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TECHNIQUES FOR
DROP SIZE MEASUREMENT
BY DIRECT PHOTOGRAPHY AND
ELECTRONIC PARTICLE SIZE ANALYSIS

by

C. Ramshaw

DECEMBER, 1965

MINISTRY OF AVIATION, LONDON, W.C.2

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R O C K E T   P R O P U L S I O N   E S T A B L I S H M E N T

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SUMMARY

A photographic technique is described which overcomes many of the problems encountered in measuring the droplet size distribution in sprays. Droplet photographs were analysed using a Mullard Particle Size Analyser as recommended in the text and it is shown that, for photographs in which the depth of field is less than the spray thickness, a high contrast emulsion leads to errors. In general it is better to avoid out-of-focus drops, but a method is suggested which permits the results to be corrected provided the extent of the spray is large compared to the depth of field.

CONTENTS

1   INTRODUCTION

The residence time of the propellents in the combustion chamber of an operational liquid bi-propellent rocket engine is of the order of 3 milliseconds. During this period the fuel and oxidant must be atomized, vaporized and their vapours mixed before combustion occurs. Since the vaporization step can limit the combustion rate and thus affect the efficiency of combustion, knowledge of the liquid surface area available for the evaporation process is required. In addition, the distance travelled by the spray in the chamber is governed by the droplet size and thus the mixing process is affected. Some measure of the droplet sizes and their distribution produced by the injectors is therefore required but it is extremely difficult, if not impossible, to obtain these measurements under engine running conditions.

As a first attack on this problem a study of the liquid injection process was initiated at the R.P.E. using liquid sprays at ambient pressure, with the intention that, when the hydrodynamic phenomena at this pressure were understood, work in more representative conditions was to be attempted. Consideration was first given to the classical techniques for spray evaluation as used by Giffen and Muraszew[1], but they were rejected because the intention was to use actual rocket propellents under simulated combustion conditions.

Droplet photography was eventually chosen because

(a) the spray population was not affected by the measurements,

(b) information on size distribution was provided,

(c) the method was general and could be applied to all systems of interest,

(d) a film scanning particle analyser was available.

This Report describes the photographic and droplet analysis techniques adopted during the first phase of the programme.

2   APPARATUS

The basic principle of the apparatus, shown diagrammatically in Fig.1, is simple. Light from a spark point source is collected by means of a condenser lens and the beam, after passing through the spray, is focussed on the nodal point of the camera lens. The spray may or may not be sliced, depending upon its angle of divergence from the injector element.

2.1   Slicer

From some injector elements, particularly the impinging jet type, the angle of divergence of the spray is wide, whereby liquid is deposited on the camera lens or condenser lens with consequent reduction in the quality of the negative. In such cases a 'slicer' was employed in which the spray passes through a system of baffles arranged to prevent liquid from reaching the lens and yet to cause minimum disturbance to the entrained air flow. In the first arrangement the spray was allowed to pass between two knife edges, but it was observed that liquid was thrown from one edge into the 'shadow' of the other. To overcome this, a second pair of knife edges was placed downstream to catch any deflected drops, and this proved effective. The use of knife edges inclined at about 45° to the direction of the spray axis prevented the entrained air stream from adhering to the downstream side of the baffle so that a relatively clean edge to the spray was obtained.

2.2   Spark source

The light source for photography was provided by discharging a 0.05 mfd condenser charged to 15 kV across an adjustable gap approximately 1 cm wide. The gap was purged with dry nitrogen and the main spark was initiated by a trigger discharge actuated by the lens shutter mechanism. The main spark travelled down a $1\frac{1}{2}$ mm diameter hole in the pyrophylite insulator block, the light emitted at the end being highly directional. This caused severe difficulties initially due to non-uniform illumination of the photographic plate. Eventually a diffuser (Kodatrace) was placed near the light exit which gave sufficiently uniform illumination over the plate and reduced the intensity by an amount corresponding to only $1\frac{1}{2}$ lens stops. Care was taken to place the diffuser close to the light exit to ensure that the effective source diameter was not increased.

The effective duration of the spark was extremely short, so much so that attempts to measure it were unsuccessful. This suggested that most of the light was delivered in significantly less than 0.25 microsecond. Even the smallest drops (< 50 micron) travelling at speeds up to 210 ft/sec were recorded sharply on the negatives.

2.3   Droplet size analyser

The droplet photographs were analysed by a Film Scanning Particle Analyser (manufactured by Mullard Equipment Ltd.). In this machine, the image of a flying spot on a cathode ray tube scans the emulsion of the negative and assigns a diameter to each drop which is equal to the maximum dimension in the

line of scan. The light transmitted depends upon the local density of the negative and typical density profiles for an in-focus and an out-of-focus drop are shown in Fig.2(a) and 2(b) respectively. The density at which the sizing circuit is triggered is governed by the clipping level control which thus determines the diameters to be recorded.

Unfortunately the sizing circuit was subject to hysteresis so that the transmitted light intensity had to fall significantly below the triggering level before the flying spot ceased to record the drop diameter. This effect is shown diagrammatically in Fig.3 where the plot of density/distance represents an out-of-focus drop of diameter D. With the clipping level set as shown, the sizing circuit is triggered at A and stops at B. With the clipping level too high the circuit fails to trigger; when too low, the circuit fails to stop, so that the displays shown in Fig.4 are recorded. The same defect was exhibited by the machine used by Belk[3].

To obtain the correct size from such out-of-focus particles it is suggested that the clipping level should be set at the mean of the two extremes depicted in Fig.2. This suggestion, which is developed in the argument below, is supported by the work of Belk[3] and Furmidge[4], and by the practical results given in para. 3.2.

