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RESEARCH MEMORANDUM

EFFECT OF PLASTIC VISCOSITY AND YIELD VALUE ON SPRAY CHARACTERISTICS OF MAGNESIUM-SLURRY FUEL

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

WASHINGTON

January 7, 1957

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RESEARCH MEMORANDUM

EFFECT OF PLASTIC VISCOSITY AND YIELD VALUE ON SPRAY CHARACTERISTICS OF MAGNESIUM-SLURRY FUEL

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SUMMARY

The plastic viscosity and yield value of magnesium slurries were varied to determine the effect on the atomization and distribution characteristics of slurry sprays from an air-atomizing-type injector. A description of the shutter and test chamber used for spray sampling is given.

Four different surface-active additives were used in preparing the 50-percent vapor-process slurries. The range of plastic viscosities was between 0.22 and 0.51 poise; and the range of yield values, between 150 and 810 dynes per square centimeter. The slurry and atomizing-gas flow were essentially constant during the tests.

The spray drops from a single-shot injector were caught on a paper pad in an open 8-inch-diameter chamber. Statistical data were obtained from the spray weight and from photomicrographs of the drops.

There was no significant variation in the spray characteristics of these slurries when tested under the same conditions.

INTRODUCTION

Combustion studies at the NACA Lewis laboratory have indicated that concentrated suspensions of magnesium powders in hydrocarbons give higher thrust in ram jets and afterburners and higher blow-out velocities than can be obtained from conventional jet fuels (ref. 1).

Since the combustion efficiency of a fuel may be a function of its spray characteristics, it is desirable to know to what degree the viscosity and yield value of magnesium slurries affect these characteristics.

The viscosity and yield value of magnesium slurries are affected by the type and quantity of surface-active additive (ref. 2). The slurries tested were made with vapor-process magnesium, and their plastic-viscosity and yield-value ranges are 0.22 to 0.51 poise and 150 to 810 dynes per square centimeter, respectively.

This investigation was conducted to determine the effects of plastic viscosity, yield value, and surface-active additive on the spray characteristics of magnesium-slurry fuels. Other investigators have found that plastic viscosity and yield value are important in flow studies (refs. 1 to 5); likewise, the viscosity of liquids, as indicated by Nukiyama and Tanasawa's first empirical equation for spray analysis (eq. (1) in ref. 6), is important in spray studies. The characteristics studied were (1) mean drop sizes, (2) drop sizes across spray cross section, and (3) spray intensity.

Because of the limited quantity of vapor-process magnesium, a spray-sampling technique using only a small amount of fuel was necessary. With this in mind, the "Pad and Microscope Method" was selected even though it was recognized that the method has limitations (ref. 7). With this method, a count of the drop number and a measure of the drop size in the sample of the spray were obtained; and, from the drop number and size, the various spray characteristics were determined.

APPARATUS AND TEST MATERIALS

Apparatus

The spray nozzle or slurry injector (fig. 1) used in this investigation is an air-atomizing type similar to that used for slurry injection in ram-jet combustors (ref. 8). For safety reasons, the tests were run with oil-pumped nitrogen as the atomizing gas instead of compressed air. The injector was designed for a slurry flow rate of about 4 gallons per hour at a pressure of approximately 10 pounds per square inch gage.

The shutter and test chamber used for spray sampling are shown in figure 1. The shutter has adjustable arms so that the shutter opening can be changed. The nozzle position in the shutter box was such that the shutter would pass about 1/32 of an inch from the nozzle tip. A rotary actuator is used for moving the shutter. Deflection of the fuel from the shutter opening, during the short interval of time before spray sampling, is accomplished by the angle of the shutter arms.

The test chamber is simply a section of 8-inch pipe with a flange on one end for attaching the shutter assembly. A set of guides is arranged inside the test chamber to keep the test pad flush with the cylindrical wall of the pipe. The test pad is a sheet of paper, used for

catching the spray sample, which will permit sufficient light to pass through it for photographing the drops.

The fuel system used in this investigation is shown in figure 2 and is similar to other magnesium-slurry fuel systems (refs. 9 and 10).

Magnesium-Slurry Fuel

In general, the procedure used for preparing the slurries and for aging the prepared slurries is described in reference 2. The composition of the slurries used in this investigation is given in table I. Slurries containing approximately 50-percent magnesium (by weight) were used because most of the previous work on magnesium slurries was done at this concentration and because 50-percent magnesium represents a useful and practical minimum to make use of the fuel desirable (refs. 1 to 4, 10, and 11). About 1/2 gallon of each slurry sample was needed for the tests.

The magnesium in the slurries was prepared at the NACA Lewis laboratory by the vapor-condensation process (ref. 12). This process yields a dilute hydrocarbon suspension of very finely divided magnesium which is concentrated to a paste by centrifuging. Each slurry was prepared by diluting the paste to about 50-percent magnesium content with the same anhydrous hydrocarbon as was used in the manufacture of the dilute suspension. Table I lists the hydrocarbon used in the various slurries. The physical properties of these three hydrocarbon blends are presented in table II.

The four surface-active additives used in the slurries for this investigation were chosen with the aid of reference 2 to give a desired range of physical properties. Listed in table I are the surface-active additives and the concentration of the additive used in the various slurries. The chemical composition and the physical properties of these additives are given in reference 3.

TEST PROCEDURE

Physical-Property Measurements

The flow curves of the various slurries obtained with the automatic concentric-cylinder rotational viscometer described in reference 13 indicated that the slurries were a plastic material and nonthixotropic. The plastic viscosity and yield value of the slurries were determined from the flow curves. These physical properties were measured on any given slurry not more than one day before it was to be tested. The plastic viscosities and yield values for the various slurries are listed in table III. Definitions for plastic viscosity, yield value, and thixotropic are given in the appendix.

Since the density of the slurries was needed in some of the calculations, the density of the various slurries was determined by weighing a known volume of the slurries tested.

Spray Sampling

The limited quantity of vapor-process magnesium available made it necessary to use the pad and microscope method for spray sampling. The general technique of this method is to catch a sample of the spray on a sheet of paper, and then measure and count the drops on the sheet with the aid of a microscope. Since the slurries tested had a sufficiently high yield value, spreading of the drops on the test sheet can be considered negligible.

Spray samples were taken with the test chamber and nozzle in both a horizontal and a vertical position. From the spray samples taken in the horizontal arrangement, a quantitative study of mean drop sizes was made; and a qualitative study of drop sizes across the spray cross section and of the spray intensity was made from the spray sample taken in the vertical arrangement. Spray intensity is weight rate of liquid flow per steradian.

