SUPPLEMENTAL REPORT AND EXPERIMENTAL RESULTS

A TECHNIQUE FOR THE INVESTIGATION OF SPRAY CHARACTERISTICS OF CONSTANT FLOW NOZZLES

by

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EXPERIMENTAL RESULTS

A part of the experimental data which have been taken to date is presented here for two reasons. First, to indicate the type of data which may be obtained with the technique previously described, and second, to show how this information may be correlated with combustion phenomena.

Drop-size distribution data were obtained on four different nozzles of the pressure atomizing type using 3.37% nigrocine in water as the sprayed fluid and covering a pressure range of 25 through 400 psi. Several different methods of analyzing the drop-size data were attempted but the plot of mean diameter, D_o, versus pressure shown in Figure 12 was satisfactory for correlation purposes and is a practical index to the variation of drop-size distribution. This is true since the size distribution curves of these nozzles are characteristically similar, varying primarily in the size for maximum number and the range of sizes produced. It is further seen that these curves of D_o versus pressure are basically similar, even though the nozzles differ considerably in capacity and spray angle. The straight line portion of these curves, obtained at pressures above 100 psi, is significant since, as will be shown later, it represents that region of operation wherein the effects of the physical characteristics of the sprayed fluid are negligible.

EFFECT OF SURFACE TENSION AND VISCOSITY

In order to correlate the test data obtained using dyed water as the sprayed fluid with the spray characteristics to be expected with the same nozzle spraying gasoline, it is necessary to investigate a range of fluid physical characteristics which include these two fluids. Thus it is necessary to determine the effects of changing surface tension from 67 d/cm (standard solution) to 22 d/cm (octane) and viscosity from 1.12 centistokes to about 0.70 centistokes. These are the two most important fluid characteristics affecting atomization and within the limits stated, surface tension is much more important than viscosity. Although the viscosity change may be fairly high on a percentage basis, the absolute change is quite small and has a comparatively small effect on the spray characteristics.

The surface tension of the sprayed fluid was decreased to a minimum of 28 d/cm by adding increasing quantities of n-Butyl alcohol to the standard solution - up to 5.5% alcohol by weight. Since this concentration approaches the limit of solubility, some extrapolation is necessary to include values for gasoline, but the error incurred is probably no greater than the spread of the experimental points. The small changes in kinematic viscosity which accompany the changes in surface tension amount to less than 0.4 centistokes and are considered negligible. It should be noted that n-Butyl alcohol is slightly soluble in the immersion fluid (kerosene) and the volume of the collected drops could decrease by as much as 5.5% but since the consequent change in diameter is less than 2%, no correction is made.

Figure 13 shows the correlation of the test data with changes in surface tension alone and includes data for three different pressures (i.e., 25, 50 and 100 psi) for one nozzle. Although the data are limited, the trend is definitely established and may be considered suitable for use with the nozzles tested in this investigation.

Certain difficulties are encountered in establishing the effective surface tension of the fluid at the time the drops are formed. If the additive used to vary the surface tension is a surface active agent, such as the aerosals, a finite time is required to change the surface forces and the values of surface tension, which are obtained statically, are then meaningless. Since this same question arises when spraying alcohol-water mixtures, it is necessary to verify the change in effective surface tension. The marked difference between the weight flow distribution curves obtained on gasoline and the standard solution from the same nozzle operating at 50 psi, led to a convenient method of confirming the changes in the dynamic characteristics of the various test solutions. Figure 14 shows the variation in weight flow distribution as the surface tension is decreased and includes the curve obtained with 100 octane gasoline.

This investigation of the effect of viscosity is limited to one nozzle and to a comparatively narrow absolute range in order to make the extrapolation of the data from the standard solution to gasoline as accurate as possible. Since the viscosity of both liquids is low, doubling the viscosity of the test solution in order to establish any effects within the required range, results in a comparatively small increase of slightly more than 1.0 centistoke. The viscosity changes are obtained by adding various proportions of glycerine to the standard solution. This also produced small changes in surface tension and in order to obtain the effect of viscosity alone, a small correction based on the known effect of surface tension is made and these data are plotted in Figure 15. The data are not conclusive but would indicate that the mean diameter decreases as the viscosity decreases, even though the change is small in the region of interest.

The physical characteristics of the various test fluids are given in Table II.

EFFECT OF DISTANCE

The theory proposed by Casteleman (4) to explain the processes of atomization suggests that disintegration continues for some time after injection of a liquid into an air stream, i.e., until the relative velocity between the two fluids has decreased to the point where disintegration is no longer possible. For atomization processes which are dependent upon this relative velocity as the primary atomizing force, the change in size distribution with distance is undoubtedly quite pronounced. However, in the case of the pressure atomizing nozzle this condition does not necessarily exist, since the forces due to the relative velocity of the two fluids are secondary to the turbulence and directional control created by the mixing chamber, tangential slots and orifice of the nozzle. The drops formed are quite small, their maximum theoretical velocities are relatively low and it can be shown that they reach their terminal velocities within a very short distance in still air. For normal operation of a nozzle, this distance is effectively increased due to the movement of the air in the general direction of the spray; such air motion being produced by the aspirating action of the spray. Thus, it would follow that the droplets themselves are formed very close to the nozzle orifice -- or more specifically, near the edge of the liquid sheet formed by the nozzle -- and that the secondary atomizing forces due to a velocity differential are dissipated within a comparatively short space.

The drop-size distribution data obtained for distances of 2, 3, 4 and 6 inches from the nozzle orifice, consistently indicate that the drops actually increase in size as the collection distance increases. This increase with distance is difficult to analyze, but, within the accuracy of the technique, the data represent the size distribution for a given point within the spray and therefore is satisfactory for this work.

Figures 16 and 17 show data which are typical of these nozzles in that the peak of the curve flattens out and moves toward the larger sizes as the distance from the nozzle increases. For otherwise constant operating conditions, this size shift is more pronounced as the distance from the nozzle increases and as pressure and/or flow rate decreases. The effects of evaporation and the tendency for the small drops to follow spray induced air currents toward the edges of the spray are undoubtedly included here but on the basis of the information available in the literature on evaporation of water droplets, it was impossible to predict any significant change in the curve and most certainly not the secondary peak near 10 microns. The movement of the small drops away from the region of maximum weight flow could not be corroborated by any weighting method designed to compensate for the varying percentages of total weight flow represented by an individual cell because the local size distributions were essentially identical. However, it is assumed that drops of all sizes are formed at about the same point relative to the nozzle, and further, that their initial velocities are essentially the same, then the large drops will overtake and combine with some of the smaller drops in their paths, causing the subsequent shift of the primary peak toward larger sizes. The fact that the secondary peak occurs near 10 microns indicates that some of the drops are small enough to follow the airstream flowing around the drops overtaking them and, therefore, are not "swept out."

If this sweeping-out action is allowed

TABLE II

PHYSICAL PROPERTIES OF SPRAYED FLUIDS

Use of Fluid	Components Per Cent by Weight: Water	Nigrocine	Additive	Surface Tension d/cm 20° C	Specific Gravity 20°/20° C	Kinematic Viscosity Centistokes: 20° C	25°C	30° C
1. **Standard**	96.63	3.37		67.0	1.003	1.1550	1.0163	.9173
2. **Effect of Viscosity**	86.93	3.37	9.70	63.3	1.029	1.489	1.328	1.182
a. Glycerol Solutions	79.92	3.37	16.71	61.6	1.048	1.847	1.622	1.423
	73.00	3.37	23.63	59.4	1.068	2.370	2.052	1.813
3. **Effect of Surface Tension**	95.13	3.37	1.50	46.0	1.008	1.273	1.126	1.022
a. -Butyl Alcohol Solutions	93.63	3.37	3.00	38.0	1.001	1.283	1.129	1.021
	90.36	3.34	6.30	28.0	.996	1.435	1.257	1.108
b. Methyl Alcohol Solutions	75.22	3.44	21.34	44.8	0.968	1.966	1.698	1.489
Note: Drop Size Data on this Solution not Reliable.	56.44	3.60	39.96	35.9	0.938	2.277	1.913	1.707
	12.45	3.97	83.58	24.7	0.821	1.360	1.231	1.132

to continue long enough, it is quite likely that the variation in local size distribution, shown by S. M. Doble (1), would be attained. However, in combustion problems, it is important that ignition should occur as soon after injection as enough fuel is atomized to give a combustible mixture (excluding the requirements of other factors). This requirement greatly depreciates the value of drop-size distribution data obtained at distances from the nozzle greater than the six (6) inch limit of the apparatus.