Consider the density profile of an out-of-focus particle in Fig.3 which has been simplified to illustrate the argument more clearly. The density rises along PQ over a distance Δ, which may be termed the degree of blurring. Similarly along RS it takes a distance Δ to fall to the background value. The correct droplet diameter to be assigned to PQ RS is that given by the intercept with XX, where XX cuts PQ and RS at their mid points. However, as there is hysteresis in the sizing circuit, the clipping level should be chosen so that the trigger point A is as far above XX as B is below it. Thus, the delays in starting and stopping the sizing circuit should be equal. (Due to the difficulty of deciding the exact density profile from a drop which has a diameter less than 2Δ, it will be assumed that such a droplet is ignored by the analyser.)

From the foregoing it is evident that the apparent spatial volume of spray being sampled depends upon the diameter of the drops being examined. Thus large drops are registered over a large depth of field while the volume within which the small drops are recorded is restricted. As a drop is ignored when its diameter is equal to or less than 2Δ, and since the degree of blurring Δ is proportional to δu (see para. 3.1), the distance over which a drop is registered is proportional to its diameter. Therefore, to obtain a realistic assessment of

the droplet size distribution, the results for a uniform spatial distribution of the spray must be normalised as follows.

If n is the number of droplets of diameter d registered by the particle analyser, the number to be used in evaluating a mean diameter is n/d. The Sauter Mean Diameter is then calculated as

$$\frac{\Sigma \frac{n}{d} d^3}{\Sigma \frac{n}{d} d^2} \quad \text{or} \quad \frac{\Sigma n d^2}{\Sigma n d} \quad .$$

To check these ideas a graticule inscribed with spots of various diameters was photographed using the Toepler optical system. The discussion of the results is presented in para. 3.2.

The Table shows that the distance over which droplets are recorded by an optical system giving 4:1 magnification is 2 × 15 mm for a machine size level* between 3 and 4, thus by proportion it will be 9 cm for size level 11. The theoretical depth of field is the largest that can be expected. In practice, the light scattering associated with sprays reduces the depth of field, and this will reduce the effective sampling volume for drops of a given size. Provided that the spatial distribution of the spray is uniform over a distance equal to or greater than the distance over which the largest drop of interest is registered then this method of evaluating the Sauter Mean Diameter is valid. It is more accurate to adopt the normalising procedure even if the spray only occupies half the distance over which the drop corresponding to size level 10 is registered. This is shown in the Appendix for a typical drop population. Clearly the use of the 'slicer' described in para. 2.1 obviates the need to correct the machine results if the distance separating the baffles is equal to the depth of field.

3   OPTICAL SYSTEM

3.1   Theoretical aspects

After experiments in which the sprays were first illuminated by a parallel and then by a converging light field, the latter was selected because diffraction rings around the drops were eliminated. The resulting optical system, shown in Fig.1, first used by Toepler and adopted for this work by

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*A machine size level of unity corresponds to a drop image of 200μ diameter at the 1:1 magnification. Other size levels are in proportion.

Moloney, has been found to be satisfactory. The reason for the absence of diffraction effects may be seen on referring to Fig.5.

Suppose a spherical wave front from a point source S (Fig.5(a)) is diffracted by a circular obstacle centred on SP, the line joining S to the point P. When SP is large, one has the diffraction of a parallel light field. If we divide the incident wave front X-X into half period zones, the contribution of separate zones to the intensity at P gives rise to the diffraction patterns shown. When the obstacle is in a converging field centred on P, then diffraction does not occur because the light arriving at P always originates from the same wave front and is therefore in phase. Provided that the light from the condenser is focussed on the nodal point of the camera lens, the diffraction rings which obliterate small drops are absent.

Even if the spark is a true point source and the condenser is not subject to aberration, the camera lens must still be located at the position of the spark image for diffraction effects to be suppressed. In practice, the divergent shadows of the drops must be focussed on the emulsion so that the distance of the spray from the camera is dictated by the focal length of the camera lens and the magnification required.

If the light from the spark is not focussed on the nodal point of the camera lens the illuminated field viewed by the lens is restricted by the aperture. Any increase of the aperture above that corresponding to the diameter of the spark image has no effect on an ideal system with no light scattering from the spray. A reduction, however, cuts down the exposure of the emulsion. As discussed in para. 3.2, light scattering is responsible for an additional reduction of the depth of field, but this is minimised if the aperture is just equal to the spark image diameter.

The introduction of droplets between the condenser and camera lens scatters nearly all the light which would otherwise reach the emulsion. Consequently the drops are registered as clear spots on a black background (i.e. a shadowgraph). The only light which is not affected by the presence of the drops is that which passes through the centre of each drop and for an in-focus drop this can usually be seen as a pin point in the centre of the white spot. If the drop is slightly out-of-focus this central ray is distributed over a wider area of the emulsion and cannot be observed. Diffuse back-lighting allows much more light to pass through the centre of the drop and causes the image to be 'hollow'. This is unacceptable to the particle size analyser.

An estimate of the depth of field which can be expected with the Toepler system is given as follows. Let the spark image I'I" in Fig.6 have a diameter D.