When the spray samples were taken with the test chamber in a horizontal position, the shutter was initially in the up position. The fuel flow from the nozzle, which commences without the flow of atomizing gas, is deflected from the bottom shutter arm to the bottom of the shutter box from where it can be drained. Shortly after the fuel flow is turned on, the shutter is actuated and simultaneously the flow of the atomizing gas is started. When the shutter reaches the end of its path, the fuel flow and atomizing gas are turned off automatically. As the shutter opening admits the spray, which takes about 1/5 second, a sample of the spray passes into the test chamber and falls on the test sheet (8 in. wide by $22\frac{1}{2}$ in. long), which rests on the lower third and extends almost the entire length of the test chamber. The test sheet was left in the test chamber long enough to permit all the drops to land. The amount of fuel on the test sheet was determined by weighing the sheet before and after each run. The general pattern of spray obtained on this type test pad is shown in figure 3.

With the test chamber in a vertical position, the procedure for spray sampling is substantially the same as with the chamber placed horizontally. In this instance, the test sheet is $7\frac{1}{4}$ inches in diameter and is located 19 inches below the spray nozzle.

The horizontal test was run first, and the vertical test was made if enough fuel remained. Usually, there was enough fuel for both tests, but the amount of fuel left for the vertical test was too small to give

good quantitative results. Therefore, the vertical-test results will be considered qualitatively. In order to determine the reproducibility of the results, duplicate horizontal tests were made on several of the slurries.

The fuel flow rate was held constant at about 4 gallons per hour, and the ratio of fuel flow rate to atomizing-gas flow rate on a weight basis was held at approximately 9. This ratio of 9 was determined with the aid of reference 8.

Photomicroscopy. - The test sheets from several trial runs with the test chamber placed horizontally were studied under a microscope to determine the general area and the number of photomicrographs needed. From this initial study it was decided that 40 photomicrographs would be necessary. The general location of these 40 photomicrographs on a test sheet is shown in figure 3 in which each circle represents the approximate center of a photomicrograph. Each test sheet was studied in order to determine the best location of the photomicrographs on that test sheet. The variation of the location of these photomicrographs on the various test sheets from that shown in figure 3 is ±0.1 inch. This variation was kept small so that good comparative results would be obtained. Figure 4 shows two typical photomicrographs.

Calibrated circles on thin glass strips were used for measuring the drop sizes between 5 and 200 microns in the photomicrographs. A calibrated scale was used for measuring drop sizes above 200 microns; drops below 5 microns were impractical to measure. For each drop which appeared as a shape other than a circle on the photomicrographs (fig. 4), a mean of the longest and shortest dimension was taken as the drop diameter. The drops in the photomicrographs were measured and counted, and the results tabulated. The only assumption made in measuring the drops is that the drop diameters measured from the photomicrographs are the same as the actual diameters of those drops. Between 1500 to 2000 drops per test sheet were counted.

The test sheets obtained with the chamber placed vertically were studied with the aid of a microscope and photomicrographs to determine qualitatively any variation in the mean drop sizes and in the spray intensity throughout the spray cross section.

COMPUTATION OF MEAN DROP SIZES

Three common mean drop sizes calculated for the horizontal tests are:

$$\text{Arithmetic mean drop diameter, } D_{10} = \frac{\Sigma(nx)}{N} \qquad (1)$$

$$\text{Volumetric mean drop diameter, } D_{30} = \sqrt[3]{\frac{\Sigma(nx^3)}{N}} \tag{2}$$

$$\text{Volume-to-surface mean drop diameter, } D_{32} = \frac{\Sigma(nx^3)}{\Sigma(nx^2)} \tag{3}$$

where

D mean drop diameter, μ

n number of drops with diameter x

x diameter of individual drop, μ

N total number of drops

Another volume-to-surface mean drop diameter was calculated using the following empirical equation which expresses the data on distribution of drop sizes in liquid sprays:

$$\log_{10}\left(\frac{1}{x^2}\frac{dn}{dx}\right) = (\log_{10}a) - \frac{bx^q}{2.3} \tag{4}$$

where a, b, and q are constants (ref. 6). When using this equation for calculating mean drop size, $\log_{10}\left(\frac{1}{x^2}\frac{dn}{dx}\right)$ is plotted against x^q, where q is varied between 2 and 1/6 until one of the plots yields a straight line. From the slope of this line, which equals $-b/2.3$, the value of b can be calculated. For the nozzle used in this investigation, a plot of $\log_{10}\left(\frac{1}{x^2}\frac{dn}{dx}\right)$ against x^q yields a straight line when q is 1/3 (fig. 5). When the values of q and b are known, the mean drop diameter in microns can then be calculated with the aid of table I in reference 6, which gives the following equation for the case when q = 1/3:

$$D_o = 4080/b^3$$

Since the weight of the slurry on the rectangular test sheets is known, assuming that no hydrocarbon evaporates, it was decided to calculate still another mean drop size which will be called the "experimental volumetric mean drop diameter" D'. In order to calculate this mean drop size, the number of drops on a given test sheet is needed. This number was approximated by assuming that the average of the number of drops observed per unit area in the photomicrographs existed uniformly over the

entire test sheet. The diameter D', in microns, was calculated from the following equation:

$$D' = \sqrt[3]{\frac{6M \times 10^{12}}{\pi \rho N}} \tag{5}$$

where

M weight of slurry on test pad, g

ρ slurry density, g/cc

ACCURACY AND RESULTS

Accuracy

The reproducibility of the results can be seen by comparing the drop-distribution plots and the various mean drop sizes of the duplicate runs (two runs made with the same slurry). Drop-distribution plots for two such tests using slurry samples 5 and 9 are shown in figures 6 and 7, respectively. Figure 7 also shows the location of the data points used for plotting the curves. The reproducibility of the various mean drop sizes can be seen in table III. The spread of the various mean drop diameters for the duplicate runs is shown in the following table as a percent of the average of the duplicate runs with the largest spread for that mean drop size:

Mean drop diameter	Spread of mean drop size for duplicate runs, percent of mean
D_{10}	±11
D_{30}	±7
D_{32}	±8
D'	±5
D_o	±14

The various mean drop sizes for the duplicate runs with slurry sample 5 are indicated in figure 6.

An analysis was made on the distribution data from one run to determine the effect of a counting error on D_{32}. This was accomplished by first adding one drop to each group of the distribution data which has less than 100 drops and calculating D_{32} and then subtracting one drop

from each group of the original distribution data which has less than 100 drops and calculating D_{32}. This analysis shows that a counting error of ±1 drop in each group of the distribution data which has less than 100 drops would give a maximum variation in D_{32} of ±15 percent.