CORRELATION WITH COMBUSTION

Utilizing the information thus far presented, it is possible to predict the mean drop diameter of the spray produced by these nozzles when spraying 100 octane gasoline and obtain the curves shown in Figure 18. The limits shown do not necessarily include the entire series of nozzles of this type, but in order to attempt a first correlation of mean droplet diameter with combustion, it is necessary to assume that it is possible to interpolate between these limits to obtain the mean diameter produced by a series of nozzles of varying flow rates or of the same flow rate and varying spray angles.

The combustion efficiency of a burner is not necessarily a criteria of the effect of varying the drop-size distribution, so it is necessary to evaluate such effects by some criteria of the reaction rate or by comparison with vaporized fuel. Figure 19 is such a comparison and Figure 20 shows the "additional" chamber length which would be required to complete combustion. It is not intended to present these data as the finished product but rather as conclusive evidence of the trend that may be expected in combustion chambers equipped with poor atomizing systems which are required to operate at low temperatures.

WEIGHT FLOW DISTRIBUTION

The weight flow distribution curves obtained on the pressure atomizing nozzles are related to the physical properties of the sprayed fluid, nozzle operating pressure, and to the physical dimensions and configuration of the internal components of the nozzle. The combined effects of these factors become evident in the shape of the sheet of liquid appended to the orifice and from which atomization actually occurs. At low pressure, where the centrifugal forces imparted to the fluid by the tangential slots are low compared to the surface tension, the liquid may take the form of an elongated hollow bulb which is closed at both ends with the drops forming at or below the closure point. Under this condition, the direction of movement perpendicular to the orifice axis when compared to the direction of flow at exit from the orifice, is actually reversed before atomization occurs. This component of motion is retained in the spray to produce the so-called reverse-flow hollow cone spray. This phenomena is more readily apparent in nozzles designed to give high spray angles, but nozzles designed for low spray angles may produce two such bulbs, one appended to the other, if the pressure is sufficiently low. As the pressure is increased, the bulb gradually opens up until atomization is occurring approximately half way up the "bulb," but the tangent at that point is nearly parallel to the axis of the nozzle orifice. Under these conditions, the weight flow distribution attains a solid cone center peak condition. Further increases in pressure cause the "bulb" of liquid to open still further until it stabilizes itself as a hollow cone which is relatively thick at top and tapers to a fine edge at the open end. At this point the weight flow distribution also becomes relatively stable, showing only slight changes for comparatively large pressure increments. It is seen that this pressure represents the point at which the physical properties of the sprayed fluid have little effect on the shape of the weight flow distribution curve, due to the comparatively high centrifugal forces imparted to the fluid by the nozzle components.

Figure 21 shows the variation in weight flow distribution as the pressure changes from 10 to 400 psi. These data were obtained at three (3) inches from the orifice, when spraying dyed water, and are typical of these nozzles. The rapid changes in distribution, which are invariably obtained through the low pressure region, are clearly shown. It is noted that a minimum pressure of approximately 100 psi is required in order to obtain a stable spray. This can be important if changes in local fuel/air ratios nozzle supply pressure changes are detrimental.

EFFECT OF DISTANCE

Changes in weight flow distribution with increasing distance from the nozzle, which are shown in Figure 22, are relatively small within the region of interest. The comparatively gentle curve obtained at six (6) inches is the result of droplet dispersion and a change in the percentage of the total spray represented by each tube -- particularly those near the outer edge of the cone. This eliminates the possibility of using a small and simple mixing chamber in order to obtain a uniform distribution of the liquid in the air and tends to complicate the design of the mixing section.

EFFECT OF FLUID CHARACTERISTICS

Since the weight distribution histograms may be obtained for most liquids, it was possible to obtain a direct comparison between gasoline and the standard fluid. Once again, the distribution curves change very rapidly in the low pressure region but become quite similar at higher pressures. This is shown in Figure 23. Comparing the gasoline curves to those obtained with dyes water, it is seen that the only basic difference between the two sets of data is the nozzle supply pressure, and further, that the spray angle at which stability is attained is essentially the same, even though the physical properties of the two liquids are different.

Although the actual histogram is the only true representation of the weight flow distribution, it is possible to approximate this curve for a symmetrical spray by means of two basic criteria, i.e., spray angle and the "peak to center ratio."* When plotted as a function of pressure, these two variables produce curves such as are shown in Figure 24, which compares gasoline with the standard fluid and includes three dotted curves which were approximated from test data obtained with liquids having different values of surface tension.

EFFECT OF AIR VELOCITY

The investigation of the effect of air velocity on weight flow distribution has just been initiated and only the results of the first configuration tested are shown in Figure 25. In this set-up, a single nozzle was mounted in the center of the tube spraying downstream. It is seen that air velocities up to 87 ft/sec have a negligible effect on the fuel distribution, except at very low nozzle pressures.

COMBUSTION EFFECTS

It is doubtful that the weight flow distribution of a nozzle has any appreciable effect on the local combustion reaction; however, several secondary factors, resulting from the initial fuel distribution pattern, must be considered in the design of a combustion chamber.

In any flow system the first of these is the relative constancy of the fuel distribution curve supplied to the combustion zone. Even though this may not be a uniform distribution, it is still possible to control local fuel/air ratios in the reaction zone and supply near optimum mixtures to the ignition under all operating conditions. The actual distribution curve is also important, since in combination with the velocity distribution it determines the variation of local air fuel ratios and what might be called combustion chamber "space efficiency."

It is suggested here that the optimum condition may be obtained when the local fuel/air ratios across the combustion chamber inlet are constant and that the velocity limit may be increased when the fuel distribution and air velocity profiles are uniform. Several configurations which incorporate these conditions are being built and will be tested.

* Peak to center ratio is tentatively defined as the ratio of the maximum unit flow rate to the unit flow rate at the center of the spray.

APPENDIX INDEX

A. Definition of Spray Characterics

B. Cell Coatings and Immersion Fluids
(Depth of Imm. Fluid)

C. Group Size Limits

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S. M. Doble
Engineering, Jan. 12, 1945