The extreme rays grazing the drop edge, O, will pass either to I' or I" and therefore the angle α_1 at which the shadow of the drop diverges will be equal to $\frac{D}{u + \delta u}$ radian. Since we shall consider only those drops which are fairly close to the nominal object plane, we may write, with little error,

$$\alpha_1 = \frac{D}{u} \quad . \tag{1}$$

For a drop which is a distance δu from the object plane, the shadow is brought to a focus F at a distance δv from the emulsion. The image formed on the emulsion will be blurred over the distance Δ where

$$\frac{\Delta}{\delta v} = \alpha_2 \quad . \tag{2}$$

If the magnification of the camera lens is m, then

$$m = \frac{\alpha_1}{\alpha_2} \simeq \frac{v}{u} \text{ (provided } \frac{\delta u}{u} \text{ is small)} \quad . \tag{3}$$

The lens formula

$$\frac{1}{v} + \frac{1}{u} = \frac{1}{f} \tag{4}$$

leads to

$$\frac{dv}{du} = -\frac{v^2}{u^2}$$

for the camera lens. Hence

$$\frac{\delta v}{\delta u} \approx -m^2 \quad . \tag{5}$$

From the above equations we obtain

$$\delta u = \frac{\Delta}{D} \left(\frac{m + 1}{m} \right) \frac{f}{m} \quad . \tag{6}$$

This indicates that, for a given degree of blurring, Δ, the depth of field, δu, is

  (a) directly proportional to the focal length of the lens, f,

  (b) inversely proportional to the diameter of the spark image, D,

and (c) decreases as the magnification, m, increases.

Two conflicting requirements now arise. To minimise D, the condenser lens must be as far as possible from the spark source, but this reduces its light gathering power. A compromise must be adopted which ensures the required light intensity on the emulsion and which gives the smallest practicable values of D. A condenser lens of large diameter and small focal length is beneficial.

It should be noted that equation (6) in no way contradicts the depth of field rule used in normal photography, in which the magnification is much less than unity and $v \approx f$. To produce a photographic negative of a given size, the depth of field is nearly inversely proportional to the focal length of the lens.

With the experimental arrangement, having the 2:1 magnification camera, the spark image diameter is 3 mm. If we require Δ to be less than 50 micron on the plate, then

$$\delta u = \frac{10 \times 10^{-4}}{0.3} \frac{3}{2} \frac{15.2}{2} \quad ,$$

i.e. the total depth of field = 0.38 cm.

If the droplets had been illuminated by diffuse backlighting, using maximum aperture (Fig.7), the angle, α_1, would be much larger, being governed by the aperture of the camera lens (up to f/4.5) and the depth of field (2 δu) would be given by

$$\delta u = \frac{50 \times 10^{-4}}{(15.2/4.5)} \frac{3}{2} \frac{15.2}{2}$$

$$= 0.017 \text{ cm} \quad .$$

Therefore the depth of field is 0.034 cm. This is one order of magnitude less than the depth of field given by the Toepler system.

Referring once more to Fig.6, it will be seen that, for the drops which are out of focus, the images differ slightly in magnification from the nominal value. The magnification of the sharp image formed at F is $\frac{v + \delta v}{u + \delta u}$, δv and δu being given the appropriate algebraic sign. The nominal edge to the image on the emulsion is at P' the mid point of Δ so that

$$\frac{v}{v + \delta v} = \frac{F' \ P'}{F \ P}$$

and the effective magnification of the out-of-focus drops at O is there given as

$$\frac{v + \delta v}{u + \delta u} \; \frac{v}{v + \delta v} \quad ;$$

i.e. the nominal magnification, v/u, has been altered by a factor of $\frac{u}{u + \delta u}$.
Since δu rarely exceeds 2 cm, the maximum variation in magnification caused by
the droplet position is about 10%. The change of magnification on the opposite
side of the plane of focus is of opposite sign and the nett effect on the
measured droplet distribution is negligible.

3.2 Experimental evaluation of optical system

The foregoing ideas were tested by photographing a graticule in the
position normally occupied by the spray. The graticule, engraved with black
spots of diameter increasing in a √2 progression from 0.031 to 0.5 mm, was
moved in steps of 3 mm from the point of sharp focus so that a series of
blurred negatives was produced. These negatives were analysed by the machine
giving the results shown in the Table. The ideal result is also included
based on the magnification of 4 provided by the optical arrangement and the
200μ size unit of the machine.

An examination of the "sharp" negative under the microscope indicated
that an uncertainty of ±0.025 mm remained which increased with the subsequent
negatives. The result at the first setting for the sharp negative shows that
at the lowest possible clipping level, about 30, the size of the spots has
been exaggerated and more particles have been included among those greater
than the first size level. The discrepancy between the ideal and actual result
becomes less at the increasing size levels largely because the uncertainty
represents a decreasing fraction of the diameter. As the clipping level (CL)
increases, the number of drops greater than the first size level increases so
that at CL = 50 the correct size distribution is given. The corresponding
clipping levels for the subsequent negatives were approximately 40, 45, 45,
50, 55. If we take the 'best' clipping levels shown above for each negative
it is seen that the size of the droplets ignored increased as the blurring
increases. This tendency is predicted by the previous discussion. While the
size limit is not quite proportional to distance from the plane of sharp focus
the assumption of linearity is a useful first approximation as it leads to the
simplification of the mean size calculations, as has been shown previously. It
must be emphasised that the test negatives were obtained in the absence of a
spray and that experience has shown that the optical density of the centres of
the drops increases with the density of the spray population. This is presumed
to be caused by light scattering, i.e. the light was incident on a drop over a

larger angle than that predicted. In the limit, backlighting as from a
translucent screen will be produced with consequent reduction in the depth
of field (Fig.7).

Originally the investigations were limited to the region close to the
point of breakup of the spray where the spatial distribution was thought to be
essentially uniplanar. However the mechanism by which the spray sheet
disintegrates is one in which the wave amplitude in the sheet must reach a
critical value before disintegration commences. Both patternation tests and
photographs taken parallel to the spray plane indicate that the wave amplitude
at breakup is usually greater than the calculated depth of field.

Extreme care was required in the photographic processing to obtain
contrast separation between the drops and their variable density background.
This was achieved by a double printing process involving the production of an
intermediate positive before final printing on a 35 mm film for analysis by
the film scanner. It was found the drop count could be varied for a given
negative by increasing the exposure given to the printing step causing the
large increase in contrast as more blurred drops were registered. If the
exposure given to the original negatives varied for any reason, a contact
printing programme involving fixed exposures would therefore give erroneous
results. Clearly it is better to restrict the spray using the 'slicer' and
ensure that more of the drops are in focus.

