 2% in detonation velocity between identical firings have been noted but variations of 4% have been found (4) for liquid explosives, with cameras which gave consistent results with solid explosives.

The most used writing speed has been 1000 metres per second, occasionally 2000 m.p.s. has been used and the highest speed ever reached was a mirror speed of ca. 67,000 r.p.m. (actual speed open to some doubt) corresponding to a writing speed of 3250 m.p.s. or $3\frac{1}{4}$ millimetres per millionth of a second. By optically enlarging the negatives even higher (apparent) speeds can be produced on the print, but much of this magnification is 'empty' and does not increase the value of the result. Fig. 12 produced in this way from a millimetre per microsecond negative, has a time scale (on the print) of about 8 mm. per micro second.

The real value of a high camera writing speed is shown in the investigation of detail. Suppose it is required to photograph a part of a charge of 5 cm. in length. If this is made to produce a 5 cm. image on the film, the writing speed must equal the velocity of detonation in order to produce a trace 45° to the edge of the film (thus giving the most accurate measurement). Now if the part to be photographed had been 50 cm. long the writing speed for a 45° record is only one tenth the velocity of detonation since there is an optical reduction in the camera of 10 to 1, assuming a 5 cm. image as before.

It is arguable whether any great increase in speed can be reached using mechanical scanning. The enormous speeds reached in television practice could be exploited and cameras are being developed elsewhere using this technique. If this method is successfully adopted the only field left for the optical-mechanical camera is the yet unexplored use of colour.

9. Acknowledgments.

Acknowledgment is made of the advice and encouragement given by Mr. L. Phillips under whose general direction this work was carried out.

/10.

10. Bibliography.

- (1) O.S.R.D. Report No. 682. Ser. 285.
- (2) Safety in Mines Research Board, Paper No.99.
- (3) D.S.I.R. (R.R.L.) Note No. MCS/398/DC.
- (4) O.S.R.D. Report No. 5609.

APPENDIX I

CALCULATION OF ERRORS DUE TO THICKNESS OF MIRROR †

by L.F. Jones.

In order to reduce the variations in the total light-path length the centre of the mirror is set at a point 0.2 inch above the centre of the drum.

Referring to Fig. 15. O is the centre of the prism (mirror)
D is the centre of the drum.

Consider the path of the reflected ray when the prism has been deflected through an angle Θ , in an anticlockwise sense, from a zero position where the incident ray strikes a corner B of the prism.

B will have moved to B^1

$$\begin{aligned} \angle BOB^1 &= \Theta \\ \text{In } \triangle POB^1 \quad \frac{OP}{\sin 45} &= \frac{OB^1}{\sin (135 - \Theta)} \\ \therefore OP &= OB^1 \left(\frac{1}{\sin \Theta + \cos \Theta} \right) \end{aligned}$$

Now refer P to cartesian Axes through D

$$\text{Let } OD = b \text{ and } OB^1 = \sqrt{2}a \text{ (prism side} = 2a)$$

$$\text{then } DP = \sqrt{2}a \left(\frac{1}{\cos \Theta + \sin \Theta} \right) - b$$

$$\text{and P is } \left(0, b - \frac{\sqrt{2}a}{\cos \Theta + \sin \Theta} \right)$$

The reflected ray PR makes an angle 2Θ with the horizontal so that the equation of Pr,

$$Y - Y^1 = m (x - x^1) \text{ is: } -Y - b + \frac{\sqrt{2}a}{\cos \Theta + \sin \Theta} = x \tan 2\Theta$$

Now where this ray strikes the drum

$$-X = R \cos \Phi$$

$$-Y = R \sin \Phi$$

where R is the radius of the drum

and Φ is the angle subtended at the centre of the drum.

$$\therefore -R \sin \Phi = -R \cos \Phi \tan 2\Theta + b - \frac{\sqrt{2}a}{\cos \Theta + \sin \Theta}$$

Multiply by $-\cos 2\Theta$

† It is understood that a similar solution has been worked out by Mr. G. Morris of I.C.I. Explosives Ltd., but no publication appears to have been made.

$$R \sin \phi \cos 2\theta - R \cos \phi \sin 2\theta = - \left(b - \frac{\sqrt{2}a}{\cos \theta + \sin \theta} \right) \cos 2\theta$$

$$\sin (\phi - 2\theta) = \frac{1}{R} \left(\frac{\sqrt{2}a}{\cos \theta + \sin \theta} - b \right) \cos 2\theta$$

If $-(2\theta - \phi) = \Omega$ it is now possible to calculate $\Omega_1, \Omega_2, \Omega_3$ corresponding to $\theta_1, \theta_2, \theta_3$ and hence obtain ϕ_1, ϕ_2, ϕ_3

$$\text{Thus, } \sin V = \sin (\phi - 2\theta) = \frac{1}{R} \left(\frac{\sqrt{2}a}{\cos \theta + \sin \theta} - b \right) \cos 2\theta$$

$$\begin{aligned} R &= 9.5 \text{ inch} \\ a &= 0.5 \text{ inch} \\ &= 0.7071 \text{ inch} \end{aligned}$$

