ENGINEERING RESEARCH INSTITUTE
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PROGRESS REPORT

ON

THE COMBUSTION OF LIQUID FUEL DROPS IN FREE FLIGHT

by

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Project M988

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FOREWORD

This report was prepared by the Engineering Research Institute of the University of Michigan on U.S. Air Force Contract No. AF 33(600)-5057. The work was sponsored by the Powerplant Laboratory, with Lt. C.B. Shepherd acting as project coordinator. Work was initiated at the University of Michigan under Project M988. This report is the third in the series prepared on various phases of this project and should be regarded as a progress report. A final report will be submitted in March of 1953, the end of the present contract period.

OBJECT

This research project has for its objective the quantitative evaluation of factors which influence the burning of liquid fuel drops for the case in which a drop is burned alone and also when a drop is burned as one of a group in air-fuel mixture.

This report is concerned only with burning groups of drops in an air-fuel mixture.

ABSTRACT

The application of the spinning disk sprayer for the production of uniform-size fuel droplets is discussed. The droplets thus produced are of such uniformity that the standard deviation is no more than 5 microns over the range of droplet size from 60 to 120 microns. Limits of flow are established beyond which the spray uniformity will diminish.

The spray is burned in open air and photographic analysis is made to determine the distribution of various-size fuel droplets withing the flame zone. The uniformity of the spray is shown to diminish as it passes through the flame zone.

LIST OF FIGURES AND TABLES

PROGRESS REPORT ON THE EFFECT OF DROPLET SIZE ON COMBUSTION

THE SPINNING DISK SPRAYER

The work reported in this section serves to extend that of Walton and Prewett[8] and of May[5]. Work done by these men established the spinning disk sprayer as a source of uniform-size drops. From the point of view of one who wishes to use this type of drop maker for supplying fuel spray to a burner, the work cited has two shortcomings: (1) The flow rates dealt with are in general low, and (2) little experience with hydrocarbon fuels has been reported. It is understood that the low flow was considered necessary, or at least advisable, in an effort to obtain as great a drop-size uniformity as possible. It was realized that, in all probability, some reduction in uniformity would have to be accepted in order to obtain drops in sufficient quantity for combustion study. One of the tasks accomplished has been to adopt tentative standards of drop uniformity and to determine the maximum rates of fuel delivery under which these standards can be maintained.

Description of Test Equipment and Procedure

An idea of the apparatus may be gained by referring to Figures 1 and 2. An Onsrud model E2C air Turbine is used to turn the disk. The collet chuck on the turbine shaft permits easy changing of disks; however, most of the work has been done with a two-inch disk. The speed of the turbine is measured with a General Radio Company Strobotac, the speed being controlled by an air pressure regulator. Fuel is supplied to the test stand through a flexible tube from a graduated burette. The fuel sprays horizontally from the disk as indicated in Figure 1.

The camera is build around a standard Rapax f4.5 lens with integral flash synchronizer. Kodak Contrast Process Ortho has been the most satisfactory film; it is used in 4 x 5 sheets. To maintain adequate depth of focus, the camera is usually stopped down to f 16 and the light source positioned to give satisfactory exposure. Light is supplied by a General Electric No. 9364688-01 Photolight. Except for flame location, exposure is not critical,

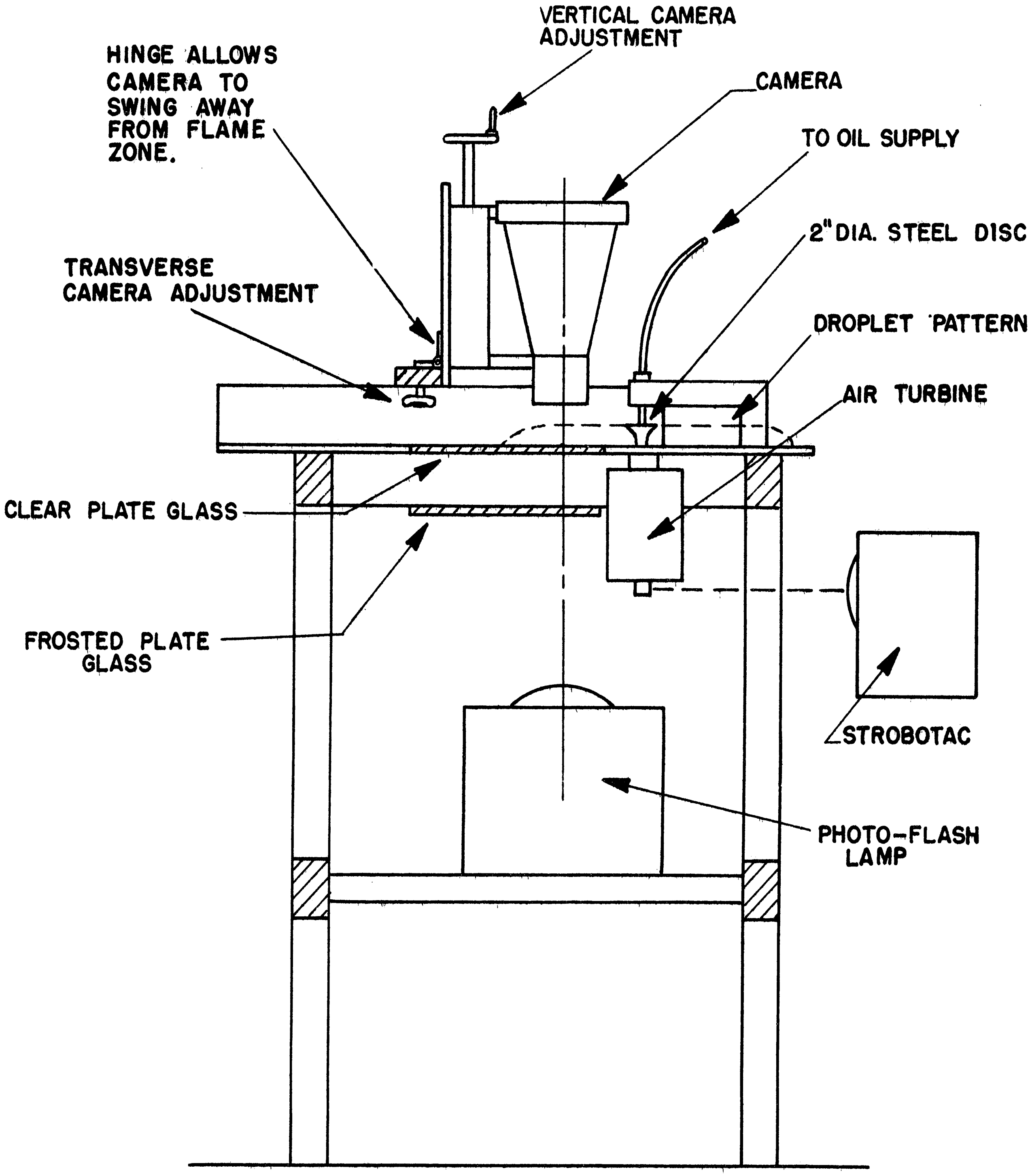


FIG. 1 EQUIPMENT FOR MAKING, BURNING AND PHOTOGRAPHING UNIFORM SIZE FUEL DROPS.