The problem cannot be solved by using a film which gives a high contrast
directly because this prevents any control over the sizing of blurred drops.
A typical log density/log exposure curve for a high contrast emulsion is shown
in Fig.8(a), whilst Fig.8(b) and 8(c) represent the local light intensity
profiles incident on the emulsion for two different exposures with the
associated density profiles. Owing to the higher exposure, the optical density
of the negative rises from the background value earlier than with a low
exposure and it is apparent that the effective drop size which would be
registered by the emulsion receiving the higher exposure has been increased
from A to B, though the operator would not be aware of this. Having once
produced such a high contrast negative, it is impossible to manipulate the
particle analyser controls to provide an accurate result. One may be also
misled into believing that the depth of field has been improved due to the
apparently small degree of blurring.

The foregoing argument indicates that any attempt to increase the drop
count, by giving an original low contrast negative plate a high exposure during
the photographic process leading to a high contrast 35 mm negative, will

produce an error if any blurred images are present. In this case the relative numbers of drops in each size band will be altered. The reduction of random sampling errors must only be achieved by analysing many negatives.

The criterion in setting the machine controls is that the direct picture (i.e. that fed to the clipping circuits) should be as clear and sharp as possible. Any alterations of flying spot current, lens aperture or photo multiplier gain to this end are admissible. This may entail some slight modification of the effective exposure in the machine but will only alter the volume of spray sampled and not the relative number of drops in the size groups.

4 RECOMMENDATIONS

(1) To obtain correct drop size distributions from spray photographs analysed in the Mullard Particle Size Analyser, the clipping level must be set at a value mid-way between that which causes 'smearing' and clearing of the picture.

(2) If the thickness of the photographed spray is equal to or larger than the distance over which the large drops are registered and this is significantly greater than the depth of focus of the optical system, then the size distribution from the Particle Size Analyser should be corrected. If n is the registered number of drops of diameter d, then the corrected number is n/d.

(3) The recommended setting for the brightness, lens aperture and photo multiplier gain controls on the Particle Size Analyser is that which gives the sharpest and clearest direct picture.

(4) Use of a direct spray photograph on high contrast film is not recommended as errors are unavoidably introduced.

<u>Appendix</u>

<u>APPLICATION OF THE DEPTH OF FIELD CORRECTION TO RESTRICTED SPRAYS</u>

In the tables below, distribution 1 is typical of that occurring in a spray while 2 is that which would be photographed if the spray thickness corresponded to the maximum distance over which a drop of five units diameter is registered. All drops larger than this therefore appear on the negative and are registered by the Particle Size Analyser. Distribution 3 is the corrected version of 2 on the lines suggested by the text. The calculation of the Sauter mean diameter for each distribution shows that it is more accurate to use the adjusted population than one directly obtained from the Particle Size Analyser even with a spray restricted to the extent described.

	Numbers of drops having the given size										
	1	2	3	4	5	6	7	8	9	10	11
(1) Actual distribution	1000	1000	500	100	100	25	20	10	5	2	1
(2) With limited depth of field	200	400	300	80	100	25	20	10	5	2	1
(3) The corrected version of (2)	200	200	100	20	20	4.1	3.0	1.25	0.55	0.2	0.1

Distribution (1)			Distribution (2)			Distribution (3)		
n	d^2	d^3	n	d^2	d^3	n	d^2	d^3
1000	1000	1000	200	200	200	200	200	200
1000	4000	8000	400	1600	3200	200	800	1600
500	4500	13500	300	2700	8100	100	900	2700
100	1600	6400	80	1280	5720	20	320	1286
100	2500	12500	100	2500	12500	20	500	2500
25	900	4500	25	900	4500	4.1	147	885
20	1000	7000	20	1000	7000	3.0	150	1050
10	640	5120	10	640	5120	1.25	80	640
5	405	3645	5	405	3645	0.55	45	400
2	200	2000	2	200	2000	0.2	20	200
1	121	1331	1	121	1331	0.1	12	133

$\Sigma nd^2 = 16866$

$\Sigma nd^3 = 64996$

$\dfrac{\Sigma nd^3}{\Sigma nd^2} = 3.86$

$\Sigma nd^2 = 11546$

$\Sigma nd^3 = 52716$

$\dfrac{\Sigma nd^3}{\Sigma nd^2} = 4.57$

$\Sigma nd^2 = 3174$

$\Sigma nd^3 = 11588$

$\dfrac{\Sigma nd^3}{\Sigma nd^2} = 3.65$

TABLE

Results of the graticule test

Clipping level	Number larger than size level										
	1	2	3	4	5	6	7	8	9	10	11
	Ideal result										
	7	5	4	3	3/2	2	2	1	1	1/0	0
Sharp negative											
30	9	6	$5\frac{1}{2}$	4	3	2	2	1	1	1	-
40	8	$5\frac{1}{2}$	4	3	3	2	2	1	1	-	-
50	7	5	4	3	3	2	1	1	1	-	-
60	7	5	4	3	2	2	1	1	1	-	-
3 mm out-of-focus											
30	8	6	4	4	3	2	2	1	1	-	-
40	6	5	4	3	3	2	$1\frac{1}{2}$	1	1	-	-
50	5	$4\frac{1}{2}$	4	3	2	2	1	1	1	-	-
60	4	4	3	3	2	2	1	1	$\frac{1}{2}$	-	-
6 mm out-of-focus											
38	$6\frac{1}{2}$	6	$4\frac{1}{2}$	4	3	2	2	1	1	1	-
50	5	4	4	3	2	2	1	1	1	-	-
60	4	4	3	3	2	2	1	1	-	-	-
9 mm out-of-focus											
40	$5\frac{1}{2}$	5	$4\frac{1}{2}$	4	3	3	2	1	1	$\frac{1}{2}$	-
50	4	4	$3\frac{1}{2}$	3	$2\frac{1}{2}$	2	$1\frac{1}{2}$		1	-	-
60	4	4	3	$2\frac{1}{2}$	2	2	1	1	-	-	-
12 mm out-of-focus											
45	5	5	$4\frac{1}{2}$	4	4	3	3	$2\frac{1}{2}$	2	1	-
60	4	4	3	3	2	2	1	1	$\frac{1}{2}$	-	-
15 mm out-of-focus											
50	4	4	4	4	3	3	$2\frac{1}{2}$	2	2	1	-
60	3	3	3	3	2	2	1.7	1	1	-	-