(2) Report on Fuel-Atomizer Nozzles

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Feb. 40. Germ. Secret

(3) Fuel Oil Atomization

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Castleman

Jour. of Res. of Bureau of Standards,
6, 369, 1931

PHOTOGRAPHS, CURVES, AND CHARTS

FIGURE 12

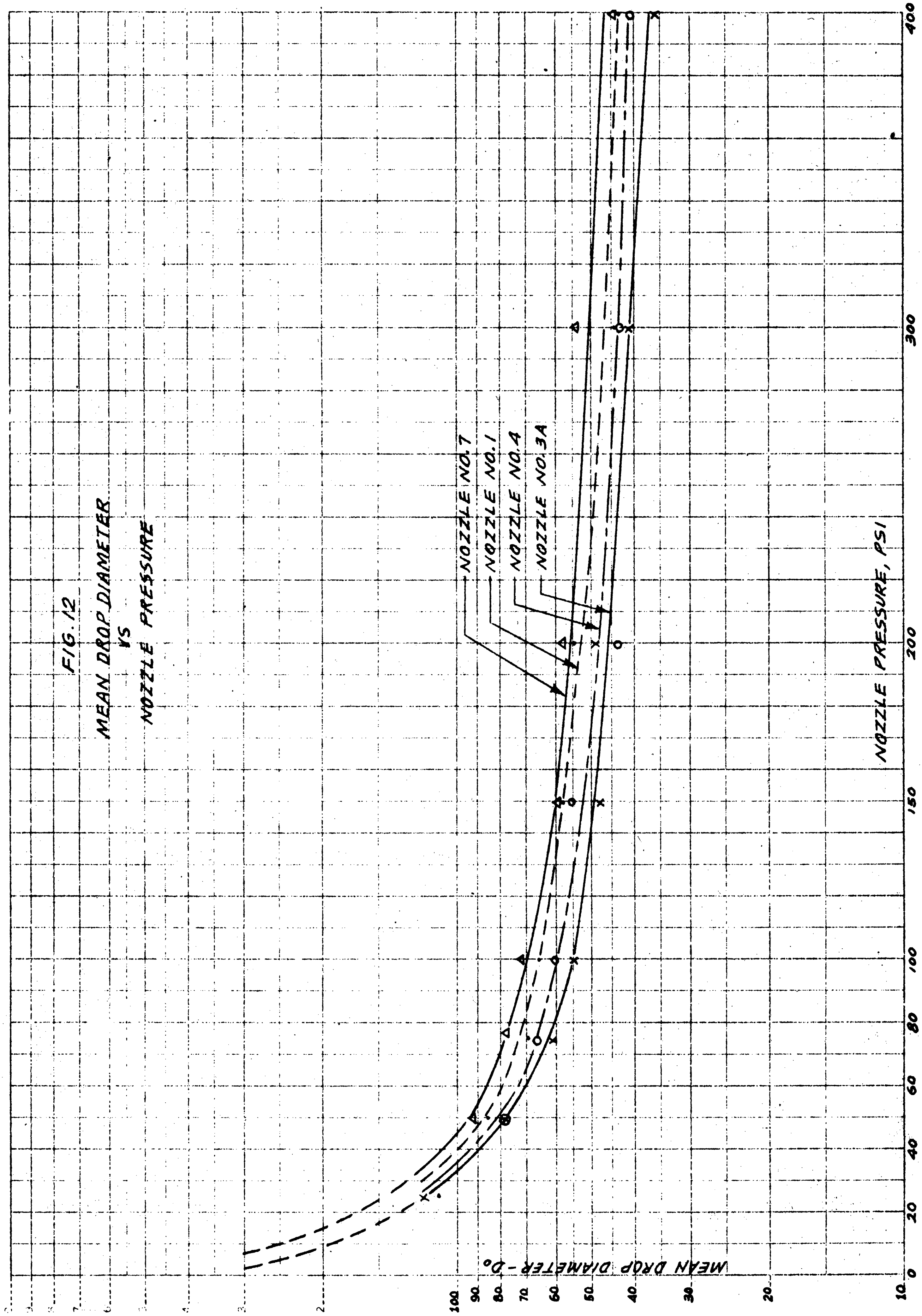
FIG. 12
MEAN DROP DIAMETER
VS
NOZZLE PRESSURE
NOZZLE NO.7
NOZZLE NO.1
NOZZLE NO.4
NOZZLE NO.3A
NOZZLE PRESSURE, PSI
MEAN DROP DIAMETER - Do
0
20
40
60
80
100
150
200
300
400
10
20
30
40
50
60
70
80
90
100

Analysis Drop Size Distribution
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Date 11-30-48

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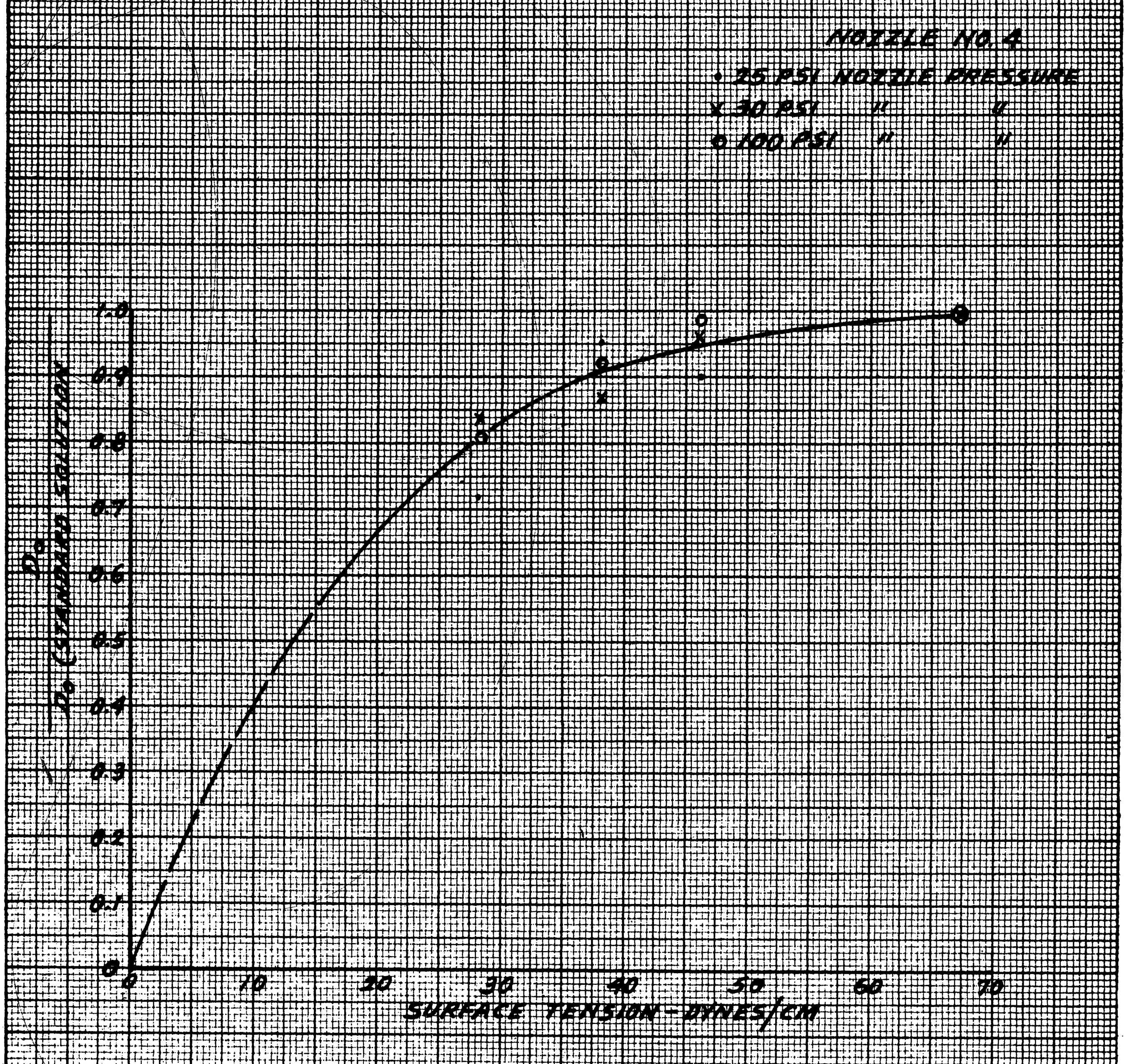
FIG. 13
EFFECT OF SURFACE TENSION
ON
MEAN DROP DIAMETER



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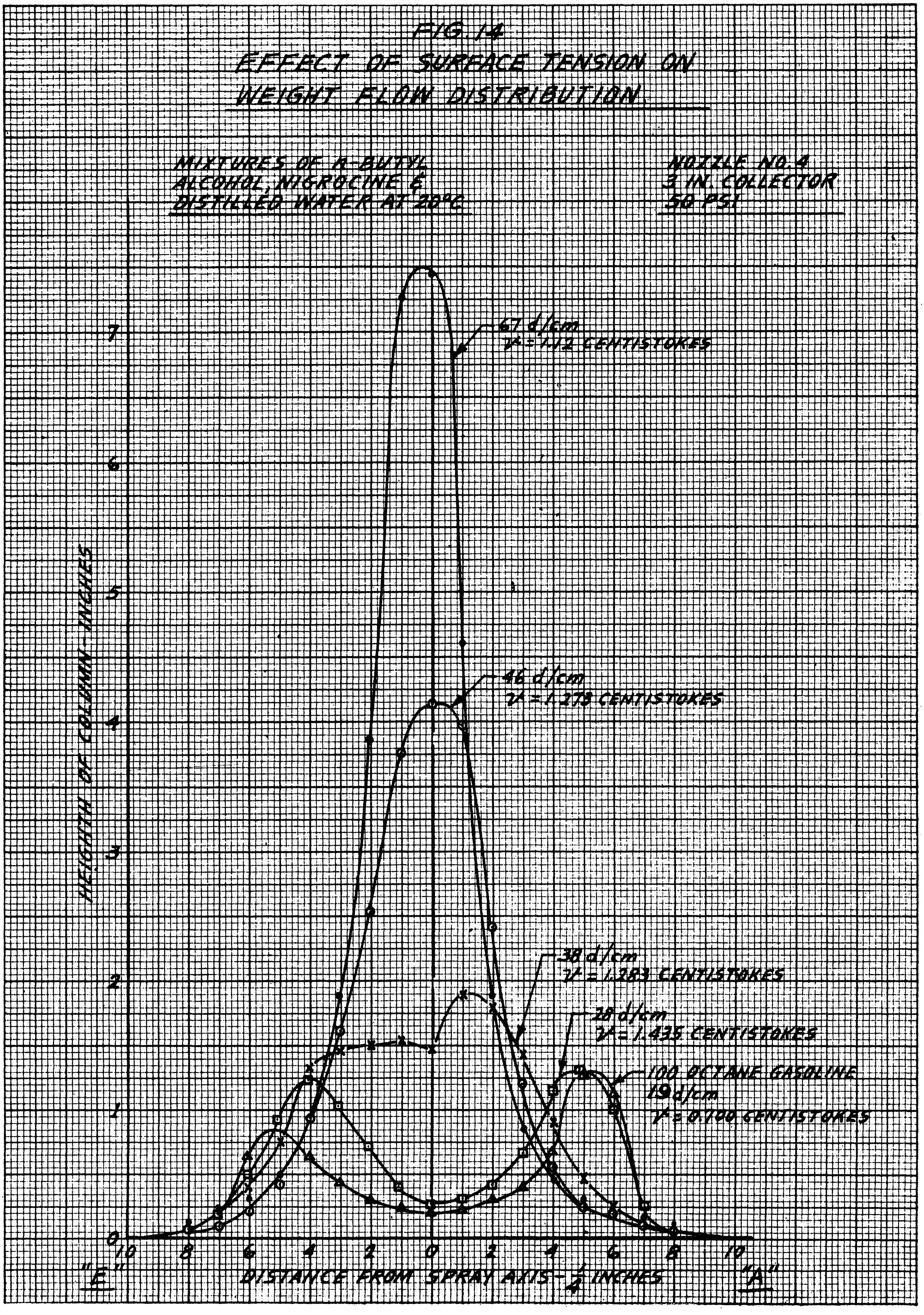