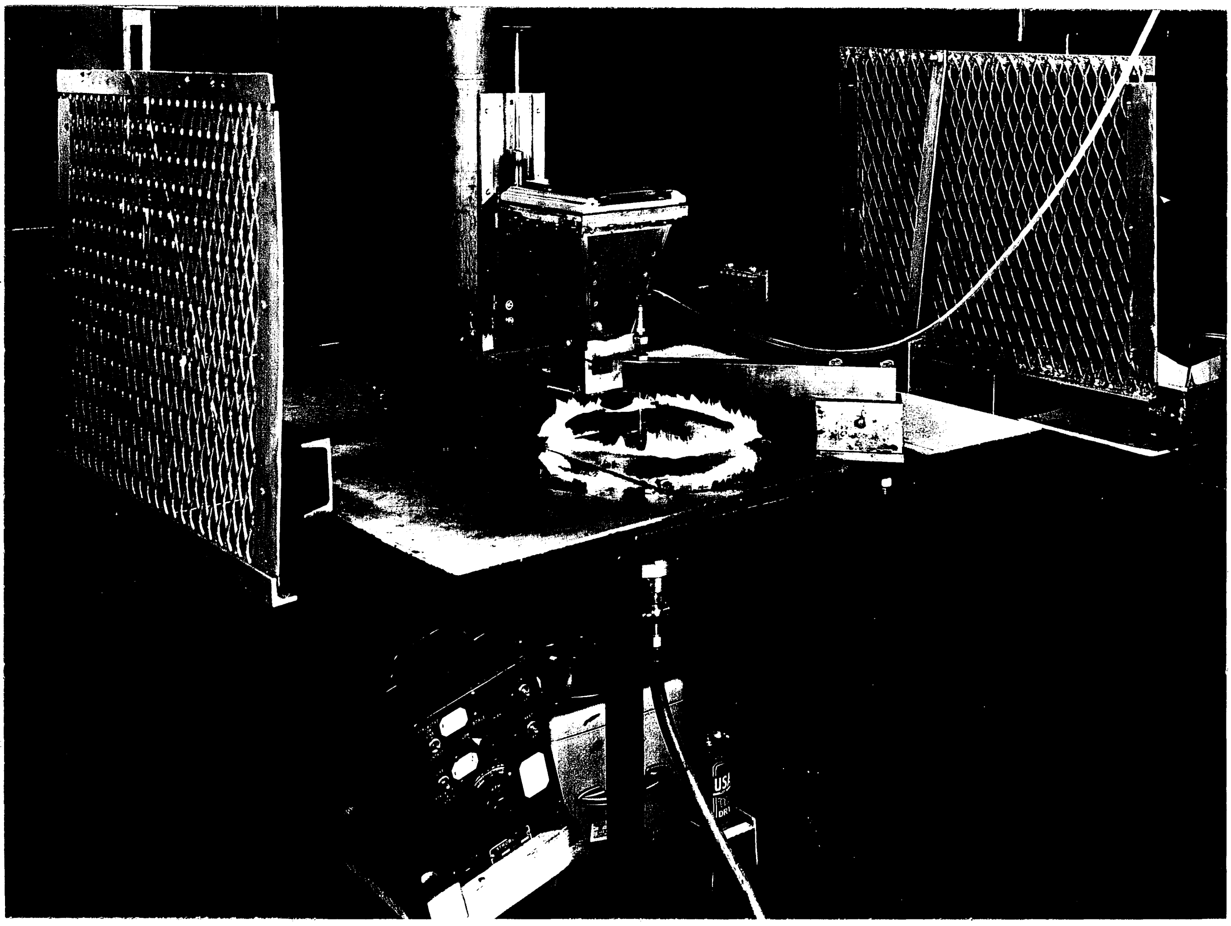


FIG. 2 Photograph of equipment for making, burning, and photographing uniform size fuel drops.

inasmuch as the light pulse duration is only a few microseconds. The light intensity is controlled for satisfactory exposure by shifting the position of the photolight and ground glass. The position of the camera and light may be shifted horizontally to accommodate changed drop sizes and may be shifted vertically in order to focus on the particular drops being investigated. Focusing is done by first placing a sharpened position indicator in the sheet of drops, then focusing the camera on the position indicator.

Meaurement of Drop Size

Although the position of the drops will shift somewhat with random air currents, care in focusing will result in pictures with significant numbers of drops evident. Of these pictures perhaps ten per cent will not be suitable because the images of the drops are not sharp enough to permit acceptable measurement. Each negative is examined by means of a Jones and Lamson comparator. Camera magnification of three, together with comparator magnification of ten, provides a total magnification of 30. Thus the images of drops encountered (from 30 to 150 microns) appear on the comparator screen as between .030 and .180 inch. A transparent gage consisting of a narrow graduated V mark is placed over the drop; the drop size is read from the scale at the point where the drop image fits the gage. The counting job is tedious though not interminable; the negatives from which data have been collected contain in general from 100 to 300 sharply defined drops.

With the present method of measurement the possible inaccuracy appears to be about + 5 microns. To speed up the counting process the drops are sorted into size intervals of ten microns. In some instances in this report the 10-micron intervals are designated by the mid-value in the interval, for example, the interval from 40 to 50 microns being designated as the 45-micron interval. There is room for arbitrariness of the person counting in selecting the interval in which the principal size is counted to the extent of the ± 5 microns. Recounts have been checked, as have also counts, by different persons and they agree within the limit stated.

One further consideration is pertinent. Fledderman and Hanson[2] have shown that the photographic image of a drop will not always represent the correct drop size; the amount of discrepancy depending upon the optical density of the negative. Although this effect is not particularly important for the size of the drops considered here, the smaller sizes observed in burning zones will necessitate correction.