A comparison from table III of D_{30} and D' shows that D_{30} is about $2\frac{1}{2}$ times larger than D'. Such a result can be considered good since only 0.1 percent or less of the drops on the test pad was measured. Other investigators using this spray-sampling method have reported errors of about the same magnitude (ref. 14). Since D_{30} for any run is always about $2\frac{1}{2}$ times D', any error in the results should be constant; therefore, no difficulty should arise in comparing the results of the various runs.

Results

The viscosity and yield value of the various slurries tested are listed in table III and range from 0.22 to 0.51 poise and 150 to 810 dynes per square centimeter, respectively. No correlation could be found between mean drop sizes and plastic viscosity, yield value, or surface-active additive. The various mean drop sizes are about (1) 45 microns for D_{10}, (2) 100 microns for D_{30}, (3) 190 microns for D_{32}, and (4) 40 microns for D'.

In all the drop-distribution plots, the parts of the curves below 20 microns and above 200 microns practically coincide, as shown in figures 6 to 8.

DISCUSSION OF RESULTS

Drop-distribution plots were drawn for each run made with the test chamber placed horizontally and were compared with one another. A comparison of such plots for five slurries is shown in figure 8. Since the plots for different slurries coincide with one another almost as closely as do plots for duplicate runs on the same slurry, it is judged that the drop size distribution of the spray for all the runs was essentially constant. A comparison of figure 8 with figures 6 and 7 shows that they are similar. These figures are also typical of all the drop-distribution plots.

Since the spread among all the D_{32} values (±13 percent of the mean) is not much larger than the spread of D_{32} in the duplicate runs (±8 percent of the mean) and since a small error in counting could introduce a

±15 percent change in D_{32} (see the section Accuracy), the variation of D_{32} may be the result of experimental error. Table III (columns 5 and 6) shows that D_{32} is about 50 to 100 percent of D_o. Since other investigators have found greater differences, the results obtained can be considered acceptable (ref. 6).

From a study of the test sheets from vertical runs, a uniform mean drop size across the spray cross section and a uniform spray intensity were observed for each run. Also, the spray intensity appeared to be the same for all the slurries tested.

The variation in yield value of the slurries, from 150 to 810 dynes per square centimeter, does not, and should not, have an effect on the spray characteristics of the various slurries because the slurry flow in the nozzle was calculated to be turbulent. In turbulent flow the friction forces are governed by the viscosity alone, which is calculated for the rate of shear in the nozzle.

A mean drop size was calculated from Nukiyama and Tanasawa's first empirical equation (ref. 6, eq. (1)) for the three hydrocarbons, assuming the flow conditions used in this investigation. This mean drop diameter for each of the three hydrocarbons was the same but was about three times greater than D_{32} for the slurries. A check of the results of other investigators shows that the mean drop size obtained from this empirical equation can be as much as 5 times greater than the observed D_{32} when $1000Q_L/Q_a$ is about 1 or more (Q_L/Q_a = ratio of volume flow rate of liquid to volume flow rate of atomizing gas at the vena contracta)(ref. 6). During this investigation, $1000Q_L/Q_a$ was greater than 1. With this in mind and with the fact that the size of the magnesium particles in the slurries was 5 microns or less (refs. 12 and 15), which is a factor of 40 less than D_{32}, it seems possible that the drop size obtained with the slurries tested was governed by the hydrocarbon in the slurry and would possibly be equal to the drop size obtained if the hydrocarbon was tested alone under the same conditions used for the slurries.

SUMMARY OF RESULTS

In determining the effects of physical properties and surface-active additives on the atomization characteristics of vapor-process magnesium slurries, the following results were obtained:

1. In the range of plastic viscosity and yield value studied, there was no variation in the mean drop sizes, drop sizes across spray cross section, or spray intensity.

2. Neither the type of surface-active additive used nor the amount of that additive had any effect on the atomization of the slurry.

CONCLUDING REMARKS

From an analysis of the results, it seems quite likely that the spray characteristics of vapor-process magnesium slurries are governed by the density, viscosity, and surface tension of the hydrocarbon in slurries. It also seems that, if an investigation were conducted comparing the spray characteristics of the hydrocarbon used in a vapor-process magnesium slurry with that of the slurry itself, the results would probably show that the spray characteristics were nearly the same. Other investigators have found that the transition loss coefficients for pipeline transitions are the same for slurries and Newtonian liquids (ref. 16).

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, October 22, 1956

APPENDIX - GLOSSARY

Flow curve - A plot of rate of shear (ordinate) against shearing stress (abscissa). When the plot is obtained by measuring the rate of shear at successively increasing shearing stresses, it is called an up curve. For decreasing rates of shear, it is called a down curve.

Plastic viscosity - The reciprocal of the slope of the linear flow curve exhibited by a plastic material.

Spray intensity - The weight rate of liquid flow per steradian.

Thixotropy - A condition in which the structure of a suspension is destroyed by agitation and is rebuilt upon rest. It is evidenced by a flow curve in which, for a given shearing stress, the rate of shear is higher on the down curve than on the up curve.

Yield value - The value of the intercept of the extrapolated linear flow curve of a plastic material with the shearing-stress axis.

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TABLE I. - COMPOSITION OF EXPERIMENTAL SLURRIES

Sample	Hydrocarbon	Additive	Additive, percent by weight	Vapor-process magnesium, percent by weight
1	JP-5	Polyoxyethylene dodecyl alcohol, 8 moles ethylene oxide	2	50
2	JP-5	Polyoxyethylene dodecyl alcohol, 8 moles ethylene oxide	3	51
3	JP-5	Lecithin	2	51
4	JP-5	Lecithin	3	51
5	90% JP-5 and 10% Diesel oil	Polyoxyethylene dodecyl alcohol, 8 moles ethylene oxide	2	52
6	90% JP-5 and 10% Diesel oil	Polyoxyethylene dodecyl alcohol, 8 moles ethylene oxide	3	52
7	90% JP-5 and 10% Diesel oil	Lecithin	2	52
8	90% JP-5 and 10% Diesel oil	Lecithin	3	53
9	90% JP-5 and 10% fuel oil number 2	Polyoxethylene dodecyl alcohol, 8 moles ethylene oxide	3	52
10	90% JP-5 and 10% fuel oil number 2	Lecithin	2	52
11	90% JP-5 and 10% fuel oil number 2	Lecithin	3	53
12	90% JP-5 and 10% fuel oil number 2	Polyoxyethylene sorbitol tetraoleate	.75	51
13	90% JP-5 and 10% fuel oil number 2	Polyoxyethylene sorbitol tetraoleate	4	52
14	90% JP-5 and 10% fuel oil number 2	Cetyl alcohol	2	52

TABLE II. - ANALYSIS OF HYDROCARBON

Fuel properties	JP-5[a,b]	90% by volume JP-5[a], 10% by volume Diesel oil[b]	90% by volume JP-5[a], 10% by volume number 2 fuel oil[b]
A.S.T.M. distillation, D86-52, °F			
Initial boiling point	348	366	354
Percentage evaporated			
5	371	376	378
10	383	390	389
20	396	400	401
30	407	418	413
40	419	428	425
50	429	434	436
60	439	444	446
70	449	454	457
80	460	472	471
90	472	496	493
95	484	520	512
Final boiling point	496	590	556
Residue, percent	1.0	1.2	1.0
Loss, percent	0.5	0	0.5
Specific gravity, 60°/60° F	0.815	0.820	0.816
Hydrogen-carbon ratio	0.160	0.159	0.159
Net heat of combustion, Btu/lb	18,600	18,575	18,600
Aromatics, percent by volume	14.8	16.8	11.9
Aniline point, °F	148.3	149.4	150.8

[a]Mil-F-5624C.