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Page FIG. 15
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FIG. 15

EFFECT OF VISCOSITY ON MEAN DROP DIAMETER

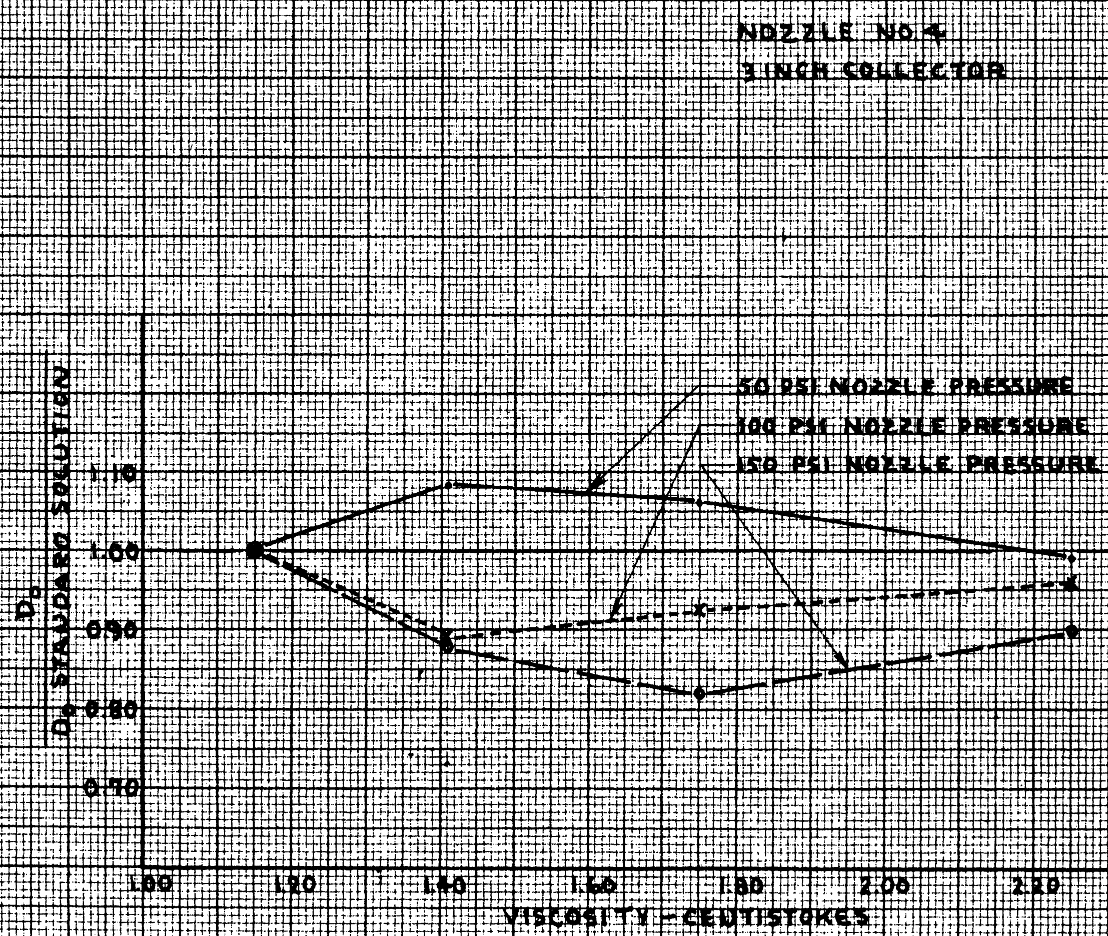

FIG. 16

DROP SIZE DISTRIBUTION
EFFECT OF DISTANCE FROM NOZZLE

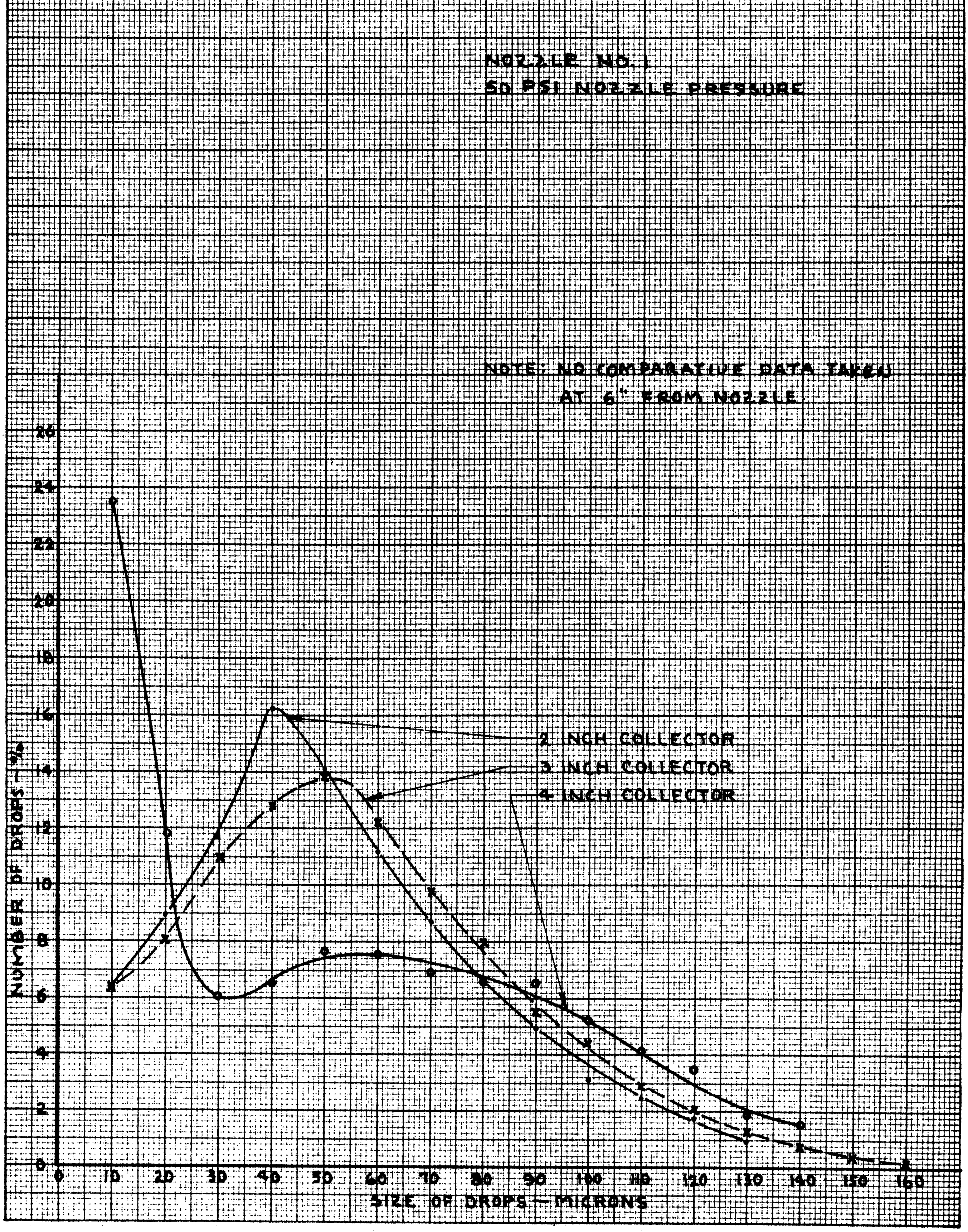

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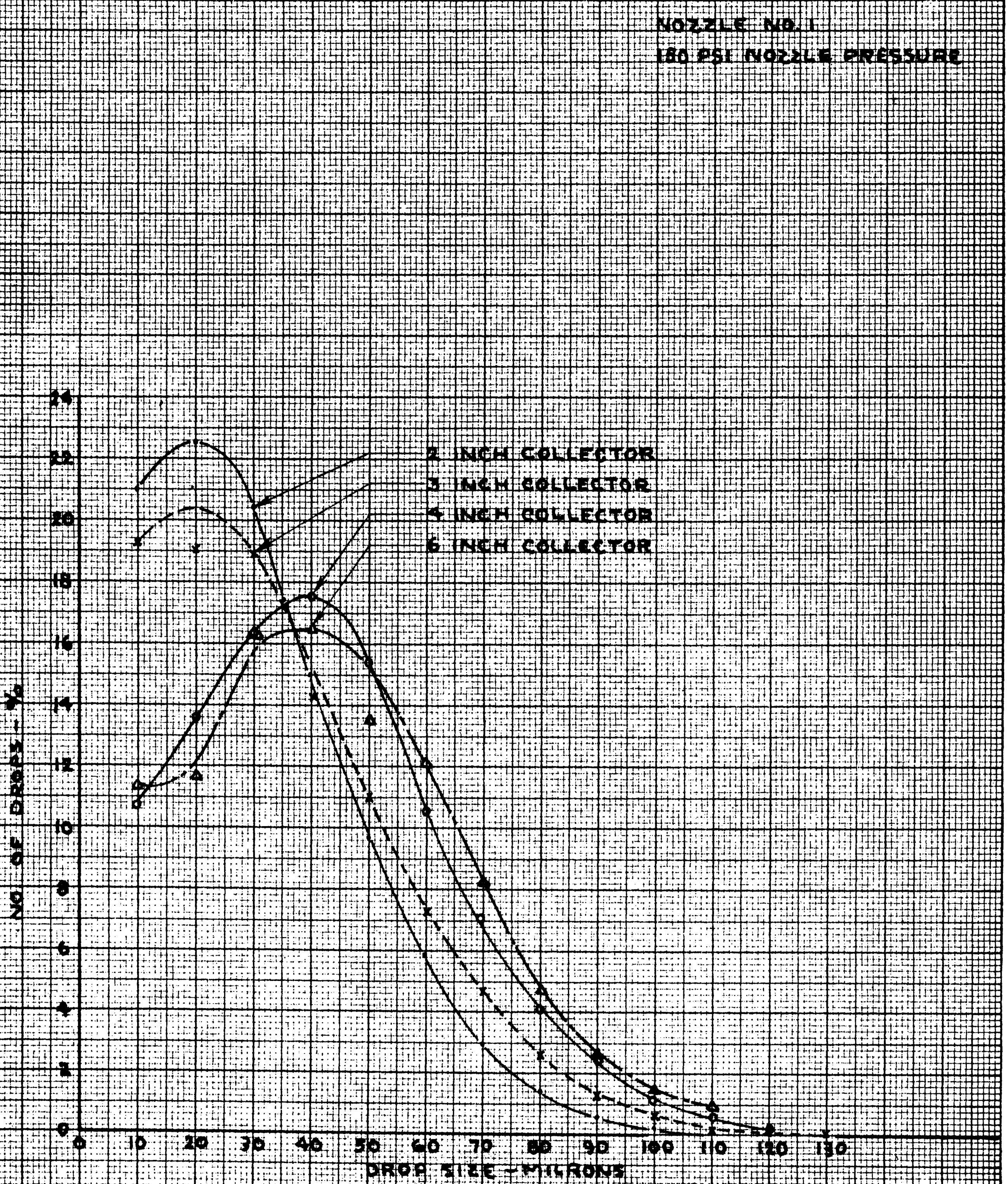
FIG. 17
EFFECT OF DISTANCE ON DROP SIZE DISTRIBUTION



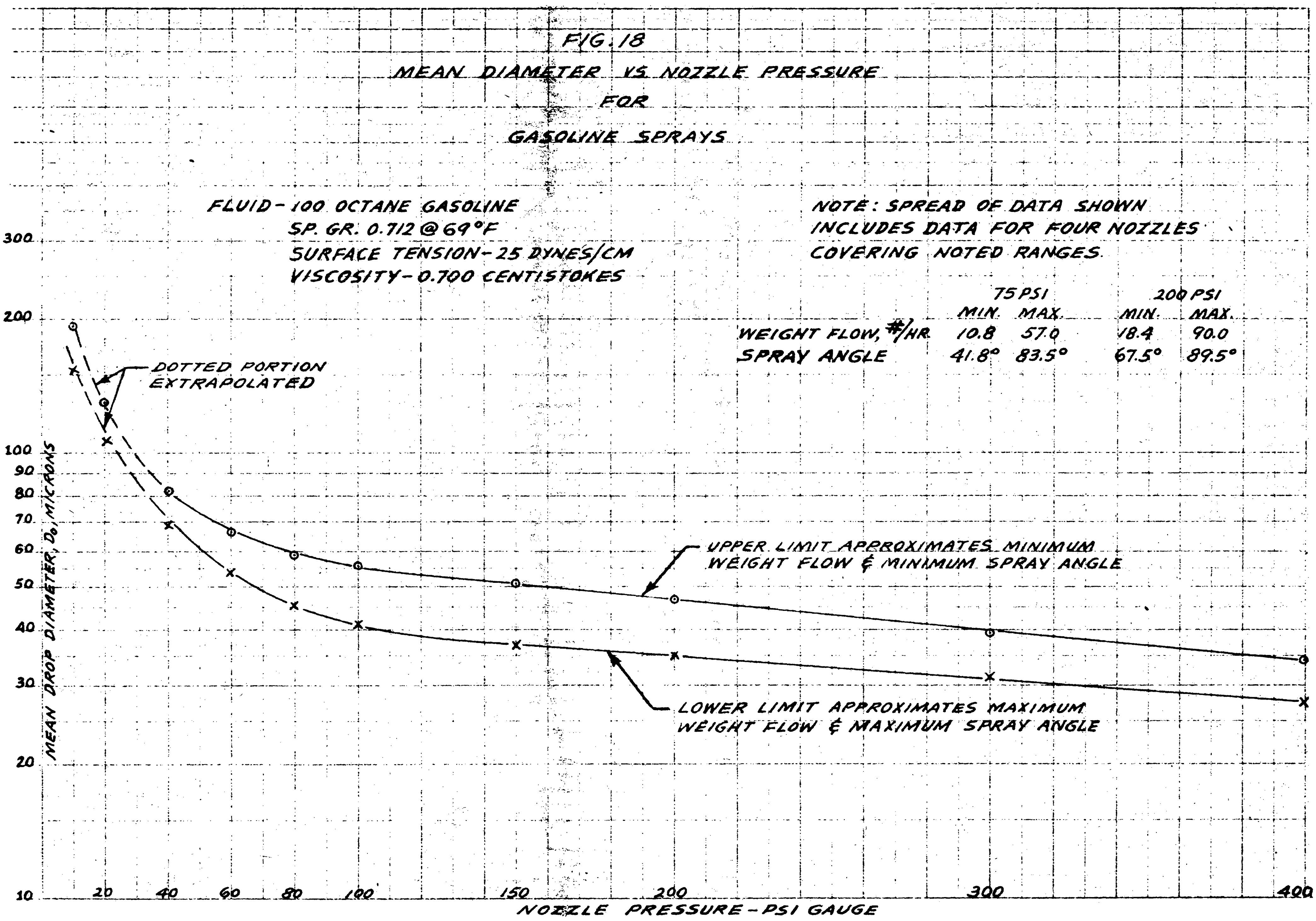


FIG. 18
MEAN DIAMETER VS NOZZLE PRESSURE
FOR
GASOLINE SPRAYS
FLUID - 100 OCTANE GASOLINE
SP. GR. 0.712 @ 69°F
SURFACE TENSION - 25 DYNES/CM
VISCOSITY - 0.700 CENTISTOKES
NOTE: SPREAD OF DATA SHOWN
INCLUDES DATA FOR FOUR NOZZLES
COVERING NOTED RANGES.
75 PSI
200 PSI
MIN. MAX. MIN. MAX.
WEIGHT FLOW, #/HR 10.8 57.0 18.4 90.0
SPRAY ANGLE 41.8° 83.5° 67.5° 89.5°
DOTTED PORTION
EXTRAPOLATED
UPPER LIMIT APPROXIMATES MINIMUM
WEIGHT FLOW & MINIMUM SPRAY ANGLE
LOWER LIMIT APPROXIMATES MAXIMUM
WEIGHT FLOW & MAXIMUM SPRAY ANGLE
MEAN DROP DIAMETER, D_0, MICRONS
300
200
100
90
80
70
60
50
40
30
20
10
20
40
60
80
100
150
200
300
400
NOZZLE PRESSURE - PSI GAUGE