Uniformity of Spray

To say that 90 per cent of the drops lie within a certain 10 micron interval does give a good idea of the nature of the spray as it is delivered from the disk. However, this narrow range spreads out as soon as the spray enters a combustion zone. In view of the changes in the distribution of drop size encountered during combustion, the size specification previously considered seems to be inadequate. Following the work of May[5] and Garner and Cheetham[4] the standard deviation from the mean will be used as the index of the central tendency of the sprays dealt with. Although this index does not seem to do justice to the range of drop sizes obtained originally, one cannot deny its subsequent utility in describing the spray as burning proceeds. In terms of this index the sprays produced are not always so uniform as the spray which May calls "homogeneous" (i.e. standard deviation 2.3 per cent of mean). However, they are more uniform than those of Garner and Cheetham (i.e. standard deviation of 25 microns, size not specified).

For purposes of dealing with spray before burning, the word "uniform" shall mean that the standard deviation is no more than five microns. This seems to be a realistic compromise between the degree of uniformity that can be attained and the desire to have enough fuel drops to supply a continuous combustion process.

As the rate of flow to the disk sprayer is increased, there is a general degradation of uniformity of spray. For the size of sprayer disk used this change of uniformity is particularly pronounced at a rate of flow which varies somewhat above 15cc per minute. Walton and Prewett indicated a critical flow above which excessive numbers of satellite drops were present. Apparently the large numbers of drops induce radial air currents and these currents increase the effective penetration distance of the satellite drops and impair the uniformity of the spray. It is evident from the work of Friedman et al[3] that, if the spinning disk is loaded heavily, the resulting spray will include the wide range of sizes common in sprays from pressure nozzles. To make reasonably certain that the flow limits will not be exceeded they have been carefully established and are represented in Figure 3. Each of the points on Figure 3 is obtained from the analysis of spray at several flow rates. An idea of the significance of this may be had from Table I, which shows data permitting comparison of spray below critical flow with spray above critical flow.

FIG. 3 SPEED VS. CRITICAL FLOW RATE
FOR A 2" DISC

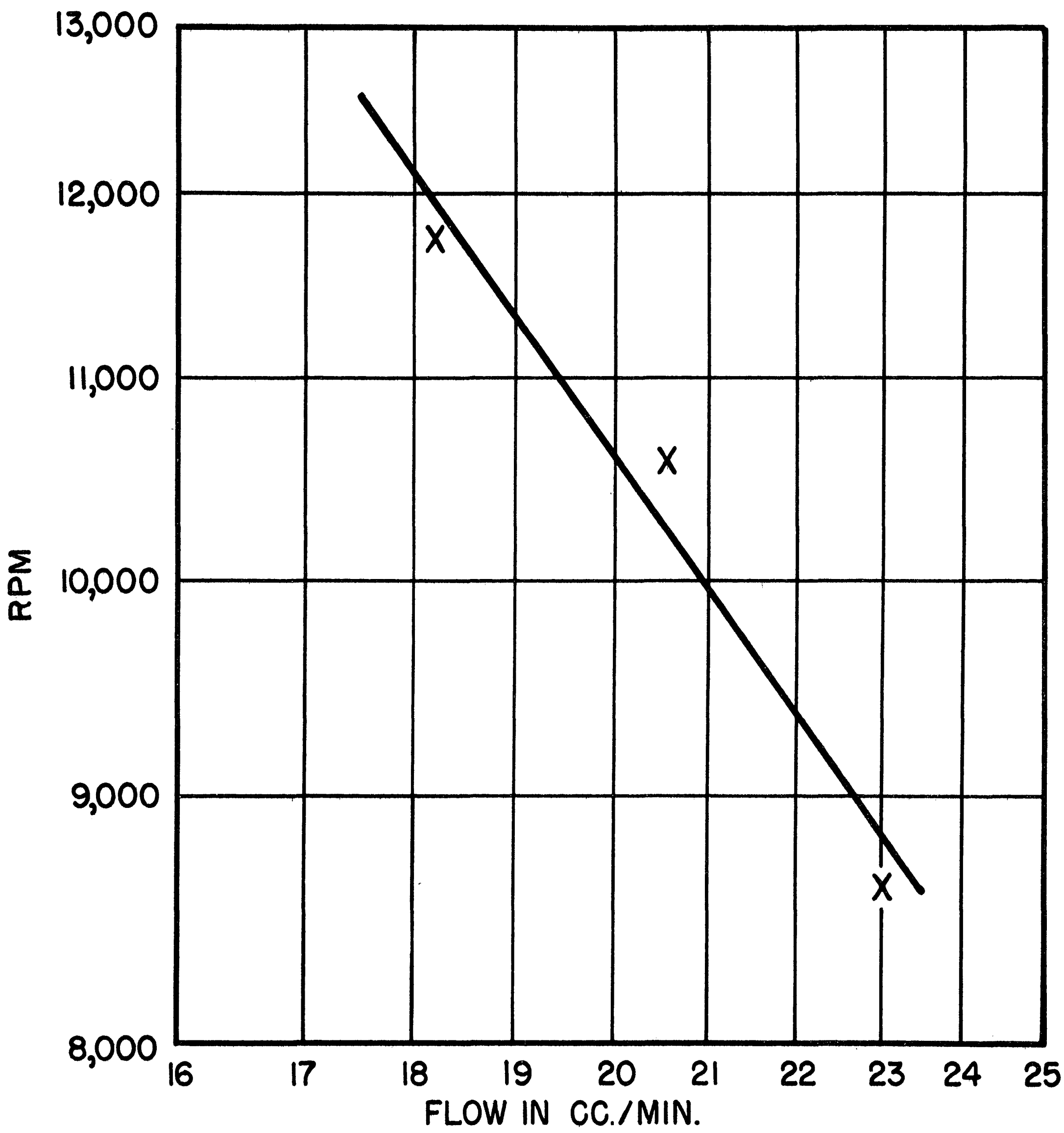


TABLE I

Summary of spray showing difference between (a) spray below critical flow, and (b) spray above critical flow.