θ	$\sin \theta$	$\cos \theta$	$\sin \theta + \cos \theta$	$\frac{\sqrt{2}a}{\sin \theta + \cos \theta}$	$\cos 2\theta$	$\text{Log}_{10} \sin(\phi - 2\theta)$	V
0	0.0000	1.0000	1.0000	0.7071	1.0000	2 .7200	3° 00'
6	0.1045	0.9945	1.0990	0.6433	0.9781	2 .6509	2° 34'
12	0.2079	0.9781	1.1860	0.5961	0.9135	2 .5714	2° 08'
18	0.3090	0.9511	1.2601	0.5611	0.8090	2 .4774	1° 43'
24	0.4067	0.9135	1.3202	0.5357	0.6691	2 .3626	1° 19'
30	0.5000	0.8660	1.3660	0.5165	0.5000	2 .2099	0° 56'
36	0.5878	0.8090	1.3968	0.5060	0.3090	2 .9858	0° 33'
42	0.6691	0.7431	1.4122	0.5008	0.1045	3 .5972	0° 11'
45	0.7071	0.7071	1.4142	0.5000	0.0000	-	
48	0.7431	0.6691	1.4122	0.5008	-0.1045	3 .5972	0° 11'

b, the offset, is calculated as follows:-

the length of a complete trace was measured as 733.6 mm. (mean of several)

This corresponds to an angle of $\frac{733.6}{9.5 \times 25.4}$ radians = 3.034 radians

which in turn corresponds to $\phi_0 = \frac{3.1416 - 3.034}{2} = 0.0538$ radians

$$\sin (\phi - 2\theta) = 0.05248 = \frac{1}{R} (\sqrt{2}a - b)$$

$$\text{Thus } 0.7071 - b = 0.4986$$

$$\therefore b = 0.2085 \text{ inch.}$$

/Now

Now referring to Fig. 16.

D is the centre of the drum.
B is the corner of the prism when the diagonal
of the prism is vertical.

Since the corner of the prism falls below the centre of the drum the extremities RoR_{90} of the trace swept out when the prism rotates, fall below the extremities of the hemispherical drum.

$$\widehat{RoD R_{90}} = (\pi - 2\phi_0) = \mu$$

Thus for the complete sweep the true angular displacement

$$\pi = \frac{\pi}{\mu} \times \mu$$

In practice, since it is difficult to locate the mirror in an exact position, or to measure the critical distance DB ($= b$) directly, the factor $\frac{\pi}{\mu}$ was derived from the actual length of trace, measured as described in the section on writing speed.

Since the traces obtained in measuring detonation velocities involve arcs which are considerable smaller than $Ro R_{90}$ an attempt is made to assess errors arising from the use of K_1 as a correcting factor.

Consider a trace ending at an angle ϕ_2 and beginning at an angle

ϕ_1

$$\phi_2 = 2\theta_2 + v_2$$

$$\phi_1 = 2\theta_1 + v_1$$

$$\phi_2 - \phi_1 = (2\theta_2 - 2\theta_1) + (v_2 - v_1)$$

This arc is multiplied by a factor K

$$K(\phi_2 - \phi_1) = K(2\theta_2 - 2\theta_1) + (v_2 - v_1)$$

$$\therefore K(\phi_2 - \phi_1) - (2\theta_2 - 2\theta_1) = (K - 1)(2\theta_2 - 2\theta_1) + K(v_2 - v_1)$$

$$\Delta = K \frac{K-1}{K} (2\theta_2 - 2\theta_1) + (v_2 - v_1)$$

Various values of Δ are evaluated as follows:-

The trace measured with the greatest accuracy is 45° to the film edge. In this camera this required a mirror rotation of 6° , or a light ray rotation of 12°

$$\text{now } \frac{K-1}{K} (12^\circ) = 24.7' \quad \left(K = \frac{\pi}{\mu} = \frac{3.1416}{3.034} \right)$$

2θ	v	$v_2 - v_1$	Δ
0°	$3^\circ 00'$	$-26'$	$+1.3'$
12°	$2^\circ 34'$	$-26'$	$+1.3'$
24°	$2^\circ 08'$	$-25'$	$+0.3'$
36°	$1^\circ 43'$	$-24'$	$-0.7'$
48°	$1^\circ 19'$	$-23'$	$-1.7'$
60°	$0^\circ 56'$	$-23'$	$-1.7'$
72°	$0^\circ 33'$	$-22'$	$-2.7'$
84°	$0^\circ 11'$	$-22'$	$-2.7'$
90°			
96°	$0^\circ 11'$		

Hence errors in assessing a 12° arc range from $+1.3'$ to $-2.7'$.

Now the corrected arc less $\Delta =$ true angular displacement of prism, so that observations at the extreme of the trace are liable to give results 0.18% too high while those near the middle of the trace give results 0.38% too low.