FIG. 19

EFFECT OF MEAN DROP DIAMETER ON BURNING PERFORMANCE AT CONSTANT MASS FLOW (565 LB/HR AIR AND 37.3 LB/HR AN-F-28 FUEL) AT VARIOUS INLET AIR TEMPERATURES

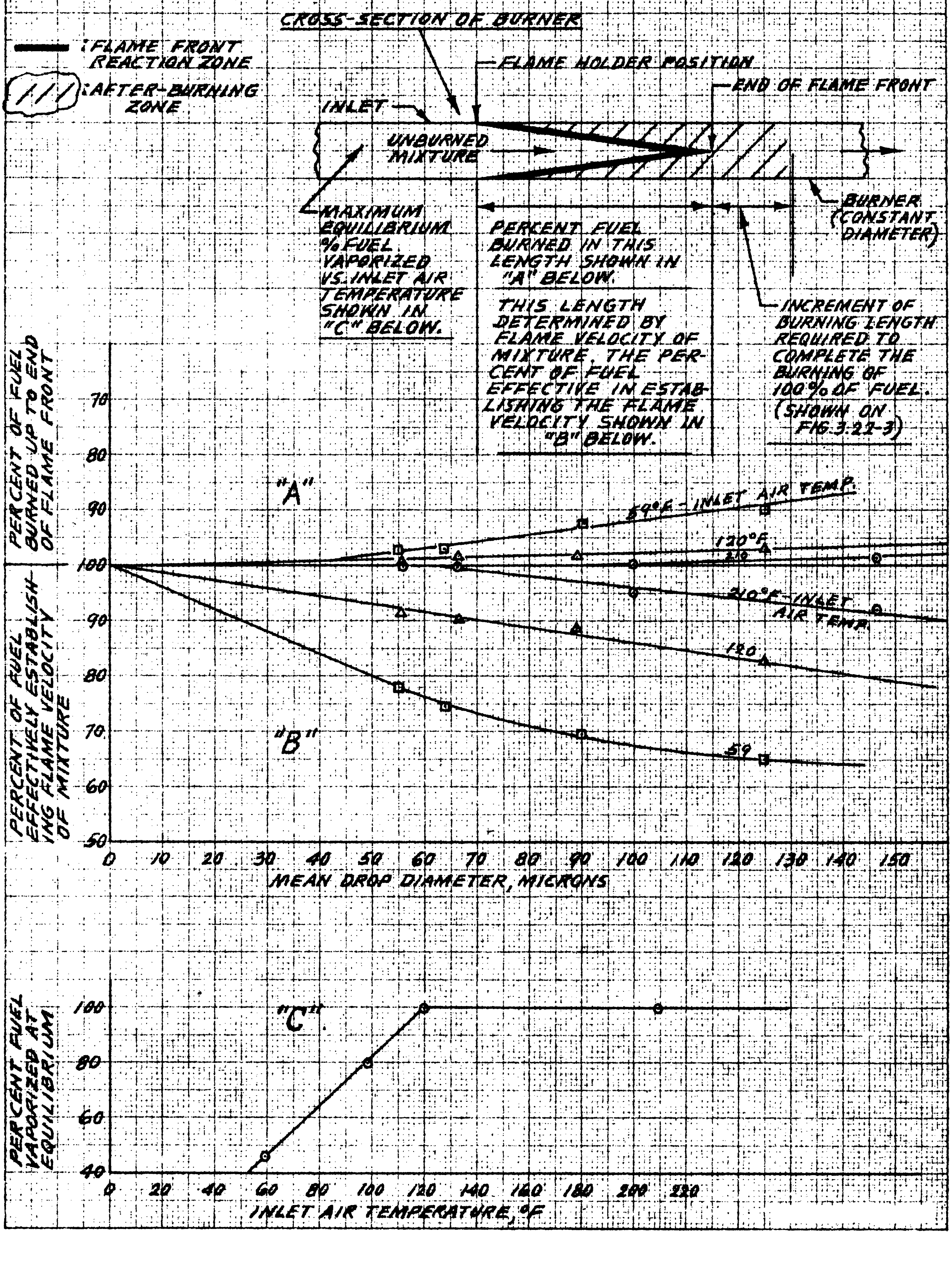
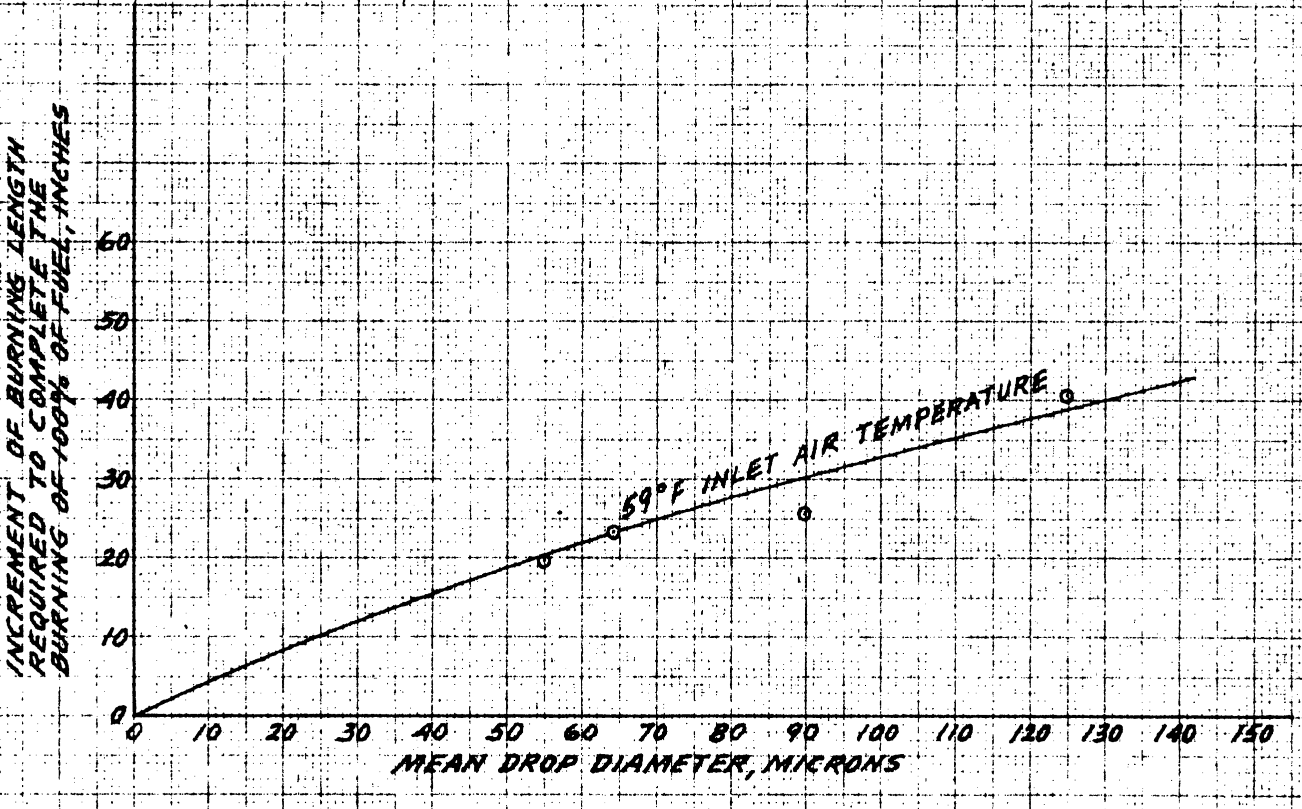


