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THE GENERATION AND BURNING OF UNIFORM-SIZE LIQUID FUEL DROPS

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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 US Air Force Contract No. AF 33(600)-5057. The work was sponsored by the Power Plant Laboratory, with Lieutenant C. B. Shepherd acting as project coordinator. The work was conducted at the University of Michigan under Project M988. This report is the fourth of a series required in the contract. In view of the contract supplement No. 52(53-308), this report also may be regarded as a progress report.

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ABSTRACT

This report is concerned with the generation and rate of burning of uniform liquid fuel drops in the range of sizes used in aircraft gas turbine combustors.

Equipment has been built which permits stabilizing a liquid drop in space by means of air drag forces and ultrasonic waves, thus permitting observation of rate of evaporation or combustion of freely suspended drops.

Clouds of smaller-sized drops, less than 150 microns in diameter, were produced by means of a spinning disk. A photographic technique was used to obtain an indication of the rate of change of diameter and the velocity of the drops while moving freely in air. Based on observation of these clouds of uniform-size kerosene drops, the mass rate of burning was found to be proportional to the first power of the drop diameter. This relationship is in agreement with the results of British scientists for single drops of much larger size.

Larger-size drops, up to 3000 microns in diameter, were produced by means of a microdropper. Equipment has been designed which will permit a fuel drop of controlled size to be dropped into a hot atmosphere and observed photographically at any time during its burning life.

SURVEY OF PREVIOUS WORK ON FORMATION AND COMBUSTION OF LIQUID FUEL DROPS

Drop-Forming by Condensation

Devices commonly referred to as aerosol generators were investigated first. These devices consist of a heater section for vaporizing a liquid, and provision for subsequently mixing the vapor with air containing nuclei. The mixture of air, vapor, and nuclei is then admitted to a condenser wherein condensation of the vapor occurs on the nuclei, each nucleus acting as a condensation center. By careful control of the vapor quantity, the number of nuclei, and condensation rate, liquid drops are formed about the nuclei and may be removed from the aerosol generator.

Professor Victor K. LeMer, with his associates at Columbia University, has done a considerable amount of work on aerosol generators of this type. Their work and aerosol generator equipment are described in References 19 and 29.

The aerosol generators made at Columbia have been used with materials such as sulfur, with a considerably lower volatility than the hydrocarbon fuels which would be of greatest interest to this project. The lower volatility has the advantage that practically no material leaves the generator in the vapor phase, which makes the operation insensitive to the ambient temperature.

The drops produced by the equipment at Columbia University range in size up to a maximum of 10 microns in diameter, with the usual size being about 0.2 micron in diameter. Experimental work is required to determine if it is possible or practical to make uniform drops of large sizes. Considerable care must be exercised to limit the variation in diameter to ± 10 per cent. The operation of the generator is extremely sensitive to changes in the temperatures of boiler and reheater. The adjustment of these temperatures is an individual matter with each generator and substance.

It therefore appears that this method of forming drops is not well adapted to hydrocarbon fuels such as kerosene, having constituents with a wide range of boiling points. This is unfortunate, since these fuels are of principal interest for this project. Furthermore, there is little experience with these devices, and the problems pertaining to making drops of larger sizes are not known.

It is believed that the spinning-disk atomizer, described later in this report, is better adapted to our task, and offers more promise for our work than the condensation method. Also, much less time and money will be required to proceed to the main objective, which is the observation of burning drops.

Mechanical Spray Generation: The Spinning-Disk Sprayer

Several scientists have contributed knowledge concerning the production of sprays by means of a spinning-disk sprayer. Much of this work was prompted by the high degree of uniformity of the spray produced by this method. May[23] found that when the smaller satellite drops were removed and when fluids which wet the disk were used, the width of 90 per cent of all drops fell within a band of 5 per cent of the mean. He reports spray with standard mean deviation of 2.3 per cent of the mean diameter, with the minimum drop size apparently 6 per cent smaller than the mean.

In some earlier work, Walton and Prewett[36] developed the means for predicting the size of drop which would be obtained from a spinning disk. This scheme necessitated the experimental determination of a constant for each fluid; however, they showed that the value was quite consistent for several liquids. This work did not include information dealing with common liquid fuels.

The shape of the disk used has been the subject of considerable investigation. Hinze[14] produced spray by means of a rotating cup; he lists three different types of disintegration that take place resulting in (a) drop formation directly from the main body of liquid, (b) ligament formation, and (c) film formation. The conditions governing the type of drop formation are indicated qualitatively as follows: Transition from state (a) to state (b) or from state (b) to state (c) is promoted by an increase in liquid flow rate, rotating speed of the cup, density, or viscosity, and by a decrease in either cup diameter or surface tension. Hinze reasoned that drops of greatest uniformity of size result under circumstances of drop formation from ligaments (b above).

To obtain spray of the greatest uniformity, Hinze lists the following requirements, among others:

1. Gravitational effects must be negligible; this means that centrifugal acceleration must be large with respect to gravitational acceleration ($w^2r > 10$ g).

2. Rotation must be free from vibration.

3. There must be a uniform supply of liquid.

4. The surface of the spinner must be smooth, particularly if the liquid layer is very thin.

Tanasawa[32] reported that the use of a spinning cup or spinning flat disk made little difference in the uniformity of the resulting spray. He obtained remarkably good high-speed photographs showing types of drop formation which in general correspond to those listed by Hinze. Tanasawa concluded that a very sharp-edged disk gives a slightly smaller drop diameter than a plane disk with a thicker edge. He reported that the edge must be very smooth in order to obtain the greatest uniformity. Tanasawa also reported the results of the use of disks having sawtooth edges; this modification resulted in a smaller drop size.

Walton and Prewett[36] state the opinion that drops of greatest uniformity are produced by the spinning disk when the drops are formed and released individually. Under these conditions the centrifugal and surface tension forces acting on the growing drops are substantially in equilibrium up to the time the drop breaks away. At higher rates of flow, inertia forces become predominant and the fluid leaves the disk edge as a thin sheet; this sheet breaks into drops, forming spray with a wide range of sizes.

By changing the rotation speed and the diameter of disk, Walton and Prewett were able to produce uniform sprays ranging in mean diameter from 15 microns up to several millimeters. These authors and also May[23] noted that the spray thrown from the disk contained a number of fine drops in addition to the main group of uniform size. These satellite drops represented about 10 per cent of the volume of the liquid sprayed and were removed from the main body of the spray as a result of their shorter penetration distance. May also reported the presence of a small number of drops having about twice the volume of the standard-size drops.

Combustion of Fuel Drops

The combustion of a liquid fuel consists of diverse and complex reactions. Spalding[30] outlines a theory for the combustion of liquid fuel based on the assumption that combustion occurs within a stagnant film adjacent to the liquid surface. The film is divided into two regions by a surface parallel to that of the liquid. The chemical reaction is assumed to take place at the dividing surface. The fuel vapor passes by diffusion from the liquid surface to the burning surface, while the oxygen diffuses to this surface from the outer boundary of the stagnant film. A small portion of the heat of combustion is conducted inward to heat the liquid and provide the latent heat of vaporization of the fuel. The main portion of the heat of combustion is conducted outward toward the gas stream. This analysis indicates that the rate of combustion of a liquid fuel is greatly influenced by the phenomena of heat transfer, diffusion, and evaporation. Evaluation of these phenomena has been hindered by difficulties involved in the analysis of the gases and measurement of the temperatures near the flame zone. Spalding was able to complete his analysis by making simplifying assumptions for many of these factors. Experimental work was conducted to support some of his theory.

Godsave[10] ignited drops suspended on a vertical filament and photographed the burning drops with a motion-picture camera. He observed the rates of burning of various fuels and pure hydrocarbons, and found that over the range of drop sizes investigated (1000-2000 microns), the burning drops decreased in size at a mass rate proportional to the first power of their diameter. The burning rate at any diameter may be expressed by an evaporation constant, as defined by the following equation:

$$x^2 = x_o^2 - \lambda t,$$

where x = drop diameter at any time t,

x_o = drop diameter at $t = o$,

λ = evaporation constant having the dimensions of length^2/time,

t = elapsed burning time.

He also obtained experimental evidence that the rate of combustion is chiefly dependent on the enthalpy of the liquid and on the latent heat of vaporization, rather than on properties such as the volatility of the fuel.

Spalding[30] has also stated that the fuel properties having the predominant effect on the combustion rate are the heat of combustion, the latent heat of vaporization, and the specific heat of the vapor. Since these properties do not vary greatly for the usual hydrocarbon fuels, it is reasonable to expect that the combustion rates will be quite similar. Thus, the difference in burning rates for gasoline and diesel fuel is due mainly to the difference in time required to reach equilibrium temperature. Spalding points out the importance of these conclusions, since they indicate the futility of trying to accelerate combustion by means of additives.

SECTION I. PRODUCING, BURNING, AND OBSERVING GROUPS OF DROPS

The Spinning-Disk Sprayer

With the work of May[23] and Walton and Prewett[36] as background, several spinning-disk sprayers were built. Early sprayers were powered by electric motors, but these have been replaced by the air turbine described below. The sprays obtained were very uniform, by normal standards, although not so uniform as had been reported by May. The lesser uniformity may be the result either of the use of a turbine or motor, with mechanical bearings and resulting vibration, or of the generally higher flow rate. For purposes of this project the degree of uniformity of spray was arbitrarily taken as that represented by a standard mean deviation of 5 microns. This decision was a compromise between the degree of uniformity that can be attained and the desire to have enough drops to supply a continuous combustion process. In view of the accuracy of measurement of drop diameter (± 5 microns), the designation seems inane. It should be pointed out that as the spray burns, the uniformity diminishes, and the distribution of sizes is such that the standard mean deviation is larger than the inaccuracy in measurement.

An early result was the extension of the work of Walton and Prewett to cover the fuel most used on this project (kerosene). Figure 1 represents these data in such form that a knowledge of sprayer disk diameter and speed will yield the size of kerosene drop to be expected. These curves were obtained by plotting the relationship developed by Walton and Prewett, with the appropriate constant determined for the kerosene used in this project. In all cases the size resulting agrees with the curve within the error of measurement. In any instance involving photographic analysis, the photograph itself usually provides a check on the diameter of the drops.

As the rate of flow to the disk sprayer is increased, there is a tendency for the spray to become less uniform. Work cited above, as well as that of Friedman et al[9], shows that if the spinning disk is loaded heavily, the resulting spray will include the wide range of sizes common in sprays from the pressure nozzles. This degradation of spray uniformity seems to be quite pronounced at a flow rate somewhat above 15 cc/min. The flow rate at which this takes place was determined for the 2-inch disk over a part of the range of operating speed and is represented in Fig. 3. For the 2-inch disk, uniform sprays were obtained for conditions to the left and below the line in Fig. 3; the three points indicated represent spray with standard mean deviation close to 5 microns. The limits expressed will vary somewhat with disk diameter (cf. Walton and Prewett's discussion critical flow,[36] page 348). Apparently as the flow rate is increased, the increased number of drops induces radial air currents sufficient to carry the satellite drops along, thus impairing the uniformity of the spray.

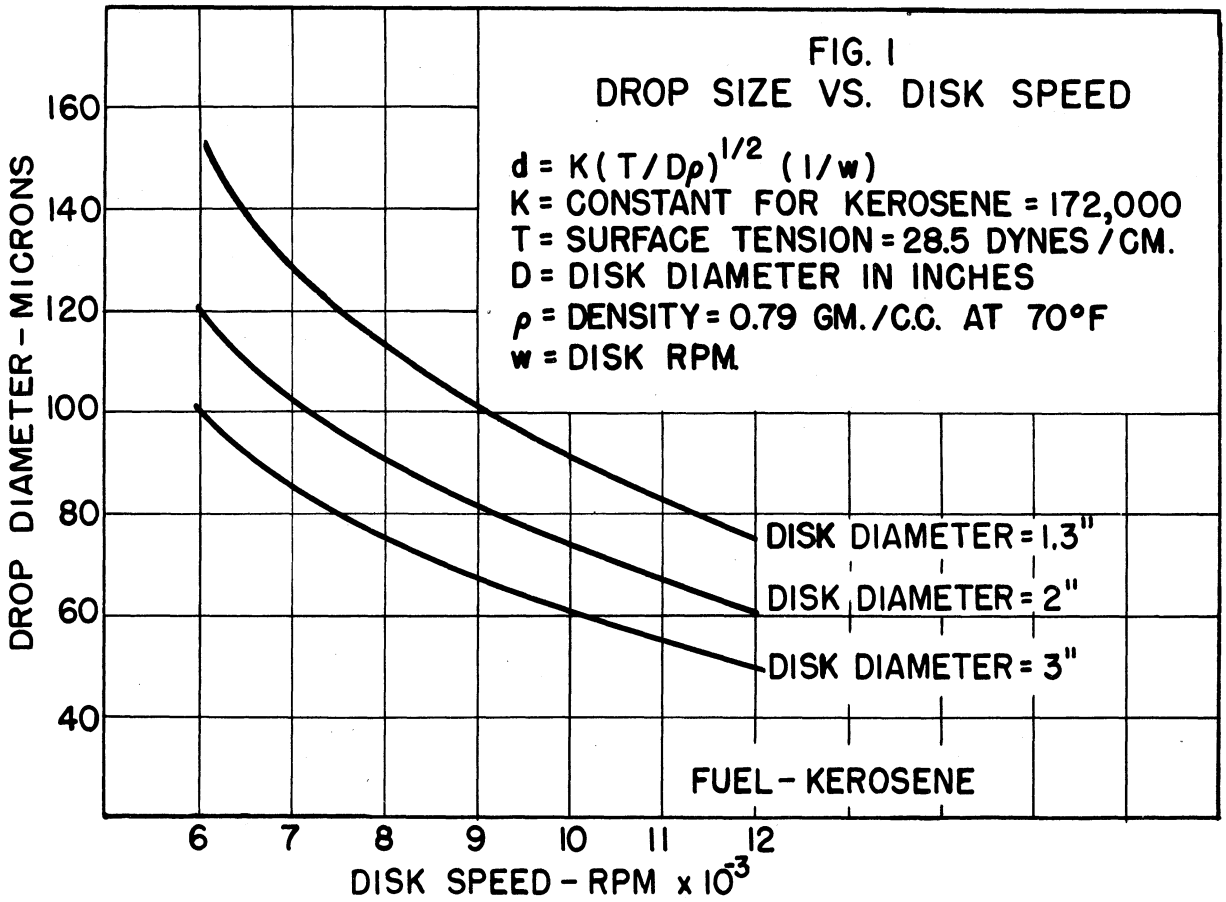


FIG. 1
DROP SIZE VS. DISK SPEED

$d = K(T/D\rho)^{1/2}(1/w)$
K = CONSTANT FOR KEROSENE = 172,000
T = SURFACE TENSION = 28.5 DYNES/CM.
D = DISK DIAMETER IN INCHES
ρ = DENSITY = 0.79 GM./C.C. AT 70°F
w = DISK RPM

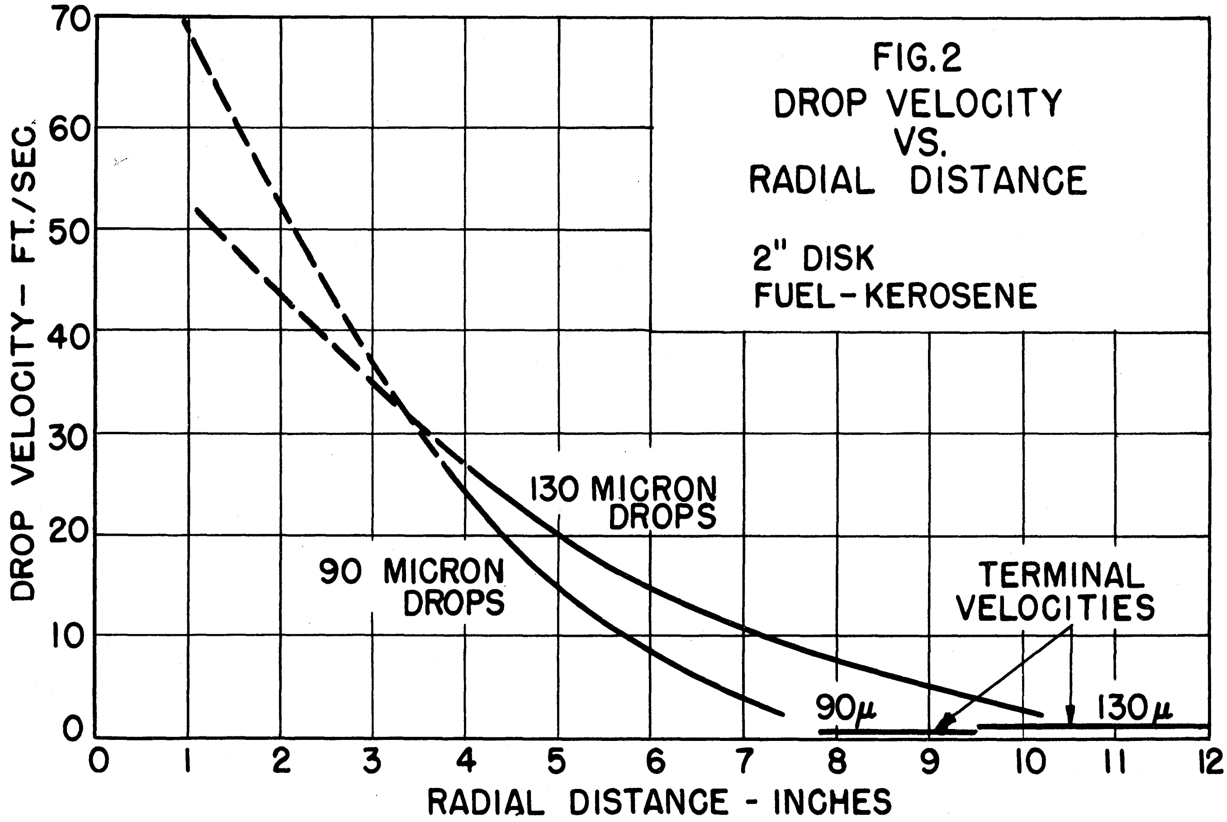
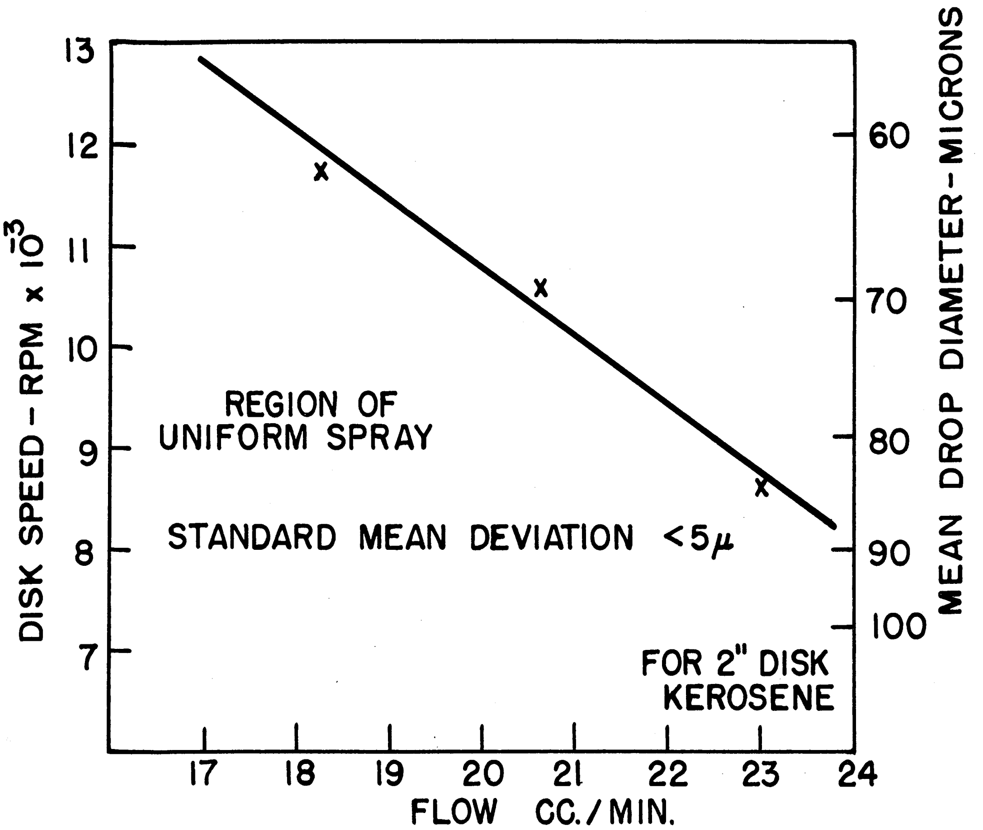