S.No.98

M.No.403/49

APPENDIX II

Figs. 1 to 16

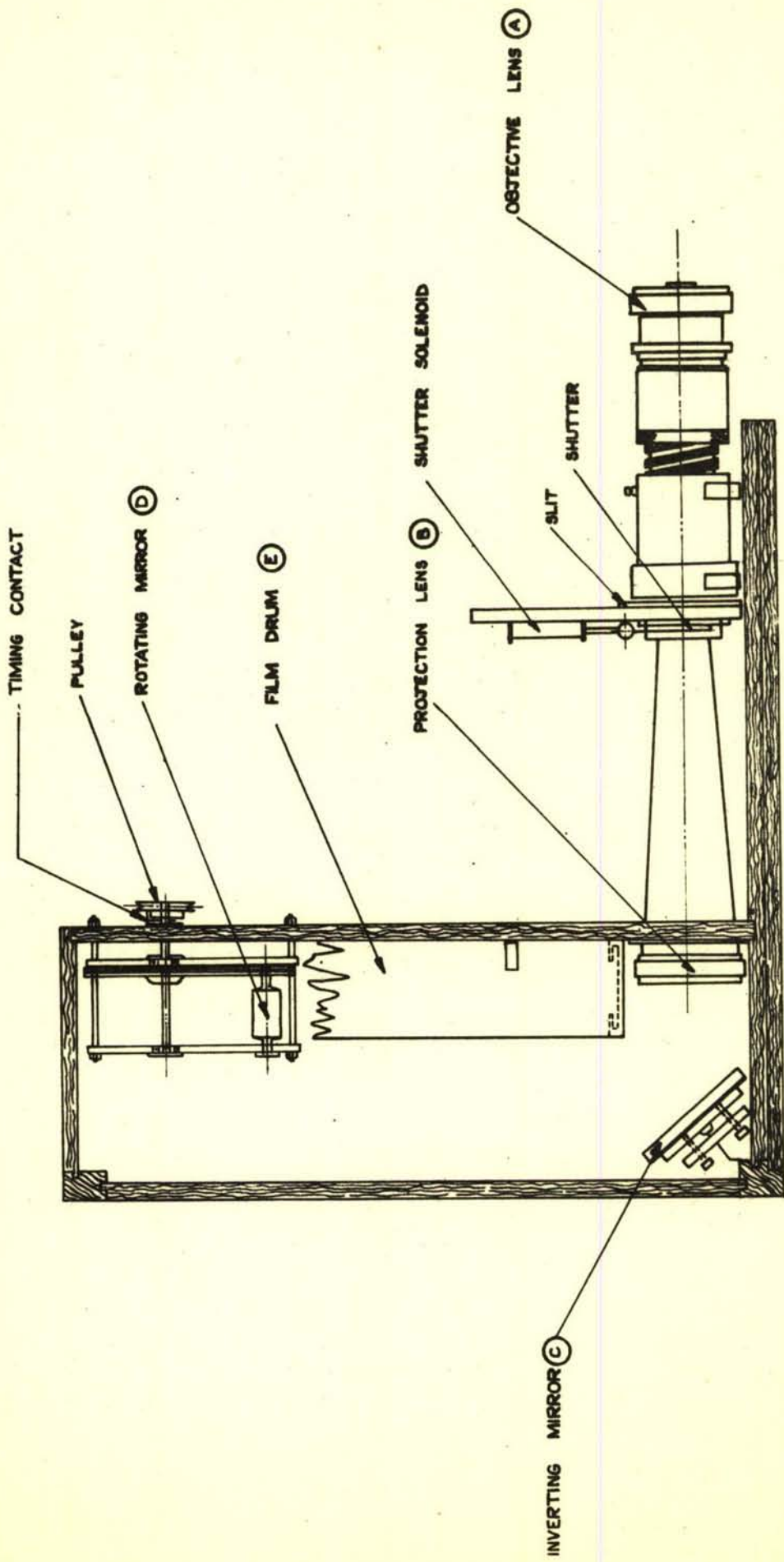


FIG 1

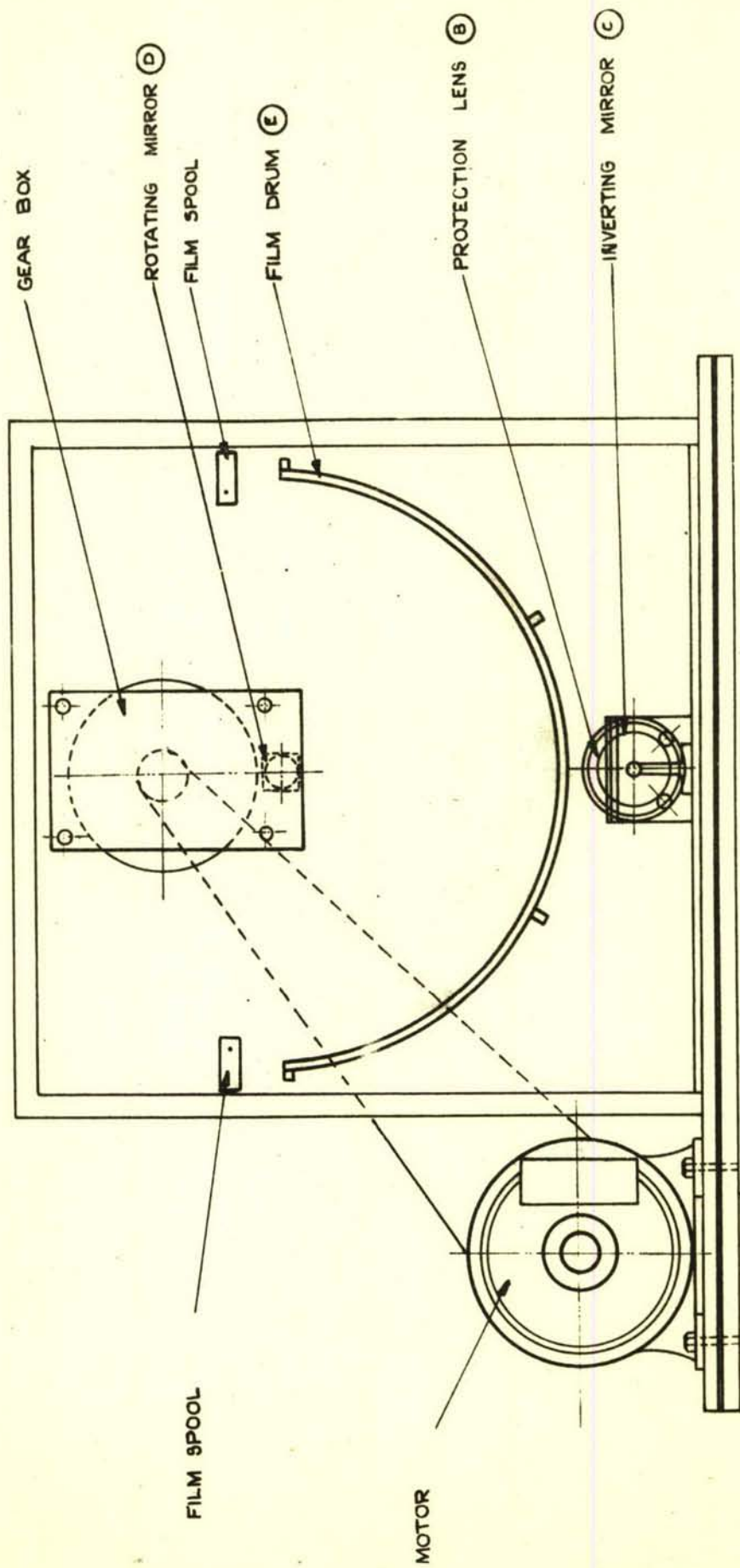


FIG 2.