[b]Hydrocarbon blend dried over activated alumina.

TABLE III. - SUMMARY OF DATA AND COMPUTED RESULTS FOR ATOMIZATION EXPERIMENTS

Run[a]	Arithmetic mean drop diameter, D_{10}, μ	Volumetric mean drop diameter, D_{30}, μ	Experimental volumetric mean drop diameter, D', μ	Volume-to-surface mean drop diameter, $D_{32} = \frac{\Sigma(nd^3)}{\Sigma(nd^2)}$, μ	Calculated volume-to-surface drop diameter, $D_o = 4080/b^3$, μ	Plastic viscosity at 27° C, poises	Yield value at 27° C, dynes/cm²
1	42	90	39	160	230	0.25	180
2	48	94	39	160	260	.22	160
3	43	99	38	190	280	.28	150
4	44	98	38	180	320	.24	150
5A	46	98	43	190	200	.22	190
5B	47	110	40	210	260	.22	190
6A	57	110	44	200	220	.26	200
6B	46	94	40	170	200	.26	200
7	49	100	42	190	210	.32	280
8	44	100	40	200	260	.31	300
9A	48	100	40	200	230	.23	200
9B	45	100	40	210	210	.23	200
10A	33	83	36	180	210	.34	250
10B	30	80	34	180	190	.34	250
11	42	93	40	170	270	.34	290
12	39	100	37	200	320	.51	810
13	43	110	41	210	340	.26	330
14	53	100	43	170	370	.36	490

[a]Run numbers correspond with slurry sample number. The letters "A" and "B" are placed after a number in which the same slurry was used for two horizontal runs.

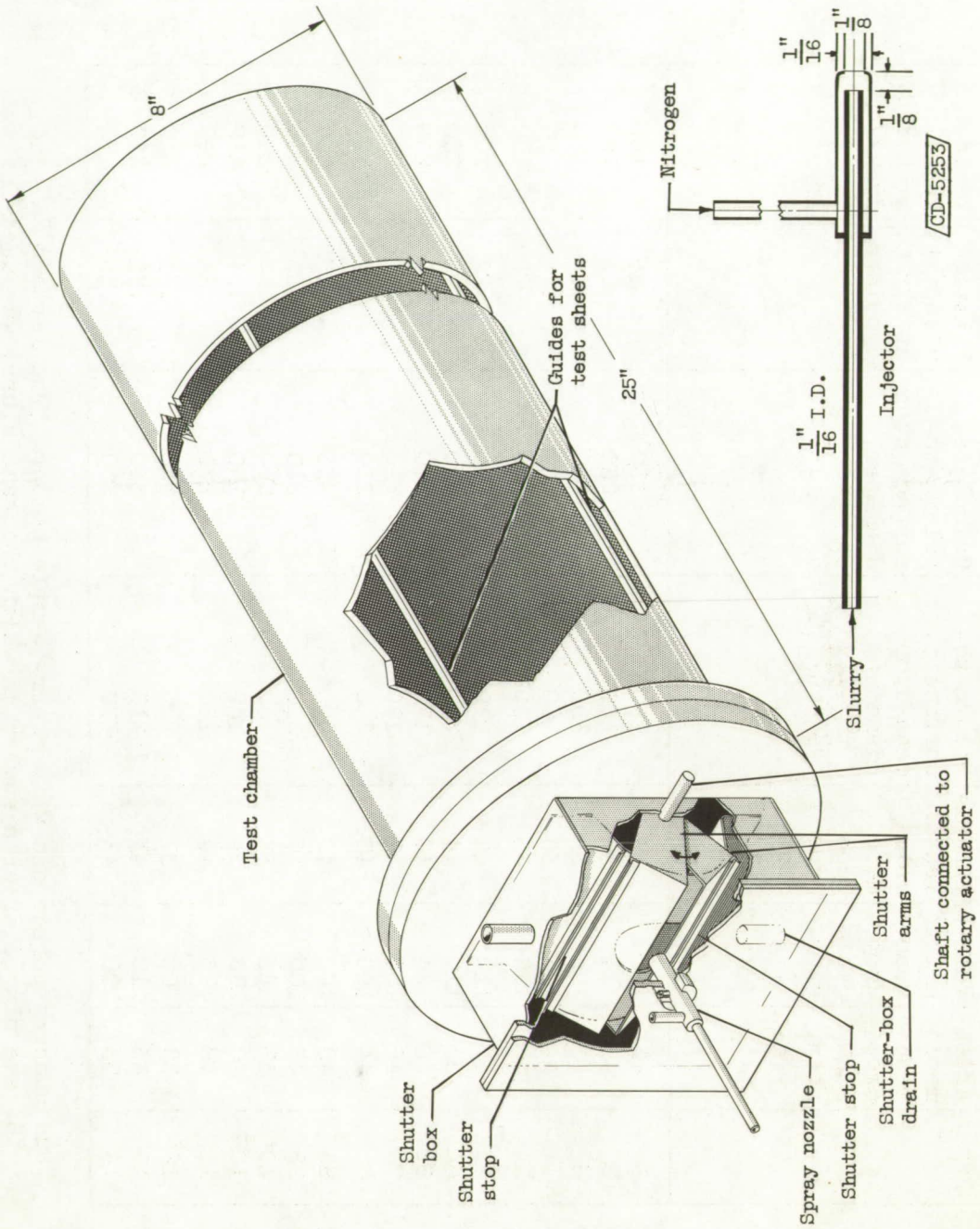

Figure 1. - Spray nozzle and test installation for spray atomization tests.