FIG. 2
DROP VELOCITY
VS.
RADIAL DISTANCE

2" DISK
FUEL - KEROSENE



DISK SPEED VS. FLOW RATE
SHOWING FLOW LIMIT FOR
UNIFORM SPRAY.

FIG. 3

The use of the photographic analysis of spray presumes that there will be a sufficient number of drops within the camera field, so that acceptable comparison of observation and theory may be undertaken. The spray from a disk sprayer is readily adaptable to photographic analysis because the spray is delivered in the form of a sheet which can be made to coincide with the plane of focus of the camera. Accepting this possibility, the number of drops appearing within the field of the camera will depend on the area covered by the camera field, the distance between the disk and the location of the camera (for combustion study this is governed largely by flame location), the drop size and velocity, and the fuel flow rate. For conditions representative of much of the work reported here (90-micron drops burning at a mean radial distance of 6.5 inches and 130-micron drops burning at a radial distance of 9 inches from the disk), the number of drops within the field of the camera would be 27 and 12 drops respectively for each cc/min fuel flow to the disk. These values are based on velocities determined photographically and represented in Fig. 2. From the consideration of the numbers of drops available, the spinning-disk sprayer seems capable of supplying a number of drops sufficient for the purposes of photographic analysis, and sufficiently uniform to satisfy reasonable standards.

Description of Test Equipment and Procedure

The apparatus used is seen in Figs. 4 and 5. The spinning disk is held in the collet chuck of an Onsrud* model E2C air turbine. The turbine chuck permits changing of disks; however, most of the work reported was done with a 2-inch diameter 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 from the disk in the form of a horizontal sheet. Either the air heater (Figs. 6 and 7) or a piece of frosted glass is placed just below the section of the spray to be photographed.

The camera is built around a standard Rapax f/4.5 lens with integral flash synchronizer. Kodak Contrast Process Ortho has been the most satisfactory film; it is used in 4 x 5-inch sheets. To maintain adequate depth of focus, the camera is usually stopped down to f/16 or f/11, and the light sources and groundglass positioned to give satisfactory exposure. Light is supplied by two General Electric No. 9364688-01 photolights in conjunction with a half-silvered mirror.

The positions of the camera, the lights, and the air heater can be shifted horizontally to accommodate different drop sizes, and the camera can be shifted vertically for purposes of focusing.

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*Onsrud Machine Company, Chicago, Illinois.

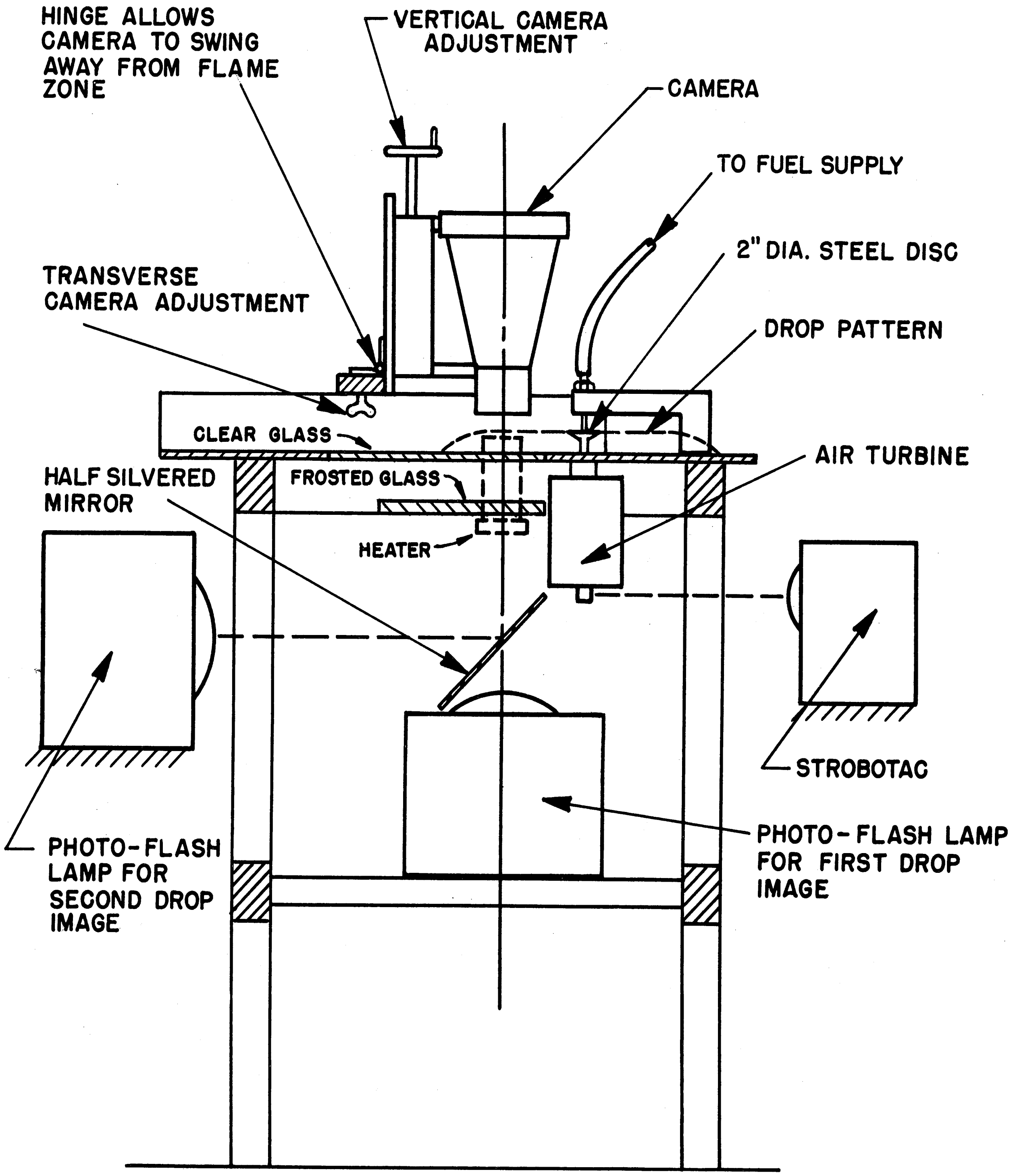

FIG. 4

EQUIPMENT FOR MAKING, BURNING AND PHOTOGRAPHING UNIFORM SIZE FUEL DROPS

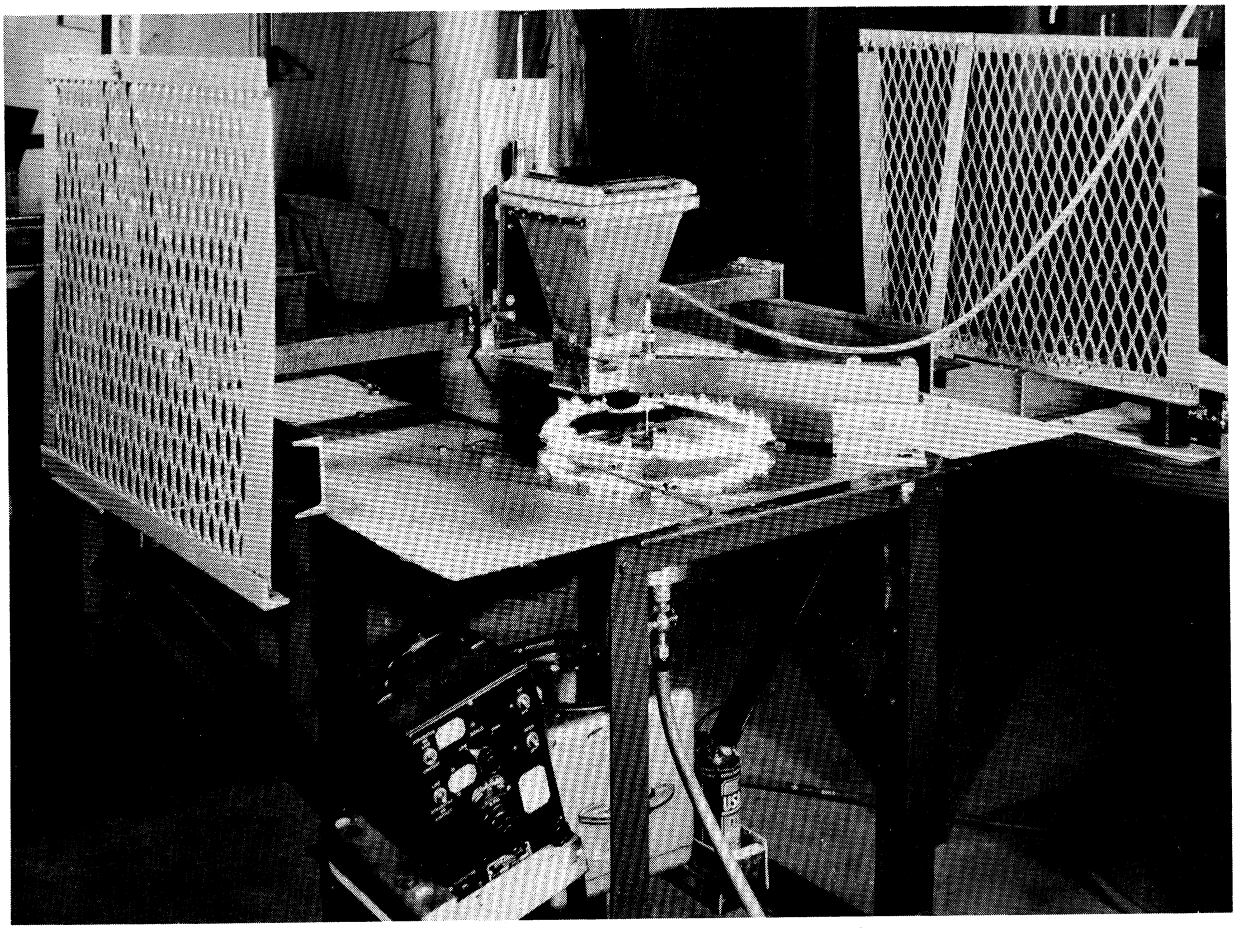

Fig. 5. Photograph of Test Stand with Normal Burning.

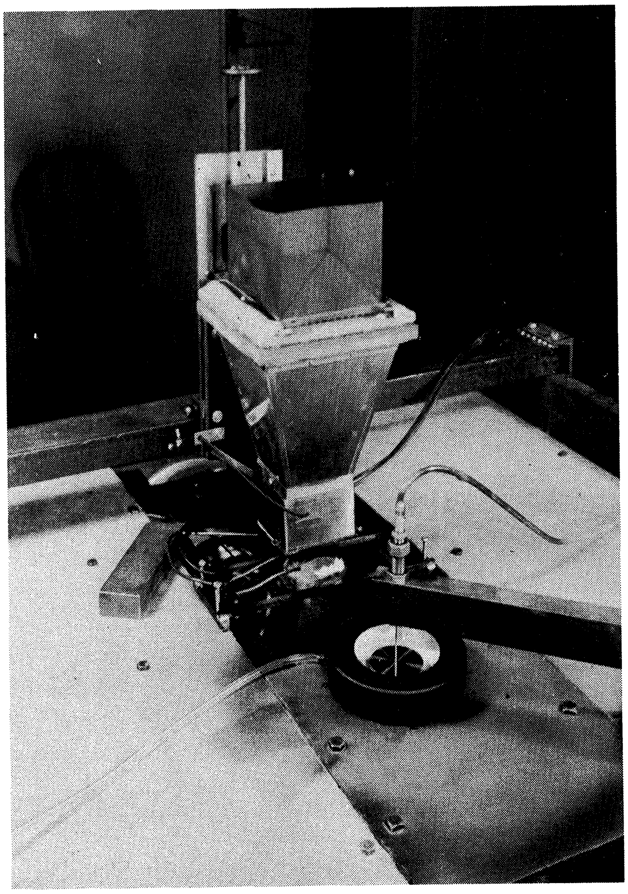

Fig. 6. Photograph of Kerosene Spray Burning in Heated Air.

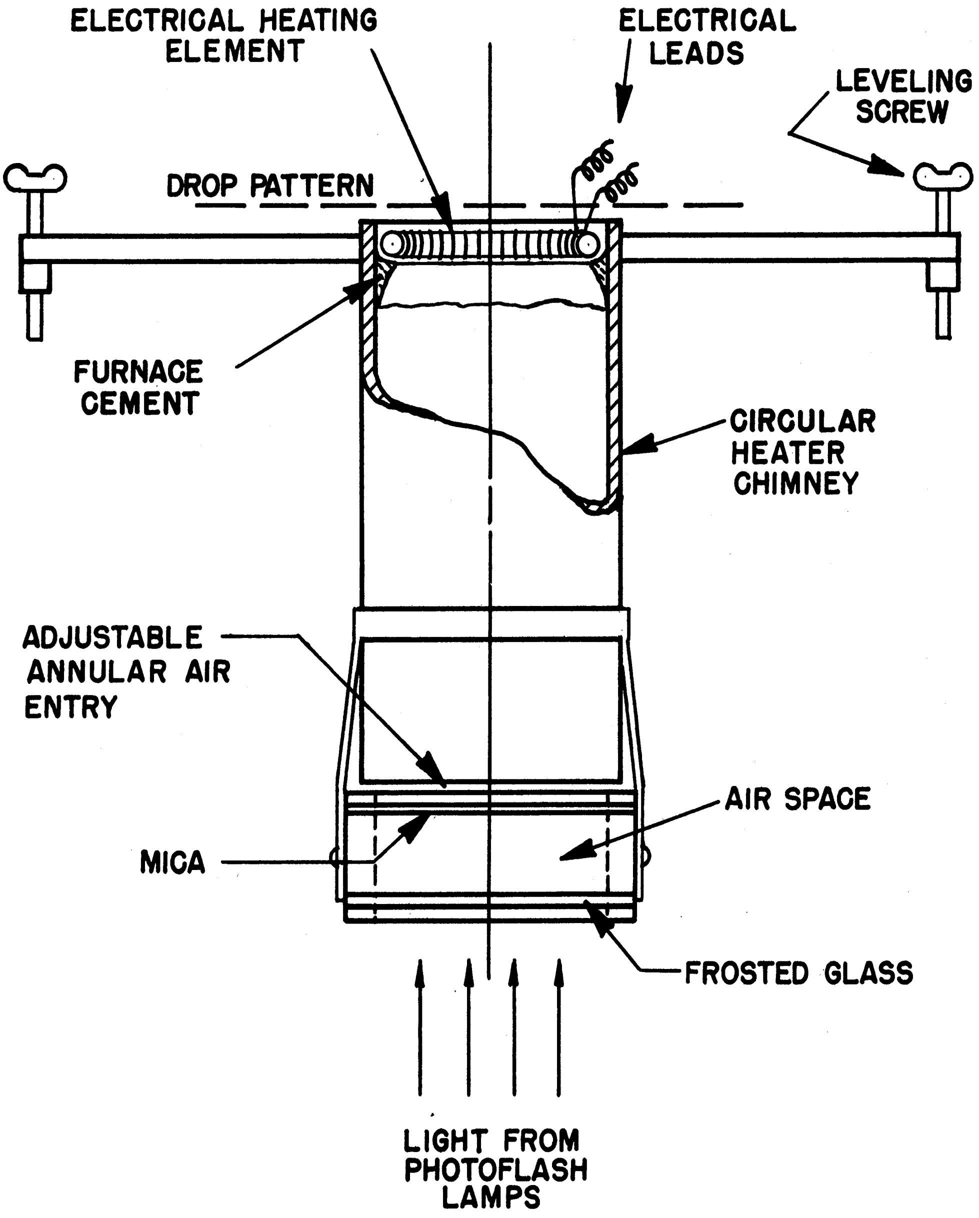

FIG. 7
AIR HEATER

The time interval between the two flashes of light is controlled by an electronic delay unit. This unit permits selection of intervals over the range 0.000155 to 0.00138 second. A circuit diagram and calibration information are included as Appendix A.