(a)

Size Interval	Number of Drops	Mean Diameter	Standard Deviation σ
30-40	1	65.7	4.26
60-70	233		
70-80	2		
80-90	10		

No. 359; RPM = 10,800; Flow = 13.3 cc/Min

(b)

Size Interval	Number of Drops	Mean Diameter	Standard Deviation σ
30-40	2	65.9	8.48
40-50	4		
50-60	9		
60-70	88		
70-80	13		
80-90	9		
90-100	1		

No. 363; RPM = 10,800; Flow 30.0 cc/Min

The Production of Uniform Size Drops

Tests similar to those of Walton and Prewett were conducted to establish the relationship between disk speed and drop size for kerosene. Essentially, the spinning disk sprayer operates by allowing the drop to leave the disk edge after the centrifugal force on the liquid is slightly greater than the forces due to surface tension. Equating forces yields the relationship

$$d = K (T/D\rho)^{1/2} \quad (1/w)$$

where

w = disk RPM
d = drop diameter in microns
T = surface tension in dynes/cm
D = disk diameter in inches
ρ = liquid density in gm/cc

Using the units stated, the constant K has been determined to be about 172,000 for kerosene with $T = 28.5$ dynes 1 cm and $\rho = .79$ gm/cc at 70°F. This corresponds to a constant of 2.88 expressed in the units used by Walton and Prewett.

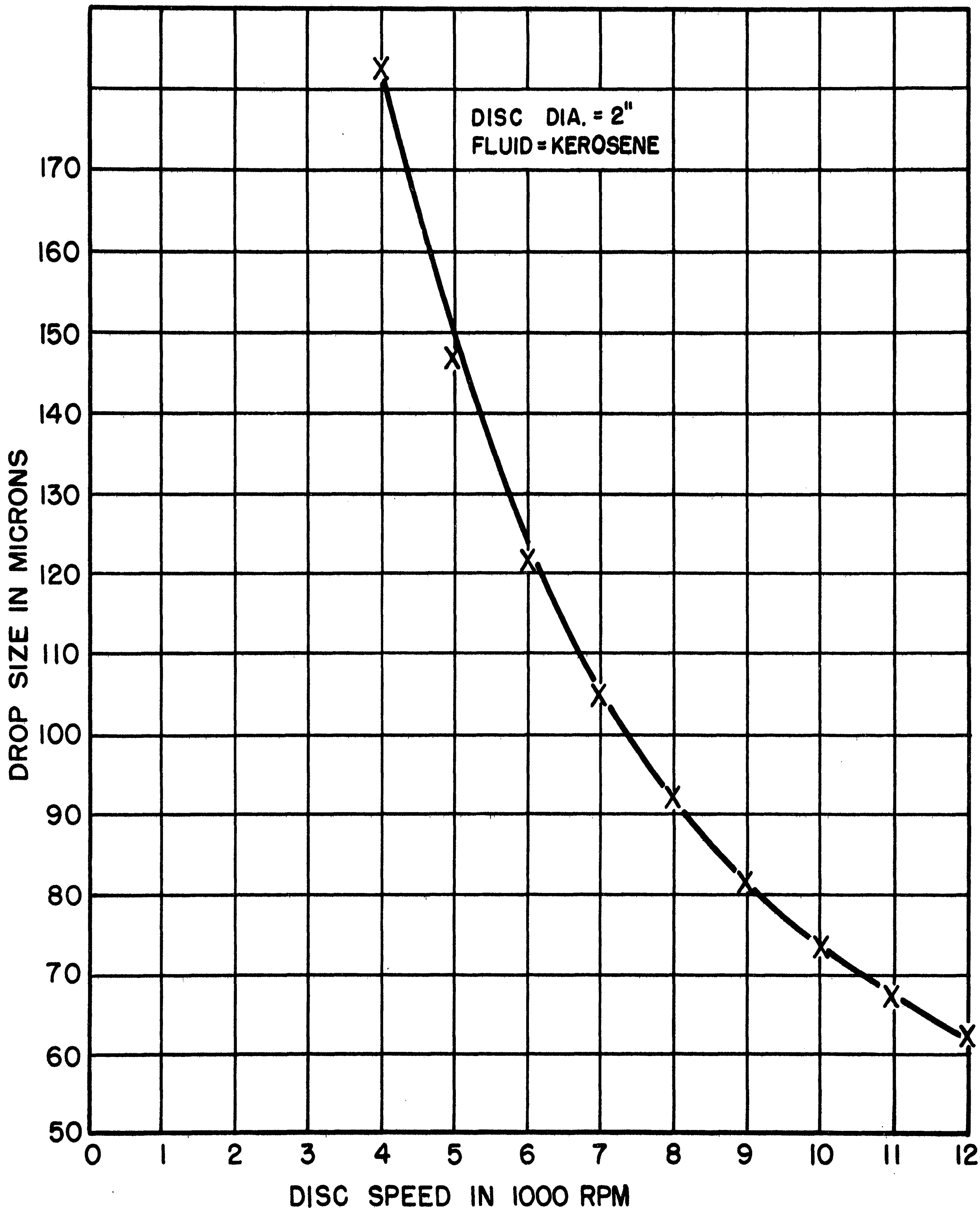
For purposes of convenience a plot was made covering the range 4000 to 12000 rpm (see Figure 4). This range of speed gives drop sizes of from 180 microns down to about 60 microns. It has been found difficult to burn the 120 micron drops in room-temperature air; drops 90 microns and below burn readily under these conditions (see Figure 2). Drops below 60 microns burn at such a short distance from the disk that photographic examination is difficult. This limitation arises from the fact that the burning takes place at a radius less than the outer radius of the turbine, the turbine casing serving to block the light necessary for photographing the drops. There are other conditions that tend to limit the suitability of the present apparatus to drops of 60 microns and above. As the drop size is reduced, the difference between the penetration distance of the principal-size drops and that of the satellites is diminished. This would tend to increase the presence of satellite drops and destroy the uniformity of drops in the combustion zone. Another objection arises from the fact that the allowable error in measurement become more significant as the drop size decreases; this effect is made all the more significant by the reduction in the slope of the size-speed characteristic (Figure 4). Toward the high-speed end it can be seen that the drop size is not so sensitive to changes in speed.

However, for sizes above 60 microns the spinning disk provides a means of producing spray in quantity sufficient for the purposes of this project. In general, the limits to the operation of the device have been determined. Some relief from these limits may be had by changing the size of the disk.

BURNING OF DROPS FROM A SPINNING DISK

Earlier sections of this report describe the standards of size of the spray delivered by the spinning disk. It is the purpose of this section to discuss the effort centered around the burning of the spray delivered by

FIG. 4 DROP SIZE VS. SPEED OF DISC.



the disk. This deals principally with problems of photographing the drops as they are passing through the flame zone, and with the interpretation of the data thus far collected. Although delays in obtaining delivery of apparatus have curtailed the work in investigating the "Effects of Fuel-Particle Size on Combustion", the basic method of analysis proposed has been shown to be suitable for use within the flame zone.

