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A PHOTOGRAPHIC TECHNIQUE FOR THE STUDY OF WATER JETS

by

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SUMMARY

A photographic technique has been developed for the close study of water jets moving with velocities ranging from 18 to 32 metres per second. Water jets with flow rates and ranges suitable for fire fighting use are being studied to determine the effects of both changes in nozzle design and the use of flow improving additives to the water.

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Joint Fire Research Organization

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1. INTRODUCTION

Comparatively few studies of water jets suitable for fire fighting have been published since Freeman's comprehensive treatise in 1889[1]. One conclusion of Freeman's, that the coefficient of discharge for the standard Fire Service nozzle may be within 2 per cent of unity, has been widely accepted as indicating that these nozzles produce the best jets for fighting fires. Murakami and Katayama[2], in their examination of discharge coefficients for a range of nozzles, confirmed Freeman's finding for conventional fire nozzles. In this context, a conventional nozzle is one whose internal profile is convex to the water, eg. a venturi type profile. Although a conventional nozzle may pass a high flow of water, the early production of spray and the ensuing dispersion and 'break up' of the jet may result in little of that water reaching a required target. Since the most direct means of applying water to a fire in a building is often via doors, windows or other restricted openings, any improvement in nozzle design resulting in a more compact jet of increased throw could enable more water to be applied even though the discharge coefficient may be less than that for conventional designs.

Experiments using minute quantities (about 30 parts per million) of soluble drag-reducing additives in fire-fighting equipment[3] had shown a marked change in the appearance of the jet leaving the nozzle. The presence of the additive reduced the pressure loss along the supply hose resulting in a higher operating pressure at the nozzle. It also resulted in a smoother, quieter, more coherent jet. At the high rates of flow used in fire fighting the value of Reynolds number (Re) is also high ($\sim 10^5$) and the flow is inherently turbulent, but the tests indicated that the generation of fine turbulence associated with the design of the nozzle had been significantly reduced. Current research is aimed at identifying the design features responsible for the formation of fine scale turbulence as this is thought to be a primary cause of surface irregularities in the jet leading to the early production of spray. The features considered most likely to be significant are:

a) abrupt changes in direction in the internal profile of the nozzle;
b) any relatively long tapering section;
c) the value of the ratio $\frac{L}{D}$ where 'L' is the length of the final parallel section of the nozzle outlet and 'D' its diameter.

Since no clear theoretical approach was available, it was necessary to examine in detail the early stages of jets from conventional and experimental nozzles to evaluate the effects of changes in design on the degree of fine turbulence produced. Direct visual assessments proved to be of limited value as were photographs with exposure times ranging from $^1/60$ to $^1/500$ seconds; these were blurred due to the image moving during the exposure. Short duration ($\sim$ 46 μs) flash photographs were better but these were also blurred by the motion of the image. The technique of image motion compensation was finally adopted in which the film is moved in the same plane and at the same speed and direction as the image (Fig. 4). The jet was illuminated by a stroboscopic flash of about 46 μs duration. Sample photographs of jets from 12.5 mm and 19 mm diameter nozzles taken using this technique are given in Plates 1 to 7. The results obtained with this method will be correlated with full scale measurements of throw for jets from a range of conventional and experimental nozzles.

2. THEORETICAL AND PRACTICAL CONSIDERATIONS

2.1 Preliminary trials indicated that:

1. From the lenses available, a Hasselblad Zeiss Planar 1 : 2.8 lens with a focal length of 80 mm produced the best definition, and
2. the minimum aperture was limited by the illumination system to f8.

2.2 Magnification

To obtain maximum detail in the photographs the highest magnification of which the system was capable was required. This was limited by the following:

2.2.1 Depth of field

The image quality was defined as having a maximum diameter circle of confusion of 0.25 mm on a print enlarged by a factor of five. This corresponds to a circle of confusion of 0.05 mm on the original negative. The minimum depth of field required was about half the diameter of the water jet under investigation, ie. 7 mm and 10 mm for the jets from 12.5 mm and 19 mm diameter nozzles respectively. The depth of field (D_F) is given by:

$$D_F = \frac{2\ c\ N\ (m + 1)}{m^2} \qquad (1)$$

where c = 0.05 mm (circle of confusion)
N = 8 (aperture of lens)
m = magnification

For the 12.5 mm jets, $D_F = 7$ mm and substituting into equation (1) gives

$$7\,m^2 - 2\,c\,N\,m - 2\,c\,N = 0 \tag{2}$$

from which $m = 0.4$. Hence the magnification for the 12.5 mm diameter jets was limited to 0.4 by the depth of field required. The corresponding figure for the 19 mm diameter jets was 0.33.

2.2.2 Velocity of film

The principle of image motion compensation (Fig. 4) requires that the magnification 'm' of the system should equal the ratio of the velocity of the film, V_F, to that of the jet, V_J, ie.

$$m = \frac{V_F}{V_J} \tag{3}$$

The maximum velocity of the film (Fig. 5) was about 6.63 metres per second. Flow rate measurements had produced a value of 17.2 metres per second for the jet velocity from the 12.5 mm diameter nozzle operating at a pressure of about 2 bar. Hence the maximum value for the magnification, limited by film velocity, was 0.385. For jets from 19 mm nozzles operating at 4.5 bar, the jet velocity was about 32 metres per second and the magnification was limited to a value of 0.2. These values for magnification are lower than those determined in 2.2.1 and therefore the velocity of the film was the factor governing magnification in these tests.

2.2.3 As the focal length of the lens (f) and the magnification (m) were known, the required lens to object distance (u) and lens to film distance (v) were determined using:

$$u = f\left(1 + \frac{1}{m}\right) \tag{4}$$

and

$$v = f(1 + m) \tag{5}$$

For the jets from 12.5 mm diameter nozzles the values calculated for u and v were 288 and 111 mm respectively. The corresponding values for the jets from 19 mm diameter nozzles were 480 and 96 mm.