The developed negatives were examined by means of a Jones and Lamson comparator. Camera magnification of 3 together with comparator magnification of 10 provide a total magnification of 30. Thus the images of drops counted (diameters of 30 to 150 microns) appear on the comparator screen as 0.030- to 0.180-inch images. A transparent gage consisting of a narrow graduated V mark is placed over the image, and the drop size is read from the scale at the point where the drop image fits the gage.

Photographic Spray Analysis

The method of photographic spray analysis used was that proposed by York and Stubbs[41]. The arrangement of the photographic apparatus is also shown in Figure 4. The light pulses, supplied by the photolights in conjunction with the half-silvered mirror, yield a double-image photograph of the fuel drops. A knowledge of the magnification, together with a knowledge of the time interval between light flashes forms the basis for spray analysis. The time delay circuit was designed to provide a maximum interval of about 0.002 second. A selector switch, mounted on the separate chassis carrying the delay line, permits ready change of interval. The circuit was calibrated by photographing a radial line on the face of the spinning disk. The two light flashes yielded two images of the line, and the angle measured between the images, together with the rpm of the disk, measured the time between flashes.

The magnification of the camera (3X) and the magnification of the comparator (10X) were established as correct within ± 1 per cent. each This was done by examining glass filaments of different sizes. The measurement of the comparator images of the filaments, and the distance between them, and subsequent comparison with direct measurements, established the comparator magnification. A corresponding examination of a photographic negative established the camera magnification.

The depth of focus was checked by photographing the glass filaments when inclined to the focus plane of the camera by a known angle. The resulting picture showed a distinct image of the middle parts of the filaments, becoming more and more blurred toward the ends. The depth of focus yielding satisfactory sharpness was 0.047 inch; this agrees well with the computed value of 0.0453 inch*. From the appearance of the glass filaments it seems likely that the spot which may be seen within the image of a drop will not be apparent if the drop lies outside the depth of focus specified. The presence of this spot, resulting from light transmitted through the drop, was used as a guide in accepting or rejecting drop images.

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*Kodak Reference Handbook, 1940

A further consideration is pertinent. Fledderman and Hanson[8] have shown that the photographic image of a drop will not always represent the correct drop size. The amount of variation depends on the optical density of the negative surrounding the drop image. The effect is significant; as the negative becomes less dense the images represent drops up to 10 and 20 per cent oversize for 137- and 30-micron drops respectively. It is probable that this effect depends similarly on the optical density of the drop image itself, and in view of this no detailed correction has been undertaken. Photographs used appear to lie within limits of density which would introduce no more than a 5 per cent error in size, even in the smaller drops (30-40 microns). The above considerations lead to the belief that drop measurements represented are within ± 5 microns of the stated value.

Local drop velocities are considered to be correct to within - 0.3 ft/sec. This variation becomes significant when the drop velocities become small, and it should be borne in mind that this refers to inaccuracy in the focus plane of the camera. The depth of focus is sufficient to permit a velocity component, in a direction perpendicular to the plane of focus, slightly greater than 0.3 ft/sec.

Initiating Combustion

The spray from the spinning disk may be ignited by holding the flame from a Bunsen burner in the region through which the drops are moving, if sufficient fuel is being sprayed and if the Bunsen flame is held so that the drops pass through the flame with moderate velocities (i.e., 2-8 ft/sec). The spray will continue to burn after the gas flame is removed. The flame from the burning drops will then extend around the disk until it forms a ring, as shown in Fig. 5. The fact that the drops burn at a radial distance less than the maximum distance attained without burning tends to reduce the uniformity of the spray. This is a result of the increased likelihood of satellite drops being present at the smaller radial distance. Inasmuch as the satellite drops are quite small for the condition under which analysis has been attempted here, they are 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. This condition is encountered particularly at higher disk speeds, when the spray is originally made up of smaller crops (60 microns and below) which burn near the edge of the disk.

The main body of drops, containing about 90 per cent of the fuel sprayed, burns close to the plane of the upper face of the disk. The radius of the burning ring will vary with drop size and liquid feed rate, and inversely with disk speed and supporting air temperature. Part of the periphery of the disk may be shielded and the fuel from the shielded part collected; this permits operation with as little of the flame ring as is desired (see Fig. 6).

Photographing Burning Drops

Once the ring of burning drops has been established, the camera must be focused. The convection currents set up by even a small flame are sufficient to raise the drops and preclude a satisfactory picture resulting from focusing on the drop location before burning was started. A position indicator in the form of a pointed wire was used in most of the work presented (see Fig. 8). First the position indicator is located just outside the burning ring and adjusted so that the tip of the wire is at the level of the flame. The camera is located by focusing on the position indicator, and then checked for horizontal position by observing the flame image on the ground glass. Minor shifting in the location of the flame will cause it to surround the pointed wire at one instant, and fall short of the wire by perhaps 3/4-inch the next. This shifting in the location of the flame, together with changes caused by drafts in the laboratory, necessitates a degree of coordination on the part of the photographer.

Provided conditions have been satisfactory, the resulting picture will show three more or less distinct regions: a region in which the drops are substantially as produced by the disk without burning, a region in which the drop diameters decrease with increased radial distance from the disk, and a region in which very few drops remain. Figure 8 is a positive print of such a photograph, the total enlargement here being 6. In the pictures of burning spray the number of drops observed is less than in the corresponding pictures without burning. In the more densely populated pictures without burning, about half of the anticipated number of drops have been observed, while in pictures of burning spray the number observed seldom exceeds 30 per cent of the calculated value. This latter reduction is reasonable if account is made for the area usually included in which few drops remain. Few small drops (30-40 microns) appear in the photographs. This may be attributed to the tendency of the spray analysis method to discriminate against the small drops, or to the fact that the small drops would be rapidly carried out of focus, or simply to the lessened probability of their being there as a consequence of the extremely short time needed to consume the drops after this small diameter has been attained.

Photographing Burning Drops Supplied with Heated Air

Figure 6 shows a small flame fed by 130-micron drops from the spinning disk. The air supporting combustion is supplied through a tubular air heater, shown in Fig. 7. Sample photographs obtained in this manner are presented as Figs. 9 and 10; these prints represent a magnification of about 9. The degree of detail revealed is typical for pictures of this type. Kerosene drops of 130 microns in diameter enter the camera field from the top, or lower side of the picture. Figure 9 reveals the presence of one double-volume drop (cf. May 23); however, the general uniformity of the entering spray is

Fig. 8. Combustion: 90-Micron Kerosene Drops.

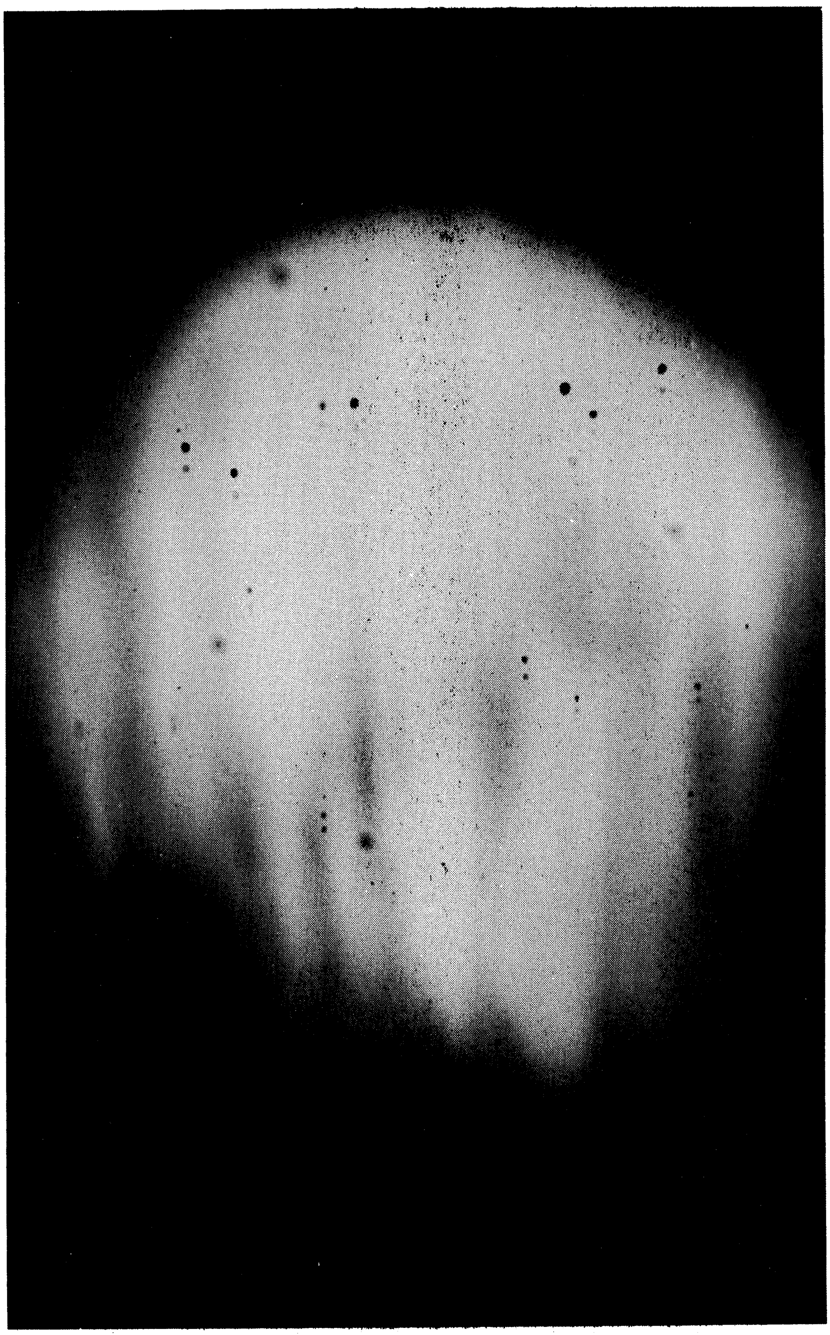


Fig. 9. Photograph of 130-Micron Kerosene Drops, Heated Air.

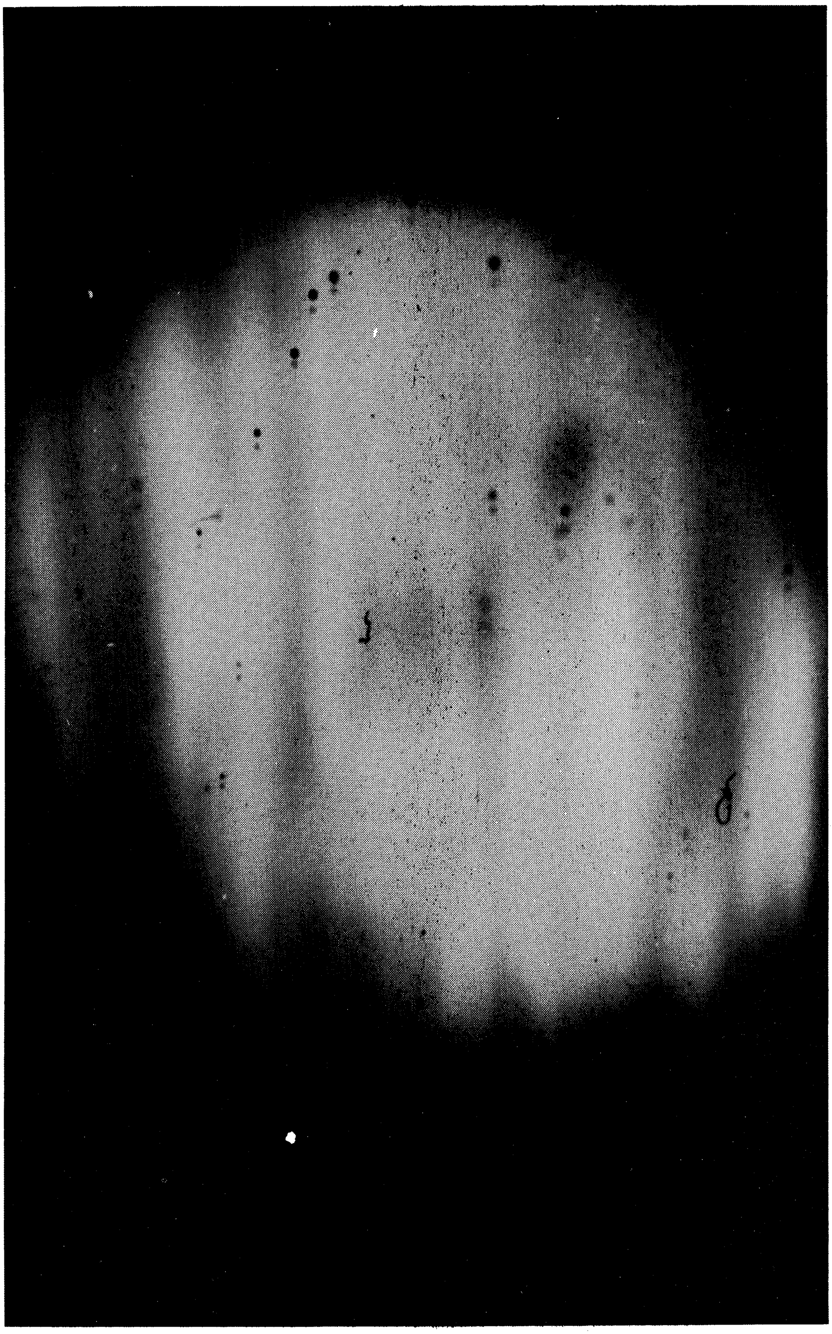


Fig. 10. Photograph of 130-Micron Kerosene Drops, Heated Air.

evident, as well as the progressive decrease in drop velocity and reduction of drop size. Figure 10 shows a reduction of drop velocity from 2 ft/sec., for the drops entering the camera field, to about 0.5 ft/sec for the 30-micron drop to the left of the position indicator (bottom center of picture).

The use of the tubular air heater effected a degree of stabilizing of the flame; thus the photographs were more consistently acceptable as far as focus and flame location were concerned. In addition, the supply of heated air permitted burning of larger-size drops (120-130 microns) than had been burned satisfactorily in open air. Moreover, the direction of the individual drops was more uniform, which was particularly noticeable in the zones occupied by the drops reduced to 30- or 40-micron diameters.

The use of the air heater should also permit the consideration of another important variable, flame temperature. Up to the present time the difficulties in measuring temperature, in regions as small as the flame zones dealt with here, have precluded systematic consideration of the effect of this variable.

The principal disadvantage arising from the use of the air heater was the restriction of the field of the camera and the corresponding reduction in the number of drops appearing in each photograph. As can be seen from the tabulation of data, the maximum number of drops appearing within the camera field not obscured by the heater was 25. A second obstacle incident to the use of the heater was the fact that part of the burning frequently appeared to take place above the body of the burner. To overcome these objections the data from several negatives are combined, as discussed below.

Intrepretation of Photographs

To systematize the counting of drops each negative is divided into zones, each zone being 1/4-inch in width, measured in a radial direction away from the disk. Inasmuch as the negative represents a magnification of 3, the actual radial distance represented in one of the zones is 0.083 inch. Since the negative is examined on a comparator, providing a magnification of the negative of 10, the corresponding zone dimension on the comparator screen is 2-1/2 inches. The task of the individual counting the drops is to determine the number of the various size drops in each of the zones. This information, together with the distance between the two comparator screen images of each drop, is recorded for the several zones through which the drop size is seen to decrease. To familiarize the reader with the procedure, a review of the analysis system follows.

Burning with Room-Temperature Air. Figure 8 is an enlargement of a representative negative obtained from photographing a portion of the burning ring sustained by 90-micron kerosene drops. Drop counts from the negatives are summarized in Appendix B, together with the results of several of the steps in the treatment of the data. The distance between the two comparator images of each drop is measured with a transparent scale. This distance, together with a knowledge of the time interval between light flashes, yields the velocity of the drop. This velocity and the corresponding drop size are ascribed to the position of the initial image. The velocity thus obtained and the radial dimension of the zone (0.083 inch) are combined to give a trans-zone time; the value of this quantity is listed for each of the drops observed. The individual times are summed and the means trans-zone time determined for all the drops found in each of the zones. By arbitrarily selecting as a reference one of the zones in which the spray is of original size, the elapsed time may be closely approximated by adding the mean values of trans-zone time for the subsequent zones. These cumulative times are listed for each of the zones. From a knowledge of the numbers of different size drops within each zone, the mean drop diameter is determined. For computation of burning time the value of the evaporation constant (λ), as used by the National Gas Turbine Establishment of England[8], is determined by plotting the square of the mean diameter against the cumulative time.

These plots display linearity down to a mean drop size of about 40 microns. Since our present photographic analysis does not perceive drops below 30 microns, it would be expected that the line would tend to flatten out as this diameter is approached. This effect may be observed in the data of several of the curves of Fig. 11, etc. For purposes of comparing burning time, the results of the experimental work are reported in terms of the time required to burn a drop with an original diameter of 100 microns. The extreme values of this burning time for kerosene drops are shown in Table I to be 0.01 and 0.027 second with the mean value of 0.019 second.

Inasmuch as the number of drops dealt with in each zone is small, some method of combining the data from two or more photographs is desirable. This problem has been common to each of the methods used for compiling data from the observation of burning drops. The procedure followed here was to determine the value of the evaporation constant, and the corresponding time for the combustion of a 100-micron drop from each photograph. Representative values are shown in Table I.