The main body of drops leaves the spinning disk in a horizontal plane; the radial distance to which each drop will penetrate depends upon the size of the drop.[5] If the drops were of precisely equal size, and if random air currents could be eliminated, the intersection of the drops with any plane perpendicular to the disk axis, and below the disk, would form a narrow circle. At any such intersection the width of the circular band provides a rough check on the uniformity of the drops. With drops of such uniformity as discussed earlier in this report, the pattern made by the drops inpinging on the test stand is a circle with radial width of about three fourths of an inch. At a radial distance somewhat less than the radius of intersection mentioned above, the horizontal velocity of the drops is quite low. In this region the vertical velocity is also low, the terminal velocity for the drops dealt with here being of the order of one foot per second.

Initiating Combustion

By holding the flame from a Bunsen burner in the region through which the drops are moving, the drops may be readily ignited. The amount of burning will depend principally upon the size of the drops, the rate at which fuel is supplied to the disk, and the location of the Bunsen burner flame. If the conditions are correct, the kerosene will burn with sufficient intensity so that the Bunsen flame may be removed. The flame from the burning kerosene drops will then advance around until it forms a ring as shown in Figure 2. The fact that the principal-size drops burn at a radial distance less than their maximum penetration without burning would tend to increase the probability of satellite drops being present in the burning zone. However, the satellite drops are quite small and may be observed to be carried up out of the way of the burning ring by rising air. In instances in which the satellite drops do burn, there are two burning zones (see Figure 5). This condition is encountered particularly at higher speed, when the principal-size drops are small and are burning near the disk edge. The main body of drops burns at a height near that of the disk surface. The radius of the burning ring will depend upon the drop size, the feed rate, and upon the temperature of the air supporting combustion. Part of the periphery of the disk may be shielded and the fuel from that part collected; this enables operation with as little of the flame ring as desired.

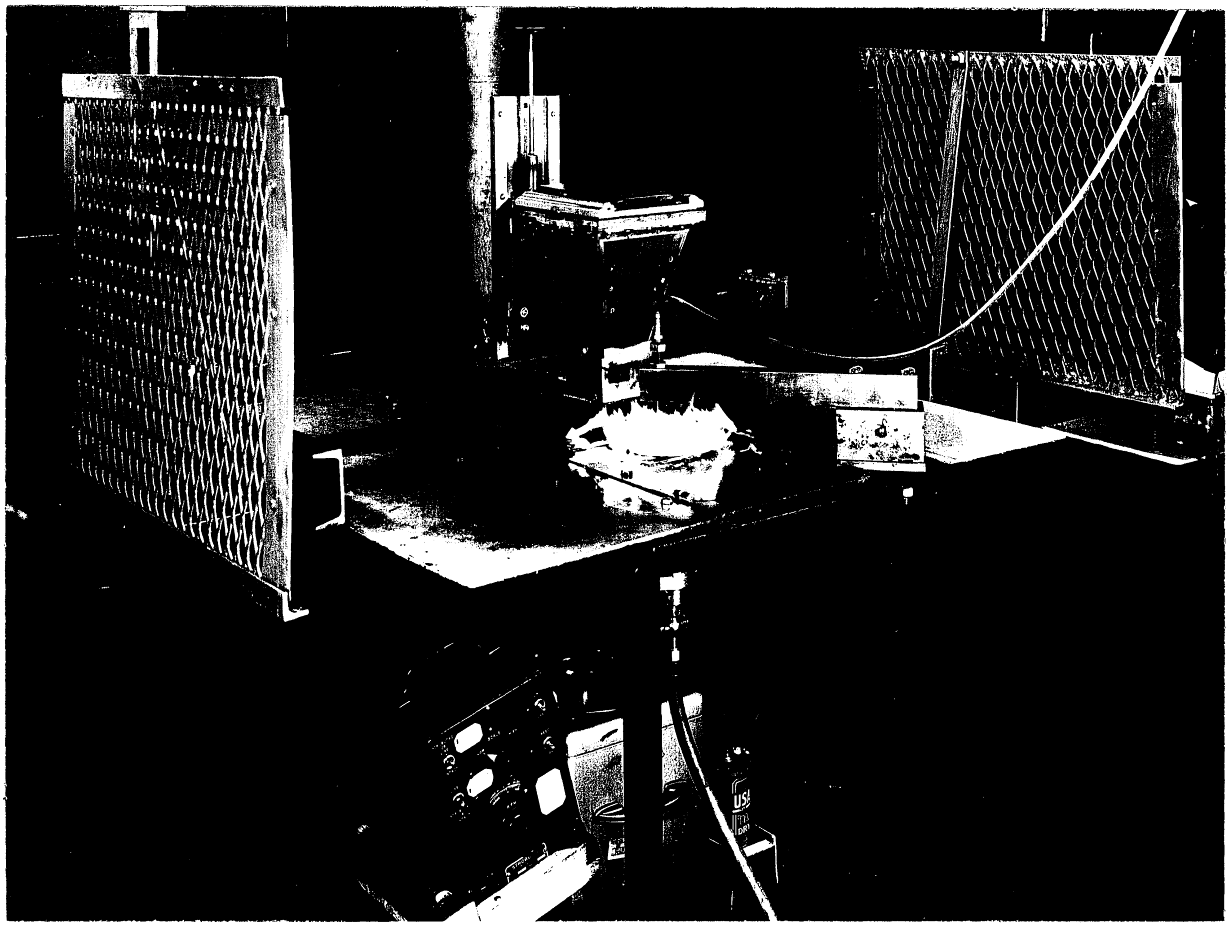


FIG. 5 Photograph showing burning in main zone, and also burning of satellite drops.

Photographing Burning Drops

Once the burning ring has been established the camera must be focused. The convection currents set up by even the smallest flame are sufficient to raise the drops and preclude a satisfactory picture resulting from focusing on the drop location before burning was started. The position indicator is used for this purpose; first, the position indicator is moved into the flame zone, then the camera is focused on the position indicator. This focusing procedure is made more difficult by random air currents in the laboratory; these may result either from drafts or from rapid movement of one's hand or the camera.

Provided conditions have been satisfactory, the resulting picture will show three more or less distinct zones: the zone in which the drops are substantially as produced by the disk without burning being present, a zone in which the drop diameters decrease with increased radial distance from the disk, and a zone in which very few drops remain. A positive print of such a photograph is shown in Figure 6. In the pictures of this type the number of drops in focus is considerably less than the number in a corresponding photograph without burning. Apparently the random currents in the flame zone break up the sheet of drops and thereby reduce the number of drops in focus. Few small drops (30-40 microns) appear in the photographs obtained thus far. This may result from the tendency of the method of spray analysis to discriminate against the small drops, or the fact that the small drops are carried out of focus more rapidly, or simply the extremely short time needed to consume the drops after the major portion of each drop has burned.