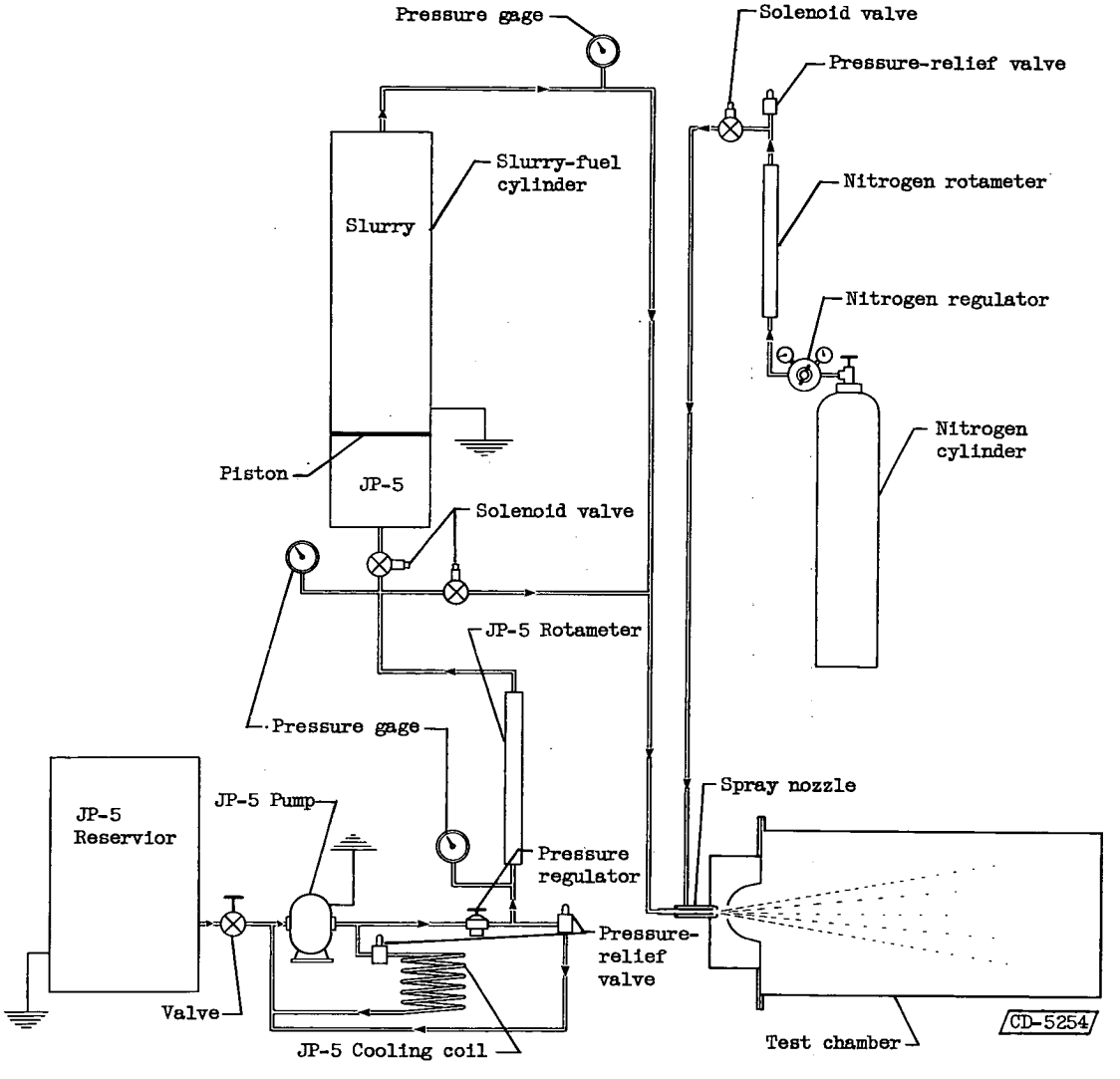

Figure 2. - Fuel-atomization flow diagram.

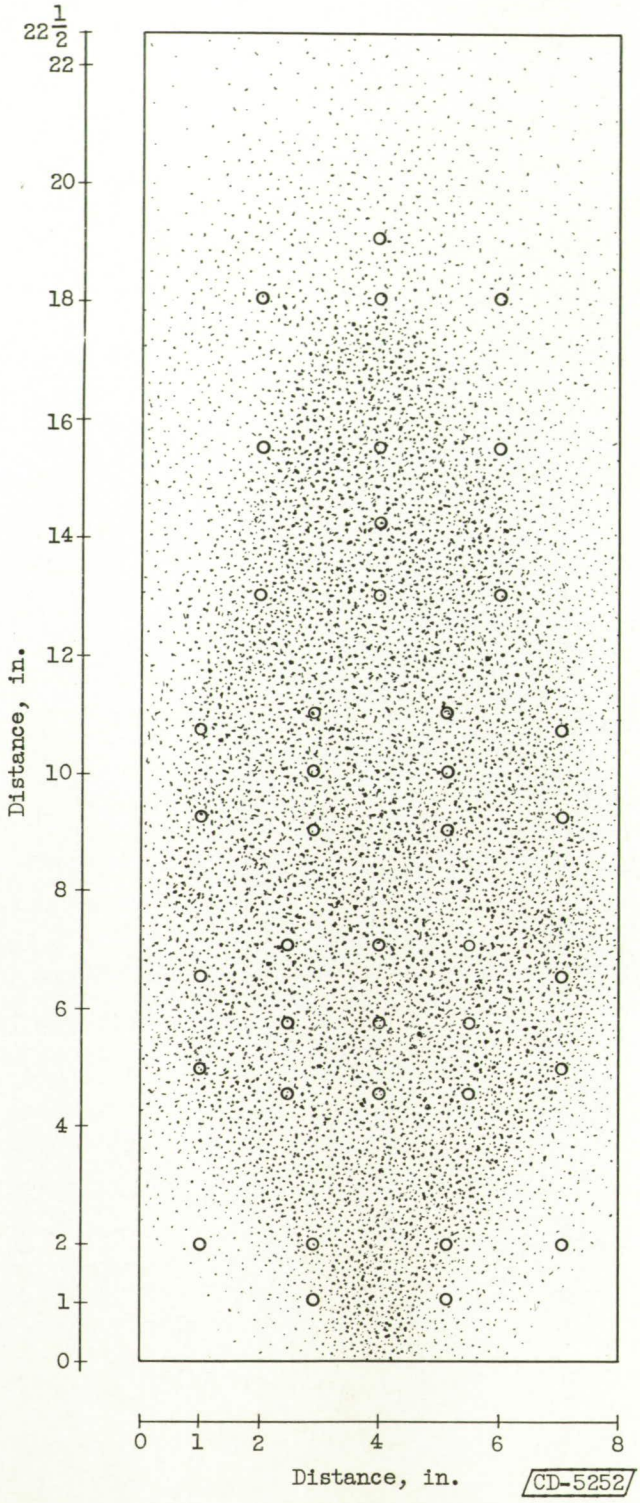

Figure 3. - Sketch of typical drop distribution on test sheet. (Circles represent approximate sections on test sheet that were photomicrographed.)