FIG. 20
EFFECT OF MEAN DROP DIAMETER
ON BURNING PERFORMANCE
(CONTINUED FROM FIG. 19 - ABOVE)



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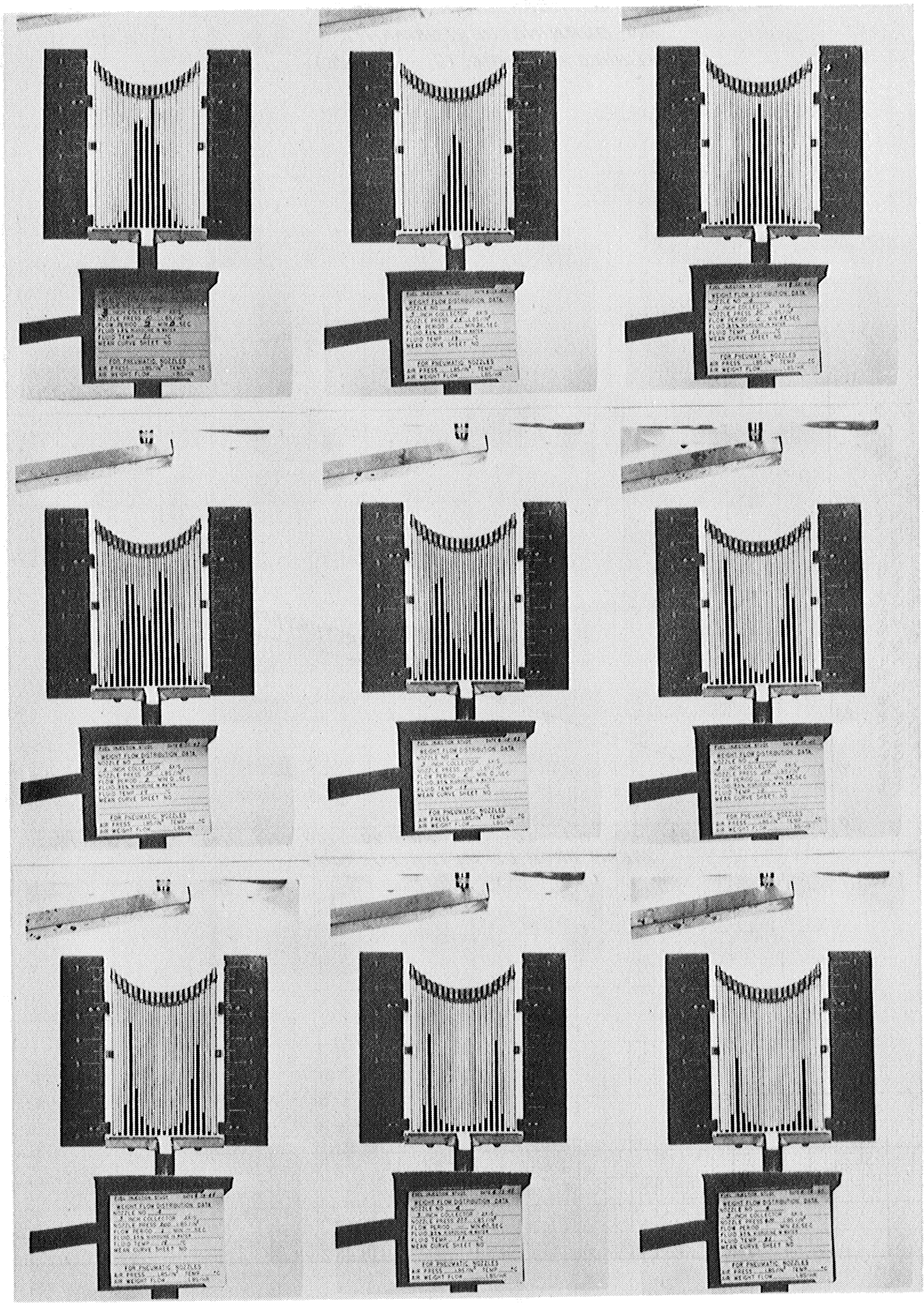
PAGE: FIG. 21

DATE: 6-4-48

MODEL:

TITLE: Weight Flow Distribution - Nozzle No. 4, Axis A-E, 10 - 400 PSI

REPORT NO.



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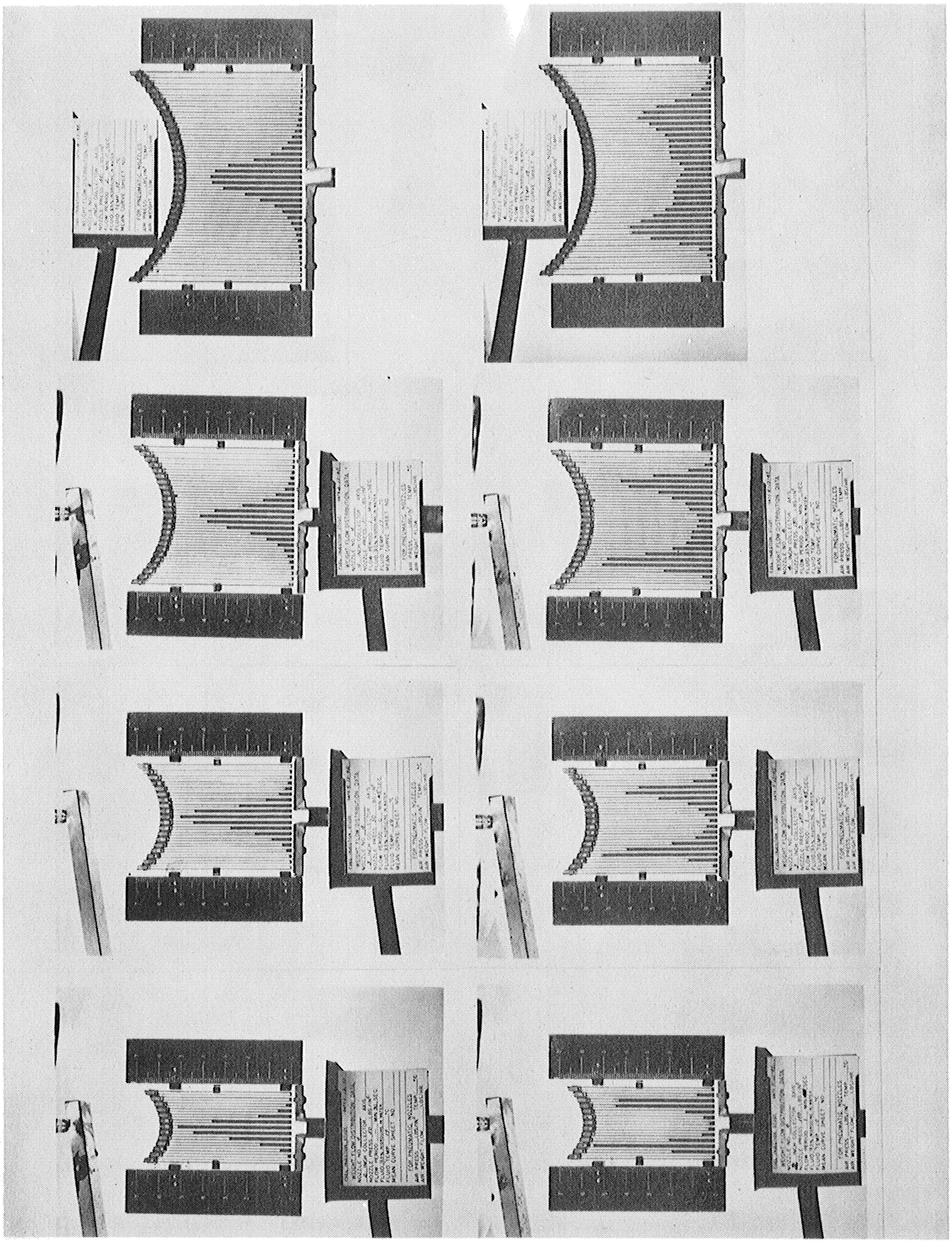
PAGE: FIG. 22

DATE: 3-1-49

MODEL:

TITLE: WEIGHT FLOW DISTRIBUTION - EFFECT OF DISTANCE
NOZZLE NO. 4 AT 50 & 150 P.S.I.