2.3 Procedure

As the position of the nodal plane within the compound lens was uncertain, the camera was placed at approximately the required object distance from the nozzle and the variable focus lens adjusted to give a clear image of a millimetre scale placed in the plane of the jet.

2.4 Errors

2.4.1 12.5 mm diameter nozzles (Plates 1-5)

Subsequent measurements of jet diameter and corresponding image diameter on the negative produced a value of 0.334 for the camera magnification at lens to object and lens to image distances of 320 and 107 mm respectively, giving a value of 9.7 mm for the depth of field. Although this did exceed half the diameter of the jet, such a low figure made it essential for the camera to be very carefully aligned with the jet before each run. The velocity of the 12.4 mm jet was about 17.2 metres per second producing an image speed of 5.745 metres per second at the actual magnification used of 0.334. The film velocity, however, was 6.63 metres per second resulting in a velocity difference of 0.895 metres per second between film and image. At the flash duration of 46 μs, the disparity arising from this difference in velocity is 0.041 mm. Despite this disparity, objects 0.23 mm across producing an image on the film 0.078 mm in diameter have been clearly recorded. The absence of image motion compensation would have resulted in the image moving 0.264 mm relative to the film during the duration of the flash.

2.4.2 19 mm diameter nozzles (Plates 6,7)

The camera magnification determined from measurements of object and image sizes was 0.18 and the depth of field was 29.6 mm. At this magnification, the image speed was 5.81 metres per second, the difference in velocity between image and film being 0.82 metres per second corresponding to a film movement relative to the image of 0.037 mm for the duration of the flash. Objects 0.49 mm in diameter forming an image on the film 0.09 mm across have been clearly recorded. Without image motion compensation the image would have moved 0.27 mm during the flash corresponding to an object movement of 1.5 mm.

3. APPARATUS

A block diagram of the apparatus is given in Fig. 1. Figure 2 shows the motor and time delay circuits and the arrangement of the apparatus is shown in Fig. 3. The apparatus consisted of:

3.1 Mechanical

A modified drum camera, Southern Instruments Type M 731, with a continuous film feed device substituted for the rotating drum. The film guides and rubbing surfaces were covered with soft felt to reduce scratching. Careful assembly with particular reference to clearances in the drive mechanism and the fitting of a smaller driven pulley enabled the film transport speed to be increased to over 6 metres per second. Acceleration of the film was improved by the use of nickel-cadmium cells of large capacity supplying about 8 and 14 volts to the motor field and armature respectively. The acceleration characteristics of the camera were determined using a stroboscope set at 20 flashes per second. The distances apart of the pulses on an exposed film showed that the film reached its maximum velocity within about 0.9 seconds (Fig. 5).

3.2 Optical

The original lens and mounting supplied with the camera were replaced with an f 2.8 Hasselblad lens with a focal length of 80 mm mounted on an adaptor giving a lens to film distance adjustable between 75 and 85 mm. As the nodal plane was near the mid-point of the compound lens this corresponded to image distances ranging from about 95 to 105 mm. At this setting, which was used for the 19 mm diameter jets, the range of adjustment of the lens enabled objects to be focussed at distances exceeding about 400 mm. For the slower moving 12.5 mm diameter jets, a high magnification was obtained by utilising an extension ring to increase the range of image distances from 100 to 110 mm. This enabled objects as close as 310 mm to be focussed. As the depth of field was limited, two radius arms were fitted to opposite sides of the camera to facilitate alignment of the camera with the jet.

3.3 Illumination

A curved semi-translucent plastic diffusing screen positioned 150 mm behind the jet served as the background for the photographs. The screen was illuminated from behind by a Dawe 1202 D stroboscope 550 mm distant from the screen. The stroboscope was set to give a single flash with a quoted mean output of 400 lux over a measured duration of about 46 μs for a 50 per cent reduction from the peak intensity. The stroboscope was triggered by a timing device set to delay the flash for about 0.9 s after the film transport was started to allow the film to attain the required velocity (Fig. 5).

3.4 Photographic

Ilford Mark 5 black and white 35 mm negative film nominally rated at 250 ASA was used for the photographs shown in Plates 1-7. This film was selected for its fine grain structure which is necessary for recording small details. As the light output from the stroboscope was barely adequate at such short exposure times, the film was developed using a dilute development technique to compensate for the uncertain conditions of exposure. This process increased the effective speed of the film without incurring the loss of detail due to the larger size of the grain typical of films of higher speed ratings.

4. FURTHER DEVELOPMENT OF THE TECHNIQUE

The photographs featured in this note should be regarded as the test results of a feasibility study of the technique and apparatus. These photographs indicate that the system is suitable for studying fire fighting jets but the following points are proposed for inclusion in the next stage of the work:

1. Time base

   Although the voltages applied to both the armature and field windings of the camera motor are measured in each test, there may be some drift of the film transport speed from the calibrated value. A second stroboscope can be used to provide a time base either by illuminating part of the diffusing screen or direct on to the film by means of a light guide.

2. Pulse intensity and duration

   The present pulse duration determined using a semi-short-circuited photocell, the output of which was displayed on a storage oscilloscope, was found to be about 46 μs for a reduction in light intensity from the peak value of 50 per cent: this is about four times longer than the specified value for the stroboscope. When this is corrected, a marked improvement in picture quality should be obtained.

3. Illumination

   A significant improvement in picture quality is most likely to result from using a short duration flash with a much greater light output than our present source. This would enable film of smaller grain size to be used and the lens aperture reduced, thereby increasing the depth of field.

4. The possibility of using a rotating shutter in front of the lens and a continuous light source to produce several exposures per run will be examined.