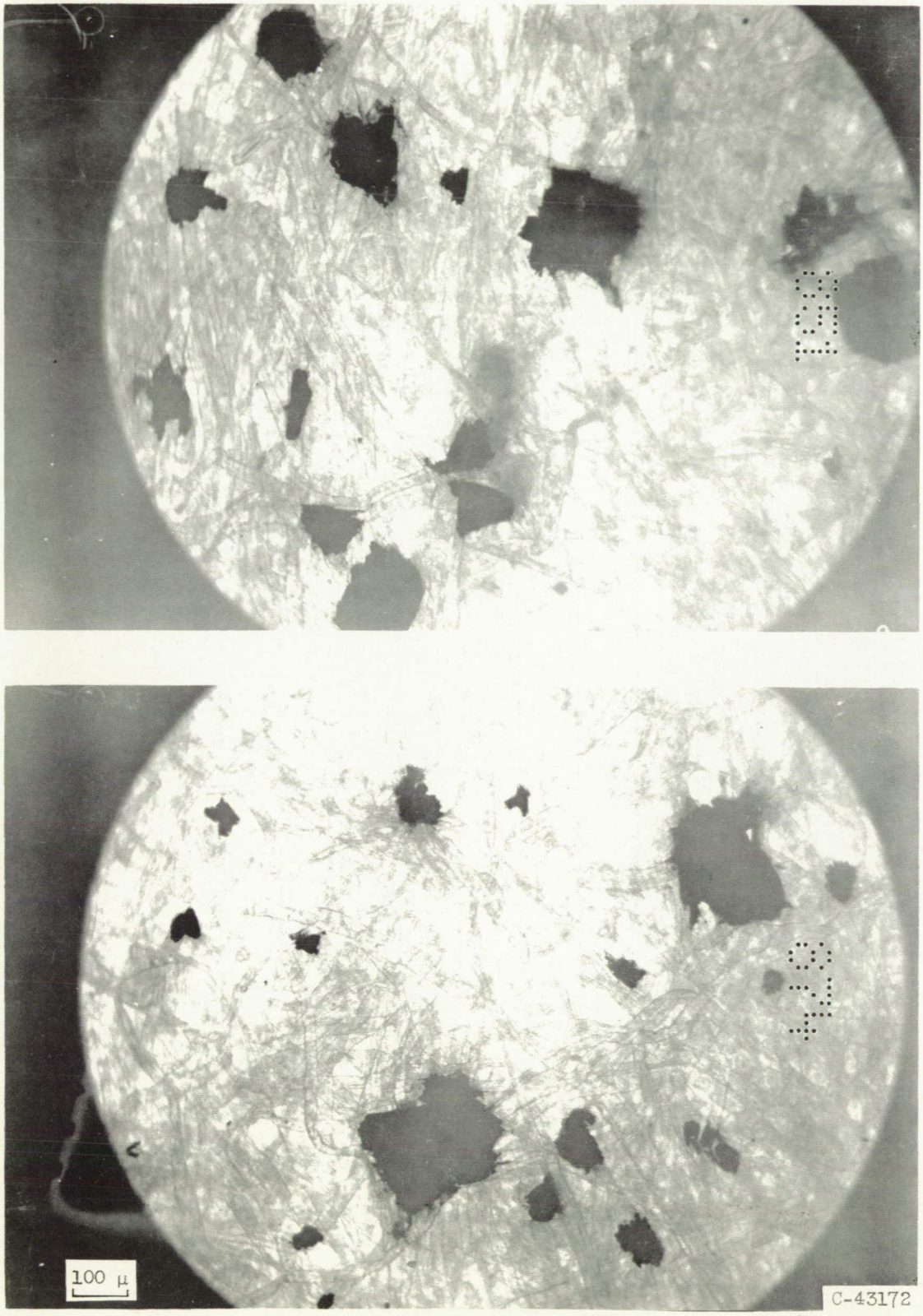

Figure 4. - Typical photomicrographs of test sheet.