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<u>No.</u>	Author	Title, etc.
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PLATE OR FILM

CAMERA LENS

CONDENSER

KNIFE EDGES OF 'SLICER'

SPRAY INJECTOR

SPARK SOURCE

FIG. 1   THE SPRAY RIG

(a) IN FOCUS

(b) OUT OF FOCUS
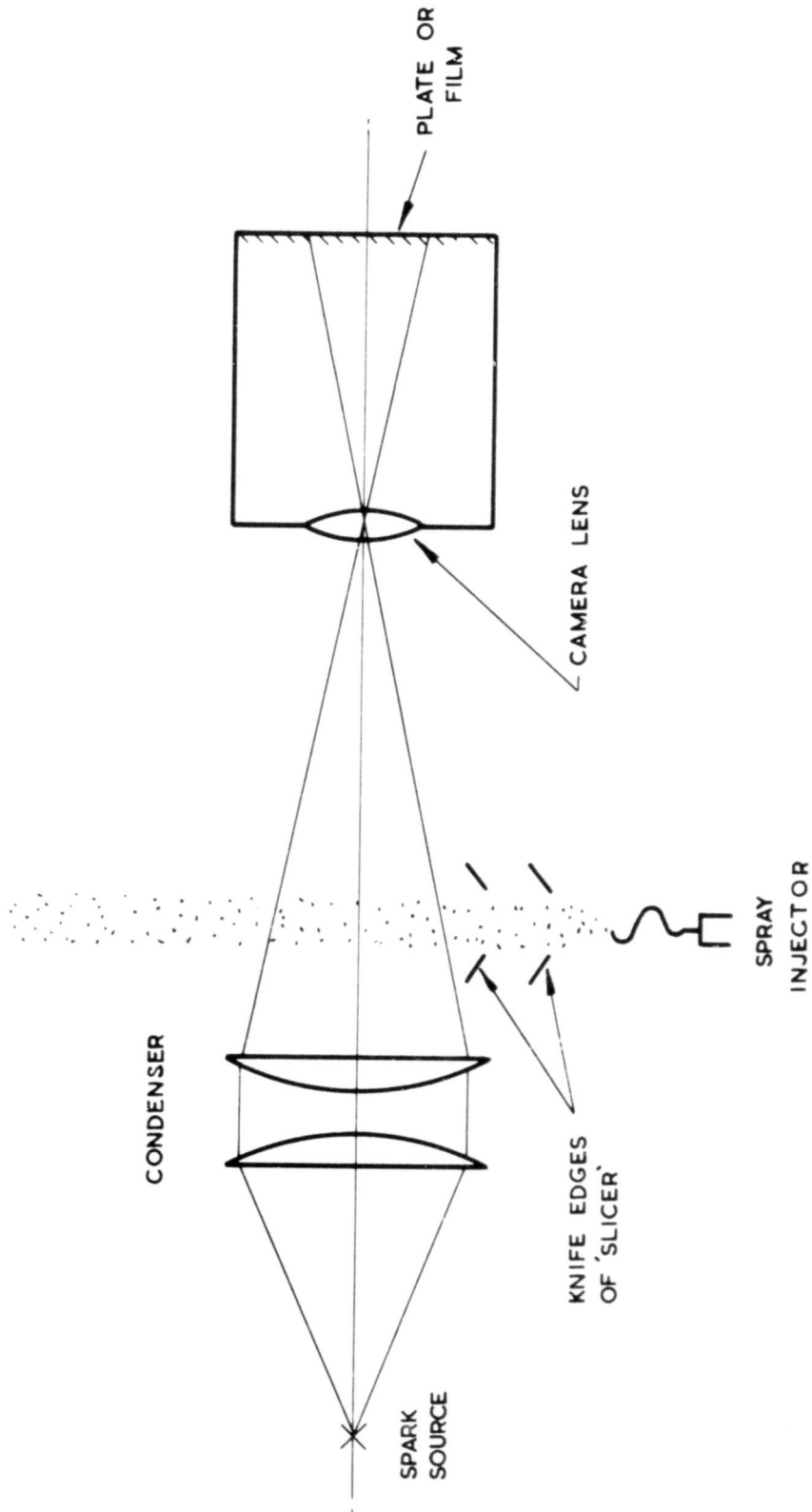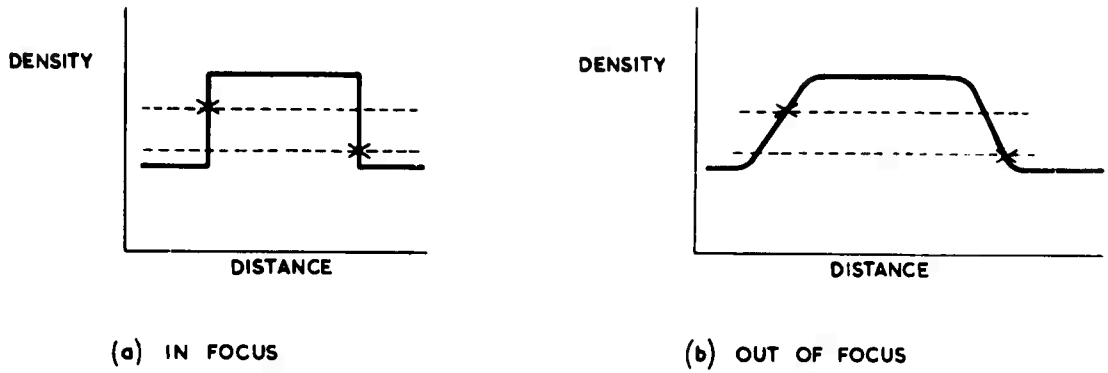
FIG. 2 TYPICAL DENSITY PROFILES
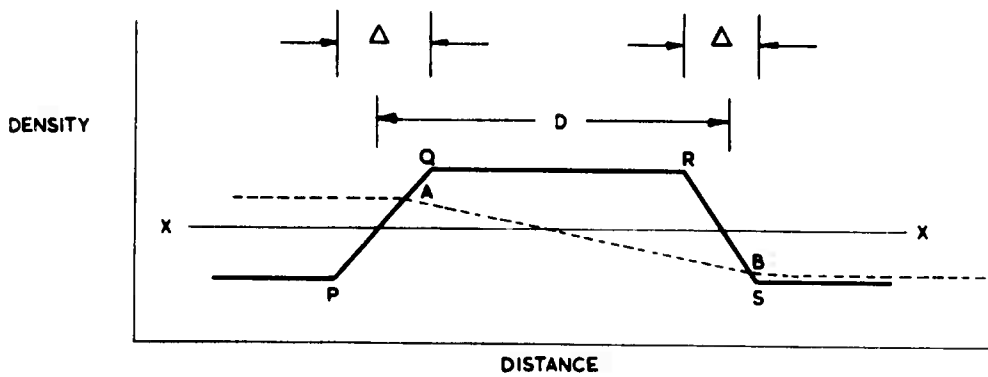
FIG. 3 THE EFFECT OF HYSTERESIS IN THE CLIPPING CIRCUIT
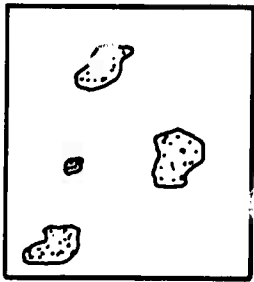
[a]
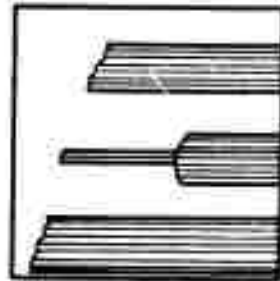
[b]