5. APPLICATIONS

Plates 1–7 indicate that the system is suitable for studying semi-transparent water jets moving with velocities up to about 32 metres per second. With minor modifications, eg. to lighting arrangements, it may prove useful in work on foam in studying the performance of branchpipes.

6. SAMPLE PHOTOGRAPHS

Plates 1–7 are included to convey an impression of the nature of the jets under examination, but the reproduction process is unable to portray much of the detail present in the original photographs.

6.1 12.5 mm ($\frac{1}{2}$ in) diameter nozzles

6.1.1 Plate 1 illustrates the jet from a standard 12.5 mm Fire Service nozzle at an operating pressure of 2.1 bar (30 psi). The jet velocity was about 17 metres per second. The abrupt change in the internal profile of this nozzle near the inlet and the drag associated with both the tapering section leading to the outlet and the parallel section at the outlet are thought to be regions which generate the fine turbulence seen as surface corrugations near the nozzle. The progressive increase in roughness of the jet surface and the early emission of spray droplets are clearly discernible.

The value of the contraction ratio, ie. the ratio of the diameter of the supply upstream of the nozzle to that of the nozzle outlet, was about four.

6,1.2 Plate 2 is of the jet produced by a 12.5 mm diameter pipe 125 mm in length ($\frac{L}{D}$ = 10) at a pressure of 1.7 bar (25 psi). A marked change had occurred in this jet at about 2.1 bar (30 psi) so Plates 2 and 3 are for pressures just below and above this value. Fine turbulence is present in the jet surface for little more than a distance of about one jet diameter then the jet surface rapidly deteriorates. The photograph shows the formation of filaments of water leaving the jet surface and separating to produce spray.

6.1.3 Plate 3 shows the jet produced by the same nozzle as in Plate 2 but operated at a pressure of 2.4 bar (35 psi). At this pressure, fine turbulence is present only in a very limited region near the outlet as the jet rapidly expands to about one and a half times the diameter of the pipe. The whole jet is in a highly turbulent state and the drag due to the motion of the jet through the surrounding air results in retardation of the outer layers and the formation of spray from within one pipe diameter of the outlet.

6.1.4 The jet shown in Plate 4 is leaving a 12.5 mm diameter sharp-edged orifice chamfered outwards at an angle of 45°. The orifice was cut in the centre of a blanking cap screwed on to the end of a 65 mm diameter pipe to represent an extreme case in nozzle design. Although the jet produced is free from fine turbulence and spray, the abrupt contraction due to the nozzle has resulted in the formation of large scale turbulent eddies clearly visible in the photograph.

6.1.5 Plate 5 illustrates the jet formed by a 12.5 mm experimental nozzle. The internal profile was shaped to avoid any sudden directional changes and machined to mate up smoothly with the supply branch. The profile was concave relative to the direction of flow and terminates in a sharp-edged orifice chamfered outwards at 45°. The significant features of the resultant jet are the absence of ripples in the jet surface caused by fine turbulence and the noticeable lack of spray droplets. As the jet progresses, some larger scale surface waves become apparent. Preliminary tests have shown that jets of water produced by this type of nozzle can carry up to 25 per cent further than jets from conventional nozzles (Plate 1) for equal nozzle exit velocities.

6.2 19 mm ($\frac{3}{4}$ in) diameter nozzles

Plate 6 is of the jet produced by a 19 mm Fire Service nozzle operating at 4.8 bar (70 psi). The jet velocity is about 32 metres per second. Fine turbulence and spray are visible for a distance of about three jet diameters after which larger disturbances in the surface indicate the onset of major turbulence.

Plate 7 shows the jet produced by a 19 mm experimental nozzle similar in internal profile to the nozzle in Plate 5. The nozzle is operating at a pressure of 6.7 bar (97 psi) to produce a jet velocity of about 32 metres per second. Small ripples in the surface adjacent to the nozzle indicate a limited presence of fine turbulence but spray production is negligible. Major turbulence becomes increasingly evident as the jet progresses but the photograph indicates that the jet surface is noticeably smoother than that of the jet in Plate 6.

7. ACKNOWLEDGEMENT

Mr D Jones, senior photographer, has materially assisted in the development of the photographic technique described in this note.

8. REFERENCES

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2. MURAKAMI, M and KATAYAMA, K. Discharge coefficients of fire nozzles. Trans. Amer. Soc. Mech. Engrs. Journal of Basic Engineering, December 1966, 706-716.

3. THORNE, P F and JORDAN, K. Preliminary experiments on the use of water additives for friction reduction in fire hose. Department of the Environment and Fire Offices' Committee Joint Fire Research Organisation FR Note 959/1973.

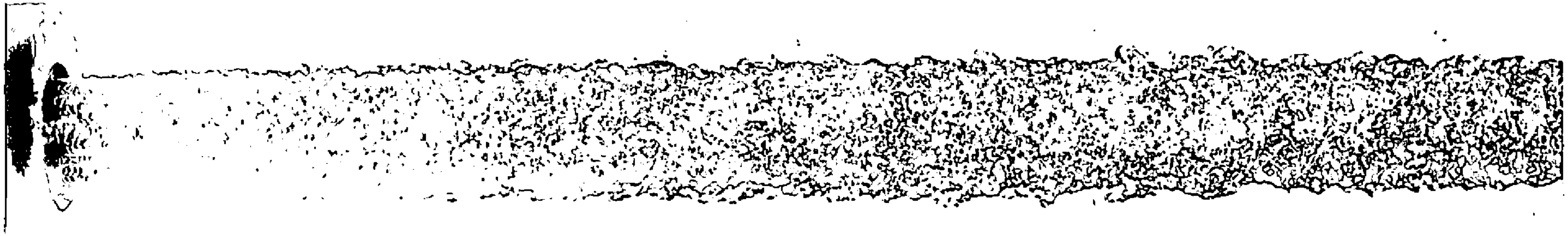


PLATE 1 STANDARD FIRE SERVICE NOZZLE,
12.5 mm ($\frac{1}{2}$ in) DIAMETER.