Burning with Heated Air. The procedure followed in collecting data from the photographs obtained with heated air is similar to that described above. The principal difference results from the smaller number of drops present, because the heater reduced the field of view of the camera. This necessitates combining data from several negatives. Appendix C contains a summary of the data obtained from 28 photographs of a flame fed with 130-micron kerosene drops supplied with heated air. To combine the data from the several negatives the last zone in which the spray was of original diameter (130 microns) was arbitrarily designated number one. For a negative showing only smaller-size spray (due to burning outside the field of the camera) the data were combined with those from a negative showing 130-micron spray as follows: The first zone in the former negative was numbered to

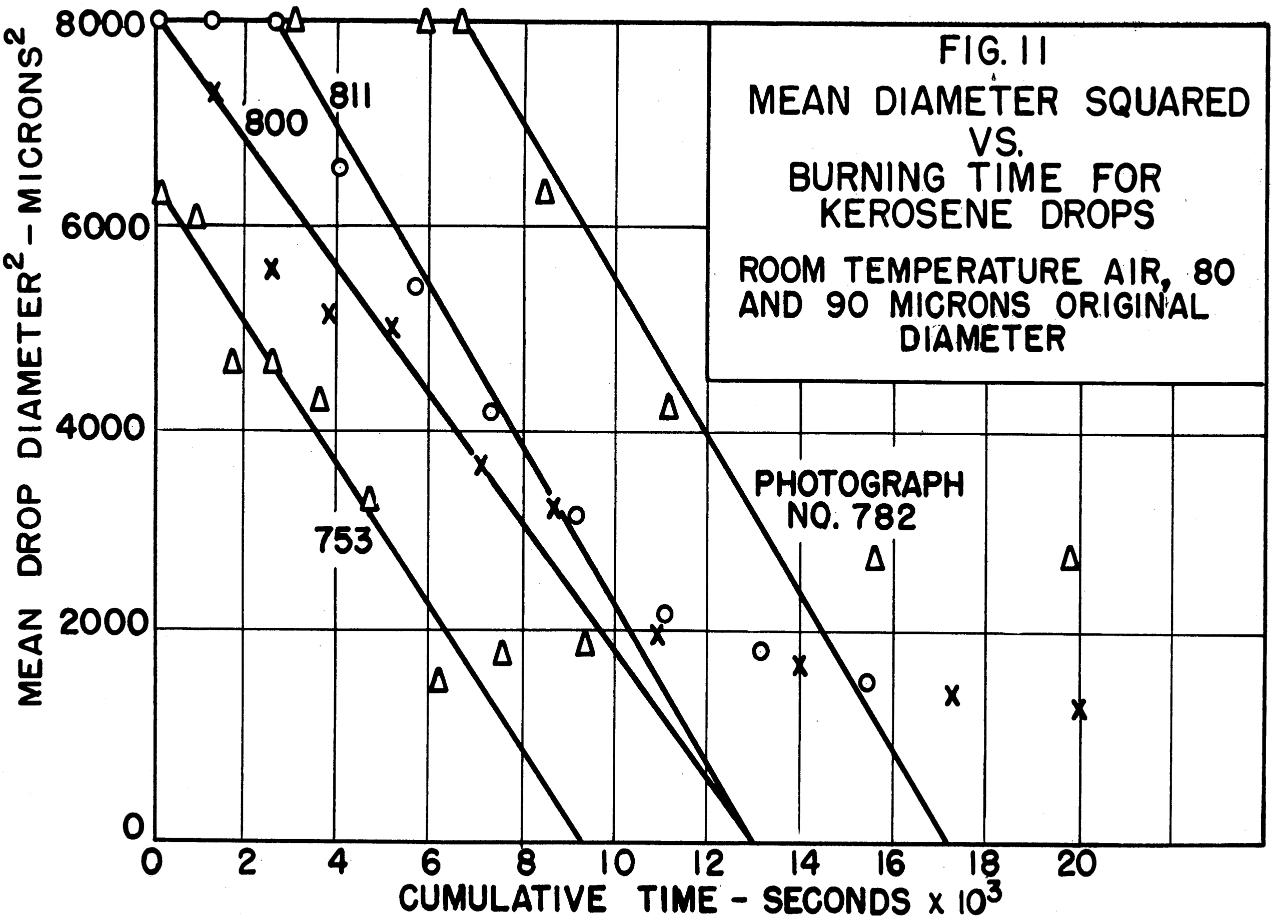


FIG. 11
MEAN DIAMETER SQUARED
VS.
BURNING TIME FOR
KEROSENE DROPS

ROOM TEMPERATURE AIR, 80 AND 90 MICRONS ORIGINAL DIAMETER

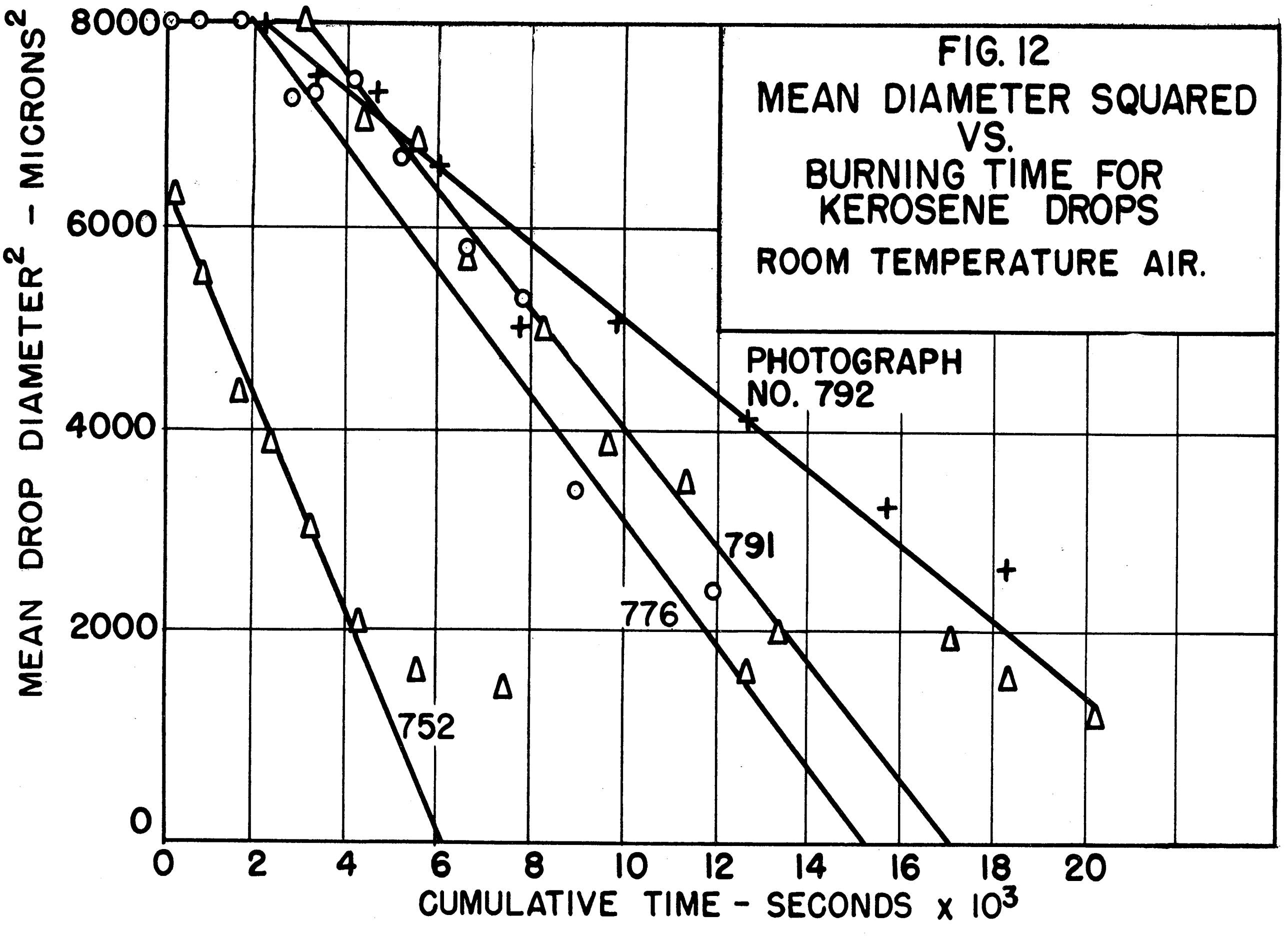


FIG. 12
MEAN DIAMETER SQUARED
VS.
BURNING TIME FOR
KEROSENE DROPS

ROOM TEMPERATURE AIR.

TABLE I

BURNING TIMES FOR DROPS OF 100-MICRON ORIGINAL DIAMETER

Fuel	Photo	Evap. Constant cm^2/sec	Drop Life for Orig. Diam. of 100 μ, Sec.
Kerosene (Heated Air)	(Average of 28)	0.0043	0.023
Kerosene (Room-Temp. Air)	(Average of 14)	0.0056	0.019
	No. 752	0.00981	0.0102
	753	0.00659	0.0152
	776	0.00568	0.0176
	782	0.00710	0.0141
	791	0.00572	0.0175
	792	0.00374	0.0267
	800	0.00568	0.0176
	811	0.00683	0.0146
n-Octane	926	0.00375	0.0267
	928	0.00513	0.0195
n-Decane	917	0.00289	0.0346
	918	0.00257	0.0389

correspond with the zone in the latter in which the mean drop size was approximately equal to the size first apparent in the former. In the event that this procedure resulted in misaligned mean velocities, the alignment was shifted by one zone in an effort to effect a compromise. For example, the data from picture No. 856 (see Appendix C) is aligned with zone 4 instead of zone 3 as would seem proper from a consideration only of drop diameters.

The information contained in Appendix C is represented graphically in Fig. 12. This curve also shows evidence of the linear relation between the square of drop diameter and time. Computation of λ from this plot yields a value of 0.0043, indicating a 100-micron drop life of 0.023 second.

Uniformity in Combustion Zones. Some concept of "uniformity" or "uniform size spray" has been implicit in a considerable amount of the work covered by this project. It is the purpose of this section to indicate just how uniform the drop size and velocity are in the region in which combustion takes place. Figure 14 shows diameter-frequency polygons for several groups of zones within which 90-micron (original diameter) kerosene spray is burning. The information recorded is taken from five photographs and aligned in a manner similar to that described above. In the plot the zones are arranged in groups of three and the frequencies of the various drop sizes are plotted for each group of zones. The reduction in mean drop size is seen to cover about 12 zones, or about 1 inch measured radially away from the disk. As the mean diameter decreases the standard mean deviation increases. It should be noted that the uniformity of the spray in the combustion zones with the group of five photographs superposed is not appreciably different from that of the spray represented in a single photograph. Figure 15 is a similar representation of burning spray, but with the spray size distribution plotted for each zone in a single photograph. Although the number of drops present in each zone is smaller, the degree of their size uniformity, as indicated by the standard deviation of drop diameter, is similar to that shown in Fig. 14. In each case the original uniformity is considerably degraded by the time the mean diameter has been reduced to half its original value. Figure 16 presents similar information relating to drop velocity within individual zones. In a zone early in the combustion region the drop velocities are seen to cover a small range of from 5.4 to 7.7 ft/sec. After the spray has proceeded about 0.4 inch farther into the flame the range of drop velocity extends from 3.3 to 6.9 ft/sec.

Results

Generation of Uniform Particle Size. The results of the work dealing with the spinning-disk sprayer are presented in Figs. 1, 2, and 3, together with the standards of uniformity discussed above. Figure 1 shows the speed - drop-size relationships for three sizes of spinning disks which conveniently deliver fuel spray within the size range of concern to this project.

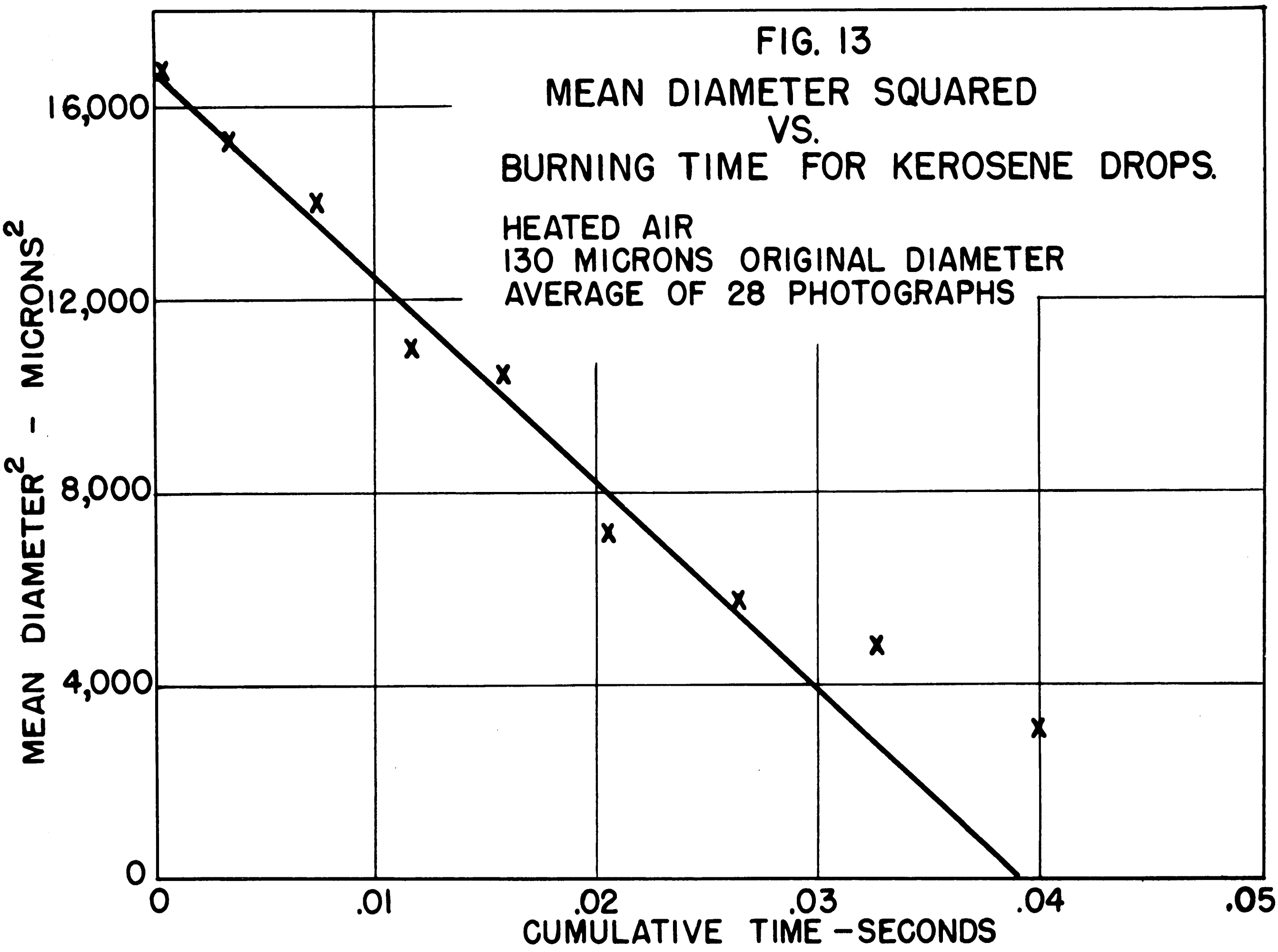


FIG. 13

MEAN DIAMETER SQUARED VS. BURNING TIME FOR KEROSENE DROPS.

HEATED AIR
130 MICRONS ORIGINAL DIAMETER
AVERAGE OF 28 PHOTOGRAPHS

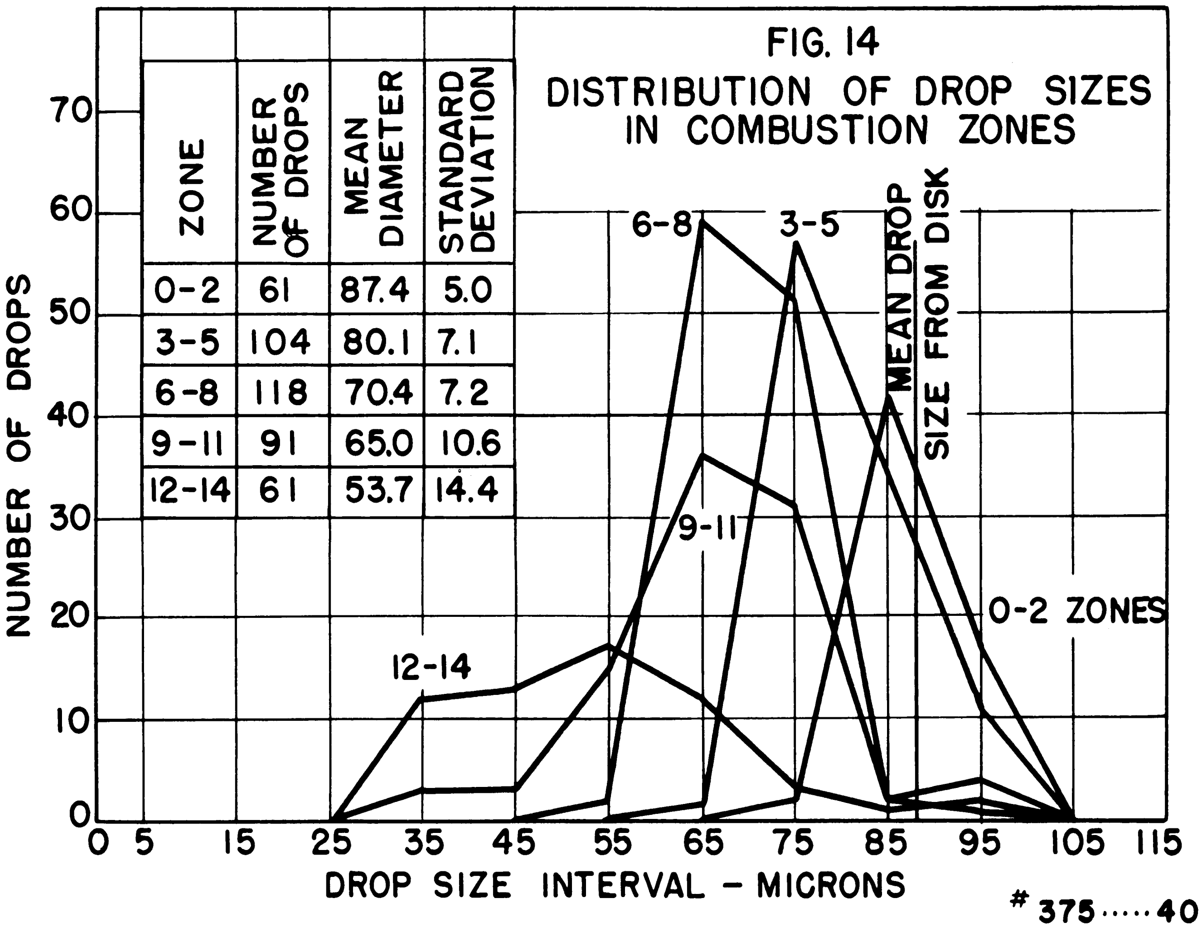


FIG. 14

DISTRIBUTION OF DROP SIZES IN COMBUSTION ZONES

ZONE	NUMBER OF DROPS	MEAN DIAMETER	STANDARD DEVIATION
0-2	61	87.4	5.0
3-5	104	80.1	7.1
6-8	118	70.4	7.2
9-11	91	65.0	10.6
12-14	61	53.7	14.4

375 405
2" DISK
8200-8500 RPM.