FIG. 4 DISPLAYS GIVEN WITH CLIPPING LEVEL [a] TOO HIGH
[b] TOO LOW
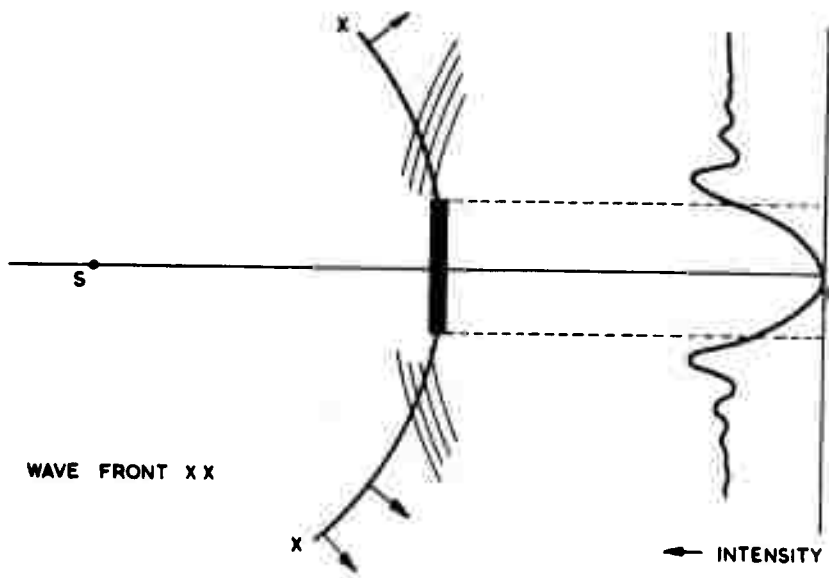
(a) DIVERGING FIELD; DIFFRACTION
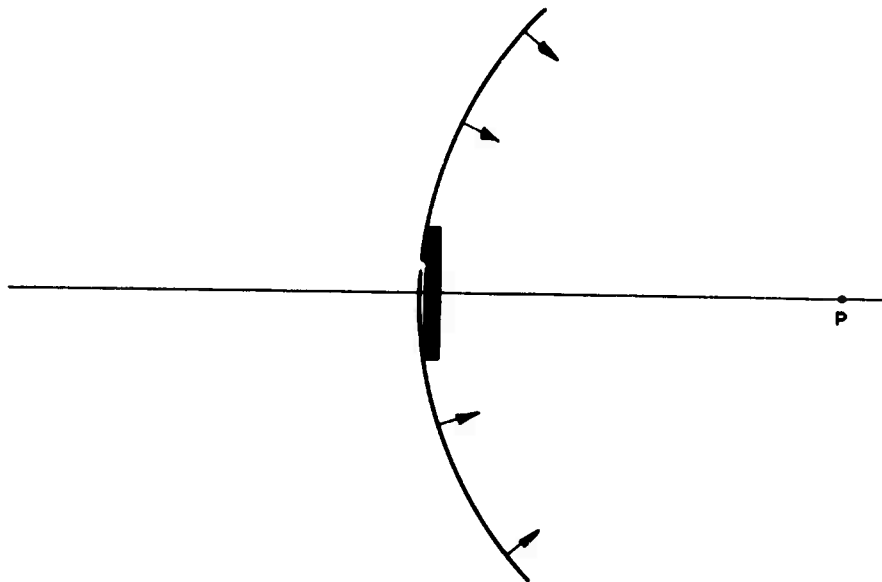
(b) CONVERGING FIELD CENTRED ON P; NO DIFFRACTION
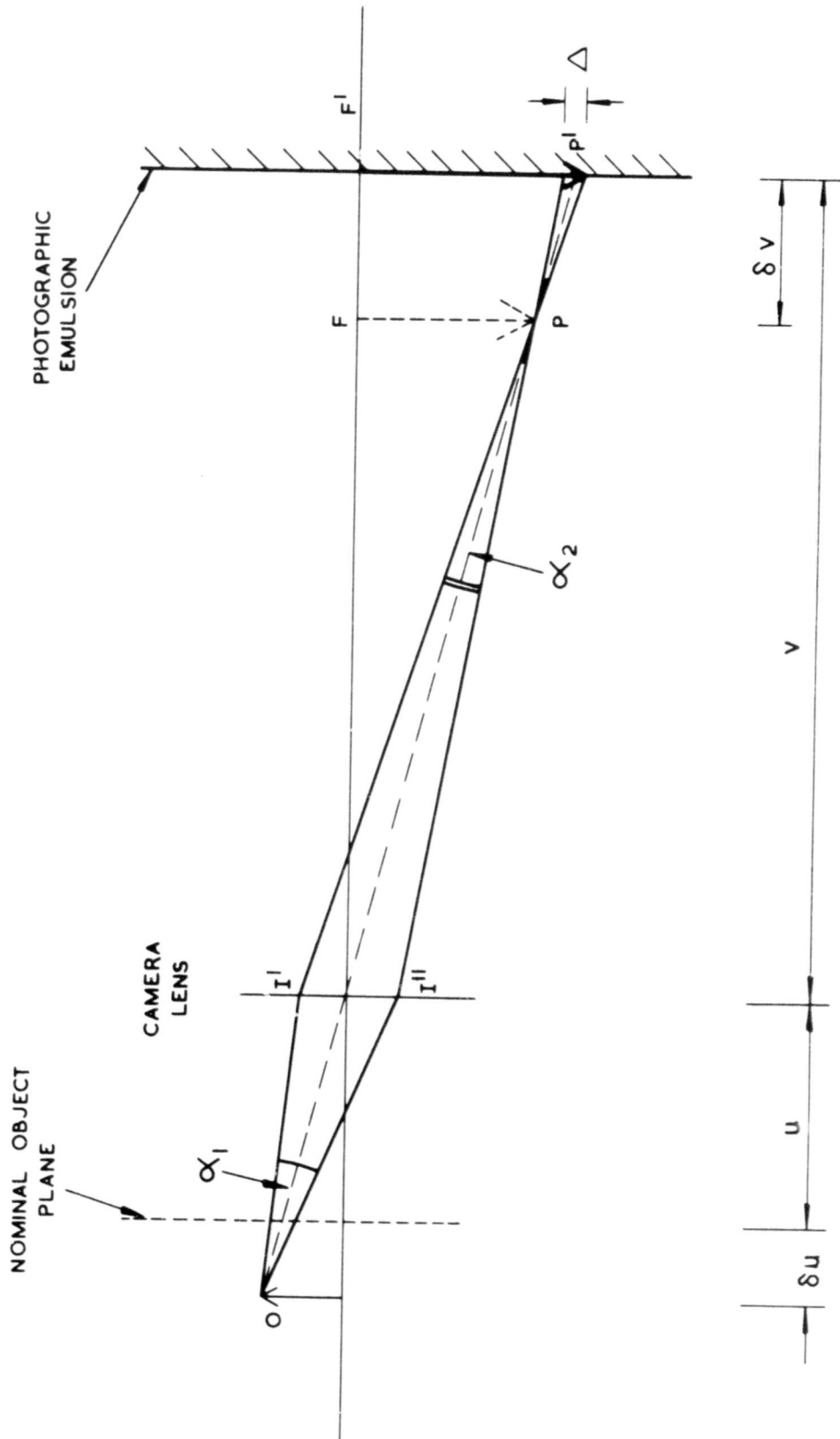
FIG. 5 DIFFRACTION EFFECTS WITH CIRCULAR OBSTACLES