Interpretation of Photographs

To systematize the counting of drops the negative is divided into zones, each zone being 1/4 inch, measured in a radial direction away from the disk. Since the negative itself represents a magnification of three, the actual radial distance represented by one of the numbered zones is .083 inch. Inasmuch as the negative is examined on a comparator, providing magnification of the negative of ten, the zone space on the comparator screen is two and one half inches. The problem of the drop counter then, is to determine the numbers of the various-size drops in each of the numbered zones.

The print shown in Figure 6 includes drops ranging from the 90-100μ interval down to the 50-60μ interval. It should be pointed out that this particular print is shown more because of its suitability for printing than for its representing the greatest observed change of drop size. Because of an imperfection in the negative or in the paper it is impossible to distinguish a drop smaller than the 50-60 micron drops shown on the contact

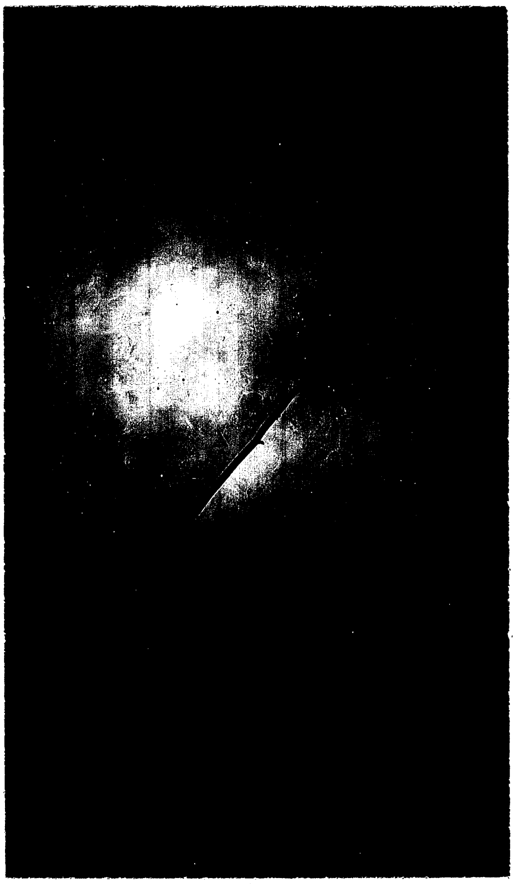


FIG. 6 Photograph showing burning drops.

print. With the added magnification of ten provided by the comparator it is relatively easy to distinguish drops down to 30 microns on the negative. Usually the spot in the center of the drop does not show on a positive print; these spots provide a check of the focus on the particular drop. The spot represents light transmitted through the drop. With the aid of a small magnifying glass such spots may be seen in several of the drops in the upper left hand corner of the print

An example of the procedure followed with the data obtained from such a photograph is presented with the aid of Table II. Graphic representation of similar data will be found in Figures 7, 8, and 9.