REPORT NO.



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DATE: 3-1-49

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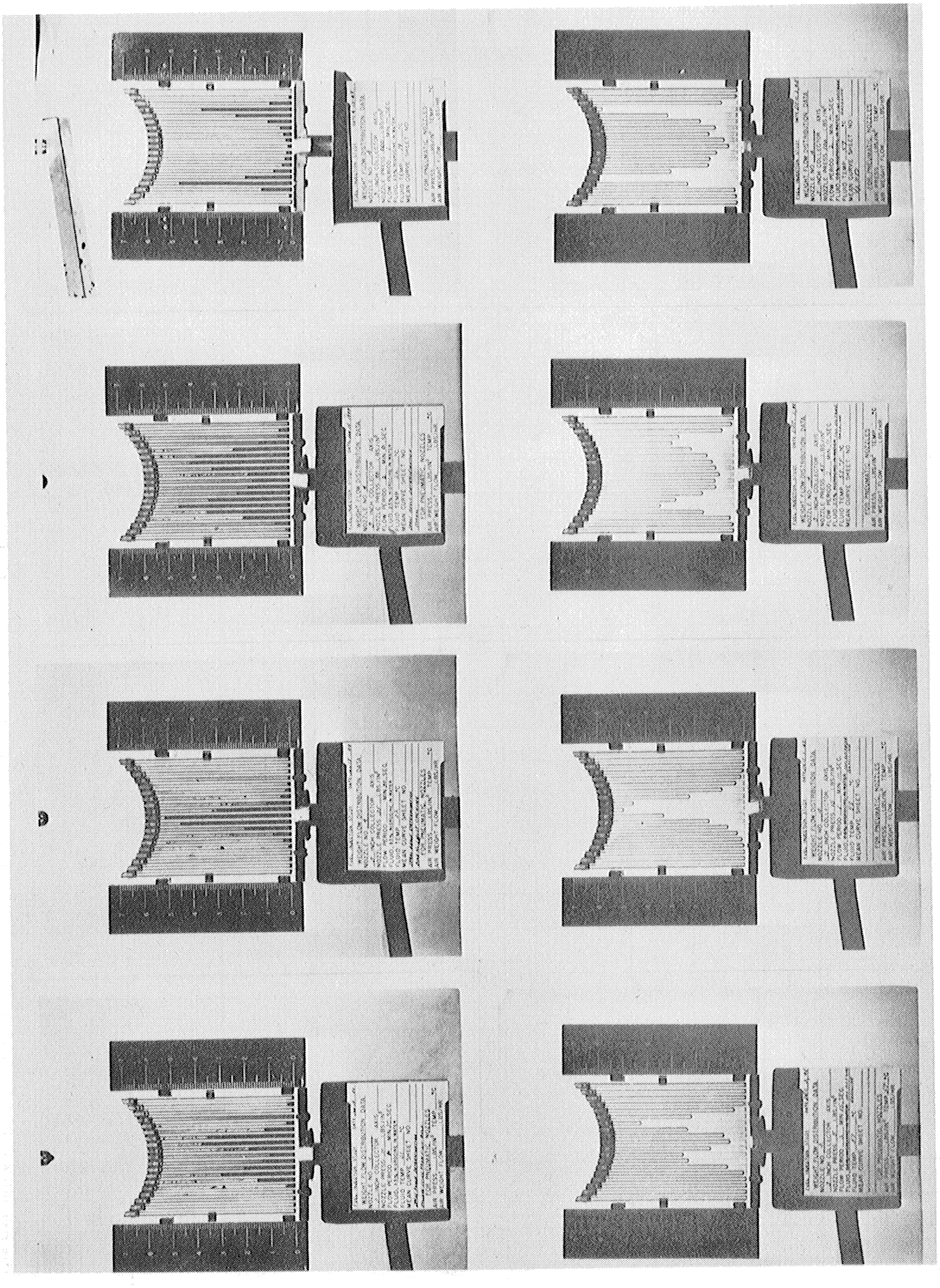
PAGE: FIG. 23

MODEL:

REPORT NO.

TITLE: WEIGHT FLOW DISTRIBUTION - GASOLINE VS. STANDARD SOLUTION



Analysis Spray Characteristics
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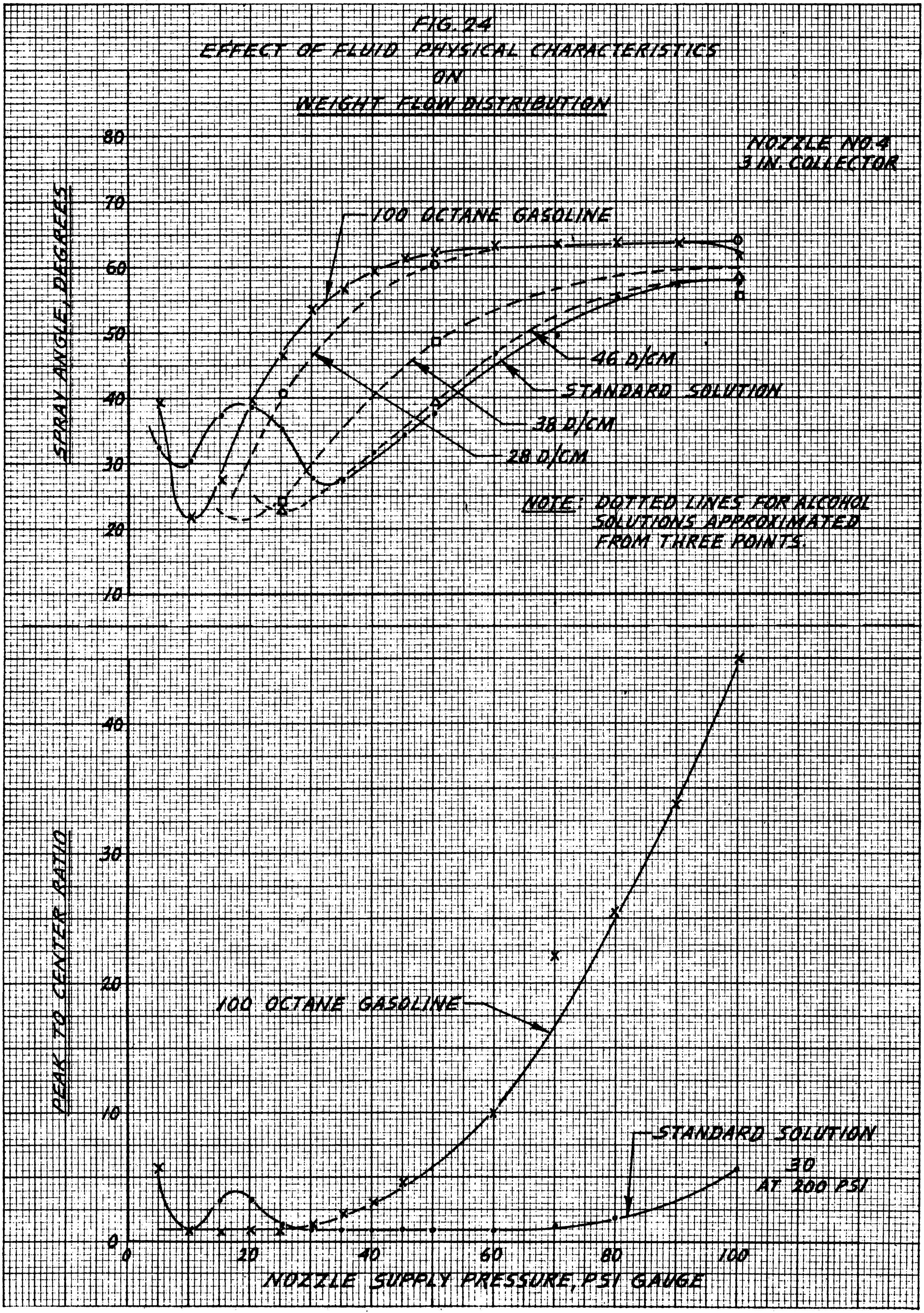

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PAGE: FIG. 25

DATE: 3-1-49

MODEL:

TITLE: WEIGHT FLOW DISTRIBUTION - EFFECT OF AIR VELOCITY CENTER MOUNTED NOZZLE SPRAYING DOWNSTEAM

REPORT NO.