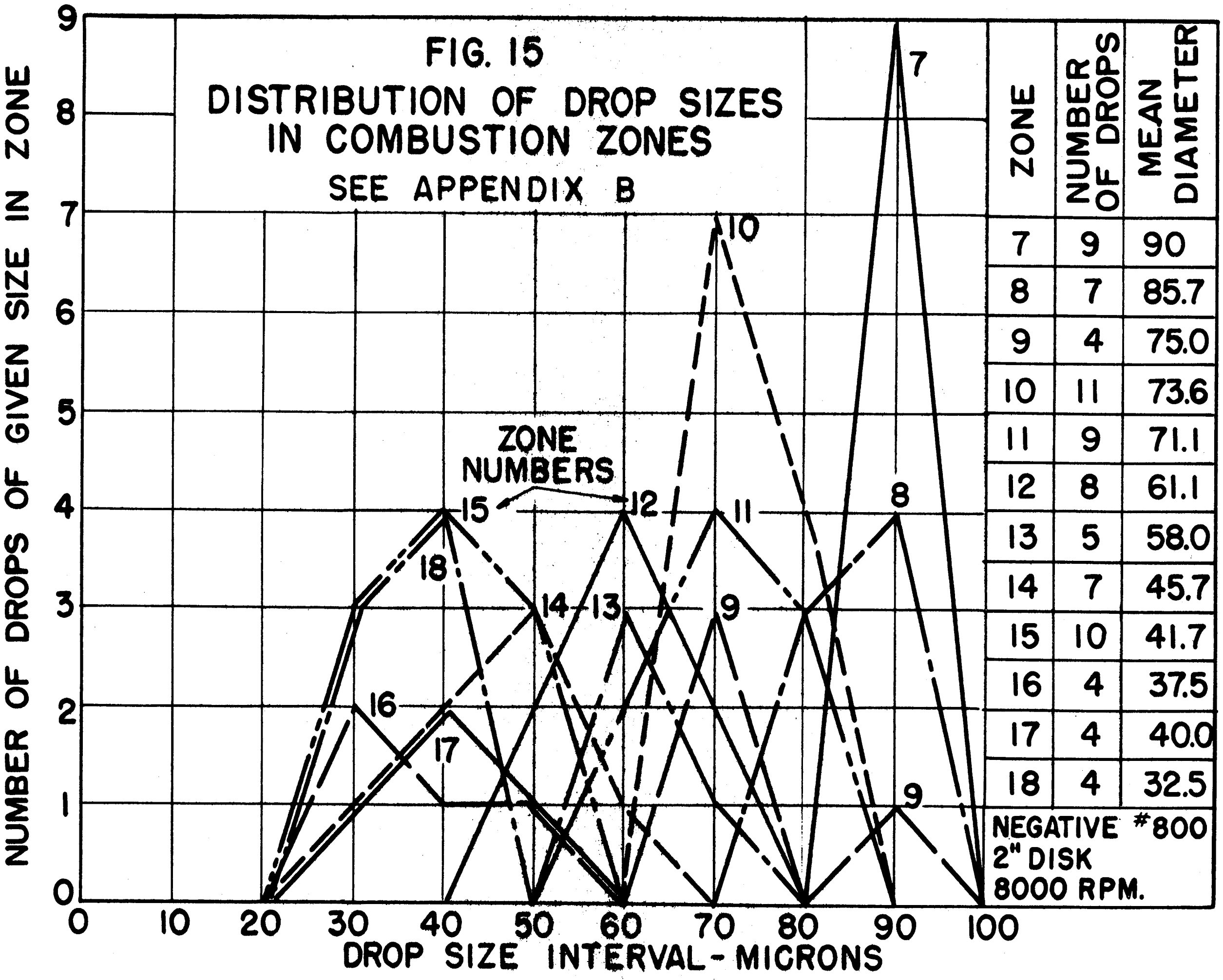


FIG. 15

DISTRIBUTION OF DROP SIZES IN COMBUSTION ZONES

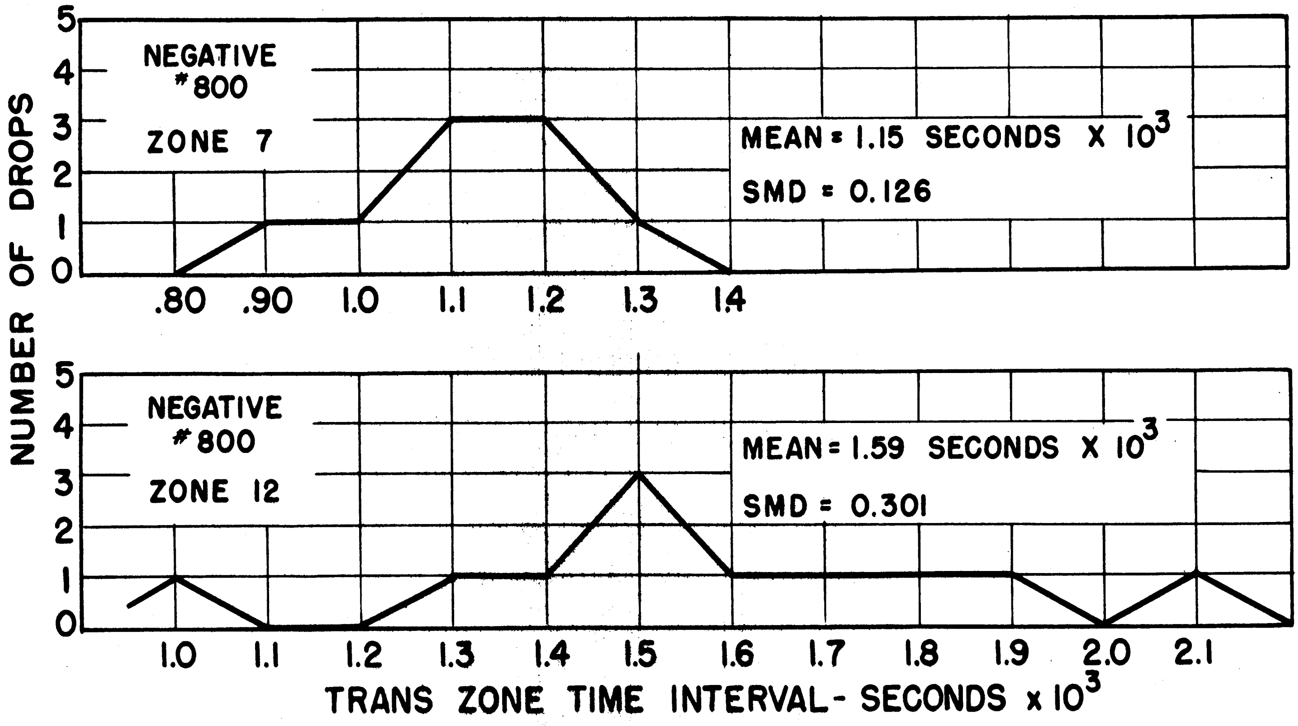
SEE APPENDIX B

ZONE	NUMBER OF DROPS	MEAN DIAMETER
7	9	90
8	7	85.7
9	4	75.0
10	11	73.6
11	9	71.1
12	8	61.1
13	5	58.0
14	7	45.7
15	10	41.7
16	4	37.5
17	4	40.0
18	4	32.5

NEGATIVE #800
2" DISK
8000 RPM.

FIG. 16

DISTRIBUTION OF DROP VELOCITIES IN FLAME ZONES



NEGATIVE #800
ZONE 7

MEAN = 1.15 SECONDS X 10^3

SMD = 0.126

NEGATIVE #800
ZONE 12

MEAN = 1.59 SECONDS X 10^3

SMD = 0.301

Figure 3 shows the flow limit for uniform spray delivered from a 2-inch disk. The limit shown is encountered when the outward flow of fuel spray is sufficient to induce radial air currents which carry the satellite drops along with the main body of the spray. The plot is presented to show the change of this limit with disk speed and fuel droplet size. It is apparent that the quantity of uniform spray of small size is rather limited. Moreover, as the droplet size becomes smaller, it becomes increasingly difficult to burn the principal size drops, without also burning the satellites; this condition results from the low penetration distance of the smaller-size spray. Figure 2 depicts the change of velocity of the spray as it moves radially outward from the disk.

Combustion of Uniform Spray. The results of the investigation of burning uniform-size spray are presented in Figs. 8 through 17. The figures, together with Table I, show three things.

1. Distribution of fuel droplet sizes within a flame supplied by uniform-size fuel spray (Figs. 13 and 14): the application of photographic analysis to the problem of spray combustion reveals that a large measure of uniformity is lost soon after the spray enters the flame. Fuel spray originally of uniform size is found to contain a wide range of drop sizes by the time the mean diameter has been reduced to one-half its original value. The standard mean deviation of drop diameter, representing the range of drop sizes found, changes from a negligible value to about 10 microns. This means that by the time a 100-micron spray has burned to a mean droplet diameter of 50 microns, the fuel droplet sizes extend over a range of about 60 microns.

2. Distribution of fuel droplet velocities within a flame supplied by uniform-size fuel spray (Fig. 16): the fuel droplet velocities exhibit increasing randomness as the drops pass into the flame zone. The standard mean deviation of drop velocity is approximately doubled in the time required to reduce the mean diameter of the drops to half the original value. This is true in a situation where no effort is made to create turbulence.

3. Plots of the square of mean drop diameter against time show a linear relationship, and this relationship may be used to determine the burning time for the fuel drops. Most of the plots (Figs. 11 and 12) show straight-line variation until the drop size decreases to about 40 microns. The smallest size discernable is about 30 microns and, as pointed out above, there are relatively few of the smaller-size drops apparent in the photographs. It would be expected, therefore, that the plots would show a tendency to level off at a value corresponding to the minimum discernable drop size. This leveling off is apparent in several of the plots.

Table I presents the values of burning time for fuel drops of 100-micron original diameter. These times are determined from observations made as the mean diameter of the burning spray decreases to about 50 microns, corresponding to a volume reduction of about 87 per cent. The values of burning

Fig. 17. Photograph of 70-Micron Toluene Drops.

time for a 100-micron drop are seen to vary over a range from 0.01 to 0.0267 second when burning in air at close to standard pressure and temperature. This variation may be attributed to experimental error, or to the fact that samples of spray within combustion zones are not sufficiently large to be representative of the mean behavior of the burning spray. In any event, the wide range of values indicates the degree of variation obtained when working with spray of 100 microns and smaller.

The range of burning time observed includes the mean value of drop life when burning in heated air. This later value, 0.023 second, is obtained from the observation of 130-micron spray. It appears that substantial heating of the combustion air has no pronounced effect on the combustion time of drops of the order of 100-micron original diameter. Trials with other fuels, notably alcohols and toluene, have been unrewarding. The alcohols have burned only at flow rates above which the uniformity of the spray is acceptable.

Toluene, as sprayed from the disk, has burned erratically, with no uniform droplet trajectory evident within the intermittent bursts of flame (Fig. 17). In the case of this fuel the present method seems capable of revealing spray within a flame in fine detail, but quantitative evaluation does not appear possible.

Conclusions

1. A successful photographic technique has been developed for observing the burning rates of fuel drops in free flight.

2. Observation of drops in the size range from 50 to 130 microns reveals a burning rate such that there is a linear relationship between the square of the diameter and time.

3. The burning life of the drop is proportional to the square of its initial diameter. The rate of change of volume, or mass rate of burning, is therefore proportional to the first power of the diameter.

4. These results are in general agreement with those of Godsave, who observed the burning of much larger individual drops suspended from a silica filament.

5. Heating of the combustion air did not produce a significant change in the burning rate of the drops.

6. The uniformity of the drop diameter of a spray diminishes rapidly as burning proceeds.

SECTION II

PRODUCING, BURNING, AND OBSERVING SINGLE DROPS

Introduction

The original objective of this phase of the investigation was to study the burning of a single drop of liquid fuel in free flight. A survey of the literature, made at the beginning of this project, led to the conclusion that a vertical-wind-tunnel design having the characteristics required to freely suspend a drop of liquid had been largely worked out by others[2] and could easily be adapted to the needs of this investigation. A wind tunnel of similar design was constructed[24] and tested, but all tests, even after design modification, were unsuccessful. It was impractical to stabilize a drop within the limits required to study a burning drop effectively.

To insure success of the investigation, subsequent efforts were directed toward the design of two different types of apparatus. The first was to be a vertical furnace in which drops would burn while falling through the heated furnace atmosphere. This design seemed to present no major technical difficulties and was constructed to insure the acquisition of some data on burning fuel drops. The second was to be a continuation of the vertical-wind-tunnel design in which the drops would burn while suspended by a rising column of air. Although the latter design presented many more difficulties, it was felt that a much better record would be obtained if a successful design of this type could be worked out.

Both pieces of apparatus have recently been completed and preliminary runs made, but as yet no runs have been made for the purpose of collecting data. Frames from one of the preliminary runs are shown in Fig. 18.

Description of Apparatus for Suspended Drop Technique

An overall view of the equipment used for suspending liquid droplets is shown in Fig. 19. The main components are the surge tank, vertical wind tunnel, ceramic tube for generating the ultrasonic field, projector, phototube detector unit, camera, and the associated electronic equipment.

The largest of these is the vertical wind tunnel, which creates a rising column of low-turbulence air in which the drop is suspended. A controlled amount of air enters the bottom of the tunnel from a large surge tank, passes up through the divergent section where the velocity is considerably reduced, and then flows through a calming section. In the calming section, the air is made to pass through six screens, each screen mesh becoming finer as

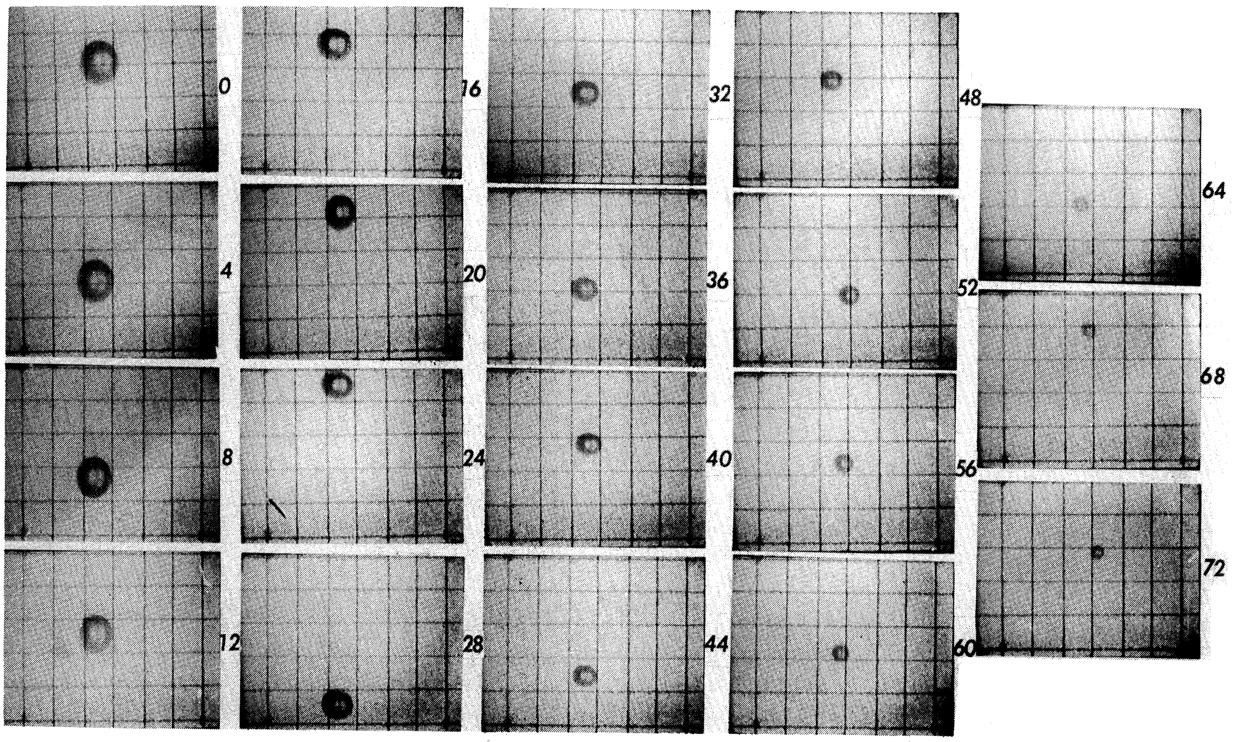


Fig. 18. Evaporating Drop at Four-Second Intervals (Alcohol-Water Mixture).