Pressure = 2.1 BAR(30 p.s.i.)

PLATE 2 JET FROM 12.5 mm ($\frac{1}{2}$ in) DIAMETER
PIPE, 250 mm Long

Pressure = 1.7 BAR (25 p.s.i.)

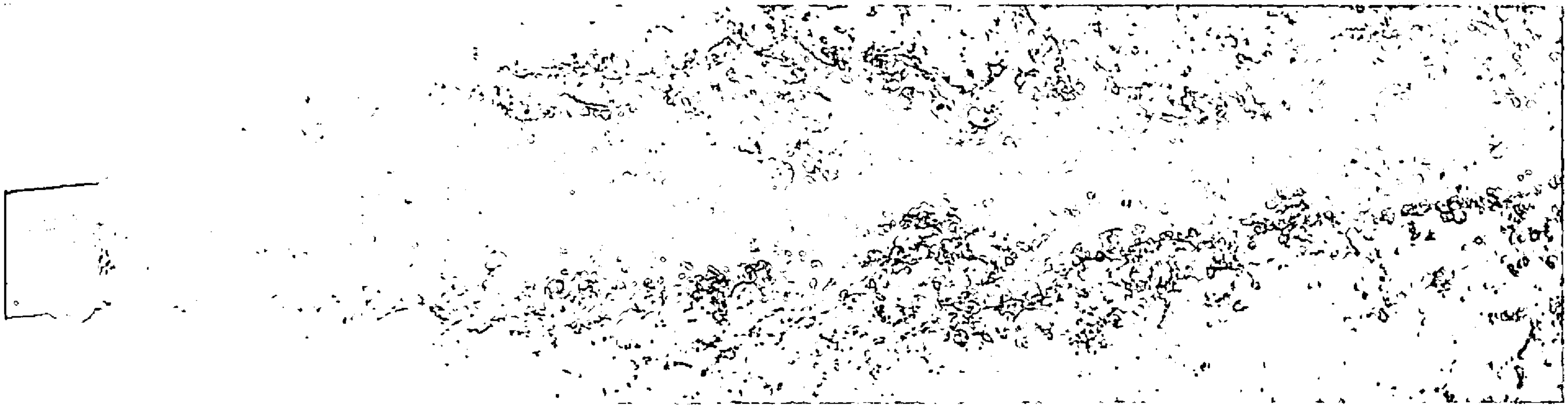


PLATE 3 JET FROM 12.5 mm (½ in) DIAMETER PIPE
250 mm long.

Pressure = 2.4 BAR (35 p.s.i.)

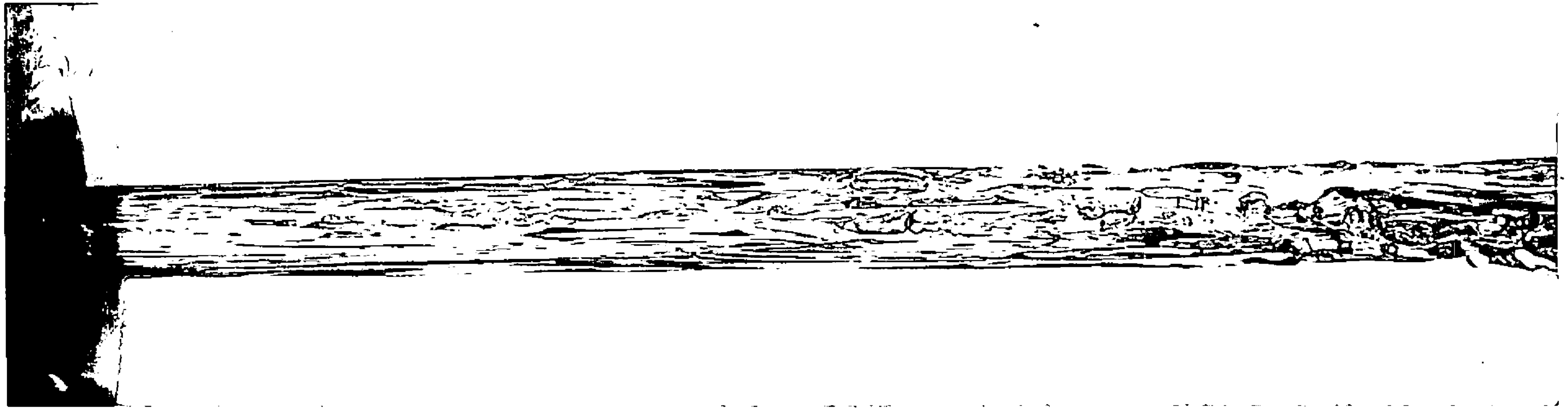


PLATE 4 JET FROM 12.5 mm (½ in) DIAMETER SHARP EDGED ORIFICE

Pressure = 2.1 BAR (30 p.s.i.)