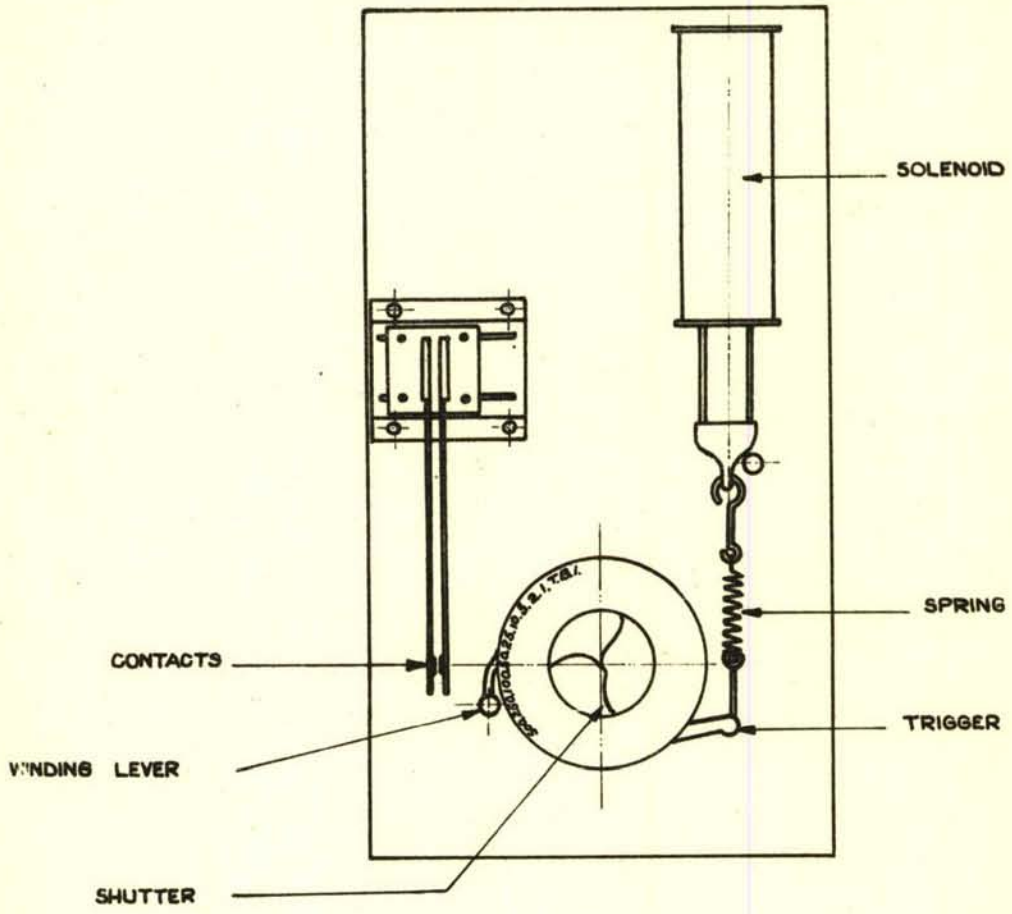


FIG 3

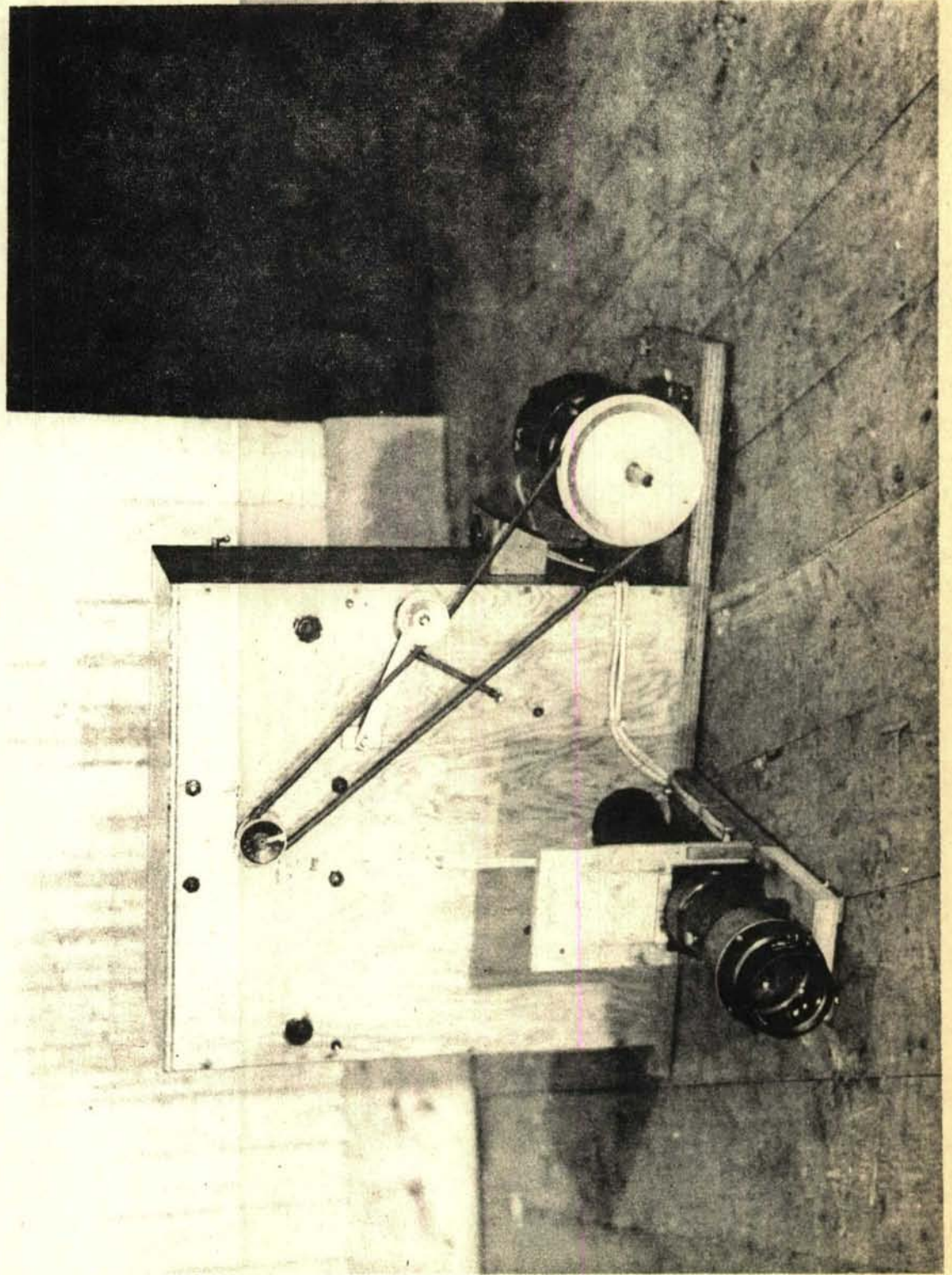