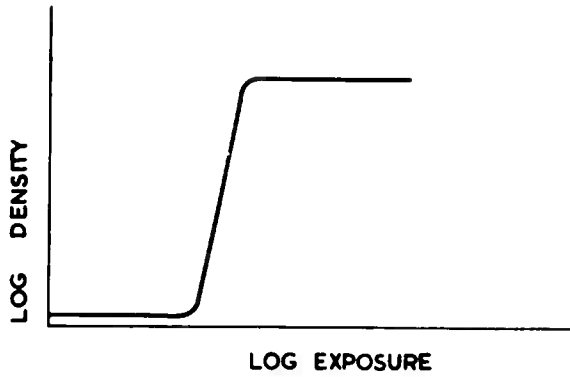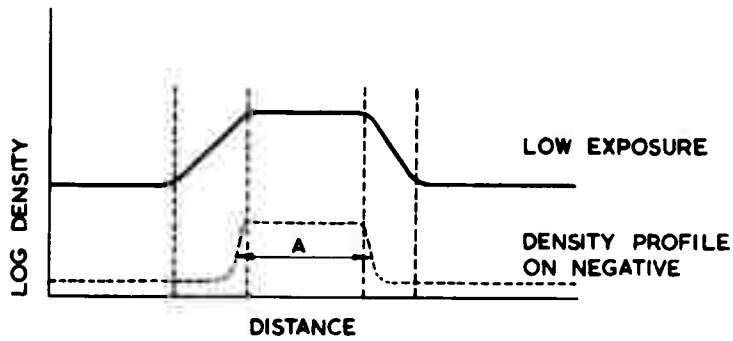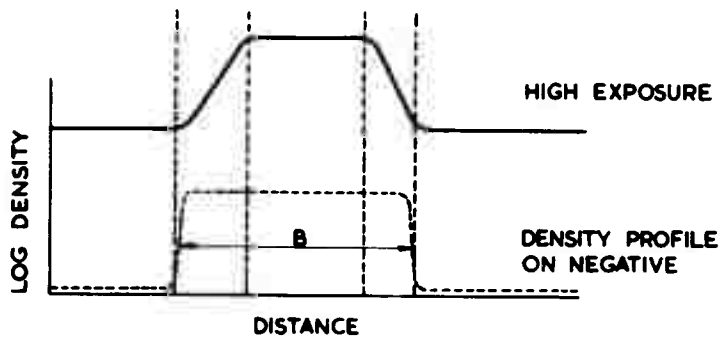FIG. 6   A RAY DIAGRAM FOR THE TOEPLER SYSTEM WITH AN OUT-OF-FOCUS DROPLET
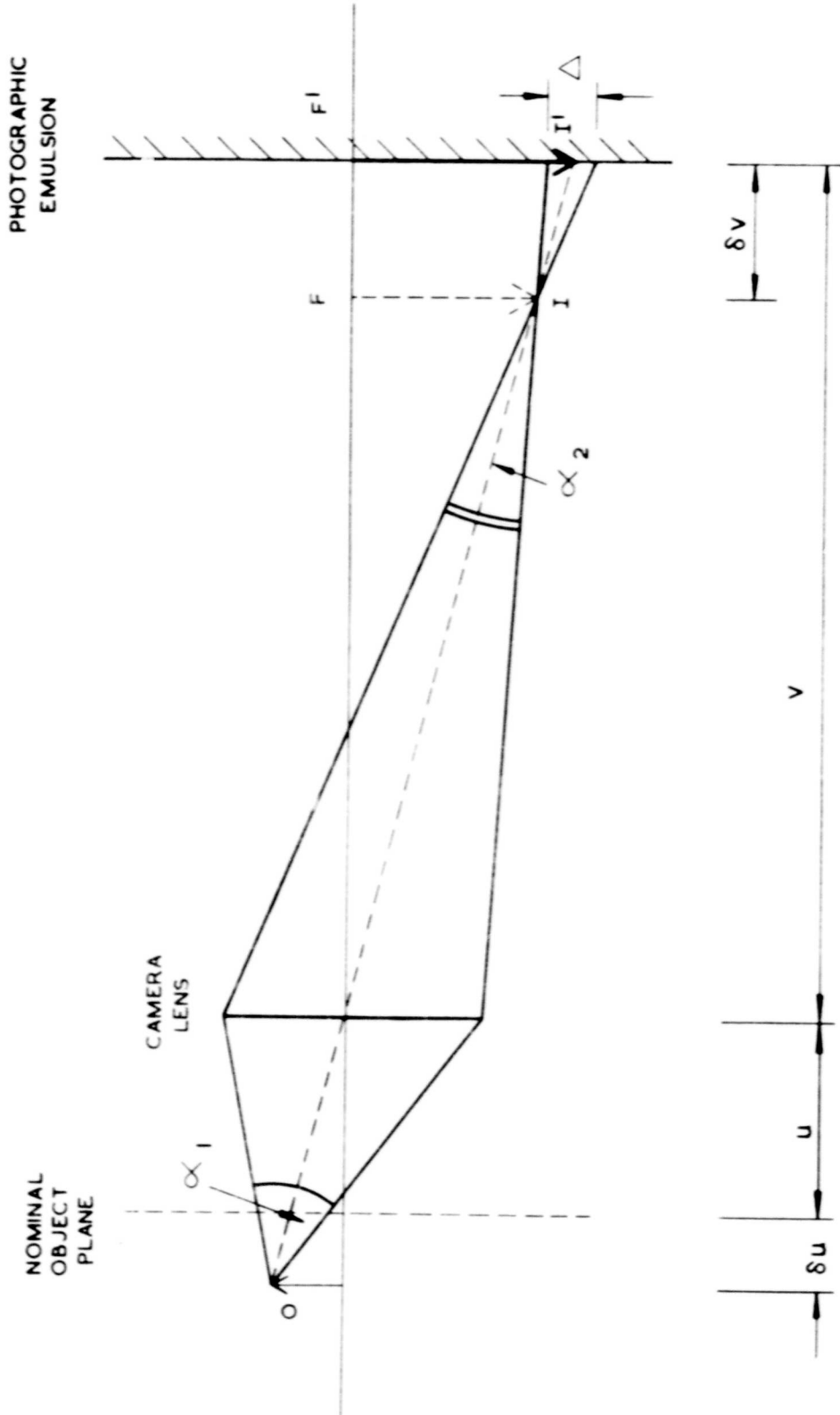
FIG. 7   A RAY DIAGRAM FOR DIFFUSE BACKLIGHTING WITH AN OUT-OF-FOCUS DROPLET

(a) A TYPICAL OPERATING CURVE FOR A HIGH CONTRAST
EMULSION

(b) LOW EXPOSURE OF HIGH CONTRAST EMULSION

(c) HIGH EXPOSURE OF HIGH CONTRAST EMULSION

FIG. 8 THE EFFECTS OF LOW AND HIGH EXPOSURE
OF HIGH CONTRAST EMULSION