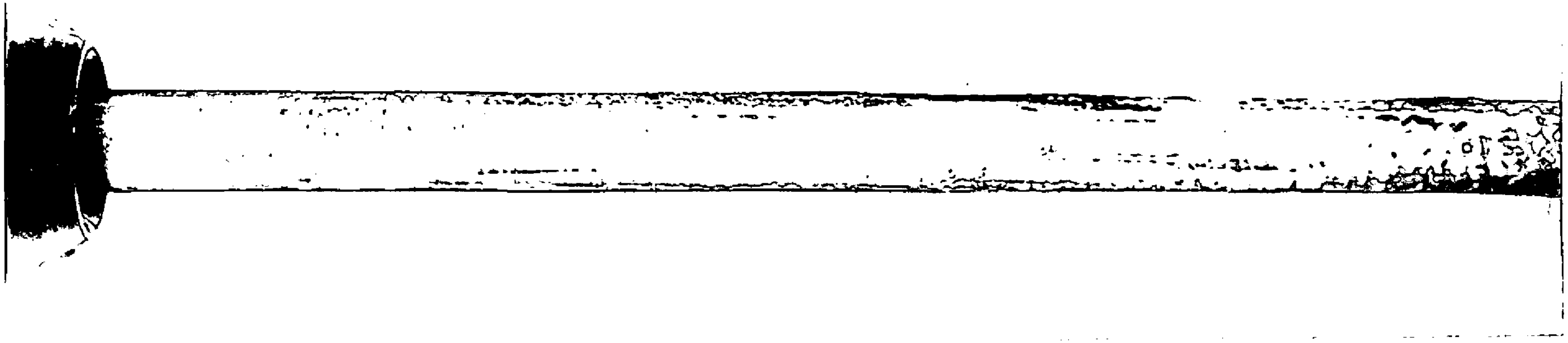


PLATE 5 EXPERIMENTAL NOZZLE 12.5 mm ($\frac{1}{2}$ in) DIAMETER

Pressure = 2.1 BAR (30 p.s.i.)

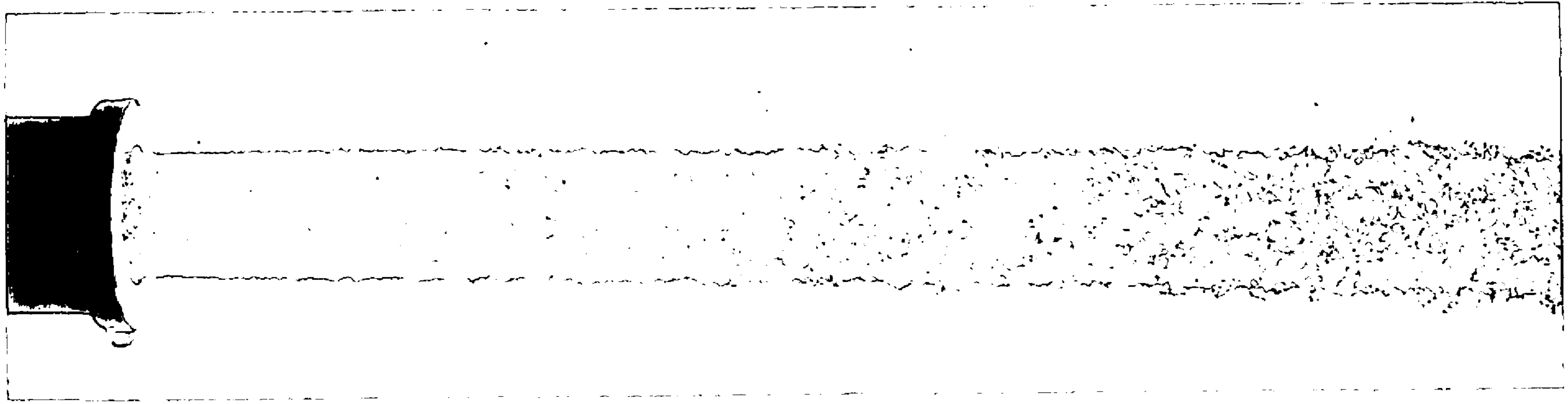


PLATE 6 STANDARD FIRE SERVICE NOZZLE, 19 mm ($\frac{3}{4}$ in) DIAMETER

Pressure = 4.8 BAR(70 p.s.i.)

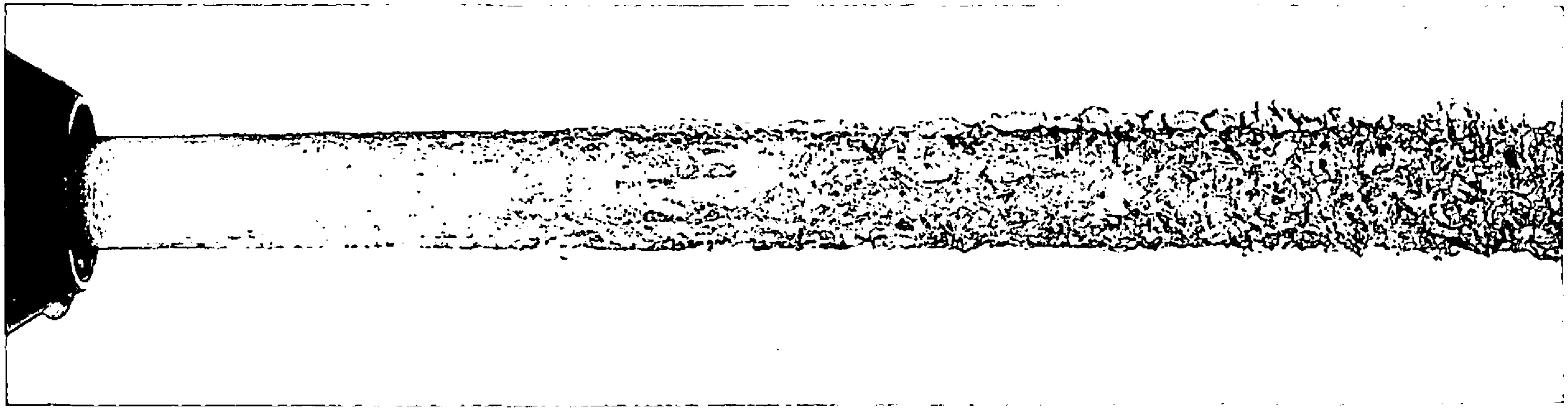


PLATE 7 EXPERIMENTAL NOZZLE 19 mm ($\frac{3}{4}$ in) DIAMETER

Pressure = 6.7 BAR (97 p.s.i.)