FIG. 4

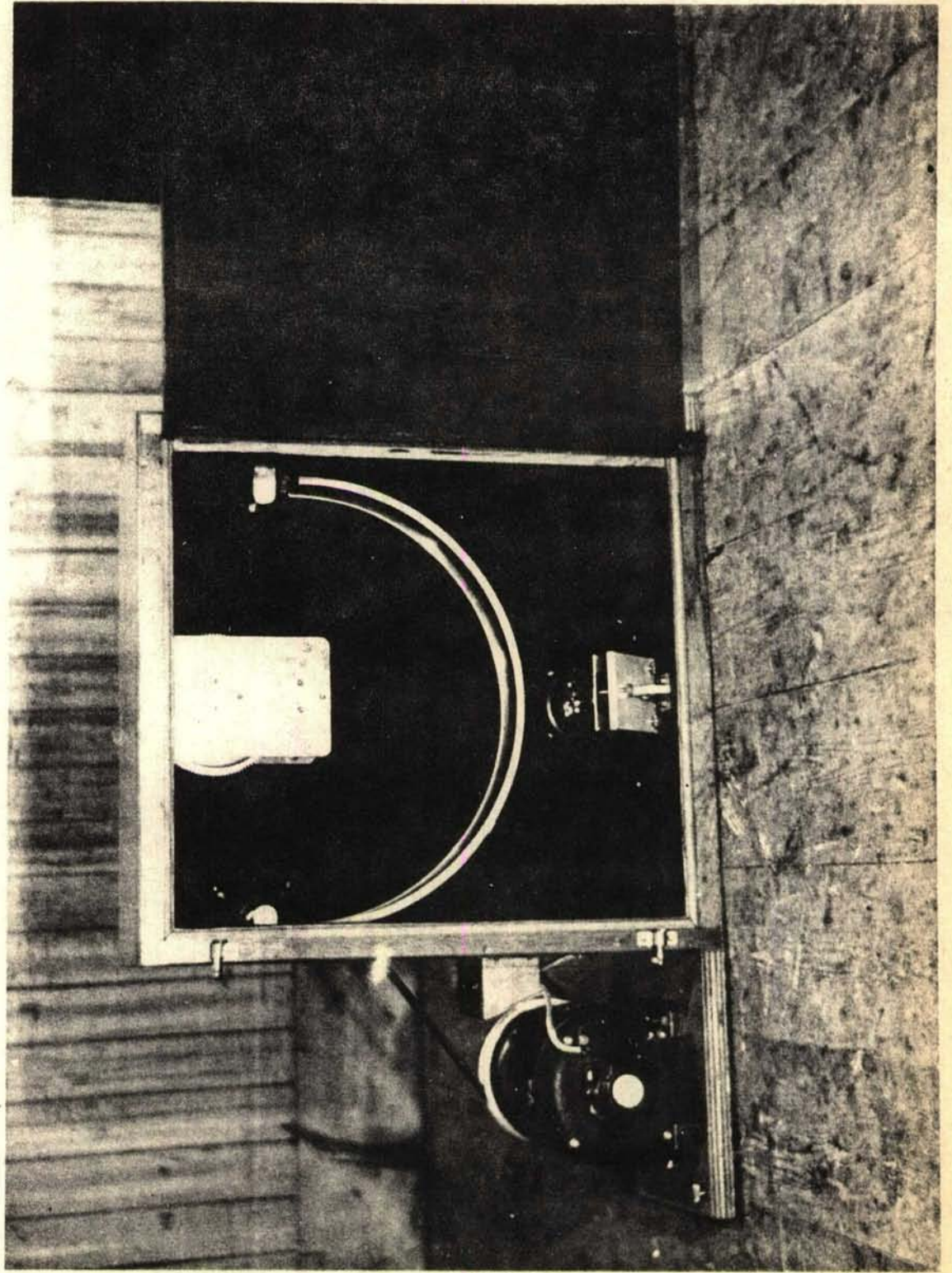


FIG. 5.