TABLE II

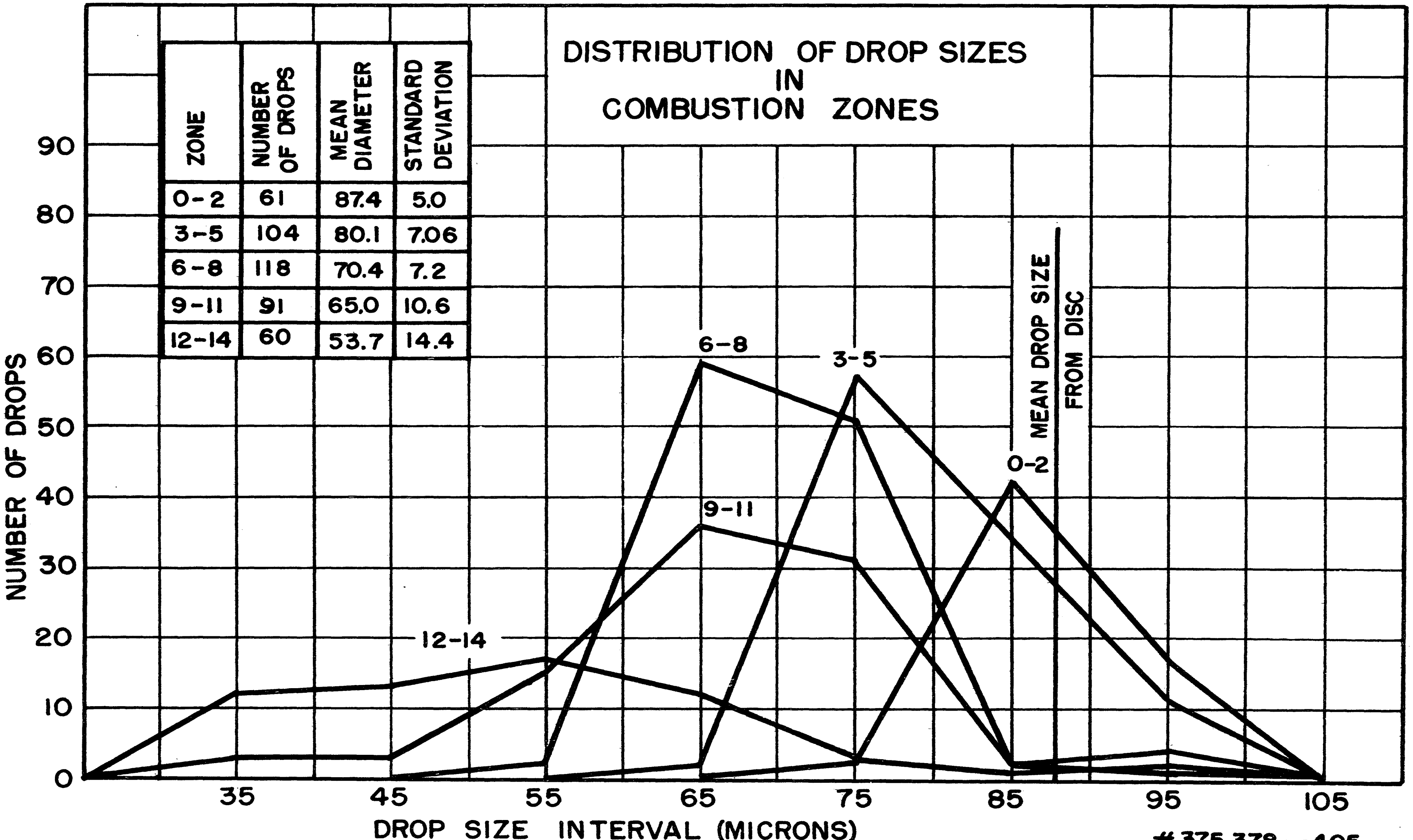
DROP SIZE INTERVAL
Microns

Radial[+] Distance	Zone	40-50	50-60	60-70	70-80	80-90	90-100	100-110	Mean Drop Size (Microns)	Standard Deviation (Microns)
5.75 - 6.0 "	0-2	-	-	-	2	13	7	-	87.7	6.0
6.0 - 6.25"	3-5	-	-	1	11	1	1	-	76.5	6.4
6.25 - 6.5 "	6-8	-	-	12	10	1	1	-	71.3	7.53
6.5 - 6.83"	9-12[x]	-	9	15	3	1	2	-	65.7	10.62
6.83 - 7.21"	13-16[x]	-	2	-	-	-	-	-	x	x

[x]Four zones included
[+]Mean radial distance from center of disk

2" Disk
8200 RPM
Pict. No. 378

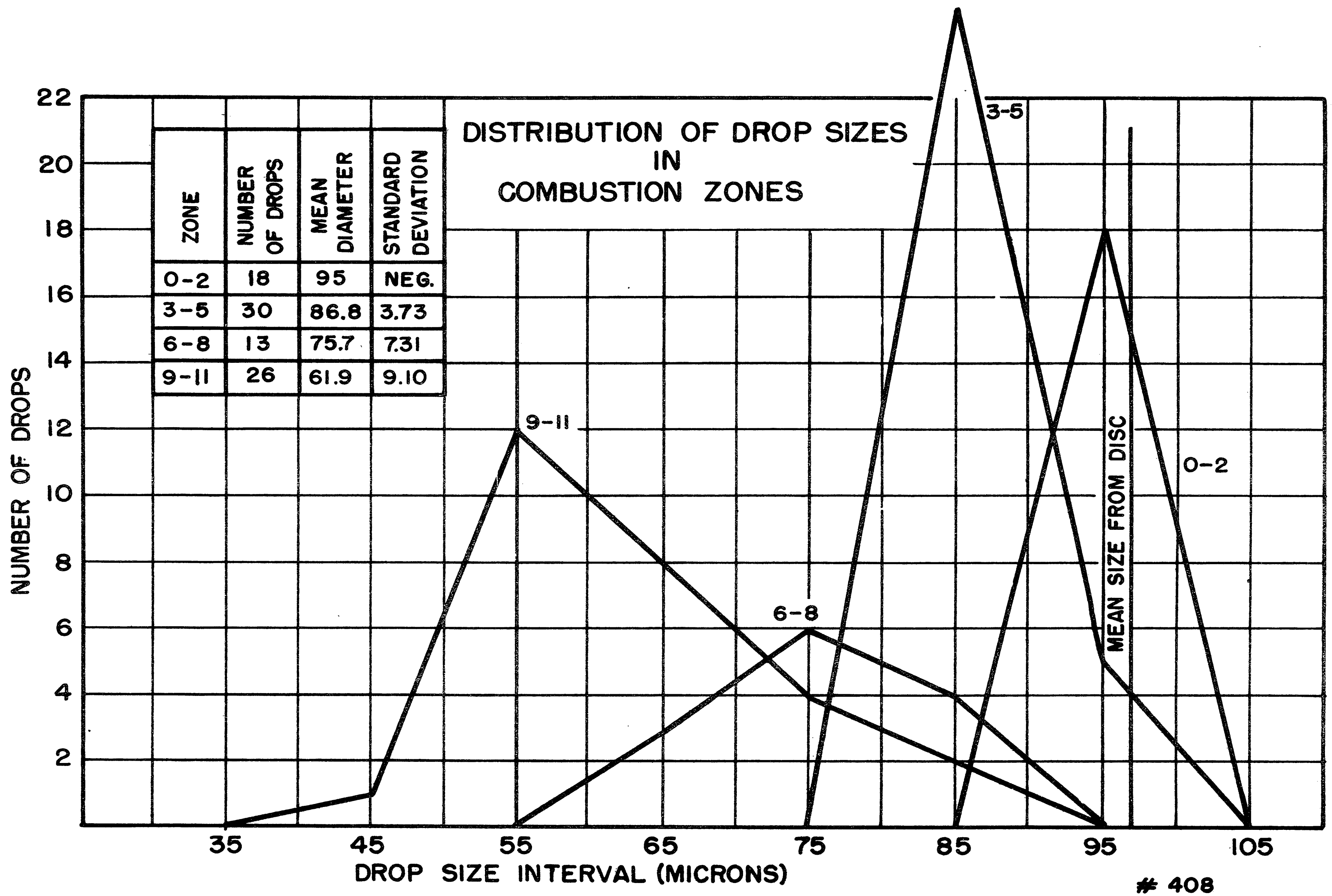
For convenience the numbered zones are arranged in groups of three or four. This has been necessary because of the small number of drops appearing in the photograph. The Table can be seen to cover about 1.4 inches of radial distance. The drops are shown to be changing in size quite uniformly as the radial distance increases. The change of size takes place in aobut 1.1 inches of travel; however, a comparison of the spray in zones 0-2 with the spray as delivered from the disk without burning indicates that some change in size had taken place before the drops arrived in the field of the camera. The mean size of the drops is shown to the right in the table; the standard deviation is also shown. It is evident from this example, as well as from the others considered, that the central tendency of the sizes of drops present is considerably reduced as the burning proceeds. Similar evidence is presented in Figures 7, 8, and 9. In each case there is a pronounced increase in stardard deviation as the drop diameter decreases.