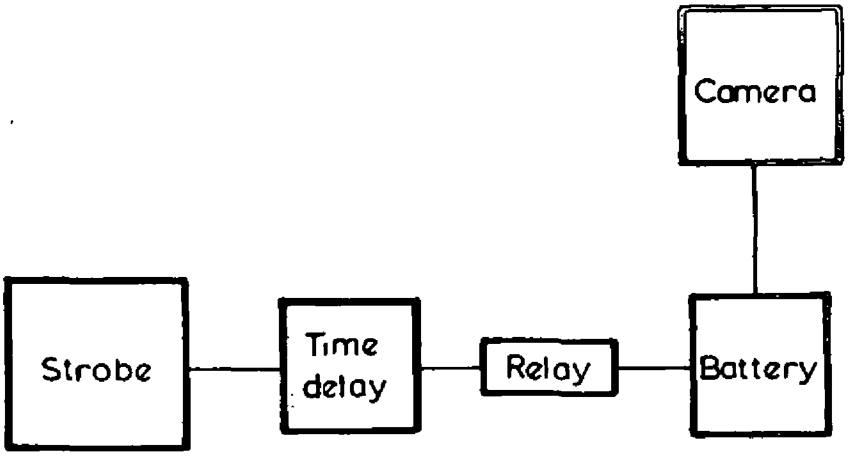


Figure 1 Block diagram of apparatus

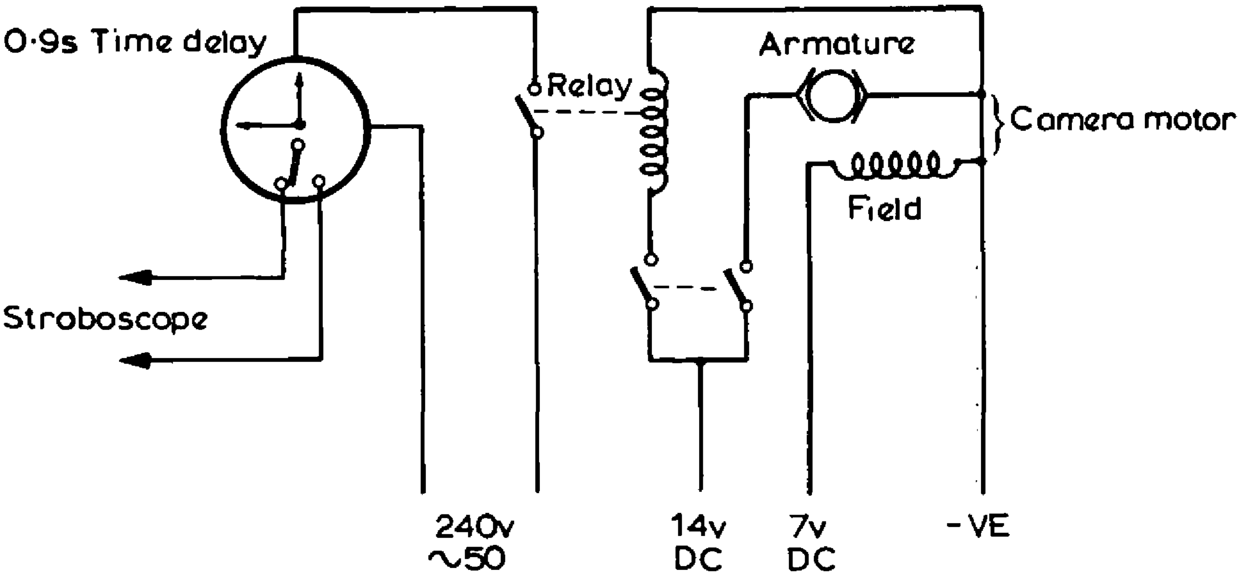