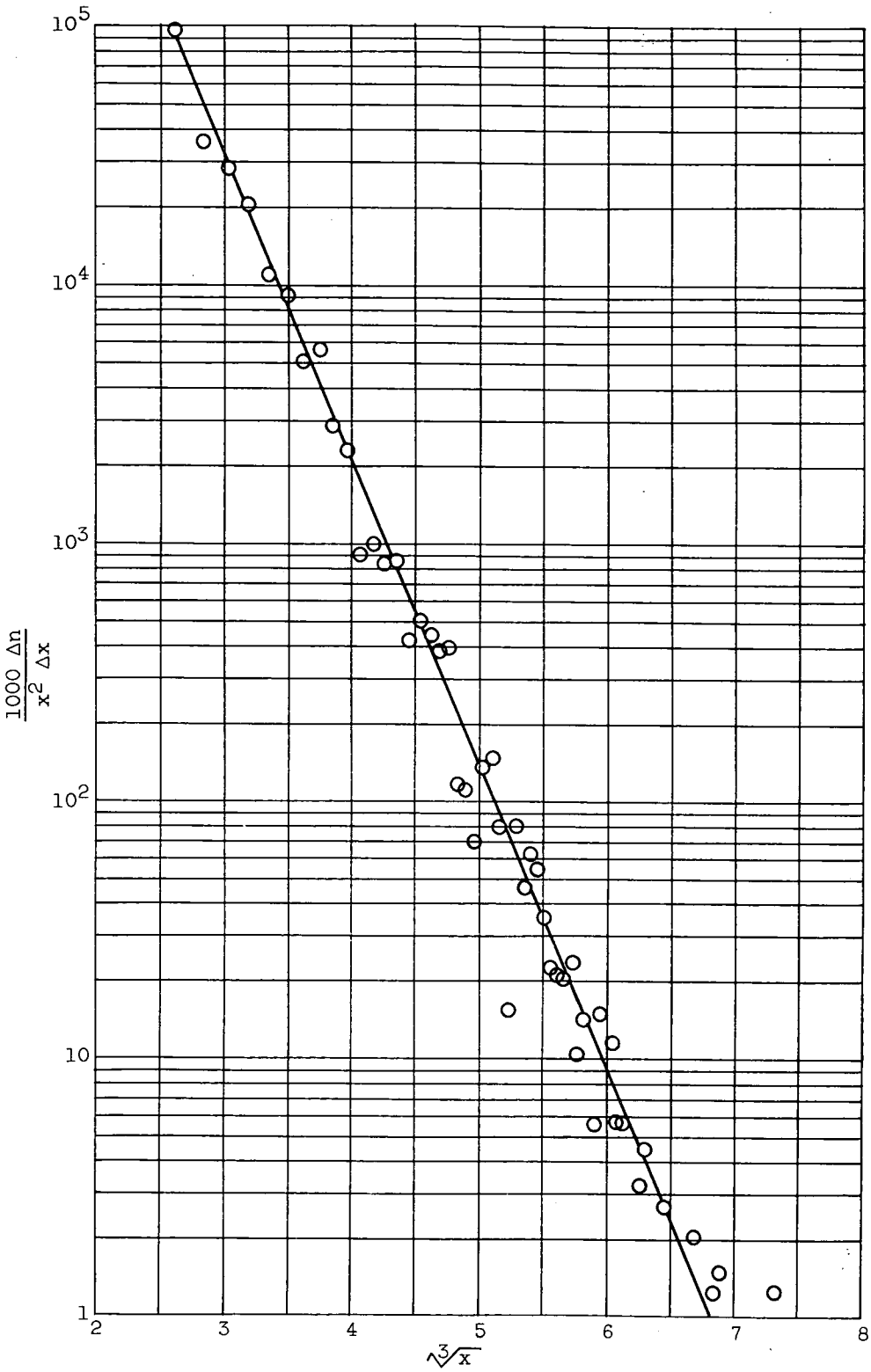

Figure 5. - Drop-size analysis from equation (4) for sample 5A. Slope, $-b/2.3 = -1.17$; D_o, 200 microns.

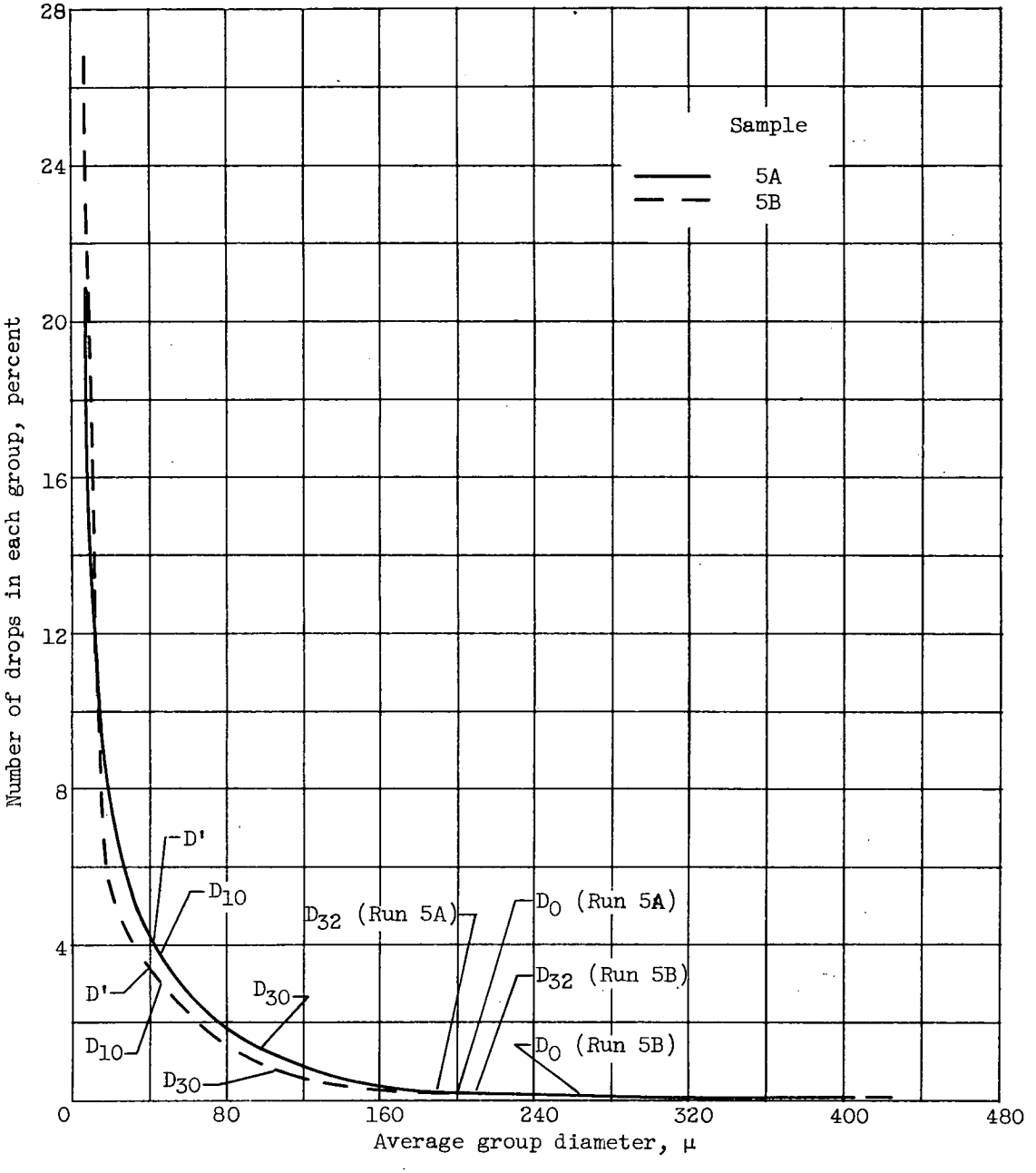

Figure 6. - Droplet-size distribution for sample 5.