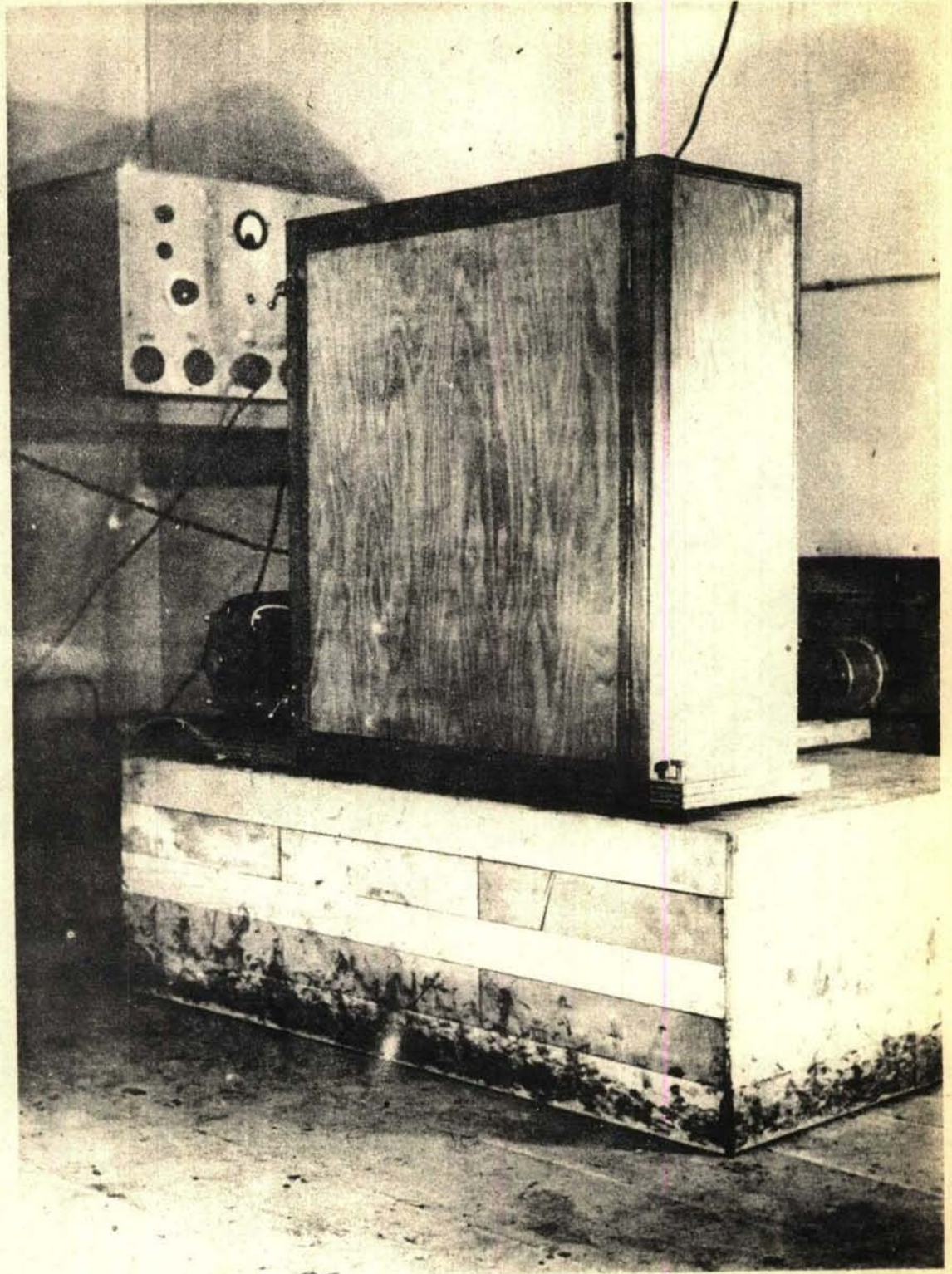


FIG. 6.
CAMERA IN POSITION

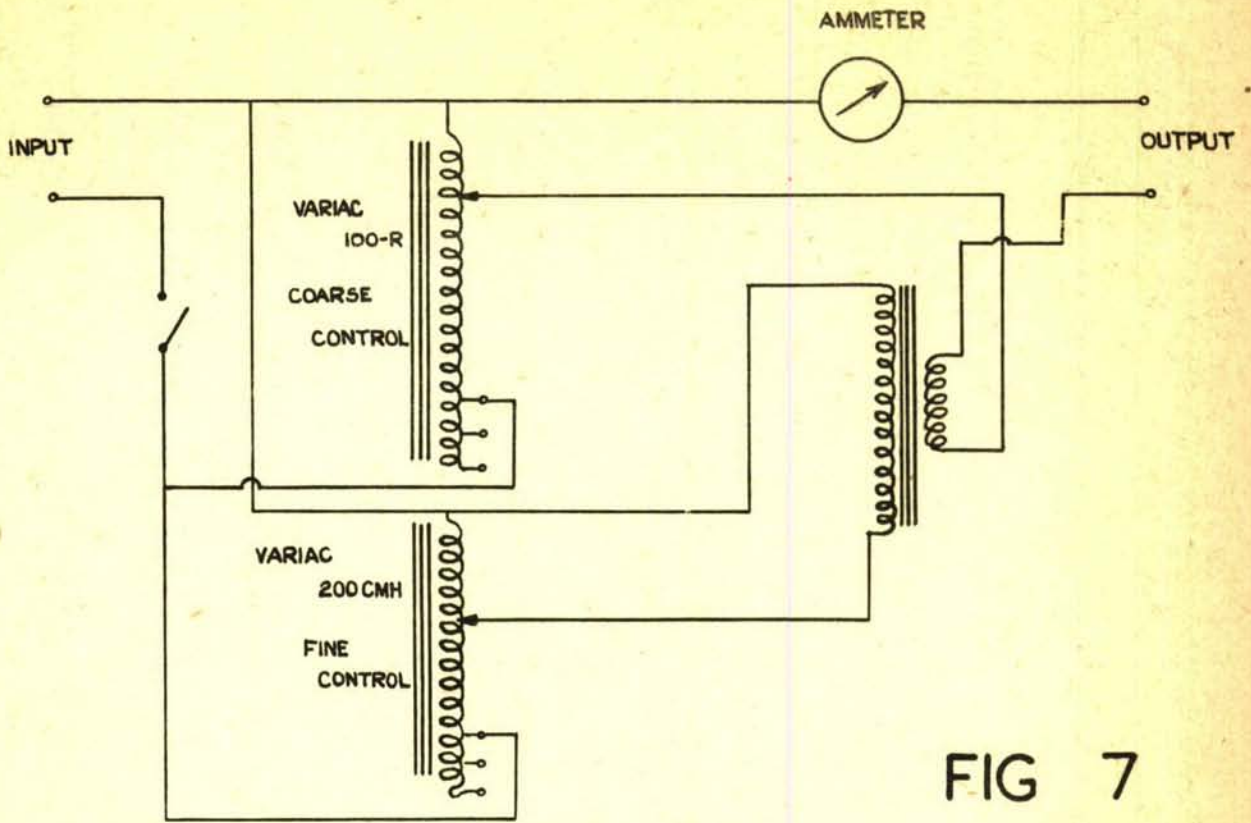


FIG 7