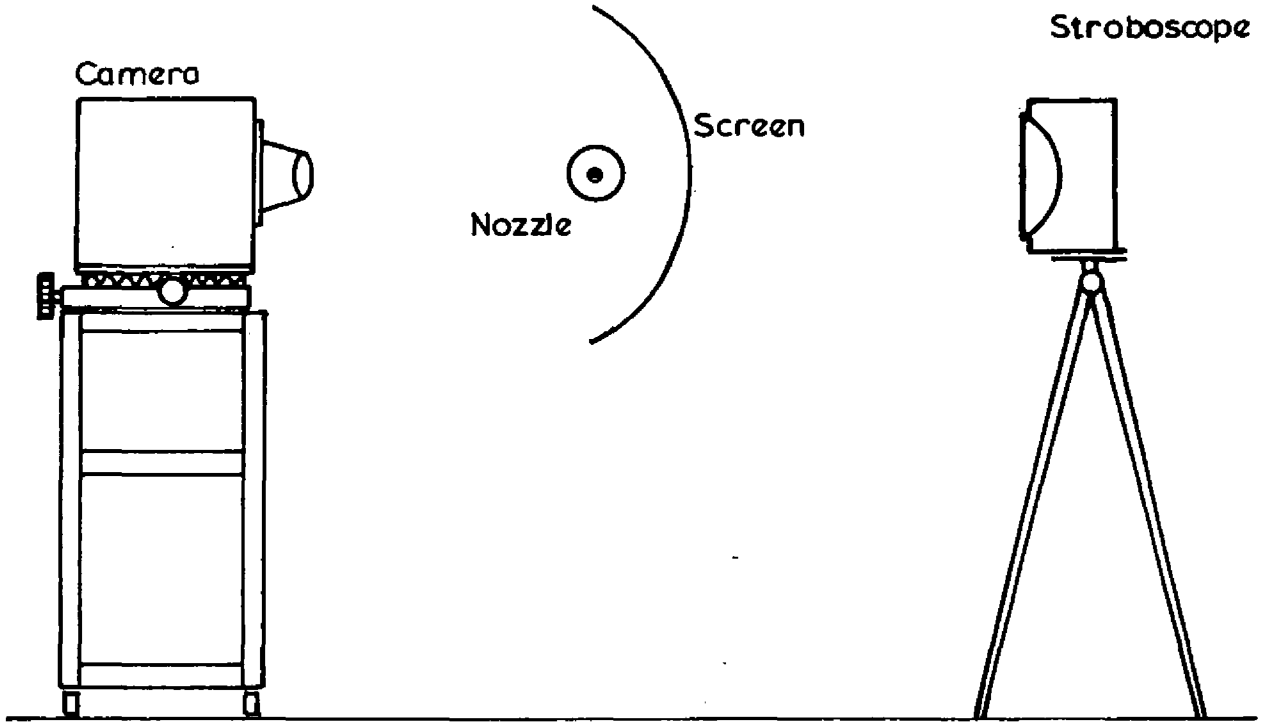
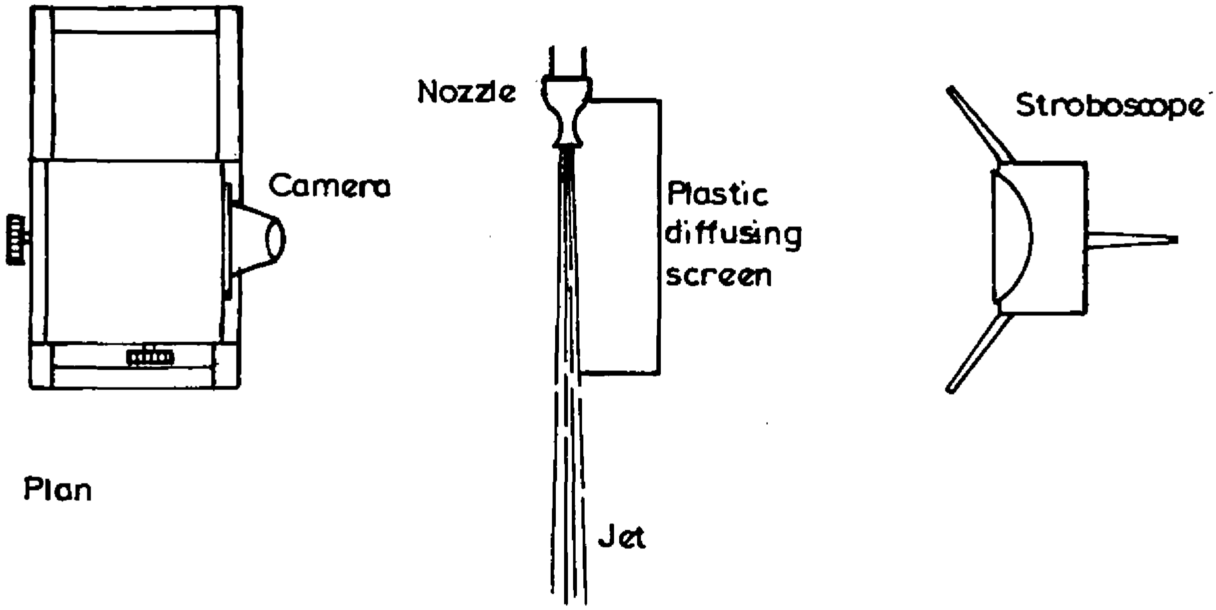