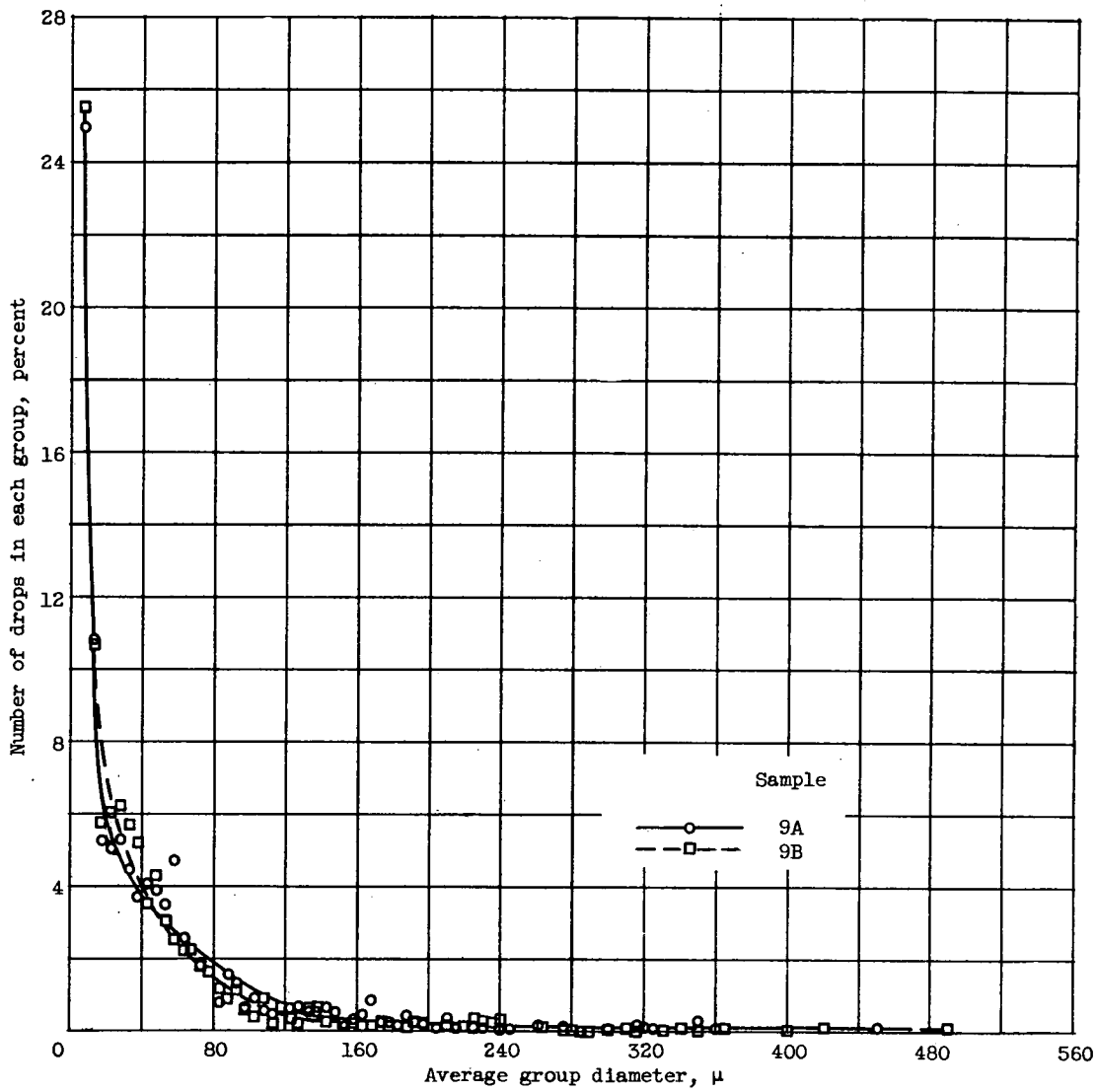

Figure 7. - Droplet-size distribution for sample 9.

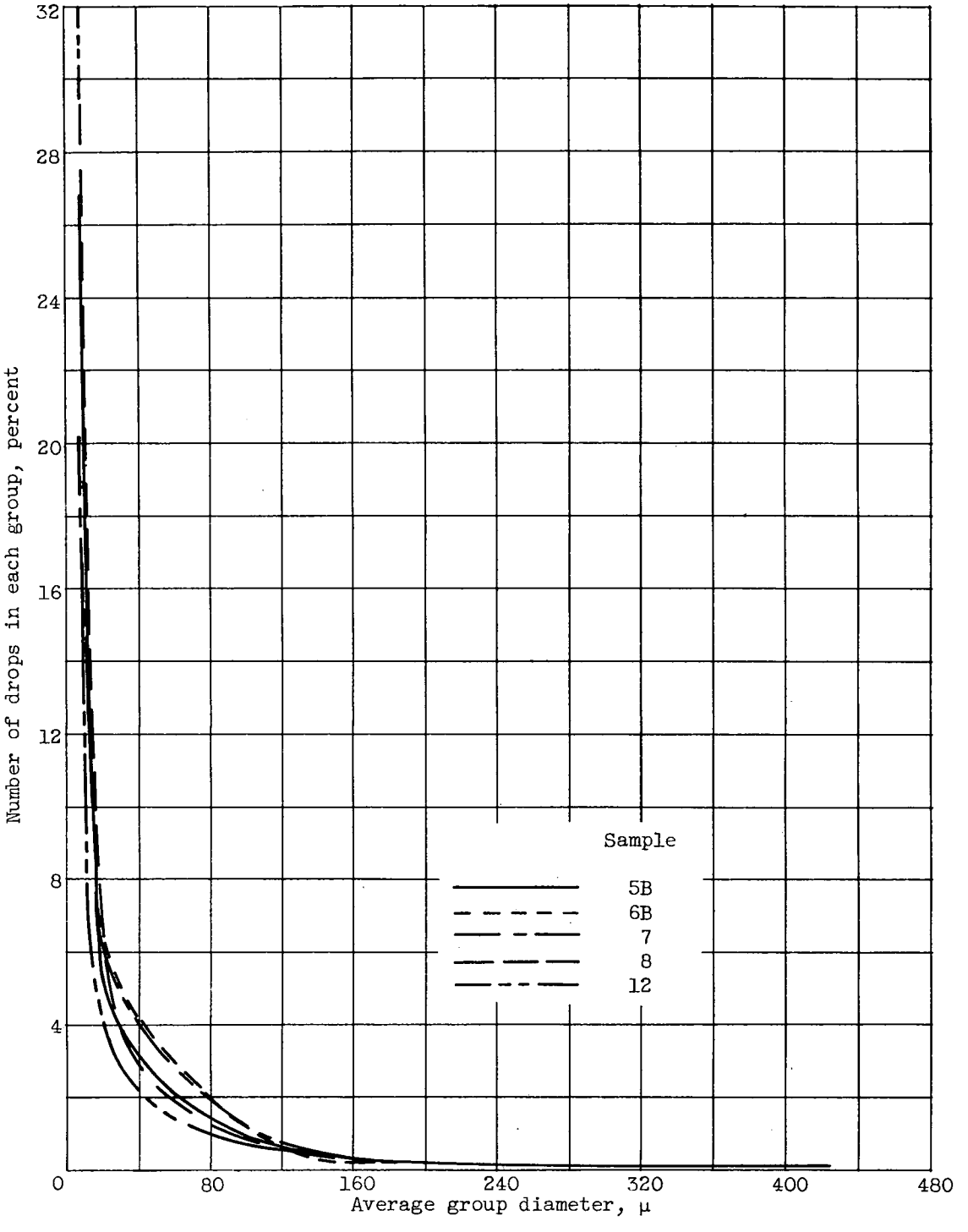

Figure 8. - Droplet-size distribution for samples 5B, 6B, 7, 8, and 12.