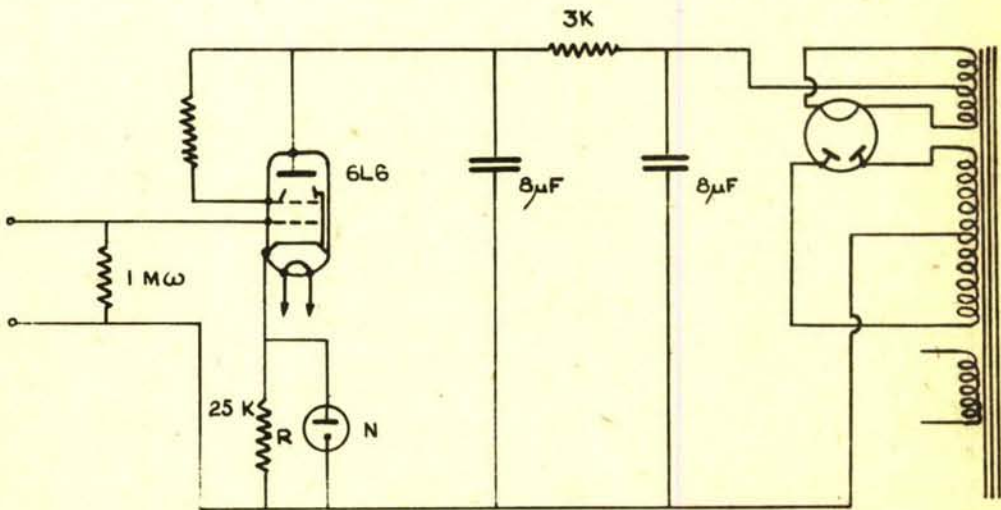
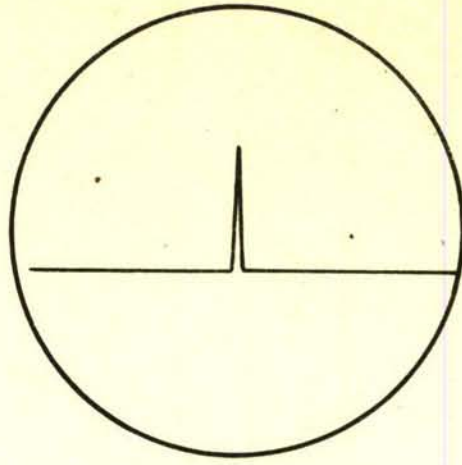
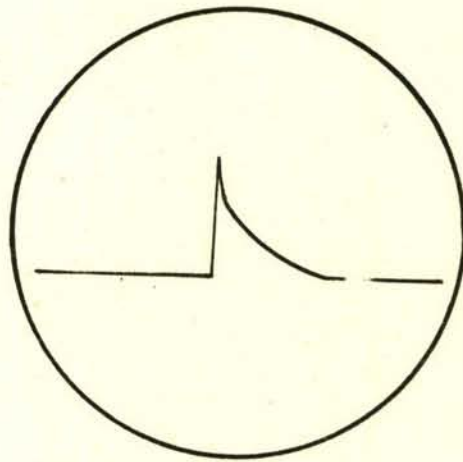