Figure 2 Diagram of motor and time delay circuit

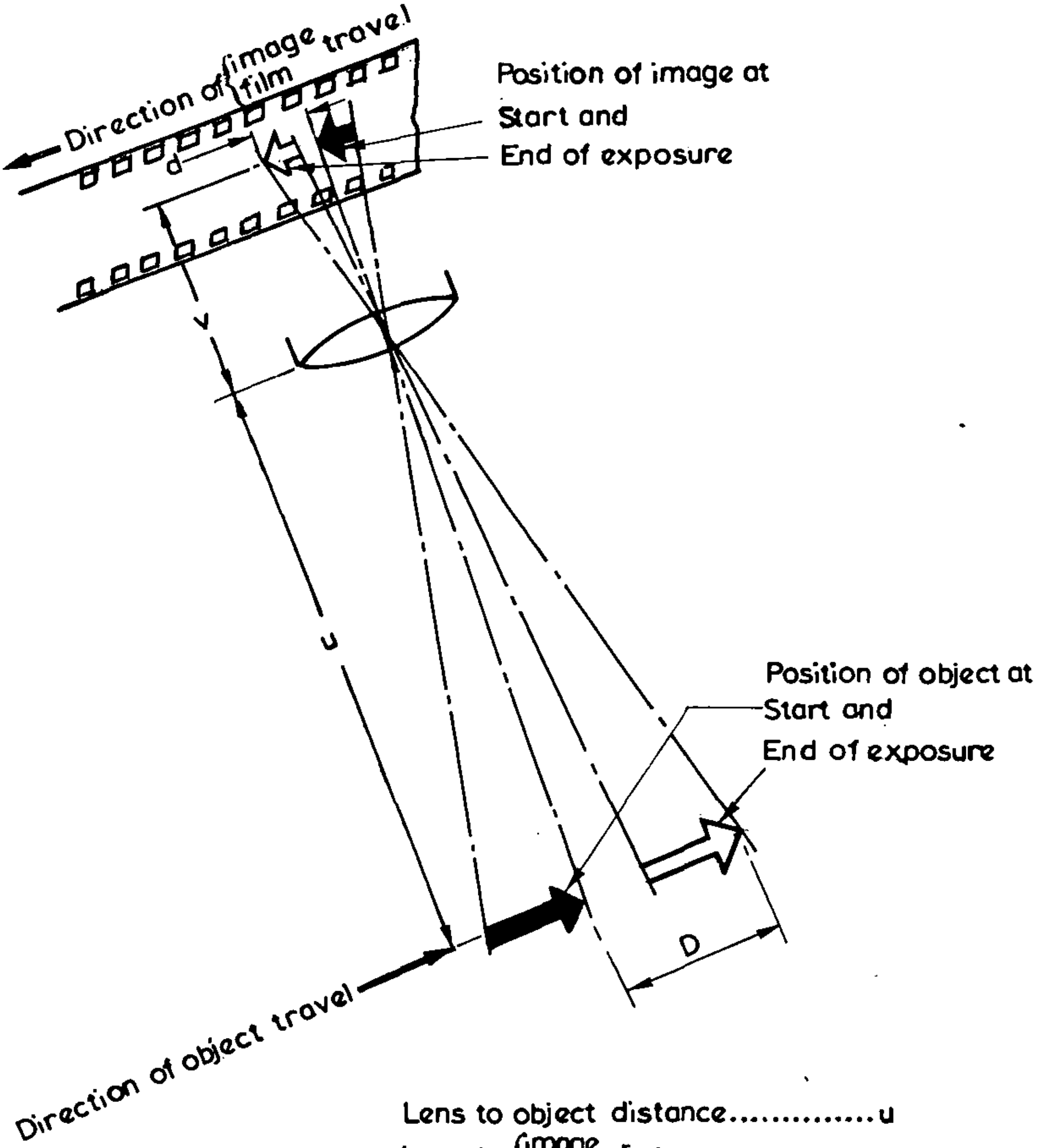


Elevation



Plan

Figure 3 Arrangement of apparatus



Lens to object distance..............u

Lens to {image / film} distance..............v

Magnification m.......................$\frac{v}{u}$

Object travel during exposure.....D

{Image / Film} travel during exposure.....d

$$\frac{\text{Velocity of } \{\text{image / film}\}}{\text{Velocity of object}} \ldots\ldots = \frac{d}{D} = \frac{v}{u} = m$$

Figure 4 Principle of image motion compensation

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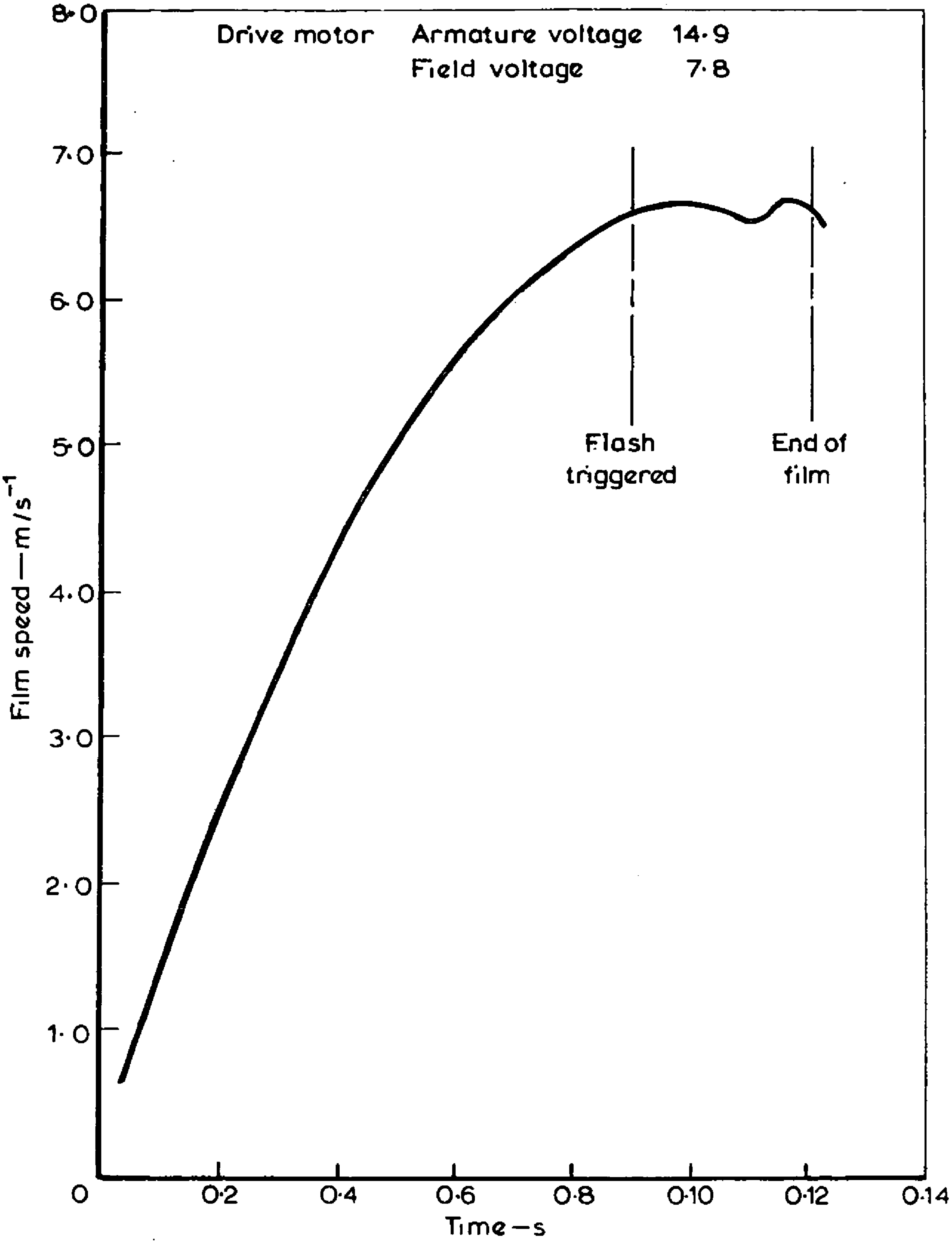

Figure 5 Film speed characteristic of camera

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