ZONE	NUMBER OF DROPS	MEAN DIAMETER	STANDARD DEVIATION
0-2	61	87.4	5.0
3-5	104	80.1	7.06
6-8	118	70.4	7.2
9-11	91	65.0	10.6
12-14	60	53.7	14.4

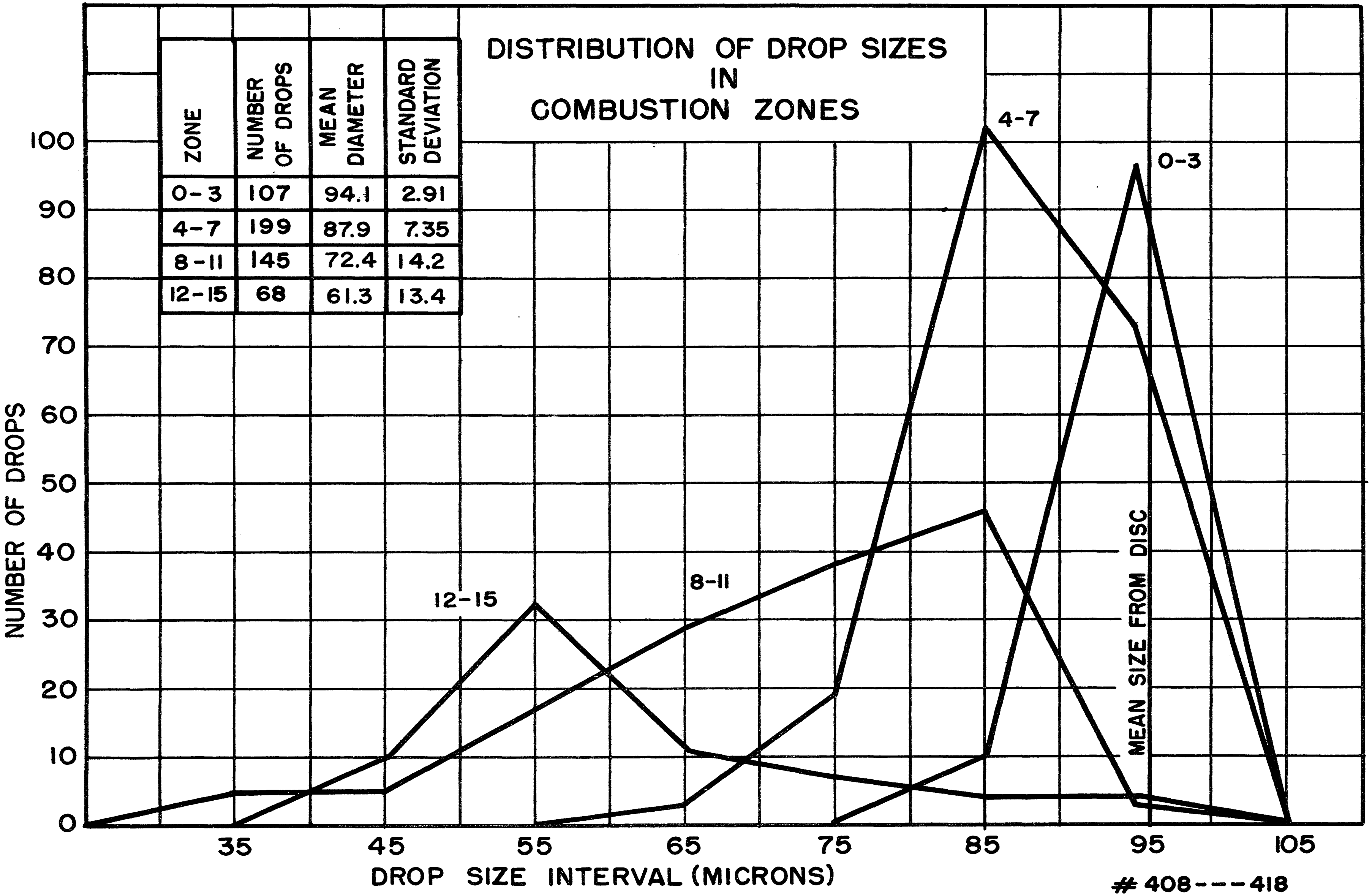
FIG. 7.

375,378--405
2" DISC.
8200-8500 RPM



408
2" DISC
7500 RPM

FIG. 8.



ZONE	NUMBER OF DROPS	MEAN DIAMETER	STANDARD DEVIATION
0-3	107	94.1	2.91
4-7	199	87.9	7.35
8-11	145	72.4	14.2
12-15	68	61.3	13.4

FIG. 9.

One principal difficulty with the example cited is that the number of drops considered is small. In an effort to overcome this, data from different pictures have been combined; these pictures were taken with all measurable conditions equal. Nevertheless, there is a noticeable shift of the location at which the drops start to change size. This presents the possibility of misalignment when combining data from several photographs. The combining is done simply by renumbering the zones on the data sheet so that the zero zone is the last zone occupied by standard-size drops. The results of such combinations are presented in Figures 7, 8, and 9. It is believed that the benefit to be had from greater numbers of drops is significant, even though deviation may be introduced in superposing the data. An idea of this may be had from a comparison of Table II with Figure 7 and of Figure 8 with Figure 9. In each case the data of a single photograph are compared with data from a group of which it is a part. In some zones the deviation does not change significantly while in the others there is a considerable difference in deviation. Further work is needed before a decision can be made regarding the manner of combining data. The same may be said in regard to establishing reasonable standards of deviation for "uniform"-sized fuel particles within the combustion zone.

Conclusions

Although work covered by this project is by no means complete, a few conclusions seem justified at this point. The photographic mehtod of spray analysis has been shown to be suitable for use in a flame zone. The adaptation of a double flash light source with suitable time interval offers the opportunity to observe the behavior of a burning spray on a manner that is believed to be novel.

The uniformity of fuel spray from the spinning disk sprayer has been confirmed and some of the limits of operation have been established for a reasonable degree of drop size uniformity. Some objections to the use of this device remain. The manner in which the spray is delivered prohibits the use of all the spray. In view of the limits of flow cited any analysis that is restricted to the use of only a fraction of the spray provided will be forced to deal with limited numbers of drops. Nevertheless, the disk provides drops in such quantity and of such uniformity as to be satisfactory for the purpose of this project.

The preliminary analysis carried out so far indicates that the uniformity of the spray decreases as the drops burn. The degree to which this takes place, as revealed by the data obtained so far, may or may not be significant. One might be discouraged by the fact that the uniformity is lost before the drops are burned. However, it should be pointed out that in most instances more than half the fuel is burned before the zone standard deviation exceeds 10 microns.

FUTURE WORK

Two principal modifications are being made:

1. A method of double flash photography is being adapted to the apparatus. This will permit the observations of drop size to be referred to a time basis and will permit comparison of experimental results with theoretical work done by Spaulding and others. It will involve the determination of burning rate for the different-sized particles together with the total burning time. Considerable delay has been experienced in obtaining needed equipment for this change.

2. The provision for changing the temperature in the flame zone, both by radiant surface and by heating the air supply has been tried. This not only helps to keep the flame steady, but it provides the opportunity for measuring the effect of another variable quantity on the combusion of the drops.

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