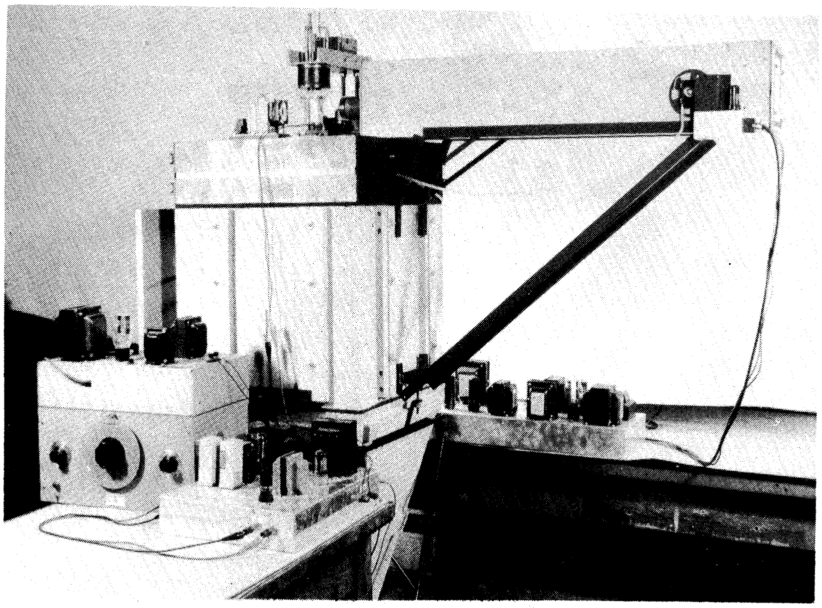


Fig. 19. Equipment for Observing Evaporation of a Single Suspended Liquid Drop.

the air nears the exit nozzle at the top of the wind tunnel. This action decreases the magnitude of the turbulence in the air stream. The air then leaves the tunnel through the large wooden exit nozzle and passes up through the ceramic tube in which the suspended drop is located. It is this air stream in the tube which provides the necessary drag on the drop to overcome the force of gravity.

A drop in an air stream of this type, however, experiences lateral forces which tend to drive it to the walls of the enclosure. These forces arise from the slight turbulences that have not been completely eliminated from the air stream and from the shape of the pressure profile across the air stream. It was found that these forces could be overcome by introducing a high-frequency standing ultrasonic field into the stream surrounding the drop. A typical ultrasonic field pattern, made visible with the aid of lycopodium powder, is illustrated in Fig. 20.

The sound field is generated by a piezoelectric tube made of barium titanate. The tube, mounted directly over the wind-tunnel nozzle outlet, is shown in Fig. 21. The photograph shows the windows which had to be cut from the tube wall for drop observations. The high-frequency excitation for the tube is supplied by an audio-oscillator. The output from the oscillator is amplified before being fed to the tube. A schematic diagram of the amplifier circuit is shown in Appendix E.

The combined action of the air stream and the ultrasonic field provides the necessary forces to suspend a drop of fuel in space freely. This action would be sufficient were it not for the transient effect of decreasing drop mass with evaporation or burning. This effect is such that the decrease in gravitational force is greater than the decrease in drag force, with the result that the drop is blown out of the tube as evaporation progresses. To overcome this difficulty, a photoelectrically controlled damper is incorporated into the system to decrease the air flow as the drop tends to rise. This action is performed in the manner described below.

The projector, shown in Fig. 19, is used to obtain an enlarged image of the suspended drop. In the projector, the drop image is split by a half-silvered mirror so that one image passes through the mirror and appears on the circular screen at the back end of the projector, while the second image is reflected at 90° and appears on the cathode of a photoelectric tube. The first image is photographed to obtain a record of the evaporating or burning drop; the second image is used to control the damper. Figure 22 is a view of the back end of the projector with cover removed, showing the half-silvered mirror, circular screen, and phototube detector unit mounted on the side of the projector. The detector units consists of a light "chopper", variable slit, and phototube amplifier chassis which carries the phototube and first stage of amplification. The purpose of the light chopper is to obtain an a-c error signal while the slit fixes the maximum amount of light passing to the phototube.

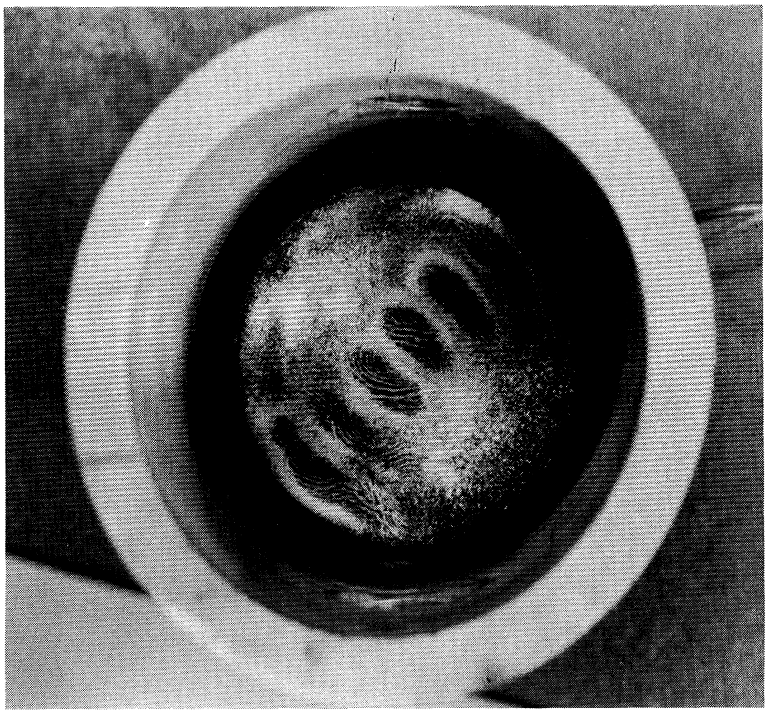


Fig. 20. Representative Ultrasonic Field Pattern in Lycopodium Powder.

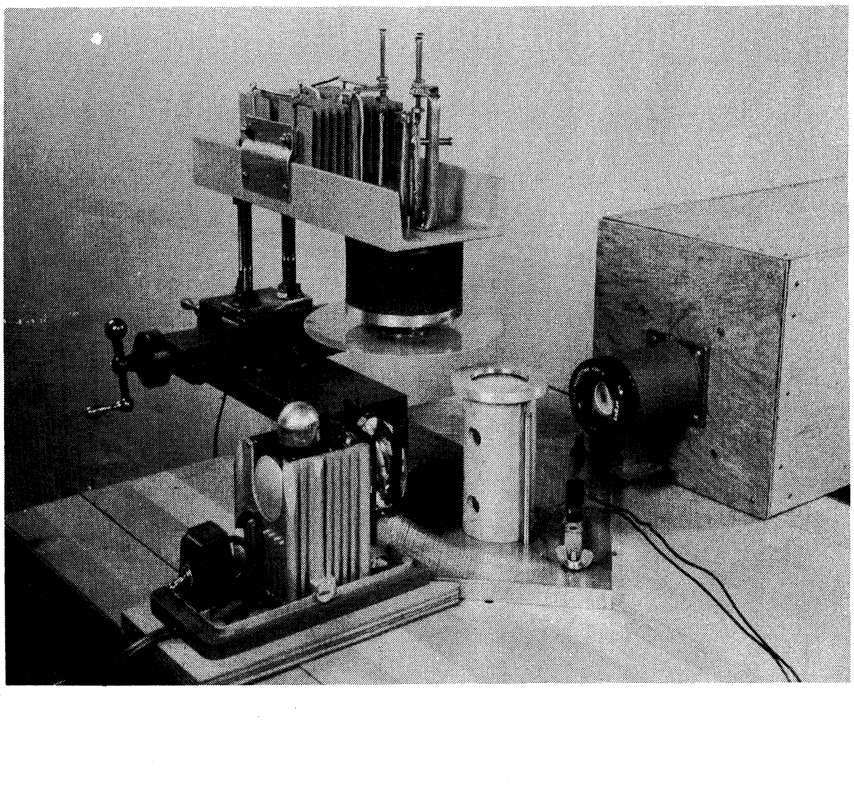


Fig. 21. Close View of Equipment Positioning and Observing a Freely Suspended Drop.

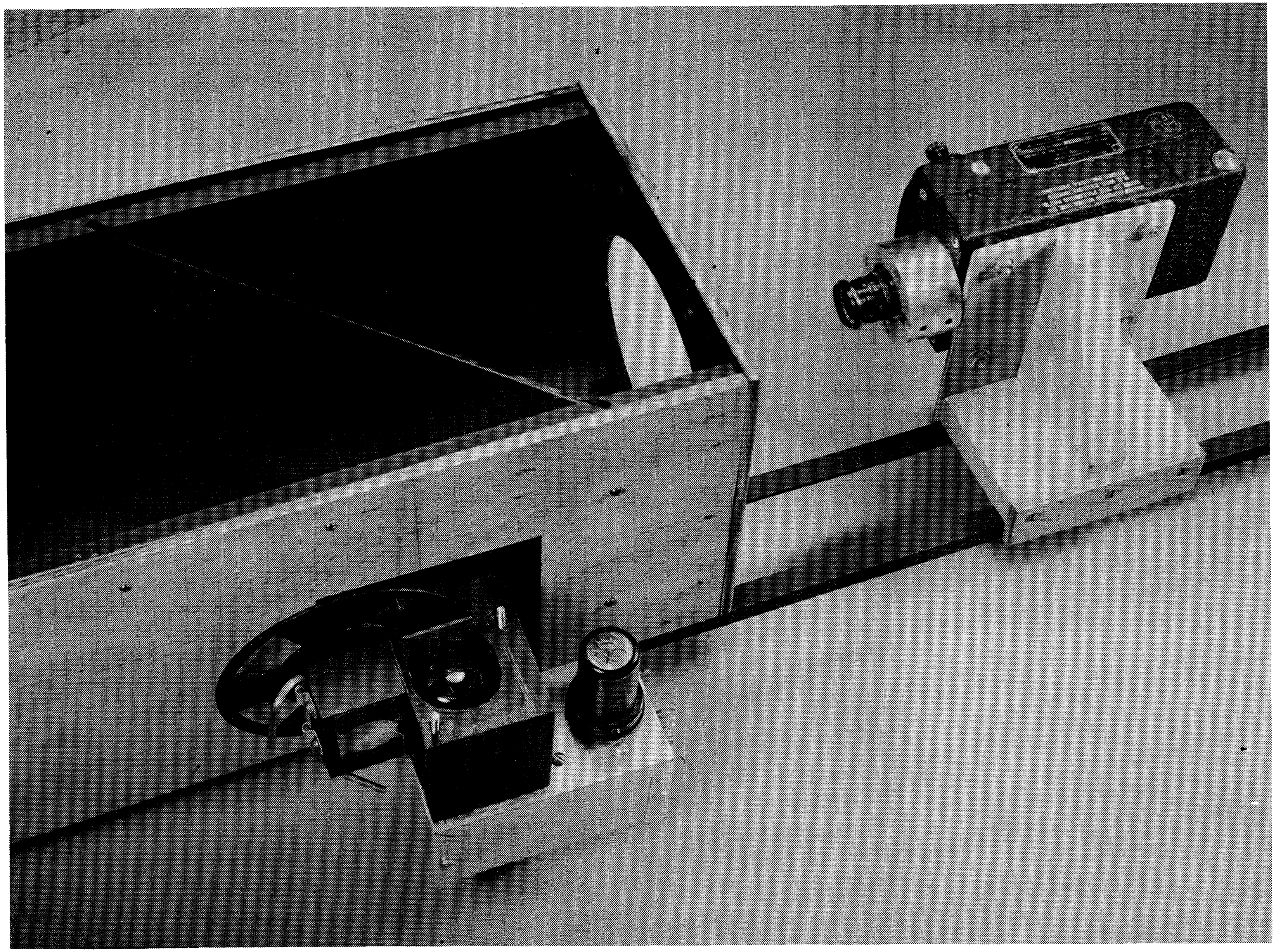


Fig. 22. Close View Showing Camera Mount and Photoelectric Position-Detector Unit.

During a run, with the drop held in a given position by the combined drag and ultrasonic field forces, the position of the drop is such that its image covers most of the slit, thereby blocking the light that would normally illuminate the phototube. This holds the damper, (see Fig. 21) in a raised position. As the drop evaporates and tends to rise, its image begins to uncover the slit. The increased amount of light on the phototube causes the damper to lower over the outlet of the ceramic tube and to decrease the amount of air emerging from the tube. This results in a decreased air velocity and causes the drop to return to a null position.

The circuit at present is not completely satisfactory, as it tends to oscillate. This is due to the inherent lags in the control system, and corrective circuits will have to be worked out to obtain stability. For the time being this will impose no great difficulty, since a satisfactory manual control can be obtained for the slower rates encountered in evaporation studies. It is believed that a workable automatic control system will be developed by the time the study progresses to the drop-burning phase.

A schematic diagram of the servo amplifier and detector circuit being used at present is also shown in Appendix E. Several modifications are being considered for both the amplifier and the detector, but no decisions have been reached at this time.

Records of the evaporating drops are being made with a 16-mm U. S. Army Air Force Type N-6 gun camera having speeds of 16, 32, and 64 frames per second. The camera comes fitted with an f/3.5 35-mm fixed-focus lens, so that a focusing mount had to be built before it could be used. Four 6-volt storage batteries are used to supply the power for operating the camera.

Description of Apparatus for Falling-Drop Technique

The vertical furnace, which was constructed to study the burning of a single droplet as it falls through a hot atmosphere, is shown in Fig. 23. The design was based, to some extent, on the furnace described by Chang[7] in his report on heavy fuel oil combustion. It consists primarily of the furnace body and entrant tube.

The furnace body measures 4-1/2 x 7-1/2 x 48 inches and is constructed of slabs of 1/4-inch thick asbestos sheet. These are held together by sections of angle iron at the four corners. Two sets of four windows are cut in the walls to permit observations of the drops. Heating is accomplished by means of eight Nichrome wire heating coils stretched lengthwise along the inside of the furnace walls. The total power output of these coils is about 7,000 watts, giving air temperatures of approximately 1400°F when measured with an unshielded thermocouple. A small opening at the bottom drains the unburned fuel from the furnace.

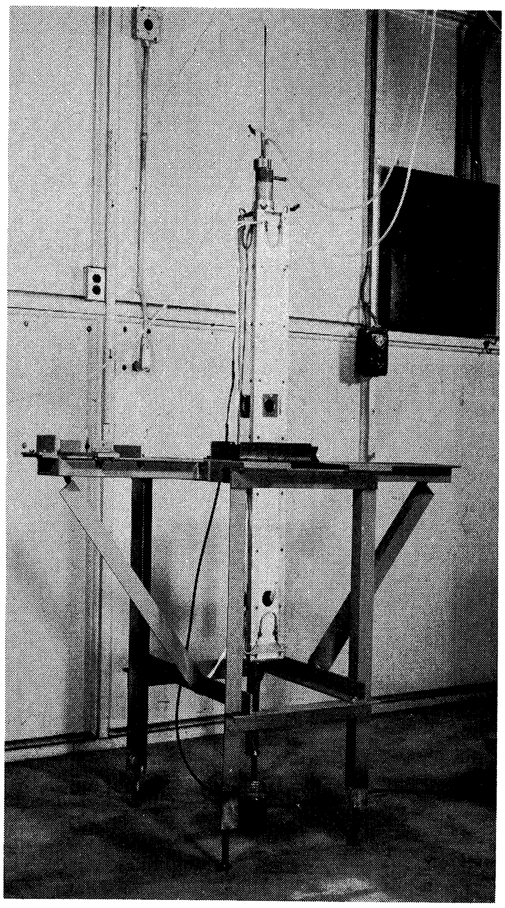


Fig. 23. Vertical Furnace for Burning and Observing Falling Drops of Fuel.

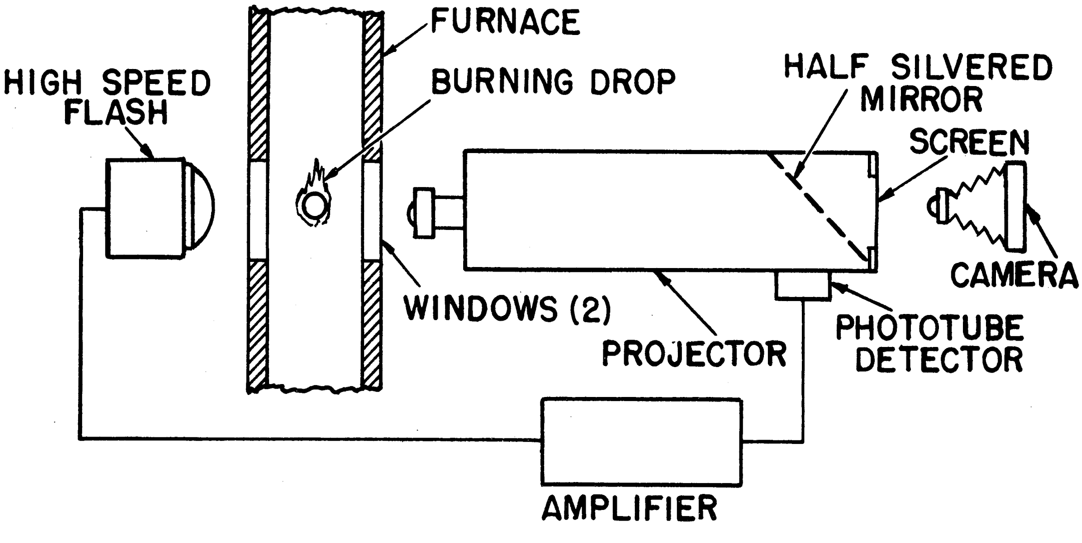


FIG. 24 SCHEMATIC DIAGRAM OF APPARATUS FOR PHOTOGRAPHING FALLING DROPS.