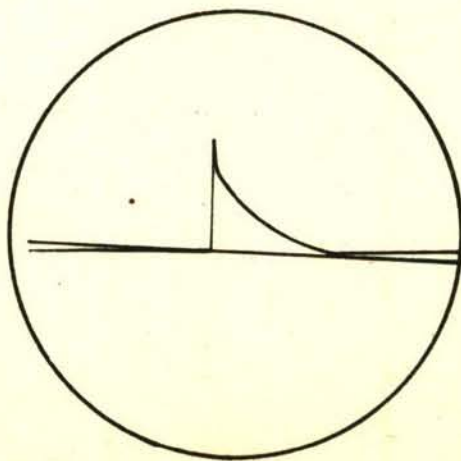
FIG 8



(A)



(B)



(C)

FIG 9

TIME SCALE \square 10 μ SEC



—
Z
I
O
S

FIG 10

TIME SCALE \square 10 μ SEC



—
Z
I
O
S

FIG 11

TIME SCALE \square 1 μ SEC



—
Z
I
O
S

FIG 12

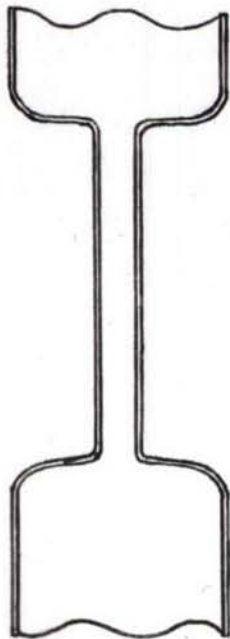
TIME SCALE $\text{L} \quad \text{I} \quad \text{O} \mu \text{ SEC}$



$\text{L} \quad \text{I} \quad \text{O} \mu \text{ SEC}$

FIG. 13.

TIME SCALE $\text{L} \quad \text{I} \quad \text{O} \mu \text{ SEC}$



$\text{L} \quad \text{I} \quad \text{O} \mu \text{ SEC}$

FIG. 14

UNCLASSIFIED

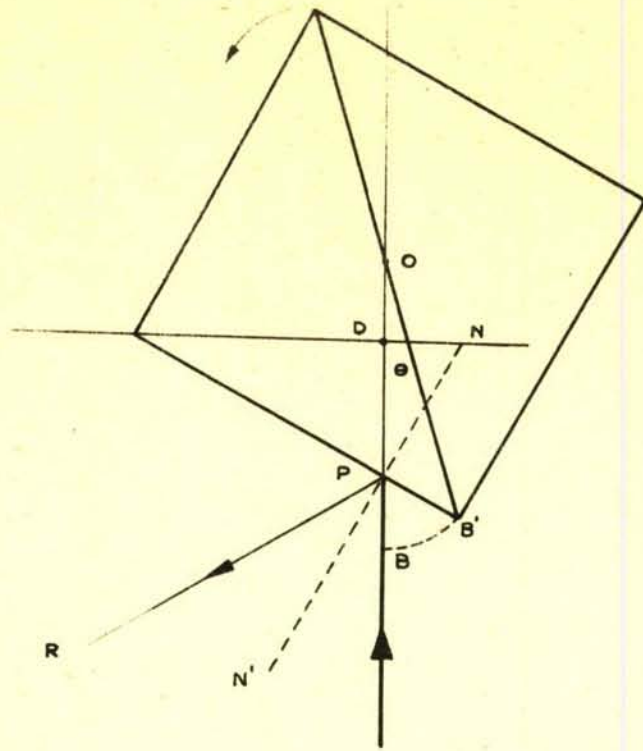


FIG 15

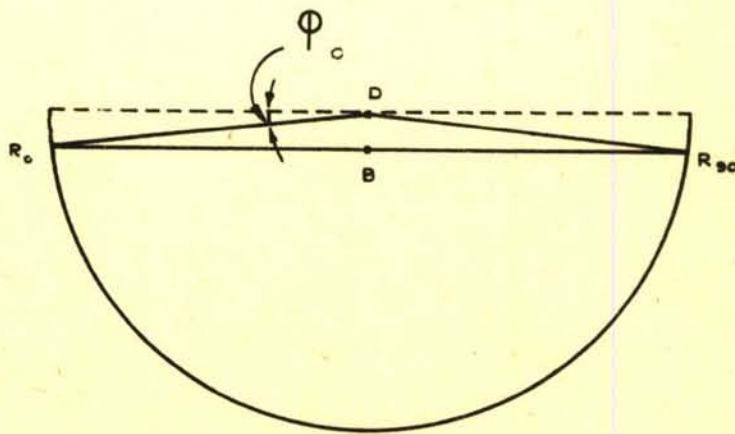


FIG. 16

UNCLASSIFIED

UNCLASSIFIED