The entrant tube extends down into the top of the furnace and consists of a water-jacketed housing for the microdropper. This is necessary to protect the microdropper from becoming overheated when exposed to the hot furnace atmosphere. In operation, the microdropper is located up within the entrant tube so that drops coming from the dropper are not exposed to the hot furnace atmosphere until they leave the bottom of the entrant tube. The distance to which the entrant tube is inserted into the furance determines the distance between the window and bottom of the entrant tube. This is the distance the drop falls through the heated atmosphere before it is photographed.

Drops are formed by the microdropper, which consists of a small hypodermic needle fitted to the end of a tubular fuel reservoir. This is surrounded by a cylinder, closed off at one end and shaped into a nozzle at the needle end[24]. An opening in the side is provided to admit air into the tube, which then flows out through the nozzle. A drop forming at the tip of the needle is located at the nozzle opening and is swept off the needle by the air passing through the nozzle. The size of the resultant drops, for a given liquid, will be a function of the air velocity and the outside diameter of the small fuel tube.

Figure 24 is a schematic diagram of the overall system, including the equipment necessary for photographing the drop. This equipment includes a projector, phototube detector and amplifier, G. E. high-speed flashlamp, and camera, all of which are used with the other equipment described in this report, and are shown in Fig. 19. In operation, the projector is trained on the path of the falling drop so that the image of the falling drop passes across the phototube, thereby triggering the high-speed flashlamp. The image that appears on the circular screen at the end of the projector is then photographed to obtain the record of the drop.

Results of the Suspended-Drop Technique

The apparatus for suspending drops of both liquid and solid particles was completed only recently, so that the results obtained since the apparatus has been in operation have been of a preliminary nature only. The very first experiments were carried out with various sizes of cork spheres. These could be held in position for any given length of time. One such sphere, having a diameter of 0.1 inch, is shown suspended in the ceramic tube in Fig. 25. Later tests were made with various liquids including water, alcohol, alcohol-water mixtures, kerosene, and gasoline. Drops of about 600 microns were formed and observed as they evaporated to about 200 microns. At this size it became difficult to keep the drops in position, for reasons as yet unknown.

Figure 18 shows the results of the first recorded run made with the apparatus. A mixture containing one part alcohol and two parts water was used to get a convenient rate of evaporation for illustration purposes

Fig. 25. Cork Ball Shown Suspended in Ultrasonic Tube. (Ball diameter - 0.1 in.)

only. The run was made at 16 frames per second at f/3.5. Distance between grid lines on the negative represents 500 microns. Total time for the run was approximately 70 seconds, this being the time required to change the drop diameter from 670 microns to 230 microns. The result is plotted in Fig. 26, showing drop diameter vs. elapsed time.

Results of the Falling-Drop Technique

Drops of burning fuel have been observed as they fall through the vertical furnace. No photographs of these drops, however, have been made to date. In the tests that have been carried out, those drops which were allowed to fall from the microdropper could be ignited by a small hot coil of wire. To accomplish ignition, the drops were made to barely touch the hot coil. These drops, of the order of 1500 microns in diameter, continued to burn throughout the length of the furnace.

As the drops are made smaller there is an increasing tendency for the drops to deviate from a vertical path. This can be controlled satisfactorily with well made dropper and air-jet parts if the two are held closely concentric.

If the furnace atmosphere is very hot, no ignition device is necessary.

Conclusions

It is hoped that the apparatus described for suspending both liquid drops and small solid particles will prove to be a new useful tool for research on the combustion of all types of fuel, both liquid and solid, and will also find applications in other fields of investigation as well. The effect of the ultrasonic field on the combustion process is not known at the present time. Since the ultrasonic field represents a form of energy, it is to be expected that it will affect the burning in some manner. Whether or not this field affects the rate of combustion, it is believed that a study of the evaporation and burning of fuel drops or solid particles utilizing this technique will prove profitable.

Acknowledgement

Mr. John Wighton, a graduate student who worked on this project, first suggested the use of an ultrasonic field (discussed on p. 30) and was the principal contributor to this technique.

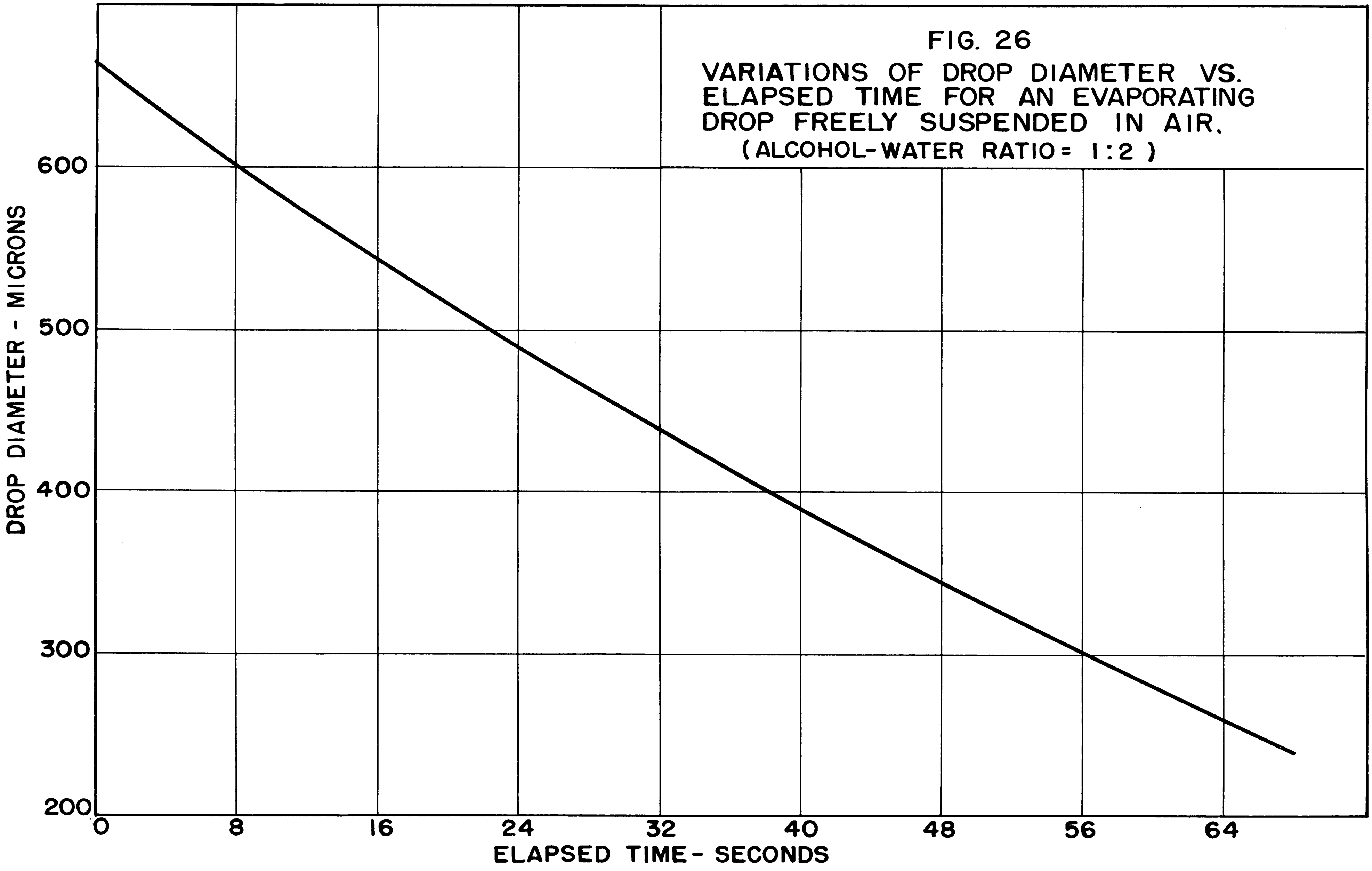


FIG. 26
VARIATIONS OF DROP DIAMETER VS. ELAPSED TIME FOR AN EVAPORATING DROP FREELY SUSPENDED IN AIR.
(ALCOHOL-WATER RATIO = 1:2)

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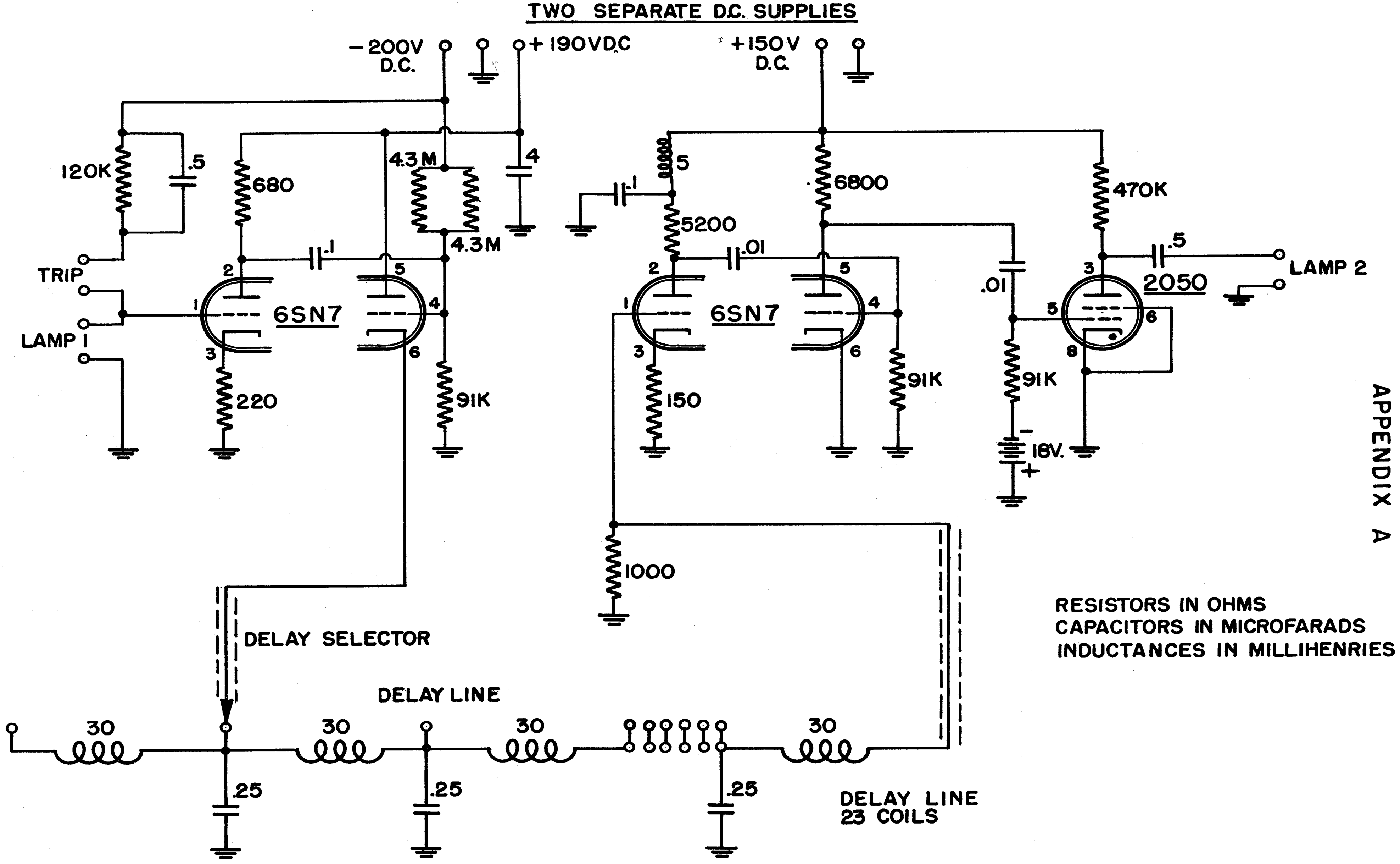
APPENDIX A

CALIBRATION OF DELAY CIRCUIT FOR TIMING OF GE PHOTOLIGHTS

Frame	Rpm	Tap. Sw. Position	Angle, Degrees	Delay, Sec x 10^4	Av Delay, Sec x 10^4
1	11,850	1	98	13.8	
2	11,850	1	98	13.8	13.8
3	11,850	1	96	13.5	
4	11,850	1	99.5	14.0	
5	13,775	2	44.5	5.39	
6	13,775	2	44.5	5.39	5.43
7	13,775	2	45.3	5.48	
8	13,775	2	45.3	5.48	
9	17,690	3	37	3.49	
10	17,690	3	38	3.58	3.55
11	17,790	3	37.5	3.52	
12	17,632	3	38	3.59	
13	20,086	4	18.7	1.55	
14	19,940	4	18.7	1.56	
15	20,384	4	20.5	1.68	1.55
16	20,684	4	19.5	1.57	
17	20,624	4	18.0	1.45	
18	20,384	4	18.3	1.50	

APPENDIX A



TIME DELAY CIRCUIT FOR PHASING TWO G.E. PHOTOLIGHTS

APPENDIX B

DROP DIAMETER AND VELOCITY FOR BURNING DROPS IN VARIOUS ZONES

Original Size of Drops: 80 Microns Combustion with Room-Temperature Air
Drop Data Summary for Negative No. 752

Zone	Drop Diameter, Microns	Mean Velocity ft/sec	Mean Trans-zone Time, sec x 10^3	Cumulative Burning Time Sec x 10^3	Mean Diam.
7	80^7	8.80	.727	0	80
8	80^3 70^4	7.70	.831	.727	75
9	70^3 60	9.35	.685	1.56	67
10	70^2 60^6	7.64	.838	2.24	62.5
11	60^5 50^4	6.34	1.01	3.08	55.6
12	50^7 40^4	5.11	1.25	4.09	46.4
13	50^5 40^7 30^3	1.65	3.89	5.34	41.3
14	50 75^2 40^7 35^3 30	1.94	3.30	9.23	39
15	50 40^{11}	1.14	5.62	12.53	41
16	40^{15}	.967	6.61	18.15	40
17					
18					
19					

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*Superscript numerals indicate number of drops.

DROP DIAMETER AND VELOCITY FOR BURNING DROPS IN VARIOUS ZONES

Original Size of Drops: 80 Microns Combustion with Room-Temperature Air
Drop Data Summary for Negative No. 753

Zone	Drop Diameter, Microns	Mean Velocity ft/sec	Mean Trans-zone Time, sec x 10^3	Cumulative Burning Time Sec x 10^3	Mean Diam.
7	80^7	7.94	.806	0	80
8	80^6 70	7.60	.835	.806	78.6
9	80 70^6 60^2	7.45	.858	1.64	69
10	80^3 70 65^2 60^3	6.60	.971	2.50	69
11	80^3 60^2 50^2	5.71	1.12	3.47	65.7
12	80 70^2 55^2 50^2 35	4.35	1.47	4.59	58.1
13	50 40 30	3.83	1.67	6.06	40
14	70 60 35^3	4.07	1.57	7.73	43.5
15	70^3 60 50 40^3	3.83	1.67	9.30	44.5
16	60 40	5.04	1.27	10.97	41.3
17					
18					
19					

DROP DIAMETER AND VELOCITY FOR BURNING DROPS IN VARIOUS ZONES

Original Size of Drops: 90 Microns   Combustion with Room-Temperature Air
Drop Data Summary for Negative No. 791

Zone	Drop Diameter, Microns	Mean Velocity ft/sec	Mean Trans-zone Time, sec x 10^3	Cumulative Burning Time Sec x 10^3	Mean Diam.
7	90^5	7.12	.90	0	90
8	90^4	6.28	1.02	.90	90
9	90^3	6.04	1.06	1.92	90
10	90^7	5.37	1.19	2.98	90
11	90^4 80^4	5.46	1.17	4.17	85
12	90^2 80^4	5.29	1.21	5.34	83
13	80^3 70^2	4.19	1.53	6.55	76
14	80^2 70^5 60	4.44	1.44	8.08	71
15	70^3 60^2 50	3.81	1.68	9.52	63
16	70^2 60^5 50^2	3.22	1.99	11.20	60
17	50 40^4 60	1.74	3.69	13.19	46
18	60 50 40^4	1.59	4.03	16.88	45
19	40 35^4	.96	6.68	20.91	36

DROP DIAMETER AND VELOCITY FOR BURNING DROPS IN VARIOUS ZONES

Original Size of Drops: 90 Microns Combustion with Room-Temperature Air
Drop Data Summary for Negative No. 792

Zone	Drop Diameter, Microns	Mean Velocity ft/sec	Mean Trans-zone Time, sec x 10^3	Cumulative Burning Time, Sec x 10^3	Mean Diam.
7	90^3	6.40	1.00	0	90
8	90^6	6.21	1.03	1.00	90
9	90^{10}	5.24	1.22	2.03	90
10	90^9 80^4	4.89	1.31	3.25	87
11	90^3 80^2	4.56	1.40	4.56	86
12	90^2 80^8	3.41	1.88	5.96	82
13	80 70^4	3.48	1.84	7.84	72
14	80^2 70^2 60	2.22	2.88	9.68	72
15	70^7 60^4 50 40	2.90	2.21	12.56	65
16	70^3 60^3 50^3 40	1.93	3.32	14.77	58
17	60^4 50^4 30	1.97	3.26	18.09	52
18					
19					

DROP DIAMETER AND VELOCITY FOR BURNING DROPS IN VARIOUS ZONES

Original Size of Drops: 90 Microns Combustion with Room-Temperature Air
Drop Data Summary for Negative No. 776

Zone	Drop Diameter, Microns	Mean Velocity ft/sec	Mean Trans-zone Time, sec x 10^3	Cumulative Burning Time, Sec x 10^3	Mean Diam.
7	90^4	8.97	.712	0	90
8	90^3	7.86	.814	.712	90
9	90^5	7.73	.828	1.526	85.6
10	90^5 80^4	7.15	.895	2.354	86.0
11	90^3 80^2	7.42	.863	3.239	86.7
12	90^4 80^2	6.79	.944	4.112	82.5
13	90 80^3	4.56	1.40	5.056	76.7
14	90 80^4 70^4	5.34	1.20	6.456	73.3
15	90 80^2 70^5 60	5.12	1.25	7.656	59
16	65 60^4 50	4.60	1.39	8.906	
17		4.26	1.5	10.291	50
18	50^3	3.93	1.63	11.79	
19					

DROP DIAMETER AND VELOCITY FOR BURNING DROPS IN VARIOUS ZONES

Original Size of Drops: 90 Microns   Combustion with Room-Temperature Air
Drop Data Summary for Negative No. 782

Zone	Drop Diameter, Microns	Mean Velocity ft/sec	Mean Trans-zone Time, sec x 10^3	Cumulative Burning Time, Sec x 10^3	Mean Diam.
7	90^5	4.38	1.46	0	90
8				1.46	90
9	90^4	3.42	1.87	2.92	90
10	90^{11}	3.50	1.83	4.79	90
11	90^9	3.59	1.78	6.62	90
12	80^4	2.32	2.75	8.40	80
13	70^5 60^3	1.80	3.55	11.15	66.2
14	60^3 50^8 40	1.59	4.02	15.70	53
15	60 50^2	2.01	3.18	19.72	53.3
16	50^2 40 30	1.50	4.27	23.90	42
17	60 50	1.19	5.38	28.17	55
18					
19					

DROP DIAMETER AND VELOCITY FOR BURNING DROPS IN VARIOUS ZONES

Original Size of Drops: 90 Microns Combustion with Room-Temperature Air
Drop Data Summary for Negative No. 800

Zone	Drop Diam. Microns	Mean Veloc. ft/sec	Mean Trans-zone Time sec x 10^3	Stand. Mean Dev.	Cumul Burning Time, Sec x 10^3	Mean Diam.	Stand. Mean Dev.
7	90^9	5.25	1.18	0.126	0	90	
8	90^4 80^3	5.34	1.30	.195	1.18	85.7	4.95
9	90 70^3	5.21	1.33	.086	.248	75	8.67
10	80^4 70^7	4.72	1.47	.257	3.81	73.6	4.82
11	80^3 70^4 60^2	4.08	1.70	.263	5.28	71	7.37
12	70^3 60^4 50^2	3.92	1.57	.301	6.98	60	7.37
13	70 60^3 40	3.03	2.29	.670	8.55	58	9.80
14	60 50^3 40^2 30	2.27	3.06	1.07	10.84	45.7	9.03
15	50^5 40^4 30^3	1.67	3.45	1.23	13.90	40	8.0
16	50 40 30^2	2.32	2.99	.782	17.35	37.5	8.3
17	50 30 30	.733	9.46	2.76	20.34	40	7.17
18	40	1.39		2.33	29.80	35.7	
19							

DROP DIAMETER AND VELOCITY FOR BURNING DROPS IN VARIOUS ZONES

Original Size of Drops: 90 Microns Combustion with Room-Temperature Air
Drop Data Summary for Negative No. 811

Zone	Drop Diameter, Microns	Mean Velocity ft/sec	Mean Trans-zone Time, sec x 10^3	Cumulative Burning Time, Sec x 10^3	Mean Diam.
7	90^4	5.12	1.25	0	90
8	90^8	5.62	1.14	1.25	90
9	90^7	4.02	1.59	2.39	90
10	90 80^5	3.92	1.63	3.98	81.6
11	80^2 70^3	3.88	1.65	5.61	74
12	70^4 60^4	3.56	1.80	7.26	65
13	60^6 50^3	3.28	1.95	9.06	56.7
14	60 50^4 40^3	2.98	2.15	11.01	47.5
15	50^2 30	2.87	2.23	13.16	43
16	50 40^2 30	1.15	5.55	15.39	40
17	40	1.18	5.42	20.94	40
18					
19					

APPENDIX C

MEAN DROP VELOCITY (FT/SEC) FOR BURNING DROPS IN VARIOUS ZONES

Original Size of Drops: 130 Microns   Combustion with Heated Air

Neg. No.	Zone 1	2	3	4	5	6	7	8	9	10	11	12
840	2.2	2.1	1.9	1.9	1.25	.8	.8	1.25				
822	2.05	1.6	1.7	1.4		1.25						
821	2.8	1.9			1.7							
836	2.2	1.8	1.65		1.75	1.25	1.35	1.6				
841	1.9	1.8	1.6	1.5	1.7	1.2	1.4	1.25				
853	2.2	1.9	1.65		1.3	1						
862	1.9	1.6	1.5	1.25								
820	2.8		2.7			1.9						
848	2.3	2.2		1.65			1.3	1	.9			
838	2.1	1.9	1.75	1.6	1.7							
858		1.8	1.8	1.6	1.35							
857		1.25	.95	.9								
834	2.05	1.8	1.7	1.2	1.6	1.35	1.1					
859		2.05		2	1.8	1.5	1.5	1	.65			
863			1.6	1.65	1.25	1.1						
843			1.9			1.4	1.1	.9	.8			
850			1.9	1.7	1.45	.95	.8	.5				
824			2.2	2.1	1.7	2						
835				1.3	1.4	1.05	1.25	1.1	.6			
856				1.45	1.2	.85	1.0	.95	.3			
825				2.1	2	1.5	1.15	1.1	.72			
865					1.9	1.43	.95	1.22	1.25	.67		
855				1.75	1.25	1.1	.9	1.25	1.25			
823					1.5	1.2	.85	.72				
860				1.55	1.72	1.32				.62		
861				2.2		1.9	1.25	1.7	1.9			
852								.95	.65	.5		
851								.95	.3	.65		
Mean Velocity	2.23	1.82	1.76	1.62	1.57	1.31	1.11	1.09	.85	.61	Ft/Sec	
Mean Trans-Zone Time	2.88	3.52	3.63	3.95	4.07	4.89	5.76	5.87	7.54	10.5	Seconds x 10^3	

MEAN DROP DIAMETER (MICRONS) FOR BURNING DROPS IN VARIOUS ZONES

Original Size of Drops: 130 Microns   Combustion with Heated Air

Superscript Indicates Number of Drops in Zone

Neg. No.	1	2	3	4	5	6	7	8	9	10	11	12
840	130^2	120^2	112.5^4	110^1	90^1	65^1	60^1	72.5^2				
822	130^1	121.6^3	116.6^3	93.3^3		75^3						
821	131^5	120^1			110^1							
836	130^2	122.5^2	120^5		112.5^4	100^1	104^5	100^1				
841	130^1	123.5^3	109^4	103.3^3	107.5^4	82.5^2	88.8^4	80^2				
853	130^5	129^4	117.5^2		90^1	66.6^3						
862	130^1	121.6^3	112.5^2	110^1								
820	130^2		125^2		105^2							
848	128^5	125^2		107.5^2			71.6^3	80^2	50^1			
838	125^3	123.7^4	118^5	107.5^2	100^3							
858		125^2	115^4	110^1	92.5^2							
857		125^1	125^1	68.7^4								
834	125^2	128.3^3	127.5^3	110^3	115^4	97.5^2	85^2					
859		125^2		99^5	97.5^2	76.5^4	73.3^3	55^3	55^3	40^1		
863			120^1	105^3	90^2	87.5^2	80^2					
843			120^5			90^4	72^5	60^2	50^1			
850			123.7^4	107.5^2	100^3	67.5^2	55^2	45^2				
824			115^5	117.5^2	107.5^2	100^1						
835				115^2	110^1	93.3^3	100^3	75^1	50^1			
856				118.3^3	109^5	82.5^6	85.7^6	77.7^4	45^1			
825				117^3	100^2	93.3^3	77.5^4	71^5	55^4			
865					110^1	80^2	66.6^3	70^8	70^3	45^3		
855				100^1	93.3^3	83.7^4	63^5	67.5^2	75^1			
823					100^1	95^2	70^2	60^1				
860				100^3	115^2	80^2				30^1		
861				100^2		70^1	60^1	70^1	100^1			
852								70^1	60^1	47.5^2		
851								65^1	30^1	60^1		
Average	129	123.8	118.5	105.3	102.6	84.5	75.8	69.9	56.8	45.6 Microns		

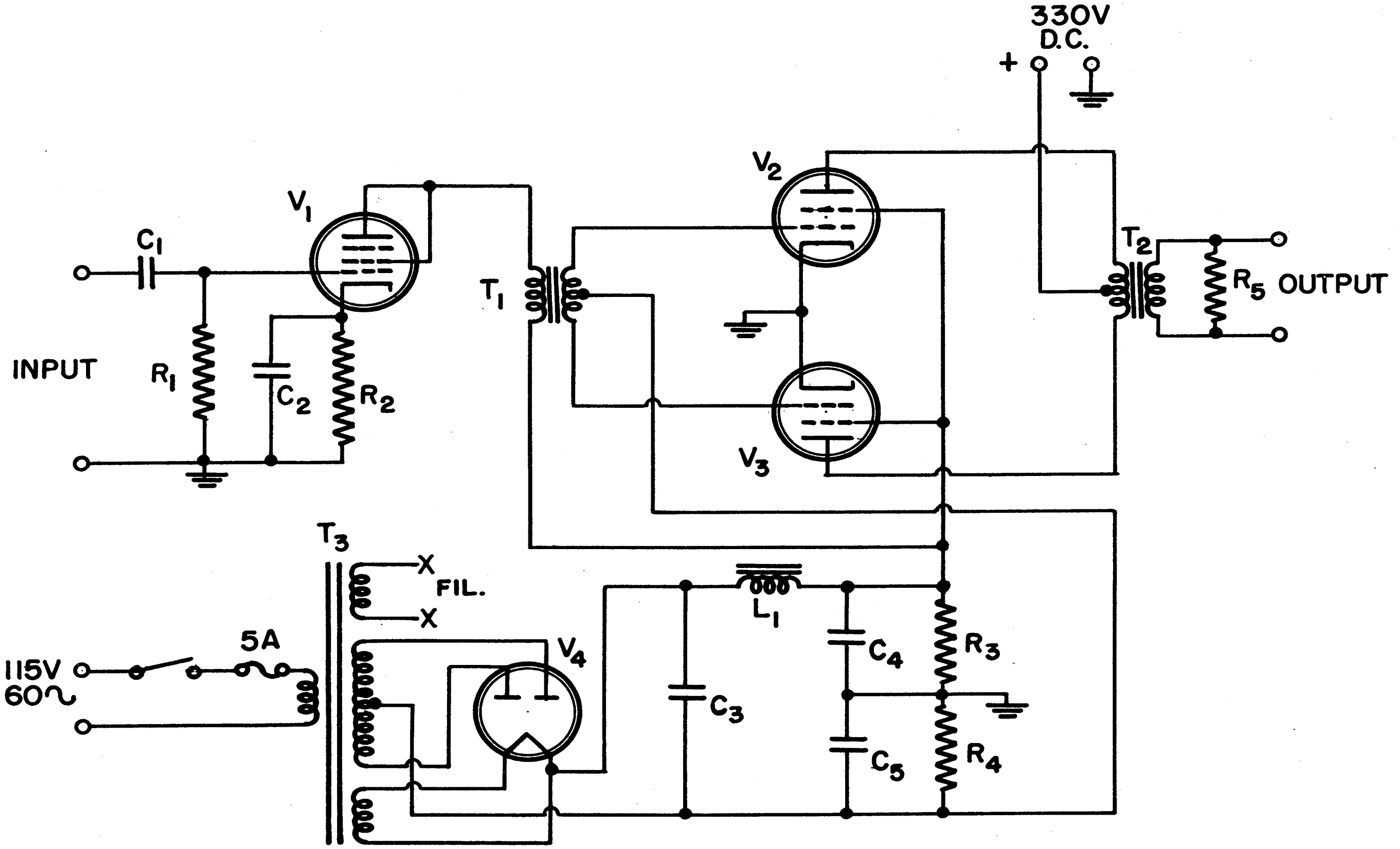
APPENDIX D

KEROSENE SPECIFICATIONS

API Gravity	43.2	Distil Initial	345° F.
Flash Point	128° F.	10	382
(Tag Closed)		20	397
Viscosity	40 Sus	30	407
(At 100° F.)		40	417
Color	26 Saybolt	50	427
Sulphur	0.080%	60	437
Cetane No.	55	70	448
Diesel Index	63	80	459
		90	470
		100	506

APPENDIX E

APPENDIX E



V_1 = 6F6

V_2, V_3 = 6L6

V_4 = 5U4G

R_1 = 0.5MEG., 1/2W

R_2 = 1700, 1/2W

R_3 = 5.1K, 30W

R_4 = 200, 10W

R_5 = 2250, 25W

C_1 = 10mmfd., MICA

C_2, C_5 = 25mfd, 25V.

C_3, C_4 = 4mfd., 400V.

L_1 = 4H AT 130ma., 100 Ohms

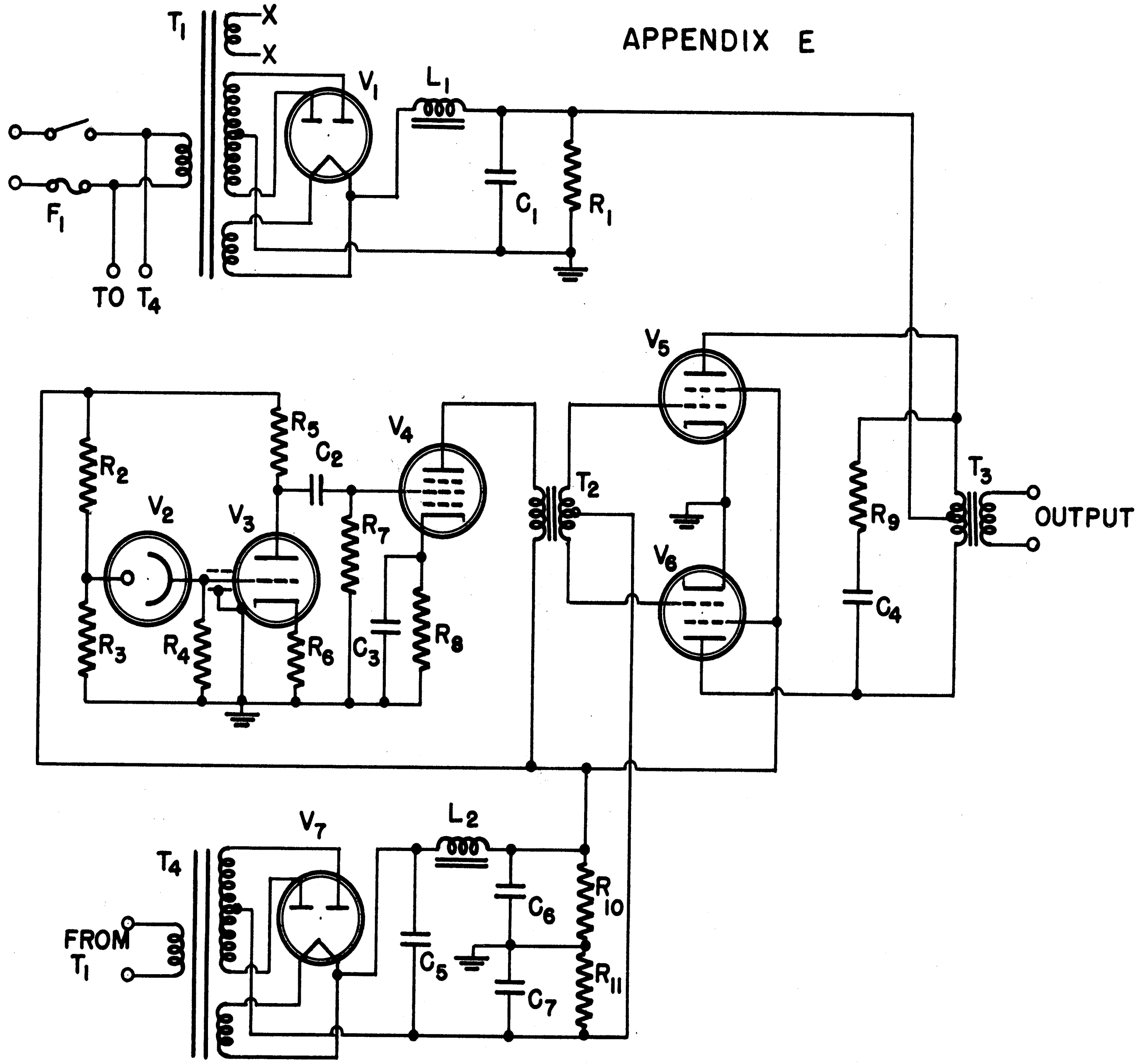
T_1 = DRIVER TRANSFORMER,
TURNS RATIO, PRI-1/2 SEC.=4:1

T_2 = OUTPUT TRANSFORMER
3800 OHM PRIMARY TO
500 OHM SECONDARY

T_3 = POWER TRANSFORMER
375-375 VOLTS AT
150 ma. D.C.

SCHEMATIC DIAGRAM OF HIGH FREQUENCY SUPPLY AMPLIFIER

APPENDIX E



V_1 = 5V4-G

V_2 = 929

V_3 = 6J5

V_4 = 6F6

V_5, V_6 = 6L6

V_7 = 5U4-G

R_1 = 50K, 5W

R_2 = 27K

R_3 = 82K

R_4 = 15 Meg.

R_5 = 100K

R_6 = 2700

R_7 = 470K

R_8 = 680

R_9 = 5K, 20W

R_{10} = 3500, 30W

R_{11} = 200, 5W

C_1, C_6 = 16 mfd, 450V.

C_2 = .001 mfd

C_3, C_7 = 25 mfd, 25V.

C_4 = .03 mfd, 1600V.

C_5 = 8 mfd, 450V.

L_1 = 4H, 250 ma.

L_2 = 15H, 150 ma.

T_1 = 400-0-400V
200 ma.

T_2 = DRIVER
1.4:1 PER 1/2 SECONDARY

T_3 = 3300Ω C.T.
240 ma. PER SIDE

T_4 = 350-0-350V
150 ma.

F_1 = 2 AMP.

SCHEMATIC DIAGRAM OF PHOTOTUBE POSITION DETECTOR AND AMPLIFIER